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Dhruv Sen Singh *Editor*

The Indian Rivers

Scientific and Socio-Economic Aspects

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To a great human being, an excellent teacher
and a renowned social worker, my father,
Shri Bhadra Sen Singh.

Foreword 1

Since the birth of civilization India has been a land where its people have bonded with rivers. Religious scriptures mention how the Ganga gushed out from the holy frozen land and how ancient cities arose on its banks as it made its way leisurely to the sea. This book is unique as it pays much needed attention to the history and perception of rivers in mythology and ancient civilizations. This fascination with rivers continues today as more and more is learnt scientifically about them: All rivers have character, and some have cut through the mighty snow-capped Himalaya and fled to the ocean blue; other iconic rivers that were once believed to have been lost are now believed to have been found, still others occur as seasonal streams fed by the monsoon rains, living short lives before they are lost in the wilderness. Yes indeed, rivers have been the very lifeline of our existence creating fertile soils and helping man to till the land, feed him by its produce and help him to navigate great distances with ease. But they have also caused considerable loss when they have broken their banks in flooding sheets of water to cause mass destruction. The last 150 years have been crucial in upsetting their natural flow established over centuries as man manipulates and regulates them for his personal needs by building dams, barrages and reservoirs.

The current book is exemplary as it tries to cover all the major river systems of the country and is written by well-known experts in the field who have devoted their lives to the study. Each drainage system is analytically examined with regard to dynamic fluvial parameters, geomorphology and societal implications. The pride of place of course goes to the Ganga. The Brahmaputra and the Yamuna receive nearly equal attention. The minor rivers of the Indo-Ganga Plain are also discussed in detail. The Son is an important river that flows through central India through mainly the Vindhyan rocks and deserves special mention as does the Narmada. The East Coast rivers such as the Mahanadi, Godavari, Krishna and Cauvery are described in detail along with their basin characteristics. One of the most interesting sections is that on the Tethyan Himalayan drainage systems in Ladakh, Lahaul and Spiti, including those of the Jammu and Kashmir region. The rivers of the Subcontinent's North-East region have a chapter devoted to them.

This contribution is unique as it collects at one place all relevant data on the major and minor fluvial systems of the country and will form an invaluable asset to all those who wishes to read the subject either for pleasure or for knowledge. Professor Dhruv Sen Singh deserves special praise for marshalling resources and experts to come up with such an excellent presentation which serves both as a ready reference as well as a book that the common man will cherish.

Lucknow, India

Prof. Ashok Sahni
FNA, FTWAS

Foreword 2

I am happy to know that Dr. Dhruv Sen Singh, Professor of Geology, Centre of Advanced Study in Geology, University of Lucknow, is editing a book on "Indian Rivers: Scientific and Socio-Economic aspects". It gives me immense pleasure to write a few words before the book appears in print.

Rivers have vastly influenced man's life from time immemorial. They have played an important role in the development of human culture in every part of the world. Besides supplying drinking water, they are urgently required for industries and other developmental projects. Our civilization, as we see it today, would not have progressed far without rivers. Battles have been fought for gaining access to and using river waters for generations. As a result, rivers have become an integral part of many international meetings and political agenda of several states and countries. Sharing of river water has always been a major issue amongst the neighbouring states of our country.

In view of the above, any book on rivers would always be welcome. I hope the book will be relevant in the context of India's developmental work. Our agrarian economy is almost solely dependent on rivers. Our government, both State and Central, therefore, place rivers on the top priority in their agenda. They frame policies for maximum utilization of river water in a judicious manner for the benefits of citizens in urban and rural areas. For this purpose, an updated database on all rivers is a major requirement.

It is also very interesting to learn that all the 37 chapters have been contributed by experts from Universities, IITs and National research institutions from all parts of the country. It presents geomorphological studies of the major river basins—the Indus, Ganga and Brahmaputra and their tributaries. Besides major basins, the book explores peninsular rivers and other rivers state-by-state and so it includes all types of rivers, i.e. snow-fed, rain-fed and groundwater-fed rivers. The proposed book is going to be the first book in the world which gives expert opinion on all major rivers of a country such as India.

I hope that the proposed book would provide useful information on Indian rivers. Apart from providing updated information on several major Indian rivers from all the major geographic segments, it incorporates results of studies into various rivers by different experts from various disciplines. The book can be an excellent source to provide essential information on Indian rivers to students, teachers, researchers, planners and common public with a sound and updated scientific and socio-economic base. I wish a great success for the book.

New Delhi, India

Prof. Ashutosh Sharma
Secretary, Government of India
Ministry of Science and Technology
Department of Science and Technology

Foreword 3

I note with immense pleasure that a great initiative of presenting the updated information on the rivers of our country has been undertaken by Prof. Dhruv Sen Singh of Centre of Advanced Study in Geology, University of Lucknow, Lucknow. I hope that the book entitled ‘The Indian Rivers: Scientific and Socio-Economic Aspects” will help to students, researchers, teachers and planners of our country.

Being an integral part of man’s life, rivers have affected human civilizations since the earliest times. It is well known that people everywhere and everyday are dependent on it for their survival. Rivers are the life giver, cleanser and purifier and are also regarded very important to society in the context of spirituality.

Keeping in view the importance of rivers, any book on the rivers is always welcome. The book presents the geomorphological and socio-economic aspects of all the major rivers of India written by experts working on Indian rivers. The three river basins of India (Indus, Ganga and Brahmputra), their major tributaries, peninsular rivers and state-wise rivers have been explained. Besides, the chapters on Saraswati river, rivers in history and rivers in Hindi literature have also been added to provide overall information on rivers at a single place. All the chapters have been authored by Professors of Universities, IITS and Scientists of Indian Research Institutions.

Rivers, being one of the most sensitive components, their importance has increased multifold in environmental reconstruction. In modern era of industrialization and development which has brought us to the brink of disaster, we need an initiative to keep the common man aware of the contemporary situation of different rivers in the country and a perspective to retain a balance of riverine environment and development.

India is a country blessed with numerous rivers (referred to as the “Land of rivers”) which bestow upon human society their utmost benefits be the social, religious and industrial. The book is an excellent compilation on rivers and their associated environments and utilization aspects. It will serve as a good reference on Indian rivers for those working on geological aspects and environmental development in the country.

I do hope the book acts as an eye-opener about responsibilities towards rivers which have been polluted and are in bad shape due to widespread urbanization, loss of the aesthetic sense as a result of discharge of industrial waste and excessive deplantation on river banks.

I wish all success for the book.

New Delhi, India

Prof. Talat Ahmad
FNA, FASc., FNASc., JC BOSE Fellow
Vice Chancellor
Jamia Millia Islamia

Preface

While working on rivers I have realized that all researchers, teachers, students and planners are providing different basic information about the rivers. There is not a single book which provides information at a single place about all the rivers. This compelled me to think about editing a book on rivers where one could get basic, accurate and precise information from a single source. And the effort is before you in the form of a book entitled "The Indian Rivers: Scientific and Socio-Economic Aspects", which would be the first book in the world to provide information about all major rivers of a country at a single source.

Water is the basic need of our survival, thus rivers are believed to be our lifeline. In India, different types of rivers with unique characteristics are present. India is a land of rivers, where rivers are worshipped like a mother. Rivers are a renewable natural resource. In view of this unique feature of the rivers, all ancient civilizations and cities of the world evolved and flourished near the banks of the rivers. For humans, rivers have become a way of life as they affect and control our culture, development and civilization. I have been privileged to see three rivers since my childhood (Chhoti Gandak, Rapti and Ghaghara) as they are situated within a periphery of about 10 km from my native place, Ropan Chhapra in Deoria district of Uttar Pradesh. Later, I got an opportunity to see and walk along all the major rivers of the Ganga Plain from their source to sink. Starting from the Gangotri Glacier where the Bhagirathi originates and the Satopanth Glacier, where the Alaknanda originates, up to the Kosi confluence with the Ganga in Bihar, I have seen all the confluences of the Ganga with its tributaries such as the Ramganga, Yamuna, Gomati, Ghaghara, Son, Great Gandak, Burhi Gandak and Kosi.

We are trying to understand the behaviour of the rivers, their dynamics, their science, their socio-economic aspects and also about what they expect from us. I have seen rural folk fully devoted to rivers from morning till evening throughout their lives because of their respect and love for nature. They understand the behaviour of a river in totality and in a better way than urban and educated people.

Natural factors everywhere have controlled and guided man, but this is for the first time in the 4.6 billion year history of earth that man is also affecting the natural factors up to some extent since the last century, and this a matter of great concern to all of us. These days rivers are causing loss of life and property due to the interference of man in its natural cycle. The encroachment of man has polluted the water, disturbed the ecosystem, changed the transporting capacity, and increased the sediment load of the river, which in turn has changed the river dynamics, ultimately leading to increasing number of disasters. India has 2.45% of the world's land area, 16% of the world's population and 4% of the world's water resources. The continuously increasing population and rapid urbanization, together with the climate change are resulting in water scarcity in many parts of the country. Therefore, there is an urgent need to ensure sustainable development of the rivers with proper management. We need to take necessary measures for optimal utilization of the rivers, making them free from all kinds of pollution and degradation. All sections of the society have to work together to address the environmental issues and the challenges facing the river sector.

Professors and Scientists from different universities, IITs and National Research Institutions with considerable experience have authored 37 chapters on various rivers. The book contains chapters on all types of rivers and their basin such as Ganga basin, Indus basin, Brahmputra basin and their tributaries, and Himalayan rivers, Ganga Plain rivers, Peninsular rivers, and also the rivers of ancient India, Hindi literature, and the Saraswati River. I hope this book will serve its main purpose of providing basic scientific and social information about all major Indian rivers to teachers, students and the common public. I am thankful to all the authors for their valued contributions.

During my journey from student stage to this stage as a teacher, I have learnt a lot from my mentors, students and society. The first chapter 'Concepts of River' is the manifestation of the same journey. I hope that this book will be accepted by all in its present form. I am looking forward to hearing from you and receiving your suggestions for improvement.

Lucknow, India Dhruv Sen Singh

Acknowledgements

I am highly thankful to the authors of the various chapters from different universities, IITs and national research institutions from all parts of the country who have contributed the chapters for a great academic and social cause. I am highly thankful to Dr. A. Sharma, Secretary, Department of Science and Technology, New Delhi, Prof. Talat Ahmad, Vice Chancellor, Jamia Millia Islamia University, New Delhi and Prof. Ashok Sahni, Lucknow for sparing their valuable time in writing the foreword of this book entitled "The Indian River: Scientific and Socio-Economic Aspects". I am grateful to my teacher, Prof. I.B. Singh, who inspired and trained me to understand the rivers and their importance. Prof. Ashok Sahni, Prof. M.P. Singh, Prof. N.L. Chhabra, Prof. A.K. Jauhri, Prof. A.R. Bhattacharya, Prof. K.K. Agarwal. Prof. R. Bali, Prof. M. Singh (CAS in Geology, University of Lucknow), Dr. Pradeep Srivastava, Dr. Jayendra Singh (WIHG, Dehradun) and Prof. U.K. Shukla (Geology Department, BHU) are thanked for their constant encouragement. Prof. Ashok Srivastava, Head, Geology Department, Amarawati University, Maharashtra helped at various stages in editing the book. The colleagues and students of the Centre of Advanced Study in Geology, University of Lucknow are thanked for their unstinted support. My students, Dr. Amit Awasthi, Dr. Vikram Bhardwaj, Dr. Bishwajeet Thakur, Dr. Dhirendra Kumar, Mr. Kailash, Dr. Nishat, Mr. Chetan Anand Dubey, Mr. Balkrishna and Mr. Neeraj Kumar are thanked for their help at various stages during the editing of the book. Department of Science and Technology, Government of India, New Delhi, and Higher Education, Government of Uttar Pradesh, Lucknow are acknowledged for financial assistance to work on rivers and the Ganga Plain. I am thankful to my undergraduate and postgraduate students who interacted and insisted me to write the basic concepts of the river.

I am thankful to many people from my place of Birth Ropan Chhapra, Deoria district of Uttar Pradesh, who have travelled with me through the ever changing terrain of the various rivers. My mother Smt. Jagdamba Singh, wife Mrs. Meena Singh, daughters Sansriti Sen and Ananya Sen and brother Dr. Chandra Sen Singh who motivated me to write this book are highly acknowledged. The book is dedicated to a great human being, an excellent teacher and a renowned social worker my father, Shri Bhadra Sen Singh.

Contents

About the Editor

Dr. Dhruv Sen Singh is an eminent Professor and a renowned teacher at the Centre of Advanced Study in Geology, University of Lucknow, India. Dr. Singh has 21 years of experience in teaching and research, primarily in the areas of climate change, glaciology, Quaternary geology, rivers of India (Ganga Plain) and natural hazards. He has published over 50 research papers in international and national journals and presented several papers in International and National conferences. He has edited and authored four books and supervised ten Ph.D. students. While working on the Gangotri Glacier, he has observed some important geological phenomena and concluded in the year 2001 and again in 2016 that retreat of a glacier is controlled by glacier and local characteristics apart from global warming and so there is no threat to the Gangotri glacier. On the basis of this observation and geological records, he explained that melting of glaciers and climate change is a natural process and had taken place earlier during the history of the earth much before the evolution of man on the planet earth. He also identified lateral erosion as a new fluvial hazard in the year 2011. He was also involved in developing the model for evolution of the Ganga Plain foreland basin. He explained and highlighted in 2002 in the Gangotri Glacier area and again in 2014 in the Kedarnath area that how the landforms and landscape in a glaciated terrain are modified by secondary processes. He is actively involved in the scientific, mainly geological knowledge dissemination and trying his best to apply Geology for the human welfare.

Dr. Singh was a member of the first and second Indian Expedition to the Arctic (North Pole Region) in 2007 and 2008. He is recipient of the Vigyan Ratna Award in 2010 by the Council of Science and Technology (CST), Government of Uttar Pradesh. His teaching capabilities and research work achieved new heights when the Department of Higher Education, Government of Uttar Pradesh, Lucknow, conferred him with the highest award of education ‘Shikshak Shree’ in 2013 and Saraswati Samman in 2014.

Concept of Rivers: An Introduction for Scientific and Socioeconomic Aspects

Dhruv Sen Singh

1 Introduction

Rivers are water bodies which flow in a definite direction in a channelized way and affect our culture and civilization. The rivers were the only source of water during the early phases of man's evolution. This is the reason why all the ancient civilizations evolved along the banks of rivers, e.g., the Indus Valley Civilization at Indus, Egypt at Nile, Babylon at Tigris, and Mesopotamia between Euphrates and Tigris and ancient cities also developed on the bank of rivers. Even in such a modern and scientific world, many of the cities are famous only because of the rivers which drain through them such as Haridwar, Rishikesh, Ayodhya and Varanasi etc. With the passage of time, humans interacted and started performing festivals, fairs, social and religious activities at the bank of the rivers. Many rituals are believed to be complete, only after taking a dip/bath in a holy river, even during adverse weather conditions. Taking a bath in a river, such as during the Kumbh Mela and Makar Sankranti, is not just a festival but it is a sense of responsibility of common citizens, as a tradition to sustain and preserve the rivers which are our lifeline. Later on, men established a day-to-day genetic relationship with the river, and in this way, the flowing water known as rivers became a way of life and icons of our culture. Therefore, they are regarded as our mother and are considered as lifelines.

During the initial phases of man's evolution, the population, urbanization, industrialization (cottage industry), and farming/agriculture were in equilibrium with the rivers and the environment. The rapidly growing population, urbanization, and industrialization are no longer in equilibrium with the river and its environment and thus, adversely affect the society and the lifeline river. In this way, the river which served as a boon has now become a bane to the society (Singh 2009).

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Man has been controlled and guided by natural factors everywhere but this is for the first time in the history of the Earth that man is also affecting and controlling the natural factors up to some extent since the last century, which is a matter of great concern to all of us. Indian rivers are characterized by narrow channels confined within the wide valleyes (Singh et al. 2010; Singh and Awasthi 2011a). Continuously increasing pressure of population growth on land has led to the intensification of settlement even within the floodplain and wide valley of the rivers. The encroachment of man within the natural cycle of river has polluted the water, disturbed the ecosystem, changed the transporting capacity, and increased the sediment load of the river, which in turn changes its dynamics. Hence, rivers cause loss of life and property due to the interference of man in its natural cycle (Singh and Awasthi 2011b).

Rivers are renewable natural resource, though their present situation is very critical. Therefore, we should plan for sustainable development and efficient management in such a way that the lifeline rivers can fulfill the growing demands of water and maintain their natural cycle.

Rivers are millions of years old whereas man (Homo sapien) is only ten thousand years old. The water of the rivers was pure for millions of years in the absence of man and was capable of supplying pure water, when men evolved on planet Earth. However, man at the cost of unplanned development in the last few decades has completely destroyed the natural system of the rivers. The rivers which served as lifelines for thousands of years for the survival of man are now looking toward man, for their survival.

2 Classification of Rivers

Rivers are classified into various catogories on the basis of different criteria.

2.1 On the Basis of Origin

The rivers can be classified into three categories on the basis of origin:

Snow-fed rivers are those which originate from the glaciers and receive water from the melting of snow and ice (Fig. 1). These are perennial rivers with high discharge and high sediment load. The fluctuation of water budget is very high between monsoon and summer seasons such as in the Ganga, Brahmaputra, Yamuna, Ghaghara, Great Gandak, and Kosi.

Groundwater-fed rivers are those which receive water mainly from the groundwater/subsurface (Fig. 2). These are the rivers with medium discharge and medium to low sediment load. The discharge is high during the monsoon season and very low during the summer such as Gomati, Chhoti Gandak, and Sai.

Fig. 1 Snow-fed River Ganga at Allahabad, Ganga Plain

Fig. 2 Groundwater-fed River Chhoti Gandak in Deoria district, Ganga Plain

Fig. 3 Rain-fed River Narmada at Jabalpur, Madhya Pradesh

Rain-fed rivers are those which receive water during the monsoon from the rain (Fig. 3). These are ephemeral rivers having water mainly during monsoon season with low suspended load such as Godavari, Kaveri, Krishna, and Narmada.

2.2 On the Basis of Stage

Rivers can be classified into three categories on the basis of stage:

Youth stage rivers are characterized by a V-shaped cross valley profile without any floodplain. The valley depth depends upon the upliftment of the river, and elevation of the region above the mean sea level. In this stage, valley deepening takes place (Fig. 4).

Mature stage rivers are characterized by valley widening through lateral erosion (Fig. 2). The sinuosity increases in the downstream direction. The river meanders in the plain regions and forms the point bar deposits, oxbow lakes, etc.

Old stage rivers neither deepen their valley like youth stage nor widen like mature stage (Fig. 5).

Fig. 4 Youth stage of the river which forms 'V'-shaped valley of the Ganga River in Himalaya at Rishikesh, Uttarakhand

Fig. 5 Dhuandhar Waterfall in Narmada at Jabalpur, Madhya Pradesh

2.3 On the Basis of Sinuosity and Channel Pattern

Braided rivers—In which the water flows through many channels separated by channel bar deposits. The sediment load and discharge are high. It is characterized by low sinuosity (less than 1.5), multiple channels, and huge channel bar deposits such as Ganga, Ghaghara, and Great Gandak.

Meandering rivers—In which the water flows through a (zigzag) meander in a single channel. The sediment load and discharge are low as compared to braided river. It is characterized by high sinuosity (more than 1.5), single channel, and point bar deposits such as Gomati, and Chhoti Gandak.

Straight rivers—In which the water flows through a single and straight channel. Both sediment load and discharge are low. It is characterized by low sinuosity (less than 1.5), single channel, and channel bar deposits.

Anastomosing rivers—In which the channels split and rejoin in the downstream part of the river. Sinuosity is generally less than 1.5. The Great Gandak River exhibits it in the middle reaches.

2.4 On the Basis of Water Storage

Perennial rivers—The rivers which are permanent, having water throughout the year.

Ephemeral rivers—The rivers which are temporary, having water mainly during monsoon season and remain dry for most part of the year.

2.5 On the Basis of Drainage Pattern

The pattern which is formed by the streams/rivers in a region and the area from which a stream gets runoff.

(a) Consequent—The river which flows in the direction of the slope of the region and is younger to the upliftment of the area, e.g., Krishna, Kaveri, and Godavari.
(b) Antecedent—The rivers which are older than the upliftment of the area such as Indus and Brahmaputra.
(c) Subsequent—A river which is tributary to the consequent river is known as subsequent such as Chambal and Ken.
(d) Dendritic—The pattern of the river which appears like a tree, as most of the Ganga Plain rivers.

2.6 *Indian Rivers can also be Classified on the Following Basis*

2.6.1 On the Basis of Location

Himalayan Rivers—which originate in the Higher Himalaya and are generally snow fed in origin such as Ganga, Ghaghara, Great Gandak, and Kosi.

Ganga Plain Rivers—which originate in the Ganga Plain region and are generally groundwater fed such as Gomati, Sai, and Chhoti Gandak.

Peninsular Rivers—which originate in the peninsular India and are generally rain fed such as Godavari, Krishna, and Narmada.

2.6.2 On the Basis of Catchment Area

Eighty-three river basins of India are divided into three groups on the basis of size of the catchment area (Rao 1975)

Group 1—Rivers having more than 20,000 km^2 catchment area are fourteen in number.

Group 2—Rivers having catchment area between 2000 and 20,000 km^2 are forty-four in number.

Group 3—Rivers having less than 2000 km^2 catchment area are fifty-five in number.

2.6.3 On the Basis of Water Divide and Catchment Area

Indus River Basin—The Indus system comprises the Indus and its tributaries, such as the Zanskar, Dras, Shyok, Jhelum, Chenab, Ravi, Beas, and Sutlej.

Ganga River Basin—The Ganga system consists of the Ganga and its tributaries such as Ramganga, Yamuna, Tons, Gomati, Ghaghara, Son, Great Gandak, Burhi Gandak, Kosi, and Mahananda. The Ganga has a large number of spill channels draining into the Bay of Bengal such as Hooghly and Gorai.

Brahmaputra River Basin—The Brahmaputra system consists of Brahmaputra known as Tsangpo in Tibet and its tributaries such as Raka Tista, Tsangpo, Subansiri, Ngang Dibang, Lohit, Kameng, Manas, Kopili, and Dhansiri.

3 River-Related Terminology and Geomorphology

- Channel—The V-shaped depression on the earth surface which is carved by the river under direct control of climate and tectonics. It is that part of the river which is filled with water.

- Valley—Valleys are carved by river dynamics under direct control of climate and tectonics. It is a negative landform of varying shape and size evolved by river deepening, widening, and lengthening of the valley. Generally, they are much more extensive than the channel.
- Valley/channel pattern—The geometry and the pattern of the channel adjust according to the water discharge and sediment load of the river. Therefore, the valley and the channel width will provide the information about the change in the nature of river channel. The valley and channel width indicate the stream flow characteristics. The wide valley indicates the natural capacity of the river to accommodate the high discharge of the river. It explains that the river was carrying higher discharge in the past when the wide valley was carved during humid climate.
- Floodplain—The flat area located adjacent to the river which floods when the water level rises in the river.
- Cliff—The river cliffs are the raised and vertical portion at the bank of a river.
- Sinuosity—The degree of meandering/curve is known as sinuosity. It is the ratio of distance between two points along the channel to the shortest distance between the same two points. If sinuosity is greater than 1.5, then the river is called meandering; if it is less than 1.5, then the river is braided in nature.
- Base level—Base level is the maximum limit of valley deepening; generally, it is the sea level.
- Graded stream—A stream which is capable for transportation of its total load. It neither degrades nor aggrades its valley.
- Aggradation—When shoreline (boundary between land and sea) shifts toward land, it results in the alleviation or valley filling in the upstream part of the river.
- Degradation—When shoreline (boundary between land and sea) shifts toward the sea, it results in deepening of valley in the downstream part of the river.
- River piracy—It is the erosional attack on one stream by another stream. The most common cause of stream piracy is the ability of one stream to extend its valley at a level lower than the adjacent stream. It takes place mainly due to headward erosion and lateral shifting.
- Tributary—which contributes and increases the discharge of a river, e.g., Yamuna is a tributary to Ganga River.
- Distributary—which distributes and decreases the discharge of a river, e.g., Hooghly is a distributary to Ganga River.
- Misfit River—The narrow channel confined within the wide valley. The channels are not proportionate in size to the valley that they occupy.
- Yazoo stream—The tributary stream which runs parallel to the main stream for tens of kilometer and then joins the mainstream.
- Alluvial fans—A cone-shaped deposits formed when a river debouches from the mountains on to the plains. Due to a sudden decrease in its velocity, the river drops down most of its load and forms a deposit which is fan-shaped and consists of alluvium known as alluvial fan (Fig. 6).
- Channel bar deposits—The deposits of sand, silt, and gravel within channel/valley of a river are known as channel bar. Its shape and size are

Fig. 6 Alluvial fan at Ny-Alesund, Arctic (Photograph taken during First Indian Expedition to Arctic in 2007)

Fig. 7 Point bar deposits in the Rapti River, near Gorakhpur, Uttar Pradesh, Ganga Plain

Fig. 8 Braid bar and lateral bar deposits in Ganga River at Rishikesh, Uttarakhand

controlled by discharge of the river, supply of sediments, and accommodation space available. The largest channel bar is formed when the discharge, sediment load, and depth of the river are high. Depending on the shape, size, and their association with various types of rivers, different types of channel bar deposits are identified such as point bar, braid bar, and lateral bar.

1. Point bar deposits—These are the crescent shape deposition of sand and gravel present at the inner side of bend of a meandering river. Deposition on point bar results from lateral migration of a meandering river during flooding (Reineck and Singh 1980) and may be as thick as the depth of the river (Fig. 7).
2. Braid bar deposits—The bedload of sand and gravel deposited within the channel of braided river are known as braid bar deposits (Fig. 8).
3. Lateral bar deposits—If channel bar is deposited at one side of a braided river, then it is known as lateral bar deposit (Fig. 8).

- Natural levee deposit—During the time of flood, river water overtops its bank and enters into the floodplain and deposits the sediments. Coarser sediments are deposited along the river bank, and finer sediments are further carried on the floodplain. Repeated deposition of sediments raised the river bank known as natural levees which dips away from the channel at a very low angle (Fig. 9).
- River terraces—River terraces are the former river valley floor surfaces. These are made up of sand, silt, and clay. Terraces are largely the products of river rejuvenation due to sea level changes under direct control of climate and tectonics and represent remnants of a river channel or floodplain when the river

Fig. 9 Natural levee in the Chhoti Gandak River Basin, Ganga Plain

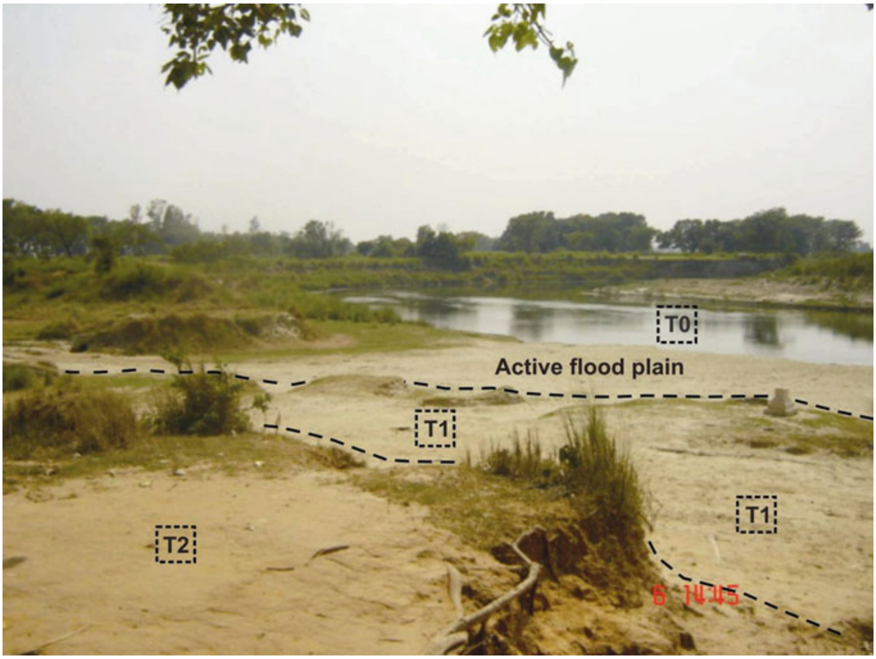

Fig. 10 Three river terraces T_0, T_1, and T_2 of Ganga Plain in Chhoti Gandak River Basin

Fig. 11 Delta at Ny-Alesund, Arctic (Photograph taken during First Arctic Indian Expedition in 2007)

Fig. 12 Estuary at Ny-Alesund, Arctic (Photograph taken during First Arctic Indian Expedition in 2007)

was flowing at a higher level. Due to the process of rejuvenation (due to upliftment of area or lowering of sea level), the same river starts carrying out vertical erosion and down cuts its earlier floodplain. The older channel or floodplain stands as a terrace above the present-day level of the river. In the Ganga Plain, mainly three river terraces have been identified such as T_2, T_1, and T_0 (Fig. 10).

- Delta—Delta is formed at a place where flowing water body joins a stagnant water body. When a river joins an ocean, it deposits a triangular-shaped body of fine-grained sediments known as delta. It was first time used for the Nile River, because the mouth of Nile River was like a delta, the fourth letter of Greek alphabet (Fig. 11).
- Estuary—Estuary is a small and narrow channel or place where river meets to ocean and mixing of oceanic and river water takes place (Fig. 12).
- Morphometry—Morphometric analysis is one of the most important tools and techniques to determine and evaluate the drainage basin responses to climate change, drainage characteristics (Mesa 2006), flash flood hazard (Angillieri 2008; Perucca and Angilieri 2010), and hydrologic processes (Eze and Efiong 2010). There is a strong need to include the geomorphological parameters of the river basin in flood analysis as these parameters govern the hydrological response of the river basin (Sinha and Jain 1998; Singh and Awasthi 2011a, b). The drainage basin parameters are analyzed using topographical sheets, satellite data, and field documentation with emphasis to its implication for flood mitigation and recharging of groundwater. Drainage network is analyzed according to Horton's laws (Horton 1945), and stream orders were defined (Strahler 1964). Various basic, derived, and shape parameters were calculated using standard methods (Kale and Gupta 2001; Reddy et al. 2004; Sreedevi et al 2004; Garde 2006; Singh and Awasthi 2011a, b).

These parameters provide useful information for the prediction of basin behavior during prolonged heavy rainfall that generate floods and suggest that water resource management and developmental planning should be done with reference to the drainage basin parameters.

- Sediment Grain Parameters—Grain size is a fundamental physical characteristic of the sediment which provides information for understanding the sedimentary processes, textural parameters, energy level of the river, and also the climate (Singh et al. 2007, 2009, 2013, 2015a, b; Saxena and Singh 2016). Statistical parameters of the grain size indicate much information about the depositional environment. The presence of coarser sediments indicates the high energy, and finer sediments explain the low energy. The standard deviation measures sorting, i.e., the spread of the grain size distribution indicates the fluctuation in the energy of the transporting capacity of the river. Skewness is the measure of asymmetry of the distribution of sediments and indicates the excess amount of fine fraction in the sediment. Kurtosis indicates the peakedness of the grain size distribution curve. The grain size decreases in the downstream direction, whereas sorting increases in the downstream direction. Sediment size provides information about the climate also.

- Facies of channel bar deposits—Facies is the sum total of all those characteristics of a sedimentary unit on the basis of which it is differentiated from others. On the basis of analysis of many channel bars, six lithofacies, namely planar cross-bedded, trough cross-bedded, low angle planar cross-bedded, ripple-laminated, climbing ripple-laminated, and laminated mud, have been identified (Singh et al. 1999; Singh and Singh 2005; Awasthi and Singh 2011; Singh et al. 2013).
- Paleocurrent analysis—It includes the determination of direction of river flow in the geological past. It can be done with the help of the directional sedimentary structures present in the river deposits (Shukla et al. 1999; Singh et al. 2009, 2013). Most commonly used features are cross-stratification and ripple marks. Cross-stratifications have their foresets inclined in the direction of river flow at the time of the sediment deposition. Ripple marks are characterized by the gentler slope at lee side and steep slope at the stoss side.

4 River System of India

4.1 Ganga River System

These rivers drain different parts of the Ganga Plain. The Indo-Gangetic Plain is one of the main physiographic regions of India lying between Himalaya in the north and Peninsular Plateau in the south. Ganga Plain occupies a central position in the Indo-Gangetic plain and extends from Aravalli-Delhi ridge in the west to the Rajmahal hills in the east, Siwalik Hills in the north to the Bundelkhand-Vindhyan-Hazaribag Plateau in the south (Singh 1996). It is one of the most densely populated regions (about 40% of India's total population) of the world because of its fertile soil, availability of water, smooth landscape, and suitable climate (Singh et al. 2011, 2013, 2015a, b). Groundwater is the main source for domestic, agricultural, and industrial uses (Bhardwaj et al. 2010a, b). The industries (Bhardwaj et al. 2010c) are polluting the surface and subsurface water quality (Bhardwaj and Singh 2011).

The Ganga Basin was formed due to the thrust loading of the Himalaya on the underthrusting plate during middle Miocene period. The sediments weathered from the Himalaya were transported and deposited by various river systems in the Ganga Basin which converted it into a plain. The river system evolved the megafans that have done the initial filling of this foreland basin (Parker 2000; Singh and Singh 2005).

Ganga Plain consists of alluvium deposited by various river systems under different climate and tectonic conditions, surface processes, and hydrological processes in which coarser sediments were deposited under high-energy environment and finer sediments during low-energy environment (Kumar et al. 1995; Srivastava et al. 2003; Singh et al. 2009). Bangar (older alluvium) and Khadar (newer alluvium) are the two morphostratigraphic units in the classical literature of the Ganga Plain (Pascoe 1917; Pilgrim 1919). Singh (1996) had classified the Ganga Plain into six geomorphic units:

(a) Upland interfluves surface (T_2)—Oldest geomorphic unit or flooding surfaces, containing older alluvium (Bangar) and highland areas.
(b) Marginal plain upland surface—These are the north and northeast sloping surfaces occurring south of the axial river, containing older alluvium (Bangar) and made up of slightly coarser sediments derived from cratonic sources.
(c) Megafan surface—Major rivers of Himalayan origin make the megafans namely Kosi megafan, Gandak megafan, Sarda megafan, Yamuna–Ganga megafan on the Ganga Plain region.
(d) River valley terrace (T_1)—Older geomorphic unit flood surfaces located several meters higher than the active floodplain, containing younger alluvium (Khadar).
(e) Piedmont zone—These are the coalescing fans developed along the foothills of the Himalaya. It includes both Bhabar and Terai belts.
(f) Active floodplain surface (T_0)—It is the youngest geomorphic surface present within the older flood surface. This surface is subjected to annual flooding during monsoon season or high discharge period.

The Ganga Plain is characterized by subtropical monsoon climate and receives moderate to high rainfall (1000–1600 mm). 80–85% of the total rainfall is received during the monsoon season (June to September).

The Ganga is the most important and sacred river of India. It reflects the culture and civilization of our country from ancient times. Many other countries have also called their major rivers as the Ganges, e.g., Po is known as the Ganga of Italy and biggest river of Sri Lanka is known as Mahaweli Ganga. The area of the Ganga River Basin covers seven states and is slightly more than one-fourth (26.3%) of India's geographical area. The percentage of basin area in each state is Uttar Pradesh 34.2%, Madhya Pradesh 23.1%, Bihar 16.7%, Rajasthan 13%, West Bengal 8.3%, Punjab and Haryana 4%, Himachal Pradesh 0.5%, and minimum 0.2% in Delhi (Rao 1975).

Ramganga, Yamuna, Gomati, Ghaghara, Son, Great Gandak, Burhi Gandak, and Kosi are the important tributaries of Ganga River, and this book contain chapters on all these rivers.

4.2 Indus River System

Indus/Sindhu River originates near Mansarovar Lake and is the longest river of Asia. It drains through the tectonically active zones of Karakoram in Tibet, Ladakh Himalaya, and Nanga Parbat in the western part of Himalaya. After traveling for a distance of about 3180 km, it finally drains in to Arabian Sea.

The Sutlej, Chenab, Jhelum, Beas, and Shyok are the important tributaries of Indus River. These rivers have been described in detail in this book.

4.3 Brahmaputra River System

Brahmaputra River is a transboundary river of Asia that drains through four countries: China, India, Bhutan, and Bangladesh. It originates from Chemayungdung Glacier, and after traveling a distance of 3000 km, it drains in to the Bay of Bengal.

The Teesta, Subansiri, Lohit, and Dhansiri are the important tributaries of Brahmaputra River. There are chapters on Teesta and Subansiri in this book.

4.4 Peninsular Rivers

The Krishna, Kaveri, Godavari, Mahanadi, Narmada, Tapti, etc. are the important peninsular rivers. There are chapters on these rivers in this book.

5 River-Related Problems

The rivers are lifeline and so every aspect of life of the people is linked with the rivers. The encroachment of man in the natural cycle of the river is the main reason for river-related problems. The industrial, domestic, and urban waste pollute the pure water of the river. The construction of embankments, mining of sand, religious activities, and blocking of natural drainage also affect the physical, chemical, and biological characteristics of the river (Figs. 13 and 14). The loss of life and property by river-borne hazards are increasing year after year, as the floodplains are not being developed in a regular manner. The increase in damage due to river-borne hazards can also be attributed to the urbanization and industrialization in areas liable to floods. Therefore, the trend of the river channel shifting within the valley should be analyzed to save the human population and settlement form fluvial hazards (Singh 2007; Singh et al. 2015a, b). The development and construction in the floodplain and at many places even within the wide valley of the river without understanding the law of nature and scientific facts have increased the problems and natural disasters.

Fig. 13 Sand mining in the Chhoti Gandak River, Ganga Plain

Fig. 14 Pollution in the river due to anthropogenic activities in the Gomati River at Naimisharanya, Sitapur, Uttar Pradesh, Ganga Plain

5.1 Impact of Climate Change on Rivers

Rivers of the Ganga Plain are characterized by a narrow channel confined within very wide valley (Singh et al. 2010). The wide valley was carved by the river in the past when the discharge was very high and the climate was humid. Due to a change in the climate from humid to arid, the discharge decreased and the valley started shrinking. Present-day channels are very narrow except during monsoon, and the rivers are a misfit stream. The valley is shrinking due to the climate change and providing space for settlement which is being affected by river-borne hazards (Singh and Awasthi 2011a, b). The impact of climate on rivers as well as on glaciers is increasing the frequency of various hazards (Singh 2014, 2015; Singh and Agnihotri 2016).

5.2 Flooding

Flood is defined by various workers in various ways. In a simple way, it is a high level of water which overtops either a natural or an artificial river bank, or rises above normal levels of river water. When discharge exceeds the capacity of the channel, flooding occurs on adjacent areas. In India, rivers are in flood when its water level crosses the danger level at a particular site, means the flow exceeds the capacity of the river channel/valley within the banks. The magnitude of the flood depends upon the intensity of the rainfall, its duration, and also the ground conditions. Flood hazard has been recognized as one of the most widespread and disastrous natural hazards and are regular features affecting thickly populated regions of India. Floods cause loss of life and property and have a significant impact upon the homeless in comparison with other natural hazards (Foster 2000). It generally originates in three ways: (1) logging and spreading of water due to heavy rains (Singh and Awasthi 2011a, b) (2) breaking of levee due to rise of water level in the river channel (Singh et al. 2015a, b), and (3) blocking of the natural drainage.

It is a common disaster and has been studied extensively for many rivers of the world. The great floods of Huang Ho in China 1931; in Bangladesh 1987 and 1988; in USA 1993; of Yangtze in China 1998; in Mozambique 2000 are all well known. Next to Bangladesh, India is the most flood affected country in the world. In India, North Bihar, Brahmaputra, and Sikkim Himalayan rivers are known and have been described for flooding (Kale 1998; Sinha and Jain 1998). Uttar Pradesh is one of the most flooded states (Dhar and Nandargi 1998; Kale 1998). It is estimated that the incidence of flooding is frequent in eastern UP due to spilling of Kuwana, Rapti, Chhoti Gandak, Ghaghara, and Great Gandak rivers (Singh 2007; Singh and Awasthi 2011a, b; Singh et al. 2015a, b). In India, floods occur during the southwest monsoon season from June to September in most part of the country. Heavy rain in 2013 caused one of the worst natural disasters. The causes of the flooding, processes, and the human responsibilities have been described by (Singh et al. 2013; Singh 2014).

5.3 Lateral Erosion

Generally, flooding is known as river-borne hazard, but lateral erosion has been identified as a new independent and important fluvial natural hazard (Singh and Awasthi 2011b). It originates because of its alluvium content made up of sand, silt, and clay in different proportions. Sand and silt are non-cohesive and unconsolidated so they can undergo weathering, transportation, slumping, and sliding. The geomorphological facies and granulometric analysis indicate that the lower and middle parts of the channel banks and sandbar deposits are made up of sand and silt which are prone to erosion, scouring, and mass movement, leading to lateral erosion (Fig. 15).

It has been observed all along the major rivers of the Ganga Plain during fieldwork that lateral erosion is a major hazard which, is active mainly during low discharge period (Singh and Awasthi 2011a, b), and also during high discharge period.

Fig. 15 Lateral erosion in Ghaghara River in Deoria district, Uttar Pradesh, Ganga Plain

5.4 Mitigation

Damage impacts can be minimized by a proper understanding of the scientific facts, better floodplain management, flood control measures, improved disaster preparedness, and flood fighting which includes the setting up of forecasting and warning systems. Forecasting and warning network should be increased for flooding. Human misery can be reduced through emergency action, effective relief, and rehabilitation measures and by providing appropriate types of insurance covers. Singh et al. (2015a, b) have prepared a flood inundation model, flood frequency curve, and flood recurrence interval for the Rapti River which can be applied to other rivers for flood forecasting.

There is an urgent need to ensure sustainable development of the water resources and its efficient management. All sections of the society (Center, State, Panchayati Raj Institutions, Urban local bodies, Industrial houses, or the Civil society) have to join hands and contribute to address the challenges in the water sector, so that the demand for water by different sectors can be adequately met. While doing so, it is necessary to ensure that environmental issues are properly addressed.

There should be strong scientific floodplain management techniques. Rather than to keep hazards (flood and erosion) away from people, there is a need to keep people away from the hazard zone (flood and lateral erosion).

6 River Linking

The river linking plan in India was conceptualized by Sir Arthur Cotton (British) as a navigation scheme. It was reconsidered in 1975 under the National Water policy–Northumbrian water Group (NWG), by Dr. K.L. Rao, the then Chairman of Clean Water Program Countrywide (CWPC). The distribution of rainfall is highly irregular and non-uniform both in terms of time and space. So water should be stored and utilized for meeting the demands throughout the year.

River linking means redrawing the geography of the country at least in terms of drainage network and so it should be done step-by-step. Interlinking of rivers is the answer to the problems of flood and water scarcity in different regions of the country and has the potential to deliver advantages such as substantial, environmental-friendly, and cost-effective hydroelectric power, enhancing food security alternative transport system of navigable waterways, generation of employment, and to reduce the migration from rural to urban areas. It will solve the problems of flood and drought. It is said that this project has enormous potential for cost-effective hydroelectric power and enhancing food security. However, it will create many problems too. The problems that will occur are financial, sociopolitical, rehabilitation, and uncertain impacts for soil, wildlife habitat, and other ecosystems. It will increase waterlogging resulting in waterborne diseases. The issue of transfer of river waters may cause severe inter-district, inter-state, inter-country disputes, which can divide the people and unity of the country. The canals (for transfer of water) have significant negative impact on prime wildlife habitat, waterborne diseases, cut across fertile agriculture land, and displacement of the people. There would be significant loss of water due to leakage and evaporation in long-distance transfer, waterlogging, and salinization of the soils. Instead of mega-engineering, we should support practical ways to use local water, including decentralized irrigation, rainwater harvesting, groundwater recharging, and recycling wastewater.

Therefore, the first prerequisite for the linking of rivers is the study of all those parameters which control the behavior of a river directly or indirectly and second of all those natural and manmade features which are going to be affected by the linking of the rivers.

Every aspect has some positive and negative points. Humans can manipulate human creations but not the natural ones. The rivers are not human artefacts, and they are not pipelines to be cut, turned, welded, and rejoined. The major Himalayan rivers draining the Ganga Plain, e.g., Ganga, Yamuna, Ghaghara, Great Gandak, and Kosi, flow for most of the months in a year with a little discharge during the summer and so linking will be useful only for certain months. The author has seen even the major rivers such as the Ganga, Yamuna, Ghaghara, Gomati, Great Gandak, Burhi Gandak, and Kosi either dry or with minimum discharge at few places during the summer.

The death of Aral Sea is a message to the entire world that we cannot divert and link the rivers. Linking of rivers means change of physical, chemical, and biological characteristics of the rivers which will be difficult for the survival of fauna and flora.

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Rivers in Ancient India

D.P. Tewari

1 Introduction

India is the land of rivers, which occupy about 329 million hectare of its area.[1] Some of these originated at the time of rise of the Himalayas, and some others are even older. These rivers can be divided into ten groups on the basis of their geographical locations:[2]

1. Indus river group
2. Saraswatī-Drishdvatī group
3. Gangā-Yamunā group
4. Brahmaputra-Meghanā river group
5. Lūnī-Chambal group
6. Narmadā-Tāptī group
7. Mahānadī group
8. Godāvarī river group
9. Krishnā river group
10. Kāverī river group

River Indus originates from the Kailas Mountain and falls into the Arabian Sea. It is mentioned in the Rigveda that River Indus was fast swifting and noise some flowing along the way fixed by the Varuṇa and is the holiest among the all rivers.[3] It had 21 tributaries which originated from sky, *dyuloka*, and earth and were

[1]www.ecoindia.com/rivers.
[2]Laha B.C., PrāchīnBhāratkāBhugol, 1972, pp. 48–64.
[3]Rigveda 10/75/2–3.

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classified into three groups each containing seven rivers.[4] Śutadri or Śatadru (Sutlej), Vipāśā (Vyās), Paruśṇī or Irāvadī (Rāvī), Aksinī or Chandrabhāgā (Chināb), Marudvridhā, Vitastā (Jhelum), Ārjikīyā, and Suśomā join it from the east and Trishṭamā, Susartu (Surū), Rasā(Śevak), Śwetī (Gilgit), Kubhā (Kabul), Mehatnū (Savan), Gomatī (Gomal), Krumu (Kurram), Suswātu, Apāyā, Anatibhā, Yavyāvatī, Vibālī, Śifa, and Hariyūpiyā from the west. Other rivers of this region are mentioned as Svetayāvarī, Anjasī, Kuliśī, Vīrpatnī, Sarayū, and Adīnā which are not yet identified.[5] Pliny has mentioned its 19 tributaries. Alberuni tells that it was known with three different names from its origin to meeting point with the Sea. It was famous as Sindhu from its origin to the confluence of River Chināb, further from this point up to Aror as *Panchanada* and from here to the confluence with the Arabian Sea as Miharan. River Indus is admired in the Rigveda in a very high tone. It describes that Sindhu is full of high quality of horses, chariots, cloths, golden ornaments, grains, and honey-yielding trees. It has a great role in fire sacrifices.

Svaśvā sindhuh surathā suvāsā hiranyamayī sukritā vājinīvatī

Urṇāvatī yuvatih sīlamāvatyutādhim vaste subhagā madhuvridham. (Rigveda 10/75/8)

It is clear from this narration that there were thick forests on the banks of this river which yielded quality wood for making chariots and sweet fruits to eat, extensive green grasslands for feeding horses, cotton for making cloths, crops yielding grains. On the banks of this river were gold mines too which provided gold for making ornaments. Rishis often use to perform fire sacrifices on its banks in this charming environment. They have prayed to God many times for the long survival of this river. The Rigveda 3/23/4 mentions the Saraswatī group of rivers as the place of fire sacrifice of the Bharatas.[6]

The Rigveda mentions two other holy rivers such as Saraswatī and Drishdvatī which originated from the Himalayas and flowing through Shimla, joined the Arabian Sea. Āranyak Parva of the Mahābhārata describes its origin from Plaksha.

Tato hi sāsarichchhresthā nadīnāmuttamā nadī

Plakshaddevī srutāra janmahapuṇya Sarasvatī. (Mahābhārata, Āranyak Parva 82/5)

Colonel Raghu Raj Singh is of view that the Saraswatī originates from the hills of Mana Pass near Deva Tal on Indo-Tibetan border at the altitude of 18,400 feet from sea level (Itihās Darpaṇa, Vol. III, No 1, 1996, pp. 34–35.). There was another river, Apāyā, which flowed between Saraswatī and Drishdvatī. B.B. Lal is of view that both the rivers Apāyā and Drishdvatī were tributaries of the Saraswatī (Itihās Darpaṇa, Vol. XI, No 1, 2005, p. 37). Thick habitations and numerous hermitages

4Ibid, 10/75/1.

5Reu FanishvarNath, Rigveda par ek Aitihasik Drishti, 1967, P. 114–117.

6Rigveda 2/41/16; KatyāyanShraut Sūtra 12/3/20, 24/6/22; LātyāyanShraut Sūtra 10/15/1, 18/13, 19/4; AśvalāyanShraut Sūtra 10/15/2, 18/13, 9/4; Sānkhyāyan Shraut Sūtra 12/6/23.

of saints were on the banks of Saraswatī. Dr. S.P. Gupta was of opinion that these 8000-year-old settlements turned into the cities of Harappan Civilization.[7] Later on, about 2600 year ago, this river started drying[8] while others are of the view that due to reduced rainfall Saraswatī started drying after 3200 B.C. and Drishdvatī started drying in about 2000 B.C. and finally both dried in about 1750 B.C. (Itihās Darpaṇa, Vol. VI, No 1, 1999, p. 13 and 15; Vol. VIII, No 2, 2002, p. 37). The Mahābhārata mentions that it dried on account of curse of Rishi Utathya even though it survived at Chamasodbheda, Śirodbheda, and Nāgodbheda. The place where Saraswatī disappeared is mentioned as Vinaśana in Tāndya Brahman and MahābhārataŚalya Parva (31/1-2). Those who take bath at Vinaśanatīrth located on the bank of Saraswatī gain the merit of Vājpeya sacrifice and live for a long time in the lunar world (*Chandraloka*).[9,10]

Rivers Gangā and Yamunā were less important in the Rigvedic times than today. It seems that both of these were smaller rivers flowing in the east to Saraswatī group of rivers. Both are prayed with Sindhu and Saraswatī.[11] There are no separate sūktas addressed to them. The Rigveda 3/58/6 mentions River Jāhnavī. The main tributaries of Gangā are Mandākinī, Nuta, Rāmgangā, Yamunā, Gomtī, Tamsā, Sarayū (Ghaghara), Gandak (Sadānīrā), Kauśikī, Tons, Son, Punpunnā, Phalgū, Sakuti, Champā, Bhāgīrathī, Ajayā, Dāmodar, Rūpanarāyan, Haldī, Keśāī, Panār, Bari Yamunā, Padmā, Meghanā, Madhumatī, Ariyālkhāl, etc. Sudās and the Tritshus defeated their enemies on the bank of Yamunā.[12] It is mentioned as Kālindī in the Bhāgavat Purāṇa, where people performed ascetic practices.[13]

Brahmaputra is the main river in Brahmaputra-Meghanā river system which was famous as Lauhitya (Lohita). It originates from the eastern part of Mānsarovar Lake and falls in Bay of Bengal. It is known as Tsangpo in Tibet. Lohita, Bari Dihinga, Disarā, Dhanashrī, Kalanga, Krishnāi, Mānas, Meghanā, Karatoyā, Dhaleshvarī, and Ichāmatī are the main tributaries of Brahmaputra. Other rivers of this system are Lakshyā, Suramā, Barāk, Manu, Padmā, Fenī, Naphā, Karṇafūlī, Hāldā, Mātāmurī, and Suvarnarekhā.

River Lūnī, which originates from the hills of Ajmer, a part of Arāvallī Range, and joins the Arabian Sea, is the main river of Lūnī-Chambal river system. It has six tributaries among which Bandī, Banās, and Saraswatī are the most important. Several chalcolithic sites have been explored along the banks of Banās River.

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[7]Gupta S.P., The Indus Saraswati Civilization an Over View of Problems and Issues, Itihās Darpaṇ, Year 4, No. 2, 1998, P. 51.

[8]Chaturvedi Rekha, AmbitamenadītamedevitameSaraswatī, VaidikSanskritiAurUsakāSātatya, Editor SitārāmDubey, P. 70.

[9]Mahābhārata, Āranyak Parva, 80/118, 82/96; Laha B.C., 1972 as above, pp. 51–52.

[10]Tāndya Brāhmaṇa 25/10/16.

[11]Rigveda 10/75/5 Imam me GangeYamuneSaraswatiShutudristomamsachatāParushnyā.

[12]Rigveda 7/18/19.

[13]Bhāgavat Purāṇa 3/4/36, 4/8/43, 6/16/16.

Another river originating from Arāvallī Range is Chambal which is a tributary of River Yamunā. Kāli Sindha, Pārvatī (PaurāṇicPārā), Kunu, Meja, Berāch (Barṇāsā), Gambhīr, Vetravatī, Ken (Kainās of Arian), Daśarṇa, and Śiprā join it. River Śiprā bears historical as well as religious importance. Ujjain, the capital of King Vikramāditya, was located on its bank. Sanskrit poet Kālidās has repeatedly mentioned this river in his writings. Its beauty has been described in verse 31 of Pūrvamegha and 6/35 of Raghuvamsa. The great temple of Mahākāleshvara is built along its bank. Māhi, Sābarmatī, and Begavatīand Bhādar are other important rivers of this system which join the Arabian Sea.

Narmadā is the oldest river of Narmadā-Tāptī river system which originates from Amarkantak Hills of Maikāl Range of mountains and falls in the Arabian Sea. The oldest human fossil is found from its deposit at Hathanorā. It has been mentioned as Revā, Samodbhava, and Mekalsutā in ancient Indian literature. It has seven tributaries. The other river flowing parallel to it is famous as Tāptī which is said to be the oldest river in the 41 chapter of Padma Purāṇa. It has eight tributaries among which Pūrṇā, Girnā, Borī, and Panjhā are important.

The principal river of the Mahānadī river system is Mahānadī which originates from the hills near Barār and joins the Bay of Bengal. It has five tributaries. Other rivers of this system are Devī, Prochī, smaller Mahānadī, Vansadharā, Lāngulinī, Rishikulyā, Trisāmā, Barabalanga, Salandī, Vaitaranī, Kumārī, Palāsinī, Koyal, and Brāhmaṇī. These all join Bay of Bengal. River Godāvarī originates from the hills of Nāsik and flowing through Maharashtra and Andhra Pradesh fells in Bay of Bengal. It is principal river of Godāvarī river system. Pūrṇā, Kadam, Prāṇhitā, Indrāvatī, Manjīrā, Sindafanā, Maner, Kinarsinī, Baingangā, Vardā, Paingangā, etc. are its tributaries.

River Krishnā in south India is an old river of Kishnā river system. It originates from the Western Ghats and flowing through Maharashtra, Mysore, and Andhra Pradesh joins the Bay of Bengal. It has 19 tributaries. Dhon, Bhīmā (ancient Sahya), Palār, Munar, and Tungabhadrā are important in them.

River Kāverī in south India has 18 tributaries. It is the main river of this river system. It originates from the Western Ghats and flowing through Tamilnādu joins Bay of Bengal. Uragpur, the capital of Cholas, was situated on its banks. Other rivers of this system are Kritamālā, Tamraparṇī, Pushpajā, Sutpalāvatī, and Vaigāī.

It is very important to discuss the view of ancient Indians about rivers. The Indian intelligence had a special outlook about the water. It is called Aap in the Rigveda which was considered as mother-like element and which bears pregnancy being in touch of Purushatatva.

> Āpo ha yad brihtīrviśvamayan garbham dadhānā janayantiragnim
>
> Tato devānām samvartatā surekah kasmai devāy havishā vidhem.
>
> Rigveda 10/121/7

There are many references in Brahamanas, where the entire world, stars, all living creatures, men, and animals are said to be originated from the water.[14] Water is one among the five elements. It was regarded a highly pure element which bears the capacity to give purity.[15] The Sukta 23 of Chapter "Landscape of the Indus River" of second Kand of the Atharva Veda describes it as free from magical deeds. It is entreated to make it free from such deeds. Therefore, the rivers were regarded as Goddess and later their images were prepared with in female form. Due to the sacred values of water *Ishta-Purta* were given religious importance and construction of water sources like digging of well, ponds and Tanks (*Vapi, Kupa and Tarak*) were regarded of great religious importance. The donation of water was regarded a great donation as mentioned in Mahabharata Anushashan Parva 65/3.

Pānīyam paramam dānam dānānām manurabravīt

Tasmat kupānścha vśpīścha taṇāgāni cha khānayet.

Those who destroy it were penalized by death.[16] Rivers being the source of water were regarded very important. Indian culture accepts it like life which protects the lives of all creatures who drink it. It was base of punyatma and sukarma. It was believed that sinners cannot cross water. All the religious rituals, marriages, social rituals, and oath in judicial practices are performed after getting water in hand. It was assumed that one gets purity after taking bath in water. Therefore, the rivers were regarded solvent of bad deeds and provider of Punya. The Mahabharata declares that if a sinner takes bath in the Ganga, he becomes absolved of all of his sins.[17] The Āranyak Parva of the Mahabharata 82/31 mentions that the person, who takes bath on the confluence of Ganga and Yamuna, attains the benefit of 10 Ashvamedha sacrifices and shares it with his family.

Gangāsangamyośchaiv snāti yah sangame narah

Daśāśavmedhamāpnoti kulam chaiva samuddharet.

Besides, the person taking bath in sangam at Prayāg gets the benefit of Rajsāya sacrifice, reading of all four Vedas and reward of telling truth (Mahabharata, Āranyak Parva 83/76-80). Such type of concept was behind taking bath at confluence of Ganga and Saraswatī. (Mahābhārat, Āranyak Parva 82/34). The person who touches the water of the Yamunā gets the benefit of Ashvamedha sacrifice and gets honor of being worshiped in the heaven (Mahabharata, Āranyak Parva 82/39). The person who passes five nights on the bank of the Indus gets a lot of gold (Mahabharata, Āranyak Parva 82/41). A bath at confluence of Ganga and Gomti at Markandeyatīrth gives the benefit of Agnishtoma sacrifice, and bath taker makes

[14]Gopath Brāhmaṇa 1/1/29; Jaiminīya Brāhmaṇa 1/140; Kaushītaki Brāhmaṇa 25/1; Śatapath Brāhmaṇa 11/1/6/1; ShuklaVimal Chandra, Vaidik Samskriti Me JalTatva, Vaidik Samskriti aur Uskā Satatya, Editor SitārāmDubey, p. 77.

[15]Rigveda 10/17/10; Atharva Veda 1/1/4-5, 15, 17; 1/6/ 33/1; 3/3/13.

[16]Manushmriti 9/279

[17]Mahābhārata, Āranyak Parva 85/88-97

free his family from all type of sins (Mahabharata, Āranyak Parva 82/70). Bath in Gandaki River gives the benefit of Vajapeya sacrifice and goes to reside in Sun world (*Suryaloka)* (Mahabharata, Āranyak Parva 82/97). Those who take bath in Kampanā River get the benefit of Pundarik sacrifice and become authorized for Sun world (*Suryaloka)* (Mahabharata, Āranyak Parva 82/99). Bath in River Viśālā gives the result of Agnishtoma sacrifice and heaven (Mahabharata, Āranyak Parva 82/100). A bath in the streams of Māheśvarī enables for Aśvamedha and Pushkaranī sacrifices and protects one from bad results (Mahābhārata, Āranyak Parva 82/101-102). A bath in Kausikī authorizes for Rajsūya (Mahābhārata, Āranyak Parva 82/113) and who take bath in Kumārdhārā becomes free from sin of killing a Brahman (Mahābhārata, Āranyak Parva 82/129-30). A bath at the confluence of the Kālikā, Kausikī and Arunā with penance of three days makes free from all type of sins (Mahābhārata, Āranyak Parva 82/135). Kartoyā bathing with three days of penance gives the results of Ashvamedha (Mahābhārata, Āranyak Parva 83/3), while bathing at confluence of Ganga with sea earns merit of 10 Aśvamedha (Mahābhārata, Āranyak Parva 83/4). A bath in Vaitaranī makes men pure like moon makes him free from all sins and he gets the religious benefit of donation of 1000 cows. He also makes pure his family and gets rebirth in higher family. A bath and water offerings to deceased relatives at the confluence of Śoṇa and Jyotirathyā rivers give the result of Agnishtoma sacrifice. Same type of faith about bath in rivers Narmadā and Godāvarī is described in Matsya Purana 186/10-11 and Brahmānda Purāna 124/93. It was believed that a bath at the origin of Śoṇa and Narmadā as well as in river Mandākinī gives result of Aśvamedha sacrifice. Kośalā River and Gangā at Shṛingaverpur give benefit of Vajapeya sacrifice. Pushpāvatī, Vardā, and Kāverī rivers give the benefit of donation of thousand cows. Bennā gives chariot with peacock; Godāvarī gives result of Gomedha sacrifice and Vāsukī world.

The Rigveda mentions River Saraswatī purifying all three Bhuvanas.[18] Manu describes Saraswatī and Drishdvatī as divine Rivers.[19] There are many examples where saints immersed themselves in the water and crossed the worldly sea. Ram buried himself into the water of Sarayū as described in Vālmīki Rāmāyaṇa, Uttar Kāṇd 110/7-28, and Mahabharata, Āranyak Parva 82/63-64. There was a tradition of ending life by jumping into the water of River Yamunā from banyan tree at Prayāg during the reign of Harsha. Kumār Gupta ended his life there according to the religious manner.[20] Dhanga also followed this pattern.[21] The Kālikā Purāṇa 24/139 describes Sarayū as a holy river. Saraswatī has always been famous as a holy river. People use to offer Piṇda to their dead relatives on its bank.[22] Epics and

[18]Rigveda 7/95/1

[19]Manushmriti 2/17

[20]Apasadha Inscription of Adityasena, Line 8-9 Śauryasatyavratdharo yah prayāgagatodhane, Ambhashīvakarīshāgnaumagnahsapushpapūjitah. B.L. Rajpurohit, PrāchīnBhartīyaAbhilekh, 2007, P. 187.

[21]EpigraphiaIndica, Vol. I, P. 146; PāthakVishuddhānand, Uttar BhāratkāRājnaitik Itihās, 2002, P. 397; Alexander Cunningham, The Ancient Geography of India, 1975, P. 328.

[22]Mahābhārata, Āranyak Parva 80/79-80; 80/119, 130–32; 81/3-4; 81/91; 82/34, 59.

Purāṇas mention Kāverī as a holy river. The Mani Mekhalai 1/9-12, 23-24 mentions its origin from Agastya's vessel for attainment of super position to the sons of Sun. Shrirangamtīrth is located on its banks. The Purāṇas describe Vaitaranī as a holy river, and it was carried down to earth by Parasurām. It is described as the river of Yama in the Padma Purāṇa, Chapter "Damodar River Basin: Storehouse of Indian Coal" and Sanyukta Nikāya 1/21.

The general concept for getting religious merit was in performing fire sacrifices but those who were unable to perform them were suggested to attain it by pilgrimage (Mahabharata, Āranyak Parva 80/38). Although the tīrthas are found located in the forests, on the hills, in the field, caves, and on the banks of lakes and ponds, the number of tīrthas located on the banks of rivers is greater. Pippalāda, Plaksha-Prashravan, Kedār, Gandharva-kūpa, Bhūteśvar, Rudrakoti, Kurukshetra, Virātnagar, and Gopāyan śikhar[23] were located on the bank of Saraswatī; Naimish on the bank of Gomti;[24] Badarikāshram, Devaprayāg, Rishīkesh, Haridwār, Shṛingaverpur, Prayāg, Varaṇasī, Bharadwāj ashram, and Gangāsāgar on the bank of Ganga; Ayodhyā on the bank of Sarayū; Vrindāvana and Bateśvar on the bank of Yamuna; Bhuvaneshvar adorned by Lingarāj, Paraśurāmeshvar, Ananda-Vāsudeva temples on the bank of Baliyānti; Virajā Devi on the bank of Vaitaranī; Panchavatī, Trayambakeśvar, Kuśāvarta,[25] Daśāśvamedhic tīrth,[26] Govardhan tīrth[27], Sāvitrī tīrth,[28] Vidarbha, Mārkandeyatīrth, and Kishkindhā tīrth on the bank of Godāvarī; Gokarṇatīrth where Bhāgiratha worshipped[29] on the bank of Sindhu; Gokarṇeśvartīrth on the bank of Brāhmaṇī River in Orissa. Kānchipurī, the capital of Cholas and also a religious center, is located on the bank of Palār, where great temples of Kamakshī, Kailāśnāthswāmin, and Rajsimhavarmeshvar are located. A big center of Buddhist studies was located there. Champā located on the bank of Gangā was a famous tīrtha.[30] The Padma Purāṇa, Chap. 11, is also of same view. It was a holy place of Jains and 12th JinaVāsupūjya was born here. Yuan-Chvang visited some Viharas located here. The hermitage of Rishi Shringa was also there. Gayā located on the bank of Falgu River, where Gayāsur worshipped, is described as a tīrth in the Vishnu Purāṇa 11/105. Footprints of Vishnu are here on the top of a

[23]Skanda Purāṇa, Prabhāsh Khand; Mahābhārata, Shalya Parva and Vana Parva; Padma Purāṇa, Shriti Khand.

[24]Padma Purāṇa, Uttar Khand, Verse 77; Mahābhārata,Āranyak Parva 82/53-55 refers that Brahmā, surrounded by Siddha rishis resides always at Naimishāraṇya. It is shelter of all tīrthas. Those who goes to Naimishāraṇya become free from all type of sins. The Gods perform fire sacrifices here. Yama also performed a sacrifice here. The river Gomtī flows through this forest (Mahābhārata, Āranyak Parva 85/5-6).

[25]Brahma Purāṇa, Chapter 80.

[26]Mahābhārata, Āranyak Parva, 81/52; 83/30; 86/2.

[27]Bhattacharya N.N., The Geographical Dictionary, New Delhi, 1991, P. 140.

[28]Ibid, P., 272.

[29]Vālmīki Rāmāyan, Bālkāṇd, 42/12

[30]Mahābhārata, Āranyak Parva, 82/114; 83/142.

hill.[31] Chapter 219 of the Agni Purana describes a hillock of Gayāshiśa as a tīrth. The advait āchārya vaishaṇava worshipped on the banks of Gangā in Nadia district at Śāntipur, where many temples have been raised. There is Chandikātīrth at Amarkantak on the bank of Narmadā.[32]

As rivers were regarded as a holy unit, people started performing fire sacrifices on their banks. Daśarath performed Aśvamedha on the bank of the Saryū,[33] Rām on the bank of the Gomti.[34] Daśarath raised sacrificial posts (*Yagnya-Yūpas*) on the bank of Tamsā (Raghuvamsa 9/20). Its bank was always full with saints.[35] Gradually, the saints built their hermitages on the banks of rivers and started reading, teaching, and research there. Ultimately, rivers became centers of knowledge. The Rigveda regards them as symbols of knowledge. Saraswatī is said to be Goddess of Mantras, and later, she became the Goddess of wisdom too. It is supposed that the hymns of the Rigveda were revealed to the seers on the bank of Saraswatī. The Ashramas of saints located on the banks of rivers became center of education. Mārkandeya ashram was located on the confluence of Gangā and Gomtī[36] where Rishi Mārkandeya worshipped for a long, Shaktipītha of Naimishāraṇya located on the bank of Gomati, where many ancient literary texts were rewritten, Ashramas of Siddhas on the bank of Śailoda,[37] Ashram of Vālmīki on the bank of Gangā at Bithūr, ashram of Rishi Shringa on the same river at Champā where a Buddhist education center flourished are worth mention. King Prasenjit and Bimbisār donated it and many institutions continued here. These all were *Dharmaśastriya* institutions, where Brahman boys were admitted as students.[38] There was Jahnu ashram on the bank of Gangā in Bhāgalpur of Bihār, where Gaivināth Mahādeva temple was famous. Traditionally, it is believed that Jahnu felt disturbed due to roaring of Gangā currents and he drunk all of the water but after the request of Bhagīrath he cut his thigh and made Ganga free to flow. Therefore, Gangā is known as daughter of Jahnu or Jāhnavī.[39] At the end point of Gangā, on an island, there is Kapilāshram.[40] Kulanch tīrth located on the bank of Gangā in eastern India was a center of Brahmaṇas of Śāndilya Gotra, who were expert in performing sacrifices.[41] Vikramśilā located on the bank of Gangā was a great education center during eleventh century A.D. There were many Buddhist Viharas. Philosophy, grammar, and rituals

[31]SamyuktaNikāya, BauddhaBhārti, Varaṇasī, 2008, 4/19;Mahābhārata, Āranyak Parva 82/84; 85/8; 93/9-10; Alexander Cunningham, Archaeological Survey of India Reports, 1962–63-64-65, P. 2.

[32]Laha B.C., 1972, as above, P. 433 and 505.

[33]Vālmīki Rāmāyan, Bālkāṇd, 14/1-2.

[34]Vālmīki Rāmāyan, Uttar Kāṇd, 91/15-17; 92/2

[35]Kālidās, Raghuvamsa, 9/72

[36]Mahābhārata, Āranyak Parva 82/70; Padma Purana, Chapter 16.

[37]Vālmīki Rāmāyan, Kishkindhā Kāṇd 43/37.

[38]Laha B.C., 1972, as above, P. 347.

[39]Ibid, P. 375.

[40]Brihaddharma Purāṇa, Chapter 22; Mahābhārata, Āranyak Parva, Chapter 106.

[41]Laha B.C., 1972, as above, P. 453.

were taught as a special course in this University. The University had six gates, where extremely learned teachers were appointed.[42] The ashram of Rishi Bhrigu was located on the confluence of Sarayū and Gangā in district of Balliā, where Parasurām regained his powers.[43] Dadhīchi ashram was located on the bank of Saraswatī, where he gave up his life for the welfare of people (Mahābhārata, Āranyak Parva 98/9-24). Kaṇva ashram was situated on the bank of river Mālinī, where he brought up Śakuntalā as his daughter. Kām ashram was located on the confluence of Gangā and Sarayū, where Śiva burnt Kāmdeva alive with a glance of his third eye.

The tasks such as cleaning, bath, nourishment, and education given by mother to her children started to be done on the bank of rivers, and rivers got the position of mother. Saraswatī is worshipped like a mother for feeding milk by her breasts,[44] and the milk never stopping to flow from them.[45] She is referred as protector of generations[46] and creator of embryo.[47] As the rivers were humanized, the Sanskrit poets started to use them as simile. Their fast flow was compared with a swift mare, and beautiful ladies were compared with River Saraswatī. They compare the slim waist and movements of ladies with the wavy currents of rivers.

The boats were first invented in India during Neolithic period. Pots of the Indus Civilization bear paintings of boat on their exterior. Rivers became the means of transportation and trade. Big cities developed on the banks of rivers during the second urbanization like Hastināpur, Kampil, Kannauj, Prayāg, Pātaliputra on the bank of Gangā; Mathurā on the bank of Yamunā; Ujjainī on the bank of Śiprā; Kāňchī, Daśapur, on the bank of Kāverī; Bhilsā and Deogarh on the bank of Betavā; Chitrakūt on the bank of Mandākinī; Māhishmatī on the bank of Narmadā; Sravasti on the bank of Achirāvatī; Padmāvatī on the bank of Pārvatī; Nagarjunkoṇdā on the bank of Krishnā etc. Ports such as Bhrigukachchha, Avanti, and Deval were developed on the banks of rivers, and international trade started through these ports.

Manu prescribed knowledge, penance, fire, meal, soil, heart, as well as water as the means of purifying body. He describes that river becomes pure through it flow (nadivegenśudhyati-Manushmriti 5/105). He was of the opinion that water purifies body, truth purifies heart, learning and penance purify Jīvātmā, and knowledge purifies wisdom.

Adbhirgātrāṇi śudhyati manah satyen śudhyati.

Vidyā tapobhyām bhutātmā buddhirgyānen śudhyati. Manusmriti 5/109

He opined that one should offer water to Devas, rishis, and pitrās after taking bath, and Agnyādhān should be performed also after taking bath.[48] Keeping in view

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42Ibid, P 453.

43Mahābhārata, Āranyak Parva 3/99, 86/50; Laha B.C., 1972, as above, P. 122.

44ChaturvediRekha, Ibid, P. 73.

45Rigveda 6/61/1-14

46Rigveda 10/30/12.

47Rigveda 10/184/2.

48Manushmriti 2/176.

the purity of water of rivers, he strictly forbade the voiding of excrements on the bank of rivers.

Na Mūtram pathi kurvīta na bhasmani na govraje

Na fāl kribhate na jale na chityam na cha parvate

Na jīrṇadevāyatane na bālmīke kadāchan

Na sasatvesu gartesu na gachchhannapi cha isthitah

Na nadītīrmāsādya na cha parvat mastake

Vāyvagnivipramādityamāpah paśyansthaiva gāh

Na kadāchan kurvīt vriṇmūtrasya visarjanam. Manushmriti 4/45-48

Manu again prohibits for throwing urine, stool, and poisonous things into the rivers.[49] He further says that one should not think about passing urine in the water.[50] He prescribes Uttamsāhas Daṇda and death penalty for those who destroy the water bodies.[51]

Ancient India gave different names, fame, forms, and honor to the rivers which are not found in any other part of the world although most of the ancient civilizations originated and developed in the river valleys. But now the modern India has changed its attitude toward rivers. Elders respect the rivers; they use to take bath in the water of it. They go for pilgrimage on the tīrthas located on the bank of rivers, but now neither the water of rivers is pure nor does it have merit of purifying things. However, not only Gangā but almost all the rivers have become polluted and nobody feel sorry for it. We have become habitual of throwing garbage, fecal matters, dead animals and joining drainages and sewer drainage into the rivers. There was a time in ancient India when there were only three sources of water: rain water, water from the rivers and tanks, and groundwater. But due to non-availability of suction pumps, the groundwater could not be much utilized. Rain water was under the control of climate or Gods. Therefore, the human society was aware of the purity of water of rivers, tanks, and lakes. They gave them respect like mother and entreated them never to dry up. Strong suction pumps are greatly responsible for the growing disrespect and negligence toward rivers. The lack of groundwater in future will certainly revive the respect and honor to the river and other natural water resources.

Reference

Laha BC (1972) Prachin Bharat Ka Aitihasik Bhugol. Uttar Pradesh Hindi Granth Academy, Lucknow, p 49; Rigveda 10/75/5

[49]Manushmriti 4/56
Nāpsumūtrampurīshamvāshthīvanamvāsamutsrijet
Amedhyaliptamanyadvālohitamvāvishaṇivā.

[50]Manushmriti 4/109
Udake Madhya rātrechaivaviṇmūtrasyavisarjanam
Uchchhishtahsrāddhabhukchaivamansāpinachintayet.

[51]Manushmriti 9/279-81.

Eternal Relation of Human Emotions and Rivers in Hindi Literature

Hemanshu Sen

1 Introduction

Rivers are the lifeline of human civilization, whose shaking waves are the pleasure of human mind and its sound is the tone of cultural beats. Their continuous flow reflects the evolution of human civilization. Actually, history of human development starts with the affiliation and coexistence with rivers as seen through "Indus Valley Civilization, Nile River Civilization," etc. Along with civilization, human culture is also embedded deeply with rivers as all rituals starting from birth to death are associated with pious water of river, holy dips, and meditation. In Indian culture, the propitious form of rivers is equated to 'motherhood'. Indian literature, especially Hindi literature, has attractive depiction of coexistence of rivers and human life.

2 Rivers in Folk Literature

Indian poets having muttered prayers of "*Har-Har Gange, Jay-Jay Gange, Jai Ganga Maiya*" feel sacred, and having this approach, they describe about rivers with proud and respect in their literature, folk culture, and minstrel. Every language has its own folk literature. It is evident that base of written literature lies in folk. Folk culture of all the Hindi dialects engrossed with rivers as this folk song aspires and expect to Ganga

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Ganga tori nirmal dhar ho rama…more man bhai

Pahir ke dhani chunariya aihon, Atal sohag ke tose mangihon

(Means—Ganga ! your pure and pious flow is pleasing to my mind, I will wear light green *saari* and pray for inviolable married life)

E-Ganga maiya tohen piyri chadhaiyon

(Means—I shall dedicate a yellow color saari for fulfillment of my wishes)

Saat balkawa dihalu sato le lihalu

Gangaji aadhwan garabh awataar, seho na barosile

(Means—Devki, the mother of Krishna, is complaining to Ganga Maiya (mother) for her seven kids killed by Kansa. She is praying for her next child by saying that you gave me seven kids but taken them back and I cannot believe for this one too)

The greatest Indian Folk Musician of twentieth century Bhupen Hazarika's Song "*Ganga tu bahti hai kyun*" is frolicking to every sensitive mind.

3 Rivers Depicted in Hindi Literature

The history of Hindi written literature is divided into four chronological parts—***Aadi Kaal*** (tenth–fourteenth century), ***Bhakti Kaal*** (fourteenth–seventeenth century), ***Reeti Kaal*** (seventeenth–nineteenth Century), and ***Adhunik Kaal*** (nineteenth century onward). During all periods (*Kaal*) of Hindi literature, sufficient, attractive, and relevant depiction of rivers is prominent.

3.1 Aadi Kaal

At this time, Raso literature was inedited in Dingle-Pingle (Rajasthani) languages, and Nath-Siddha Yogis inflicted the texts (*granthas*) for Hath-yoga and awakening of yogis (*kundalini jagran*). In the process of *kundalini jagran* (source of vital energy), Hath-yogi used to call *Nari* (stalk/tube pipe) *Ida, Pingla, and Shushumna* by the name of Ganga, Yamuna, and Saraswati (prominent rivers of India). Gorakhnath—the famous nath yogi accepted the importance of holy water of Ganga as

Sahaj sheel ka dhair sharer, so girahi ganga ka neer (Gorakhnath)

(Means—A married man who hold simplicity, and morality in his life is similar to the holy water of Ganga)

Vidyapati, an eminent poet of *Aadi kaal*, connects this era to *bkakti kaal*. At this time, writers started their writings with (*Mangalacharan*) the prayer of god

Bad such saar paol tua teere, chodhaeit nikat nayan bah neere
Karjori vinamao vimal tarange, pun darsan hoe punmat gange
Ek apraadh chhemab mor jaani, parsalmai pay tum paani
Ki karab jap tap jog dhaane, janam ka tanath ekhis mane
Bhanai Vidyapati samdaon tohi, ant kaal janu bisarah mohi (Vidyapati)

(In these lines, Vidyapti is praying to mother Ganga to forgive all his mistakes and not to ignore in the last moments of his life.

3.2 Bhakti Kaal

The golden era of Indian literature "***Bhaktikaal***" comes just after the period of *Aadikaal*. *Bhaktikaalin* poets have described interdependence of literature, society, and nature very effectively. *Bhaktikaal* is again divided into four parts namely *Sant kaavya, Sufi kaavya, Krishna kaavya*, and *Rama kaavya*. The best poets of these four branches are Kabir (*Sant kaavya*), Malik Mohammd Jaysee (*Sufi Kaavya*), Surdas (*Krishna Kaavya*), and Tulsidaas (*Ram kaavya*). All these poets created characters and heros in their poetry in such a way that they seem to have strong association with nature, especially with the rivers. These characters are incomplete without their natural ambience of rivers, ponds, villages, and mountains. Padmavati, the heroin of Malik Mohammad Jaysee and Krishna, the hero of Surdas are framed around Mansarovar (Pond) and the river Yamuna, respectively. They play, act, shape up their character and develop the philosophy of life around rivers in their stories.

The poets of *Bhaktikaal* signify the truth, facts, philosophy, and gratitude of life in characteristics of rivers, such as

Keerati bhaniti bhooti bhali soi, sursari sam sabkar hit hoi (Tulsi Das 2003)

(Means—This epic Ramcharitmaanas is like holy river Ganga, which is benevolent for all)

Paani hi te him bhaya, him hwey gaya bilai
Jo kuch tha soi bhaya, ab kachu kaha na jai (Kabirdas)

(Means—Kabir describes through water and ice that the creation, evolution, and dissemination are nothing but the transformation of real element)

Dekhiyat kalindi ati kaari
Aho pathik kahiyo un hari so, bhai virah jur jaari (Surdas)

(Means—Surdas describes that black color of Yamuna River is because of fire of separation)

Kaha maansar chaah so pai, paaras roop ihan lagi aai

Bha nirmal tinha payanh parse, pawa roop roop ke darse (Jaysi)

(Means—*Mansarova r* (divine pond) says his wishes got fulfilled to see the immortal beauty of Padmawati (Goddess), and her beauty is like touch stone "Paras". Mansarovar became the pure and pious by touching the feet of Padmawati and obtained that beauty also).

To express the absolute desire of human life means lustfulness of life. Tulsidas used the natural elements

Sabke hridaya madan abhilasha, lata nihari navahi taru sakha

Nadi umagi ambudhi kanhu dhai, sangam karahi talab talai (Tulsi Das)

(Means—Every heart has the lustful desire such as tree bent for *lata* (climber), and river flows with strong desire to meet ocean. All the water bodies meet each other with great desire)

Bhumi partaba dhabar paani,jimi jivahin maya liptaani (Tulsi Das)

(Means—The soul is as pure as god, but when it detached from god and takes birth, it is bound by the social desire. Just like the rainwater is very pure until it touches the ground after that it becomes dirty water. Thus, by using the symbol of water, Tulsidas expresses the relation of god and soul.)

Meera, a very strong lady siege of *bhakti-kaal* wishing to get peace and calm with river Yamuna

Chal manwa jamna ka teer

Wa jamna ka nirmal paani seetal hoe sareer (Meera)

One of the greatest moral poets, Neetikaar Rahim, expresses the moral values of life by using river, sea and, other water bodies

Dhani rahim jalpank ko, laghu jiya pjiyat aghaay

Udadhi badai kaun hai, jagat piyaso jaye (Raheem)

(Means—Be thankful to small water body which satisfies the thirst of thirsty, but the endless large ocean cannot be praised as it cannot satisfy the thirst of world)

Thus, the writers of *Bhakti-kaal* simply describe secrets and the mysterious facts of life, society, and world through river water and water bodies, and undoubtedly, this was their great achievement.

3.3 Reeti-Kaal

The third period of Hindi literature comes after the golden period of *Bhaktikaa*l. Actually, this is the most artistic and poetic period of Hindi literature. All the epics and literature of this period were based on the poetic principals and rules. All the epics and books of this *kaal* are started with *mangalacharan* (pray to god) that includes the Ganga *stuti* and Yamuna *stuti*. They express their sympathetic and emotional attachment to the rivers. Ghananand, the most eminent poet of Reetikaal, expressed his emotions with very creative, artistic, and literary sense but in very scientific way. It is actually not a common expression but the rarest one. The poet of seventeenth century is describing his feeling of loneliness (broken heart) with the system of water cycle

Biraha-rabi saun ghat-vyom tajyon,bijuri sikhivai ekli chhatian,

Hiya saagar te drag megh bhare,ughre barsai din aou ratiyan

Ghananand jaan anokhi dasaa, na lakhaun dai kaise likhaoun patiyan

Nit saavan deethi son baithak main tapke baruni tihin olitiyan (Ghananand)

(Means—The fire of separation is like sun, body is like sky, and shivering heart is like thunder. The fire of separation evaporates the water from heart ocean and filled eyes with cloud from where it rains continuously, because of hindering vision I am unable to write a letter to beloved as it is dropping down through eyelashes)

Bhikharidas, The acharya of reetikaalin sahitya, describes in his poem that by serving the Ganga River, one can get the immortal power of Indra (King of Deity)

Je tat poojan ko biswwarai se angan ki malinaai,

jo tum jeevan let hai, jeevan det hai je kari aap dhithai

daas na paap surapi tapi arujaai hitu ahitu bilgaai

gang tihaari tarangan so sab paawe purandar ki prabhutai (Bhikharidas)

3.4 Adhunik Kaal

After the period of Reetikaal, **Adhunik kaal** emerged with new consciousness, awakening, and new emotions. The greatest achievement of this age was the literature written in ***prose*** form. The literature of this age sets the new standards, concepts, and principles in the fields of emotions, lyrics, language, style, skill, creativity, esthetics, etc. New pattern and new vision were the main characteristics of the literature. The authors of this age express the nature in a new way; in earlier times, the nature was described like blazing or provoking factor, but during this period, nature was described like human being. Actually, the writers of this age describe the nature such as teacher, mother, beloved, friend, and sage. All the natural elements could successfully hold the sensitive, sentimental, and heart-touching images of emotional conditions and impulses of human mind.

The new scientific approach and knowledge reflect into the literature. The nature, the rivers, and other water bodies have been expressed by the writers in different ways, in a new pattern with new style. They wrote about the evolution of river, their flow, their continuity, liquidity, kindness, motive, their integral part, about their murmuring sound, etc.

The **poem** of **Adhunik Kaal** is again re-divided into the following:

1. **Bhartendu Yug (1857–1903) AD**
2. **Dwivedi Yug (1903–1921) AD**
3. **Chhayavaad Yug (1921–1936) AD**
4. **Pragativaad Yug (1936–1943) AD**
5. **Prayogvaad Yug (1943–1952) AD**
6. **Nayee Kavita** and **Adyatan Kavita (1952 AD onward)**

The first part of this adhunik kaal is **Bhartendu Yug (1857–1903**). The poets of this age create a very live and dynamic image of river. Depiction of river is so lively that river seems vivid.

Nav ujjwal jaldhaar haar heerak si sohat

Bich bich chhahrat bund, Madhya muktamanu pohat

Lol lahar lahi pawan ek paiy ek imi awat

Jimi nargan man vividh manorath karat mitawat (Bhartendu Harishchand)

(Means—The continuous flow of Ganga River is looking like a necklace of diamond and droplets which disperse are like glowing pearls. The dancing waves are coming one to another and disappear because of wind just like human desire.)

Tarani tanuja tat tamaal taruvar bahu chhaye

Jhuke kool saun jalparsan hit manhu suhaye (Bhartendu Harishchand)

(Means—Poet is describing the natural beauty of tamaal trees (evergreen tree) in the bank of Yamuna River (the daughter of Sun). They are bending to touch the pious water of Yamuna. Whole natural view is looking very calm and beautiful)

Dwivedi Yug (1903–1921) is second part of Adhunik kaal. The poet of this age also writes much more about the Indian River. Jagannath Das Ratnakar, a famous poet of this age, wrote about the emergence of Ganga River on earth. In his book 'Gangavataran' he wrote

Nikasi kamandal taiy umadi nabh mandal khandati

Dhai dhar apaar veg saun vaayu vihandati

Bhayo ghor atishabd dhamak saun tibhuvan tarjain

Maha megh mili manahu ek sangahin sab garijaiy (Jagannathdas Ratnakar)

(Means—After coming out from the *Kamandal* (an earthen), Ganga river overflowing to the sky and running with impetuosity like a storm, its thumping and rambling sound filled in *tribhuvan* (sky, ocean, and earth) seems like all the clouds of sky are meeting and roaring together.

Rashtrakavi Maithilisharan Gupt (*Rashtrakavi*—The National poet of India) wrote about the pure and clean depiction of water.

Sakhi nirakh nadi ki dhara

Dhalmal dhalmal chanchal anchal jhalmal jhalmal tara (Maithili Sharan gupta)

(Means—Friend! Look at the shaking, unsteady, trembling current of river whose edges are radiant and glittering like stars. Actually, it is showing the purity, piousness, and speed of water)

Chhayawad Yug (1921–1936) was the next stage of Adhunik Kaal, which is known for the poetry of romanticism. All the poets of this age were romantic to their writings.They expressed their emotions in their own ways. The literature of this era is full of strength, energy, emotion, beauty, and imagination. The main characteristic of this *Chhayawaadi* literature is to express the mystery, beauty, capability, and quality of nature.

One of the most popular poets of *Chhayawad* Jayashankar Prasad wrote about the evolution of human life on psychological ground

Himgiri ke uttung shikhar par, baith shila ki sheetal chhanh,

Ek purush bheege nainon se, dekh raha tha pralaya prawah,

Neeche jal tha upar him tha, ek taral tha ek saghan

Ek tatva ki hi, pradhanta kaho use jad ya chetan (Jayshankar Prasad)

(Means—The first man (Human) of the earth '*Manu*' was all alone at the time of Pralaya (dissolution of earth), and he was sitting at the top of Himalaya and looking below with tears. The earth sunk with water and mountains was covered with snow. There is only one element in both the forms which implies "the god" and "the world".)

Uth uth ri laghu laghu lol lahar

Karuna ki nav angdai seemalyaanil ki parchhain si (Jayshankar Prasad)

(Means—Dancing and shaking waves are coming one after another, and it seems that it is the twist of mercy and the reflection of fragrant breeze)

Sumitranandan Pant, the nature poet of Hindi literature, creates a depiction of Ganga of summer season. At that time, the volume and momentum of Ganga go down and it seems like a slim and beautiful lady. It is one of the best examples of personification

Saikat saiya par dugdha dhaval, tanvangi ganga greeshm viral,

Leti hai shrant-clant, nishchal, taapas baala, ganga niramal

shashimukh se deepit mridukar tal,

Lahren un par komal kuntal,gore angon par sihar –sihar, lahrata taar-taral sundar

Chanchal-anchal sa neelambar (Sumitranandan Pant)

Pragatiwad Yug (1936–1943) The literature of Pragatiwad has deep association with the society. "This literature depicts joy, problems, disappointments, and all the social sanctions of society in reality. They do not carry rhetoric way of describing the river and nature. This pattern of realistic expression could also be seen on depiction of rivers" (Hemanshu Sen 2015). Surya Kant Tripathi 'Nirala', *Mahapran* poet of Hindi literature, describes the Ganga river with its social affiliation

Katki main ganga nahan ki badhi umangen
Saji, gaadiyanchale log manchadti change
Mele main, kheti ke kuch saaman kharide,
dekhe haathi ghoderabbe, laute seedhe (Nirala)

(Means—A common man who goes to *kartik mela* (fair) takes a holy dip in Ganga, buys something for farming, some toys, and other personal useful things)

Baba Nagarjuna describes the natural look of Ganga in evening

Madir thir lahar dolti chhahar, sham ka prahar
Lahar par lahar simat kar sihar, jodti bandh
Chhand mradu kal kal, dhara chal
Aur gagan ki magan tarika chanchal
Jhank-jhank jhim-jhim kar
Sikud sihar jaati sharmakar, mradul lahar par (Nagarjun)

(Means—The arousing passion and steady wave, which is shaking slowly in evening. The waves are coming to one over another and softly shaking with murmuring sound. The flirtatious star of sky peeping in the shaking waves and feel shriveling, thrilling, and bashful.)

On the other hand, as a *Pragatiwadi* poet, he writes about the tendency of the poor people who live in the bank of river

Pravah main khisakti ret ki le rahe toh
Bahudha avatarit chaturbhuj narayan oh
Khoj rahe paani main jaane kaustubh mani,
bidi piyenge (Nagarjun).

(Means—A poor person who lives at bank of river is in search of coins thrown by people, like invaluable things just for *bidi*-smoking)

Prayogwaad Yug (1943–1952) and **Nayee Kavita** (1952 onward) have philosophical approach to express the nature. Actually, "Prayogwaad is known as the age of experiment (prayog) for style, simile, symbol, language, etc. This time, poetry was not in a traditional pattern but focused on the local language, philosophical view, and realistic depiction of the most insignificant person (*laghu maanav*) of society. Even the smallest part of the scenario was not ignored by the poets" (Hemanshu Sen 2015). In the depiction of river, Sacchidanand Heeranand Vatsyayan 'Ajneya' (initiator of *Prayogwaad*) expressed the philosophical idea of life.

Jan jeevan ki ajasra pravahmayee nadi jiske neeche se bahti hai –
Mudti, bal khati
Naye marg phodati
Naye karare todati
Chirpariwartansheela, saagar ki or jati jati jati (Ajneya)

(Ajneya describes high association of river and life. Similar to life, rivers also take turn and twist, making new path, breaking stability, prone to change and finally meeting its end to ocean, the ultimate)

Rambilas Sharma, an eminent critique and writer, wrote about the social value of Ganga, where people gathered in a fair

Swapn dekhate dheere-dheere ja rahe
Sakarghati kar paar jahan lahra rahi
Sar sar karti ganga ki dhar wahan
Rang biranga kolahal karta bada
Baalu par mela hai ek juda hua (Ram Bilas Sharma)

Bharat Bhushan Agrawal, a famous poet, compares the life and river and wishes to overcome the miseries of life

Jeevan dhaara
Phir ek baar
Him ki kaara ko tod phod
Akshaya prashast jeevan dhara
Vasudha ki chaudi chhati par
Satwar/amand
Bah paayegi mag sarsaati
Kal kal gaati (Bharat Bhushan Agrawal)

(Means—The lifeline… will break the prison of ice, i.e., miseries, and will overflow on the broad bosom of earth with strong existence of life. It will flow to make the way happy with murmuring sound.

Girija Kumar Mathur is expressing the joy of eminent rivers of India

Narmada, betawa, kshipra ki avilamb dhaar
Jin par hemantkuhase si chhaayee rahti
Yug se yug tak (Girija Kumar Mathur)

(Means—Rivers such as Narmada, Betwa, and Kshipra have continuous flow, and there is a long-lasting mist of *hemant* (season around November)

4 Rivers in Hindi Prose

The Hindi prose literature writing was started in Adhunik Kaal; similar to other languages, Hindi prose has so many forms as novel, drama, story, essay, etc. In every form of prose writing, the rivers have been expressed with their huge importance and value. In fact, hundreds of book have been dedicated to the river and other water bodies, e.g., *Ganga Maiya, Boond aur Samudra, Betawa bahti* *rahi, Nadi ke dweep, Bahti Ganga, Kosi ka ghatwaar, and kasi ka assi*. Actually, in prose literature, not only the positive senses have been strongly expressed but the negative aspect of the society and human mentality was also depicted by the rivers. In a biographical novel '*Maanas Ka Hans*' (based on the biography of Tulsidas), Amrit Lal Nagar wrote about the faith and tendency of Indian society

> Sabere kaa samay hai.Ramghat par snaan karne waale bhadra varg ke nar-naariyon ki bheed hai.Aaj basant panchmi ka din hai.Saryu tat ke maidaan main kai sau marbhukon ki bheed ekatra hai. Dhani nar-naariyan ramghat par nahakar in marbhukhon ke age mutthi do mutthi ann daalkar swarg main apna sthan banayenge aur dharti par aaj ke din saikadon ka pet bharega (Amrit Lal Nagar).

(Means—In the morning time, a huge crowd of male and female gathered to take a holy dip in Ramghat on the occasion of *Basant Panchami* (fifth day of spring), and there are hundreds of baggers gathered at the bank of Saryu. Having a holy bathe on Ramghat, the rich will donate something to the baggers and will ascertain their place in heaven and hundreds of baggers will subsidize their hunger today)

Actually, the canvas of Hindi literature during Adhunik kaal is so broad that every form of literature, their symbols, element, depiction, creations cannot be completely described in one article. In Adhunik Kaal, the river implicates the human life. The velocity of the river, their continuity, novelty, liquidity and longevity reflects the continuous growth of human civilization. Writers of today understand and accept the importance of coexistence of human and river. Undoubtedly, human life flows like a continuous and long-lasting river. In words of Sumitra Nandan Pant

> Is dhaara saa hi jag ka kram
>
> Shashwat is jeewan ka udgam
>
> Shashwat hai gati.shshwat sangam (Sumitranandan Pant)

(Means—The world is like a continuous flow. The evolution of life is immortal. The movement is long lasting, and association of society is eternal).

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Landscape of the Indus River

Anil Kumar and Pradeep Srivastava

1 Introduction

Indus River is one of the largest rivers in the world which originates from the Mount Kailas (5182 m asl) in the Gangdese range of southern Tibet. The river drains through the tectonically active zones of Karakoram in Tibet, Ladakh Himalaya, and Nanga Parbat in the western syntaxis of Himalaya. The geological, geomorphological, and geophysical investigations on the sediments of the Tibet, Ladakh, and Indus fan implicate that predecessor of Indus was a centripetal drainage that filled the basin in Ladakh Himalaya until $\sim$45 Ma, and subsequently due to regional uplift during early Miocene (<26 Ma), the present westerly flowing Indus River came into existence (Clift et al. 2001; Sinclair and Jaffey 2001). The catchment area of Indus River ($\sim 1 \times 10^6$ km^2 and $\sim$3000 km length), from source to sink, placed it on 12th position in the world largest rivers. The upper $\sim$470-km reach of Indus drains through Tibet and Ladakh Himalaya and then it cuts through Nanga Parbat Haramosh Massif (NPHM), where it diverges its path and starts flowing southwestward. Fourteen major tributaries which contribute a lot of water and sediments to the Indus are Sengge and Gar in Tibet, Zanskar, Suru, Shyok, Shigar, Gilgit, and Kabulin the Higher Himalaya and Gomal, Kurram, Jhelum, Chenab, Ravi, Beas and Satluj in the Punjab plain of Pakistan. The major locations in the upper Indus valley to downstream are Nyoma, Upshi, Leh, Nimu (Indus–Zanskar confluence), Khalsi, Dah Hanu in Ladakh, Skardu (confluence with Shigar), Jaglot (confluence with Gilgit), Attock, Dera Ismail Khan, Hyderabad in Indus plain Pakistan (Fig. 1).

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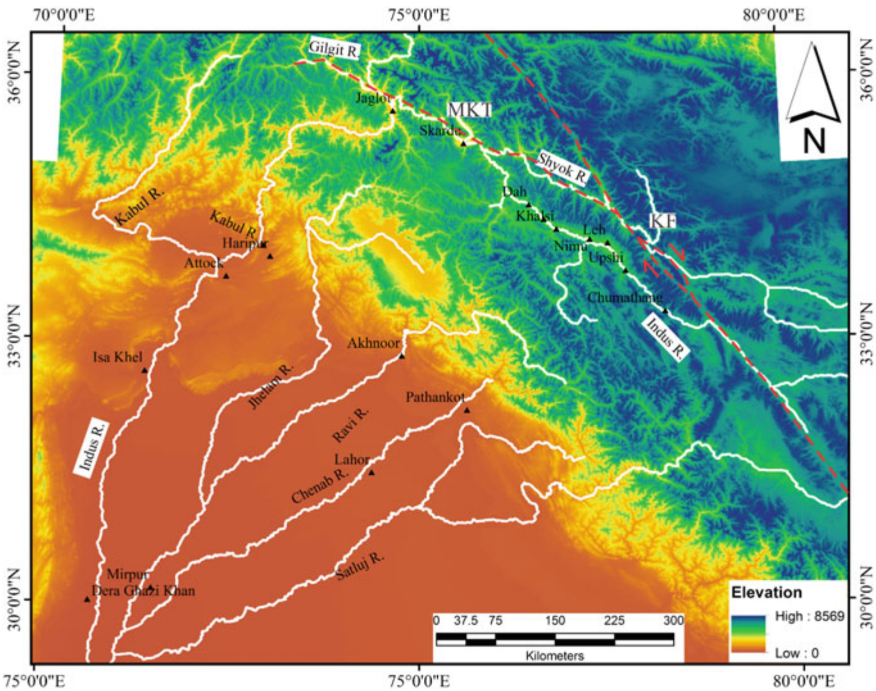

Fig. 1 Topographic image of Indus and its tributaries. The major location in the NW Himalaya and Punjab plain (Pakistan) in the Indus River's catchment. The Indus River aligned itself along Karakoram Fault (KF) in SW Tibet and entered into NE Ladakh by diverging 90° at upstream Chumathang. The *dotted red line* represents dextral strike-slip Karakoram Fault (KF)

The glacial melt water, Indian Summer Monsoon (ISM), and moisture brought by westerlies are the major source of water for the Indus River. Glacial melt water coming from Gangdese, Karakoram, Ladakh, and Kohistan contributes 40 and 60% is contributed by ISM. The river has also played a major role in the existence and growth of civilization along its bank. The Indus Valley Civilization, one of the ancient known civilizations, exists along the Indus during ~6000 BP.

1.1 Geology Along the Indus Basin

The origin of Indus and Tibet-Himalaya is closely linked with each other. The Indus River has been flowing along the Indus Tsangpo Suture Zone (ITSZ) since early Eocene. The ITSZ is the zone that archives collisional geology of Indian and Eurasian plates. The Kohistan–Ladakh island arc, Khardung volcanics, and Lhasa-Karakoram block are situated north to the ITSZ and Indus Molasse, and Tethyan sediments and High Himalayan Crystalline Complex lie toward south

(Brookfield and Andrews-Speed 1984; Thakur and Misra 1984; Searle et al. 1990; Henderson et al. 2010a, b, 2011). The Trans-Himalaya and Lhasa-Karakoram block represent the southern margin of Eurasian plate and are the assemblages of low grade metamorphosed Paleozoic—Mesozoic sedimentary rocks (Henderson et al. 2011). The Ladakh plutonic complex has multiphase intrusive geological history in between 103 and 20 Ma (Thakur and Misra 1984; Wu et al. 2007).

The Cambrian to Eocene Tethyan sediments, south to the ITSZ, consists of meta-sedimentary and sedimentary rocks deposited at the passive margin of the Indian plate. The ITSZ sedimentary rocks (carbonate and siliciclastic) are detached from Zanskar ranges by Zanskar Back Thrust at south and Upshi–Bazgo Thrust from Ladakh Batholith at north (Brookfield and Andrews-Speed 1984). The principal units of ITSZ consist of both marine and terrestrial sediments, derived from Indian and Eurasian plates during collision, on lapping to the Ladakh Batholith (Thakur 1983; Brookfield and Andrews-Speed 1984; Thakur and Misra 1984; Garzanti and Van Haver 1988; Henderson et al. 2010a, 2011). The continuous northward movement of Indian plate deformed the Molasse intensely, where several north verging thrusts and folds are formed (Searle et al. 1990). These faults presumably are active during late Quaternary to recent.

The Indus River aligned itself along the dextral strike-slip Karakoram Fault (KF), SW Tibet and entered into the NE Ladakh at Thangravia Hundri Formation by diverging its path in the vicinity of ITSZ. In Ladakh, it runs through both Indus Molasse and Ladakh Batholith, whereas in Leh Valley, it largely follows the suture zone (litho-tectonic contact of Indus Molasse and Ladakh Batholith). From Spituk downstream, river migrated to the highly deformed Indus Molasse and entered into narrow gorge. Further downstream near Dah Hanu, it flows into Ladakh Batholith. Downstream Skardu, at NPHM, represents the northwestern syntaxis of the Himalaya, which has been evidenced as highly active zone due to the activity along the Raikot fault (Burbank et al. 1996; Leland et al. 1998). In Pakistan foreland basin, the bedrock of Indus are clastic carbonates of Murree and Kamlial formations (Paleocene–Eocene). The plain of Indus represents the late Quaternary sediments having boulders, sand, and slit till Indus delta.

2 Geomorphology

The Indus, all through its course from Tibet to Pakistan plain, exhibits breadth of landscape that resulted due to its continuous adjustment to tectonics uplift of Himalaya and varying climate through the time. In the upper reaches of Karakoram zone, it flows as anastomosing braided stream in a wide valley, becomes narrower, and incises the bedrock downstream.

In the NE Ladakh, near Nyoma (4143 m asl), the average valley width increased up to ~4 km, which is widest in the Ladakh Himalaya (Fig. 2a). Downstream of Mahe (4131 m asl) (~35 km from Nyoma), the channel pattern changes from braided to meandering, and the valley width decreases to ~180 m, where the

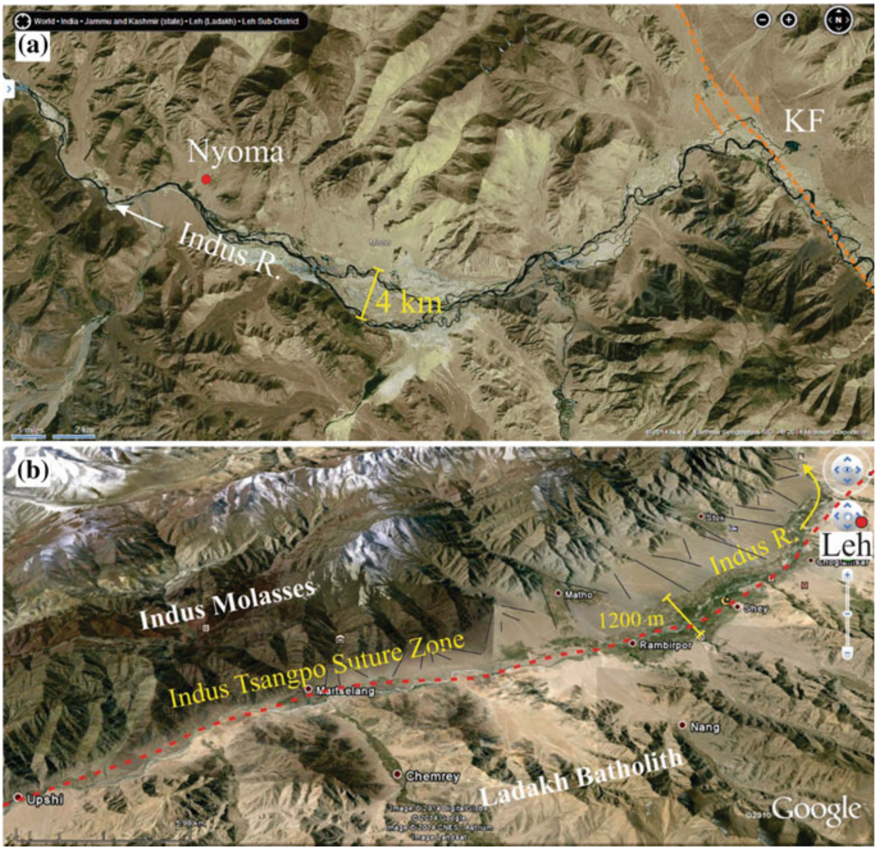

Fig. 2 **a** Indus flowing along the Karakoram Fault (KF). In the northeastern Ladakh, braided pattern of Indus has maximum valley width of ~4 km. Near Mahe, the valley becomes narrower and river flows as meandering channel. **b** The Indus flowing along the ITSZ in the Leh Valley, where the average valley width is ~1200 m. Here, the Indus diverted its path from suture zone to molasse downstream to Leh

channel gradient increases from 0.75 to 7.2 m/km (Fig. 3). Further at Leh, the Indus shows sudden drop in its gradient from 7.2 to 1.8 m/km and channel braids in a ~1200 m-wide valley (Fig. 2b). At Leh huge glacial outwash fans emerging from left and right banks in the form of amphitheater valleys and alluvial fans, respectively, contribute sediments for valley fill terrace in the Leh Valley (Sant et al. 2011a, b). The fan building has been completed between 47 and 29 ka, and a channel aggradation phase began from 28 to 25 ka (Kumar and Srivastava 2017).

Further downstream, Nimu to Dah Hanu, the river flows in a narrow gorge, where it incises into the bedrock and forms one level of strath terrace and one filled terrace (Fig. 4). At Nimu, the Zanskar River drains into the Indus and contributes huge amount of sediments. The Shyok and Shigar meet with Indus at Keris and Skardu, respectively. The active channel width near Skardu increases up to ~5 km,

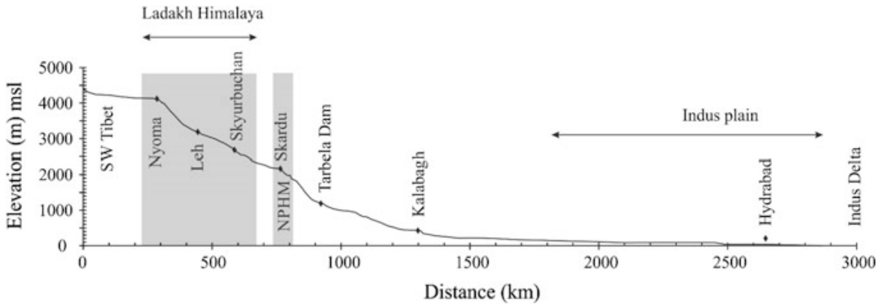

Fig. 3 Longitudinal river profile of Indus from SW Tibet to Indus delta. In the upper reaches (SW Tibet), it is almost flat, in NE Ladakh (downstream Nyoma), the gradient of the Indus is sharply increased, whereas in the Leh Valley, it again reduced. A sudden increment in Indus gradient is also marked at the confluence with the Zanskar River. In Nanga Parbat zone, the slope of Indus again increased

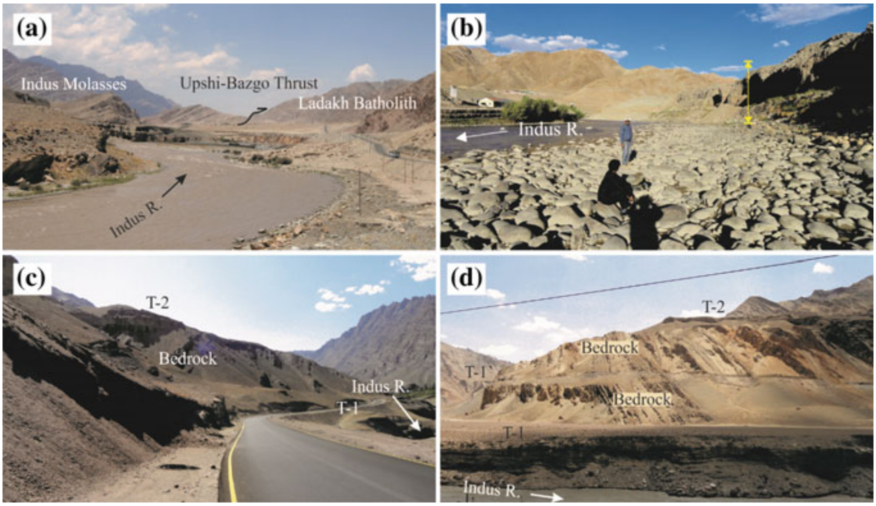

Fig. 4 **a** Upshi-Bazgo thrust located near Kharu, **b** A panoramic view showing the valley fill-type sequence located at Stakna, near Leh. Downstream Leh ~60 and ~83 km, 2–3 levels of strath terraces are shown in **c** at Saspol and **d** at Khalsi, respectively

where the gradient is 3.3 m/km. As Indus enters in NPHM and the Raikot fault zone, the gradient increases sharply to 10.8 m/km (Cronin 1989).

Further downstream, the Indus flows in Siwalik foreland basin (Fig. 1). The gradient of the river decreases to ~0.5 m/km and follows a meandering pattern with channel width ~420 m. As the river enters into the Indus plain, it converts into braided and opens its threads into ~4.5-km-wide channel. The average channel gradient reduces to ~0.25 m/km near the confluence of Chenab.

Downstream to this confluence, the gradient further reduced to 0.1 m/km (Fig. 3), where Indus flows in several threads and drains into the Arabian Sea. In the Arabian Sea, it makes one of the world's largest delta and submarine fan.

2.1 Landforms Along the Indus River

Ladakh Himalaya has various paleo-landforms, which are mainly associated with glacial moraines, fluvial deposits (filled and strath terraces), debris flow deposits, huge fans, paleo-lake deposits, and eolian deposits. Through the Quaternary time, the preservation of these landforms is tremendously sensitive to any climate change or orogenic activity. The erosional processes developed and modified the topography related to these landforms with the space and time. The moraines are extensively studied landform in the Ladakh Himalaya (Fort 1983; Burbank and Fort 1985; Brown et al. 2002; Damm 2006; Owen et al. 2006; Dortch et al. 2010, 2013). These studies suggest the presence of ten glacial stages in Leh and Nubra valleys. The Indus Valley glacial stage dated as the oldest one, ~430 ka (Owen et al. 2006). The detailed glacial stages are given in Table 1.

The sediment generated by these glacial events were further aggraded the river valleys of this region. In the late Quaternary, the valley filling and incision are also reported in both Indus and Zanskar rivers (Burbank et al. 1996; Leland et al. 1998; Phartiyal et al. 2013; Blothe et al. 2014). The staircase terraces in the Indus (Fig. 5a) and Zanskar valleys, suggest the valley filling initiated between ~83 and 50–20 ka, remained as relict strath terraces at ~160–80 and 30–40 m above the river level, respectively. However, these valleys were incised at the rate of 2.2 ± 0.5 and 1.5 ± 0.2 mm/a (Blöthe et al. 2014; Kumar and Srivastava 2017). The straths of Indus River, at NPHM, northwestern Himalayan syntaxis, have a lower strath (<7 ka) and a higher strath (>7 ka). The lower strath has rapid incision at the rate of 9–12 mm/a, whereas the higher strath incised the bedrock at lower rates, 1–6 mm/a (Burbank et al. 1996; Leland et al. 1998).

Table 1 Glacial advance in Ladakh Himalaya (Owen et al. 2006; Seong et al. 2008; Dortch et al. 2010, 2013)

S. No.	Glacial stage	Age (ka)
1	Indus valley	~430
2	Leh Valley	~311
3	Dishkit-3, Kar and Skardu glacial	~146
4	Ladakh-4, Dishkit-2, and Pangong-2	~80
5	Bazgo	~61
6	Dishkit-1 and Pangong-1	~46
7	Ladakh-2	~20
8	Ladakh-1	~13.9
9	Ladakh cirque	~1.7
10	Pangong cirque	~0.4

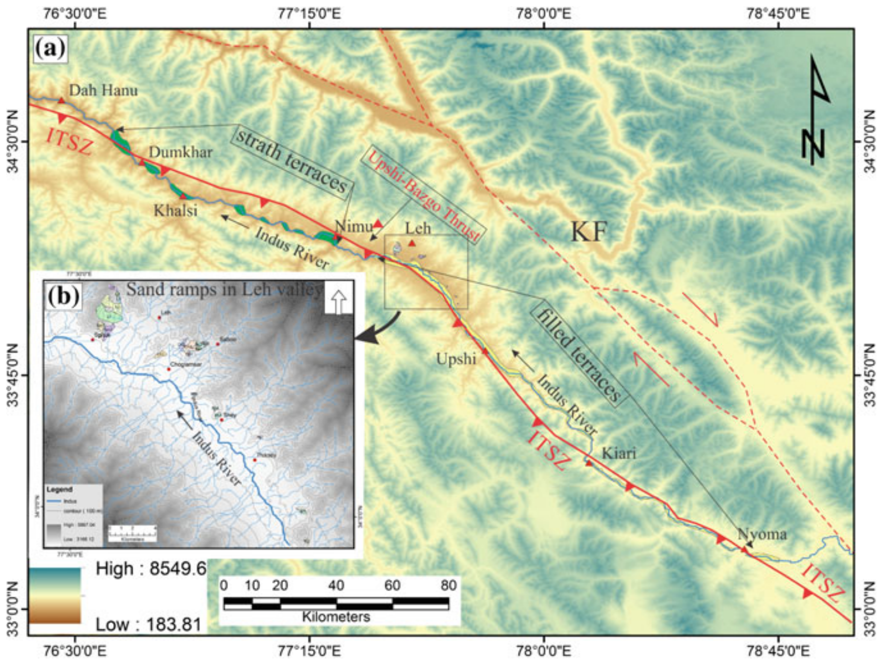

Fig. 5 **a** Map showing the extension of filled and strath terraces along the Indus River in the vicinity of Karakoram Fault, Upshi-Bazgo thrust, and ITSZ. The yellow and green polygons indicate filled and strath terraces (modifies Kumar and Srivastava 2017). **b** The inset map of Leh Valley showing the sand ramps (21 in number) (after Kumar et al. 2016)

The paleo-lakes in Ladakh are being used to understand the paleo-climate and neotectonics. The paleo-lake deposits at Spituk, Lamayuru (50–30 and >35 ka) and along the lower reaches of Indus River (~136 km) from Nimu to Batalik at Saspol, Rizong, Khalsi, Achinathang and Biamah dated to ~11, 17–14, 15–5, ~11, and 14–6 ka, respectively, indicates rise in lake level from 35 to 5 ka and characterized as increase in temperature or monsoon effect in Ladakh Himalaya (Kotlia et al. 1997; Phartiyal et al. 2005; Nag and Phartiyal 2015).

The sand ramps in Ladakh were located mainly in wider valleys, therefore, there may be a relation with the valley width (available sediment) and sand ramps accumulation. In Leh Valley, around Spituk, Leh, Choglamsar, Saboo, Shey, Thiksey, and Stakna, 21 numbers (Fig. 5b) of sand ramps were located, out of them five were studied in detail (Kumar et al. 2016). The Optically Stimulated Luminescence (OSL) chronology from Spituk, Choglamsar, Saboo, and Shey sand ramps suggests that the accretion of these ramps was started before ~44 ka and continued up to ~8 ka. The eolian activity was dominant between 25 and 17 ka (MIS 2; Kumar et al. 2016).

2.2 Climate

The regional climate in the upper reaches of the Indus, i.e., in southwest Tibet, NW Ladakh, and NPHM, is cold and semiarid. The annual average precipitation in these regions is <150 mm, whereas in the lower reaches of the Indus, in the plain (Pakistan), the mean annual rainfall is ∼500 mm. Two major climatic systems, ISM and westerlies, affect the discharge of Indus significantly. June to September, ISM dominates water budget of the Indus (Shichang et al. 2000). The westerlies get active in the winter (November to February) and cover SW Tibet, Ladakh, and Kohistan regions with 1–10 m snow. This snow melts in every summer and contributes about 40% discharge of Indus. The average of 30 years (1930–1960) minimum and maximum temperature changes, relative humidity, rainfall and wind speed of Ladakh region (Bhatnagar and Gandhi 1991) are shown in Fig. 6

2.3 Hydrology

The river discharge in a terrain has the potential to expound the hydrological and climatic settings. The modern average discharge gauge data of Indus River (at Leh)

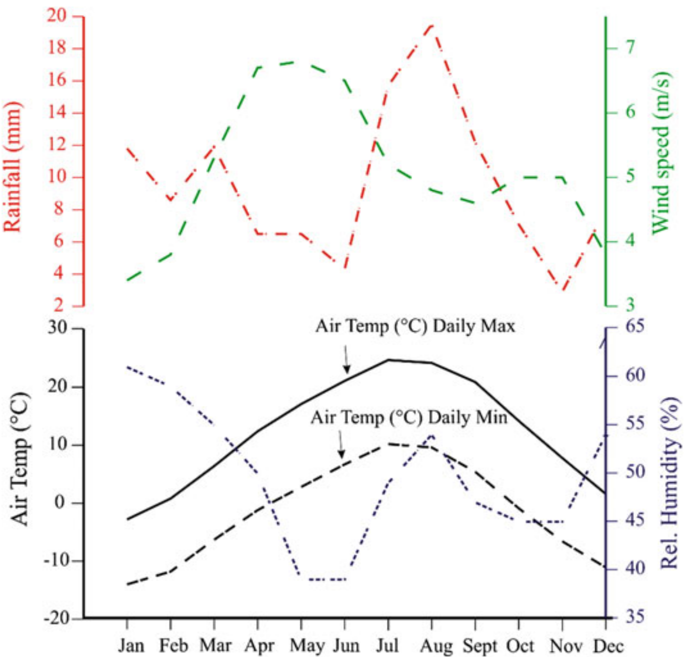

Fig. 6 Average 30-year climatic data of Ladakh Himalaya from 1930 to 1960 showing monthly fluctuation in maximum and minimum temperatures, relative humidity, rainfall, and wind speed

has been collected from the Leh irrigation department. The average discharge of Indus is 198.3 ± 45.4 m^3 s^{-1} for the month of August, year 2002–2006. The paleo-discharge of any river can be estimated by using empirical formulas (William 1978; Mears 1979; Costa 1983; O'Connor 1993). The paleo-discharge of Indus River is estimated using clast geometry method using empirical formulas:

$$v_b = 5.9D_I^{0.5}$$
$$\bar{v} = 1.2v_b$$
$$Q = A.\bar{v}$$

where v_b = riverbed velocity, D_I = clast's intermediate diameter, $\bar{v}$ = average river velocity, Q = palaeo-discharge (m^3/s), and A = valley width × depth (thickness of individual sedimentary unit)

The paleo-discharge at Stakna (dated with OSL dating, 47 ± 0.3 ka), has been calculated from empirical method (4457 m^3 s^{-1}) and normalized with the modern discharge at Leh. The modern hydrological budget of Ladakh region has direct connection with the precipitation (Fig. 6), this implies that at 47 ± 0.3 ka BP, the climate was relatively warmer and wetter which increased the Indus discharge 22 times from the present.

3 Socioeconomic Importance

The flow of the Indus River largely influences the socioeconomic conditions of agriculture-based economy in India and Pakistan. In Indian context, Indus along with its tributaries is the lifeline for the people living in the cold and hard terrain of Ladakh. It supplies water for both drinking and irrigation. The Leh and adjoining areas are the attraction point for the tourists which increase the economic values of this terrain. The Alchi is the only dam in this terrain which starts supplying electricity in this area from August 2014. A small turbine is also running through the link canal at Kharu. The Indus River is very famous for trout fish in Ladakh and Indus dolphin in Pakistan. The ecosystem of temperate forests of Himalaya is also supported by Indus and its tributaries.

The Indus River supplies water to the 80% agricultural land of Pakistan. Several barrages, dams, canal, and links constructed on the Indus supplies water for irrigation and drinking. About 1.2 million people of Pakistan depend on mangrove forest and its resources on the Indus delta (Salman 2002). The rural people living around the delta largely depend on the fishing. The Indus River's sediment is highly fertilized and actively helping in economic growth of the Pakistan.

3.1 Natural Hazards

Arid part of Himalaya is prone to episodic rainfall events that usually occur during the summers. The intense monsoon year brings more moisture than normal monsoon year, which penetrates the orographic barrier and precipitates in the drier Himalaya. The sediment supplied due to landslide and hill slope erosion during the episodic rainfall events exerts cascading impact in the downstream areas. More than 600 lives and 60 villages were destroyed in Ladakh (Hobley et al. 2012) in the August 2010 flood; at that time, Indian Air Force records 250 mm of rainfall in less than an hour at Leh airport although the normal August rainfall is only ~12 mm. In the plains of Pakistan, the Indus has a long history of flooding and related hazards. The floods in the years 1928, 1929, 1955, 1957, 1959, 1973, 1976, 1988, 1992, 1995, 1996, and 1997 are well documented that demonstrate their damaging nature and their hostile impact on society (Uddin et al. 2013). These floods can occur due to abnormal rainfall, cloud burst, and glacial lake burst.

Landslides are another major natural hazard in the Indus basin that usually occurs during high rainfall periods. The combination of high rainfall and landslide initiates debris flows that often dam the river and form landslide dammed lakes. The subsequent burst of such lakes creates havoc in the downstream regions. These landslides also occur due to unnatural reasons such as vibrations caused by movement of army trucks and slope instability induced by human interventions. Earthquake can be another major cause that can induce landslides. In the year 2005, more than 1000 people lost their lives, largely due to the earthquake-induced landslides in Kashmir (Owen et al. 2008). Human interference, like construction of dams and canal, changes the natural fluvial regime. The discharge of river has changed drastically from 10×10^9 m^3 to 13×10^9 m^3 during 1993–2003. The construction of barrage, dams over the Indus in the Indus plain (Pakistan), limit the sediments and fresh water supply, resulted to change in the deltaic ecosystem and mangrove forest land. A large part of population, reliant on Indus water are suffering with the lack of adequate water due to dams and barrages.

Increasing population pressure along the Indus River has polluted the Indus River in Ladakh and Pakistan. In Ladakh, the tourism is increasing year over year that stirs pollution in the Indus. The factories along the Indus in Pakistan drains their effluent directly into the Indus, increases the Indus water toxicity and are attributed to the death of Indus dolphin and fishes.

4 Conclusion

The Indus River has been the cradle of civilizations through the ages evolved vis-à-vis the Himalaya. The basin exhibits a full spectrum of fluvial geomorphology that archives the evidences of past climate and tectonic perturbations. Erosion and sedimentation are the basic functions that any river system undertakes to build up the landscape. The Indus landscape suggests that human intervention can aggravate or subdue any of the processes and that can be hazardous to society.

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The Ganga River: A Summary View of a Large River System of the Indian Sub-Continent

S.K. Tandon and R. Sinha

1 Introduction

For thousands of years, civilizations have taken root and prospered in the south Asian region, leading up to a population 'hot spot' accounting today for almost a sixth of the globe's population. Rivers, more so large river systems, have constituted the fundamental basis for sustaining the civilizations of this region. Most importantly, three large rivers—the Indus, the Ganga, and the Brahmaputra—have together contributed to the building up of extensive fertile alluvial plains that add up to an area of well over a million square kilometers, which were extensively used by humans over the millennia. Indeed, the Indus–Ganga–Brahmaputra (IGB) plains constitute a significant part of some of the world's largest water and sediment routing systems such as the Himalaya–Bengal–Nicobar and the Himalaya–Indus submarine fan systems that originated as a consequence of the post-Himalayan uplifts.

2 Drainage Organization, River Course, and Major Urban Settlements

The Ganga, one of the largest river systems on the globe, originates at Gaumukh at an elevation of $\sim$3800 m near the Gangotri Glacier and traverses a length of 2525 km through eleven states of northern and eastern India, until it meets the sea in the Bay of Bengal (Fig. 1).

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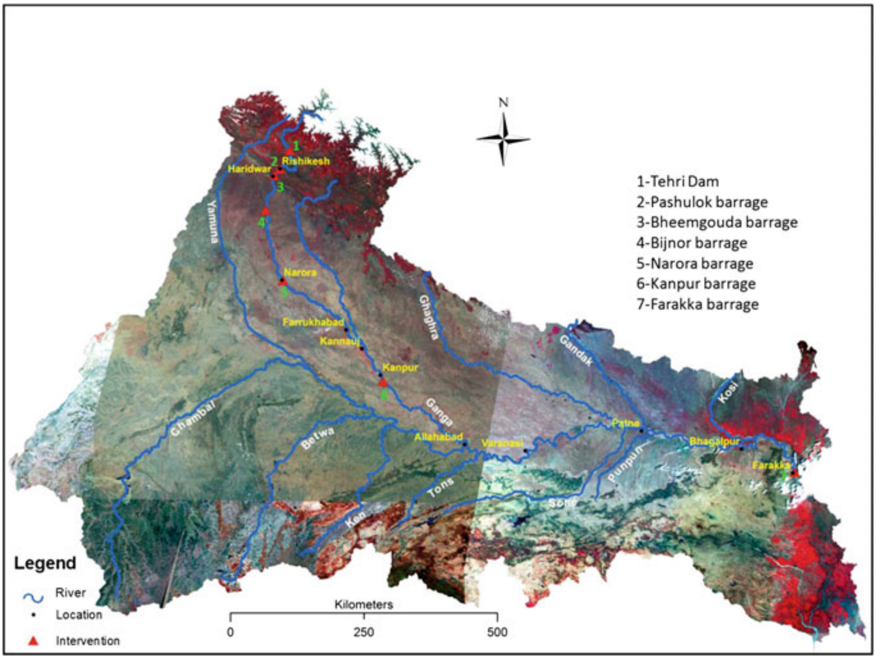

Fig. 1 Course of the Ganga river and major tributaries; major urban centers are also shown

The headwaters of the Ganga are constituted by the Bhagirathi and the Alaknanda, which join at Deoprayag in Uttarakhand. Besides, there are four other headwater streams, namely the Dhauliganga, Nandakini, Pindar, and the Mandikini (Fig. 2).

The Ganga continues its journey in the Himalayan hinterland downstream of Deoprayag, exits the mountainous terrain at Rishikesh, and a few kilometers further downstream debouches on to the proximal part of the Ganga Plain at Haridwar, a town of immense cultural and religious significance. From here onward, the river is oriented toward the southeast for over 800 km until its journey to Kannauj, Farukkhabad, and Kanpur. At Kannauj, the Ganga is met by the Ramganga with an average annual flow of about 500 m^3/s. Further downstream of Kanpur, the Yamuna and the Ganga join at the Triveni Sangam at Allahabad, where the latter contributes 2950 m^3/s (Jain et al. 2007), or ∼58.5% of the combined flow. Notwithstanding the importance of many of the other major tributary confluences in the system, this confluence of the Yamuna and the Ganga is perhaps the most unique as the Yamuna's discharge has a large volume of water and sediment that has been collected from rivers flowing from the hinterlands of the cratons to the

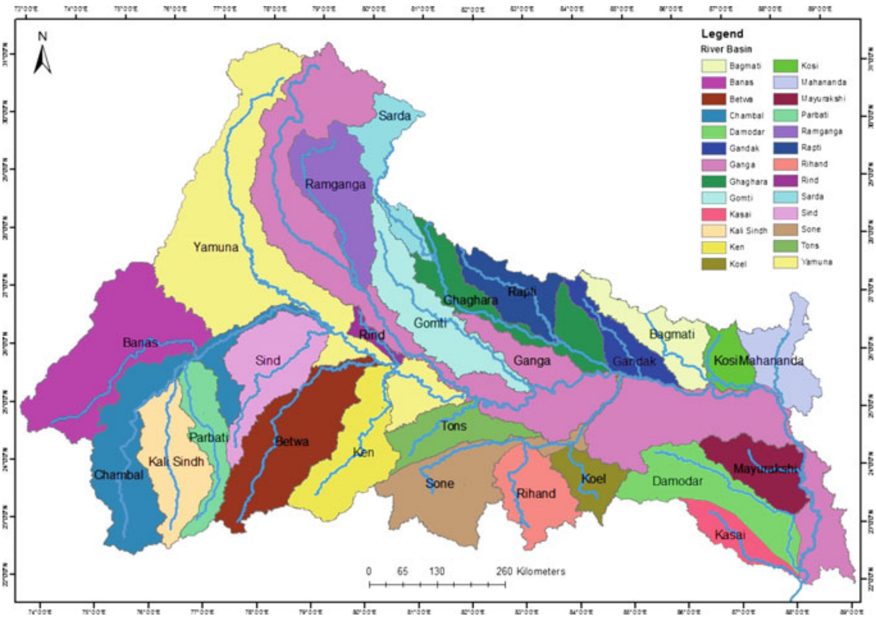

Fig. 2 Sub-basins in the Ganga river system

south; these rivers flowing from the south include the Chambal, Sind, Betwa, and the Ken, the latter two having been linked by a river-interlinking project.

Downstream of Allahabad, the river flows eastward, is met by the Tons, Son, and the Punpun from the south, and the Gomti, Ghagara, Gandak, and Kosi rivers from the north. Annual average flows of the peninsular-sourced rivers—the Tons and the Son—are 190 and 1000 m^3/s, whereas those of the Himalayan-sourced Gomti, Ghaghara, Gandak, and Kosi are 234, 2990, 1554, and 2166 m^3/s, respectively. Downstream of Allahabad, the river takes an easterly course and continues its journey to Patna via Mirzapur and Varanasi, the latter city being the most important cultural and religious center in the region. Varanasi is also one of the oldest cities and was known as Kashi in ancient India. Beyond Patna, the Ganga traverses through the volcanic rocks of the Rajmahal Hills, before entering the deltaic area near Farakka, close to the border with Bangladesh. Near Pakur, the river branches into its first distributary channel, the Bhagirathi-Hooghly. The Hooghly River is fed by the Bhagirathi and the Jalangi rivers that meet at Nabadwip. Also, the Hooghly is joined by tributaries that flow from the southeast; these include the Damodar, Rupnarayan, Ajay, and Haldi. The largest of these, the Damodar is 541 km long and has a drainage basin of $\sim$25,800 km^2 (Fig. 3).

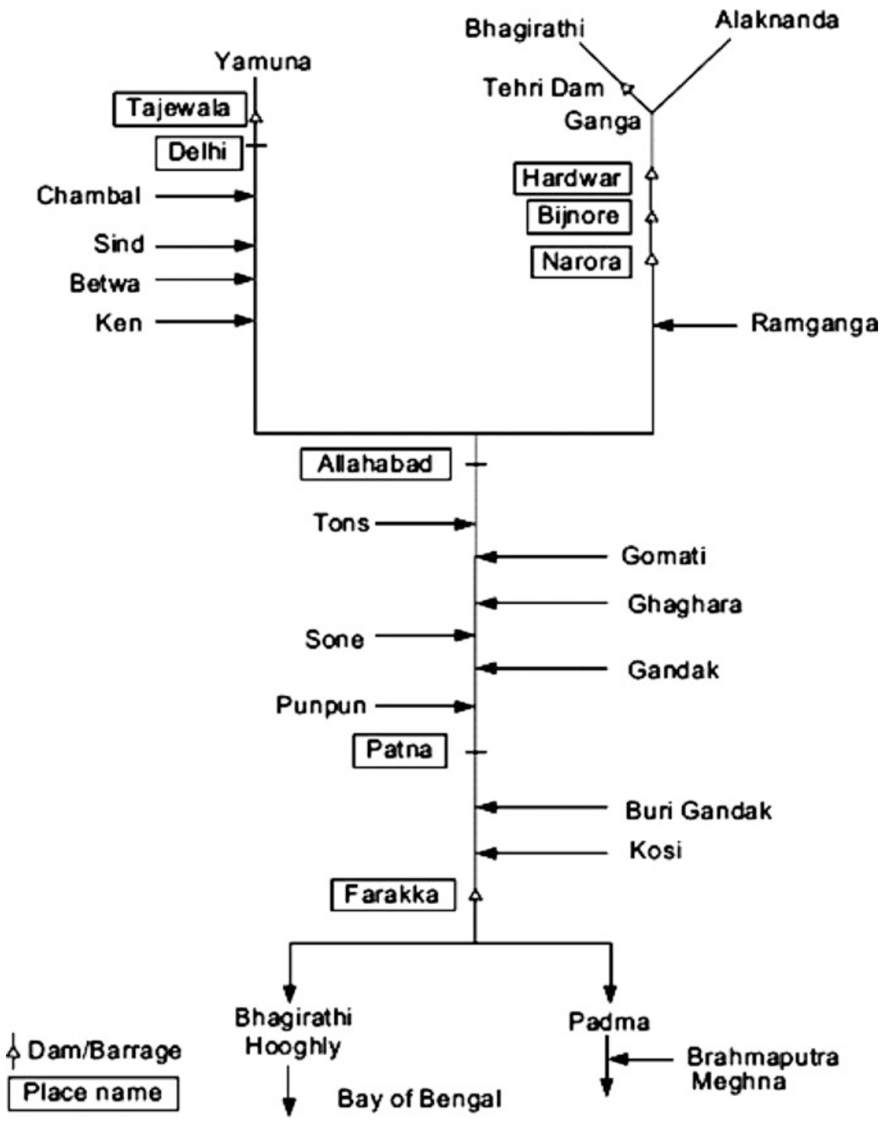

Fig. 3 Line diagram of the Ganga and its major tributaries (adapted from Jain et al. 2007)

3 Geomorphology, Hydrology, and Soils

After flowing through a mountainous valley, the Ganga flows into the Himalayan foreland, the upper most part of which is represented by vast low relief plains. In the central part of the Indus–Ganga–Brahmaputra plains, the Ganga Basin formed as a

NE–SW-oriented elongate depression that is bounded to the north by the Himalayan thrust sheets, and over significant areas in the south by the Bundelkhand and cratons (Sinha and Tandon 2014). The basin accounts for almost a quarter of India's landmass, 30% of the water resources, and supports almost 40% of India's population.

The depth to the basement in the plains is variable from a few kilometers to a few tens of meters toward its southern margin. The Ganga plains have been built by two distinct hinterlands—the Himalaya in the north and the cratons to the south (Sinha et al. 2009). Sinha and Tandon (2014) indicated that the mountain-fed tributaries of the Ganga such as the Yamuna, Ramganga, Ghaghara, Gandak, and Kosi are commonly braided systems with relatively higher discharges than those of the sinuous foothills-fed and plains-fed rivers.

The Ganga trunk channel shows variable patterns, braided–low sinuosity meandering being a common pattern. Some reaches of the Ganga, for example, that between Allahabad and Varanasi show a meandering pattern; similarly, the Yamuna after meeting the Chambal also shows a meandering pattern due to the increased hydrological and sediment inputs being routed through the Chambal from the cratonic highlands (Sinha and Tandon 2014). Throughout the plains, several of the smaller plains-fed rivers exhibit high sinuosity meandering patterns.

On the basis of hinterland types (Himalayan and cratonic), hinterland-basin interactions, along-strike geomorphic variability, and sea-level controls, Tandon et al. (2008) proposed the following simple classifications of the Ganga dispersal system (Fig. 4):

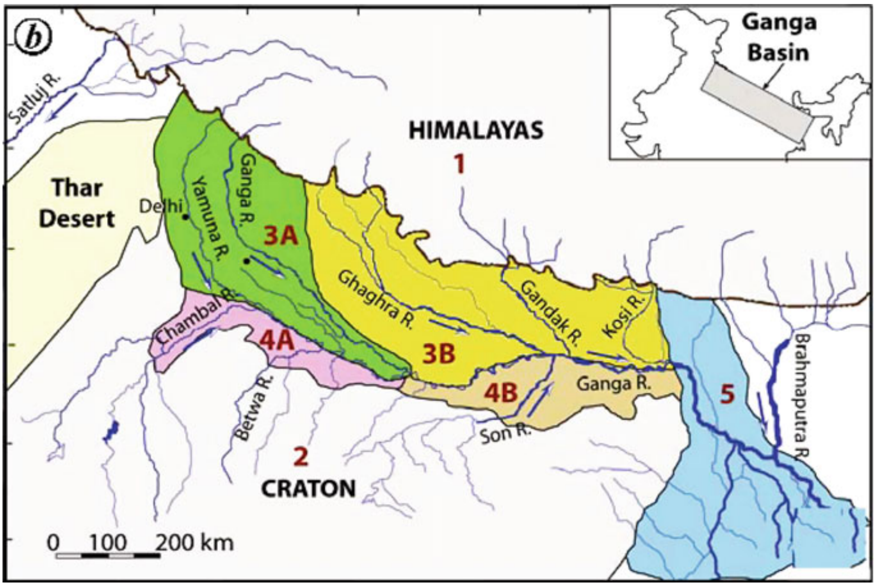

Fig. 4 Stream power-based classification of the Ganga dispersal system (after Tandon et al. 2008)

(1) Himalayan hinterland,
(2) Cratonic hinterland,
(3) Northern Ganga alluvial plains divisible into subcomponents (A) western part made up by tributaries with high-stream power and incised valleys and (B) eastern part made up of rivers with high stream power and aggradational valleys,
(4) Southern Ganga alluvial plains south of the Ganga and the Yamuna made up of tributary systems that are sourced in the cratonic highlands; these are further subdivided in two subcomponents based on the relative incision characteristics of the plains, and
(5) Lower Ganga plains and distributary-delta system south and east of Farakka.

Within and across these major units of the Ganga plains, considerable geomorphic diversity has been noted by the previous workers (Sinha et al. 2005). The main landscape elements include the (a) proximal piedmont zone, (b) main Ganga valley, (c) inactive floodplains and valley margin, (d) major interfluve systems that are elevated tracts, and (e) major tributary domains such as the Chambal and the Kosi. As a consequence of variable along-strike hinterland–basin interactions, the eastern parts of the plains, mostly in Bihar, are dominated by a fan–interfan setting, whereas the western part of the plains is marked by a valley–interfluve setting (Fig. 5) (Jain et al. 2012; Tandon et al. 2008).

Rainfall and subsurface flows are the main sources of water with meltwater from the Himalayan glaciers in the source region constituting a subordinate component, and estimates vary from a fifth to a third of the total water input. Much of the water is received in the Ganga system during the monsoon season from June to September; the mouth of the Ganga begins to receive rainfall in the first week of June, which then gradually advances up to the northern and western parts of the basin during June and July. An examination of the spatial patterns of rainfall shows that the lowest

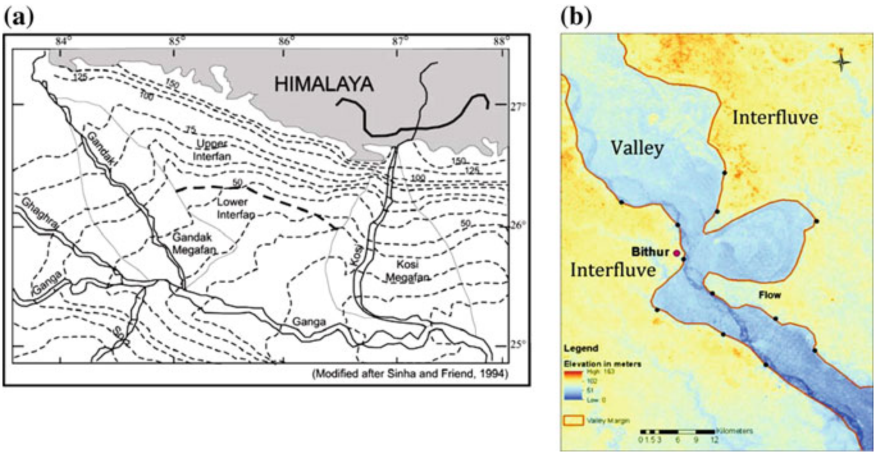

Fig. 5 Geomorphic diversity in the Ganga plains. **a** Fan–interfan system in the eastern Ganga plains. **b** Valley–interfluve system in the western Ganga plains

precipitation in the basin is in Haryana (~500 mm per annum), whereas in the eastern part of the plains, there is up to ~1600 mm rainfall per annum and even heavier annual precipitation of ~2200 mm in some parts of the adjoining Himalayan hinterland (Fig. 6). Despite the fact that a larger proportion of the catchment area lies in the catchment zones of the peninsular-sourced tributaries, they contribute no more than forty percent of water to the Ganga River System (TERI 2011).

On the basis of average annual discharge, the river systems in the Ganga plains can be divided into two groups, namely large river system and smaller river system. The large river system is mountain-fed stream and includes Yamuna, Ganga in WGP (up to Kanpur), Ghaghra, Gandak, and Kosi. The average annual discharge of these rivers varies from 1500 to 3000 m^3/s. The Ganga River is the trunk river of the Ganga plains, and its hydrological properties downstream of Kanpur indicates the cumulative effects of large river systems, as other large rivers such as Yamuna, Ghaghra, Gandak, and Kosi join it in further downstream reaches. The smaller river systems include the Ramganga, Gomti, Rapti, Burhi Gandak, Baghamti, and Kamla Balan. The average annual discharge of these river systems ranges from 70 to 500 m^3/s. The trunk river Ganga shows increase in average annual discharge from upstream to downstream, which is also accompanied by increase in average sediment load. Sediment load in the Ganga River basin first decreases and reaches to minimum value at Kannauj (15 Mt/year). However, further downstream, the sediment load starts increasing with values of 228 Mt/year at Allahabad and 729 Mt/year at Farakka. This increase is attributed to input from tributaries in eastern UP and north Bihar draining from Nepal. Sinha et al. (2005) reported a

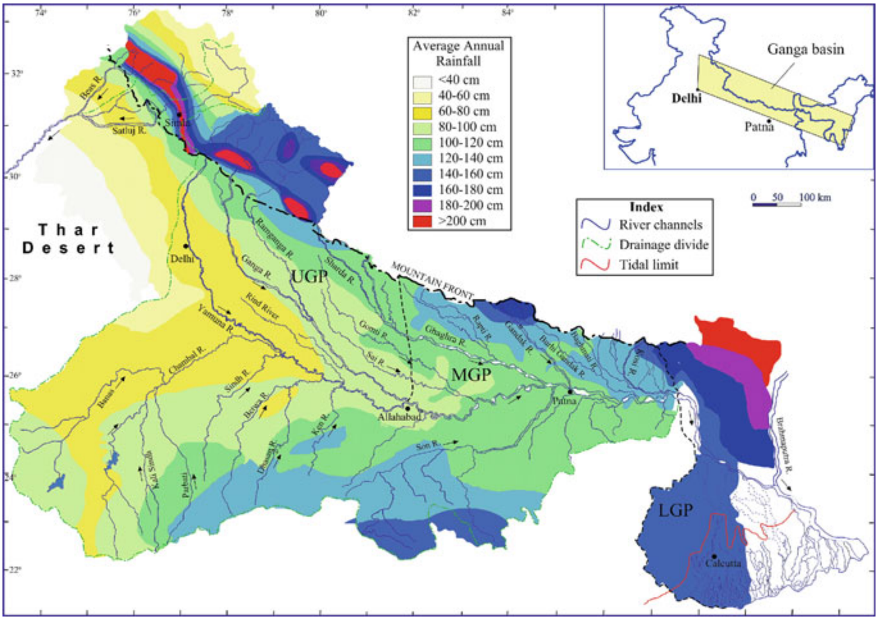

Fig. 6 Spatial distribution of rainfall in the Ganga basin

significant variability in hydrological characteristics of the tributaries of the Ganga River System in the Western and eastern plains manifested in stream power and sediment yield. While the western Ganga plains is characterized by tributaries with high stream power (40–43 W/m^2) and low sediment yield (197–342 t/km^2/year), those in eastern plains show low stream power (6.36–20 W/m^2) and high sediment yield (647–2774 t/km^2/year). It was suggested that this hydrological variability is manifested in geomorphic diversity across the plains.

The Ganga Basin with its vast area of more than 860,000 km^2 in India is characterized by the occurrence of a wide variety of soil types (Fig. 7). Ten classes of soils that include (1) mountain soil, (2) submountain soil, (3) alluvial soil, (4) red soil, (5) red and yellow soil, (6) mixed red and black soil, (7) deep black soil, (8) medium black soil, (9) shallow black soil, and (10) laterite and lateritic soil are developed under the variable lithological, climatic, and morphological conditions developed in different parts of the basin (Mukherjee and Dasgupta 1983, in TERI 2011). The most prominent soil type in the basin is the alluvial soil, covering more than 52% of the basin, which is rich in nutrients and supports a variety of crops such as wheat, jowar, bajra, smaller millets, pulses, maize, cotton, jute among other food and commercial crops.

Because of over-exploitation and intensive irrigation, and the increasing inputs of various fertilizers and agrochemicals, degradation of soil is commonly observed in the form of increased salinity in Haryana, higher alkalinity in western Uttar Pradesh, calcareous soils in Bihar, and soil acidity in West Bengal (TERI 2011).

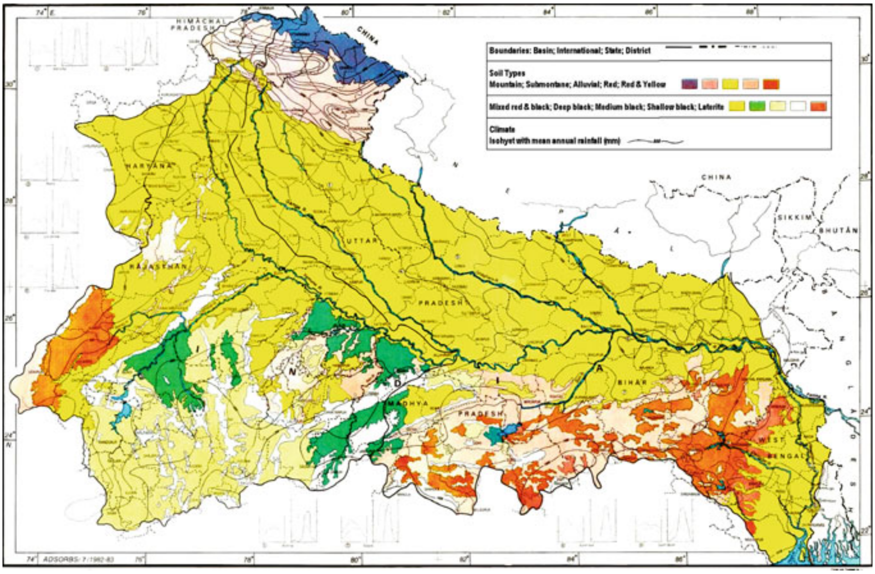

Fig. 7 Soil map of the Ganga basin (*Source* Mukherjee and Dasgupta 1983)

4 Socioeconomic Aspects

The Ganga River System and its basin are of considerable significance from both socioeconomic and sociocultural standpoints, as well as from the aspect of ecological economics. Water abstraction from the Ganga River has been practiced for more than a century and a half via several major canal systems. The Upper Ganga canal originating from Haridwar is 230 km long with a discharge of 300 m^3/s; the lower Ganga canal has a discharge of more than 150 m^3/s. There are more than 600 medium and major irrigation projects that cover a command area of ~36% of the basin, i.e., 427,226 km^2 (TERI 2011). The major projects, besides functioning as waterways for irrigation, also serve the purpose of flood control during the high flows of the monsoon season.

The net irrigated area in the basin is ~361,000 km^2; repeated irrigation takes place for raising more than one crop in a year. Human occupation over the millennia and the burgeoning population in the recent decades have resulted in strong pressures on the land; this has resulted in the replacement of most of the natural vegetation by agriculture (Fig. 8).

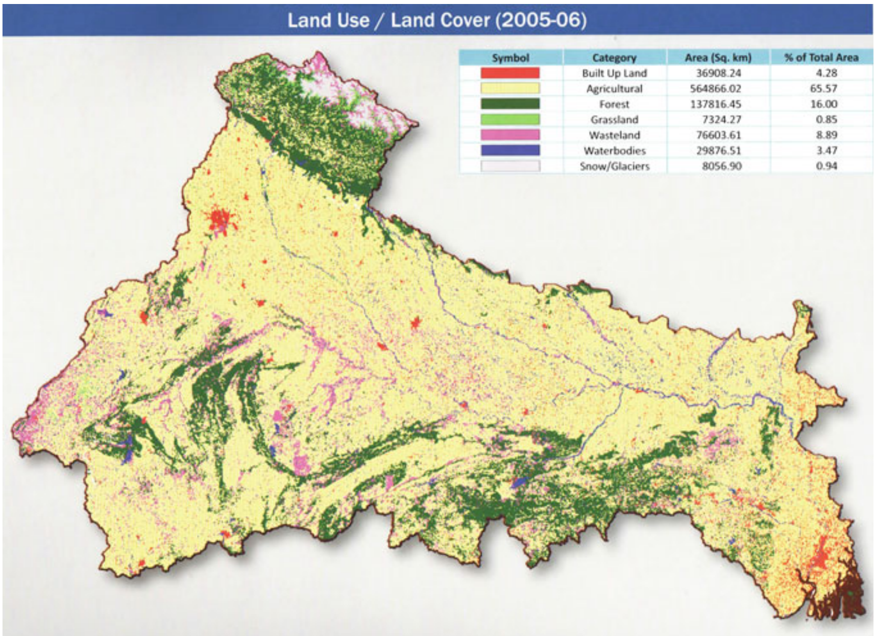

Fig. 8 Land-use/land-cover map of the Ganga basin (CWC 2012)

5 River Hazards in the Ganga Plains

Several rivers draining the Ganga Basin are prone to two major river hazards—river dynamics and floods—and these are intricately interrelated. The dynamics of the rivers is primarily driven by channel instability caused by extrinsic factors such as tectonics or intrinsic factors such as excessive sedimentation and local slope variability. Further, flooding in several rivers such as the Kosi River does not occur as classic overbank flooding due to excess inflow but is generally triggered by a breach in the embankments which have ironically been constructed for flood protection. In most cases, breaches in the embankments are associated with channel instability coupled with human factors such as poor maintenance.

Fluvial dynamics in the Gangetic plains was initially reported by Shillingfield (1893) and followed by several workers. Many of these papers focused on the westward movement of the Kosi River in north Bihar plains. Shillingfield (1893) opined that the progressive westward movement of the Kosi River would be followed by the eastward movement in one great sweep which proved to be true when the Kosi River avulsed by ~120 km in August 2008 (Sinha 2009; Sinha et al. 2014). On an average, the Kosi has shifted by about 100 km in the last 200 years and is related to the shifting process with the cone (megafan) building activity, sediment deposition, rise of bed levels (Gole and Chitale 1966), and the unidirectional channel shifting occurring progressively from one edge of the cone to the other edge. Apart from the major rivers such as the Kosi, the smaller rivers draining the north Bihar plains are equally dynamic. The migration histories of the Burhi Gandak River along with that of the Ganga around Samastipur (Phillip et al. 1989, 1991), decade-scale avulsions of the Baghmati River (Sinha 1996; Jain and Sinha 2003, 2004) are well documented.

Though the rivers of UP plains are not as dynamic as the north Bihar rivers, they do show some channel movement over a long time period. In the area between Bithoor and Kanpur Railway Bridge, the Ganga River shifted from right to the left bank between 1910 and 1945 and this was attributed to the highly irregular shape of the valley in the area, the 1924 flood causing major changes in floodplain and the location of railway bridge on the extreme right of the flood plain. The Ghaghra River in UP plains has also shifted by ~5 km at certain places, on either side of the active channel over a period of seven years between 1975 and 1982, and was related with the neotectonics in the area (Tangri 1986; Srivastava et al. 1994). The Sarda River is characterized by several westward lateral shifts at different places in between Banbasa barrage (Nainital district) and Palliakalan village (Kheri district) (Tangri 2000). Roy and Sinha (2007) documented the upstream and downstream movements of two major confluence points in the Ganga plains, namely the Ganga–Ramganga and the Ganga–Garra confluences over a century-scale period. The net movement of the confluence points was shown to be as large as ~18 km in case of the Ganga–Ramganga confluence, and the major processes influencing the movement of confluence points are avulsion, local movements by cutoffs, river capture, and aggradation.

6 Water Pollution

River water pollution, ecological loss, and degrading health of the Ganga is a matter of the most serious concern; the issue of cleaning up and rejuvenation of the Ganga River is a national priority. As is well known, the river provides large volumes of water for domestic, industrial, and agricultural purposes, apart from serving several cultural and spiritual needs of the population that inhabits the basin. Stressed further by the exponential increase in population, urbanization, industrialization, the intensive use of fertilizers and agrochemicals, and the abstraction and storage of ever-increasing volumes of water, the quality of water of the Ganga River and its major tributaries continues to deteriorate rapidly.

Major sources of pollution include point sources, such as domestic and industrial wastewater discharges, and non-point sources such as runoff from agricultural fields, solid waste disposal sites, and the runoff impacted by various river-front activities such as bathing ghats. The river system is subjected to 3 billion liters of industrial effluents per day. The major sources of industrial pollution are related to the following sectors—pulp and paper (Uttarakhand), metal artifacts (western Uttar Pradesh), sugar and distillery (western Uttar Pradesh), tanneries (Uttar Pradesh, West Bengal), and jute and textiles (West Bengal).

In terms of domestic waste, 179 class 1 cities generate ~11000 MLD of wastewater and 147 class 11 cities generate ~1000 MLD of wastewater (TERI 2011). Highest generation of domestic wastewater along the river Ganga takes place in Kolkata (618 MLD), followed by Kanpur (339 MLD), Patna (249 MLD), Allahabad (208 MLD), and Varanasi (187 MLD) (TERI 2011). The treatment capacity gap is large for most of these cities.

The Ganga Basin states have a load of ~10 million tonnes of chemical fertilizer each year, in addition to a pesticide load of ~21,000 tonnes (TERI 2011). This application of fertilizers and pesticides has grown over the past few decades with the intensification of agriculture; however, the transport and fate of these anthropogenically introduced loads are rather poorly understood.

Under the Ganga Action Plan phases I and II, there have been efforts to increase the sewage treatment plant capacity, particularly in the five states of West Bengal, Bihar, Jharkhand, Uttar Pradesh, and Uttarakhand.

7 Concluding Remarks

The role played by the Ganga River in sustaining and nurturing a substantial part of India's population is commonly encountered in most narratives of river and water in our country and obviously cannot be overstated. The Ganga River and its basin provide critical resources and ecosystem services to eleven states within India, accounting for thirty percent of India's water resources and provisioning life sustaining support in terms of soil fertility, food security, and ecological habitats to both the burgeoning human population and the animal and plant communities. Despite its value as a resource system and its being the provider of invaluable ecosystem services, the Ganga River system is in poor health because of over-exploitation on many fronts by humans including the unsustainable activities that lead to large-scale pollution over large areas of the network and the basin.

Because of the central role played by the Ganga in our life, it has been declared as the national river and has been the subject of several investigations and studies. More recently, the MOEF supported a program on the Ganga River Basin Management Plan (Gangapedia 2012) and this plan identified some fundamental premises for management of the Ganga River. These are as follows:

(a) River must be allowed to flow continuously,
(b) Riverine processes must be understood in terms of both longitudinal and lateral connectivity,
(c) River requires adequate space for its own functions,
(d) River should be recognized as an ecological entity and be allowed to function as such, and
(e) River should be kept free from all kinds of waste.

While it is recognized that these premises are overriding and emphasize eco-hydrological and ecogeomorphological approaches to river basin management, rivers will continue to be used by humans for a variety of purposes, although increasingly under intense scrutiny to eliminate unsustainable methods and practices.

Therefore, river futures ought to be determined on the basis of multi-disciplinary assessments as opposed to single discipline engineering-oriented approaches that are rooted in command and control strategies to the management of river systems.

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Ganga: The Arterial River of India

Pramod Singh, Dhruv Sen Singh and Uma Kant Shukla

1 Introduction

The Ganga, a glacier-fed river originating in the Higher Himalaya, is the main river that drains the northern plains of India. It along with its tributaries work like arteries that for several millennia have been the perennial source of water in the regions through which it flows. The sediment and water brought by this river has supported agriculture and proliferation of several cultures all along its tract from Himalaya to Bangladesh. The Ganga River is formed by joining of many rivers, namely the Bhagirathi, Alaknanda, Mandakini, Dhauliganga, and Pindar, in the Himalaya. All the major tributaries of Ganga originate from the glaciers in the Higher Himalayas. The Alaknanda rises from Bhagirathi Kharak and Satopanth glaciers (Fig. 1) located towards eastern slopes of Chaukhamba peak, whereas Bhagirathi originates from the Gangotri glaciers from Gaumukh (Fig. 2). Both these rivers are forming sacred places for Hindu religion at Gangotri and Badrinath. Unlike the Higher Himalaya, the mountains in the Lesser Himalaya have gentle slopes and undulating topography. Alaknanda River in this part is joined by Dhauliganga River at Vishnuprayag, Pindar River at Karnaprayag and Mandakini River at Rudraprayag. After joining these tributaries, the river carries forward name as Alaknanda the longest of all the above. Finally, the Alaknanda joins the Bhagirathi River at Devprayag forming the main trunk river known as the Ganga River (Fig. 3). Moving further south, the river flows through rocks of Siwalik range that have

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Fig. 1 Satopanth and Bhagirath Kharak glacial vallies separated by Balakun ridge (birth place of Alaknanda River), Garhwal Himalaya

Fig. 2 Snout of the Gangotri Glacier known as Gaumukh (birth place of Bhagirathi River), Garhwal Himalaya

Fig. 3 Confluence of Bhagirathi and Alaknanda at Devprayag which forms Ganga, Garhwal Himalaya

height varying from 250 to 800 m. The main trunk river Ganga initially flows westwards after Devprayag and passes through the outer (southern) Himalaya (Siwalik) before coming out of the mountains at Rishikesh from where it starts flowing south and enters onto the plain at Haridwar, which is another sacred place of Hindus (Fig. 4). As a result of joining of the tributaries and entering into region of higher rainfall, the volume of water of the Ganga River increases many fold when it exits the mountain. The volume of water shows marked seasonal variations, and there is higher flow during rainy season from July to September, whereas during summer from April to June the flow is maintained mostly by the snow melt and ground water and flow declines during winter.

Ganga River flows in SE direction in the central part of Ganga Plain and forms the major trunk river after coming out of the hilly tract. At Allahabad, the river takes a northerly swing and starts flowing in north–east direction before attending eastern trend after the confluence with Ghaghara (Shukla and Raju 2008; Shukla et al. 2012). The river on its way to the Bay of Bengal is joined by number of tributaries (Fig. 5). While flowing through the state of Uttar Pradesh, it is joined on the left bank by Ramganga near Kannuaj, Gomati near Saidpur and Ghaghara near Chhapra (Fig. 6). Yamuna, a right bank tributary of Ganga River joins at Allahabad. On entering the state of Bihar, Great Gandak, Burhi Gandak and Kosi join it along the left bank and Son along the right bank at Hajipur near Patna, Gogri Jamalpur, Kursela and Digwara, respectively. All these rivers except Son and

Fig. 4 Ganga River at Rishikesh, Uttarakhand showing mid channel bar and side bar deposits

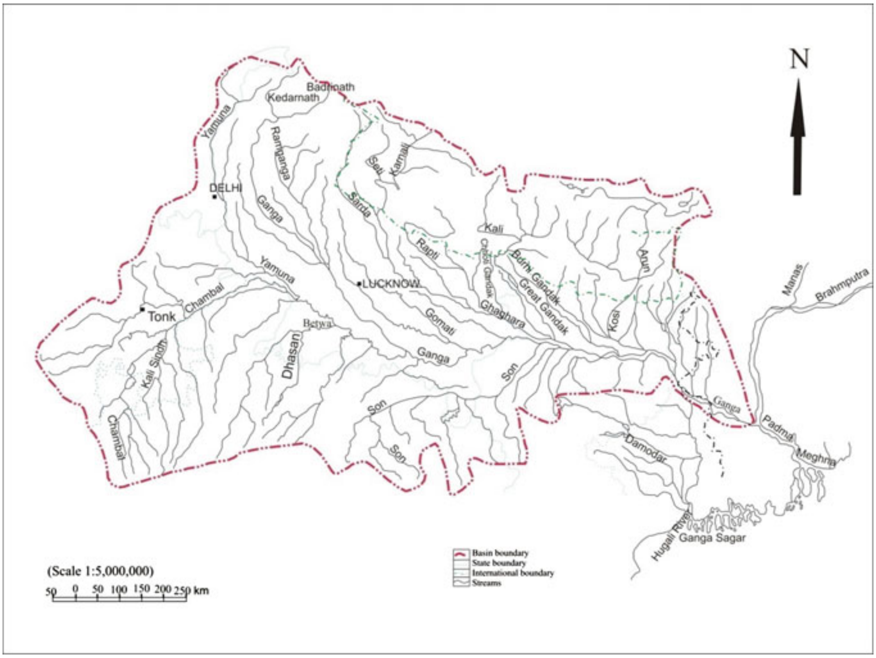

Fig. 5 Map showing tributaries of Ganga River and its river basin

Fig. 6 Confluence of Ghaghara and Ganga at Chhapra in Bihar, Ganga Plain

Gomati are Himalayan glacier-fed rivers. Ganga is joined by Hoogli River from the west on entering West Bengal, the last Indian state, through which Ganga flows before entering into Bangladesh. In Bangladesh, the main branch of Ganga is known as Padma till the Yamuna the largest distributary of the Brahmaputra River joins it. Further downstream, the second largest distributary of the Brahmaputra, the Meghna River, feds the Ganga. It finally empties out into Bay of Bengal and forms a 350-km-wide largest delta of the world known as Sunderban delta. Table 1 shows the origin and confluence places of various tributaries of the Ganga River.

2 Geomorphology

The Ganga Plain is an active foreland basin formed due to collision of the Indian plate with the Eurasian plate (Burrard 1915). The Ganga River, the trunk river of the Ganga Plain, passes through a wide range of climatic zones, from cold and frigid in the Himalaya to humid subtropical in the Ganga Plain with three seasons i.e. winter (November to February), summer (March to mid-June) and monsoon (mid-June to October). In the Ganga Plain region, several geomorphic features have evolved through time under the influence of tectonics, climate, sediment distribution and redistribution processes operating in different region (Gohain and Parkash 1990; Gole and Chitale 1966; Mohindra and Parkash 1994; Singh and Ghosh 1992; Singh et al. 1999, 2009). Earlier studies distinguished the Ganga Plain sediments

Table 1 Tributaries of Ganga River, the origin place and the confluence place with the Ganga River

S. No.	Name of river	Origin point	Confluence place with the Ganga
1	Ramganga	Namik Glacier, Uttarakhand Himalaya	Kannauj, Uttar Pradesh
2	Yamuna	Yamunotri, Uttaranchal Himalaya	Allahabad, Uttar Pradesh
3	Gomati	Pilibhit, Uttar Pradesh	Saidpur, Uttar Pradesh
4	Ghaghara	Matsatung Glacier, Himalaya	Chhapra, Bihar
5	Son	Amarkantak, Chhatisgarh	Digwara, Bihar
6	Great Gandak	Sumeshwar Hill, Nepal Himalaya	Hajipur, Bihar
7	Punpun	Chota Nagpur, Jharkhand	Patna, Bihar
8	Burhi Gandak	West Champaran, Bihar	Gogri Jamalpur, Bihar
9	Kosi	Gosain Dham Peak, Nepal	Kursela, Bihar
10	Mahananda	Darjiling, WB, Himalaya	Godagiri, West Bengal
11	Damodar	Palamu, Jharkhand	Fulta Point, West Bengal

into older alluvium known as Bangar and the younger alluvium known as Khadar (Pascoe 1917; Pilgrim 1919). Later, the use of remote sensing techniques along with field studies helped in further refinement of the knowledge and identification of various geomorphic features of regional significance hitherto difficult to appreciate only on field-based studies (Singh and Ghosh 1992; Pal and Bhattacharya 1979). Singh (1996) distinguished several depositional geomorphic surfaces formed at different times in response to varying climate, discharge, sediment supply and tectonic activity during the late Quaternary in the Ganga Plain. The oldest of these surfaces is known as the upland interfluve surface (T2) formed of fine sediments and is presently out of reach of the active river flooding. This surface occupies regions between several south flowing rivers in the northern part before they join the main trunk Ganga River. The origin of this surface is still not clear as one thinking is that these have been laid by distinct interfluves sedimentation process involving sheet flows and sediment transfer from the Piedmont Plains by small rivers flowing over it (Singh 1999; Shukla and Bora 2003; Shukla 2009), whereas the other believes that these are older detached floodplains of the present river systems (Sinha et al. 2008). These sediments are oldest and due to long hiatus in deposition have developed mottling and calcretization. South of the main east–west axial Ganga river channel lies the marginal upland surface that is considered time equivalent of northern interfluve surface T2. The remote sensing data reveal another large-scale Megafan Surfaces (MF) along the river from its exit point of the Himalayan rivers on to the plain that extend for several 10's of km up to the northern margin of the central EW axial Ganga River. These presently inactive megafans are inferred to have formed during the late Pleistocene and form the relict features over which are imprinted several active and inactive drainage patterns such as anastomosing channels (Sinha 1995; Srivastava et al. 2003; Singh and Singh 2005). The MF is mostly sandy formed during higher sediment water discharge and higher slopes (Shukla et al. 2001; Shukla and Bora 2003; Singh and Singh 2005). Laterally, these MF surfaces merge with the older T2 surface which underlies it.

The present active channels have incised into the MF surface. The Ganga Megafan deposits have been divided into four zones by Shukla et al. (2001), i.e. the gravelly bedded stream, sandy braid plains, anastomosing channel plain and meandering channel and interfluves. The northernmost geomorphic surface bordering the foot hills is the Piedmont zone. It is gravely adjacent to the foothill and is known as Bhabar. Further south, it becomes sandy and is known as Terai. The gravel beds that form the major Piedmont zone sediments are either clast or matrix supported laid by channels and mass flow, respectively. At present due to decrease in sedimentation, the Piedmont zone does not receive sediment by channels and instead the main depositional event occurring over it is through mass flow or sheet flooding (Shukla and Bora 2003; Shukla 2009). The Piedmont zone sediments either lie over megafan surface or the T2 surface. The gravelly part of the Piedmont fan is highly uneven and exhibits surface relief of 1–2 m, whereas the distal sandy Terai part forms low-lying swamps and ponds.

In the plain region, the older T2 surface that does not receive flood water from the present day active channel. The development of T1 surface is thought to be due to later incision into the T2 surface as a result of rejuvenation of Ganga Plain River system due to neotectonic activity accompanied with intensification of monsoon between 10 and 5 Ka. This led to carving out of broad valleys at levels lower than the T2 surface. The coarser grained T1 surfaces were left out as terrace surface several metres above the valley carved by the incised river. The occurrence of paired T1 terraces supports the view of their development by the incision of its own floodplain sediments by the present day active channels. At present, the T1 surface exhibits gully erosion and is occupied at places by vegetation. This surface is situated few metres above the present day river channel is occasionally flooded.

The present day active Ganga River channel is incised in the T1 surface and is bordered by narrow 1–4 km wide active floodplain (T0 surface) situated at levels 2–3 m below the T1 terrace surface, whereas the active channel itself is 1–2 km wide. The T0 surface gets regularly flooded by overtopping of the present channel. The geomorphic landforms exhibited by the T0 surface include the oxbow lakes, abandoned channel, levee, meander cutoff, swamps and crevasse splays and low-lying areas (Fig. 7). The present day Ganga River channel exhibits different forms and sediment characteristics along its 2000 km track in the Ganga Plain. In its initial track over the plains, the Ganga River follows a straight path along N–S direction up to Bijnor cutting along the PF. The river in this part has higher gradient and is braided containing large braid bars. The sediment texture ranges from gravel to fine sand. After Bijnor, the river flows in NW–SE direction and exhibits low sinuosity and remains wide up to Fatehgarh after which the valley shows a gradual decrease in width up to Kanpur. At Kanpur and Bithoor, it is characterized by high cliff bordering the channel (Fig. 8). The prominent tributary joining the main Ganga River in this sector is Ramganga from north at Kanauj. The width of river channel and floodplain exhibits significant changes in this segment (Singh et al. 2010). It has been described that the narrow channel confined within wide valley is the main feature of Ganga and also its tributaries due to climate change (Singh et al. 2010). The channel gradient along this track shows a decline (Singh 1996), and the

Fig. 7 Low-lying area at Ropan Chappra, Deoria district, Uttar Pradesh in Ganga Plain

Fig. 8 Cliff all along Ganga River near Bithoor, Kanpur, Ganga Plain

sediment is predominantly made up of fine sand and forms channel bar, lateral bar and point bar deposits that contain cross-beds, ripples, climbing ripple cross-laminations and plane beds (Fig. 9) (Kumar et al. 1995; Shukla et al. 1999). Downstream of Kanpur the active river valley continues to narrow down further and becomes only 1 km wide at Unchahar after which it again starts widening and attains a width of ~7 km at Allahabad. In this section, river exhibits braid bar, lateral bar and point bar. The river in this part becomes highly sinuous, and the floodplains also become very narrow. The river is joined by Yamuna River, another major Himalayan river, from south. The river in this stretch gets closest to the peninsular craton and at Allahabad takes a sinistral turn and starts flowing ESE. After Varanasi, the River Ganga further bends and starts flowing in NE direction up to Patna. In this stretch, river is spindle shaped with lower valley width towards Varanasi (~7 km) and Patna and maximum in between near Balia where it becomes ~36 km wide. The major tributary joining from north in this part is Ghaghara and Great Gandak rivers and Son River from south. The resulting increase in sediment supply has probably led to build-up of several large river islands. Other geomorphic features present are the oxbow lakes and the meander scars. In this region at some places, the basement rocks intrude into the alluvium (Fig. 10).

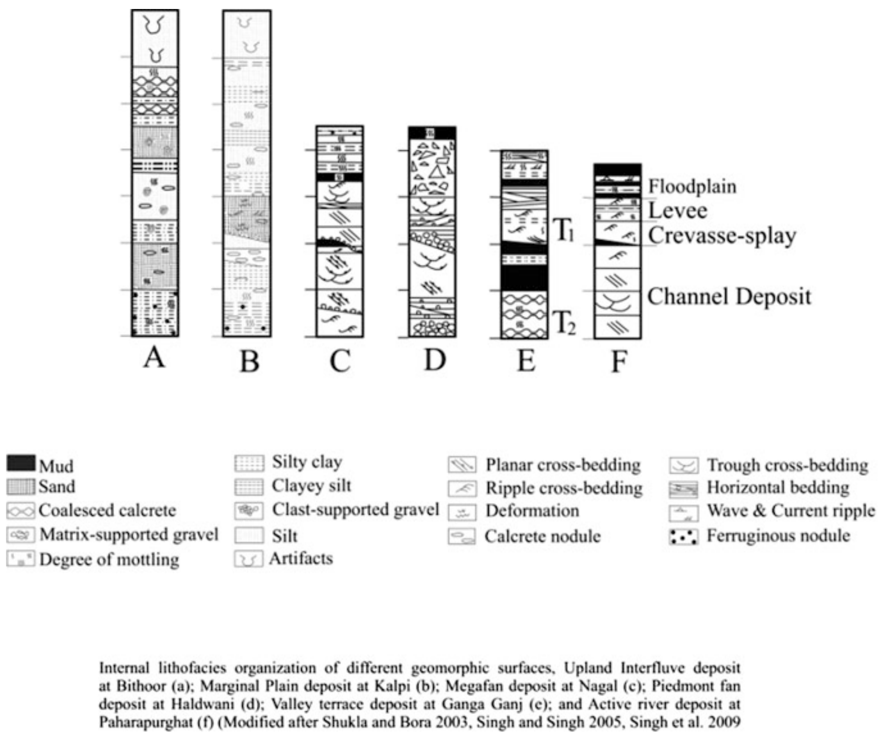

Fig. 9 Lithologs and internal lithofacies organization of different geomorphic surfaces of Ganga Plain

Fig. 10 Peninsular rocks coming out of alluvium in Ganga River at Sultanganj, Bihar, Ganga Plain

Downstream after the confluence of Great Gandak, the valley width again shows an increase and river takes a dextral bend and starts flowing in SE direction before the next dextral bend at Shibganj after which it starts flowing in SSE direction before meeting Bay of Bengal. In this section, the valley is confined by the craton towards the south, whereas in north it merges with the plains. The major tributaries joining in this part are Burhi Gandak, Kosi and Mahananda River. The river sinuosity further increases in this part, and the river is braided with many channel bars and islands. The river here shows increased frequency of lateral shifting that has resulted in numerous abandoned meander scar and braid bars. After travelling few km from Farakka, the river enters Bangladesh where it has formed tidally influenced delta known as Sunderban.

2.1 Sedimentology of Ganga Plain

The Indo-Gangetic Basin acquired an asymmetric form due to rigid nature of Indian craton and produced a wedge-shaped sedimentary fill which is thickest near the mountain foot and thinning out southwards towards the peripheral bulge of the craton. Near the Himalayan Mountain foot, thickness of alluvium is 4–7 km, while towards the craton it decreases only to a few hundred metres. The basement of basin is highly irregular characterized by many structural highs and faults that influence the history of the basin fill since its inception. The Ganga Basin occupying the central position in the Himalayan foreland basin is an oversupplied and underfilled sedimentary basin. North of River Ganga the rocks of the Precambrian Lesser Himalaya and the Tertiary Siwaliks forms the basement of alluvium, while in south across the Ganga River rocks of the Precambrian Vindhyan Supergroup and the Palaeozoic Gondwana rocks form the basement (Singh 1996). The part of Ganga Basin lying north of the trunk River Ganga is made up of Himalayan derived sediments, while south of the river craton has contributed the sediments to fill the basin. The Himalayan derived sediments are mica–rich and feldspathic producing greywacke type sediments. While sediments derived from craton are devoid of mica, they are pink coloured and arkosic in nature due to abundance of orthoclase (Shukla et al. 2012). The sub-surface stratigraphy of the Ganga Basin is made up of alternating horizons of multistoried sands and lensoid silty mud horizons giving rise to confined and unconfined aquifers supplying potable and irrigational waters to this densely populated region (Shukla and Raju 2008; Awasthi and Singh 2011; Bhardwaj and Singh 2011).

The Ganga Plain is drained by numerous Himalayan- and groundwater-fed rivers depositing huge amount of sediments. Under different climate, tectonics and base-level conditions, a number of geomorphic surfaces of regional significance shows varying internal lithofacies organization have evolved in space and time. Figure 9 shows the lihounits and sedimentary log of different geomorphic units of Ganga Plain. The upland interfluve surface (T2 surface) is being the oldest and acting as the basement for rest of the geomorphic element is internally highly diversified comprising many lithofacies representing sedimentation by sheet flow processes operating on the Doab areas mainly during the rainy season (Kumar et al. 1995). Study of interfluve deposits in the Ganga Plain in different cliff section shows that in most of the cases, the vertical succession of 10–15 m can be divided into three distinct facies associations (Singh et al. 1999; Shukla and Bora 2003; Singh and Singh 2005). The facies association A, comprising almost 2–3 m thickness, is dominated by variegated sandy clayey silt shows extensive development of ferruginous nodule. It is followed by facies association B, which is 4–10 m thick, comprising silt-sand-rich facies and often grading into shell bearing mud. The topmost facies association C is calcrete-rich (Fig. 9). The calcrete development may take place in any of the facies associations. The few metres of the facies association C is highly modified and exhibits human impact. The ferruginous nodule bearing facies association A may indicate humid climate and low relief. The sandy facies association B implies humid climate but enhanced relief. Calcrete bearing facies association C, when associated with porous silt-sand horizons, may indicate increased evaporation and water table fluctuation in raised areas, probably in periods of decreased rainfall. The calcrete development in shell bearing mud and silty clays of pond origin may have CO_3 content contributed by dissolution of calcareous shells. Therefore, in a time span of few kiloyears, the vertical distribution of lithofacies associations may be related to climate change, whereas the spatial distribution may be controlled due to tectonics in the area of deposition.

The Marginal Plain Upland Surface (MP), located south of axial River Ganga and Yamuna, is considered time equivalent to T2 surface. It exhibits mottled silt, interbedded silt and mud, channelized sand, variegated clayey silt and cross-bedded calcrete lithofacies (Fig. 9), and the succession represents sedimentation in sloping topographic depressions, small sandy-gravelly ephemeral channels which rework the MP and form the alluvial fans propagating to north from south (Ghosh et al. 2016). Some of the gravelly deposits are fossiliferous containing archaeological artefacts and remains of elephant, horse, and other domestic animals along with human bones which are partially or fully fossilized.

The Megafan deposits are made up of multistoried sand bodies often incorporating sub-metre thick silt and clay lenses which are rippled-parallel laminated and contain burrow structures (Singh and Singh 2005). Individual channelized sand bodies are lensoid in cross-section, 4–10 m thick and are small- to large-scale cross-bedded. Few metres of megafan deposits are represented by mottled silt and clay horizons indicating vertical accretion by sheet flow processes (Shukla et al. 2001; Singh and Singh 2005). From proximal to distal parts of the fan deposits, there is in general decrease of grain size from gravel in the proximal parts to sand and silt in the mid-and-distal parts. Lake deposits are also found associated with the megafan deposits mainly in the distal parts.

The Piedmont Fan consists of gravelly deposits with the presence of sand and silt-mud, and shows a prominent facies difference within a radial distance of 30–50 km between the proximal and the distal fan areas (Shukla and Bora 2003). The proximal part of the fan (0–15 km) is generally gravel, the middle part (15–30 km) contains gravel sand and sandy gravel, and the distal part of the fan (30–50 km) is sand-mud dominated without gravels (Shukla 2009). The piedmont deposits are made up both rivers-borne gravels representing humid climate and enhanced tectonics in the hinterland, and debris flow deposits implying dry climate of emplacement (Fig. 9).

The River Valley Terrace (T1 surface) exhibits rippled and cross-bedded silt, sand and lensoid units of silty mud representing sedimentation in channel-floodplain and lake deposits. These deposits are generally 1–4 m thick and regularly receive sediments from the flooding of present day river channels (Fig. 9). The grain size of the sand of T1 surface is coarse than the sands of present day river channels representing a phase of climatic amelioration. The rivers of Ganga Plain (T0 surface) are flowing following a SE slope and posses braided or meandering pattern with narrow floodplains. These rivers are carrying Himalayan derived silt-fine-grained greywacke sand and depositing mud on the floodplains. Depending upon the channel patterns, the rivers are forming point bar and braid bar deposits which are small- to large-scale cross-bedded characterized by unit bar amalgamation or lateral accretion (Shukla et al. 1999; Shukla and Singh 2004; Singh et al. 2009; Singh and Awasthi 2011). Sedimentation on the floodplains is also taking place in levee and crevasse channels deposing rippled silt and mottled mud. The river deposits are characterized by fining upward sequences (Figs. 9 and 11).

Fig. 11 Fining upward sequence in gravel deposits of Ganga River at Haridwar

2.2 Geochemistry

The Ganga River which debouches on to the plain at Haridwar has deposited huge amount of sediments in the Ganga Plain region. The Ganga River sediments are derived from the three major tributaries, i.e. Bhagirathi, Alaknanda and Mandakini that flows through the rocks of the Higher Himalaya, Lesser Himalaya and the Siwaliks. The sediments deposited over the Gangetic Plain by the Ganga River are known to be very fertile and has, therefore, supported large population in the states of Uttarakhand, Uttar Pradesh, Bihar and West Bengal.

Recent geochemical studies including the rare earth elements carried out on the river sediments in the Himalayan region that form the higher reaches of Ganga River indicate that the sediments are compositionally closer to the rocks of Higher Himalayan crystalline series (Singh 2009, 2010) with minor contribution from the rocks of Lesser Himalayan series. This and other studies on Ganga River sediments (Singh 2009, 2010) show it to be texturally, mineralogically and chemically immature. Texturally, the sediments are composed of sand and silt with minor amount of clay. The primary minerals present in the sediments are quartz, plagioclase, K-feldspar, muscovite and biotite. The major element composition shows lower degree of weathering. Even the mobile elements such as Na, Ca and K in the sediments are close to the composition of the source rocks. The immaturity of sediments from the upper reaches of Ganga River suggests that it is basically a mechanically ground up source rocks. The cooler climatic conditions along with higher relief in the mountainous region of Himalaya have been envisaged as the reason for this immaturity (Singh et al. 2010).

In the plain region, the slight deviation in composition of different suite of sediments in different geomorphic units, compared to the source, has been inferred mainly due to textural and mineralogical sorting (Singh et al. 2010). The clay minerals, although less, are mainly composed of illite, chlorite, smectite and kaolinite. The floodplain sediments contain higher percentage of Al compared to the bedload due to preferential addition of mica at the time of flooding due to its hydrodynamic nature. The higher concentration of Al due to mica enrichment in the floodplain sediments has been found to have resulted in increase of values of weathering parameters such as chemical index of alteration (CIA) which give false impression of higher degree of weathering. Compared to the active floodplain sediments, the older interfluves sediments show relatively higher degree of weathering, which suggest that the sediments from the older interfluves may have undergone some amount of chemical weathering after their deposition. Thus, the fertility of Ganga Plain sediments can be explained due its unweathered nature of recently deposited sediments and presence of 2:1 clays that are capable of holding the nutrients being released by weathering of interfluves sediments for longer duration.

3 Socio-Economic Importance

River Ganga is considered the holiest of all the Indian rivers and is as a symbol of India's age-long culture and civilization. Religion and rituals in towns along the Ganga River are so deeply embedded in the life of the people residing here that it has blended with their culture making it difficult to distinguish between them. It has attained importance in life from birth to death. Large number of religious towns and cities have proliferated along its bank from upper reaches up to its lower end. The important pilgrimages established near the origin of its tributaries are Gangotri, Kedarnath and Badrinath near the origin of Bhagirathi, Mandakini and Alaknanda rivers, respectively. Rishikesh and Haridwar form the important religious places at the exit point of River Ganga from the Himalaya on to the plains. Haridwar is considered as one of the seven holiest places according to Hindu mythology. This place and Rishikesh, Haridwar and Varanasi are famous for Ganga Aarti (Fig. 12). Allahabad is another important pilgrimage for Hindus where River Yamuna and the mythological Saraswati meet River Ganga and the confluence is known as Sangam. Kumbh Mela is an important festival celebrated at Sangam that attracts lakhs of people and is one of the world's largest human gatherings. Varanasi located along the bank of River Ganga is considered as the seat of Lord Shiva by Hindus and also the place of attaining moksha. People visit to Varanasi for the last rites with the belief that performing the last rites here will lead to moksha. It also attracts the Siberian birds during winter (Fig. 13). The last pilgrimage site along the Ganga is

Fig. 12 Ganga Aarti at Varanasi, Uttar Pradesh, Ganga Plain

Fig. 13 Siberian birds in Ganga River at Varanasi, Uttar Pradesh, Ganga Plain

the Gangasagar, where the Ganga meets Bay of Bengal. A dip in water here means liberation from all sins.

The large number of pilgrims visiting these places also supports the economy of the local people living here. The sediment and water brought by the river Ganga have supported life of millions of people for centuries. The fertile soil has been supporting agriculture, and the water is used for irrigation. The important modern canal drawing water from the River Ganga for irrigation purpose is the Upper Ganga Canal and its branches that begin at Haridwar and have a combined length of 9,575 km and the Lower Ganga Canal, extending 8,240 km with its branches, begins at Naraura. Some of the crops that can be cultivated along the river include rice, sesame, sugarcane, millets, wheat, potatoes, sugarcane, jute and seeds. Fishing is another economic practice followed along the river.

The Ganga water level rises above the danger mark at many cities and causes flood in Allahabad, Mirzapur, Varanasi, Balia in UP and Patna, Munger and Bhagalpur in Bihar and also in Jharkhand and West Bengal during monsoon in 2016. It has broken the previous record at Patna, Bhagalpur and Balia of UP as per Central Water Commission news. It causes death of many people and half a million people were evaluated.

The heavy and multiday rain in 2013 caused devastating floods and the Kedarnath tragedy which was one of the worst natural disasters since the tsunami of 2004. Singh (2013, 2014) has described the causes and the human responsibilities of Kedarnath tragedy. It affected Haridwar, Bijnor, Allahabad, Bulandsaher, etc. in the downstream. Desiltation of the river, proper and planned sand mining and construction of dams needs to be planned scientifically and as per the law of nature.

4 Conclusions

The Ganga is the longest and most revered Indian river. On its way from the Himalayas to the Bay of Bengal, it is joined by many tributaries that originate either in the Himalayas or in the Ganga Plain or in the craton towards south. The channel pattern of Ganga River apart from change in gradient is also influenced by volume of water and sediments added to it by these tributaries. The vast alluvial plains have built up as a result of interplay of climate, tectonics and sea level changes. It is the lifeline of people living in the Gangetic Plains as it is a perennial source of water in this region, and vast tracts of alluvial sediments deposited by it have supported agriculture for centuries. Its importance has been realized by people along its bank since beginning, and hence it has been worshipped as god and its bank has become places of religious importance and pilgrimage. The religion along its bank has got become so embedded in the people living here that it has also influenced their culture.

Despite of such an importance, the recent human practices and economic growth along its bank have resulted in its pollution to unsustainable levels. Further, the indiscriminate building of dams along the river and its tributaries has affected the flow of water to such a level that it almost becomes dry at places. Such injudicious pollution and exploitation of this river is slowly resulting in slow death of life and culture that has flourished since time immemorial. It is high time that a proper planning is made for sustainable use of this river.

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The Brahmaputra River

Sunil Kumar Singh

1 Introduction

Rivers are the dominant pathways to transfer continental particulate and dissolved materials to the global oceans and in turn control both their sedimentary and geochemical budgets. Rivers draining the belts such as the Himalaya contribute significantly to the sedimentary and dissolved material budgets of the global ocean, for example, they supply about one-fourth of the total global sediment input to the oceans. The Ganga-Brahmaputra river system draining the Himalaya is one of the largest rivers systems of the world, first in sediment supply and fourth in water discharge (Sarin et al. 1989). The Brahmaputra delivers 670 km^3 of water, 1000 million tons of sediments and 100 million tons of dissolved material annually to the Bay of Bengal (Milliman and Meade 1983; Milliman and Syvitski 1992; Hay 1998; Sarin et al. 1989; Singh et al. 2005). Most of the discharge of the Brahmaputra is associated with South–West (SW) monsoon. The intense rainfall in the basin and uneven distribution of the discharge cause frequent floods in the Assam during every SW monsoon creating havoc and disturbing lives of millions of people. This basin also experiences flash flooding such as one occurred in year 2000 (Rai and Singh 2007). The floods in the Brahmaputra deposit large volume of sediment in the plain, part of which get removed by bank erosion in following years. The Brahmaputra basin is characterised by intense physical and chemical weathering reflected by its large sediment and solute flux. Both physical and chemical weathering in this basin are among the highest in the world and controlled by relief and SW monsoon. Most of the weathered materials are supplied to the ocean during SW monsoon, between June and September. Extreme erosion and weathering in the basin, particularly in the higher reaches, result in regional and global changes.

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Intense erosion evacuates large amount of materials causing enhanced uplift due to isostatic rebound in mountain ranges and consuming a disproportionate amount of atmospheric CO_2 (Raymo and Rudimann 1992). Further chemical weathering in the basin contributes significantly to the evolution of sea water chemistry.

2 Brahmaputra River System

The Brahmaputra is known by different names along its course. Figure 1 shows the elevation map of the Brahmaputra basin along with its tributaries. The Brahmaputra originates in the snow-covered Kailash Mountain (the Jimayangzhong Glacier) in Trans-Himalaya, flows eastward on a very gentle slope ($\sim$0.001) for $\sim$1200 km along the Indus-Tsangpo Suture in Tibet (Fig. 2) and known as theYarlung Tsangpo, Tsangpo, Sangpo or Yaluzangbu in this stretch. The Tsangpo takes a U-turn, known as Big Bend, (Fig. 1) after Pai at 95°E around Namche Barwa Mountain of the Eastern Syntaxis, making deep gorge of $\sim$5075 m depth (The Guinness Book of Records, 1996). The river then turns south and enters Arunachal Pradesh of India at Singing where it is known as the *Siang* or *Dihang* and having a steep gradient ($\sim$30 m/km) with turbulent flow. It is known as the Brahmaputra after entering the Assam plains and merging with the Dibang and the Lohit (Fig. 1). In the plains of Assam, the Brahmaputra flows in WWS direction with wide, deep

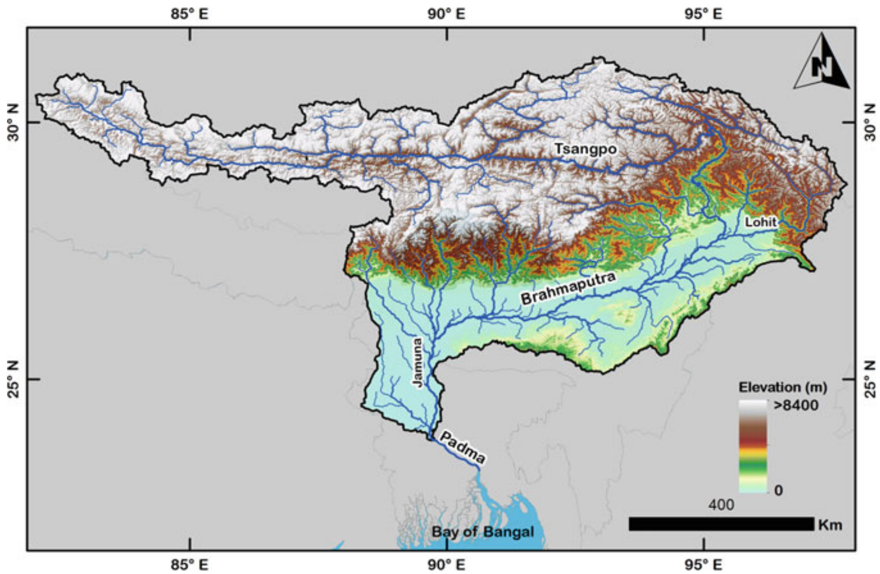

Fig. 1 Digital elevation map of the Brahmaputra River System. Different regions of the basins are marked in this figure

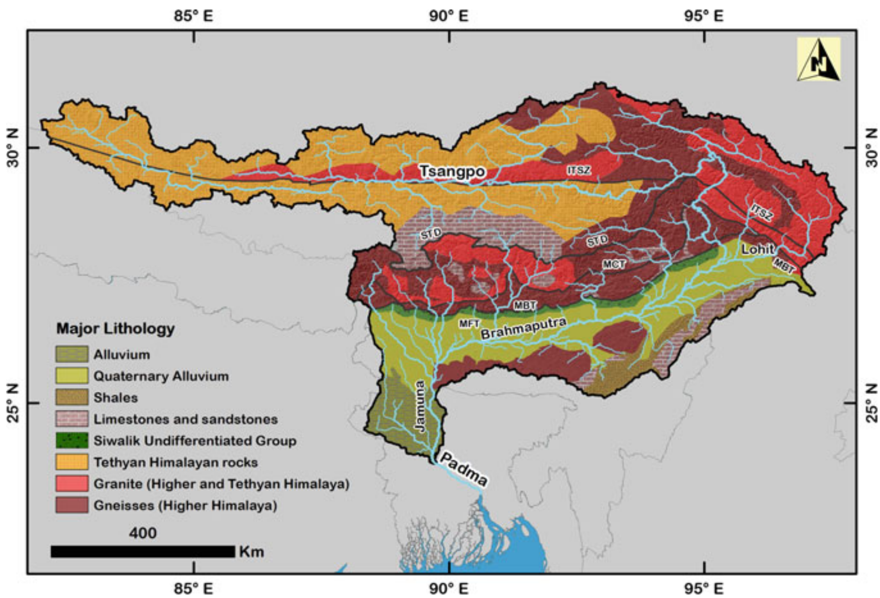

Fig. 2 Lithological map of the Brahmaputra Basin. Important geological zones and boundaries are shown

and braided channel. Taking a southern turn, the Brahmaputra enters Bangladesh as the Jamuna near Dhubri and meets the Ganga at Arichaghat.

Out of the total length of 2900 km of the Brahmaputra from its origin in the Kailash Mountain to Arichaghat, 1600 km lies in Tibet, 900 in India and the remaining 400 in Bangladesh (Kumar 1997). Along this entire stretch, it receives many tributaries. The Lhasa He (Zangbo), Doilung and Nyang Qu (Fig. 1) are its major tributaries in Tibet. The Parlung Zangbo with a very high gradient merges with the Tsangpo near the deep gorge after Pai.

The Subansiri, Ranga Nadi, Jia Bhareli, Puthimari, Manas and Tipkai are the major tributaries from the Himalaya joining the Brahmaputra in the Assam plain from the north. The Dibang and Lohit draining the Mishmi Hills are the major eastern tributaries, whereas the Burhi Dihing, Dhansiri and Kopili, the southern tributaries, merge with the Brahmaputra in the Assam Plain (Fig. 1). The Teesta, a large tributary draining the Himalaya, joins it in Bangladesh.

The Brahmaputra basin lies in distinct geological and climatic zones, extending from the dry region of Tibet in the rain shadow of the Himalaya to the eastern basin receiving extremely high rainfall. Temperature varies by about 40 °C in the basin. Its basin has varying lithologies, evaporites, carbonates and various kinds of silicates.

The entire drainage basin of the Brahmaputra system can be separated into six zones (Fig. 1):

(i) Tibet
(ii) Eastern Syntaxis
(iii) Eastern Drainage or Mishmi Hills
(iv) The Himalaya
(v) The Indo-Myanmar and Naga-Patkoi Ranges
(vi) The plains of Assam and Bangladesh.

Geology of these sections is presented in Fig. 2 and summarised below:

(i) *Tibet*—This sub-basin consists of turbidites and ophiolites of the Indus-Tsangpo Suture Zone and Trans-Himalayan gabbroic to granodioritic batholiths. The Lhasa Block includes Precambrian orthogneisses and metasediments. Several evaporite deposits are present in the basin (Hu et al. 1982; Pande et al. 1994; Pascoe 1963). The Himalayan tributaries of the Tsangpo drain the northern slope of the high Himalaya on gneisses and Palaeozoic to Eocene Tethyan sedimentary rocks (Fig. 2).
(ii) *Eastern Syntaxis*—The rocks of this region are metamorphosed severely. The gneisses of the Indian Plate are exhumed from the Trans-Himalayan Plutonic Belt (TPB). Quartzites, phyllites and marbles surround the calc-alkaline plutons of the TPB in this zone.
(iii) *The Eastern Drainage or the Mishmi Hills*—The Mishmi Hills are composed of calc-alkaline diorite-tonalite-granodiorite complexes and tholeiitic metavolcanic rocks of island-arc affinity (Kumar 1997). It is considered as the eastern continuation of the Trans-Himalayan Plutonic Belt. The Tidding Suture, eastern continuation of Indus-Tsangpo Suture (Fig. 2) with chlorite-schists, amphibolites and carbonates, defines the boundary between the Trans-Himalayan Plutonic Belt and the Himalaya. The Lohit and Dibang drain the Mishmi hills (Fig. 2).
(iv) *The Himalaya*—The Siang and other northern tributaries (the Subansiri, Ranga Nadi, Jia Bhareli, Puthimari and Manas) drain the southern slope of the Himalaya. The geology of the Himalaya in this section is similar to that of its central and western parts comprising the Higher and the Lesser Himalaya and the Siwaliks (Fig. 2). The Higher Himalaya consists of schists, gneisses and marbles with amphiboles at some locations. Migmatites and Miocene leucogranites are also common in certain locations. The Lesser Himalaya is composed mainly of quartzites, schists, Precambrian limestones, dolostones, shales and quartzites along with orthogneiss bodies and dolerite sills.
(v) *Indo-Myanmar Ranges and Naga-Patkoi ranges*—Cretaceous-Eocene pelagic sediments, Eocene-Oligocene turbidites and Naga ophiolites are the major constituent of this section. The southern tributaries (the Dhansiri and Kopili) drain them along with granite and gneisses of the Indian basement of the Shillong Plateau and the Mikir Hills (Kumar 1997).

(vi) *Plains of Assam and Bangladesh*—The plains of the Assam and the Bangladesh are made of the fluvial sediments brought by the Brahmaputra River. In addition, the Indian basement is exposed in some regions in Assam.

3 Climate and Geohydrology

Climate of the Brahmaputra basin is highly variable with cold and arid drainage of the Tibet and humid subtropical drainage in the Himalaya, the Mishmi hills and the Naga-Patkoi ranges with varying temperature. The Higher Himalaya, the Tethyan Himalaya and the Eastern Syntaxis are alpine. Lesser Himalaya and the Mishmi Hills are cooler and wet (Kumar 1997). The Siwalik section of the Himalaya along with the Indo-Myanmar Ranges and Assam Plains experiences hot and humid climate. Temperature in Tibet varies from −5.0 to 20 °C (Guan and Chen 1981). The temperature in the plains goes as high as 40 °C and drops to 0 °C at places.

The majority of the Brahmaputra basin, except Tibet, receive south-west monsoon during June to September. The annual precipitation in the rain shadow zone of the Tibet is about 300 mm (Fig. 3). The Siang drainage, Mishmi hills and part of the Indo-Burman ranges receive heavy precipitation, as high as 5000 mm/year (Fig. 3). The southern slopes of the Himalayan drainage of the Brahmaputra get an

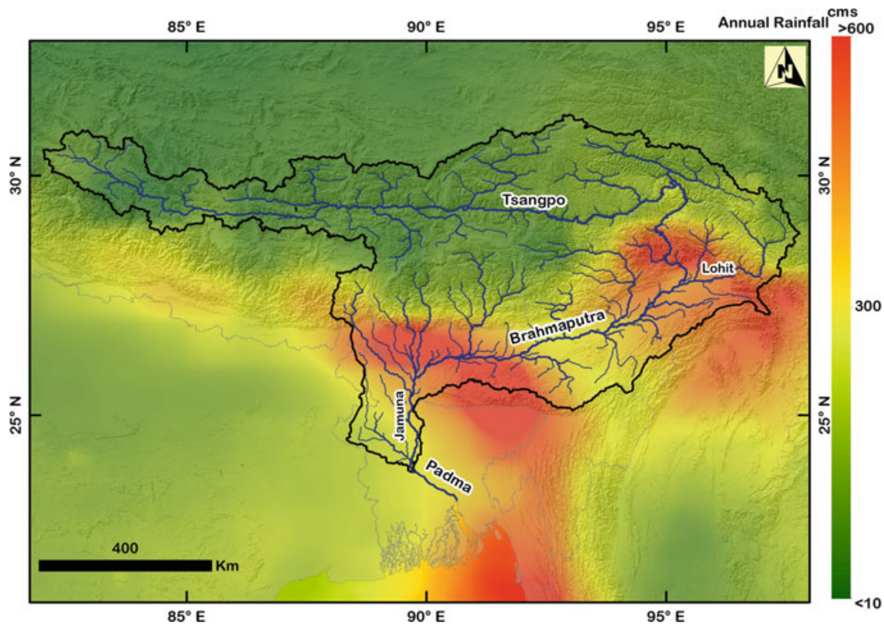

Fig. 3 Annual precipitation in the Brahmaputra basin for last 10 years (Based on TRMM data) showing high rainfall over the Siang, Mishmi Hills, the part of the Naga-Patkoi Ranges and Shillong Plateau

annual rainfall between 1000 and 3000 mm, which increases to about 5000 over the Shillong Plateau and in the Teesta and the Manas basins (Fig. 3). The Naga-Patkoi and the Indo-Myanmar ranges get very heavy rainfall of 4000–5000 mm/year. The place receiving the highest rainfall (~13,000 mm/year) in the world, Cherrapunji, is based here.

The Brahmaputra system drains a total area of about 630,000 km^2. One-third of its drainage lies in the Tibet (Fig. 4) at an average elevation of 5000 m contributing only about 10% of its total water discharge at the outflow in Bangladesh. The southern slopes of the Himalaya cover an area of 120,000 km^2 of the Brahmaputra drainage, whereas the plains of Assam and Bangladesh together constitute an area of 200,000 km^2 with the Mishmi Hills, ~50,000 km^2. The southern drainages make up the rest of the drainage lying in the Indo–Myanmar and Naga–Patkoi ranges.

The discharge of the Brahmaputra mainstream (Tsangpo) at Nugesha in Tibet is 19 km^3/year, which increases to 60 km^3/year before the Eastern Syntaxis (Fig. 4). It increases to 670 km^3/year at Bahadurabad in Bangladesh (www.grdc.sr.unh.edu). The meltwater, groundwater and rainfall contribute equally to discharge of the Tsangpo in Tibet (Guan and Chen 1981). SW monsoon rainfall contribution dominates the water budget of the Brahmaputra at its outflow (Fig. 5).

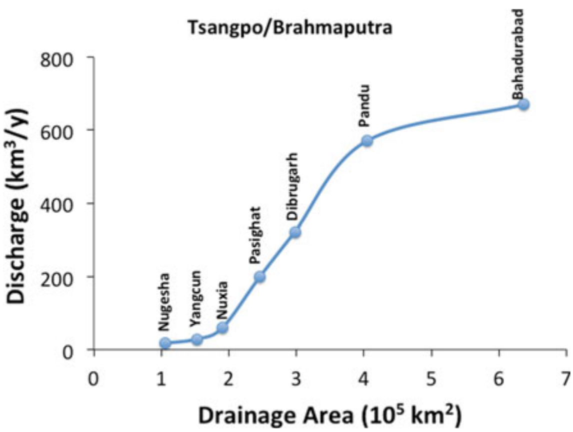

Fig. 4 Discharge of the Brahmaputra as a function of drainage area

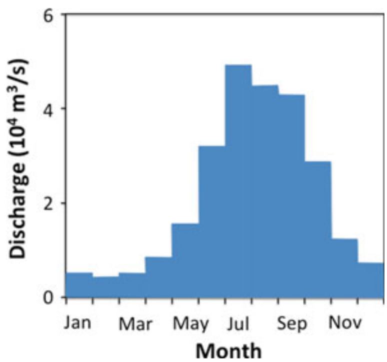

Fig. 5 Monthly discharge of the Brahmaputra at Bahadurabad (from www.grdc.sr.unh.edu) showing dominant control of SW monsoon

4 Erosion and Weathering in the Brahmaputra Basin

The Brahmaputra river system supplies 1000 million tons of sediment and 100 million tons of dissolved matter annually from a drainage area of 6,300,000 km^2 indicating high physical and chemical weathering in the basin.

Physical Erosion: Singh and France-Lanord (2002) based on the Sr–Nd isotope composition of the sediments collected from the Brahmaputra basin and the sediment flux data of the Brahmaputra estimated the erosion rates in the various parts of the Brahmaputra basin which is similar to those reported by Zeitler et al (2001) and Stewart et al (2008). High erosion in the Eastern Syntaxis is driven by the high stream power of the river in this region. The estimated erosion rates in the Brahmaputra basin vary from 0.2 mm/year in Tibet to 14 mm/year in the Eastern Syntaxis Zone (Singh et al. 2006). The erosion rate estimated for the Eastern Syntaxis Zone is one of the highest in the world (Milliman and Meade 1983). The erosion rate over the Eastern Himalaya is $\sim$2 mm/year similar to those reported in central and western Himalaya (Singh et al. 2008).

The intense and focussed erosion in the Eastern Syntaxis Zone supplies about half of total sediment flux of the Brahmaputra to the Bay of Bengal. This large evacuation of sediments results in higher uplift of the region because of isostatic rebound. High peaks of Namche Barwa (7750 m) and Gyala Peri (7150 m) might have been resulted due to this uplift.

Chemical Erosion: It has been proposed that enhanced silicate weathering in the Himalayan region during the Cenozoic has contributed to global cooling (Raymo and Ruddiman 1992). A number of studies have been carried out to determine the present-day silicate weathering rates and CO_2 consumption due to silicate weathering in the drainage basin of the Ganga, the Brahmaputra and the Indus river systems based on the major ion chemistry of these river waters and their dissolved $^{87}Sr/^{86}Sr$ (Sarin et al. 1989; Krishnaswami et al. 1992, 1999; Pande et al. 1994; Singh et al. 1998, 2005, 2006; Galy and France-Lanord 1999; Karim and Veizer 2000; Dalai et al. 2002; Bickle et al. 2001, 2003, 2005; Rai and Singh 2007; Hren et al. 2007). These studies demonstrate that the present-day silicate weathering rate and the corresponding CO_2 consumption rate over the Himalayan drainage are higher compared to the world average. The silicate weathering rates, in most of these studies, were estimated based on the dissolved major ion data of the rivers and forward modelling using Cl-corrected dissolved Na (Na*) as a proxy of silicate weathering (Krishnaswami et al. 1999; Galy and France-Lanord 1999; Singh et al. 2005). Silicate weathering rates derived by this method are prone to uncertainties. Another approach is the use of $^{87}Sr/^{86}Sr$ of the Himalayan river water as a proxy of silicate weathering (Krishnaswami et al. 1992; Pande et al 1994; Singh et al. 1998; Galy et al. 1999; Dalai et al. 2003; Bickle et al. 2001, 2003, 2005; Singh et al. 2006). This approach relies on the general trend of higher $^{87}Sr/^{86}Sr$ in silicates compared to that in carbonates. In the Himalaya, the reliability of this general trend has been doubted due to the presence of carbonates with high $^{87}Sr/^{86}Sr$ (Quade et al. 1997; Singh et al. 1998; Galy et al. 1999; Bickle et al. 2001). More doubts have been raised on the applicability of this approach because of the occurrence of silicates with low $^{87}Sr/^{86}Sr$ (mantle like; ~0.704) in the drainage basins of the Brahmaputra (Singh and France-Lanord 2002) and in the Indus, which overlap with some of the carbonates.

HCO_3^- in water during silicate weathering comes from soil CO_2, but in the case of carbonate weathering equal amount of HCO_3^- are derived from soil CO_2 and the carbonate itself. Depending on the sources of the bicarbonate ions, their $\delta^{13}C$ will be quite distinct. During silicate weathering, $\delta^{13}C$ of the bicarbonate ions will be determined by the type of vegetation in the drainage, i.e. C3 and/or C4, whereas for carbonate weathering, besides the type of vegetation, it will also depend on the $\delta^{13}C$ of the carbonates being weathered. $\delta^{13}C$ of the bicarbonate ions for silicate weathering will be ~−18 and ~−5‰ for the C3 and C4 plants, respectively and that for carbonate weathering it will be −9 and −2.5‰ (Das et al. 2005; Singh et al. 2005).

In this study, the combined use of $^{87}Sr/^{86}Sr$ and $\delta^{13}C$ is explored to assess the silicate and carbonate weathering contributions to DIC in the Brahmaputra waters composed of multiple types of silicates with varying $^{87}Sr/^{86}Sr$ based on the data of the Brahmaputra basin taken from Singh et al (2005, 2006).

The $\delta^{13}C$ of the particulate organic carbon (POC) measured in the Brahmaputra sediments average −24 ± 1.3‰ (range: −27 to −22‰, $n = 20$; our unpublished data) suggesting *C*3 type of vegetation. CO_2 from organic carbon will produce bicarbonate (DIC) with $\delta^{13}C$ of ~(−16 ±1) ‰, after taking into account the fractionation of ~+8‰ during CO_2 to HCO_3^- conversion. In case of carbonate weathering, $\delta^{13}C$ of DIC would be −9‰ as 50% of bicarbonate in this case is derived from carbonate with $\delta^{13}C$ of ~0‰. Thus, the $\delta^{13}C$ of DIC would be distinctly different for silicates and carbonates derived DIC and, therefore, can be used as a proxy to derive their relative contribution to the DIC budget. The Brahmaputra waters are ideally suited to test this, as they are under-saturated in calcite (Singh et al. 2005).

Measured $^{87}Sr/^{86}Sr$ and $\delta^{13}C$ in the river water are determined by contribution from silicate and carbonate lithology, and relation among them can be represented using following mass balance equations:

$$\left(\frac{^{87}Sr}{^{86}Sr}\right)_r = \left(\frac{^{87}Sr}{^{86}Sr}\right)_s * f_s + (1 - f_s) * \left(\frac{^{87}Sr}{^{86}Sr}\right)_c \quad (1)$$

$$(\delta^{13}C)_r = (\delta^{13}C)s * f_s + (1 - f_s) * (\delta^{13}C)c \quad (2)$$

where r, s and c represent river water, silicate and carbonate, respectively. f_s is the fraction of Sr and DIC derived due to silicate weathering. Eliminating f_s from both equation and by comparing them, one can get a relation between $(^{87}Sr/^{86}Sr)_r$ and $(\delta^{13}C)_r$ as

$$\left(\frac{^{87}\mathrm{Sr}}{^{86}\mathrm{Sr}}\right)_r = (\delta^{13}\mathrm{C})_r * \left[\frac{\left(\frac{^{87}\mathrm{Sr}}{^{86}\mathrm{Sr}}\right)_s - \left(\frac{^{87}\mathrm{Sr}}{^{86}\mathrm{Sr}}\right)_c}{(\delta^{13}\mathrm{C})_s - (\delta^{13}\mathrm{C})_c}\right] + \left[\frac{\left\{\left(\frac{^{87}\mathrm{Sr}}{^{86}\mathrm{Sr}}\right)_c * (\delta^{13}\mathrm{C})_s\right\} - \left\{\left(\frac{^{87}\mathrm{Sr}}{^{86}\mathrm{Sr}}\right)_s * (\delta^{13}\mathrm{C})_c\right\}}{\left\{(\delta^{13}\mathrm{C})_s - (\delta^{13}\mathrm{C})_c\right\}}\right] \quad (3)$$

This is an equation of straight line between δ^{13}C and ^{87}Sr/^{86}Sr of the river water, and the slope of the line will depend on the difference between $(^{87}\mathrm{Sr}/^{86}\mathrm{Sr})_s$ and $(^{87}\mathrm{Sr}/^{86}\mathrm{Sr})_c$ as for a given vegetation type, which is mostly C3 in the case of the Brahmaputra, difference between $(\delta^{13}\mathrm{C})_s$ and $(\delta^{13}\mathrm{C})_c$ is fixed. In the Brahmaputra drainage, three types of silicates are present, i.e. Himalayan silicates with ^{87}Sr/^{86}Sr $\sim$ 0.78, Siwaliks silicates ($\sim$0.725) and Calc-alkaline silicates ($\sim$0.704) and on a plot of ^{87}Sr/^{86}Sr versus δ^{13}C, they will represent three lines. δ^{13}C and ^{87}Sr/^{86}Sr for the silicate and carbonate end members are also plotted, and three lines joining them in Fig. 6 represent the mixing between three types of silicates and the carbonate. It shows that the data are converging to carbonates and fanning out towards silicates as three types of silicate lithology are present in the Brahmaputra drainage. The data for the Brahmaputra mainstream and for the Himalayan and southern tributaries show different trends. Himalayan tributaries fall on the line defined by Himalayan silicates and carbonates except for the Ranga Nadi. It falls on the Siwaliks trend as it flows mostly in Siwaliks. Southern tributaries fall either on Siwaliks trend as they have Siwaliks type of silicates (Singh and France-Lanord 2002) or towards

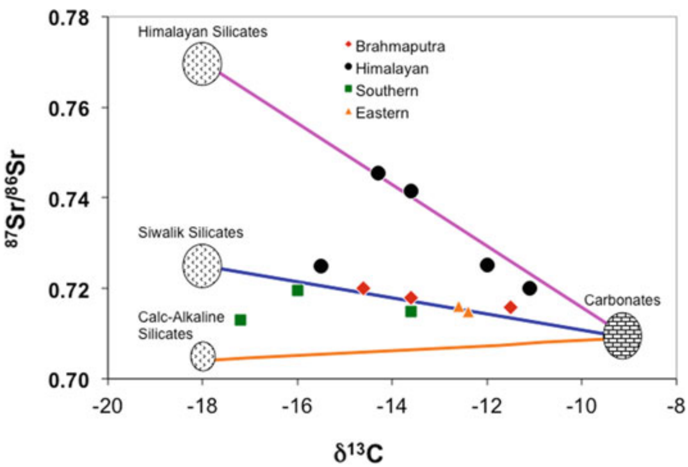

Fig. 6 Mixing diagram of δ^{13}C versus ^{87}Sr/^{86}Sr of waters of the Brahmaputra River System. The end member values for silicates and carbonates are also shown. The Brahmaputra drainage has three types of silicates with different ^{87}Sr/^{86}Sr and hence the three silicate members. Lines between end members are the mixing lines. The data point fall on these lines attesting to their sources from two end members, silicates and carbonates

cal-alkaline trend. Calc-alkaline silicates are present in the eastern and some of the southern tributaries. The data of the Brahmaputra mainstream fall mostly on the line defined by the carbonates and Siwalik type of lithology. The silicates of the Brahmaputra are a mixture of the silicates from the Himalayan and cal-alkaline lithology which are similar to those of the Siwaliks, and hence the data of the Brahmaputra fall on the mixing line defined by the silicates of Siwaliks and the carbonates. The silicates of the Siwaliks in the Eastern Himalaya were derived from the Himalayan and calc-alkaline silicates, and their $^{87}Sr/^{86}Sr$ are similar to those of the modern sediments of the Brahmaputra (Singh and France-Lanord 2002).

Earlier study (Singh et al. 2005) has shown that the Brahmaputra waters are mostly under-saturated with respect to calcites and hence HCO_3^- are not lost from the water due to calcite precipitation. Based on the Fig. 6, the silicate contribution to dissolved Sr and DIC in Himalayan tributaries ranges from 20 to 60%, in the southern tributaries 50–90%, in the eastern tributaries ~40% and for the Brahmaputra at Guwahati ~50%. These are consistent with the proportion of cation derived using major ion and also with clay content of the sediment (Singh et al. 2005). Chemical erosion and silicate erosion are quite high in the Brahmaputra basin. The silicate erosion rate and associated CO_2 consumption the Eastern Syntaxis are much higher, 38 t/km^2/year and ~2 million mole/km^2/year, respectively (Singh et al. 2005). Later study in the Eastern Syntaxis (Hren et al. 2007) confirmed these extremely high erosion and CO_2 consumption rates.

5 Conclusion

Brahmaputra drains different regions characterised by very diverse lithology, climate and geohydrology. Influenced by SW monsoon and relief, it supplies large quantity of particulate and dissolved material to the Bay of Bengal resulting in very high physical and chemical erosion. Both physical and chemical erosion rates are very high in the Eastern Syntaxis which is driven by high stream power of the river in this region. High physical and chemical erosion results in high uplift rate due to isostatic rebound and large consumption of atmospheric CO_2. The Brahmaputra basin consists of three types of silicates based on their $^{87}Sr/^{86}Sr$, and their elemental ratios are also variable due to presence of the Himalayan and calc-alkaline silicates. The predominant vegetation in the Brahmaputra is of C3 type with $\delta^{13}C$ of ~ −24‰. $\delta^{13}C$ of the dissolved inorganic carbon along with $^{87}Sr/^{86}Sr$ holds the potential of apportioning silicate and carbonate weathering. $\delta^{13}C$ and $^{87}Sr/^{86}Sr$ of the river water of the Brahmaputra based on the material balance calculation shows that about half of its dissolved Sr and alkalinity are derived due to silicate weathering and the CO_2 consumption due to silicate weathering in the Brahmaputra drainage at Guwahati is $\sim 6 \times 10^5$ mol km^{-2} year^{-1}, higher than that of the Ganga and much higher than the global consumption. CO_2 consumption associated with silicate weathering in the Eastern Syntaxis is among highest in the world, even higher compared to some of the basaltic terrains.

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Alakhnanda–Bhagirathi River System

Sandeep Singh

1 Introduction

India has large numbers of rivers where human civilizations have flourished in the past. There has been change in landform caused due to interplay of climate overtime, which led to distribution of human settlement. According to "River Basin Atlas of India (2012)", 5125 dams and a number of barrage, weirs, etc. have been erected for the water resource projects for irrigation purpose as well as hydro-power generation and river transport. The Himalayas is the birthplace of many important rivers which are perennial in nature. Among those, there are three main river systems joined by many large and important tributaries. These three main rivers are Brahmaputra, Ganges and Indus, which are responsible for shaping up of the Himalayan landforms. These river systems have also been responsible for the erosion and transportation of large sediments from the Himalayan region and depositing them in foredeep basin in front of the mighty mountain chain known as Indo-Brahmaputra-Gangetic Alluvial Plain.

The Ganges is a very long river in the Indian subcontinent with many tributaries, and it occupies the central part of the three main river systems. The name Ganges has been christened after crossing Devprayag, "*Prayag*" of Alakhnanda (left-bank tributary) and Bhagirathi (right-bank tributary). "*Prayag*" is a Hindi word which means "*sangam*" in Hindi and "confluence" in English. According to Hindu mythology, *Prayags* are very holy places for carrying out important Hindu rituals. The Alakhnanda–Bhagirathi rivers, originating in the north-western part of Uttarakhand state (Fig. 1a), are characterized by rugged river drainage systems. These rivers are a

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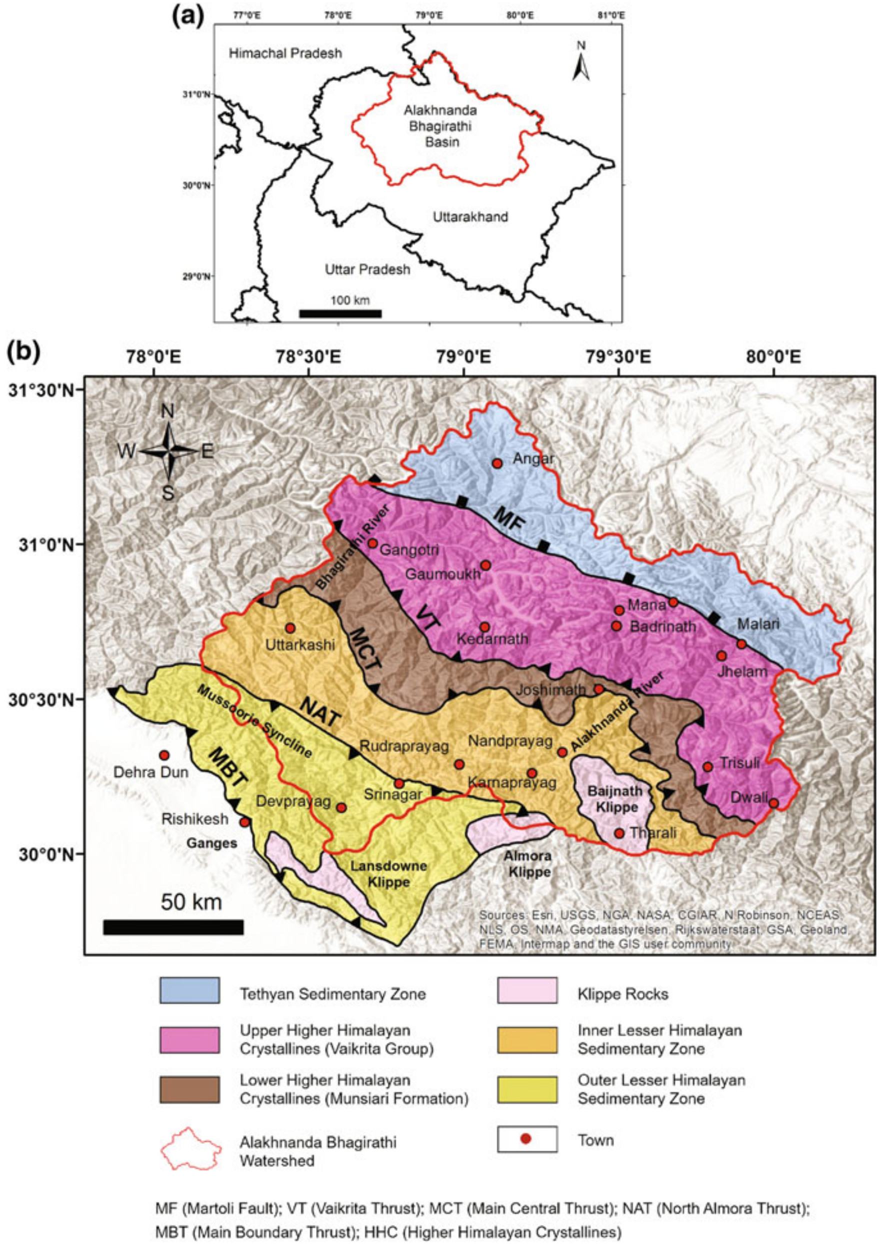

Fig. 1 **a** Location of Alakhnanda–Bhagirathi river system in Uttarakhand state. **b** Geological map of Alakhnanda–Bhagirathi valley based on own observations and published literature

typical example of antecedent rivers, which are going across the Himalayan range through primary geologic structures (Montgomery and Stolar 2006) and post-date both metamorphism and development of collision-related structures.

2 Alakhnanda–Bhagirathi River System

The Alakhnanda River originates from the foot of Satopanth and Bhagirathi Kharak glaciers and flow downwards past Mana village meeting with the Saraswati River (right-bank tributary). The Saraswati River emerges from Tara Glacier and travels through V-shaped gorges within moraines. Further downstream, it goes through the Badrinath valley which is a bowl-shaped valley developed due to glacial action. Further downwards, it moves through narrow valleys and meets with the Ghrit Ganga (right-bank tributary) near Hanumanchatti and further goes downwards to Pandukeshwar and joined by Bhyunder Ganga (left-bank tributary), which originates in the Valley of Flowers. After Pandukeshwar/Govindghat, the Alakhnanda further moves through wide valley and gentle slope for some distance followed by a narrow valley with steep terrain. It meets with Dhauliganga (left-bank tributary) at Vishnuprayag. The gentle slope with a wide valley indicates damming effect due to paleo-landslides. Although Dhauliganga carries more water and sediments in comparison to Alakhnanda but after Vishnuprayag the stream is known as Alakhnanda. Dhauliganga originates from high peaks near Niti Pass and travels through Malari (very wide valley, probably developed due to paleo-landslide at downstream of Malari), Jhelam, Juma, Tapovan (crossing Vaikrita Thrust) and to Vishnuprayag at the base of Joshimath (Fig. 1b).

From Vishnuprayag below Joshimath, the Alakhnanda River forms a longitudinal valley and travels towards the west with a steep valley on north side and paleo-landslide on southern slope where the Joshimath town is situated. Between Joshimath and Pipalkoti, several small rivers (Urgam nadi, Patal Ganga, Garur Ganga and Mena nadi with steep gradient) meet the Alakhnanda River. Further downwards, the Alakhnanda travels through narrow gorge crossing the Main Central Thrust (MCT), near Helang, to Pipalkoti and meets with Birahi Ganga (left-bank tributary) at Birahi. The River Birahi Ganga originates from high group of peaks of Trishul and Nanda Ghunti. After crossing the MCT, the gradient of river reduces drastically and it loses the characteristics of flowing through deep gorges. Further down, it reaches Nandprayag where it meets with Nandakini River (left-bank tributary). Nandakini River originates from the glacier below Nanda Ghunti and Trishul in the Nanda Devi Sanctuary. After meeting with Alakhnanda, it further flows as Alakhnanda only. Further, Alakhnanda River meets with the Pinder River (left-bank tributary) at Karanprayag. The Pinder River originates from Pindari Glacier in Bageshwar district and travels through small towns and villages and merges with River Alakhnanda and thereafter flows as the Alakhnanda.

At Rudraprayag, Alakhnanda meets with the Mandakini River (right-bank tributary). Mandakini originates from the Chorabari Glacier near Kedarnath (wide glaciated valley) and flows through Sonprayag where it meets with Vasukiganga and flows further downwards through narrow gorge and meets Alakhnanda at Rudraprayag after which the stream is known as Alakhnanda. After a short distance, it enters into a very wide valley near Srinagar, Garhwal, formed due to damming of the river mouth near Kirtinagar because of paleo-landslide (Sundariyal et al. 2007). Further downwards, river travels in a somewhat wide valley and meets Bhagirathi at Devprayag. Beyond, Devprayag, Alakhnanda and Bhagirathi travel as the Ganges.

Through the ages, the River Bhagirathi has been considered mythologically the main source stream for the Ganges River; however, in hydrological terms, Alakhnanda rather Dhauliganga is considered the source stream on account of length and discharge. River Alakhnanda and its tributaries have a total length of about 664.5 km, whereas Bhagirathi and its tributaries have about 456.5 km (Fig. 2a, b).

The Bhagirathi River originates from snout (Gaumukh) of Gangotri Glacier, which is the largest valley glacier originating from the western face of Chaukhumba massif and flow north-west to Gaumukh through a broad U-shaped valley. After Gaumukh, river reaches Gangotri town where it meets with Kedar Ganga (right-bank tributary) from where it travels further downwards in deep gorge and meets with Jadh Ganga (right-bank tributary) at Bhaironghati. Further downwards, it travels to Harshil, and after crossing the Bhagirathi Granite it enters into a wide valley developed due to paleo-landslide near Jhala. Within the wide valley, Bhagirathi meets with Jalandhari Gad (right-bank tributary) near Harshil and Siyan Gad (left-bank tributary) near Jhala. Further downwards, Bhagirathi River travels through deep gorge and reaches Bhatwari crossing Vaikrita Thrust near Gangnani. Bhagirathi River crosses the MCT near Sainj and comes to Maneri village and further downwards to Uttarkashi where it meets with Aasi Ganga (right-bank tributary). Further downwards, it travels through Dharasu, Chinyalisaur to old Tehri town where it meets with Bhilangana (left-bank tributary), and now these areas have been submerged due to the construction of Tehri Dam Reservoir. Bhilangana itself rises at the foot of the Khatling Glacier south of Gaumukh and joins by Balganga at Ghansali. From Tehri, the Bhagirathi travels through Himalaya to reach Devprayag where it meets with Alakhnanda (Fig. 3).

The available images of Devprayag show variations of water colour in both the rivers indicating a change in the nature of rivers with the change in seasons. The pattern of change in colour follows a trend; before the onset of monsoon, the colour of Bhagirathi River is clear, whereas water in the Alakhnanda is muddy. After the monsoon, the Bhagirathi carries muddy water, whereas the Alakhnanda carries clear water.

Various studies including isotopic studies (Bhattacharya et al. 1985; Rai et al. 2009; Maurya et al. 2011) indicate that the source of water discharge is a combination of snow melt water, surface runoff of southwest monsoonal rain and groundwater. During climatic changes overtime, the sediments supplies have varied, and in the upper reaches of river valleys the slopes being very steep and

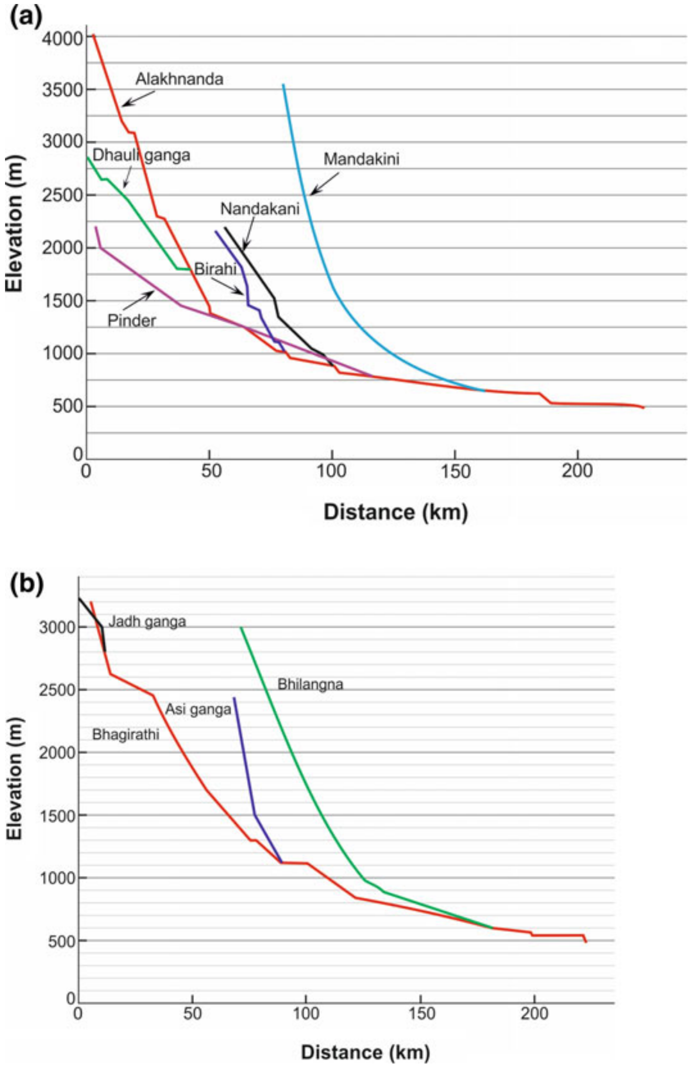

Fig. 2 **a** Distance travelled and elevation difference of the Alakhnanda river and its tributaries. **b** Distance travelled and elevation difference of the Bhagirathi river and its tributaries

unstable regularly cause landslides and block rivers. The deposition of sediments behind these paleo-landslide zones took place and formed river terraces, and due to incision of valleys these terraces have been exposed along Alakhnanda–Bhagirathi river valleys (Srivastava et al. 2008).

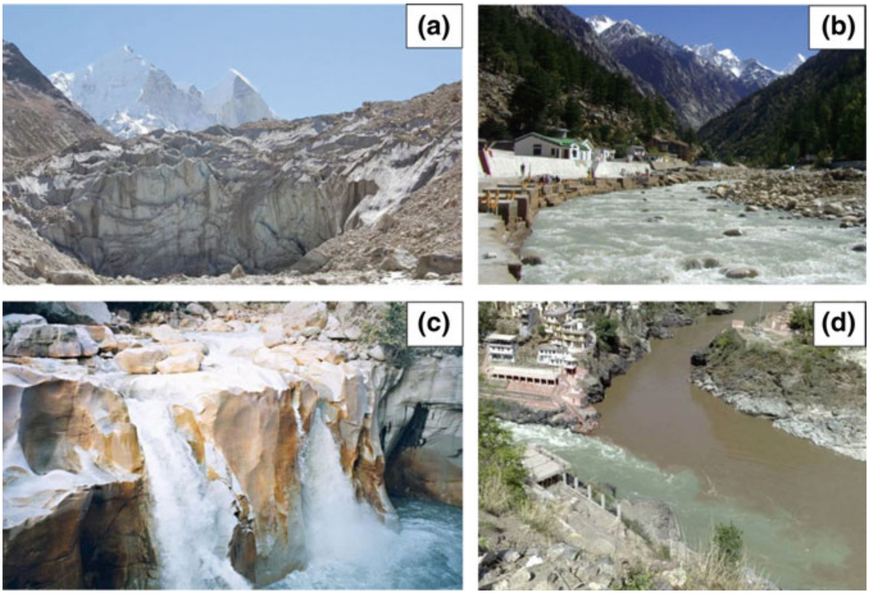

Fig. 3 **a** Photograph of Gangotri Glacier at Gaumukh. **b** Photograph of Bhaigrathi river at Gangotri. **c** Bhagirathi river making waterfall just downstream of Gangotri town. **d** Confluence of Alakhnanda (right-bank tributary) and Bhagirathi (left-bank tributary) before onset of monsoon

3 Geological Framework

The Indian Plate was a part of the Gondwanaland forming the southern landmass on the earth's surface. Indo-Australian Plate got detached from Gondwanaland and moved northwards for about 2400 km from the South Pole across equator and collided with Eurasian Plate not later than 57 Ma (Leech et al. 2005). The collision of these plates led to the formation of the Himalayas. With the rise of Himalayas, the monsoon circulation system was established, which led to fast erosion and generation of large quantities of sediments. These sediments were further transported downwards, deposited within central portion of frontal foredeep basin popularly known as Ganga Alluvial Plain (GAP). After the formation of monsoonal circulatory system, there have been prominent climatic changes which shaped the drainage system of Himalayas. In general, river drainage occupies rugged, deep and steep-sided valleys having overall dendritic drainage patten, however, at places they are parallel in nature indicating a strong litho-tectonic control.

Both Alakhnanda and Bhagirathi rivers have originated within the upper Higher Himalayan Crystallines (HHC): however, a few tributaries have their origin from Tethyan Sedimentary Zone close to Indo-China border (Fig. 1b). These tributaries (Dhauliganga and Jadh Ganga) cross Malari Fault (Virdi 1986) or Martoli Fault (Shah and Sinha 1974; Gururajan and Choudhary 1999) which is also known as the South Tibetan Detachment System (STDS). This fault demarcates the boundary between Tethyan Sedimentary Zone and upper Higher Himalayan Crystallines (Vaikrita Group) and also seldom defines as Dar-Martoli Fault (Kumar et al. 1972). The fault is demarcated by the sudden change in the lithology of the weakly metamorphosed sedimentary sequence of Tethyan Himalayan Sedimentary Zone (Martoli Formation of Haimanta Group) and high-grade metamorphic rocks of the upper HHC (Valdiya 1977, 1980). The nature of this tectonic contact is characterized by the structural features of extensional tectonics present in the metasediments near the contact zone (Singha 2007).

The upper HHC comprises of Vaikrita Group of rocks which is immediately coming close to Malari Fault along Alakhnanda river basin (Valdiya 1977), whereas along Bhagirathi river basin it has wide zone of Cambro-Ordovician ($\sim$485 Ma) two mica granites which has tectonically emplaced tourmaline-bearing leucogranite of $\sim$22 Ma age (Jain et al. 2002 and references therein; Singh et al. 2003a) before coming into Vaikrita Group of rocks. The Vaikrita Group of rocks contain high-grade metamorphic rocks as well as low-grade metamorphic rocks along with a narrow zone of migmatites at the base of Sukhi climb (Singh et al. 2003b, 2004). Along Alakhnanda river basin, the upper part of Vaikrita Group of rocks has been classified as Badrinath Formation (Thakur 1993), which has the presence of migmatites and insitu melt generated due to Himalayan collisional tectonics (Singh et al. 2004). The Pandukeshwar Formation and Joshimath Formation (Virdi 1986) occur just below the Badrinath Formation.

The contact between upper and lower HHC is marked by the Vaikrita Thrust which was first recognized by Valdiya in 1977; this marks the tectonic boundary between the high-grade rocks of Vaikrita Group and the underlying Munsiari Formation. In different sections of Himalaya, Vaikrita Thrust has been designated with different name and position (Nepal $\equiv$ MCT-II; Arita 1983). In Alakhnanda river basin, Vaikrita Thrust lies about 8 km north of Main Central Thrust (MCT) and characterized by thin zone of intense shearing; however, there is no break across the contact, and between upper and lower HHC. However, there exists a marked difference between ε_{Nd} (0) and present-day values with average being ~ -16 and $^{87}Sr/^{86}Sr$ ratio being 0.78759 for Vaikrita Group and ~ -25 and 0.90528, respectively, for Munsiari Formation (Singha 2007). Along Bhagirathi river basin, the Vaikrita Thrust is marked by the development of phylonites between Loharinag and Gangnani.

The lower HHC is characterized by mica schist and gneisses and have been designated as Munsiari Formation (Valdiya 1977). This lower HHC is very narrow in the Alakhnanda river basin, whereas it is somewhat thicker in the Bhagirathi river basin and comprises of porphyroblastic granite gneisses of Paleoproterozoic age which is missing in the Alakhnanda river basin.

The base of Munsiari Formation (lower HHC) is demarcated by Main Central Thrust (MCT), was first delineated by Heim and Gansser (1939), in the Alakhnanda river basin which is located between the Berinag quartzite and/or Calc zone of Tejam of Lesser Himalayan Sedimentary and the Crystallines of Higher Himalaya. The MCT is defined by broad shear zone ranging from several hundred metres to several kilometres wide on either side of the thrust plane and not as a single plane.

It appears to be developed in a tectonic mélange derived from both the HHC and Lesser Himalayan Sedimentary Sequence (Pecher 1978; Arita 1983; Hubbard 1989; Schelling and Arita 1991; Macfarlane et al. 1992; Hodges et al. 1996; Vannay and Hodges 1996; Vannay and Grassemann 1998; Wyss et al. 1999; Ahmad et al. 2000; Stephenson et al. 2000; Jain et al. 2002; Singh et al. 2003a, b; Singha 2007). The nomenclature and positions of the MCT remain debatable in present scenario (Yin 2006). Along Alakhnanda river basin, the MCT passes close to Helang and along Bhagirathi river basin close to Sainj.

The rocks of the Lesser Himalayan Sedimentary are mostly unmetamorphosed, and near the MCT it gets weakly metamorphosed to chlorite zone. Most of the rocks of this domain are calcareous by nature along Alakhnanda river basin and quartzitic along the Bhagirathi river basin. Chlorite and quartz-sericite schists are present in the vicinity of the MCT and are underlain by quartzite, shale and limestone forming part of the Inner Lesser Himalayan Sequence. This sedimentary belt can be traced from the Shimla area to the border of Nepal for about 350 km and has been designated as Garhwal Group of rocks (Valdiya 1980). This group mainly comprises predominantly quartzite and metabasics with intercalations of phyllites and chlorite schist and is correlatable with the Berinag Formation (Heim and Gansser 1939). Southernmost rock of Inner Lesser Himalayan Sedimentary is Nagthat Quartzite with phyllites and basic metavolcanics. The boundary between outer Lesser Himalayan Sedimentary sequence and inner Lesser Himalayan Sedimentary sequence is characterized by southerly dipping North Almora Thrust (NAT) which has been earlier termed as Tons Thrust (Valdiya 1980). The rocks of outer Lesser Himalayan Sedimentary sequence is characterized by Chandpur Formation with intercalated light and dark grey-to-green coloured phyllites inter-banded with fine-grained sandstone, quartz arenite just south of NAT up to Devprayag.

4 Socio-Economic Scenario

Along Alakhnanda–Bhagirathi river system, 95 projects have been either present or proposed to generate more than 1200 MW power. These power projects have affected environment and socio-economic scenario of the river basin. These power projects though generated storage of water for irrigation and in a way also controlled floods downstream, but also changed the environmental balance.

It is important to delineate socio-economic impacts in terms of economic, demographic, cultural, health and natural resource characteristics along with the environment flow assessment before implementing the projects. The river basin has its own inherited problem of seismicity and landslide due to their presence in active Himalayan Orogenic Belt. Apart from these, excessive rainfall and cloudburst have compound effect due to Himalayan landform.

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River Ramganga: A Less Discussed Tributary of Ganga River

Ajai Mishra, Shalini Verma and Daya Shankar Singh

1 Introduction

Water is the most precious gift of the nature for human civilization, living organisms, and natural habitat along with the generation of major geomorphic units on the earth surface. It is used for drinking, cleaning, agriculture, transportation, industry, recreation, animal husbandry and producing electricity for domestic, industrial, commercial use, etc.

The quality, quantity, and availability of water are one of the most important environmental, social, and political issues at global level. Water is key driver of social and economic development. It also has a basic function in maintaining the consistency of natural environment. However, water is only one of a vital natural resource and it is imperative that water issues could not be considered in isolation. The integrated Water Resources Management (IWRM) is a process, which promotes the coordinate development and management of water, land, and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" Global Water Partnership (GWP 2000).

It means development of water resources in that way which balance social and economic needs and also ensures the protection of ecosystems for future generations. A watershed or drainage basin-like landform is defined by highpoints and ridgelines that descend into lower elevations and stream valleys.

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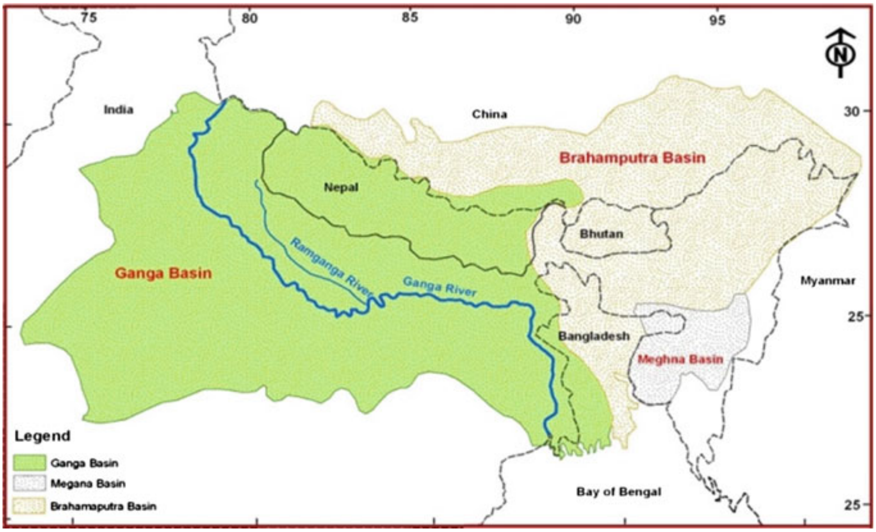

Fig. 1 Maps of Ganga, Brahmaputra, and Meghana Basins (after Mirza 2003)

2 Ganga Basin River System

On the basis of origin, direction of flow, dimensions, channel characteristics, and hydraulic parameters, rivers of the Ganga plain have been classified into three categories as Himalayan source rivers; groundwater-fed rivers of the alluvium; and peninsular source rivers (Singh 1996) (Fig. 1).

The snow-fed or mountain-fed rivers such as the Ganga, Ghaghara, Gandak, Kosi, and the Ramganga transfer huge quantum of sediments from their source areas because of high relief and consequently form large depositional areas in the plains. The snow-fed rivers are generally multichannel, braided systems, characterized by higher discharge and sediment load in comparison with the single-channel, sinuous foothills-fed and plains-fed river systems. The River Ramganga originates from Himalayan region, but the portion covered in the alluvial terrain shows that the gradient and the flow of the rivers play an important role in controlling the river morphology. In case of alluvial region where the rivers are in mature stage, the slow rate of change in the controlling factors gets accommodated by changes in the channel pattern, incising of river valleys, formation of old meanders, scars, palaeochannels, ox-bow lakes, etc.

The Ramganga Watershed: The Ramganga River originates at a place known as “Diwali Khal” at an altitude of 2926 m in the Himalayas (Gairsain) and passes through Chakhutia, Bhikia Sain, Darchula, and Kalagarh habitations in Uttarakhand and enters in the state of Uttar Pradesh. Ramganga watershed rises in the Himalayan region at latitude 30° 5′–27° 18′N and E79° 16′–80° longitude at an altitude of about 3,048 m above mean sea level (Fig. 2).

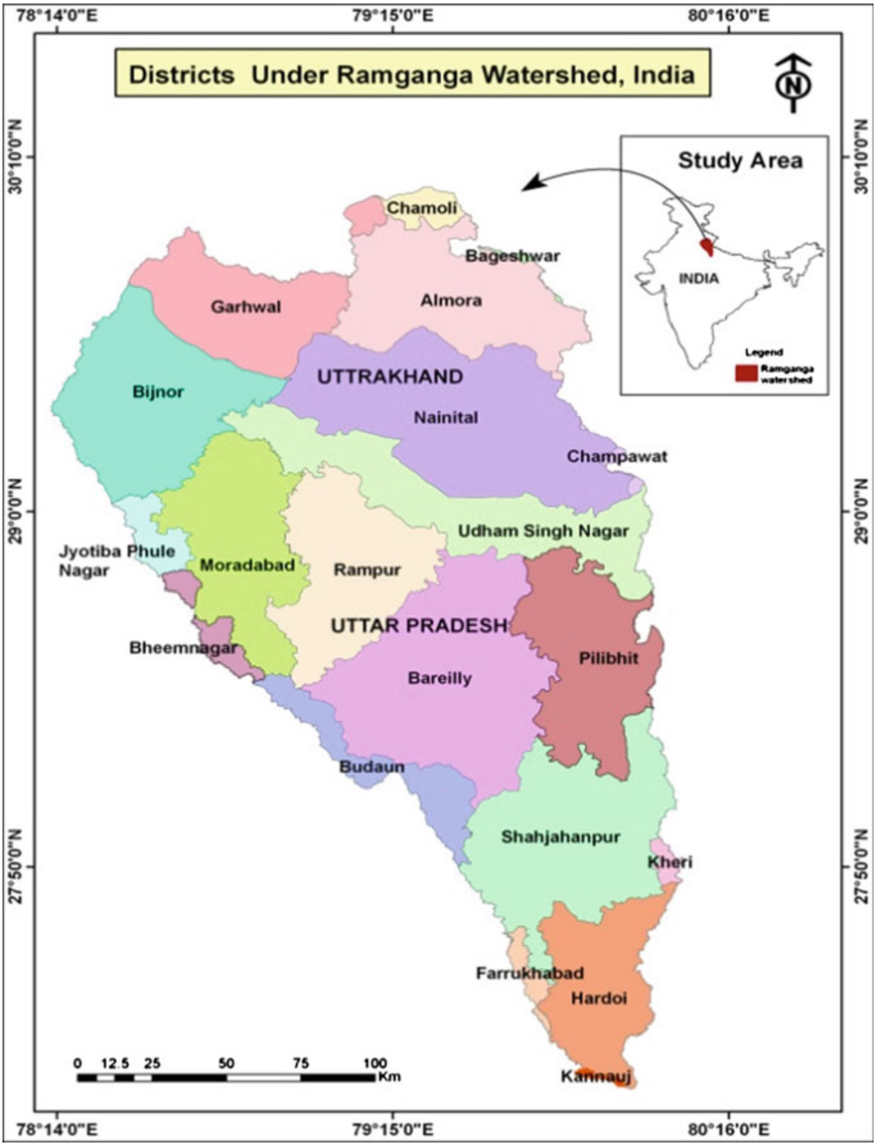

Fig. 2 Maps of Ganga, Brahmaputra, and Meghana Basins (after Mirza 2003)

Its major tributaries are Mandal, Khoh, Bagul, Gangan, Aril, Kosi, Deoha (Garra). The overall drainage pattern of the area is sub-dendritic and high relief. Ramganga watershed covers about 36% area in Uttarakhand and about 64% area in Uttar Pradesh, and district-wise area falls under Ramganga watershed. The Ramganga River flows to S–E direction from its origin for about 32 km before it turns right and flows in the S–W direction, successively through Almora and Garhwal districts for about 112 km. In

Uttarakhand, Ramganga River covers four districts Almora, Pauri Garhwal, and Chamoli and by the Corbett National Park River flows in Nainital district.

The river emerges from the high hills and enters into plains at Kalagarh near the border of Garhwal region. At Kalagarh, a storage dam has been constructed across the river to capture the velocity of water and converts the exuberant water supply for hydroelectric generation that can be used by the local region for household and industrial electric purposes.

Beyond Kalagarh, it descends upon the plain area, the river flows in a S–E direction through the districts of Bijnore, Moradabad, Badaun, Rampur, Bareilly and the Farrukhabad district in the extreme N–E of tahsil Farrukhabad (Toposheet map No. 54 M/10) and flows along the eastern border separating the district from district Shahajanpur for a distance of about 17 km. It then runs through district Hardoi, and finally, it touches the Ganga opposite Kusumkhor in tahsil Kannauj in Kannauj district

In Ramganga watershed, the low land through which it passes, on the subsiding of the inundation, it often makes a fresh channel for itself or leaves behind it a sterile deposit of sand.

The important features found in the area are various meander courses, abandoned channels, ox-bow lakes, etc., and also forming marshy/flood plain area. The area is highly fertile in alluvial plain with fine- to medium-grained sandy aquifer heaving high transmissibility.

Lithologically, the upper part of area of Ramganga watershed has been dominated by phyllites and schists. Extreme N-E corner of the catchment is covered by limestone, quartzite, and graywake. Near Kalagarh, the rocks of the catchment belong to the lower, middle, and upper Siwalik which are capped by horizontally deposited recent gravel traces at different elevation. Middle and lower part of watershed belongs to alluvial region of Ganga plain (Fig. 3; Tables 1, 2 and 3).

3 Physiography, Climate, Relief, and Drainage

Steep hills, deep, narrow valleys, and alluvial plain are the characteristics of the watershed. Due to such formation, the watershed is well drained.

The watershed is drained by tributaries such as Mandal, Khoh, Aril, Kosi, Garra, Bhagul, Dehla besides Ramganga River. Number of natural springs and winter snowfall on the high peak of the region keep the river perennial. The Ramganga River Basin experiences a sub-humid, sub-tropical climate within a vast monsoon regime of the Great Plains. Diverse climate conditions are observed because of the large variation in the altitude of the watershed area, and the lower valley is usually hot and uncomfortable in the months of May and June, while the hilltops are generally cool even in June. Sharp frost is usual in the winter months. The annual rainfall in the region varies from 87 to 125 cm. Variation in the temperature is extreme, and in summer months the minimum and maximum temperature ranges between 19 and 48 °C, while in winter months the minimum and maximum temperature ranges between 20 and 20 °C, respectively.

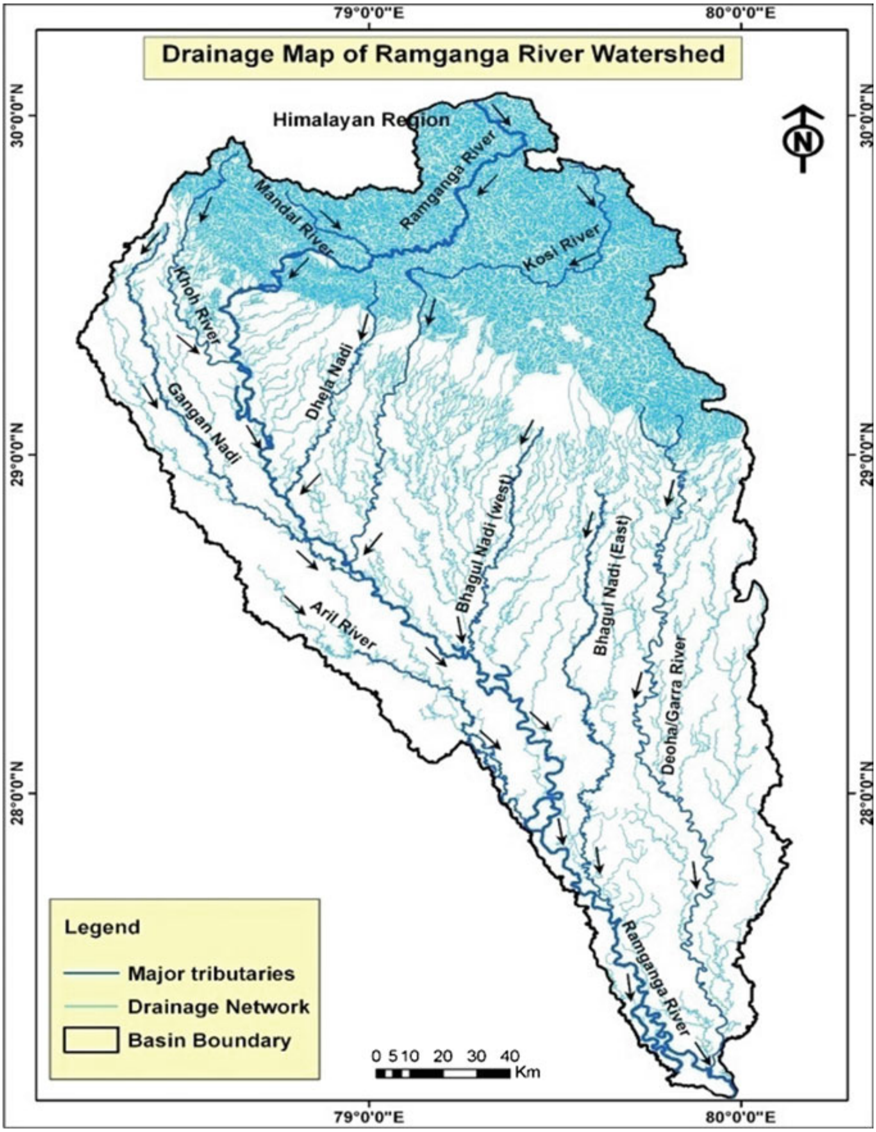

Fig. 3 Maps of Ganga, Brahmaputra, and Meghana Basins (after Mirza 2003)

3.1 Inferences Based on Some Studies

The Kannauj and Moradabad, two important districts falling under the Ramganga watershed, show important and diversified variations subjected to varying

Table 1 Area covered under Ramganga watershed at Uttarakhand

S. No.	District name	Area (km^2)	Total area in Uttarakhand (%)
1	Almora	2511	22.2
2	Bageshwar	25	0.2
3	Chamoli	253	2.3
4	Champawat	58	0.5
5	Nainital	4019	35.5
6	Pauri Garhwal	1985	17.5
7	Udham Singh Nagar	2466	21.8
	Total	11,317	100

Table 2 Area covered under Ramganga watershed at U.P.

S. No.	Name of the district	Area (km^2)	Total area in Uttar Pradesh (%)
1	Bijnor	2727	13.5
2	Moradabad	2303	12.7
3	JP Nagar	342	1.8
4	Bheemnagar	309	1.5
5	Rampur	2328	11.5
6	Budaun	882	4.3
7	Bareilly	4105	17.5
8	Pilibhit	2190	11.2
9	Shahjahanpur	3122	16
10	Farrukhabad	176	0.9
11	Hardoi	1716	8.4
12	Kheri	84	0.5
13	Kannauj	30	0.2
	Total	20,314	100

morphological and chemical characteristics: one is known as brass city of India, and other is the confluence point of Ramganga with the river Ganga.

The water quality of groundwater and surface water shows contamination at various locations of Kannauj and Moradabad districts with heavy metals such as Fe, Mn, Cu, Pb, and Cr. The water pollution in both districts is because of anthropogenic activity (due to industrialization and excessive use of inorganic fertilizers in agriculture practices).

The water potential zones for the districts Kannauj and Moradabad show good potential for recharging and rain water harvesting prospect and can be used for sustainable development with regard to environmental enhancement. The suitable artificial recharge structures such as recharge shaft, recharge pit should be adopted for the abandoned handpumps/ tubewells. Rooftop rainwater harvesting structures (Moradabad district and Kannauj districts) in urban areas should be adopted.

Table 3 Hydrological characteristics of the rivers of the Gangetic plains (Sinha et al. 2003)

River	Type	Total basin area (10^3 km^2)	Average annual discharge (cumecs)	Average sediment load (mt/year)	Discharge area (cumecs/km^2)	Sediment yield (10^3 t/year/km^2)
Ganga (Hardwar)	Mt	95	757	14	8	0.15
Ganga (Kannauj)	Mt	240	1252	15	5	0.06
Yamuna	Mt	366	2949	125	8	0.34
***Ramganga**	**Mt**	**31**	**482**	**10**	**15**	**0.31**
Gomti	PI	30	235	6	8	0.20
Rapti	Ft	20	–	15.6	–	0.78
Ghaghra	Mt	127	2993	125	24	0.98
Gandak	Mt	43	1555	82	36	1.91
Burhi Gandak	PI	10	273	15	27	1.50
Baghmati	Ft	8	189	7	23	0.87
Kamla-Balan	Mx	3	68	8	23	2.67
Kosi	Mt	95	1792	193	19	2.03
Ganga (Farakka)	Mt	648	14,555	729	22	1.125

*Signifies the study area

3.2 *Characteristic of Drainage Basin*

The drainage setup in the entire Ramganga watershed shows variations in association with geomorphological setup comprising of mountain belt, the foothill part, and the fertile Gangetic plain. The drainage network in Ramganga watershed initially shows NE–SW trend and when it enters into Gangetic plain a sharp turn is observed to NW–SE trend which represents the flexure bend and possible path of Ganga plain. The asymmetry in River Ramganga and its tributaries on the left bank shows perpendicular relation to the main Ramganga and gives a straight linear expression in N–NE to S–SW and also reflects high tectonic control in their flow.

Morphmetrically, the Ramganga watershed from its origin point “Diwali Khal” (Gairsain) up to its confluence near Kannauj shows high drainage order up to ninth level. This shows huge development of drainage due to tectonic as well as climatic perturbations. The Ramganga watershed shows varying levels of terrain evaluation and geomorphic setup. This can be observed with the reflection that is subjected along with elevation, in contrast with fine to moderate, and uneven texture of Ramganga watershed (Mountain, Piedmont, and Ganga plain zones).

The elevations also give a reflection of the spatial evolution of the Ramganga watershed and its basin characteristics, as it is observed that the basin has an elongated shape and this shape owes reflection of Ganga basin. The slopes of Ramganga watershed shows ragged topographic that terminates together with sloping surfaces indicating huge variation of geomorphic setup in the entire basin.

There is a positive correlation between the stream order and stream length, and this morphmetric variation in Ramganga watershed shows high degree of asymmetry that can be subjected to subsurface modification of Indian plates with reference to Gangetic plains. This positive correlation indicates the future variation in stream order and stream length will take place. The sub-watershed of Ramganga River in both left and right banks shows high stream order and increased stream length which indicate continuous erosion of the drainage basin.

Effective and efficient water management options need to incorporate both structural and nonstructural measures including water conservation, augmentation of this natural resource (especially groundwater assets by artificial recharge techniques). The integration of watershed study with development may be a beginning to initiate watershed level studies in terms of quantitative as well as qualitative standards.

3.3 Socioeconomic Impact

At the confluence of Ramganga and Kalagarh River an embankment dam has been constructed 3 km upstream of Kalagarh River in Pauri Garhwal which is also known as Kalagarh Dam. This dam is built in the project of “Ramganga Multipurpose Project” for the irrigation and hydroelectricity, which affect the social and economic values of the population. The alluvium of Ramganga River is best suited for sugarcane crop, and all the major sugar industries are situated on the cities along which the Ramganga River is drained. Except sugarcane, wheat, rice, and potato crops are also cultivated in this alluvium.

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The Yamuna River: Longest Tributary of Ganga

Nishat and Dhruv Sen Singh

1 Introduction

The Yamuna River, a major right bank tributary of Ganga, originates from the Yamunotri glacier near Banderpoonch peaks in the higher Himalaya at an elevation of about 6387 m amsl (Fig. 1). It is the largest tributary of Ganga River and related with a Hindu God, Lord Krishna. It travels a distance of about 1370 km in the alluvial plains through Uttarakhand, Uttar Pradesh, Himachal Pradesh, Haryana, Rajasthan, Madhya Pradesh and Delhi, and finally joins the Ganga at Allahabad (Fig. 2a, b). The Yamuna enters the plains at the Dak Pathar, up stream of Ponta Sahib (a famous religious place of Sikha).

Draining the southern slopes of the Himalaya in its upper reaches, the Yamuna River flows through the vallies carved by glaciers during the last ice age. The slope gradient of the river is steep in this part. In the upper stretch of 200 km, it receives water from many tributaries such as Rishi Ganga, Kunta, Hanuman Ganga, Tons and Giri. Yamuna River Basin covers about 35.4% area of the Ganga Plain, which are densely populated and thickly vegetated. The catchment area of the Yamuna River lies in the Himalaya, Peninsular Plateau and the Ganga Plain. The catchment area of the Yamuna River is about 40.2% of the Ganga Basin (CPCB 2006).

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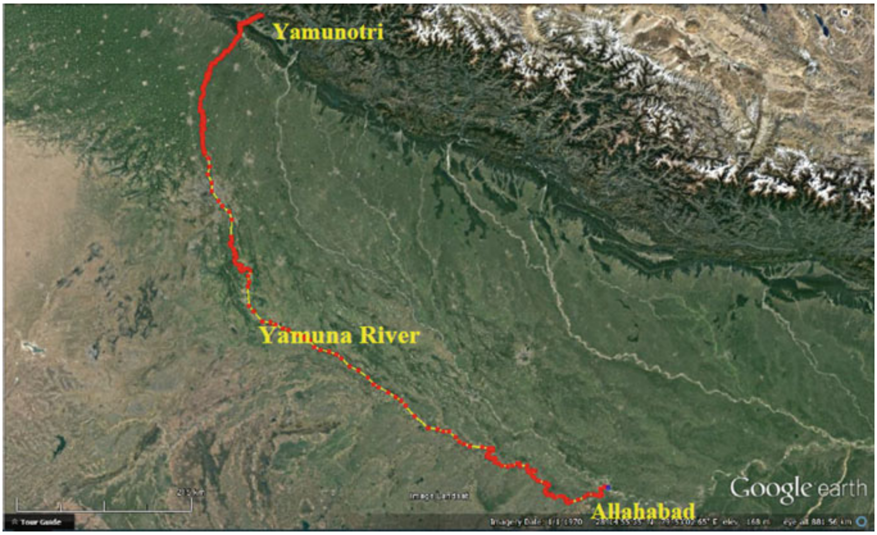

Fig. 1 Location map of the Yamuna River on Google satellite data

2 Climate

The Yamuna River Basin is confined to alpine, subalpine, temperate and subtropical vegetation in the Himalaya, Peninsular Plateau and Ganga Plain. The mean annual temperature during day time varies from 30 to 35 °C with a maximum of ~40 °C in summers and a minimum of ~18 °C during winters. The rainfall is controlled by south-west monsoon with a maximum rainfall during July and August. The discharge of the river is controlled by monsoon. During non-monsoon period (October–June), the discharge of the river reduces significantly and some part of river stretch becomes dry, whereas during monsoon period (July–September), the discharge of the river increases significantly.

3 Geomorphology

Physiographically, India is classified into three: the Himalaya in the north, Peninsular Plateau in the south, the Indo-Gangetic Plain in between. The Indo-Gangetic Plain is the largest alluvial deposit and most densely populated plain

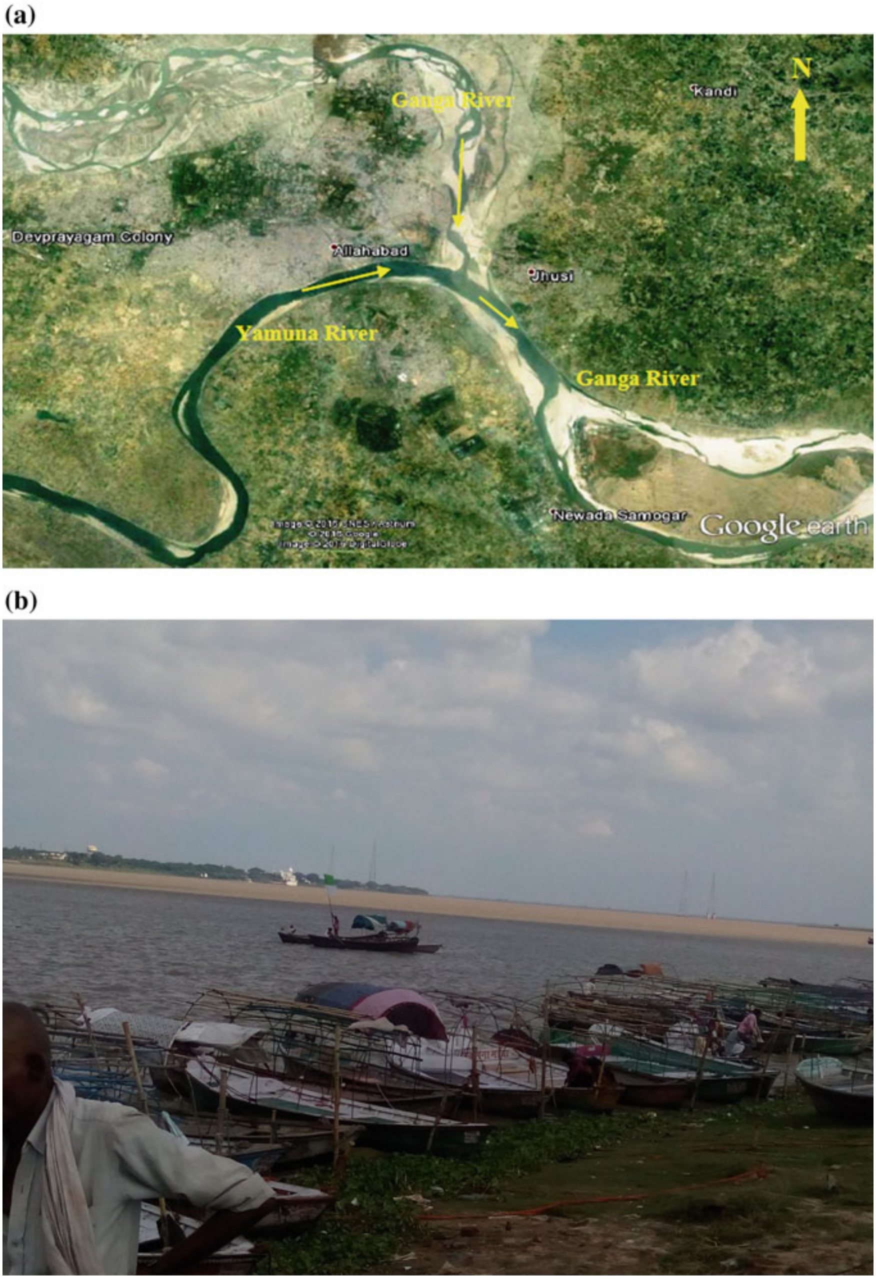

Fig. 2 **a** Confluence of Yamuna with Ganga at Allahabad, Uttar Pradesh in Ganga Plain, **b** Confluence of Ganga and Yamuna forming Sanagam at Allahabad, Uttar Pradesh in Ganga Plain

in the world which was formed by the deposition of terrigenous clastic sediments from streams of the Indus, Ganga and Brahmaputra River systems (Singh 2001). The Ganga Plain is the central part of the Indo-Gangetic Plain (Singh 1996)

The Yamuna River Basin is divided into six geomorphic subdivisions such as Yamuna-Ganga mega fan, Piedmont zone, Marginal plain upland surfaces, Upland interfluve surfaces (T_2), River valley terrace surfaces (T_1) and Active flood plain surfaces (T_0) (Fig. 3). Each geomorphic unit contains the micro-geomorphic elements such as ox-bow lakes, point bars, braid bars, cut-off meanders, sand ridges, ponds and lakes. The river is geomorphologically and tectonically active (Goswami et al. 2009) and is tending to recover its natural size. Yamuna River Basin is in the mature stage of topography and evolution of fluvial system. The region of the Yamuna River is famous for the well-developed ravines (Fig. 4).

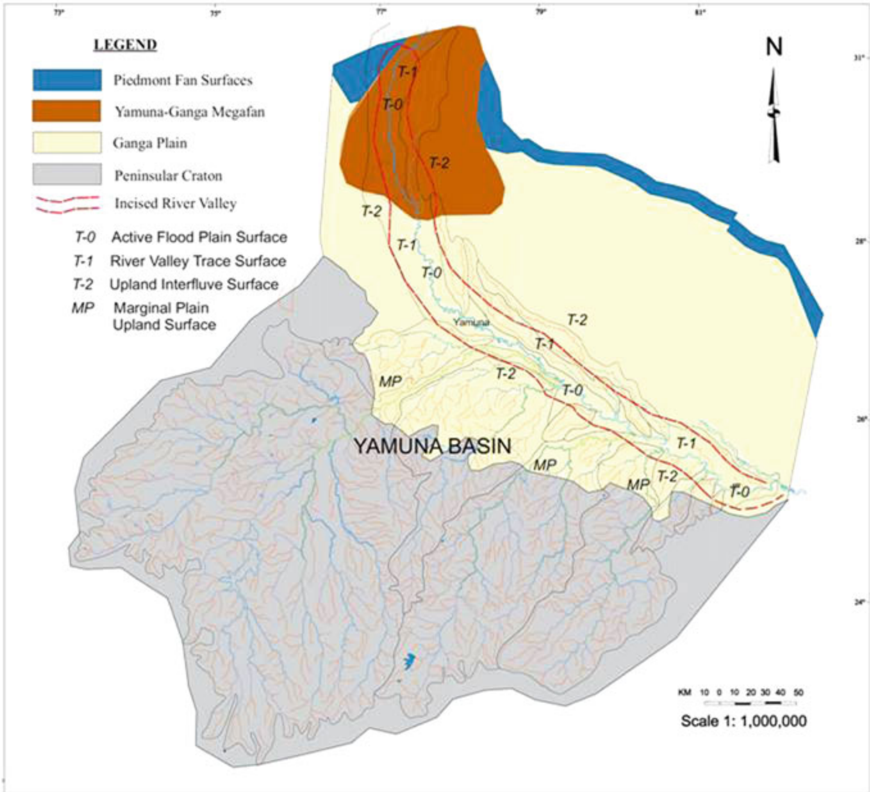

Fig. 3 Geomorphological map of Yamuna River Basin with catchment area and different geomorphic surface

Fig. 4 Ravines in Yamuna River Basin and Ganga Plain

4 Morphometry

Yamuna River Basin is a sixth order drainage basin and its drainage pattern is characterized by dendritic in southern part tributary and parallel type in northern part. Yamuna River Basin consists of nine tributaries out of which four tributaries contribute from north, left bank such as Hindon, Karwan, Sirsa and Arind, and five from south right bank Gambhir, Chambal, Sind, Betwa and Ken. Their catchment area lies in the Ganga Plain as well as the in Peninsular region. Each left bank northern tributary basins (NTB) and right bank southern tributary basins (STB) are separated by a drainage divide. It is a topographic ridge separating two adjacent drainage basins. Each one of these tributaries has its own catchment area and tributary system. Each tributary basin is distinct in size, shape and catchment area having similarity in some aspects such as drainage pattern, drainage density and texture (Strahler 1964).

It is important to mention here that the drainage areas of above left bank tributaries are much smaller as compared to the drainage area of right bank tributaries of Yamuna River which are only 6% of the total area. The right bank tributary basins are Gambhir, Chambal, Sind, Betwa and Ken, in which tributary basins of Gambhir and Chambal are located in west and south-west direction in the Yamuna River Basin. Perimeter is the length of the drainage divide or boundary of the basin which is drawn from the topographical maps (Strahler 1964). Perimeter of (northern) left bank tributaries ranges from 335 to 670 km and for (southern) right bank tributaries it ranges from 730 to 2750 km. It illustrates that southern portion of the basin is stretched over large area. The basin length for northern left bank tributaries ranges from 150 to 310 km, and it is parallel to the main drainage line, and for southern right tributaries, it ranges from 289 to 570 km.

The geomorphic evolution of the Yamuna River Basin is governed by its drainage basin characteristics including drainage basin area, relief, slope, subsurface geology and prevailing environment. Morphometric analysis provides the characteristics of drainage morphology in response to changing fluvial characteristics with changing climate conditions. The range of order for northern tributary basins (NTB) is 2–3, whereas it ranges from 4 to 5 for southern tributary basins (STB). The area occupied by the NTB is less than the STB. This shows that the southern right bank tributary basins (STB) are highly asymmetric. The drainage density is low and texture is very coarse. The drainage texture (T) and circularity index (*Rc*) indicate that channels are located away from each other and the drainage network is dendritic. The average bifurcation ratio (*Rb*) of most of the river basins is in the normal range (3–5). It explains that the drainages are natural and not influenced by the geological structures (Singh and Awasthi 2011a, b). The drainage density is low and texture is very coarse for the Yamuna River basin. Morphometric map of Yamuna River Basin is given in (Fig. 5). The characteristics of the drainage basins of Yamuna River and range of values are given in Table 1 and irrigation canals in Yamuna river basin in Table 2.

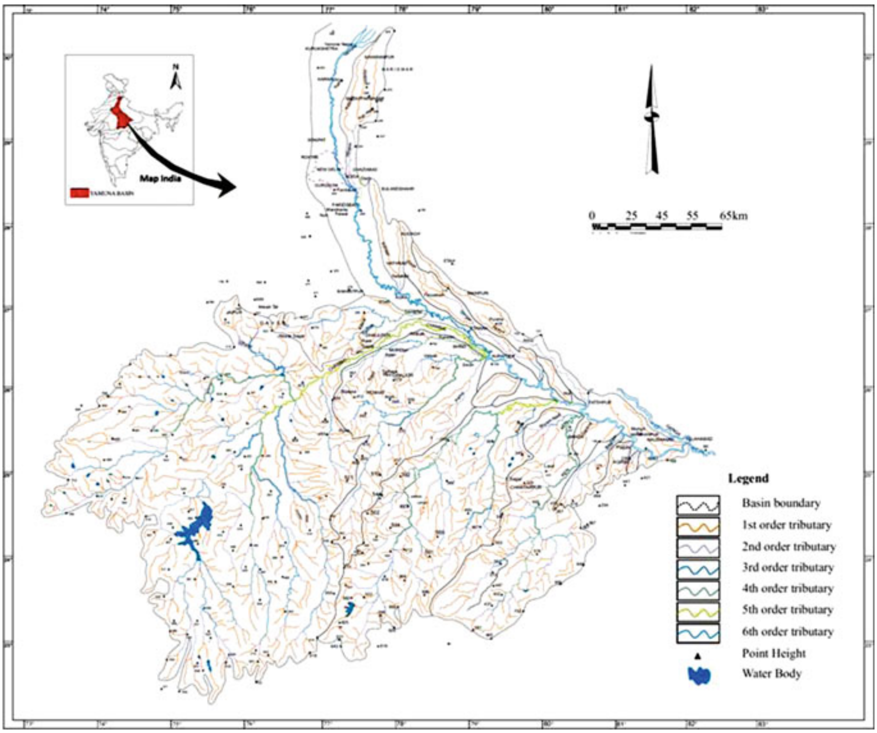

Fig. 5 Morphometric map of Yamuna River Basin

Table 1 Basin characteristics and range of values for drainage basins of Yamuna River

Basin characteristics	Range in values
Basin area	330682.437 km^2 (covering Southern Ganga Plain including peninsular craton i.e. peripheral bulge)
Strahler order	1–6
Length of overland flow	4.43–7.94 km
Basin length	150.00–570.90 km
Total stream length	226.2–12931.8 km
Basin relief	49–709 m
Relief ratio	0.001–4.66
Highest point in basin	854 m on basin perimeter of Chambal
Highest point on basin perimeter in plain	854 m on western drainage divide of Chambal basin in South
Lowest point in basin	90 m at confluence of Yamuna with Ganga
Main channel change in elevation	603–90 m

Table 2 Irrigation Canals in Yamuna River Basin (modified after CPCB 2006)

Canal	Origin	State
Western Yamuna Canal (WJC)	Right bank of Yamuna River at Hathnikund/Tajewala barrage	Haryana
Eastern Yamuna Canal (EJC)	Left bank of Yamuna River at Hathnikund/Tajewala barrage	Uttar Pradesh
Agra Canal	Right bank of Yamuna River at Okhla barrage	Two districts of Mathura and Agra in Uttar Pradesh
Gurgaon Canal	Takes off from Agra canal at a distance of around 8 km from its off take at Okhla barrage	Interstate project between Rajasthan and Haryana

5 Surface and Subsurface Facies

The surface deposits become subsurface due to subsidence and subsequent deposition over it. The ability to store sediments within sedimentary basin depends on the accommodation space available and supply of sediments, which is controlled by fluvial dynamics and gradient of the alluvial river valley in direct response to climate and tectonics (Singh et al. 2009). Each alluvial successions describes the geometry, proportion and spatial distribution of different types of fluvial deposits. Mega-geomorphology and sedimentation pattern near Kalpi has been described by Sinha et al. (2002).

Surface facies were identified on the basis of cliff sections exposed on the bank of Yamuna River. Three surface facies were identified (Fig. 6). Facies I is characterized by lower most unit and consist of light-brown clayey silt with

Fig. 6 Cliff section on Yamuna River Bank near Kalpi, Uttar Pradesh and Ganga Plain

medium-grained sand, mottled silt with calcrete. The mud-dominated succession of this facies is comparable to the facies of upland terrace surface of the central Ganga Plain. Facies II is 12–35 m thick which is characterized by coarse sand, gravel and calcrete with grey coloured fine-grained sand along with micaceous content. Facies III is composed of fine to medium-grained sand with lenses of mud. These units are characterized by mottled, fine-grained sand and interrupted by thin bands of mottled silt and clayey silt. Singh et al. (1999) has described the three facies from the cliff exposed on Yamuna bank at Kalpi.

Three types of depositional domains are identified in the right and left bank of Yamuna River: (i) upland interfluves terrace surface (T_2), (ii) river valley surfaces (T_1) and (iii) active flood plain surfaces (T_0).

On the basis of subsurface data of Central and State Groundwater agencies, three subsurface facies has been identified: (a) sandy gravel (b) silty sand and (c) silty clay.

6 Natural Hazard

The Yamuna River Basin is affected by many natural hazards. The Himalayan part of this basin has the problem of landslides due to slope failure and hill slope erosion in direct response to mass movement which is triggered by rain. Many cities such as

Delhi, Allahabad and their adjoining areas are adversely affected by flood almost every year. The industrial and urban domestic waste has polluted the river at Delhi, Mathura, Agra and Allahabad. The illegal land mining is also one of the major problems. The soil erosion which forms the ravines is a major hazard to the people of this region.

7 Socio-economic Importance

The Yamuna River is related with Lord Krishna and so it has a special place in Hindu religion. Taj Mahal one of the seven wonders of the world is located in Agra at the bank of Yamuna River and attracts tourists from all parts of the world (Fig. 7). Delhi the capital of India is also located on the bank of Yamuna River. Yamuna River Basin is one of the most densely populated regions due to high fertility of soil and availability of water and hence plays a critical role in human society as a major source of fresh water, water ways transportation and water resources. Yamuna Basin has been considerably affected by these human activities ranging from agriculture to industries. River banks are suitable, ideal places for settlement from ancient times, which have now evolved as big cities. These cities in its catchment areas are dependent on it for a combination of economic and social purposes.

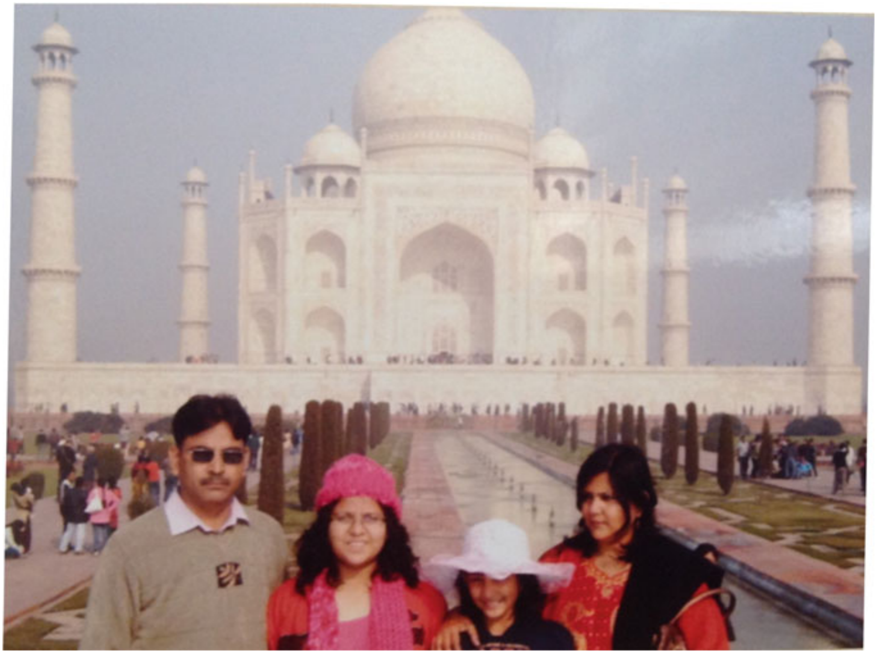

Fig. 7 Taj Mahal wonders of the world located at the bank of Yamuna River in Agra

Yamuna River reaches Hathnikund/Tajewala in Yamuna Nagar district of Haryana state, where western Yamuna canal and eastern Yamuna canal have been constructed for irrigation. During summer, water is not allowed to flow in the downstream part of the river to Tajewala barrage and so the river is dry in some stretches between Tajewala and Delhi. The Yamuna enters Delhi near Palla village. For supplying drinking water to Delhi, a barrage has been constructed at Wazirabad. Water is not allowed to flow beyond Wazirabad barrage during summer due to insufficiency of water to fulfil the demand of water in Delhi. Again at Okhla, there is a barrage.

Irrigation is the major way of harnessing the water of the Yamuna River. About 92% of the water of the Yamuna River is used for irrigation. There are four canals for irrigation to transport the water of Yamuna River to the command areas.

The important cities located at the left bank of the Yamuna river are Karnal, Panipat, Sonipat, New Delhi, Faridabad, Mathura, Vrindavan, Agra, Kalpi, Hamirpur, Mau and Naini (Allahabad) and those at the right bank are Saharanpur, Shamli, Baghpat, Delhi, Noida, Gautambudha Nagar, Sikandarabad, Hirangaon, Firozabad, Etawah, Auraiya and Allahabad.

8 Conclusion

The tributaries of the Yamuna River are either rain-fed or ground water-fed rivers. In this area, there is a huge demand of water and so that water management is important. We can utilize these areas for thick vegetation, rain water harvesting and recharging the ground water table for better land and water management.

It is required to strengthen the mechanism and management for the effective control of water pollution from point source by socio-economic aspects and law enforcement measures.

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The Gomati River: Lifeline of Central Ganga Plain

Anjani K. Tangri, Dhirendra Kumar, Dhruv Sen Singh and Chetan Anand Dubey

1 Introduction

Gomati is one of the major groundwater-fed rivers of Ganga Plain. In mythology, it is believed that the Gomati River is the daughter of Sage Vashistha. During solar eclipse, devotees believe that taking a bath in the Gomati is equivalent to the bath taken in the river in Kurukshetra.

It originates from Gomath tal (formerly known as Fulhar *Jheel*) (Fig. 1) near Madho Tanda town of Pilibhit district. After traveling a distance of about 940 km. through the Pilibhit, Shahjahanpur, Hardoi, Sitapur, Lucknow, Barabanki, Sultanpur, Jaunpur, and Ghazipur districts of Uttar Pradesh (Fig. 2) and finally drains into Ganga River near Saidpur/Kaithi in Ghazipur district of Uttar Pradesh (Fig. 3). The place of origin is located near the Piedmont zone of the Ganga Plain.

A total of 23 major and minor tributaries contribute to Gomati River from its origin to its confluence (Fig. 4). After traveling 20 km from its origin, a very small river Gaichi (Gaihaaee) is the first tributary of Gomati River. Gomati River continues to be a narrow stream until it reaches Mohammadi Kheri (Tehsil of Lakhimpur Kheri district and about 100 km away from Gomati's origin) where it is joined by some tributaries such as Sukheta, Chuha, and Andhra Chuha, and from this location, the river is well defined. Further downstream, other tributaries join

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Fig. 1 Photograph showing origin of Gomati River, Gomath tal near Madho Tanda, Uttar Pradesh

this river such as Kathana River at Mailani and Sarayan River at Lakhimpur. Sai River is the major tributary of Gomati River which joins to Gomati River near Rajepur in Jaunpur district. The Kukrail nala and Behta nala are the fourth order tributary, which joins the Gomati River at Lucknow (Kumar et al. 2015). At the confluence of Gomati River with Ganga River near Kaithi, famous Markandey Mahadeo temple is situated.

The flow of Gomati River is characterized as sluggish throughout the year, except during the monsoon season when heavy rainfall causes manifold increase in its runoff. Thus, the Gomati River receives its maximum water budget in monsoon season. The annual discharge of river is about $7390 \times 106\ m^3$ (Rao 1975). During rainy season, river level and flow velocity increases, this huge amount of water overtops the banks and results in the flooding of the low-lying part of the basin. During flood time, the water level of the Gomati River rises and falls about 3 m per year.

2 Gomati River Basin

The Gomati River basin is an elongate basin draining more than 30,000 km^2 area within Ghaghara–Ganga interfluve (Doab) region, in central part of the Ganga Plain and situated between 80° 00′ to 83° 10′E longitudes and 24° 40′ to 28° 40′N

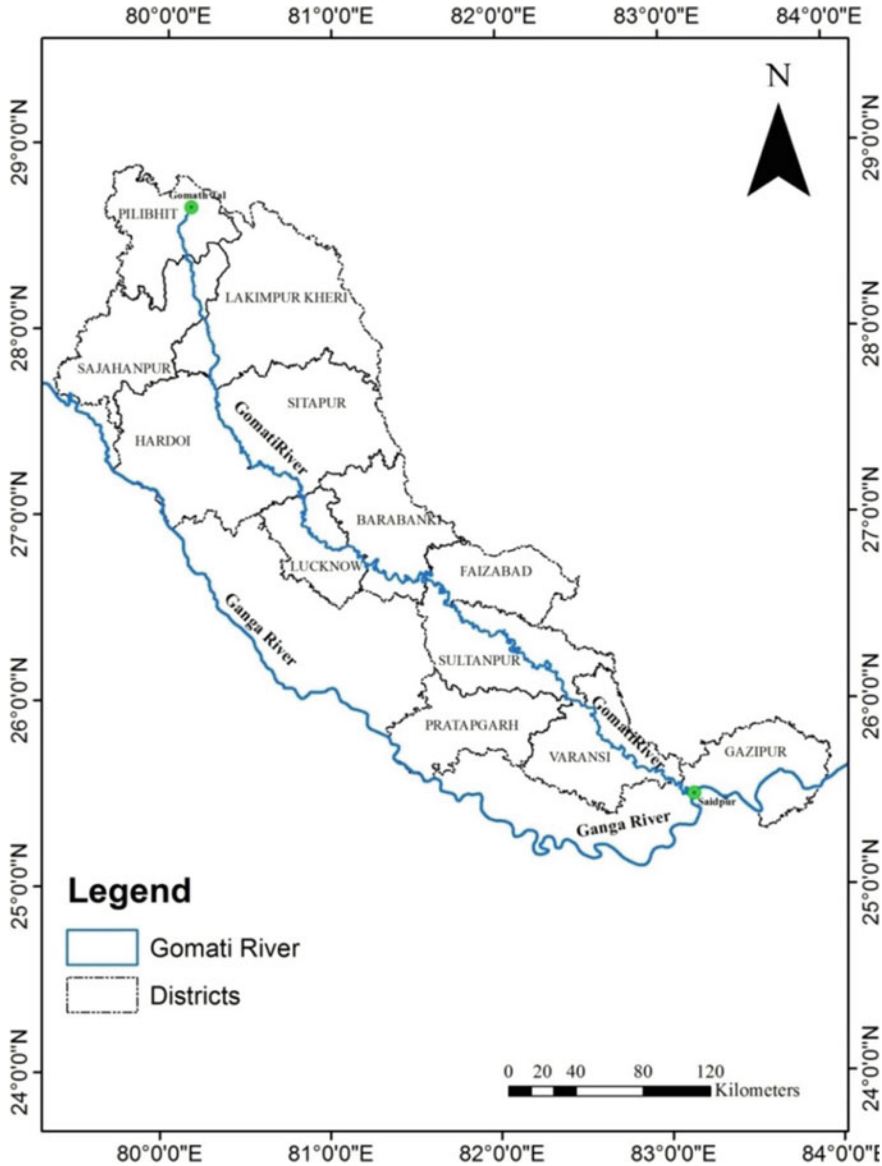

Fig. 2 Map showing districts along which Gomati River flows

latitudes. The upper part of the basin includes Pilibhit, Lakhimpur Kheri, and Shahjahanpur district while the central part includes Hardoi, Sitapur, Barabanki, Lucknow and Unnao districts, and Faizabad, Raebareli, Sultanpur, Pratapgarh, Jaunpur, and parts of Varanasi district of Uttar Pradesh fall into lower part of

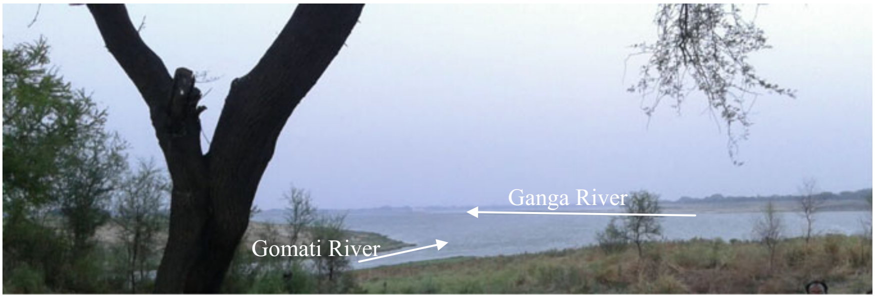

Fig. 3 Photograph showing confluence of Gomati River with Ganga River near Saidpur, Uttar Pradesh

the basin. The general trend of the basin is NW–SE, nearly parallel to Himalayan front.

The basin is essentially composed of unconsolidated sediments produced by weathering and erosion of the Himalayan and Peninsular rocks. Lithologically, the surface sediments are composed of inter-layered, 1–2 m thick, fine sand and silty mud deposits showing extensive discontinuous concrete horizons (Singh 1999). These sediments are exposed in the cliff sections along the Gomati River.

2.1 Climate

Koppen's classified the whole Indo-Gangetic Plain into the humid subtropical climate (*Cwa* system). The *Cwa* system is a unique classification, and it is applicable for Indo-Gangetic Plain only. The river basin experiences the three major seasons annually viz. winter, summer, and monsoon. The winter season starts from November to February, and it downs the mercury to near about 2–22 °C. Winter season experiences the cold wind of Siberian origin and receive very low rain fall. Most of the rainfall during this season is a result of cyclonic disturbances or westerlies only. Winter season slowdowns the process of weathering (either chemical or mechanical) and erosion. Summer season starts with the beginning of March and continues up to the mid-June. In summer season, mercury fluctuates in between 28 and 44 °C and most part of the basin experiences the hot local wind known as the *loo*. The cyclonic rainfall gives some relief to human beings in summer season. During this time, weathering and erosional processes are governed mainly by the wind action. The monsoon season starts from June and continues up to the mid-September. During this time, the humidity is very high and most part of the basin experiences heavy rain. Heavy rain advances the velocity and sediment

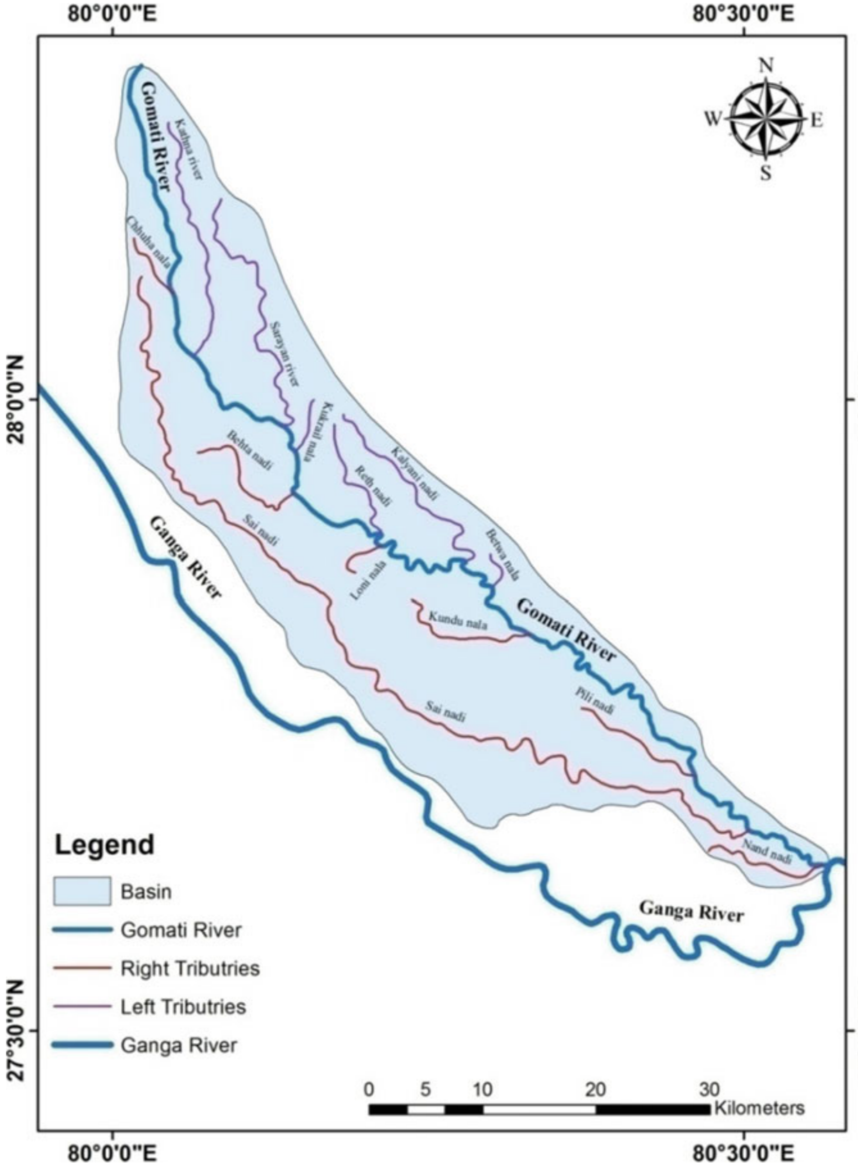

Fig. 4 Map showing major tributaries of Gomati River

supply of the river, which influences the process of weathering and erosion; these processes develop and modify most of the geomorphic features of the basin.

3 Geomorphology

The basin of the Gomati River exhibits three regional geomorphic surfaces such as (1) active flood plain surface (T0), (2) river valley terrace surface (T1), and (3) upland terrace surface (T2) (Fig. 5). Each geomorphic surface of the basin

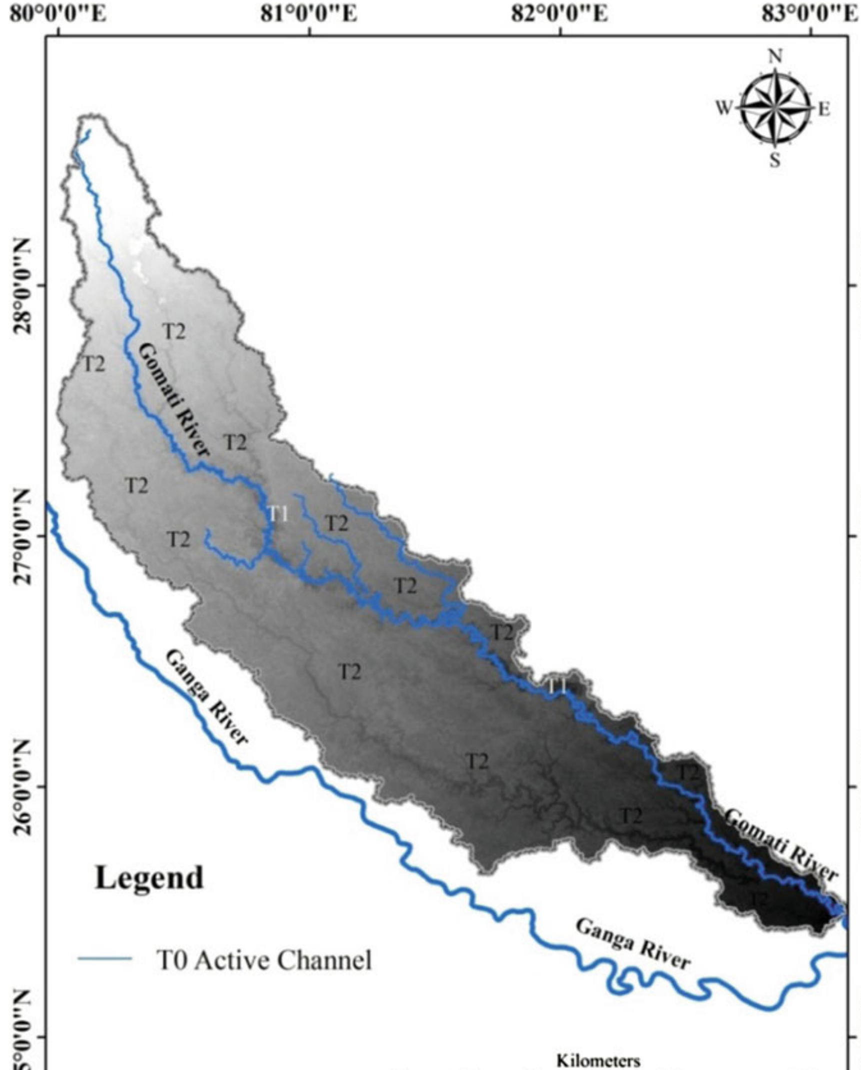

Fig. 5 Map showing major geomorphic surfaces of Gomati River basin

contains various micro-geomorphic features such as ponds, lakes, meander scars, palaeo-channels, and ox-bow lakes. Active channel of Gomati River exhibit crescent shaped point bar deposits, of which the dimensions are highly variable from one point to another point (Fig. 6). The number and size of bar deposits increases in the lower segment of the river.

3.1 Digital Elevation Model (DEM)

The Digital Elevation Model (Fig. 7) of Gomati River basin shows maximum elevation of 213 m in the Piedmont zone of Ganga Plain and minimum elevation of 58 m near the confluence point with Ganga River.

4 Hazards

Gomati River basin is affected by two types of hazard: (1) natural hazards and (2) anthropogenic hazards

4.1 Natural Hazard

Floods are one of the most common river-borne hazards which affects the life of millions of people directly or indirectly every year. According to Foster (2000), although floods cause less loss of life than earthquakes, drought, and cyclone but have a significant impact upon homelessness in comparison with other natural hazards. Historical record suggest that the flood could be one of the strongest causative factors behind the extinct of Harappan civilization.

India is one of the most flood-affected countries in the world. Uttar Pradesh is one of the most flooded states in India, the other four being Bihar, West Bengal, Assam, and Orissa. Uttar Pradesh has experienced massive flooding in 1998, 2000, 2001, and 2008. It is estimated that 30 districts of this state are seriously prone to flooding. The incidence of flooding is frequent in the rivers of Ganga Plain, which is broadly the result of spilling of rivers such as Kuwana, Rapti, Chhoti Gandak, Ghaghara, and Great Gandak (Singh 2007, 2009).

Singh et al. (2015) have described all the possible reasons for flooding in Rapti River and proposed a model that when the flood will be catastrophic. The water depth map, flood rating curve, and flood recurrence interval can be used to forecast and forewarn the society.

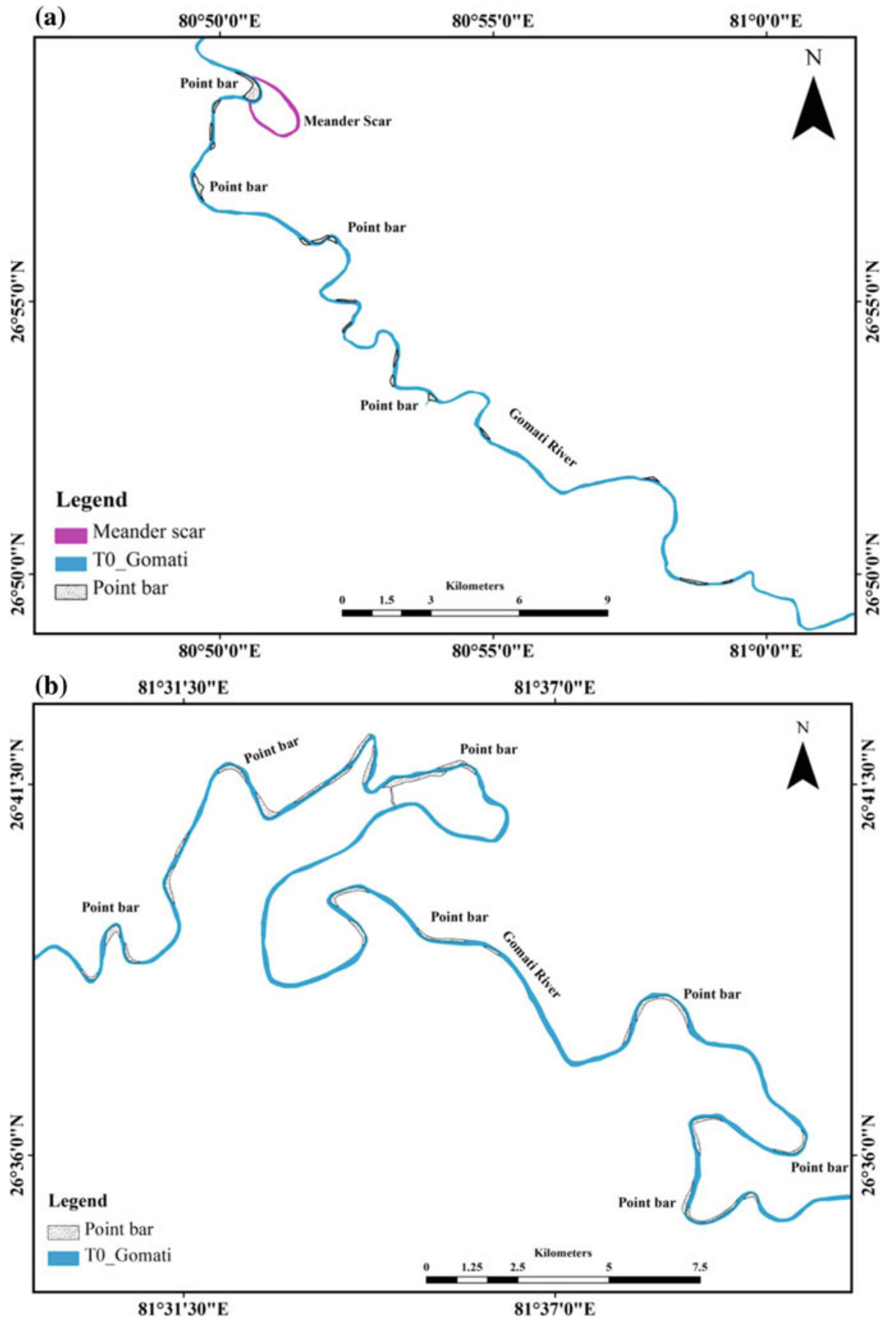

Fig. 6 Map showing geomorphology of active channel of Gomati River

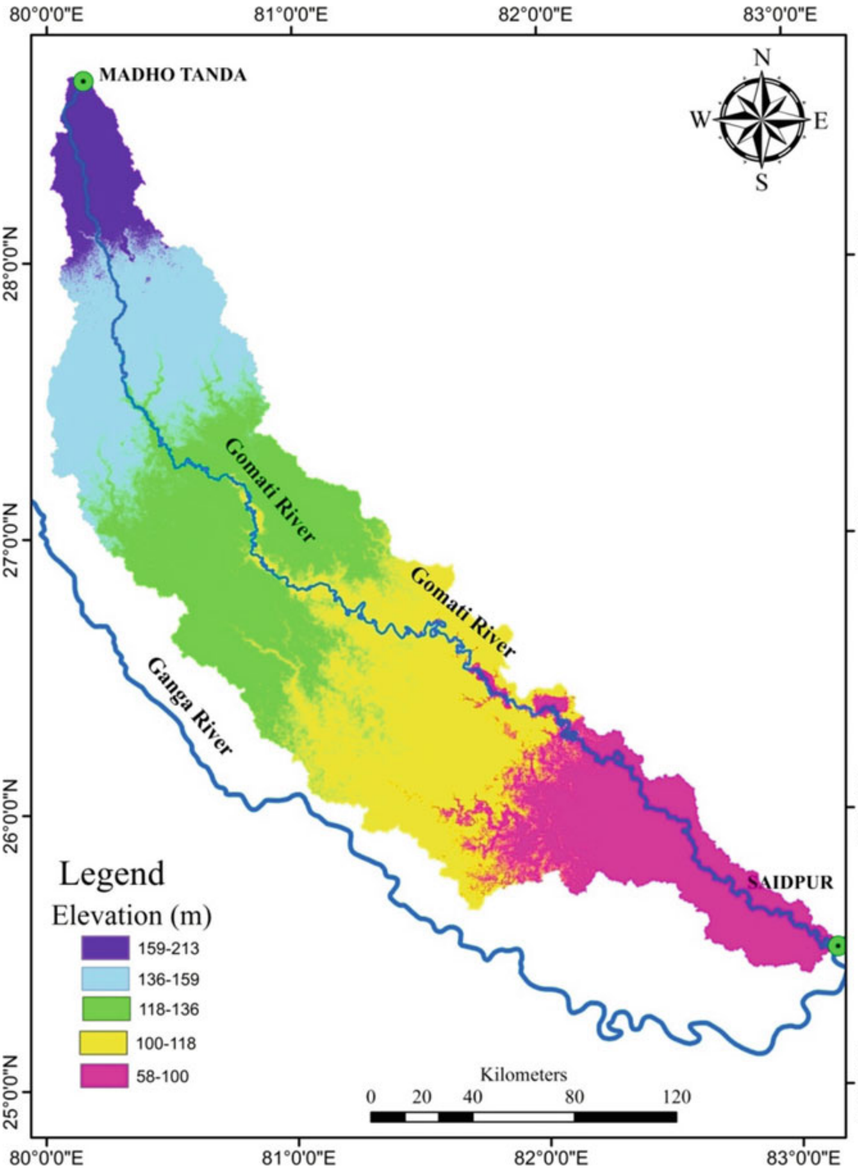

Fig. 7 Map showing the digital elevation model (DEM) of Gomati River basin

4.1.1 Flood in Gomati River

It is evident that the Gomati River has very sluggish water flow, low runoff, and low water budget throughout the year, however during the monsoon season; the heavy rain brings the situation of catastrophic flood in the low-lying area. Since, there is a

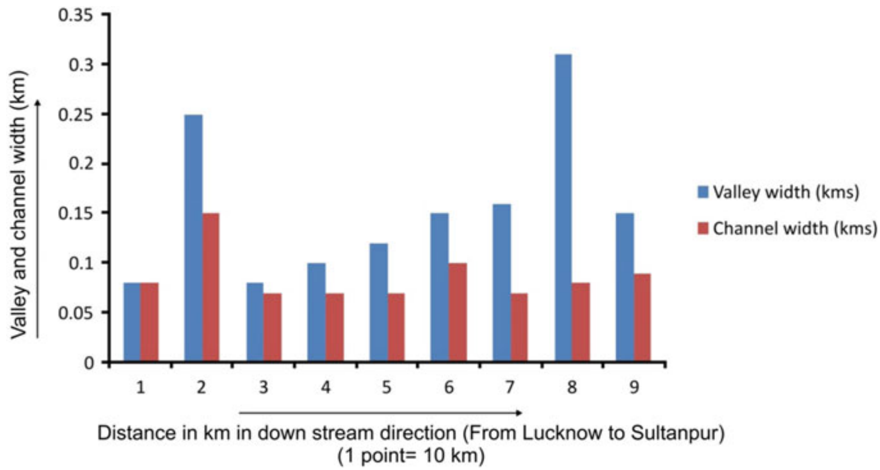

Fig. 8 Graph showing valley width and channel width ratio of Gomati River

not much difference between the valley width and channel ratio of the Gomati River (Fig. 8); therefore, at the time of heavy rain, water easily over tops or crosses the bank of the river and brings situation of catastrophic flood. The highest flood was recorded on September 13, 1894, when river water rose to a height of 1.4 m above normal high flood level and maximum discharge was 234,000 cubic feet per second (Chandra 2000).

4.1.2 Lateral Erosion

Generally, only one river-borne hazard is known that is flooding; however, while working on the Ganga Plain Rivers, it is observed in the field that the lateral erosion is also operating as an independent fluvial hazard (Singh and Awasthi 2011). The textural immaturity of the soil is one of the most prominent causative factors behind the lateral erosion by any river of Ganga Plain.

4.2 Anthropogenic Hazard

Gomati River suffers from the problem of contamination of water in most part of the area; it suffers mainly the problem of dumping of industrial waste related from sugar factories, distilleries, and domestic waste related to sewage and dumping of garbage. The river water near Lucknow region mostly suffers from the problem of oxygen level deficiency, and it affects the ecosystem of aquatic life. At present, about 25 km distance of the river from its origin has been dried and the experts of the various countries are trying to save the origin of Gomati. It is believed that the heavy silt deposit and depletion of groundwater table are the main cause behind this situation.

5 Socio-economic Importance

It is well known that the Ganga Plain is one of the most fertile lands in world and made up of Quaternary alluvium. The Gomati basin contains mostly two type of alluvium, the older alluvium (Bangar) and the younger alluvium (Khadar) (Singh 1996). The soil of Gomati River basin is very fertile and favorable for all type of seasonal crops, i.e., Rabi, Kharif, and Jayad and best suited for various crops such as sugarcane, wheat, rice, maize, and banana. The soil of Gomati–Kalyani interfluve is most suitable for menthol, opium crop, and this region is the leading producer of these two crops. Instead of fertility, the water of the Gomati River fulfills the basic needs of more than twelve districts of Uttar Pradesh including the capital Lucknow.

5.1 Major Canal Network in Gomati River Basin

The Sharda River water is impounded at Banbasa Barrage in Nainital district of Uttarakhand, from where the main Sharda canal originates. This main Sharda canal is further bifurcated into three branches in Pilibhit district. These three branches are:

- The Main Hardoi Branch
- Kheri Branch
- Feeder channel which feeds the Sharda Sagar

Sharda River water is stored in the Sharda Sagar, and a subsidiary Hardoi branch canal is taken out from the zero point of the Sharda Sagar. The area where the feeder canal meets the Sharda Sagar and the subsidiary Hardoi branch is taken out from the Sharda Sagar is known as Zero point of the Sharda Sagar reservoir. The upstream side of the Sharda Sagar reservoir is known as the tail point. Another feeder canal is drawn out from the main Sharda canal and feeds water to the Sharda Sagar reservoir from its tail point.

The Hardoi branch and the Kheri branch of the Sharda canal along with its tributaries and minors traverse the entire Gomati River basin. The Kheri branch of the Sharda canal further bifurcates into the Kheri branch and Sitapur branch.

The major canal network of the Gomati River basin consists of the Hardoi branch, Kheri branch, Sitapur branch, Sandila branch, Sultanpur branch, Jaunpur branch, Lucknow branch, and Mariyahau branch of the Sharda canal. These branches further bifurcate into a number of its distributaries (disty), namely the Maholi disty, Misrikh disty, Banaura disty, Bharawan disty, Jindana disty, Nawabganj disty, Chilbila disty, Chanda disty, Ramganj disty, Peng disty, Pihani disty, Bhadaicha disty, Pandarwa disty, Amethi disty, Dih disty, and Jethwara disty. Instead of these major canal networks, some multiple minors also contribute in draining the entire Gomati River basin. As such, the wide network of canal system and its distributaries and minors cover up the entire Gomati River basin (Fig. 9)

5.2 Gomati River in Lucknow

After approximately traveling 240 km distance from its origin, the Gomati River enters Lucknow, through which it meanders. Lucknow is situated on 26° 52′N latitude and 80° 56′E longitude and above 124 m from mean sea level. The urban center covers an area of about 250 km^2, which is expanding year after year at an exponential rate. As it enters Lucknow, water is lifted from Gomati River at Gaughat pumping station for the city's water supply. As many as 28 city drains in the Lucknow area drain untreated sewage water into the Gomati, thereby badly polluting it. At the downstream end of the Gomati in Lucknow city is the Gomati Barrage which impounds the river, converting it into a stagnant lake.

The river, which is a major source of drinking water for the people of Lucknow, is polluted the most owing to the daily discharge of millions of liters of untreated domestic waste. Besides Lucknow, the river also supplies drinking water to 14 other towns located on its banks including Lakhimpur Kheri, Sultanpur, and Jaunpur.

The Gomati River is the main source of water supply to the Lucknow Urban Centre. At Lucknow, the available discharge in the Gomati River is around 500 MLD during lean period, while in the monsoon period; the discharge reaches around 55,000 MLD. For most part of the year, the discharge on an average is around 1500 MLD only. Lucknow urban area has around 407 tube wells (Uttar Pradesh Jal Nigam, 2005). These 407 tube wells produce around 190 MLD of water. Various private colonies and institutions have installed about 100 tube wells to fulfill their water requirement. The post monsoon season is associated with the depositional phase of the river due to low water discharge.

In 1960, Lucknow recorded its highest flood level at 113.2 m with large parts of the city being inundated. To protect the habitations, earthen embankments have been constructed all along the bank of the river as well as on Kukrail nala, to a top level of 114.4 m. In case of heavy rains and floods, the pumping stations pump storm water across the embankment into the river so as to prevent water logging in the city. A part of Lucknow urban area, the Gomati Nagar settlement is located on the Gomati River flood plain and as such water logging does occur in some localities during rains. Except in years of abnormal rainfall, the Gomati gives no trouble, yet damage is frequently caused by floods and their consequent effects.

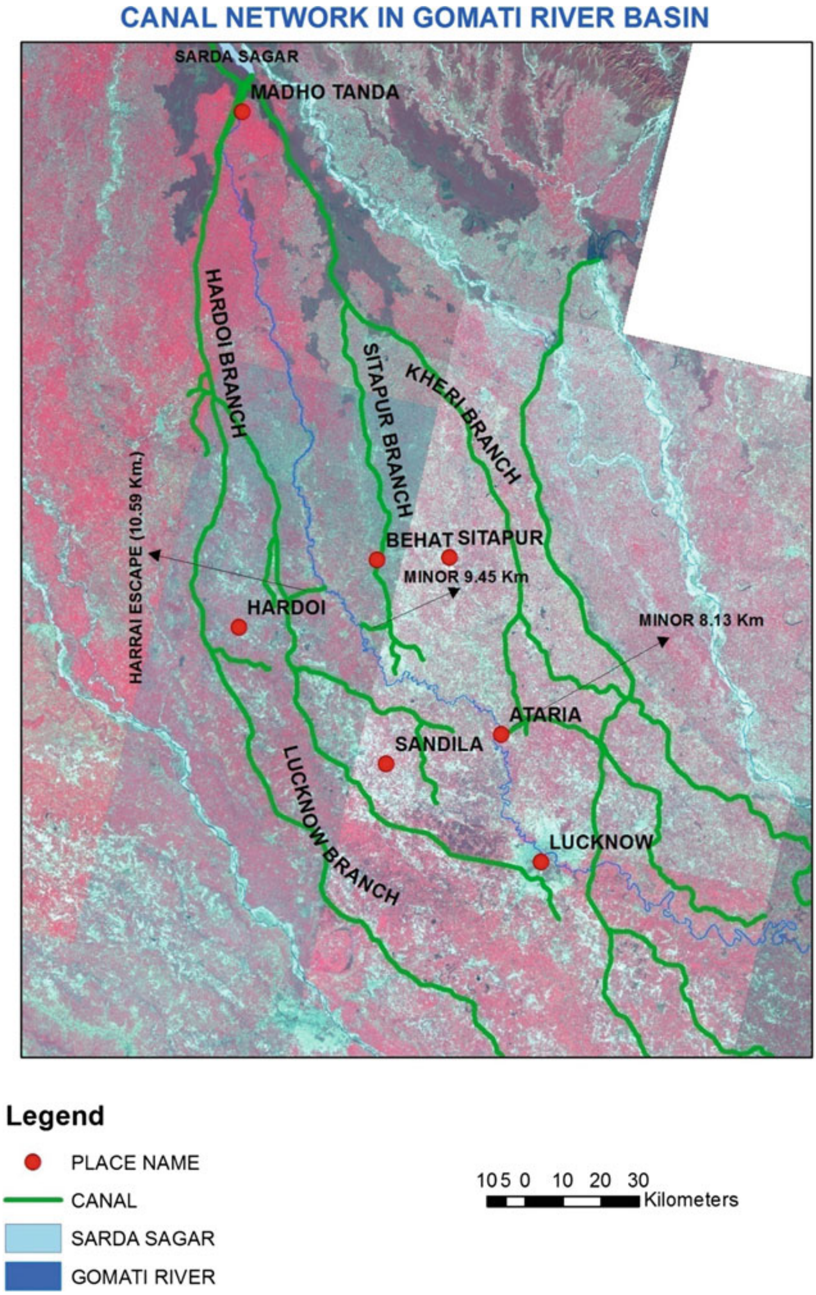

Fig. 9 Satellite imagery showing of canal network in Gomati River basin

5.2.1 Drains and Their Discharge

There are 28 major drains, 14 are present on the Cis-Gomati area, i.e., the southern part and 14 are present on Trans-Gomati area, i.e., the northern part of Lucknow city (Fig. 10). Some of these drains are big and carry sludge discharge of as much as 78 MLD, while the smaller drains carry only 0.5 MLD discharge (Table 1).

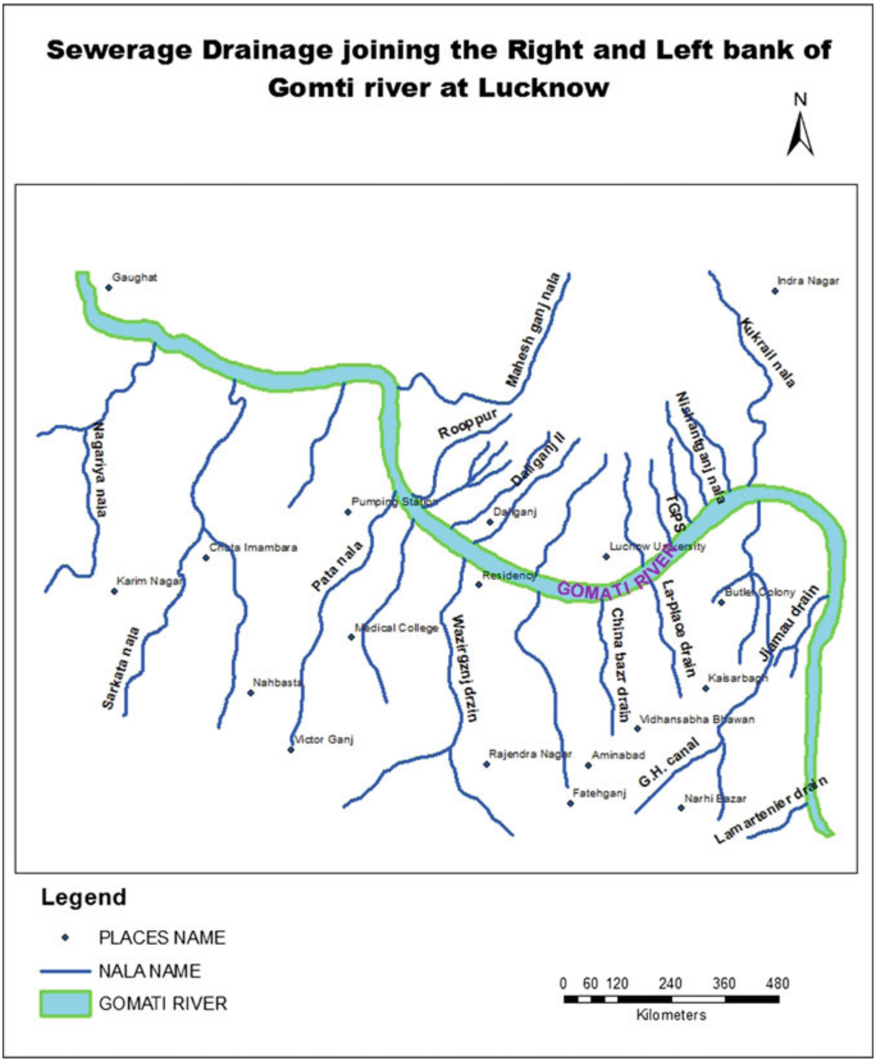

Fig. 10 Map showing sewerage network of Gomati River at Lucknow

Table 1 Wastewater load at various outfall drains in Lucknow city

Name of the drain Cis-Gomati (right bank)	Discharge (MLD)	Name of the drain Trans-Gomati (left bank)	Discharge (MLD)
Nagariya drain	10.00	Maheshganj drain	4.570
Sarkata drain	34.57	Rooppur drain	0.656
Pata drain	18.54	Mohan meakins drain	5.187
Drain downstream of NER	01.00	Daliganj drain I	12.275
Wazirganj drain	75.60	Daliganj drain II	6.950
Ghasiyari mandi drain	19.53	Arts college drain	8.890
China bazar drain	07.01	Hanuman setu drain	0.825
La-place drain	03.00	Trans-Gomati Pumping Station	1.640
Cis-Gomati Pumping Station	19.64	Kedernath drain	3.400
Joppling road drain	03.00	Nishatganj drain	1.700
G.H. canal	106.20	Babapurwa drain	0.65
Jiamau drain	03.00	Kukrail drain	50.000
Lamartenier drain	01.00	Weeping sewers of city	34.500
Drain upstream of rail bridge	03.00	Gomati N. drainage	25.00
Total	305.09	Total	156.24

Grand total: 461.33 MLD

6 Conclusion

Gomati River is a life line for the millions of people living in the Central Ganga Plain. The depleting water budget in the river systems has been a cause of major concern and needs to focus to revive the river system, otherwise, it would became a dying river systems of the Ganga basin. Sharda River flowing north of the place of origin of Gomati River is a Himalaya river and is flooded with excessive water which inundates and causes havoc in large adjoining areas. This excess water of Sharda River could well be transmitted to upper reaches of Gomati River through the interlinking processes. This on one hand would mitigate the damages caused by excess water in Sharda River and at the same time rejuvenate the otherwise dying Gomati River.

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Ghaghara River System—Its Current Status and Value to Society

Rajiva Mohan

1 Introduction

Ghaghara River is a tributary of Ganga River. This river originates near Lake Mansarovar in Tibetan Plateau. It joins the Sarada River in India at Brahma Ghat after travelling through the Himalayas in Nepal (Fig. 1). The length of Ghaghara in Nepal is 507 km. However, it has a total length of 1080 km up to its confluence with the Ganga River at Doriganj near Chhapra town in Bihar. It is called Kauriala and Karnali in Nepal.

1.1 Origin

The origin of Ghaghara River (Fig. 2) lies in the glaciers of Mapchachungo near Mansarovar Lake at an elevation of 4800 m. The river enters Nepal after flowing for about 72 km and flows south and is known as the Karnali River (Source: http://en.wikipedia.org/wiki/GhagharaRiver).

1.2 Catchment and Major Tributaries

The Ghaghara River has a catchment of 127,950 km^2 spread over India and Nepal, out of which about 55% lies in Nepal and remaining 45% lies in India. The catchment of Ghaghara is shown in Fig. 3. Ghaghara enters into India at Kotia Ghat

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Fig. 1 Location map of Ghaghara River

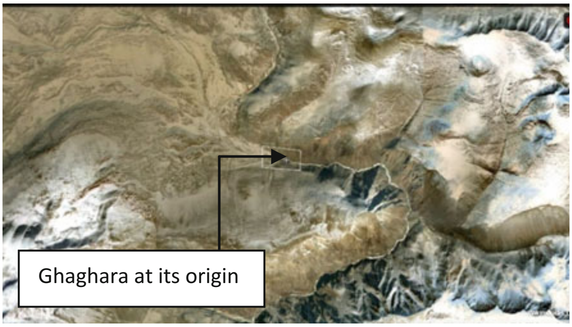

Fig. 2 Ghaghara River at its origin

near Nepalganj. The Sharda, Saryu, Chau-ka, Kuwano, Rapti, Chhoti Gandak, and Jharahi are the major tributaries of Ghaghara in India. In Nepal portion, the Seti River in the western part of the catchment joins the Karnali River. Another tributary, the Bheri rises in the western part and drains the eastern part of the catchment; it meets the Karnali River near Kuine Ghat in Surkhet. Further, it splits into two

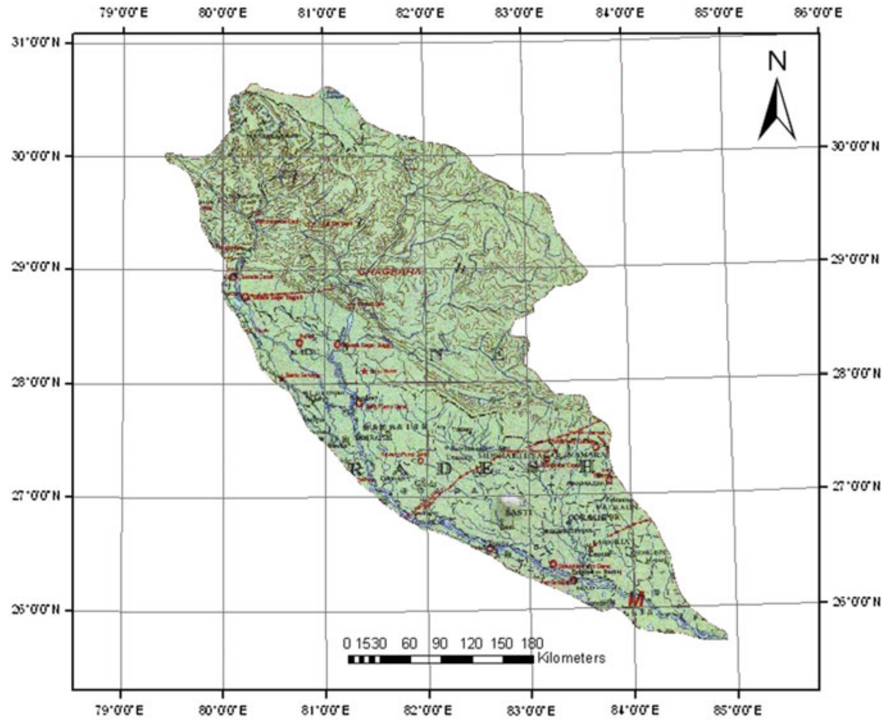

Fig. 3 Ghaghara River catchment

Table 1 Length of Ghaghara and its major tributaries in U.P

S. No.	River name	Length (km) (as interpreted from IRS Satellite data of October 2006)
01	Sarada	253
02	Ghaghara	620
03	Rapti	555
04	Burhi Rapti	201
05	Kuwano	333
06	Saryu	229
07	Ami Nadi	229
08	Rohini	154
	Total	2574 km

branches, the Geruwa and Kauriala near Chisapani and rejoins the Indian border and forms the proper Ghaghara. The West Rapti, the Kali (or Mahakali), and the little Gandak are the other tributaries originating in Nepal.

The length of Ghaghara and its major tributaries in Uttar Pradesh is given in Table 1.

1.3 Religious Significance

River Saryu which is another name for Ghaghara in some parts has been referred in Ramayana. Saryu once upon a time was lifeline of Ajodhya, where King Dasharath ruled. Hindu devotees consider a holy dip in the Saryu to be moksha dayini as Lord Rama is supposed to have immersed himself in the Saryu River to return to his heavenly form.

1.4 Administrative Zones and Districts

Ambedkar Nagar, Azamgarh, Barabanki, Basti, Balrampur, Ballia, Bahraich, Deoria, Faizabad, Gonda, Gorakhpur, Kheri, Kushi Nagar, Maharajganj, Mau, Pilibhit, Sitapur, Shrawasti, Siddhartha Nagar, Sant Kabir Nagar of Uttar Pradesh and Siwan district in Bihar are the administrative districts in India falling in the Ghaghara catchment (Fig. 4).

Akabarpur, Ajodhya, Faizabad, Bahraich, Barabanki, Basti, Deoria, Barhal Ganj, Gonda, Gorakhpur, Khaililabad, Sitapur, Siddhartha Nagar, Sant Kabir Nagar, Kamhariya Rajesultanpur, and Tanda in Uttar Pradesh and Chapra, Siwan, and Sonepur in Bihar are the important towns in India.

In Nepal, five districts, namely Dolpa, Humla, Jumla, Kalikot and Mugu fall in Ghaghara catchment's Karnali zone.

This zone has the lowest population density in Nepal, and there are no large settlements on the banks of the river.

Henceforth, the major characteristics of the region are described mainly for India portion of the basin with some exceptions in cases where information on Nepal portion was also available.

1.5 Climate

The climate of the catchment is a tropical monsoon consisting of three seasons i.e. summer, winter, and monsoon. The range of maximum annual mean temperature is between 44.4 and 44.8 °C, and the minimum range of the annual mean temperature is between 4.3 and 5.4 °C. The range of average annual rainfall in the catchment is from 900 to 1400 mm. The evapo-transpiration in the basin ranges approximately between 1700 and 1950 mm. The annual mean wind speed is nearly 5 KMPH in the catchment.

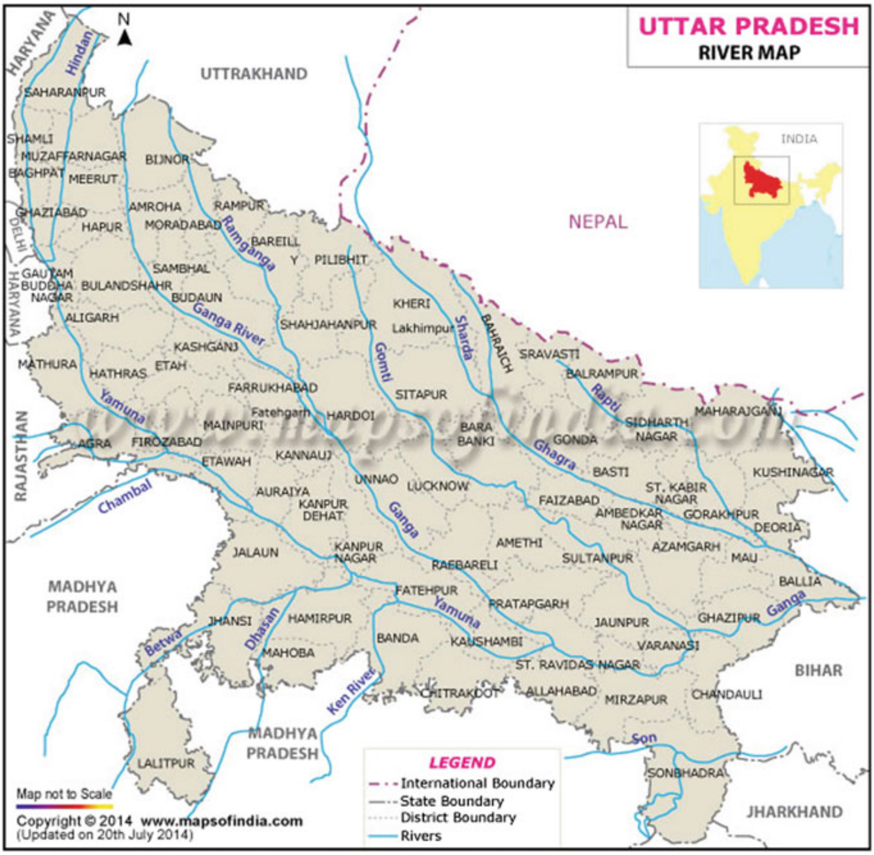

Fig. 4 Administrative districts falling in Ghaghara basin

Table 2 Average annual water yields

Basin	Area of basin (km^2)	Average annual yield (million m^3)	Specific yield/discharge	
			Thousand m^3/km^2	m^3/s
Ghaghara basin	127,950[a]	94,400	743	2993

Source Ganga Basin, CPCB-ADSORBS/7/1982–83
[a]Total area including basin in Nepal

1.6 Surface and Ground Water

Surface water Availability: Average annual water yield due to the rainfall in Ghaghara basin (Table 2) for River Ghaghara is reported to be 94,400 million m.

Table 3 Annual flow volume and share of catchment of U.P

River	Discharge site	Annual inflow (M ham)	Share of catchment of U.P. (M ham)
Ganga	Varanasi	6.72	4.29
Gandak	Balmiki nagar	3.3	1.04
Ghaghara	Turtipar	6.24	6.2
Son	Chopan	1.14	0.15
Gomti	Naighat	0.49	0.49
Total		17.89	12.21

Source Tenth Five Year Plan of U.P. (http://planning.up.nic.in/annualplan0203/aplan_main.htm)

Table 4 Water potential in average year

Basin	Area (km^2)	Ground water Potential (Mm^3)	Average surface water potential (Mm^3)	Total water potential (Mm^3)
Ghaghara	47,000	15,837.30	25,018.03	40,855.33

The flow of rivers in Ganga Basin is recorded by Central Water Commission (CWC), and this data is a confidential data. The data which is not confidential and available for the catchment part in U.P. at different Gauge sites is given in Table 3. The data indicates that the maximum flow is at Ganga followed by Ghaghara, where as Gomti is reported with minimum flow.

Total Water Potential: Total available water resources in Ghaghara basin are given in Table 4.

1.7 Ground Water Level

The groundwater levels are measured by U.P. Groundwater Department through a network of hydrograph stations including shallow piezometres which are located throughout the Ghaghara basin. The ground water level data of the Ghaghara basin districts reveals that range of ground water level is from 0.91 to 8.58 m bgl in pre-monsoon and 0.4 to 7.46 m bgl in post-monsoon season.

2 Geomorphology

The topography in India portion is generally flat and sloping. Ghaghara basin forms the part of the Ganga Plains. The Ganga plain is bordered by the Himalayan mountainous zone in the north and by the Bundelkhand plateau in the south. The Ghaghara plains are underlain by thick loose alluvial sediments deposited by the River Ghaghara and its tributaries (Fig. 5).

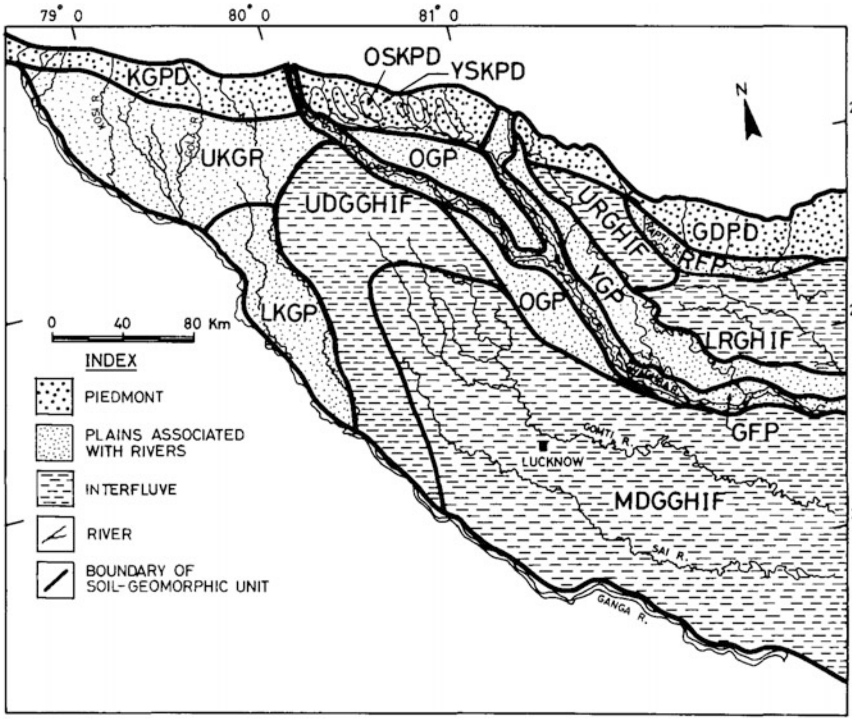

Fig. 5 Geomorphology of Ghaghara basin and adjoining areas

The surface slopes towards south-eastwards except near river banks. Geomorphologically, the region exhibits upland terrace surface, river valley terrace surface, present-day river channel with narrow flood plains, natural levee, and point-bar deposits. All these geomorphic features are made up of alluvium of different ages and depositional in nature. In Nepal portion, Karnali River exposes the oldest part of the Sivalik Hills of Nepal.

2.1 *Soil-Geomorphic Units*

Soil-geomorphic units here have been described on the basis of the remote sensing results from a study carried out by Shrivastav et al. (1994). In this study, the IRS FCC's were used for demarcating the soil-geomorphic units which are given in Table 5.

Table 5 Physiographic characteristics of various soil-geomorphic units in Ghaghara basin and adjoining areas

Soil-geomorphic units (symbol)	Physiographic characteristics
Kosi-Gola Piedmont (KGPD)	Slight relief, parallel drainage, well drained, forested, and cultivated land in parts
Young and Old Sihali-Kandra Piedmont (YSKPD) and (OSKPD)	Moderate relief, parallel drainage, and well drained
Gholis-Dhohania Piedmont (GDPD)	Slight relief, parallel drainage, and well drained
Ghaghara Flood Plain (GFP)	Well drained and braided pattern
Rapti Flood Plain (RFP)	Well drained and straight to meandering pattern
Young Ghaghara Plain (YGP)	Well drained, marshy areas, and old channels
Old Ghaghara Plain (OGP)	Well drained and linear pattern
Upper Kosi-Gola Plain (UKGP)	Moderately drained, parallel, and dichotomic pattern
Lower Kosi-Gola Plain (LKGP)	Moderately to poorly drained and marshy areas with palaeochannels
Upper Deoha/Ganga-Ghaghara Interfluve (UDGGHIF)	Moderately to poorly drained and slightly salt affected in south
Middle Deoha/Ganga-Ghaghara Interfluve (MDGGHIF)	Poorly to very poorly drained and highly salt affected
Lower Deoha/Ganga-Ghaghara Interfluve (LDGGHIF)[a]	Poorly drained and moderate to high salt efflorescence
Upper Rapti-Ghaghara Interfluve (URGHIF)[a]	Moderately to poorly drained and forested in parts
Lower Rapti-Ghaghara Interfluve (LRGHIF)[a]	Very poorly drained and highly salt affected

[a]After Mohindra (1989)

2.2 *Morphology of Different Soil-Geomorphic Units*

Morphologically three major landforms (piedmonts, plain associated with rivers, and upland interfluves) have been identified in the above referred study. Within each land form, a number of soil-geomorphic units have been demarcated (Fig. 5).

2.3 *Piedmont*

This zone occurs along the base of the Siwaliks and is 20–30-km wide. The unit slopes steep southerly (3–5 m/km) and has a parallel to sub-parallel drainage pattern with high drainage density. The Kosi-Gola Piedmont (KGPD) and the Gholia-Dhohania Piedmont (GDPD) in the west and east, respectively, which are marked by very weakly developed soil are the two sub-units in this zone.

In the recent past probably due to tectonic upliftment, the central part of the piedmonts zone, between Ghaghara and Sarada rivers, has undergone severe dissection. Two soil geomorphic units are identified in this zone, viz. (i) areas marked by very weekly developed soil named Young Sihali-Kandra Piedmont (YSKPD); and (ii) areas with moderately developed soils and still not affected by erosion, named as Old Sihali-Kandra Piedmont (OSKPD).

2.4 Plains

The plains have moderately to poorly developed soils. They include the Kosi-Gola Plain, Ghaghara Plain, and Rapti Flood plain.

The Kosi-Gola Plain and the Kosi-Gola Piedmont to the north are regarded as genetically related. The drainage density and rate of sedimentation decrease from north to the south.

2.5 The Rapti Floodplain (RFP)

The Rapti River after entering the plains flows to the southeast for about 35 km and then takes an easterly course which seems to be controlled by faults. The Rapti floodplain is arc shaped, having width of 15–20 km in central part and narrower in both upstream and downstream.

2.6 The Ghaghara Plain

The Ghaghara plains are formed by the Ghaghara River and its tributary Sarada River and are 10–40-km wide. This plain has been subdivided into three sub-units, viz. the Ghaghara Floodplain (GFP), the Young Ghaghara Plain (YGP), and the Old Ghaghara plain (OGP).

2.7 Interfluves

The Interfluves are upland areas and have moderately to strongly developed soils. The interfluves have been divided in two sub-units, viz. Deoha/Ghaghara and Rapti-Ghaghara interfluves.

2.8 Faults

The major faults identified in the study area are mostly along the major rivers, viz. Ganga, Deoha, Sarada, Ramganga, Ghaghara, and Rapti. Other than this, three more faults, viz. Balrampur-Lucknow, Utraula-Amethi, and Himalayan Frontal Faults have also been identified in the area (Fig. 6).

3 Socio-economic Importance

3.1 Soil Characteristics

The characteristics of the soil in Ghaghara basin may be described as discussed below.

Soil Texture: The soil of Ghaghara basin is predominantly loamy and is suitable for cultivation of all types of crops as the fertility status and water holding capacity of this soil are very good.

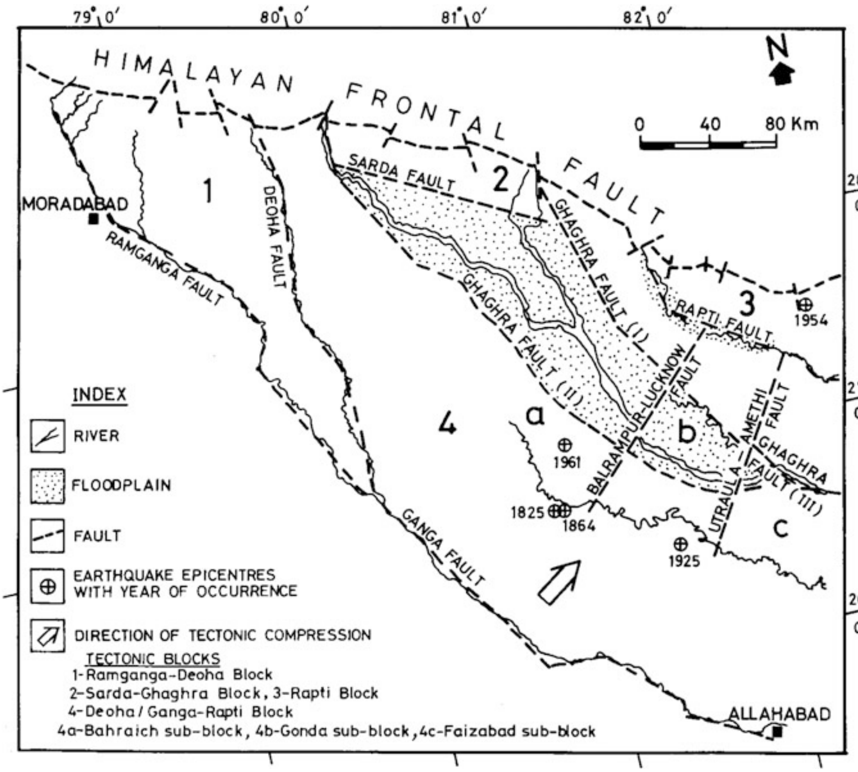

Fig. 6 Major faults in Ghaghara basin and adjoining areas

Soil Depth: The soil in Ghaghara basin is predominantly 'deep'. Soils in the basin considering soil depth are suitable for all climatically adapted crops.

3.2 Ghaghara Basin Irrigation System

The irrigation in the Ghaghara basin is provided by the Sarada, Sarada-Sahayak, and the Sarayu canal systems. Sarada-Sahayak system was conceptualized to assist (Sahayak) the water of the Sarada by augmenting the flow of the Sarada (that was a run-of-the-river diversion from the Sarada/Mahakali River) with the flow of the Ghaghara/Karnali; The tail ends of the older Sarada system were then hydraulically disconnected from the Sarada and extended to form the Sarada-Sahayak system fed by the new diversion. The Sarayu canal system is much newer. The systems are, however, in bad conditions due to lack of adequate upkeep and, as a result, the productivity is low.

Sarada Sahayak Pariyojna: The Sarada Canal was constructed some seventy-five years ago to serve the Ganga-Ghaghara area. A run-of-river supply canal leading flow off the Sarada River at Banbasa was designed to provide irrigation water to sixteen districts and provide protection from recurring famines. Its design capacity is 350 cumec but supply reduces to as low as 130 cumec during winter and summer before the effects of the snow melt are felt. The Sarada Sahayak Pariyojna was conceived in 1967 as a run-of-river scheme to augment the Sarada Canal system (now hydraulically disconnected from the old Sarada distribution system) with the Sarada Barrage on the Sarada River and the Girija Barrage on the Ghaghara River linked by a canal. The design capacity of the Sarada-Sahayak feeder canal is 650 cumec and the area designed to be irrigable in the Sarada-Sahayak is about 1.93 million ha of gross command area (68% irrigation intensity in Kharif and 47% irrigation intensity in Rabi), although the actual area irrigated is supposed to be only about 0.83 million ha of gross command area. This kind of discrepancy between the design and actual areas irrigated is common in all the systems in U.P. and arises from a variety of factors. The original design had some assumed cropping pattern and irrigation intensities that are still assumed to be true and not reflective of the changed condition today or of farmer requirements. The distribution system consists of the main branch canals (six in the Sarada-Sahayak system), the distributaries, minors, and watercourse outlets (Sarada Sahayak Pariyojna, Revised Project Document, Uttar Pradesh Irrigation Department, November 1985).

Saryu Nahar Pariyojna: The Saryu Nahar Pariyojna is a run-of-river scheme. A barrage was constructed in the Saryu River in 1984. It feeds water to the Saryu Main Canal. A barrage on the Rapti River augments the main canal supply via a link canal and has a discharge capacity of 95 cumec (Saryu Nahar System Report, Uttar Pradesh Irrigation and Drainage Department, undated).

3.3 *Fish Biodiversity Status*

Ghaghara and Gandak rivers are the ideal habitats for the Ganges Dolphin. A study conducted to assess the current freshwater fish biodiversity status of River Ghaghara in Uttar Pradesh, India, has indicated that altogether, there are 62 species of fish representing 48 genera and 24 families. Ghaghara River supports food fish, aquarium fish, and also sport fish.

3.4 *Natural Hazards*

3.4.1 Flood Hazards

The Ghaghara basin and its tributaries pass through 20 districts of U.P. The major rivers which cause floods in Ghaghara basin are Sarada, Rapti, Ghaghara, Burhi Rapti, Kuano, Saryu, Ami and Rohini. There are number of streams/nala which originate from Himalayas and join Ghaghara River and its tributaries. A total of 18.73 lac ha of area was affected by floods in the various districts due to Ghaghara and Rapti rivers during one of the severest flood in 1973. In general, entire Ghaghara basin is affected by floods but Gorakhpur, Deoria, Basti, Sant Kabir Nagar, Siddhartha Nagar, Mau, Maharajganj, Kushinagar, Azamgarh, Ballia, Gonda, and Bahraich districts are more prone to floods. The severity of floods along Ghaghara may be understood by the fact that length of marginal embankments along Ghaghara is about 586.77 km. Although Ghaghara basin has faced several severe floods in recent times, year 1978 has been the worst. The flood levels at most gauge sites in the Ghaghara and Rapti rivers remained above danger level marks for more than two months.

3.4.2 River Bank Erosion

The erosion of the river banks along Ghaghara has been causing enormous problem. The impact of erosion is non-recoverable. The main reason for erosion along Ghaghara River is increase in population along banks, construction of building and roads, and other anthropogenic causes.

3.4.3 Earthquake Hazards

The Ghaghara basin area can be classified into two zones—zone 4 and zone 3. The zone 4 falls along the Tarai belt in the northern part of basin and zone 3 in the remaining part of the basin area. Zone 3 is characterized as moderate-risk zone, and zone 4 is classified as high-risk zone.

Table 6 Pollution level in different stretches of the Ghaghara River

Location	Existing level
Ghaghara at Deoria	B
Rapti after confluence of Rohini, Gorakhpur	B
Saryu at Ajodhya	D

Source CPCB-2002

3.4.4 Anthropogenic Hazards

Surface Water Quality: The surface water quality at Ghaghara River and its tributaries is monitored by Central Pollution Control Board (CPCB), through the Parameters, viz. physical (temperature, pH, EC), bacteriological (total coliform and faecal coliform), and organic pollution (DO, BOD, COD). Based on the rivers' water quality data for the year 2002, the observations are summarized in Table 6.

BOD load discharged by grossly polluting industries in Ghaghara River, Sharda River, Saryu River, and Rapti River is estimated to be 1256, 560, 2495, and 3946 kg per day, respectively.

Ground Water Quality: Ground water in Ghaghara basin is the major source of irrigation as well as drinking water; however, the ground water in the area has increased contamination in the form of nitrate, heavy metal, pesticides, arsenic, fluoride, etc., due to natural weathering, leaching from the industrial setups, excess exploitation of ground water, and sewage.

3.4.5 Degradation of Wetlands

The wetlands in Ghaghara basin are in serious threat due to the silting, depletion or complete drying of lakes, growth of water hyacinth, and encroachment of wetlands due to urbanization or agriculture activities and discharge of effluents from the industries in the vicinity.

4 Conclusions

The Ghaghara basin at present although does not experience any major global environmental issues such as ozone depletion, global warming, and acid rains. However, due to increased demand for resources; changing land-use patterns, load on air, water and land; rapid urbanization; migration to urban areas; increased and concentrated generation of pollution and wastes; greater need and attention on increasing industrial and agricultural productivity could marginalize environmental priorities of the basin.

The other priority of the basin could be flood protection works, viz. construction of embankments, anti-erosion works, drainage improvements, and a forestation. Further, improvement in flood forecasting, desilting of river, and formulation of suitable plan for fish development and fish biodiversity and drinking water security also need proper attention.

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The Rapti River: Odyssey from Nepal to India

Biswajeet Thakur and Dhruv Sen Singh

1 Introduction

A river is a natural waterway, comprising chiefly of freshwater, which flows towards ocean, lake, sea or another river. The rivers form an integral part in the hydrological cycle. The river channels in India chiefly flow into the Bay of Bengal in the east or in the west in the Arabian Sea. The Indian rivers play a vital role in the livelihood of the Indian people as they act as the major source of irrigation in the agricultural sector and domestic productivity, and also for potable water, cheap transportation and electricity for a large number of people all over the country. The Indian rivers also bear major role in Hindu religion and are considered sacred by all the Hindus in the nation.

The Rapti River originates from south direction of a prominent E–W ridgeline midway between the western Dhaulagiri Himalaya and the Mahabharat Range (1000–3000 m) at an elevation of 3200 masl (Upreti and Yoshida 2005; Dahal 2006) (Fig. 1). The West Rapti River (known in Nepal), one of the major river channel in west Nepal, has two major tributaries—(1) the Madi River and (2) Jhimruk River (Pathak et al. 2007). The Rapti River basin occupies an area of around 4,500 km^2 in which the Jhimruk River basin accounts for 960 km^2. The watershed of Jhimruk River mainly covers the Pyuthan district of Nepal, and this is the point from where the Rapti originates. The Rapti in this zone is known as West Rapti River as it flows in west direction until it takes a sharp turn and moves towards Uttar Pradesh in India.

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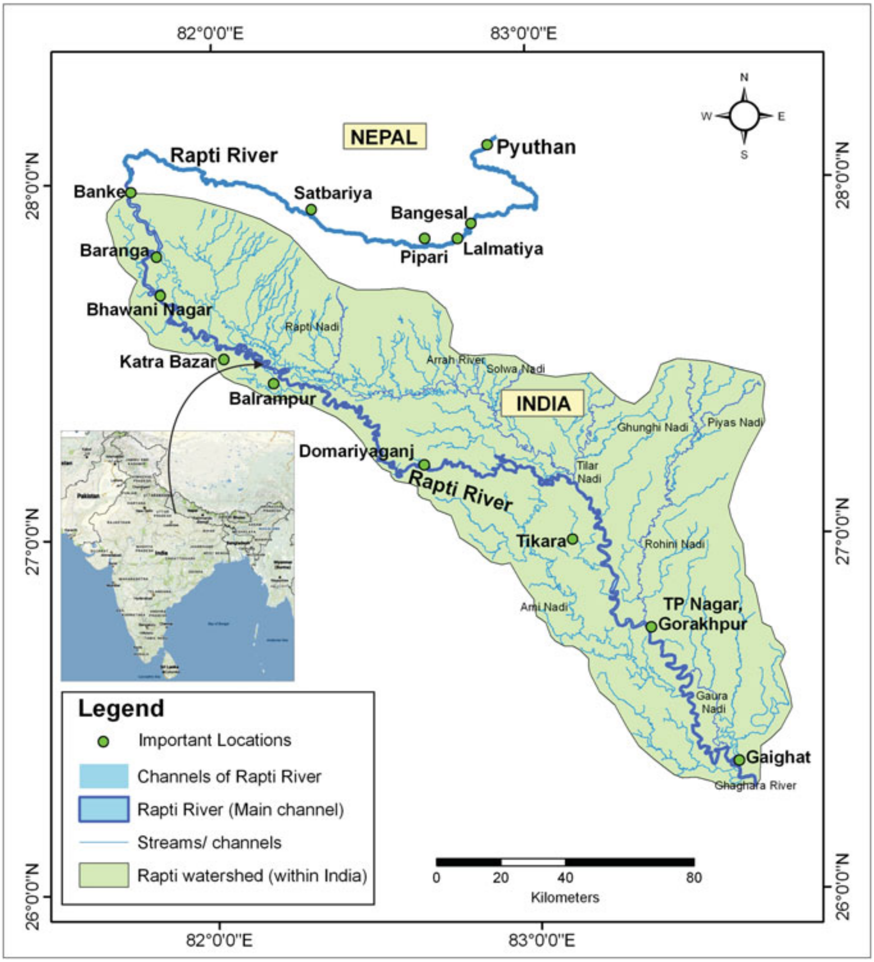

Fig. 1 Drainage basin of Rapti River from origin to confluence point

The wide basin of the river is very diverse in nature due to topographical expression under direct control of geology, altitude, climatic, biological and land use conditions. The river in this region is primarily bounded by the Siwaliks in the south and Lesser Himalaya zone in the north and separated with each other by the Main Boundary Thrust (MBT) (Pathak et al. 2007). In this zone, the Siwalik rocks are primarily comprise of sedimentary rocks (mudstone, sandstone and conglomerate), whereas, the rocks of the Lesser Himalayas characterize low grade metamorphic rocks (e.g. slate, phyllite, metasandstone and quartzite). Generally, the range terrain is very rugged with deeply dissected gullies and steep slopes.

The Rapti River tumbles down from the rugged highlands south of Kham Magar. The terrain is highly uneven, and the Rapti flows in a very narrow stretch in this zone with high degree of sinuosity. Along the western region, the tributary of Rapti in the Nepal region is the Madi Khola which rises in north-western Rolpa district and then joins Lungri Khola which drains north-eastern Rolpa. This, in turn, crosses into Pyuthan and same to be known as Mardi. The Mardi is then joined by east-flowing Arunkhola at Devithan, and here it enters a gorge through the Mahabharat Range (1000–3000 m).

To the east of the Mardi lies the Jhimruk Khola River, one of the main tributaries of the West Rapti in Nepal. This river mainly drains into the Pyuthan district where it swings around its channel in a narrow range and forms a braided channel for a distance of about 9 km till it reaches Khaira where it eventually takes a sharp right angle turn towards south for approximately 2.5 km. The Jhimruk River below the Cherneta area separates the boundary between Pyuthan and Arghakhanchi districts. The river here flows in a narrow valley and steep slopes while it enters into the Mahabharat Range and after traversing a distance of approximately 40 km joins the Mardi River and finally came to be known as Rapti River. However, in this small traverse of the River Jhimruk, it can be very well observed that the channel is narrow with wide channel bar deposits. The channel swings in a very high sinuous manner in the narrow stretch and shows 90° turn in most of the regions giving evidence to neo-tectonic (Della Seta et al. 2004).

The main odyssey of the Rapti channel emerges from its gorge into the lower Siwalik and Dang districts where the channel can be seen cross-cutting its own channel and making a bar in this part of the stream. The channel is surrounded by high mountainous and rugged terrain with cross-cutting edges in most of the traverses in the narrow belt of channel flow. The numerous small channels and streams make their way into the main Rapti channel in the Siwaliks. At Bhalubang Bazaar, near Mahendra Highway bridge, the Ransing River joins the Rapti channel and at this juncture, the channel widens with huge broad valley floor and huge sediment deposit. The channel cuts sediment itself to pave way for run-off, and thus a classic example of the braiding channel can be observed at this juncture. The river continues to flow in a broad valley with major and minor swings and loops in WNW direction for a distance of 100 km until it reaches the Banke district. Here, it again takes a sharp 90° turn and moves into Indian border in straight north-south direction for about 15 km. Thereafter, it enters into Bahraich district of Uttar Pradesh in India and flows in SE direction. The channel here meanders with fresh deposited sand units and numerous meander scars which show the continuous swing in the fertile Ganga Plain till it reaches Parsha Dehria (27° 49′ 41″N, 81° 50′ 28″E) in India. From this location, the river again changes its course from NE to SW in a prominent straight segment for a distance of approximately 17 km reaching Acharaura Shahpur (27° 42′ 59″N, 81° 45′ 57″E). In this small traverse also, the river actively takes part in forming loops and meanders with numerous point bars, channel bars and meander scars (Fig. 2) However, the river flows in N-S direction from Skikari Chaura (27° 47′ 16″N, 81° 46′ 12″E) up to Mahadewa, Uttar Pradesh. The river after crossing the Mahadewa locality takes a major NW–SE course and follows this

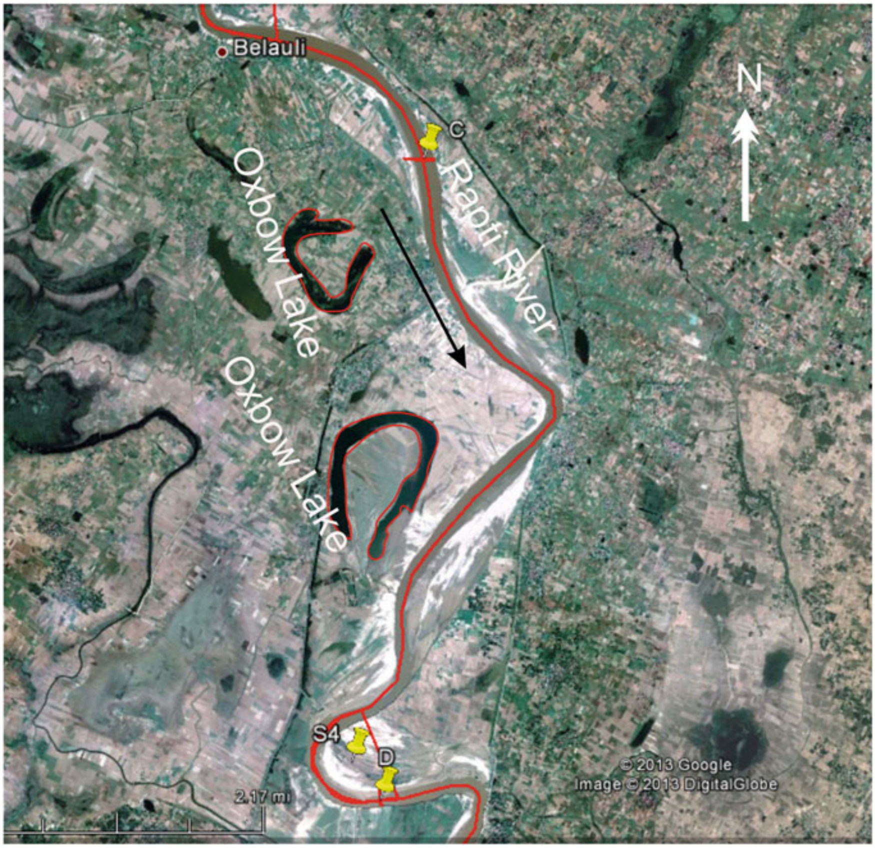

Fig. 2 Rapti River showing oxbow lakes, point bars and meander scars

path for approximately 160 km in Mejhuka (27° 06′ 05″N, 83° 09′ 41″E) in Siddarthnagar district. In this entire large stretch also, the river can be observed for having large valleys with extensive floodplain deposits. The high concentration of the point bars, channel bars, cut-off meanders, ox bow lakes, palaeo-channels and meander scars justify the changing scenarios of the Rapti River as one of the most migrating rivers in the Ganga Plain. In this traverse also, the swing in the channel with high meandering in the narrow water channels indicates a major structural control (Srivastava et al. 1994; Pati et al. 2011). The work by Pati et al. (2011) gives evidences of exceptional widening of the Old Ghaghara Plain (OGHP) and the Rapti Floodplain (RFP) towards SW, as compared to downstream and upstream courses of these rivers. This was probably due to the tilting of Bahraich and Gonda sub-blocks towards the SW and mainly caused due to shifting of Ghaghara and Rapti rivers from NE to SW (Srivastava et al. 1994).

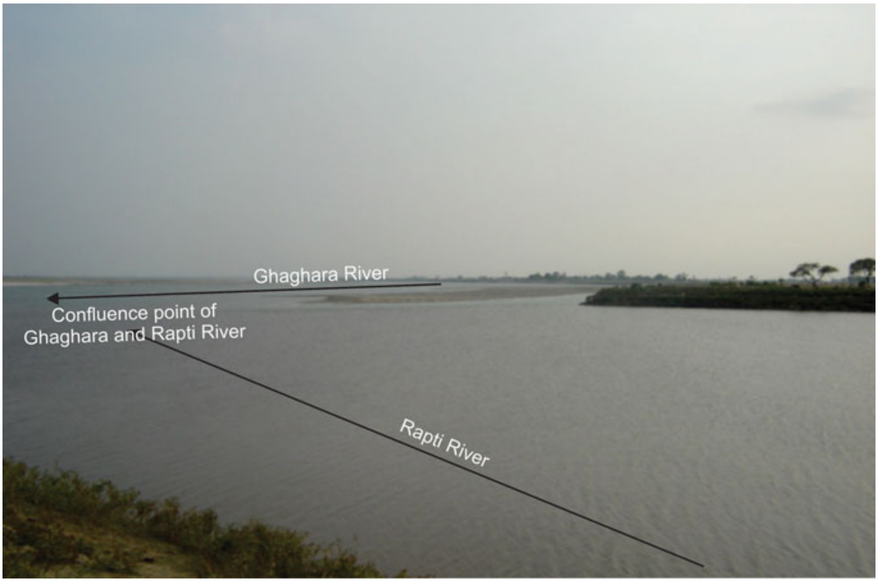

Fig. 3 Confluence of Rapti and Ghaghara rivers near Barhaj, Deoria District, Uttar Pradesh, Ganga Plain

The Rapti River at the Mejhuka village takes a major N–S turn in the downstream and continues to flow in this direction till it reaches Bokta Tal, Goarkhpur ($\sim$42 km). In this part also, the channel has numerous very acute loops. Here, the deposition in the floodplain has large-scale lateral bars with incised valleys. From the Bokta tal up to Ilahi Bagh, Gorakhpur ($\sim$10 km), the river travels in E–W direction in a straight laminar flow but makes two prominent loops giving evidence to structural set-up in this stretch (Della Seta et al. 2004). The river then drains towards NW–SE direction and finally joins the Ghaghara River travelling a distance of 100 km downstream near Barhaj at Kaparwaa Ghat, Uttar Pradesh (Fig. 3). This traverse also experiences swings to a great deal, and at few instances it makes 90° turn in most cases which is an evidence of structural control or neo-tectonic activity (Della Seta et al. 2004; Pati et al. 2011).

2 Tributaries of Rapti River

The Rapti River watershed within the Indian region covers an area of approximately 14,565.00 km^2 and perimeter of 688 km until it joins the Ghaghara River. The entire watershed within the Indian boundary marks the foundation for creation of small to medium to large channel and streams that directly or indirectly join the Rapti River or its tributaries. The India Index Map on 1:50,000 scale for the major tributaries has been shown in Fig. 4. The Rapti River has mainly 47 channels that

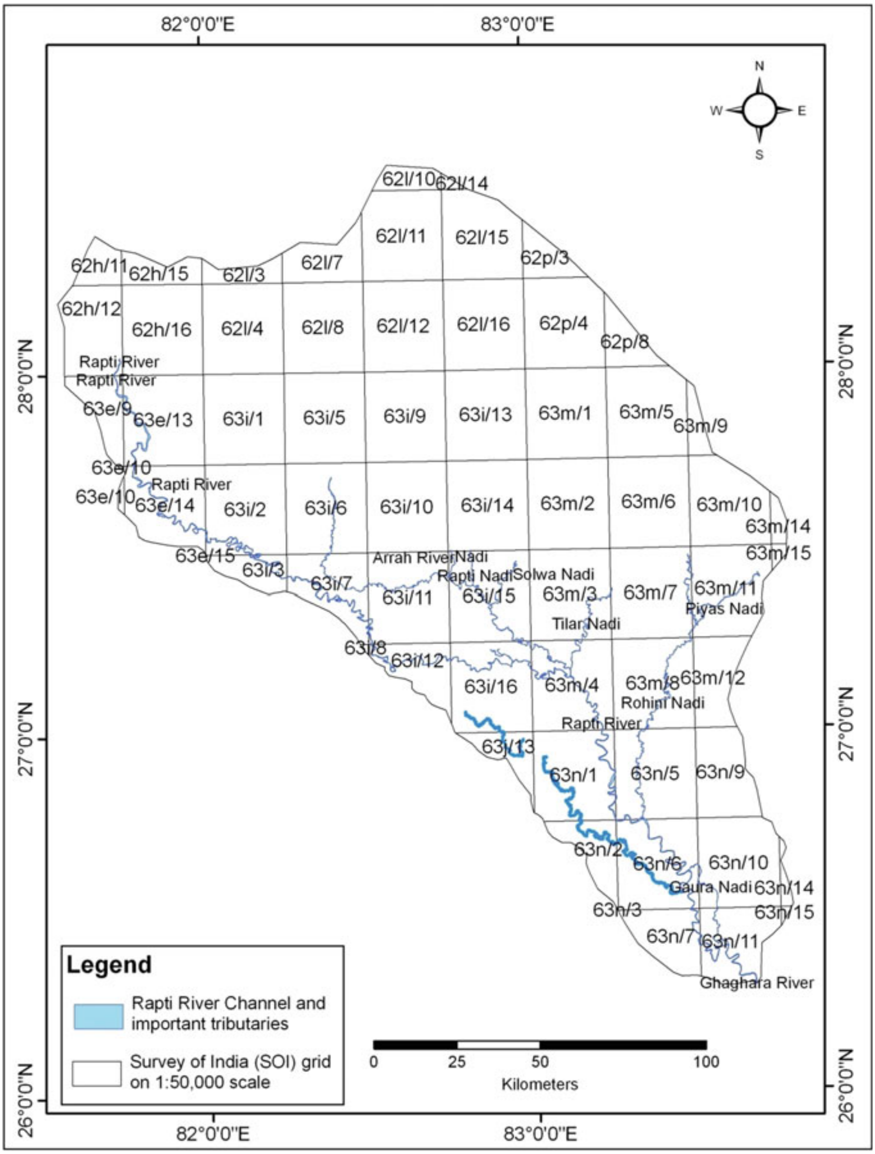

Fig. 4 SOI index for Rapti River watershed on 1:50,000 scale

lie within its watershed. Along the left bank, 36 tributaries contribute while at the right bank, 11 feed the Rapti River. The total lengths of all the channels and streams are listed in Table 1. Apart from these channels, there are numerous small drains that take active part in the Rapti watershed but as no name is assigned to the channels they are referred as drains. The channels either originate from the foothills

Table 1 Tributaries of Rapti River watershed along with their origin points

S. No	Name	Origin point Longitude/latitude	Total length
	Left bank tributaries of Rapti River		
1.	Tura Nadi	83° 32′ 13.392″E, 26° 59′ 4.198″N	64.128
2.	Temar Nadi	83° 30′ 8.611″E, 27° 2′ 3.285″N	6.483
3.	Tardini Nadi	83° 17′ 14.78″E, 26° 26′ 35.555″N	121.337
4.	Suraikurda Nadi	82° 7′ 47.957″E, 27° 51′ 59.582″N	13.273
5.	Solwa Nadi	83° 17′ 4.476″E, 26° 44′ 22.069″N	6.372
6.	Rapti Nadi	82° 23′ 27.895″E, 27° 42′ 37.535″N	55.800
7.	Poh Nadi	83° 27′ 19.301″E, 27° 17′ 16.711″N	56.124
8.	Piyas Nadi	83° 42′ 22.718″E, 27° 25′ 33.297″N	24.622
9.	Pharend Nadi	83° 31′ 28.795″E, 26° 51′ 16.145″N	58.514
10.	Parasi Nadi	82° 37′ 39.292″E, 27° 17′ 14.864″N	36.398
11.	Nakti Nadi	82° 25′ 16.063″ E, 27° 29′ 35.82″ N	13.675
12.	Nakta Nadi	83° 41′ 23.643″E, 26° 37′ 18.309″N	34.246
13.	Muranga Nadi	81° 58′ 14.877″E, 27° 56′ 1.143″N	10.927
14.	Malaun Nadi	83° 35′ 2.002″E, 27° 17′ 27.314″N	9.537
15.	Majhna Nadi	83° 36′ 42.344″E, 26° 57′ 57.483″N	98.131
16.	Lamwar Nadi	83° 3′ 30.84″E, 27° 19′ 56.693″N	11.387
17.	Kuahi Nadi	82° 25′ 48.374″E, 27° 27′ 51.739″N	63.5144
18.	Kharjhar Nadi	82° 15′ 39.806″E, 27° 31′ 20.175″N	14.209
19.	Karna Nadi	83° 43′ 22.217″E, 26° 41′ 20.468″N	67.612
20.	Kalan Nadi	83° 21′ 36.945″E, 27° 10′ 38.738″N	44.395
21.	Kain River	81° 50′ 36.553″E, 27° 50′ 24.979″N	49.728
22.	Kagni Nadi	83° 16′ 25.741″E, 27° 20′ 51.204″N	29.826
23.	Henga Nadi	82° 10′ 36.972″E, 27° 42′ 58.032″N	10.490
24.	Ghunghi Nadi	83° 26′ 22.781″E, 27° 28′ 27.531″N	72.173
25.	Gainjawa Nadi	82° 5′ 6.917″E, 27° 53′ 51.859″N	6.191
26.	Dangmara Nadi	82° 10′ 55.546″E, 27° 51′ 10.787″N	68.085
27.	Dahla Nadi	83° 15′ 57.501″E, 26° 58′ 27.786″N	32.812
28.	Chilwa Nadi	83° 32′ 11.821″E, 27° 1′ 15.996″N	56.078
29.	Bilar Nadi	82° 54′ 12.126″E, 27° 22′ 19.013″N	25.992
30.	Bhambhar Nadi	82° 36′ 28.442″E, 27° 34′ 8.358″N	27.022
31.	Bhainsima Nadi	82° 6′ 35.149″E, 27° 52′ 43.119″N	17.626
32.	Bathwa Nadi	83° 33′ 21.907″E, 26° 29′ 52.264″N	26.775
33.	Baliya Nadi	83° 36′ 14.057″E, 27° 10′ 3.219″N	30.947
34.	Bagheta Nadi	83°33′ 35.149″E, 27° 25′ 38.762″N	26.429
35.	Akrazi Nadi	82° 39′ 54.005″E, 27° 14′ 52.821″N	47.276
36.	Gaura Nadi	83° 28′ 21.512″E, 26° 36′ 36.327″N	43.973

(continued)

Table 1 (continued)

S. No	Name	Origin point Longitude/latitude	Total length
	Right bank tributaries of Rapti River		
1.	Suwawan Nadi	82° 33′ 7.734″E, 27° 10′ 49.962″N	1.555
2.	Sonwan Nadi	83° 30′ 8.611″E, 27° 2′ 3.285″N	13.897
3.	Sikri Nadi	82° 58′ 29.214″E, 26° 51′ 26.04″N	16.307
4.	Khudwa Nadi	82° 0′ 9.227″E, 26° 47′ 50.542″N	35.475
5.	Budha Nadi	82° 54′ 28.363″E, 27° 7′ 37.716″N	24.654
6.	Binhi River	83° 6′ 21.601″E, 27° 5′ 15.635″N	17.879
7.	Bhakla River	81° 41′ 14.302″E, 27° 54′ 53.975″N	28.333
8.	Barar Nadi	83° 3′ 45.262″E, 26° 56′ 36.064″N	26.365
9.	Baran Nadi	82° 58′ 46.184″E, 27° 6′ 47.331″N	44.235
10.	Ami Nadi	82° 41′ 2.714″E, 27° 6′ 59.31″N	186.443
11.	Taraina Nadi	83° 10′ 49.893″E, 26° 35′ 56.912″N	54.529

part or begin from the Ganga alluvial plains. The inclination of the channels originating from the foothills mainly shows NE–SW or N–S trends in their flow regime, but the streams imitating from the fertile Gangetic alluvial plains follow the trend of Ganga basin i.e. NW–SE trend.

The Rohini and Piyas rivers of the watershed play a major role in the catchment as they originate from the gently sloping units of the foothills and then traverse along the fluvial plain until they join the main channel. Several small channels and rivulets join the Rohini River, and these streams and rivulets swell up with water and debris during the monsoonal periods; this makes the banks to become prone to overflow and erosion.

3 Natural Hazards

The river is highly catastrophic and leads to natural hazards such as flooding and landslides. This is mainly caused due to the embankment structures, flow and water holding capacity of channels. The changes are in the reduced water supply during the monsoonal periods also lead to channel migration, washing away of croplands, erosion of fertile soils, etc. Sometimes, due to high water logging, the crops are damaged to a great extent. Due to the water logged circumstances, the whole crop cycle and production get severely affected. Furthermore, the people become victims of water-borne diseases such as diarrhoea, cholera, dengue and Japanese encephalitis, as the flood waters stagnate and the natural lines of drainage are disrupted (Wajih 2002; GEAG Report 2008; Wajih et al. 2010; Thomas 2011). The severely affected cases under these domains are well known from the areas of Gorakhpur, Deoria, Maharajganj and Sant Kabir Nagar districts.

The main channel of Rapti River in Uttar Pradesh is also known for its devastating role. In the Gorakhpur district, it is termed as "Gorakhpur Sorrow" and this is due to its high flooding event which is more or less prominent every year (Singh 2007, 2009; Singh and Awasthi 2011a, b; Singh et al. 2015). As the watershed has vast expanse, it comprises of swamps and local water bodies (*Jheels*), which vary from large sheets of water during the rains while become shallow marshes or even arable land during the dry season (Gupta et al. 2013).

The role of the embankments and escarpments along the channel have led the river bed to rise, which in turn caused declining of river's carrying capacity and hence increased chances of flooding. In the same way, the water logging in the region has blocked the developments (roads, railways, canals, urbanization, etc.) to a great extent in the districts of Maharajganj, Deoria, etc. In some cases, the excessive rainfall has caused overflowing of low and poorly formed riverbanks due to silting and clogging. The flood hazard at present has become more unpredictable due to high water logging in certain areas and has created an immense harm to life and property and has become an obstacle to development in the region.

The flood impacts are not affecting only during the monsoonal periods but also left the aftermath in terms of losses and damages of life and property. The effects of flooding have caused damage to the socio-economic classes, gender, age, etc., along with health and sanitation to a great extent.

This eventually leads to changes in the course of the rivers, shifting and migration of the channels, reduces the land capacity and swaps much of the fertile soil in the catchment.

4 Socio-economic Importance

The Rapti River has an important role both in the Nepal and India, not only does it as an important bearing agriculture purpose but also important for the flooding events during the monsoonal realm (Das 1968; Singh 2007; Singh et al. 2015). The Rapti River water is harnessed for hydroelectric power generation in Cherneta and Pyuthan districts as well as utilized for rice cropping in Bahun and Chhetri districts of Nepal. The land is very fertile for the crops. There is problem due to malaria that affects the local people. The Dang Valley and the Mahabharat Range have levelled, and gently sloping lands support the agricultural sector. In the middle hilly regions mainly north of the crest of the Mahabharat Range, the districts of Pyuthan and Salyan have good alluvial plain deposits favouring the rice growth. The Rapti River in the Indian terrain is very dynamic and adjudicates the various fluvial processes which are either helpful for irrigation projects.

In the basin area, paddy is the main crop, particularly in areas having older alluvium (clayey) soil, with few minor rabi crops such as pulses and oilseeds. Madua, kerav, kodo, chana, jau, savan (millet and legume crops) and a little bit of wheat, sugarcane and bajra (pearl millet) are also sown. Presently, the wheat crop has also gained its attention. Crops such as madua and kodo (millets) that grew in the past are now almost ceased (Gupta et al. 2013).

5 Conclusions

The Rapti River originates from the Siwaliks, Nepal, covering approximately 700 km shows varied and diversified characteristics of fluvial geomorphology during its odyssey from origin point to India. In the traverse, the Rapti River shows prominent E–W flow in the Nepal region within deep gorges and elevated terrain. Various channel complexities, i.e. braided to meandering channels, straight to curved paths and wide to narrow valleys in the flow regime make it exclusive. Furthermore, the water characteristic in terms of carrying and holding capacity, the bank deposits and flood and run-off characteristics makes it an important part in delivering to the system. The high fertile soil in the watershed, cropping pattern, flooding and landslide studies makes the Rapti River a highly dynamic system and interesting field of interest for understanding fluvial geomorphology tectonics and climate-induced activities.

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The Chhoti Gandak River: Parinirvan Place of Gautam Buddha

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1 Introduction

Chhoti Gandak, a small meandering groundwater-fed river, is the lifeline for people of many districts in eastern Uttar Pradesh. This river basin is well known for sugar cane industry in India and internationally famous as a parinirvan place of Gautam Buddha. It originates near Dhesopool in the swampy terai region of Ganga Plain in Maharajganj district of Uttar Pradesh (Fig. 1). It joins the Ghaghara River near Gothani in Siwan district of Bihar (Fig. 2) after flowing for a distance of about 250 km. It drains in the Gorakhpur, Maharajganj, Kushinagar and Deoria districts of Uttar Pradesh, and Gopalganj and Siwan districts of Bihar, between 24°07′–27° 07′ N latitude and 83°48′–84°15′ E longitude at the border of the Uttar Pradesh and Bihar states (Fig. 3). The maximum height (*H*) is 102 m towards foothill near Dhesopool, and the minimum height (*h*) is 60 m near Gothani, the end point of Chhoti Gandak (Singh and Awasthi 2011a).

Chhoti Gandak is one of the best studied river basins of India. It forms an elongate river basin with gentle slope gradient. It has been studied for control of tectonics and climate (Singh et al. 2009), water quality using principal component analysis (Bhardwaj et al. 2010a), environmental repercussions of cane sugar industries (Bhardwaj et al. 2010b), hydrogeochemistry of groundwater and anthropogenic control (Bhardwaj et al. 2010c), implication of drainage basin parameters (Singh and Awasthi 2011), surface and groundwater quality characterization (Bhardwaj and Singh 2011), shallow subsurface facies (Awasthi and Singh 2011), vegetation and climate change (Trivedi et al. 2011), sedimentology

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Fig. 1 The origin of Chhoti Gandak River in terai area of Ganga Plain

Fig. 2 Confluence of Chhoti Gandak River with Ghaghara near Gothani, Bihar in the Ganga Plain

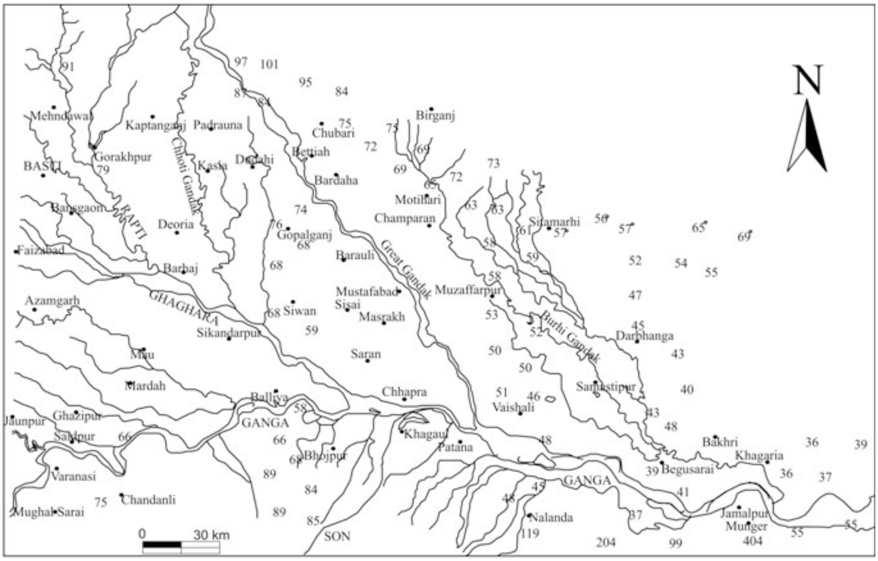

Fig. 3 Location map of Chhoti Gandak River showing adjoining rivers, cities and point heights

and channel pattern (Singh et al. 2013), multiproxy record of monsoon variability (Singh et al. 2015), multiproxy records of vegetation and monsoon variability since 1350 AD (Saxena and Singh 2016).

This region has a subtropical monsoon climate. The hot summers are followed by wet monsoon and cold winters. The area consists of clay, silt, sand and gravel mixed in different proportions of Quaternary age. The deposition of sediments in the Ganga Plain takes place in the river channel and interfluve areas located between rivers. Sedimentation in the interfluve areas is done by sheet flow (Kumar et al. 1995), low-lying areas, small channels, lakes and ponds (Singh et al.1999) and in the channel areas in form of channel bar deposits by the rivers (Singh and Singh 2005). Chhoti Gandak River Basin consists of older and younger alluvium (Singh and Singh 2005) (Fig. 4) and is characterized by muddy-sandy sequences with medium sand layers (Awasthi and Singh 2011).

A number of tributaries contribute to the Chhoti Gandak River and form the dendritic drainage pattern. The important right bank tributaries are Khekhra, Hirna, Maun, Kanchi and Koilar, and Khanua is the main left bank tributary. The meandering nature of channel has left a number of abandoned channels and oxbow lakes that retain water mostly from the effluent seepage of the groundwater and precipitation during monsoon season. Major town/cities situated on the right bank of Chhoti Gandak are Nichlaul, Maharajganj, Kaptanganj, Salempur and Lar, whereas the important locations on the left bank are Siswa Bazar, Kushinagar, Kasia, Pathardewa, Bhatpar Rani and Gothani.

Fig. 4 Older alluvium (*buff colour*) and younger alluvium (*cream colour*) at the bank of Chhoti Gandak River, Ganga Plain

2 Geomorphology

Chhoti Gandak River exhibits point bar, natural levee, point bar complex, upland terrace surfaces, river valley terrace surfaces, present-day active channel, meander cut-off, abandoned flood plain and oxbow lakes as the main depositional geomorphic units which also explain about the river metamorphosis (Fig. 5). Major geomorphic and sedimentological variations, which changes discharge of river, supply of sediment and mean grain size of the channel sediments, force an adjustment to the nature of the channel, and the channel transforms its state and adjusts to maintain the equilibrium (Awasthi and Singh 2012). The dynamics of river channel adjustment during the period of instability are inadequately understood and have not been studied in detail.

In proximal part, river shows a narrow channel and exhibits very low relief. This area remains swampy almost throughout the year with densely mixed forests. The middle part of the basin is characterized by narrow channel in the wide valley exhibiting a 'misfit' river with a gentle slope gradient. The presence of abandoned channels, meander scars and oxbow lakes are the characteristic features of middle part. In the distal part, Chhoti Gandak shows entrenched channel with cliffs of about 7–8 m high. Number of ponds, tals, lakes and low-lying areas are important geomorphic features in the distal part of the river basin.

Fig. 5 Point bar deposits in the Chhoti Gandak River, Ganga Plain

3 Morphometry

Long-term fluvial dynamics and its responses to exogenic changes are playing important role in the evolution of drainage network. The drainage basin parameters were carried out in the laboratory and verified in the field for mitigation of flood and groundwater recharging (Singh and Awasthi 2011a). Figure 6 shows the Chhoti Gandak River Basin and its stream. The analysis explains that the first-order streams are dominant, slope gradient is gentle, surface run off is low, sediment production is low, infiltration rate is high, and the value of basin relief is low. The spreading of water and concentration of peak discharge in the distal part of the river basin and low water storage capacity explains that high precipitation in catchment area leads to flood in the distal part of the river basin. The value of the bifurcation ratio (4.34) indicates that the drainage is natural and not influenced by the geological structures such as lineaments and faults (Singh and Awasthi 2011a). Most of the Ganga Plain Rivers are draining towards SE due to local slope gradient topography and lineaments (Singh and Rastogi 1973).

The morphometric parameters explain the nature of basin behaviour which may be used to predict the flood during continuous rainfall. It also explains that management, development and planning for water resources should be done in the light of drainage basin parameters and land-use pattern.

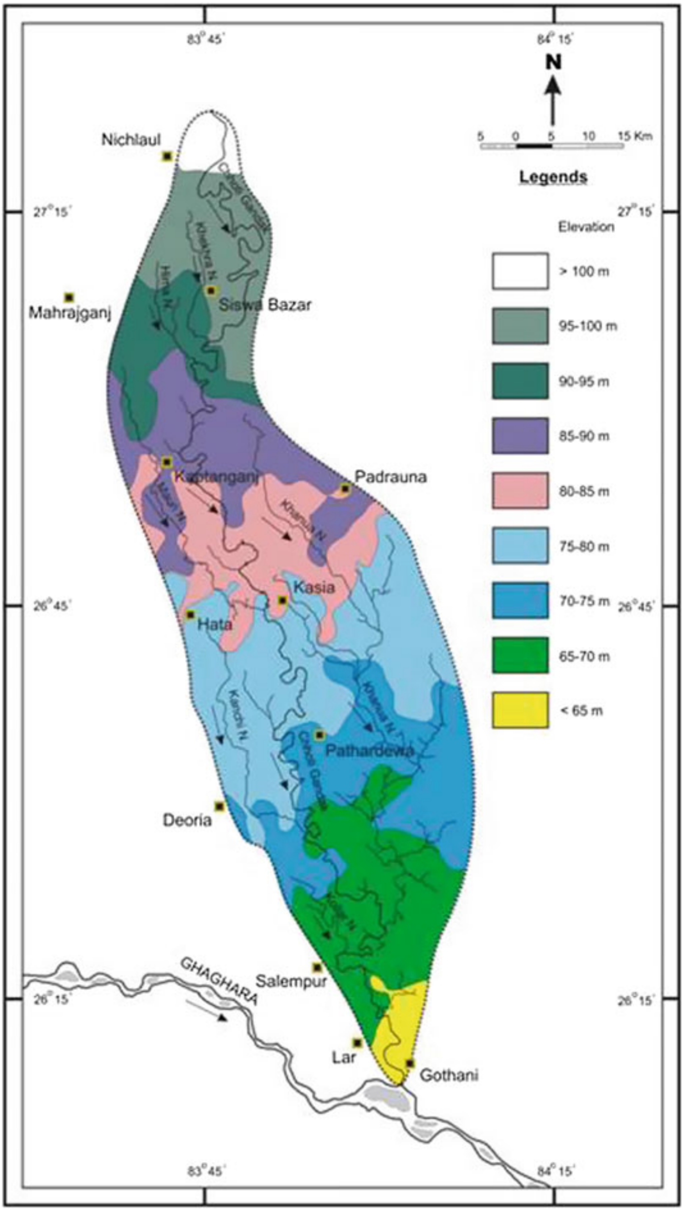

Fig. 6 River basin of the Chhoti Gandak River, Ganga Plain showing elevation, and *left bank* and *right bank* tributaries

4 Geochemistry

The role of hydrogeochemistry in understanding the influence of major processes of transport, dispersion and deposition of the constituents in fluvial system of Chhoti Gandak River Basin has been carried out in detail (Bhardwaj and Singh 2012), which may help to evolve the methodology for detailed seasonal hydrogeochemical investigations for other river basins. The sedimentology and geomorphology of the area would help in understanding the mobilization of major and minor constituents and weathering products of this dynamic fluvial system. The hydrogeochemistry of the Chhoti Gandak River (Bhardwaj et al. 2010a), natural and anthropogenic contribution to the water chemistry and water quality using principal component analysis (Bhardwaj et al. 2010b) and the environmental repercussions of sugar cane industries (Bhardwaj et al. 2010c), especially the metal quantification in top soil and subsurface water as well as the quality assessment of surface and subsurface water (Bhardwaj and Singh 2011), have been carried out.

Hydrogeochemistry of the basin includes the major ion chemistry, seasonal variation in solute concentrations and the source and mechanisms controlling the major water chemistry. It also includes major ion chemistry, seasonal variation in solute concentration, water mineral equilibrium, major hydrochemical facies during pre-monsoon, monsoon and post-monsoon season, and discussion regarding seasonal variations in concentration and mean chemical composition. The chemical analysis of Chhoti Gandak River reveals that like most of Indian rivers, the Chhoti Gandak River is alkaline in nature. Calcium and bicarbonate are the dominant ionic constituents in the water of Chhoti Gandak River. Bicarbonate accounts for 57% of the TDS and 63% of total anions. High concentration of bicarbonate indicates dominance of chemical weathering in Chhoti Gandak River Basin. Water chemistry of Chhoti Gandak River Basin is largely controlled by weathering of the rocks and little contributions from atmospheric and man-made sources. The estimate of bicarbonate fractions indicates that about 90% of the bicarbonate in the water of Chhoti Gandak River is derived from the carbonates and the rest is contributed by silicate weathering. A remarkable seasonal and spatial variation is noticed in solute concentrations in the water chemistry of Chhoti Gandak River. Most of the dissolved ions have their maximum concentrations in pre-monsoon season and minimum concentration during post-monsoon season. Seasonality in the ionic concentrations is probably related to the flow regime of the rivers. The concentration is increased by evaporation due to high temperature during low water flow during non-monsoon period, while the dilution effect of atmospheric precipitation in the monsoon seasons (high flow regime) is responsible for low ionic concentration.

The environmental repercussion of sugar cane industries in this river basin includes physiochemical details of soil, industrial swamp water and groundwater with cation-anion chemistry, metal quantifications with respective assessments. Cation exchange capacity and sodium adsorption ratio are calculated, which is an indicator of the soil fertility. The naturally occurring and anthropogenically induced metals in the soil were distinguished. The geochemical properties, industrial waste disposal, inadequate application of agrochemicals and their interaction with environment describe the implementation of sustainable integrated wastewater management plan in this and similar industrial regions. The soil is alkaline with dominance in Ca^{2+} that causes flocculation. The soils are not salt-affected as indicated by SAR values and EC. The concentration of Cu, Zn and Pb in the soil is high due to high specific absorption which makes these elements not to leach down. The Cu, Zn and Pb values in soils are higher due to domestic and agrochemicals such as sewage sludge, applications of Cu/Zn-based fungicides, and applications of animal manures. The soils are classified as low potential ecological risk with respect to Cu, Zn and Pb. The groundwater is contaminated with concentration of metals due to industrial waste, leaching in the soil and agricultural run-off (Fig. 7).

Water quality investigations explain the surface and groundwater suitability for industrial, domestic and agricultural purpose. It indicates that anthropogenic activities affect the socio-economic developments with spatial variation in water quality and are closely related with the hydrological characteristics. For domestic purposes, water is suitable; however, at some stations, it is unsafe for drinking. The groundwater and surface water are suitable for livestock. The surface and subsurface water can be used for irrigation purpose for most of the soil as indicated by Wilcox diagram, US salinity diagram, permeability index and residual sodium carbonate. The high vales of magnesium hazard indicate restricted use for irrigation at some stations. Most of the waters are supersaturated for dolomite, calcite and aragonite and so not useful for industrial uses or can be used after accessing the demand in terms of chemistry of the particular industry. The chemical composition of river water and its downstream variation is controlled by land use, amalgamation of natural sources and anthropogenic activity near the river.

Fig. 7 Sugar cane industry in Chhoti Gandak River Basin, Ganga Plain

5 Sedimentology

The sediment grain parameter, palaeocurrent pattern and facies analysis of the point bar and natural levee deposits has been analysed to understand the sedimentology of the fluvial landforms of the Chhoti Gandak River (Singh et al. 2009, 2013). The study describes that the size of point bar, sorting, skewness, kurtosis of the sediments and discharge of the river increases, whereas the mean size of the sediment decreases in the downstream direction. Six point bar lithofacies, namely planar cross-bedded, trough cross-bedded, low angle planar cross-bedded, ripple laminated, climbing ripple laminated and laminated mud, and four natural levee lithofacies, such as mottled silt, mottled silty sand, shelly clayey silt and alternating silt and clay, were identified (Singh and Singh 2005; Singh and Awasthi 2009).

6 Subsurface Facies

The subsurface borehole data of Central Ground Water Board and State Ground Water Departments, together with the data collected in the field provide the subsurface information (Awasthi and Singh 2011). Coarse-and fine-grained sediments such as gravel, sand, silt and clay are the main components of different facies which were formed under various sedimentary environments. Sandy facies are formed by high energy river; however, clayey facies are formed beyond the river by low-energy ponding conditions. Top silt-clay unit is followed by boulders and gravels of colluvial and fluvial origin in the northern part around Nautanwa and Nichlaul. The sediments are micaceous often carbonaceous and fossiliferous which are coarser in north and finer in the south of Gorakhpur (Dwivedi et al. 1997). Palaeo-‘Bhur’ sand are isolated sand mounds and ridges of moderate elevation encountered in the area north of Ghaghara River, around Maharajganj and Deoria. They overlay the older alluvium and designated as palaeo-‘Bhur’ sand in order to differentiate it from the Bhur sands (Pascoe 1973). These deposits are devoid of primary sedimentary structures. The deposition of ‘Bhat’ alluvium took place after the deposition of older alluvium and palaeo-‘Bhur’ sand which is well exposed in the eastern part around Kaptanganj and Padrauna. Lacustrine deposits present in the south-eastern part comprising of grey silt and clay with freshwater shells are deposited in low-lying areas and palaeochannels over older alluvium.

7 Climate Change and Monsoon Variability

The climate change and monsoon variability have been analysed in this river basin which is yet not well understood in many parts of the country. Geological records of Ropan Chhapra tal in Deoria district of Chhoti Gandak River Basin provide information to climate change and monsoon variability from 400 to 1200 AD using various proxies (Singh et al. 2015). The environmental magnetic parameters and their ratios (χ_{lf}, χ_{ARM}, SIRM/χ, S-Ratio, $B_{(0)CR}$ and HIRM) inferred dominant antiferromagnetic mineralogy independent of grain size variation.

The lower δ^{18}O values around 480, 540 and 700 AD and from 800 to 1200 AD indicate high intensity of ISM during warm and humid conditions.

The higher silt content 800 AD onwards is due to increase in surface run-off due to increased precipitation, and high clay percentage around 500, 580 and 740 explains low-energy (ponding) conditions during weak Indian Summer Monsoon (ISM). The well-sorted sediment explains the uniform energy condition and constant bottom water depths of lacustrine environment. The sediment textures, mineral magnetic parameters and stable isotopes study indicates intense ISM at ~480 and ~540 which resulted flood around 700 AD and weak monsoon at 580 and 740 AD which caused drought at 500 AD The strong summer monsoon during ~800–1200 AD is synchronous with MWP, whereas after 1200 AD, the weak monsoon coincides with onset of the Little Ice Age (LIA) (Singh et al. 2015). Pollen proxy records from 1.2 m deep sediment profile from the Ropan Chhapra Tal have revealed that between 1350 and 600 year BP, open grassland vegetation comprising largely grasses and heathland taxa viz., Asteraceae, Chenopodiaceae/Amaranthaceae, etc. with sprinkle of trees viz., Holoptelea, Symplocos, Acacia, etc. occurred in the region adjoining to the lake under a dry climate with moderate monsoon rainfall (Trivedi et al. 2011).

The lacustrine sediments of 90-cm-thick profile of Nikahari Tal (lake), near Ropan Chhapra in Deoria district Chhoti Gandak River Basin, were also analysed for climate and vegetational changes since about 1350 AD using pollen analysis, sedimentology and AMS radiocarbon date (Saxena and Singh 2016). The scantiness of tree and shrubby taxa along with higher percentage of clay in the beginning indicates relatively warm and less humid climate than today. The expansion of forest grove within the grassland as a consequence of enhanced precipitation during ~1420–1620 AD. Higher percentage of silt content is due to enhanced precipitation which increases the surface run-off and high water budget under strong ISM during above period. A highly variable vegetation scenario existed during 1620–1900 AD is a consequence of fluctuating climatic conditions. The variable percentages of silt and clay indicate the increase and decrease in the surface run-off so as the water column and energy in the lake, in direct response to enhanced and weak ISM, respectively. High percentages of clay elucidate stagnant low-energy ponding condition under weak ISM during the Little Ice Age (LIA). Pollen analysis coupled with sediment grain parameters indicates intense ISM from 1400 to 1600 AD and 1850 AD onwards and weak monsoon around 1600–1750 AD. The signals of weak monsoon around 1650, 1770 and 1850 AD are synchronous with the Little Ice Age.

8 Geohydrology

The water discharge of this river is in direct response to the ISM in the catchment area. Average and normal rainfall is beneficial for the society, whereas heavy rain causes flood and affects the society. Table 1 shows the rainfall at various stations in

Table 1 Rainfall data in different years in Chhoti Gandak area (in mm)

S. No.	Year	Deoria	LAR
1	1972	863.40	929.90
2	1974	2117.40	1400.30
3	1976	879.70	908.50
4	1978	1116.40	1040.70
5	1980	2308.80	1320.60
6	1982	1253.80	696.73
7	1984	1781.90	1013.84
8	1985	849.80	798.40
9	1994	564.7	812.3
10	1995	543.7	905.8
11	1996	881.4	1057.7
12	1997	705.8	655.7
13	1998	1158.0	1309.7
14	1999	839.9	1097.0
15	2000	953.9	1367.6
16	2001	687.9	1380.2
17	2002	581.8	938.8
18	2003	–	–
Average		768.5	1058.3

this river basin. This region is adversely affected by flood and depletion of groundwater. It has been described that whenever rainfall is high, there is flood in the Chhoti Gandak River Basin (Singh and Awasthi 2011a).

9 Natural Hazards

The fluvial hazards are classified mainly in two classes: (a) direct hazards and (b) indirect hazards. Direct hazards encompass physical damages caused by water and/or flowing water such as flood and lateral erosion (Fig. 8). Indirect hazards include water-borne diseases/adverse effect on living being (flora and fauna) caused by polluted soil and water logging. Flood is one of the most disastrous natural hazards, which mainly affects north-east part of the Ganga Plain (Singh 2007). Widening/shallowing and aggradation/degradation of river channel are the analogous processes of lateral erosion. Widening of river channel in its middle reaches is the process of lateral erosion. Lateral erosion takes place due to tilting and migration in preferred direction due to active tectonics in the river valley (Singh and Awasthi 2011b). The highly sinuous and dominance of sandy and silty facies are the places prone to lateral erosion, and the high discharge stations are prone to flooding. Singh and Awasthi (2011b) have described the lateral erosion as a new

Fig. 8 Lateral erosion in the Chhoti Gandak River, Ganga Plain

independent natural river born hazard from the Ghaghara River near the water divide of Chhoti Gandak river basin which is active even when the discharge of the river is low.

10 Mitigation

It has been described that the increasing trend of disasters indicates the unplanned development. The unsustainable development is responsible for the fluvial disasters. Understanding the processes of river channel adjustment with respect to water discharge, size of the sediment, and sediment load of the channel is important for the successful river basin management (Singh and Awasthi 2011a). The pressure of population on land has forced the man to settle within the peril zone of the river. This unplanned settlement makes the lateral erosion a devastating natural hazard (Singh and Awasthi 2011b). Desiltation of the channel and ponds along with the construction of new pits and ponds is prerequisite to mitigate the problem of floods which will also recharge the groundwater. At some places, embankments have been constructed to prevent the society from flooding, whereas casing a river by artificial levee/bank without proper analysis of the fluvial dynamics of the river and its basin is not the permanent solution of recurring flood hazards, but it resulted in catastrophic flooding by levee breaching (Singh et al. 2015). Hence, it is of utmost importance that the fluvial dynamics is to be studied in detail for integrated flood management to keep population and property away from river hazards.

11 Socio-Economic Importance

Tourism and sugar cane industries are the famous source of economy besides the regular agricultural product. Kushinagar is internationally famous as a place of Lord Buddha. Lord Buddha attained Nirvan around 400 BC at Kushinagar, the followers of Buddhism from all parts of the world visit the Kushinagar every year.

Chhoti Gandak River Basin is one of the most fertile and sugar cane industrial belts of India. The sugar industry plays an important role in the economy of the Deoria and Kushinagar districts. Since over a considerable period, this basin has been overexploited and indiscriminately used for the disposal of domestic and industrial wastes and it has invariably received tremendous pollution load. The alarming growth rate of population, unplanned urbanization and industrialization in this region are putting tremendous pressure on the proper management of the water and land resources. These activities have created many environmental hazards such as water and soil pollution, depletion of groundwater level, flood, water logging and problem of alkaline soils. Economic and social developments are closely associated with the nature of the hydrological network. The quality of groundwater in general is suitable for domestic purposes. The quality of groundwater and surface water is suitable for livestock. The Pb, Cu and Zn in the soil are found significantly higher than normal values. Metals such as Fe and Mn in the groundwater are more than the permissible limit as prescribed by the World Health Organization (WHO) (Bhardwaj et al. 2010b).

Integrated waste and waste water management plan is suggested for sustainable development of the soil and water resources in this area for sustainable development and also to maintain the human health (Bhardwaj et al. 2010b). Mitigation of these problems has socio-economic aspect as this river basin is a major contributor to the national food grain stock.

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The Son, A Vindhyan River

Chinmaya Maharana and Jayant K. Tripathi

1 Introduction

In the central part of India, the Son River is mainly flowing through the Vindhya ranges and is a major southern (right bank) tributary of the Ganga River (Fig. 1). The total length of the river is 784 km, out of which about 500 km lies in Madhya Pradesh, 82 km in Uttar Pradesh and the remaining 202 km lies in Jharkhand and Bihar (Rao 1975; India WRIS Project Team 2014). The total catchment area of the basin is 71,259 km^2 (Rao 1975). The Son River originates in the Amarkantak hills of Maikal range at an elevation of $\sim$600 m in Madhya Pradesh, and it merges with the Ganga River 30 km upstream of Patna in the state of Bihar. It flows north–northwest through Madhya Pradesh and turns eastward after encountering the southwest–northeast running Kaimur range of the Vindhyan Supergroup. The river provides good quality water for irrigation and drinking purposes, and among important resources on the river and its tributaries are many dams, reservoirs and hydropower generation plants serving in the region for irrigation and electricity generation.

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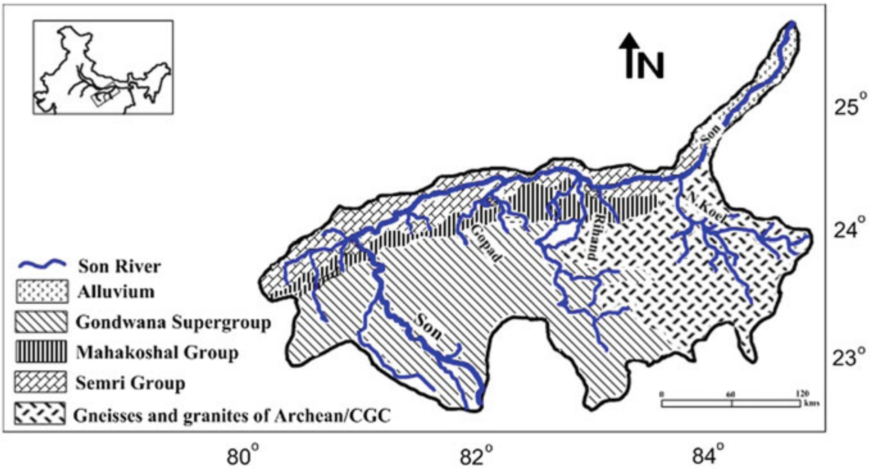

Fig. 1 Drainage basin and geology of the of Son River (after Maharana et al. 2015)

2 Tributaries of the Son River

The major tributaries of the Son River are Rihand, North Koel, Gopad, Banas and Kanhar rivers. All of them emerges in the highlands and flow in a northward direction to join the Son River. Among these, the Rihand is the longest and the principal tributary of the Son River.

The Rihand River flows through the states of Chhattisgarh and Uttar Pradesh. The river rises from Matiranga hills, in the region south-west of the Mainpat plateau. It flows towards the north, roughly through the central part of Surguja district, for 160 km with a catchment of 17,110 km^2 (Rao 1975). The Rihand and its tributaries form a fertile plain in the central part stretching from around Ambikapur to Lakhanpur and Pratappur. Then, it flows north into Sonbhadra district of Uttar Pradesh before joining the Son River. Its main tributaries are the Mahan, Morana (Morni), Geur, Gagar, Gobri, Piparkachar, Ramdia and Galphulla. Many seasonal and perennial rivers join the Rihand reservoir (Govind Ballabh Sagar) such as the Kanchan, Mayar and Azir.

The North Koel River emerges from the Ranchi plateau and enters Palamau division, below Netarhat near Rud in Jharkhand. From its source to its confluence with the Son River its length is about 260 km and since it drains a catchment area of at least 10,360 km^2 (Rao 1975), it naturally contributes a large supply of water to the Son River during the rainy season. The North Koel, along with its tributaries, meanders through the northern part of Betla National Park. The principal tributaries are the Auranga, Amanat and Burha.

The Gopad River originates from the hills on the north of Sonhat plateau in the Sarguja district of Chattisgarh covering an area of 5,998 km^2 (Rao 1975). Initially, it receives water from the Goini and Neur rivers. The Sehra, Kandas and Mohan are its important tributaries. The Gopad merges with the Son near Bardi. The Kanhar tributary of the Son River flows through the states of Chhattisgarh, Jharkhand and Uttar Pradesh over an area of 5,903 km^2 (Rao 1975). The Kanhar originates on the Khudia plateau in Jashpur district of Chhattisgarh. It merges with the Son River to the north-east of the village of Kota. It has a rocky bed almost throughout its course and flows swiftly through forested areas with some waterfalls located along the track of the river. The Theme, Lanva, Pandu, Goita, Hathinala, Suria, Chana, Sendur, Kursa, Galphulla, Semarkhar, Riger and the Cherna nallah are important tributaries of the Kanhar.

3 Geomorphology

The Son River has a sharp gradient of 70–80 cm per km in the stretch from Rohtasgarh to Dehri. After entering into the Bihar plains, it flows with an average gradient of 30–50 cm per km (Sahu et al. 2010). The channel of the Son River is very wide (about 5 km) at Dehri and shallow in the plains. However, the river is moderately incised having 8–16 m bank cliffs in downstream of Daudnagar up to Koelwar (Sahu et al. 2010). The floodplain of the Son River is narrow with a width of 3–5 km.

Drainage: The tectonically controlled Son River flows along the Son Narmada lineament. It has been suggested that the tectonic resettlement process causes changes in the Son River courses (Ghosh 2015). However, Lakshmanan (1970) has suggested that the course of the Son River has been controlled by lithology and not by any major faulting and the present drainage of the Son basin was superposed from Deccan trap cover. The denudation of Deccan traps has led to the exposure of the older formations. All the northward-flowing tributaries join the mainstream of the Son River by a process of differential and headward erosion.

Most of the tributaries of the Son River to the south of the Kaimur range, with a few exceptions, have a northerly or north–northwesterly course before joining the Son River. Over a long distance, the Son River flows through the soft Kheinjua rocks of the Lower Vindhyans. Oldham et al. (1901) suggested unilateral drainage of the Son River, while Lakshmanan (1970) suggested that it was due to the higher altitude of the eastern edge of the Satpuras and general north-northeasterly slope (Fig. 2).

Channel morphology: The Son River in the plains of Bihar shows a braided character with many braid channel sandbars in its course up to the Ganga River (Fig. 3). Sahu et al. (2010) suggested from the study of palaeochannels that the most dynamic part of the river starts from Daudnagar with nine major avulsions within this reach up to Koelwar (about 90 km channel length). They have found evidence of channel incision at an average rate of 2.50 cm/year from the available discharge and gauge height data from Koelwar (for the period of 1961–1989) indicating the degrading nature of the river. Geddes (1960) described that the Son River is flowing in a megafan created by itself.

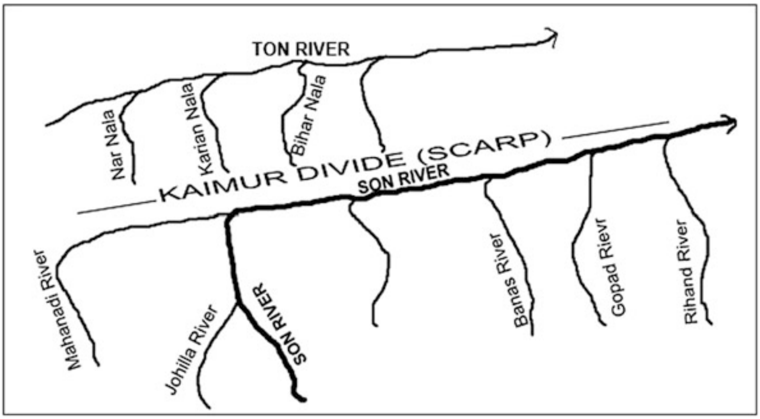

Fig. 2 Major drainage trends and unilateral drainage of the Son River (redrawn after Lakshmanan 1970)

Fig. 3 Field photograph is showing braiding in the Son River

4 Geology

The Son River drains through various peninsular lithological units during its course. The major lithological units within the Son River basin are the Gondwana and Vindhyan Supergroups, Mahakoshal Group, Central Granitic Complex (CGC) and Quaternary alluvium (Fig. 1). The Son River principally flows through Gondwana Supergroup (sandstones and shales), Semri (sandstone, shale, carbonates) and Kaimur (sandstone, shale, minor carbonates) Groups of the Vindhyan Supergroup and Quaternary alluvium. Its tributaries Rihand, North Koel and Gopad drains through Gondwana, Mahakoshal Group, Archaean gneiss and Central Granitic

Complex (gneisses and granites) (Lakshmanan 1970; Ray 2006; Ramakrishnan and Vaidyanadhan 2008).

Williams and Royce (1983), Williams and Clarke (1995) and Williams et al. (2006) have studied the late Quaternary sedimentary sequence in the Middle Son valley. They identified and mapped five widespread alluvial formations. The formations, from oldest to youngest, are the Sihawal formation, Khunteli formation, Patpura formation, Baghor formation and Khetaunhi formation. The Sihawal formation overlying bedrock consists of alluvial fan and debris-flow gravels in a clay matrix, which is overlain by reworked aeolian clay. The next three formations consist of alluvial sands, clays and gravels with marked unconformities. The youngest unit is made up of alluvial sands and clays and forms the lowest terrace in the landscape. The Middle Son valley possesses a long and rich record of hominin occupation from all periods of the Palaeolithic, which is rare for the other sites of India (Jones and Pal 2009).

Singh (2014) analysed the tectonic landforms and various geomorphic features related to the drainage pattern present in the Narmada–Son Lineament zone of southern Sonbhadra district in Uttar Pradesh. He demonstrated using aligned drainage, parallel and linear valleys, offset channels, peculiar river profile section and scarps that the area is undergoing active deformation, and the N–S to NNW–SSE and E–W to ESE–WSW are the most recent active trends of the study area.

5 Soil, Vegetation and Climate

Major groups of soils in the Son River basin include deep medium black soil, mixed black and red soil, red soil, alluvial and lateritic soil in the upper reaches of plateau and uplands of Madhya Pradesh, Uttar Pradesh and Bihar (Department of Farmer Welfare and Agriculture Development; Central Ground Water Board 2013a, b, c). In the lower reaches, the alluvial soils of Uttar Pradesh and Bihar range from sandy, silty loam, to loamy in nature (National Bureau of Soil Survey and Land Use Planning 2003; Central Ground Water Board 2013c).

The upper reaches of the Son River basin mainly within the Madhya Pradesh state is heavily forested. The important forest types here are tropical moist, tropical dry and subtropical broad-leaved hill forests. Teak, sal and other miscellaneous trees are major flora in these forests. In the middle portion, the Vindhyan forests consist mostly of scrub. These forests are composed of dhak, teak, mahua, salai, chironji and tendu. The river in the alluvial plain mainly consists of grasses and scrub. The major crops of the Son River basin include paddy, wheat, maize, jowar, barley, bazra, urad, moong and sugarcane.

The Son River basin has a subtropical climate. It has a hot dry summer (April–June) followed by monsoon rains (July–September), and a cool and relatively dry winter. In the upper reaches, the average annual rainfall is about 900–1,300 mm, and the average annual temperature is 25 °C. In the southern Uttar Pradesh, it has a tropical monsoon climate with an average annual temperature of

25 °C and average annual rainfall of 1,250 mm. In the Ganga plains of Bihar, the Son basin experiences 100–140 mm of rainfall and 27 °C temperature annually on an average basis.

6 The Son River Water

The hydrogeochemistry of the Son River water was studied by Maharana et al. (2015). As usual for the Indian rivers, most of the measured parameters exhibit a relatively lower concentration in the post-monsoon as compared to the pre-monsoon season. They have shown that Ca^{2+}, Mg^{2+} and HCO_3^- are major ionic species in the river water. The influence of continental weathering aided by secondary contributions from groundwater, saline/alkaline soils and anthropogenic activities in the catchment appears to be controlling the river water chemistry. The carbonate weathering dominates over the silicate weathering in controlling water composition of the river. The study indicated that the Son River water is good to excellent in quality for irrigation and also suitable for drinking purposes.

7 Socio-economic Importance of the Son River

The major cities located along the bank of the Son River are Shahdol in Madhya Pradesh, Sonbhadra in Uttar Pradesh, Dehri and Patna in Bihar. The Ban Sagar Dam, a multipurpose river Valley Project on the Son River, is important for both irrigation and hydroelectric power generation in the region. One of the oldest irrigation systems in the country was developed in 1873–1874 with an anicut across the Son at Dehri in Bihar. Water from the Son feed canal systems on both sides of the river and irrigate large areas. The canals are of enormous benefit to the agriculture in the region. Sand mining, both legal and illegal, from the Son River bed, has been a serious threat to the ecosystem and health of the Son River. According to the India WRIS Project Team (2014), the Son sub-basin has 69 dams located in Madhya Pradesh, 64 dams in Chhattisgarh, 14 dams in Jharkhand and 12 dams in Uttar Pradesh. The famous Ban Sagar, Rihand and Obra hydropower plants occur in the Son River basin. The basin has total seven powerhouses, among them three in Madhya Pradesh, two in Uttar Pradesh and one each in Jharkhand and Bihar (India WRIS Project Team 2014). A decreasing trend in the hydropower generation has been observed in the last three decades for the Son River valley hydroelectric power generation (South Asia Network on Dams, Rivers and People 2011). The Kaimur wildlife sanctuary is situated in the famous Kaimur hills range of Kaimur district of Bihar near Bhabua. Many waterfalls and lakes decorate the valley portion of the sanctuary. The main wildlife of this sanctuary is tiger, leopard, sloth bear, four-horned antelope, chinkara, Indian wolf peacock, hornbill and marsh crocodile (India WRIS Project Team 2014).

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The Great Gandak River: A Place of First Republic and Oldest University in the World

Dhruv Sen Singh

1 Introduction

Great Gandak is a left bank tributary of the Ganga River (Fig. 1a) which flows in Nepal and India. It is a snow-fed, braided river which is characterized by high discharge, high bedload and low load of suspended sediment. It originates in the Higher Himalaya (Fig. 1b), near Nhubine Himal Glacier in the Mustang region of Nepal Himalaya. A considerable portion of its catchment lies in the glacial region. In Himalayan reaches, it is called Sapt Gandaki, because it receives water and sediment from seven different rivers, from west to east these are Kali or Krishna Gandaki, Seti, Marshyandi, Darondi Khola, Burhi Gandaki, Thaple Khola and Trishuli. The river flows through one of the highest mountain peaks of the world Dhaulagiri (8167 m) and Annapurna (8091 m) and forms the world's deepest gorge and canyon and so the drainage pattern is antecedent.

The Great Gandak locally known as Narayani brings Shaligram (nodules containing ammonoids, believed as God Vishnu Narayan in Hindu religion) from its origin up to Tribeni Ghat in Nepal. The main stream of Great Gandak is Kali Gandaki, and the largest tributary is Marshyandi. The Kali Gandaki river flows southward through a steep gorge which is one of the deepest gorge in the world. The Great Gandak crosses the southernmost foothills of the Himalaya known as Siwaliks and enters into the terai region of Nepal, west of Sumeshwar hills, at the Indo-Nepal border at Tribeni (120 m) (Fig. 2). Sonaha, Manaha and Panchanad River join the Great Gandak near Tribeni.

The river enters in India at Bhainsalotan (Balmiki Nagar) of West Champaran district in Bihar. There is a berrage/dam near Bhaisalotan from where four canals are emerging, two in east and two in the west for Nepal and India. Great Gandak flows southeast for about 300 km in the alluvial plain through West Champaran,

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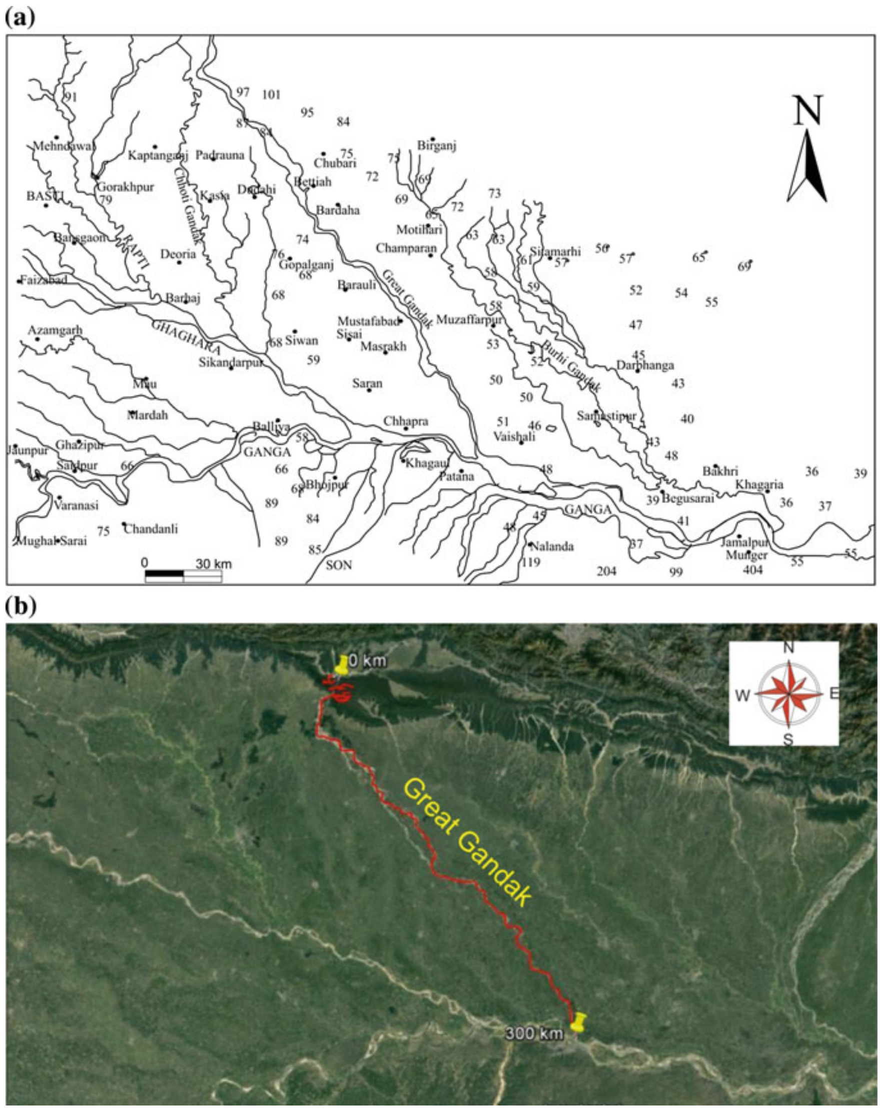

Fig. 1 **a** Location map of the Great Gandak River showing cities, elevations, and adjoining rivers. **b** Location map of the Great Gandak River on google satellite data

East Champaran, Muzaffarpur, Gopalganj, Siwan, Saran and Vaishali districts of Bihar state and Maharajganj and Kushinagar district in Uttar Pradesh. It eventually joins with the Ganga, downstream of Hajipur in front of Patna at an elevation of about 44 m (Fig. 3). Near the confluence of Ganga and Great Gandak rivers a big diara known as Raghopur diara is formed where about 50 villages are situated.

Fig. 2 Showing the Great Gandak River at Tribeni in Nepal where it debouches on to the plain at the border of India and Nepal

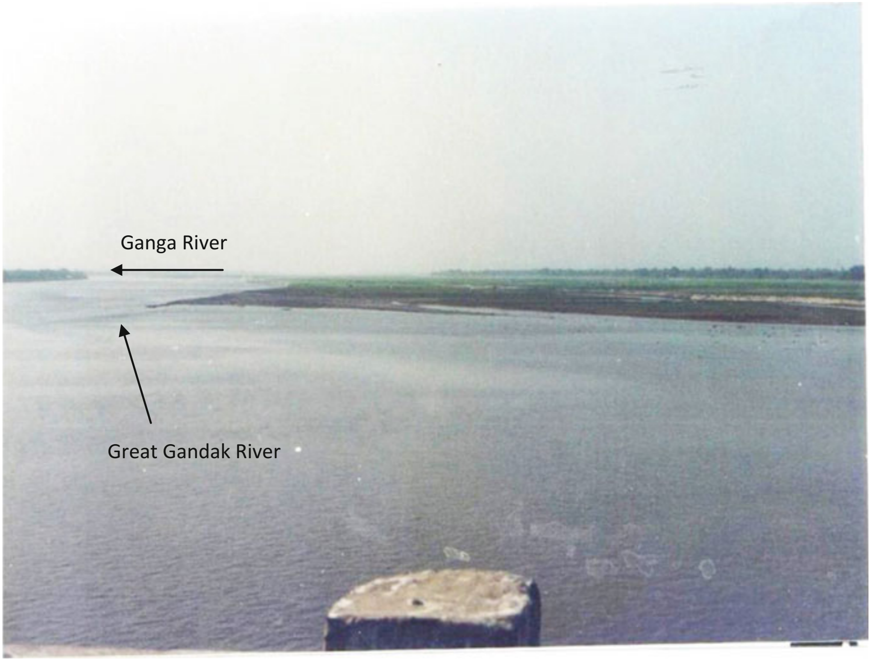

Fig. 3 Showing the confluence of Great Gandak River with Ganga downstream of Hajipur near Patna in Bihar, Ganga Plain

The Gandak River basin consists of many glaciers and glacier lakes in the Nepal Himalaya. Retreat of glaciers and damming by moraines has increased the formation of lakes. The formation of glacial lake and its outburst flood events occurring in Nepal have been frequently reported in news papers for many decades. Recently, the glacial lake outburst flooding and the landslide lake outburst flooding caused the Kedarnath tragedy (Singh and Mishra 2002; Singh 2013, 2014).

In the upper reaches, river flows along the international boundary of Nepal with Bihar of India for a distance of 20 km. After this, it makes the state boundary between Maharajganj and Kushinagar districts of U.P. and Champaran district of Bihar up to Tengri Ghat. In the downstream part, it forms the district boundary of Gopalganj, Siwan, Chhapra and Sonpur with Champaran, Muzaffarpur and Vaishali of Bihar state, respectively. The tributaries of Gandak River are only small rivers (Nalas) such as Kakara Nala and Bodha Nala. No large river joins the Great Gandak throughout its reach. Most of the tributaries emerges from foothills and joins the Great Gandak in Champaran district of Bihar. Generally, the old and abandoned channel of Great Gandak join, splits and forms the anastomosing channel pattern and thus increases and decreases its water discharge.

2 Geomorphology

It has been identified and reported that Great Gandak forms a megafan at the border of eastern Uttar Pradesh and north-western Bihar (Singh and Singh 2005). The megafans consist of sediments eroded from the rapidly uplifting Himalaya. The Gandak Megafan is drained by a number of rivers, which are now entrenched due to climatic fluctuations and base-level adjustments. These rivers rarely overtop their banks and therefore unable to modify the surface configuration of the fan further. Hence, the fan is now a 'relict' (Singh 1996) 'landscape fossil' (Mukerji 1990). In the active phase, the rivers were distributing the sediments on the surface of the fan during bankfull stage and within the channel during low water stages. The geomorphology and pedology of the Gandak Megafan have been described by Mohindra and Parkash (1994) and Mohindra et al. (1992).

From west to east streams such as Rohini, Chhoti Gandak, Jharahi, Daha, Gandaki, Dabra, Mahi, Great Gandak, Baya, Dhanauti, Balan and Burhi Gandak drain the surface of the fan (Singh and Singh 2005). These streams are arranged in a radial pattern, which is one of the most important geomorphic features of a fan. Irrespective of meandering and braiding pattern (Fig. 4), the channels of all the streams are more or less straight in their course and do not show any significant changes in the direction of flow. These streams either join themselves or drain into the Ghaghara or Ganga (the fan boundary streams). Some of the streams originate in the Himalaya while others on the fan surface (alluvial plain). Those originating from Himalaya are braided in nature, while those originating on the fan are meandering in nature and are either ground water-fed or rain water-fed.

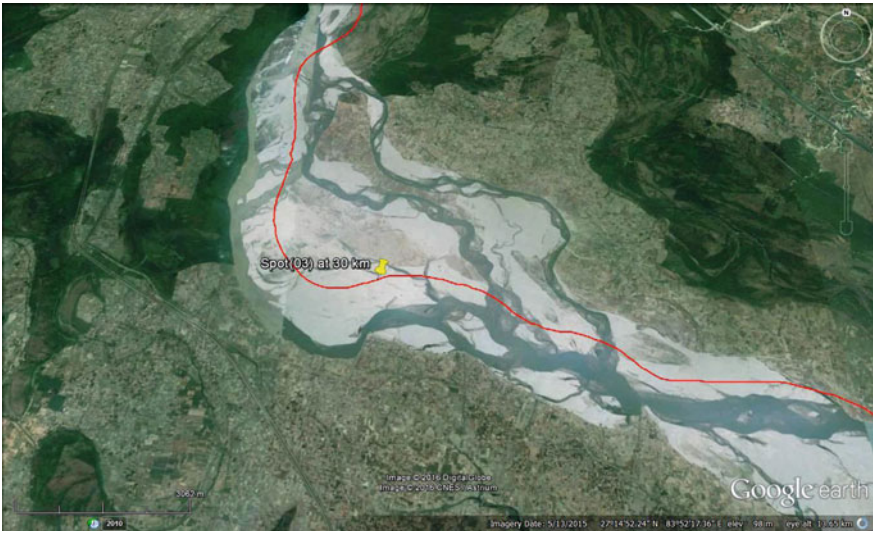

Fig. 4 Showing Braided channel of the Great Gandak River, Ganga Plain

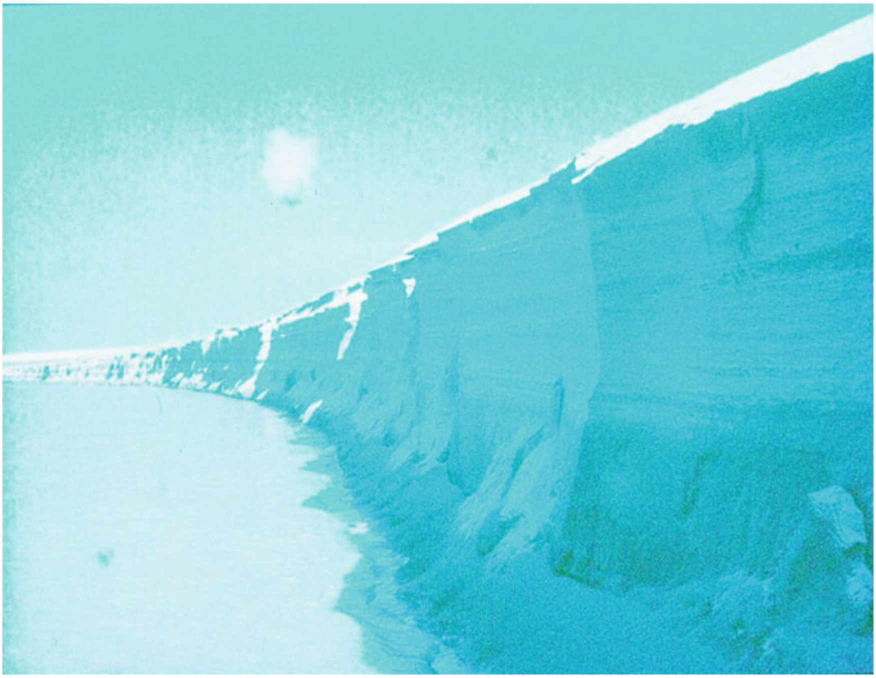

Fig. 5 Showing the cut section of the Braid bar deposits in Great Gandak River at Chhitauni in Uttar Pradesh and Bagha of Bihar, Ganga Plain

The slope gradient of the Great Gandak in proximal, middle and distal part is 60, 42.80 and 15.80 cm/km, respectively. The mean size of the sediments is 1.88, 2.43 and 3.10 ϕ, respectively, in the proximal, middle and distal parts. The valley of the Great Gandak River is very wide. The channel splits and rejoins in the downstream part. At many places, two channels are separated many kilometres from each other. The braid bar deposits are kilometres large in size. The braid bar deposits (Fig. 5) if located far away from each other provide the place for cultivation which keeps on shifting after every monsoon season and or flood event and often becomes the reason for disputes to acquire the land.

The calculation of channel width, valley width and sinuosity of Great Gandak River is shown in Table 1. The valley width varies from 0.50 to 10 km (Figs. 6 and 7),

Table 1 Showing valley width, channel width and sinuosity (Station number is increasing in the downstream direction, no. 1 towards origin and no. 28 is near confluence)

Station	Valley width (km)	Channel width (km)	Elevation (m)	Channel length (km)	Straight length (km)	Sinuosity
1	0.43	0.20	115	1.14	1.11	1.0
2	2.0	0.22	100	1.27	1	1.2
3	4.63	0.31	100	1.61	1.43	1.1
4	5.13	0.29	97	1.49	1.24	1.2
5	3.0	1.10	94	6.38	5.10	1.2
6	9.39	0.34	92	6.32	4.60	1.3
7	7.16	1.17	91	3.53	2.86	1.2
8	4.16	1.08	87	5.42	4.67	1.1
9	4.37	0.35	82	3.50	2.87	1.2
10	6.12	0.17	78	2.06	1.89	1.0
11	9.78	0.25	79	0.52	0.47	1.1
12	10.0	0.45	76	0.89	0.78	1.1
13	9.21	0.28	74	0.63	0.52	1.2
14	7.82	0.44	73	0.69	0.59	1.1
15	8.51	0.78	71	1.05	0.80	1.3
16	9.0	0.45	68	0.83	0.75	1.1
17	4.66	0.97	67	2.26	2.12	1.0
18	4.1	0.39	64	2.87	2.60	1.1
19	6.87	0.57	64	0.83	0.77	1.0
20	2.45	0.44	59	0.55	0.52	1.0
21	4.63	0.12	58	0.64	0.57	1.1
22	5.44	0.49	56	0.78	0.67	1.1
23	3.39	0.73	54	0.39	0.34	1.1
24	4.35	0.53	54	0.99	0.90	1.1
25	3.1	0.79	52	0.65	0.59	1.1
26	2.40	0.79	50	0.88	0.85	1.0
27	3.0	0.41	48	0.93	0.84	1.1
28	3.99	0.35	47	0.63	0.61	1.0

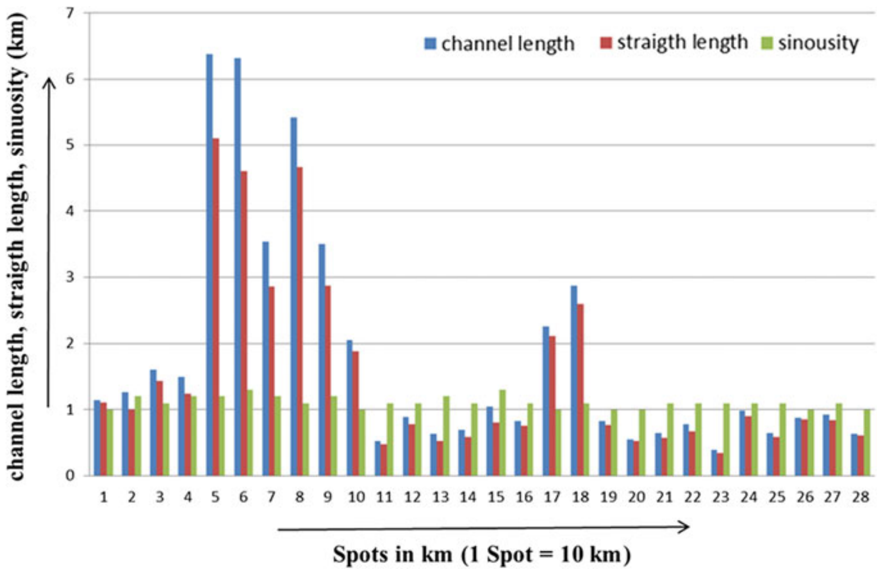

Fig. 6 Graph showing relationship between valley width, channel width and sinuosity of Great Gandak River (Station number is increasing in the downstream direction, no. 1 towards origin and no. 28 is near confluence)

Table 2 Showing the variation in valley width, channel width and sinuosity in the proximal, middle and distal part of the river

S. No.	Part of the river	Valley width (km)	Channel width (km)	Sinuosity
1	Proximal	0.43–2	0.20–0.31	1.0
2	Middle	2–10	0.31–0.97	1.0–1.2 or 1.3
3	Distal	10–3	0.97–0.35	1.2–1.1 or 1.0

minimum in the proximal part and maximum in the middle part of the river (Table 2). The channel width varies from 0.20 to 0.97 km (Fig. 7). The sinuosity of the river at all spots varies from 1 to 1.3 (Figs. 6 and 8) and shows the river is braided in nature.

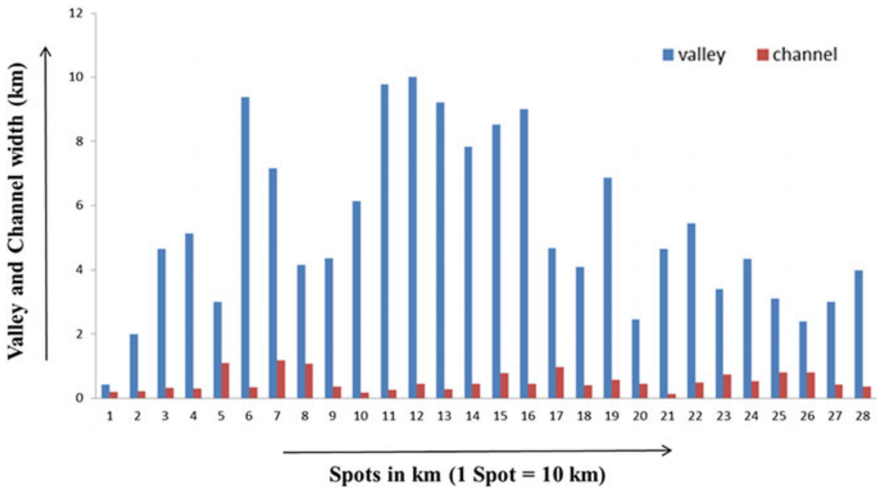

Fig. 7 Graph showing valley width and channel width ratio of Great Gandak River (Station number is increasing in the downstream direction, no. 1 towards origin and no. 28 is near confluence)

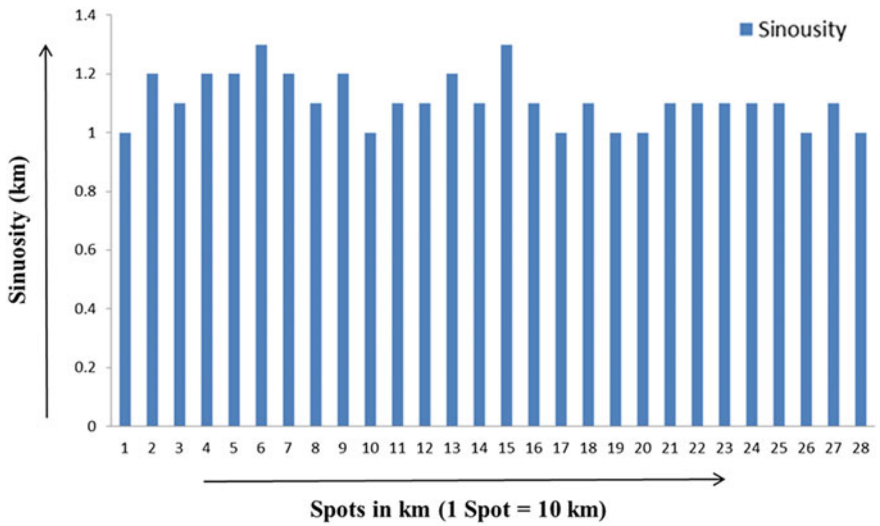

Fig. 8 Graph showing sinuosity of Great Gandak River (Station number is increasing in the downstream direction, no. 1 towards origin and no. 28 is near confluence)

3 Geohydrology

Perennial nature and heavy discharge of the river have been utilized for irrigation purpose, and a barrage was constructed at Bhaisalotan in west Champaran of Bihar. The discharge of the Gandak starts rising in late June. The increase in discharge is due to (i) more melting of ice and snow in the Himalaya and (ii) contribution of rainfall in the river basin during monsoon. The discharge increases from early June to late August every year. September onwards, the discharge decreases every year at each station. Peak discharge at all the stations occurs in August. Discharge value varies from year to year in response to strength of monsoon and snow melting. In all the years, the maximum to minimum discharge at every station varies by a factor of 10–20.

4 Natural Hazards

The river is shallow and shifts within its valley. The valley is very wide and the split channels are several kilometres away from each other. Many villages have evolved and located within the valley and between the channels. Flood management is trying to control the floods by providing total immunity from the effects of all magnitudes of floods modifying the floods by means of structural measures and non-structural measures. Learning to live with the floods by means of other non-structural measures is the goal of flood management (Singh and Awasthi 2011). Besides flooding which affected the basin in years 1998, 1999, 2000, 2001, 2002, 2003, 2004, 2008 and 2012, lateral erosion also affects the area. Lateral erosion has been identified as independent new river-borne hazard in 2011 in the Ghaghara River (Singh and Awasthi 2011).

5 Socio-economic Importance

The important cities and towns in the Indian part of the Great Gandak River are Valmikinagar (Bhainsalotan), Bagaha, Bettiah, Gobindganj and Hazipur and at right bank Chhitauni, Baikunthpur and Sonpur. Great Gandak is famous for hydroelectric power plants in Nepal. The government of Nepal and the Government of India have an agreement on the irrigation, power project, and barrage and canal head. The Gandak River provides irrigation to Nepal, U.P. and Bihar. A barrage and dam had been constructed from where canals are emerging for India and Nepal. The Valmiki Ashram, Chitwan National Park and Valmiki National park are located on its bank. Chitwan National park established in 1973 is a world heritage site and the oldest national park of Nepal which is famous for one horn rhinocerous and tigers. It is believed that at the bank of this river, the great epic, 'Ramayana' was written by Rishi Valmiki. Valmiki National Park of West Champaran, Bihar, is famous for tiger reserves. Both parks are located within 5–10 km distance. The Saligrams stones (black ammonite) are found in the Great Gandak River near Muktinath. These naturally formed stones are used to worship Lord Vishnu.

Vaishali and Nalanda, the capital of one of the states in northern India during Buddha's time and the Buddhist monastic university of that time are situated at the bank of this river. The first republic of the world, i.e., Vaishali is also located at the bank of Great Gandak River.

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The Burhi Gandak: Most Sinuous River

Dhruv Sen Singh, Abhay Kumar Tiwari and Pawan Kumar Gautam

1 Introduction

Burhi Gandak is a left bank tributary of the Ganga River. It is meandering in nature and flows in the southeast direction. The Burhi Gandak river basin is bounded by Himalaya in the north, by Ganga River in south, by Kosi River in the east, and by Great Gandak River on the west and makes the eastern boundary of the Gandak Megafan (Singh and Singh 2005) (Fig. 1a, b). It originates in the terai area of Chautarwa Chaur near Bishambharpur, West Champaran district in Bihar state (Fig. 2). It is known as Sikrana in its upper reaches. Harha, originating near Someshwar Hill, receives water from many small mountainous rivers and is known as Masan when it comes to plain and is the main source of water to Sikrana. Singha, another mountainous river, originating near Someshwar Hill, splits into two, one joins Harha/Masan near Churharwa and the other known as Ramrekha joins Sikrana. Masan and Ramrekha rivers join to form Sikrana at Lauria Nandangarh, and contribute significantly to its discharge. Dhanauti, a highly sinuous almost abandoned river (field observation), meets with Sikrana (Fig. 3) near Pakridayal village, Motihari, and after this confluence, the Sikrana is known as Burhi Gandak. The right main channel of Bagmati meets Burhi Gandak near Rosera and affects its discharge during monsoon season. Traversing a distance of about 400 km in the alluvial plain, Burhi Gandak joins Ganga near Gogri Jamalpur, Khagaria district of Bihar (Fig. 4a, b, c). The Burhi Gandak basin is spread over the West Champaran, East Champaran, Muzaffarpur, Samastipur, Begusarai, and Khagaria district of Bihar.

There are about thirty-two streams which contribute to the Burhi Gandak. Some foothill rivers also join it in the Champaran district. The important tributaries of

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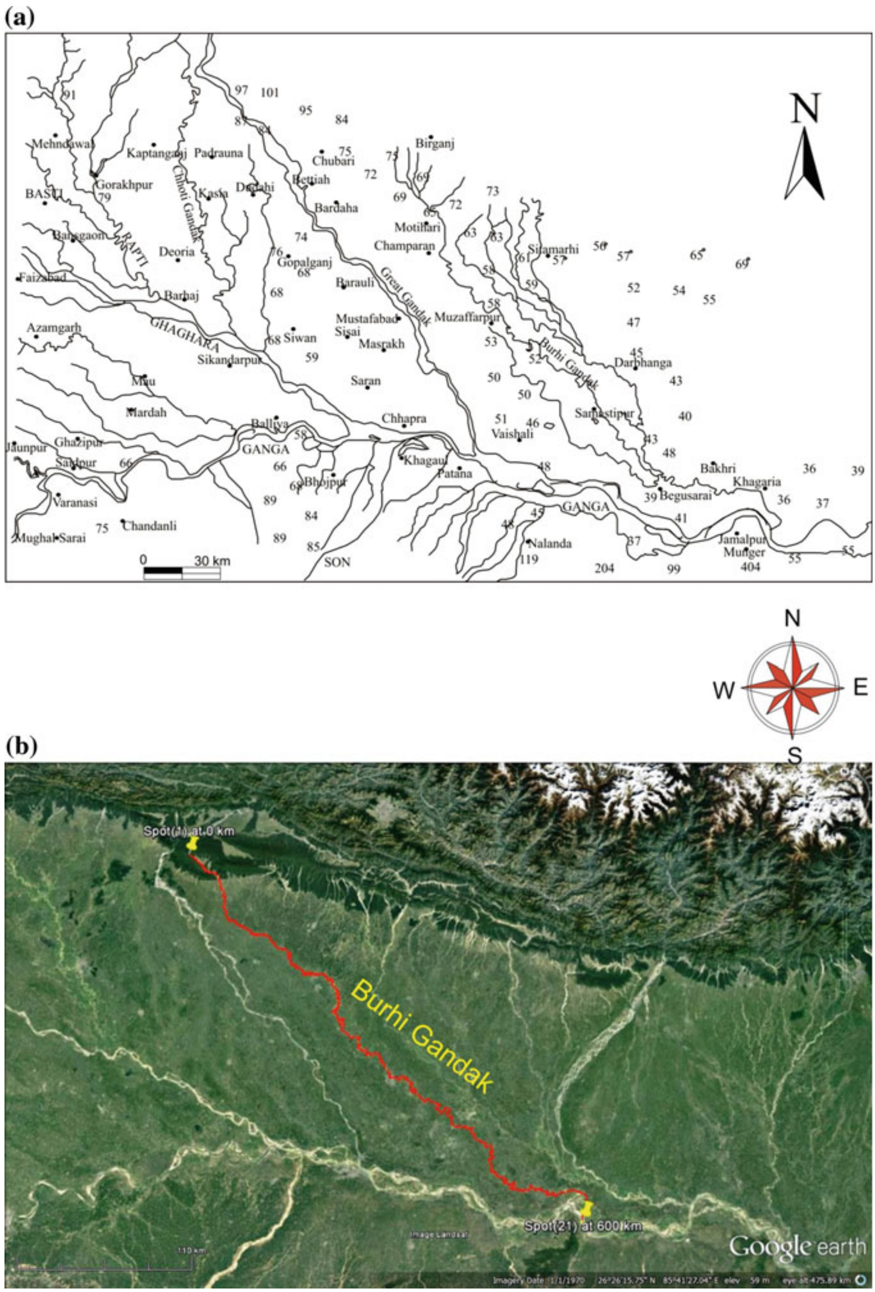

Fig. 1 **a** Location map of the Burhi Gandak River showing cities, elevations and adjoining rivers. **b** Imagery showing location of the Burhi Gandak River in the Ganga Plain

Fig. 2 Sikrana River near its origin (Burhi Gandak in upstream region) in Champaran district of Bihar, Ganga Plain

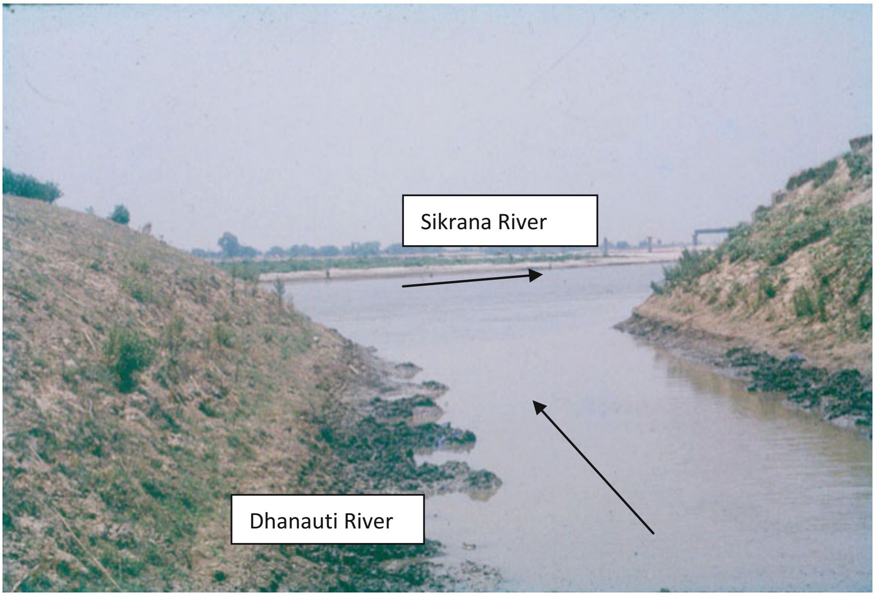

Fig. 3 Showing confluence of Dhanauti with Sikrana near Pakridayal, Motihari in Bihar, Ganga Plain

Burhi Gandak are Masan, Ramrekha, Singha, Pandai, Urai, Konhra, Parah, Gadh, Tiar, Jamni, Dhanauti, Nuna, Kedana, Baler, Sikta, Tilawe, Manjhar, Hawa, Dudharwa, Dera, etc.

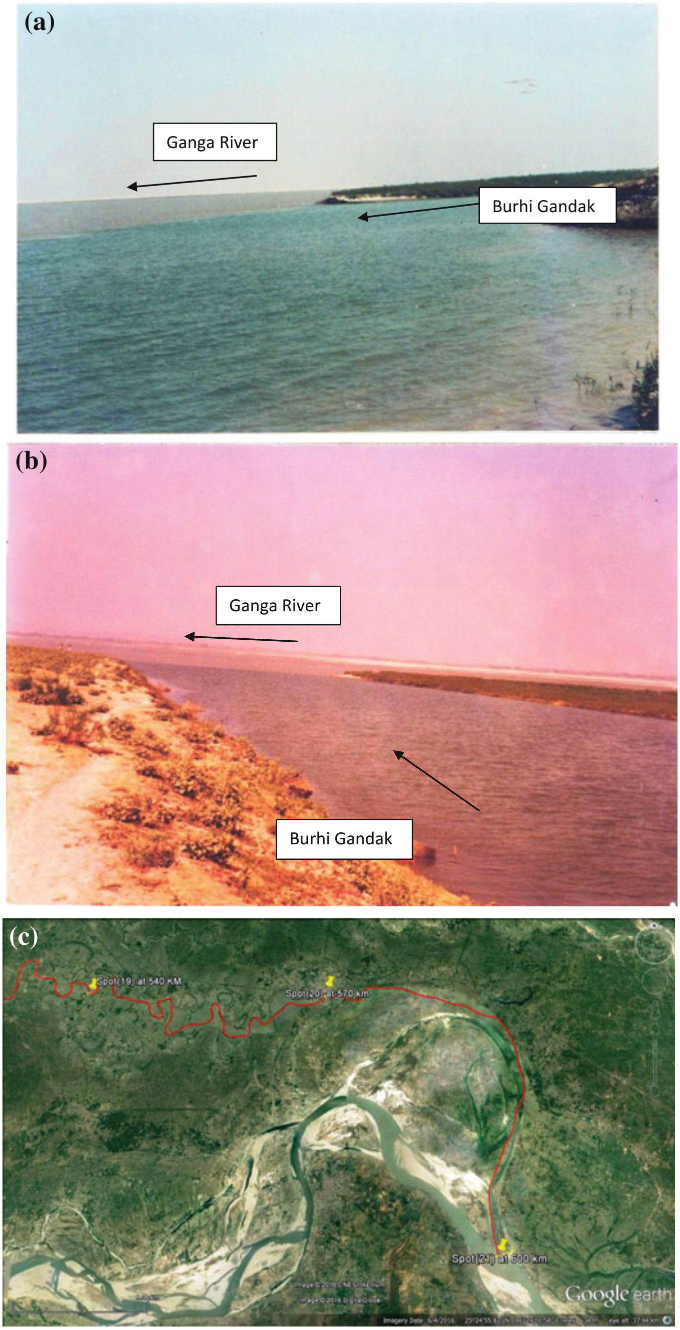

Fig. 4 **a** Showing the confluence of Burhi Gandak River with Ganga River near Gogri-Jamalpur in Bihar, Ganga Plain. **b** Another view showing confluence of Burhi Gandak with Ganga at Gogri-Jamalpur in Bihar, Ganga Plain. **c** Showing confluence of Burhi Gandak with Ganga at Gogri-Jamalpur in Bihar, Ganga Plain

2 Geomorphology

Burhi Gandak River exhibits point bars (Fig. 5), oxbow lakes, meander scars (Fig. 6), and abandon channels. In the middle and downstream part of the river, the river terraces (Fig. 7a, b), point bars, floodplain deposits (Fig. 8), and natural levee deposits are very prominent. The channel is shallower in the proximal part; however, the entrenchment increases in the downstream part.

The Burhi Gandak is highly meandering (Fig. 9) in the Samastipur and Begusarai districts. At many places the river channel splits which, rejoin in the downstream part of the river forming the anastomosing channel pattern.

The slope gradients in the proximal, middle, and distal parts are 69.0, 12.0, and 8.60 cm/km, respectively. And the mean size of the sediment is 2.03, 2.44, and 2.94 ϕ, respectively (Singh and Singh 2005). The valley width varies from 20 to 800 m, minimum in the proximal part and maximum in the distal part (Fig. 10). The channel varies from 10 to 350 m, minimum in the proximal part and maximum in the distal part. The elevation is maximum 230, 124, and 90 m in the proximal part and minimum 43, 38, 31 m in the digital part. The calculation of channel width, valley width, and sinuosity of Burhi Gandak River is shown in Table 1, and graph between these three is mentioned in Fig. 11.

The sinuosity varies from 1.1 to 5.9 except with one spot where it is 13.9 (Fig. 12). The sinuosity is low in proximal part and high in the middle part and again low in distal part (Table 2).

Fig. 5 Showing point bar in Burhi Gandak River at Muzaffarpur in Bihar, Ganga Plain

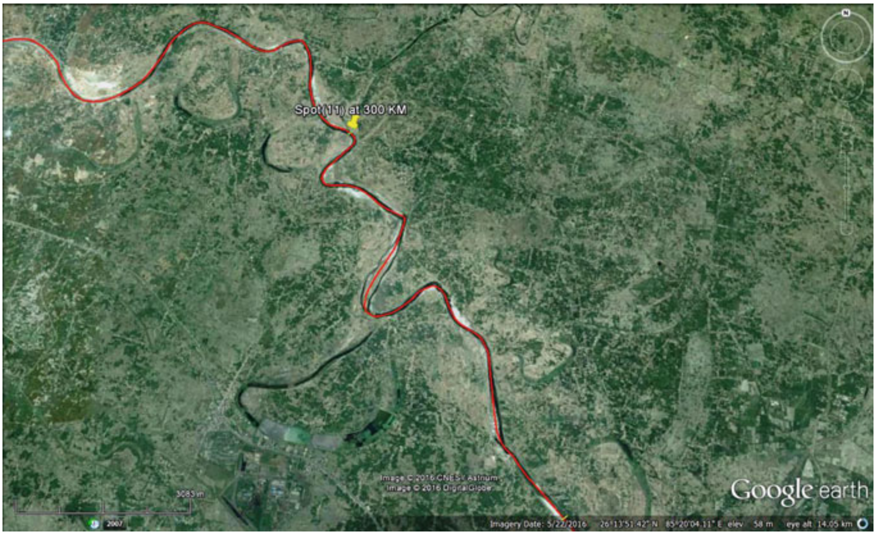

Fig. 6 Showing meander scars and meander loops in the Burhi Gandak River, Ganga Plain

3 Geohydrology

The analysis of rainfall data for several years in every month for this river basin explains that the maximum rainfall occurs between the second half of June and the first half of the September. These months contribute for about 87% of the total rainfall. The discharge of the Burhi Gandak rises in early July, and peak discharge occurs in the month of August. The discharge decreases from the month of September. The ratio of maximum to minimum discharge at different stations is different and very variable for different years. The river is groundwater fed; therefore, the discharge is directly proportional to precipitation/rains in the season with strong fluctuations. It has been observed and explained that whenever rainfall is high in a river basin, it causes floods (Singh 2007, 2013, 2014; Singh and Awasthi 2011a, b; Singh et al. 2015).

4 Natural Hazards

Bihar is India's most flood affected state. Maximum area of the catchments of snow-fed rivers draining Bihar lies in Nepal/Tibet. The high water discharge and huge sediment load carried by rivers are dropped in the Bihar Plain, thus reducing the water holding capacity of the river. Burhi Gandak is a river which is well known for frequent flooding. In the flood of 1998, 2001, and 2004, the embankment of Burhi Gandak was damaged at many places which caused loss of life and property. In 2007

Fig. 7 **a** Cliff in Burhi Gandak River at Mehsi in Bihar, Ganga Plain. **b** Cliff in Burhi Gandak River at Khagaria in Bihar, Ganga Plain

and 2012, breaches of embankment due to heavy rainfall cause catastrophic flooding in the basin. At West Champaran, the flood water reaches up to the railway track. An embankment has been built along the river to protect Khagaria city from the flood.

The accommodation space of a river should be calculated to understand its water storage capacity. So that a relationship between precipitation and water holding capacity of the river can be established. A flood inundation and flood frequency

Fig. 8 River channel with floodplains in Burhi Gandak River, Bihar, Ganga Plain

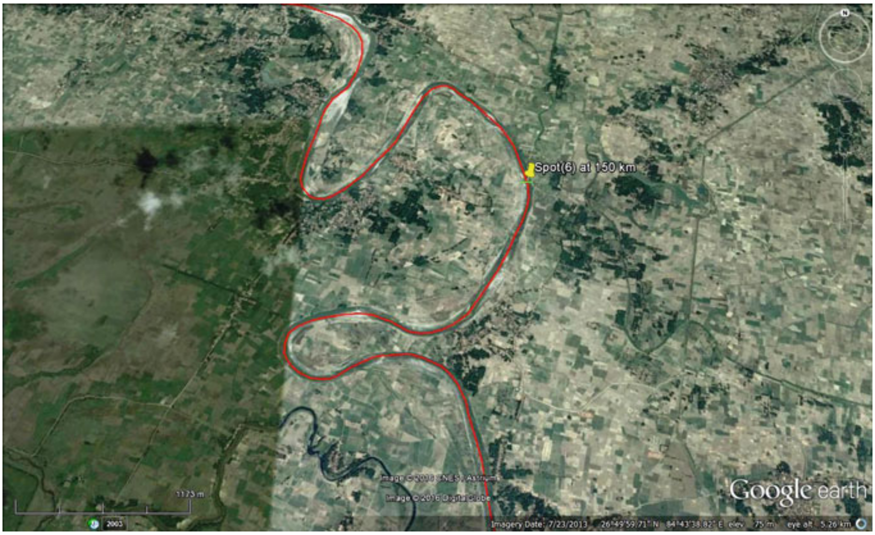

Fig. 9 Tight meanders in the middle and lower part of the Burhi Gandak River, Bihar, Ganga Plain

map should be prepared to forewarn and to save the people. The artificial levee should be constructed by analyzing the discharge of the river in such a way so that the channel/valley bracketed between embankments/levee should accommodate the water even during high/peak discharge of the river (Singh et al. 2015).

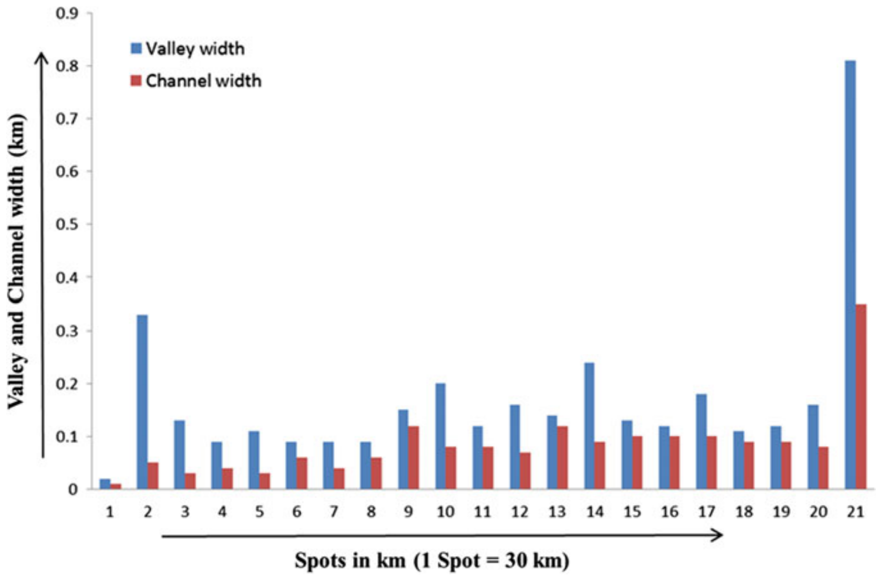

Fig. 10 Graph showing valley width and channel width ratio of Burhi Gandak River (Station number is increasing in the downstream direction, no. 1 towards origin and no. 21 is near confluence)

Table 1 Valley width, channel width, and sinuosity of the Burhi Gandak River at different stations in different parts of the river

S. No.	Part of river	Valley width (km)	Channel width (km)	Sinuosity
1	Proximal	0.02–0.33	0.01–0.06	1.2–4.6
2	Middle	0.2–0.16	0.04–0.12	1.6–13.9
3	Distal	0.11–0.81	0.1–0.35	1.1–5.4

5 Socioeconomic Aspects

It is the lifeline for the people of about five districts in Bihar. The important cities and towns located at its left bank are Madhubani, Siwaipatti, Kishanpur, Rosera, Majhaul, Khagaria, Gogri, and Jamalpur, and right bank cities are Lauria Nandangarh, Motihari, Pipra, Mehsi, Motipur, Kanti, Muzaffarpur, Samastipur, and Narhan.

The local people consider it as Ganga. It also causes loss of life and property during floods due to poor planning and management. It provides the sand as the raw material for the construction and building industry. It also provides the lime ($CaCo_3$) through the bivalve and gastropod shells to the rural people for local consumption and to prepare the lime at local scale for tobacco. Many rituals are performed at its bank.

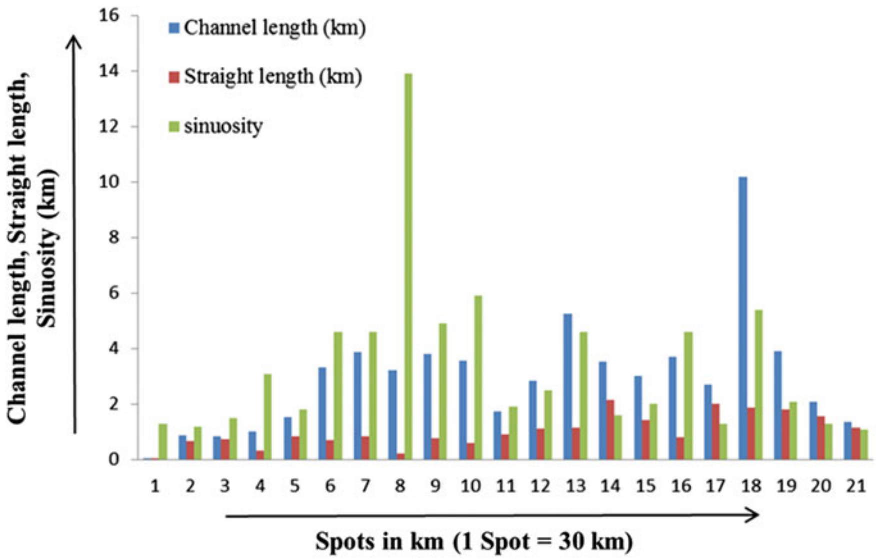

Fig. 11 Graph showing relationship between valley width, channel width, and sinuosity of Burhi Gandak River (Station number is increasing in the downstream direction, no. 1 towards origin and no. 21 is near confluence)

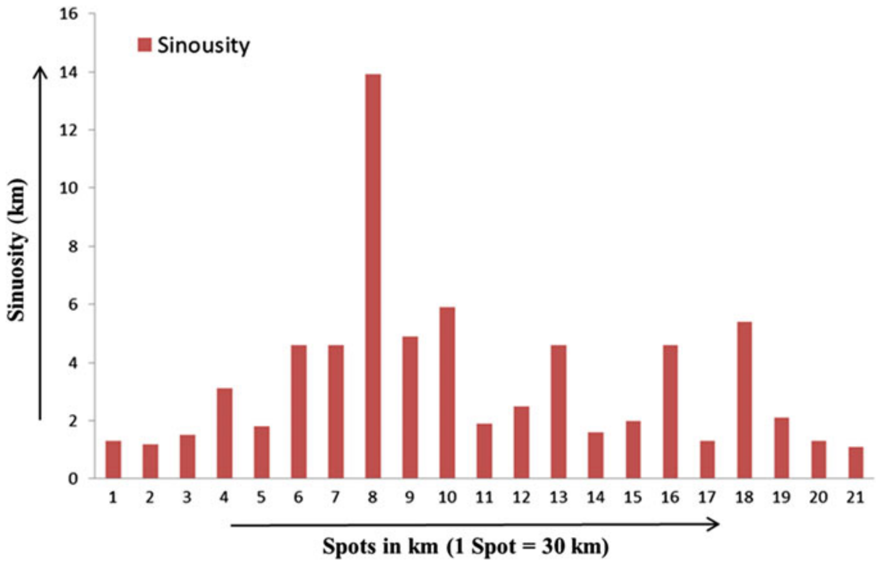

Fig. 12 Graph showing sinuosity of Burhi Gandak River (Station number is increasing in the downstream direction, no. 1 towards origin and no. 21 is near confluence)

Table 2 Variation in the valley width, channel width, and sinuosity of Burhi Gandak River at proximal, middle, and distal parts (Station number is increasing in the downstream direction, no. 1 towards origin and no. 21 is near confluence)

Station	Valley width (km)	Channel width (km)	Elevation (m)	Channel length (km)	Straight length (km)	Sinuosity
1	0.02	0.01	230	0.04	0.03	1.3
2	0.33	0.05	124	0.87	0.67	1.2
3	0.13	0.03	90	0.84	0.73	1.5
4	0.09	0.04	81	1.02	0.32	3.1
5	0.11	0.03	79	1.53	0.83	1.8
6	0.09	0.06	73	3.33	0.72	4.6
7	0.09	0.04	71	3.89	0.83	4.6
8	0.09	0.06	65	3.21	0.23	13.9
9	0.15	0.12	65	3.80	0.77	4.9
10	0.20	0.08	58	3.56	0.60	5.9
11	0.12	0.08	59	1.73	0.90	1.9
12	0.16	0.07	56	2.85	1.12	2.5
13	0.14	0.12	51	5.26	1.14	4.6
14	0.24	0.09	54	3.52	2.15	1.6
15	0.13	0.10	47	3.01	1.44	2.0
16	0.12	0.10	45	3.69	0.80	4.6
17	0.18	0.10	44	2.72	2.00	1.3
18	0.11	0.09	45	10.17	1.87	5.4
19	0.12	0.09	43	3.90	1.80	2.1
20	0.16	0.08	38	2.10	1.56	1.3
21	0.81	0.35	31	1.36	1.14	1.1

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The Dynamic Kosi River and Its Tributaries

Vikrant Jain, Rakesh Kumar, Rahul Kumar Kaushal, Tanushri Gautam and S.K. Singh

1 Introduction

Rivers are the most pervasive feature which shows the remarkable diversity and morphology. These diverse rivers also provide the basic need for human living, and hence, human establishments have continued to develop along the rivers. Rivers also provide a natural path for downstream flux transfer driven by gravitational forces. This flux variability in association with energy of flowing water defines the dynamic character of a river system. The Kosi River and its tributaries are such dynamic rivers, which are regarded as the most dynamic river systems in the world. (Gole and Chitale 1966; Wells and Dorr 1987; Jain and Sinha 2003a).

Kosi River, an antecedent river, originates from the Tibetan Himalayas and cuts the Himalayan ranges before forming a megafan on the alluvial plain. It drains about 60,000 km^2 of basin area in Nepal and north Bihar (Sinha and Friend 1994). The Kosi River system is a group of seven tributaries. The three major tributaries namely Sun Kosi, ArunKosi and TamurKosi join at Tribeni in Nepal and form the

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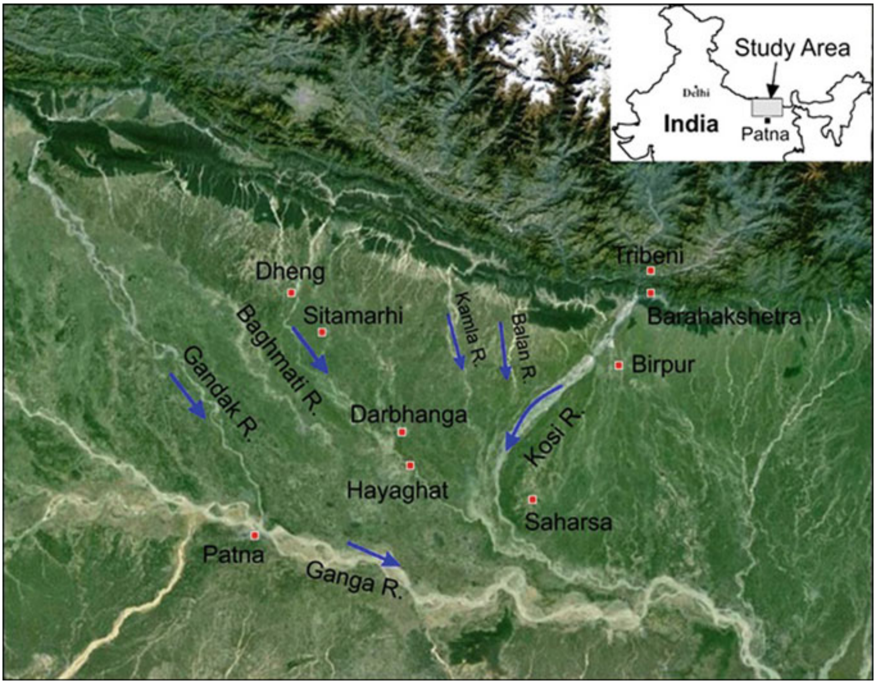

Fig. 1 Location map of the Kosi River and its major tributaries in north Bihar plains, eastern India (*Source* Google earth)

Kosi River. The Kosi River debouches on the plains through a long deep gorge at Barakshetra and further downstream enters to India through Birpur (Fig. 1). It travels a total distance of about 736 km to join with the Ganga River near Kurusela in Bihar.

The Kosi River is further joined by its major tributaries at downstream reaches. The Baghmati River, the Kamla–Balan and the Adhwara River systems are the major western tributaries, which join the Kosi River on its right bank (Fig. 1). The Baghmati River, a foothills-fed river system, originates from Shivpuri Hills in the Nepal Himalaya and passes through Kathmandu before debouching on the plains. The Kamla–Balan is a mixed-fed river system, where one of its main rivers originates from the Siwalik Hills, whereas another river originates within the plains area. The Adhwara River system is a group of various streams, which mostly originate from the Siwalik Hills. The left bank of the Kosi River is being fed by several small tributaries and palaeochannels, which were earlier part of the main Kosi River system.

2 Geomorphology and Geology

2.1 Topography and Geology of the Basin Area

The Kosi River originates from an altitude of 7000 m in the Himalaya (Fig. 2). The river, during its journey from north to south, passes through various geological boundaries and climatic belts with topographic variability from ∼7000 to ∼50 m.

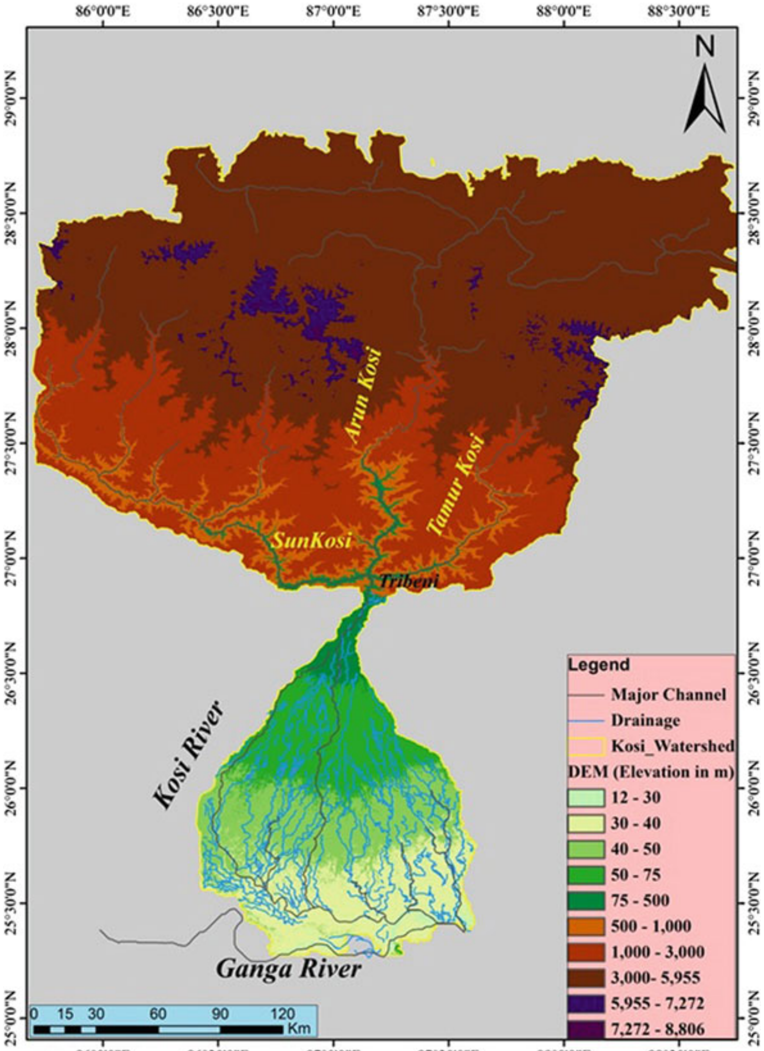

Fig. 2 Topographic variability in the Kosi River basin on the basis of SRTM DEM data

The hinterland area includes the rocks of the higher Himalaya, lesser Himalaya and subHimalaya (Siwaliks). The Kosi River basin is characterised by eight peaks with 8000 m elevation (e.g. Sagarmatha) and 36 glaciers and 296 glacier lakes (Bajracharya et al. 2007).

Hinterland of its major tributaries is less steep and at lower elevation. The Baghmati River originates from Sheopuri hills in Nepal at an elevation of 1500 m. It drains the lesser Himalaya, Kathmandu Nappe and Siwalik terrains. The hilly area is tectonically active, and mountain front is characterised by higher uplift rate in comparison with other river basins. The river travels around 195 km distance and drains around 2600 km^2 area in the mountainous region. Area of the Baghmati River basin is about 8848 km^2 (Jain and Sinha 2004). Other tributaries namely Kamla River and most of the channels of the Adhwara River system originate from the Siwalik terrain, while Balan River originates within the plains area and supported by groundwater.

The alluvial plain area of the Kosi River and its tributaries is characterised by fan–interfan setting. The megafan is a cone-shaped depositional landform on the alluvial plains. It has been formed by high sediment flux, extreme seasonal discharge variation and adequate spacing between major drainage lines (Gupta 1997; Leier et al. 2005). This megafan surface is characterised by circular contour patterns and radial drainage lines (Geddes 1960). The tributaries of the Kosi River namely the Baghmati, Kamal–Balan and Adhwara rivers drain the interfan area, which separates the two megafans, namely Kosi megafan and Gandak megafan.

The megafan area is characterised by steeper gradient (>20 cm/km) in comparison with the interfan area, which is characterised by gentle floodplain gradient (10 cm/year) (Geddes 1960; Gohain and Parkash 1990). The megafan surface is generally around 5–20 m higher than the interfan surface. This higher elevated surface of the megafan is also characterised by different topographic levels. The Kosi megafan surface has been further classified in terms of old and young alluvial plain on the basis of distribution of various landforms (Gohain and Parkash 1990). Gole and Chitale (1966) have termed the formation of this megafan as inland delta building activity, which leads to extensive deposition. The megafan is characterised by multiple thick sand bodies of around 20–30 m, indicating the reoccupation of channel in the past, though significant differences exists between the proximal and distal alluvial architecture of the Kosi megafan (Singh et al. 1993; Sinha et al. 2014a). In comparison with this, the stratigraphy of the interfan region is characterised by 10–25 m thick, but narrow sandy channel bodies separated by equally thick mudstone units, which suggests that the channels were stably positioned from tens of thousands year in this area (Sinha et al. 2005a).

The megafan and interfan area are also governed by active tectonic features (Valdiya 1976; Dasgupta et al. 1987; Agarwal and Bhoj 1992; Jain and Sinha 2005). Various subsurface transverse faults have been reported in this area, which are seismogenically active (Valdiya 1976; Dasgupta et al. 1987). Vertical movement along these faults is responsible for variability in channel slope, which in turn governing the river processes and morphology in this region (Agarwal and Bhoj 1992; Jain and Sinha 2005).

2.2 Hydrological and Morphological Characteristics

Hydrological and morphological characteristics of the Kosi River and its tributaries are governed by its source area characterisation. The hydrological and morphological characteristics of the 'mountain-fed' Kosi River are significantly different than the 'foothills-fed' Baghmati River and 'mixed-fed' Kamla River system (Sinha and Friend 1994).

The Kosi River is one of the world's highest silt-carrying rivers. It transport around 43 MT/year suspended sediment load at downstream region (Sinha and Friend 1994), whereas the annual suspended loads of the Kosi River near mountain front (Barahkshetra) is around 119 MT/year (Nayak 1996). Its hinterland area, which is more than five times of the megafan region, is not only a high relief terrain but also characterised by various zones of high-intensity rainfall (Sinha and Friend 1994). Higher intensity rainfall on the steep and tectonically active mountain is responsible for extensive sediment erosion and hence higher sediment supply to downstream reaches. The river has been embanked from both sides since 1963. High sediment load in the embanked river has also caused extensive channel siltation, especially near the mountain front and at upstream of the Kosi Barrage.

Discharge characteristics of the Kosi River are quite variable and especially the difference between discharge at monsoon and non-monsoon period is around 5 times (Sinha et al. 2008). Monthly average discharge of the Kosi River fluctuate form 500 to 6000 m^3/s, while the mean annual flood discharge lies around 8000 m^3/s near Birpur (Sinha and friend 1994). Twenty years of peak discharge data of the Kosi River is characterised by annual variability at each station, though peak discharge values at upstream station are generally higher (Sinha and Jain 1998). In general, discharge at downstream reaches during monsoon period remains higher than the bankfull capacity (Fig. 3). Even the most probable flood (MPF) and the mean annual flood (MAF), which represent discharges corresponding to return period of 1.58 and 2.33 years, respectively, have higher value than the bankfull discharge of river. It indicates insufficient carrying capacity of the channel and frequent flooding during monsoon period.

Both the Baghmati and the Kamla–Balan River are characterised by extremely variable peak discharge and frequent overbank spilling (Sinha and Jain 1998). The sediment load and sediment concentration data of these rivers indicate that these river basins are prone to erosion and the sediment supply into these rivers is quite high. These rivers reflect 0.84 and 1.11 mt/y/km^2 sediment yield, respectively, which is significantly higher than the major rivers of the world (Sinha and Friend 1994). Most of the sediment load comes from upstream basin area, which is particularly high during the monsoon season. Bank erosion process at middle-stream region further contributes wash load, which varies from 60 to 90% of the total sediment load. The midstream reaches of the Baghmati River receive, on an average, more than 3 million tonnes of sediment every year. Moreover, midstream reaches are characterised by a gentle slope which led to decrease in stream power. Increase in sediment load and decrease in stream power are responsible for

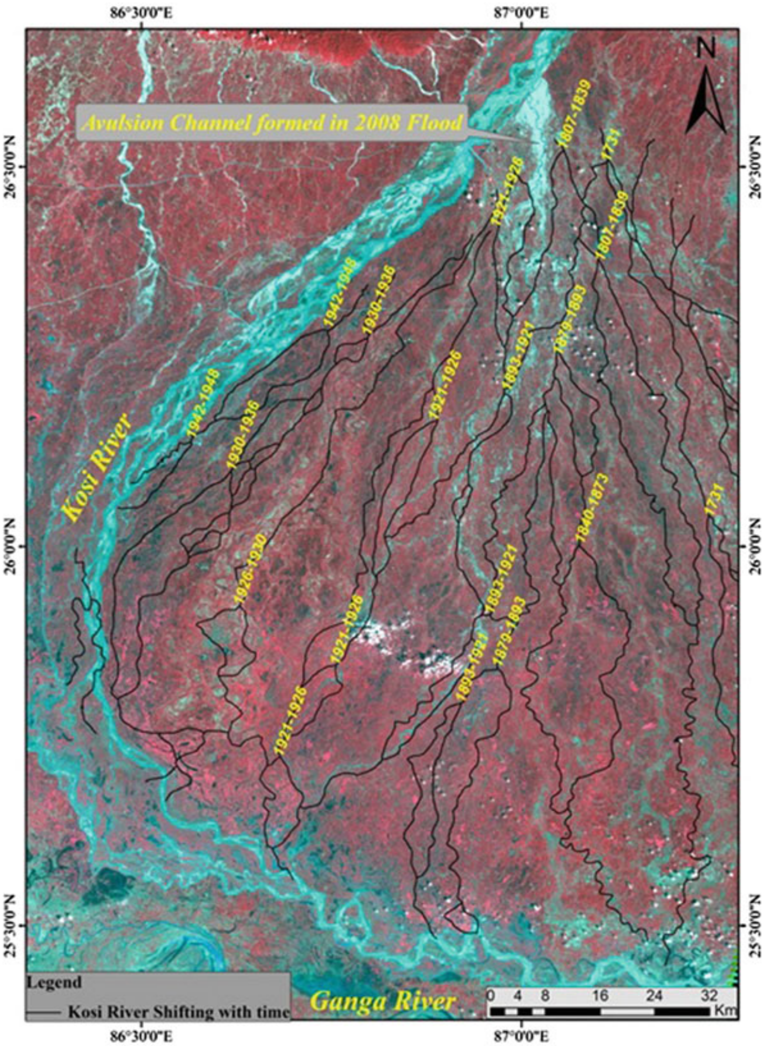

Fig. 3 Hydrological characteristics of the Kosi River, Baghmati River and Kamla–Balan River. The bankfull discharge at all the stations of these rivers is less than the average discharge parameters. Less carrying capacity of these rivers is responsible for frequent flooding during monsoon period (modified after Sinha and Jain 1998)

extensive deposition in the middle-stream region. Hence, channels in interfan area are shallower and prone to avulsion and flooding.

The Baghmati River shows comparable values of peak discharge at upstream (Dheng) and downstream (Hayaghat) stations for different return periods. However, lower value of bankfull discharge and slightly higher value of MPF and MAF at upstream gauge station (Dheng) would make it more prone to flooding.

Table 1 Regression equation for sediment rating curve for different rivers

River	Station	Total suspended sediment load equation	Regression coefficient	Coarse and medium fraction equation	Regression coefficient
Baghmati	Dhengbridge	$\text{Log}(Q_{susp}) = 1.97 * \log(Q) + 3.03$	0.912	$\text{Log}(Q_{susp}) = 1.76 * \log(Q) + 3.14$	0.905
	Hayaghat	$\text{Log}(Q_{susp}) = 1.52 * \log(Q) + 5.11$	0.905	$\text{Log}(Q_{susp}) = 1.60 * \log(Q) + 3.65$	0.901
Kosi	Baltra	$\text{Log}(Q_{susp}) = 1.15 * \log(Q) + 6.11$	0.800	$\text{Log}(Q_{susp}) = 1.14 * \log(Q) + 4.19$	0.762
Kamla–Balan	Jaynagar	$\text{Log}(Q_{susp}) = 1.61 * \log(Q) + 5.99$	0.827	$\text{Log}(Q_{susp}) = 1.70 * \log(Q) + 4.75$	0.834
	Jhanjharpur	$\text{Log}(Q_{susp}) = 1.66 * \log(Q) + 5.83$	0.896	$\text{Log}(Q_{susp}) = 1.73 * \log(Q) + 4.10$	0.871

Source Sinha and Jain (1998)

In Kamala–Balan River system, the location of Jaynagar and Jhanjharpur stations are on different channels; hence, downstream variability could not be analysed. However, higher values of MAF and MPF in comparison with the bankfull discharge at both stations indicate frequent and extensive flooding. Moreover, comparison of the discharge values correspond to recurrence interval of 50 and 100 years with bankfull discharge suggests severe flooding condition in these river basins during moderate to rare rainfall events.

All these rivers are characterised by high sediment load due to high erosion rate in their hinterland area. The spatial variability in the erosion processes and its sensitivity with hydrological forcing in the hinterland area are better represented by sediment rating curve. The regression equations of the sediment rating curve for the total as well as for the coarse and medium fraction of suspended load are provided in Table 1 (after Sinha and Jain 1998).

The higher intercept value for Baltara, Jayanagar and Jhanjharpur stations suggests that upstream basin area of the Kamla–Balan River is highly erosion-prone. However, the slope of rating curve of the Baghmati River for both the grain sizes is around 50–70% higher than the Kosi River, which highlights sensitivity of erosion process in the hinterland region of the Baghmati River in response to hydrological forcing. Further, geochemical fingerprinting of the Baghmati sediment suggested around 80% of sediments in the alluvia plains are generated in the Siwalik terrain (Jain et al. 2008). The major contribution of the Siwalik rocks in the sediment load is because of higher uplift rate of the Siwalik Hills and higher rainfall intensity in this region (Jain et al. 2008).

Morphologically, the Kosi River basin is a braided river system throughout its reach. Whereas the interfan rivers are of braided nature only near the mountain front, while downstream reaches are of meandering nature. The channel size and morphological parameters (width–depth ratio, Sinuosity and Braid–channel ratio) for the Kosi, Baghmati and Kamla–Balan rivers suggest that the last two rivers have multiple channels, with low braid–channel ratio in a few upstream reaches immediately after debouching into the plains (Sinha and Friend 1994). But these rivers are dominantly single channel and moderately sinuous river for the rest of their course.

Fig. 4 Field photographs of the main channel and abandoned/palaeochannels. **a** The main Kosi River at upstream reaches. **b**, **c** The abandoned palaeochannels of the Kosi River over its megafan surface. **d** The main Baghmati River at upstream near Dheng. **e** The main Baghmati River at midstream reaches near Belwa village. River has shifted its position and now it flows parallel to the alignment of bridge pillars, which were earlier planned across the flow. **f** Abandoned channel of the Baghmati River near Dhankaul village

The midstream reaches of the Baghmati River shows a well-developed anabranching nature (Jain and Sinha 2003a). Many of its channels have been abandoned, while new channel have been initiated at different time intervals (Fig. 4). Further, decrease in width–depth ratio of the Baghmati River channel highlights the channel variation from wide to shallow channel in upstream to narrow and deep channel in downstream reach. The longitudinal profile of the river is characterised by three different knick points, which are related with subsurface tectonic activity (Jain and Sinha 2005). In general, the channel morphological variations in the Baghmati River are governed by hydrological characteristics of the river. However, impact of neo-tectonic movements on the channel morphology is also evident at some reaches.

3 Socio-economic Importance

Anomalous variability in the hydrological and geomorphological processes is responsible for major river hazards in the basin area. The Kosi River basin is densely populated area; hence, hydrological and geomorphological processes closely govern the socio-economic development of the area. The Kosi River is also termed as the ‘Sorrow of Bihar’ because of extensive river hazards associated with this river. The hazards due to these anomalous hydrological and geomorphic processes have been further discussed in detail.

3.1 Fluvial Dynamics

The Kosi River is one of the most dynamic rivers in the world. The shifting nature of the Kosi River at different time periods is recorded on the megafan surface as various palaeochannels (Fig. 5). Frequent shifting of the main channel has not only

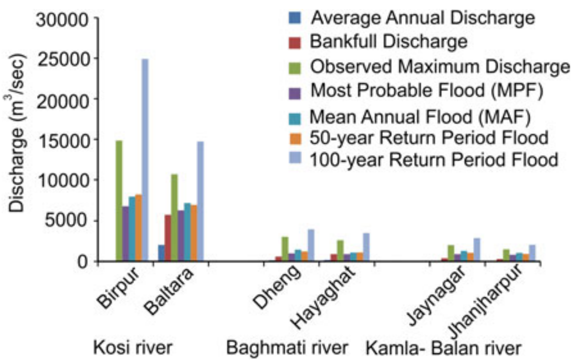

Fig. 5 Distribution of palaeochannels over the Kosi megafan highlights the dynamic behaviour of the Kosi River. The Kosi River has shifted westward around 120 km in last 300 years over its megafan surface. A recent avulsion in 2008 has caused a major eastward shift of the Kosi River. It was later forced to return back to its original channel through a major river engineering exercise. Presently, Kosi River is flowing in its main channel, which is at the western margin of the megafan (Details of palaeochannels: Gole and Chitale 1966; Wells and Dorr 1987)

caused higher rate of sedimentation over the vast area but has also created extensive damages on the megafan surface.

Available records of last two and half centuries indicate that the river has frequently altered its path in a westerly direction, and it has laterally shifted almost 120 km (Gole and Chitale 1966; Wells and Dorr 1987; Gohain and Parkash 1990). Though the channel shifting over a fan surface is common and is an autocyclic processes, but the higher frequency of such processes on the Kosi megafan make it distinct with other rivers. The average frequency of channel movement for the Kosi River is of 24 years. It is among the lowest in the world compared to 1400 years for the Mississippi River. The river shows sudden changes in river path, which are termed as avulsion processes. Avulsion process is governed by variation in channel gradient (Jain and Sinha 2004; Sinha et al. 2014b). A recent detailed work on the basis of DEM analysis and high resolution field mapping has shown that the Kosi River bed at upstream locations is around 2–3 m higher than its adjoining floodplain surface across the embankment (Sinha et al. 2014b). Hence, cross-valley slope is significantly higher than the down-valley slope at these sites, which makes a potential condition for channel avulsion. Further, planform map also shows that the main channel flow was aligned to the left bank from last few years and had caused significant damage to the embankment. Damaged embankment at potential avulsion sites was the main causative factor for the major avulsion in 2008. Integration of such cross-sectional studies with the planform mapping can serve as an important tool for better management of such dynamic river systems.

In the interfan area, the anabranching midstream part of the Baghmati River is also highly unstable. The frequent channel shifting at the midstream reaches of the Baghmati River is again governed by avulsion processes. The Baghmati is termed as a 'hyper-avulsive' river system, and it provides a unique example of dynamic behaviour at a low energy condition (Jain and Sinha 2003a). A detailed study of the Baghmati River system on the basis of topographic maps and satellite images at different temporal scales and field verification of abandoned channels provide channel migration history for 230 years (1770–2000) (Jain and Sinha 2003a). The midstream anabranching reach of the Baghmati River is characterised by 8 major avulsions and several smaller avulsions in the 30 km wide floodplain (Fig. 6). It represents a very high decadal scale avulsion frequency. The main Baghmati River has shifted in NE direction due to these frequent avulsion processes. This fluvial dynamics in the area is governed by hydrological and morphological characteristics of the river coupled with neotectonics in the area (Jain and Sinha 2004). This period is also characterised by broadening of anabranching pattern from 60 to 75 km long anabranch due to upstream shifting of the bifurcation point. However, the present-day map indicates that most of the bifurcation channels got abandoned, and the anabranching Baghmati River system is changing into a single channel meandering system.

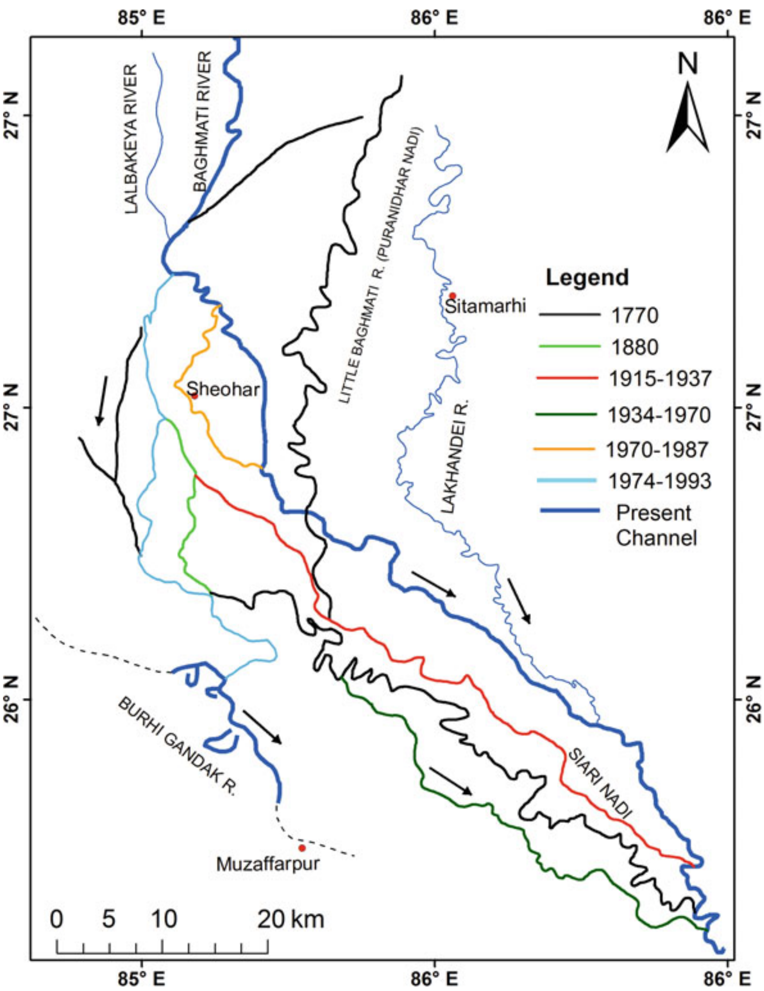

Fig. 6 Baghmati River with its palaeochannels. The Baghmati River in the interfan area is also highly dynamic in nature and known as 'Hyper-avulsive' river. Various channel avulsions at different locations and at different times have shifted the channel at different positions. Presently, the Baghmati River is flowing as single channel, and its position is at the east of all the palaeochannels (modified after Jain and Sinha 2003a)

3.2 *Flood Hazard*

The Kosi River and its tributaries are frequently affected by flood hazard in comparison with other Himalayan rivers in western part of the Ganga Plains. The damages caused by these floods to crop, private properties, public utilities and the loss of life are enormous in these river basins. Therefore, it is very important to understand the causative factor for spatial variability in flood hazard.

Flooding in the Kosi and its tributaries is due to extensive channel siltation, which is a function of energy distribution within the channel and variability in sediment supply. Stream power in a channel represents the available energy for geomorphic work, while power required to transport the river sediment is defined by critical power. These two parameters govern the channel processes (Bull 1979), and the threshold condition for aggradation and degradation is defined as:

$$\text{Threshold for aggradation/degradation} = \frac{\text{Stream Power}}{\text{Critical Power}} \tag{1}$$

Aggradation occurs when the threshold will be less than 1.0 or when stream power will be less than the critical power. The Kosi River and its western tributaries are characterised by very high sediment load but with low stream power values. Hence, these low energy systems are characterised by extensive siltation of the channel, which makes the channel shallower and reduces its carrying capacity (Jain and Sinha 2003b; Sinha et al. 2005b; Valdiya 2011).

Flood hazards along the Kosi and in its tributaries are not only governed by hydrological processes, but also these are dominantly governed by geomorphic processes and geomorphic characteristics. In case of the Kosi River, a geomorphic process, i.e. avulsion process governs the flood hazard in the basin area.

Major flooding events in the Kosi River basin are related with breaching of embankments. Chronological sequence of such flooding events and its damages are documented in detail by Mishra (2008). These events cause maximum damage in comparison with overbank flooding. Avulsion can affect an area far from the main channel, where flood preparedness may be absent or insufficient. For example, the major flooding in the Kosi River basin during 2008 has affected the centre part of the megafan. This major flood disaster due to breaching of the embankment has shifted the channel flow by tens of km far from the main channel, where flood preparedness was almost absent. This avulsion has caused shifting of around 85% volume of water in the newly formed channel, which was around 20 km wide during peak flooding time. This catastrophic event due to change in the flow path towards central part of the megafan has affected hundreds of villages and hundreds of thousand people.

Topography controls the path of newly created channel. Hence, a detailed understanding of surface topography can help to predict the path of newly formed channel, which could be used to predict the inundation area after major breaching. Recently, Sinha et al. (2013) had developed a model on the basis of topographic analysis and predicted the path of new channel after avulsion. Such analysis for all potential avulsion sites may help to improve the flood management strategies. Further, flood preparedness and management in the Kosi River basin need integrated approach with incorporation of hydrological, geomorphological, land cover and social data. One such flood risk index (FRI) for the Kosi River basin explains flood distribution in the upstream, midstream and downstream reaches, and such maps may be used for floodplain zoning (Sinha et al. 2008).

The Baghmati River is also severely affected by flood hazard. However, flooding in this river basin presents interesting scenario. Flooding is highly variable and unevenly distributed in the Baghmati River basin. Only five channel reaches are highly flood-prone (Jain and Sinha 2003c). Uneven spatial flood distribution itself suggests the complexity of flooding and involvement of several factors in generation of flood at particular area. The drainage network is one such parameter, which plays a major role in defining the hydrological response of a river system. Variability in drainage pattern defines the tributary influence on flood hazard in the Baghmati River basin (Jain and Sinha 2003d). A geomorphological instantaneous unit hydrograph (GIUH)-based approach has shown that a unit hydrograph (UH) for the ungauged hinterland mountainous area of the Baghmati River basin can be generated on the basis of drainage network pattern. The drainage network is commonly expressed by Horton's morphometry ratios i.e. bifurcation ratio (R_B), area ratio (R_A) and length ratio (R_L). These morphometric ratios directly contribute to the equations of GIUH (Jain and Sinha 2003d). Further, a regression analysis on these equations suggested that length ratio is the most significant parameter in hydrological analysis (Jain and Sinha 2003e). The tributaries of the Baghmati River with higher length ratio are responsible for flooding at their confluence points, whereas other tributaries does not cause any major flooding at confluences with the main river (Jain and Sinha 2003e). Another important factor is the subsurface deformation in the basin area. Flooding may also occur at any channel reach without any increase in discharge, if the channel capacity will be lowered. Such condition occurs at upstream of any uplifting zone (Holbrook and Schumm 1999). In the Baghmati River basin, reaches at upstream of the East Patna Fault are characterised by flood hazard, even though average discharge is less in comparison with upstream reaches (Jain and Sinha 2005). Hence, flooding scenario in the Baghmati River basin is not a simple hydrological phenomenon, but it provides a typical example of external control on hydrological processes. The severity of flood hazard along these five reaches is related with the drainage network pattern of tributary sub-basins, neotectonic movements and topographic variability in basin area (Jain and Sinha 2003c).

3.3 Waterlogging Hazard

Waterlogging is another important hazard in these river basins, and it is termed as 'slow hazard'. It affects large area and cause misery to people for much longer duration. Waterlogging in North Bihar Plains is now become a major hindrance for the economic growth, which causes un-productivity of land surface especially affects the agricultural land. This overtime also increases the salinity factor and further reduces agricultural productivity. Frequent flooding in low laying area gives the waterlogging a permanent problem that leads to poor economic set-up and may cause socio-economic vulnerability. North Bihar plains are characterised by significant variability of waterlogging risk, which is highlighted in a classification map through integration of geohazard and socio-economic vulnerability (Pandey et al. 2010). Such maps with deeper process understanding may be used at planning of such hazard management strategies.

Waterlogging problem is common in low-lying area. The downstream region of the Baghmati River is one such low-lying area affected by extensive waterlogging problem, where water flows from interfan to higher elevated surface of the Kosi megafan. This region is also characterised by subsidence as it lies between tectonically active East Patna Fault (EPF) and Munger–Saharsa Ridge Fault (MSRF) (Jain and Sinha 2005). This area not only receives discharge contribution from upstream region through the Baghmati, the Kamla–Balan and the Adhwara rivers but also it experiences backflow from the Kosi River during monsoon period. Hence, water remains in the area for longer time, which leads to the formation of number of marshes, swamps and ponds and is characterised by poor drainage system (Jain and Sinha 2005).

Further, the Kosi megafan surface is also affected by waterlogging problems, even though it is characterised by higher average gradient and higher surface elevation. The distribution of waterlogged area in the Kosi megafan is significantly affected by dense network of rail-road transport network on the megafan (Kumar et al. 2014). The dynamic behaviour of the Kosi River through the avulsion process has been resulted in a dense network of south flowing palaeochannels, which mostly activates during the monsoon period. However, embankments related to rail-road transport on the Kosi megafan are mostly E–W and are cutting the palaeochannels at many locations. These intersections have been classified as connected, partially connect and disconnected intersections on the basis of nature of connectivity (Fig. 7). The numbers of disconnected intersection points have

Fig. 7 Nature of geomorphic connectivity over the Kosi megafan. The high density of 'disconnected' channels is responsible for waterlogging problem on the Kosi megafan surface

increased in recent past, which has been resulted in waterlogging conditions at many places. Quantitative analysis of these data points suggests that disconnectivity on the megafan surface has increased by 45% due to rail-road transport structures constructed in last 55 years (Kumar et al. 2014). Hence, better management of the waterlogging problems on the megafan surface also need a well-designed transport structures with sufficient passage for water flow.

4 Conclusion

The Kosi and the Baghmati rivers present a typical example of highly dynamic river systems. The dynamic nature of these river systems are a product of an excellent feedback mechanism between geology–geomorphology–hydrology and fluvial hazards. The dynamic nature and flooding in these river systems is related with less carrying capacity of the channel, which is due to higher rate of channel siltation of the channel. These rivers are characterised by high sediment supply and less stream power; hence, aggradation is a dominant process which also leads to avulsion process. Geomorphic characteristics including the pattern of drainage network also control the hydrological response of a river basin. High sediment supply in these river systems is governed by inherent factors such as higher uplift rate, steep hillslopes and high-intensity rainfall in the hinterland area. The main problem of high sediment supply from upstream and channel siltation problem at downstream reaches cannot be controlled for longer time. There is a need to include these new process understanding in the stream management approaches and to develop an integrated sustainable plan for flood management. For example, reduction in bankfull capacity of major channel due to siltation may be managed through proper distribution of fluxes in palaeochannels and through optimum utilisation of carrying capacity of these palaeochannels of the Kosi megafan.

The new approaches for dynamic rivers should follow the globally accepted approach of ‘management’ rather than focussing on the ‘control’ approach. There has been a paradigm shift at different parts of the world from ‘river control’ to ‘river management’. The first approach involves only engineering solutions and addresses only the ‘effect’ at a local scale, while later approach includes multidisciplinary analysis at different scales and addresses the ‘cause’ of the problem (Jain et al. 2012; Jain 2013). Jacketing of rivers through embankment is a long-term flood management practices in India. However, it has been debated at various forums and at different times. Flood damage data suggests flood affected areas in India have increased with time, even though various efforts were made to control the floods (Aggarwal and Narain 1996; Sinha and Jain 1998). At present, flood is one of the most disastrous natural hazards in India and especially in north Bihar plains. Repeated failure of flood control measures calls for an urgent need of a multidisciplinary approach for flood analysis, which should include hydrological, geomorphological and geological understanding of the river basin. These dataset should be incorporated in planning the sustainable management practices at cross-over scales rather than the flood controlling measures at local scale.

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Analysis of Mahananda River Basin Using Geospatial Data

Narendra Kumar Rana

1 Introduction

The River Mahananda is a large tributary of the Ganga River, originates from the Mahaldiram range, near Chimli (Latitude 26° 55′ 40″N and Longitude 88° 14′ 04″ E) at an elevation of 2200 m. It meanders conspicuously through the lower Himalaya and the North Bengal plain for a distance of about 470 km and meets the mighty Ganga on the left bank (Bharti 2000). After the Mahananda, the Ganga continues its course and forms its own delta by its distributaries and then merges into the combined delta of the Ganga, Brahmaputra and Meghna rivers. It flows through the states of Bihar and West Bengal in India. Besides, it is an international trans-boundary river that touches the boundary of Bangladesh. The right bank tributary of the River Mahananda, i.e. the Mechi forms part of Nepal's eastern boundary with West Bengal. In the present study, some aspects of river basin geomorphology is analysed with input from geospatial data. Geospatial data refer to information that is tagged with geographic reference with respect to its location. In the present study, geospatial data from different sources are used that include digital data of Landsat TM of Path 139 and Row 41 and 42 acquired on 15 November 2011 and ETM+ data of 21 April 2014 and ASTER data of N25E087 and N27E088 acquired on 17 October 2011. The data are processed through ARC MAP 10.0 and ERDAS IMAGINE software.

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2 The Mahananda Basin and Its Drainage

The catchment area of the Mahananda basin is shared by three nations i.e. Nepal, India and Bangladesh. The River Mahananda is a hill-fed river as it is originated in the Darjeeling hills. After flowing about 20 km upstream, the river left the hilly terrain and enters into the plains near Siliguri in West Bengal. Downstream of Siliguri city, the Mahananda flow in a south-westerly direction and finally meet the mighty Ganga. In few stretches, it forms the boundary between India and Bangladesh. Major tributaries of the Mahananda are Balason, Mechi, Ratwa and Kankai. The River Balason is one of the most important right bank tributaries that joins river below Siliguri. The eastern Kankai is also a dominant tributary of Mahananda that joins the master stream on the right bank near Kuttighat, whereas the western Kankai is the most significant right bank tributary that carries higher discharge than the Mahananda. The Chenge is another right bank minor tributary that joins the Mahananda upstream at Taibpur railway bridge. The River Donk is one of the principal left bank tributaries that meets the main stream near Belwa village. The total length of the Mahananda is about 320 km, and the total drainage area is 14,500 km^2 in India. Its width varies considerably downwards and at the lower portion near its confluence with the mighty Ganga estimated to be 340–400 m; the Ranochondi stream along with the River Dauk and Chokor (often considered as a single river) forms the Trinai of Mahananda.

The river basin extends from 24° 58′ to 27° 10′N latitude and from 87° 6′ to 88° 31′E longitude. It shows typical dendritic drainage pattern (Fig. 1). The river basin has two distinct catchment area; the upper catchment consisting of part of Sikkim Himalaya and the lower Gangetic plains. The basin experiences a very hot and relatively humid monsoonal type of climate. The proximity to the Bay of Bengal on the southern part and the alignment of the Himalaya and that of the Meghalaya Plateau situated on the north-eastern side determine the climatic character. January is the coldest month with a temperature range of 17–21 °C. The temperature starts rising gradually throughout the region from February. Monsoon became active by first week of June. The rainfall is fairly widespread in the basin, i.e. 120 to more than 400 cm, with uneven seasonal and spatial distributions. The basin receives rainfall from four different sources namely; westerly disturbances of winter, local depressions during March–May, monsoonal rainfall and cyclonic disturbances. However, the last two account for the major precipitation in the region.

3 Geomorphology

The River Mahananda is a hill-fed river, and its basin is bounded by Kosi Megafan on the west and Tista Megafan on the east (Chakraborty and Ghosh 2010). The general morphology of the basin may be divided into the northern hilly area and southern plains. The southern part of the basin is marked by monotonous surface

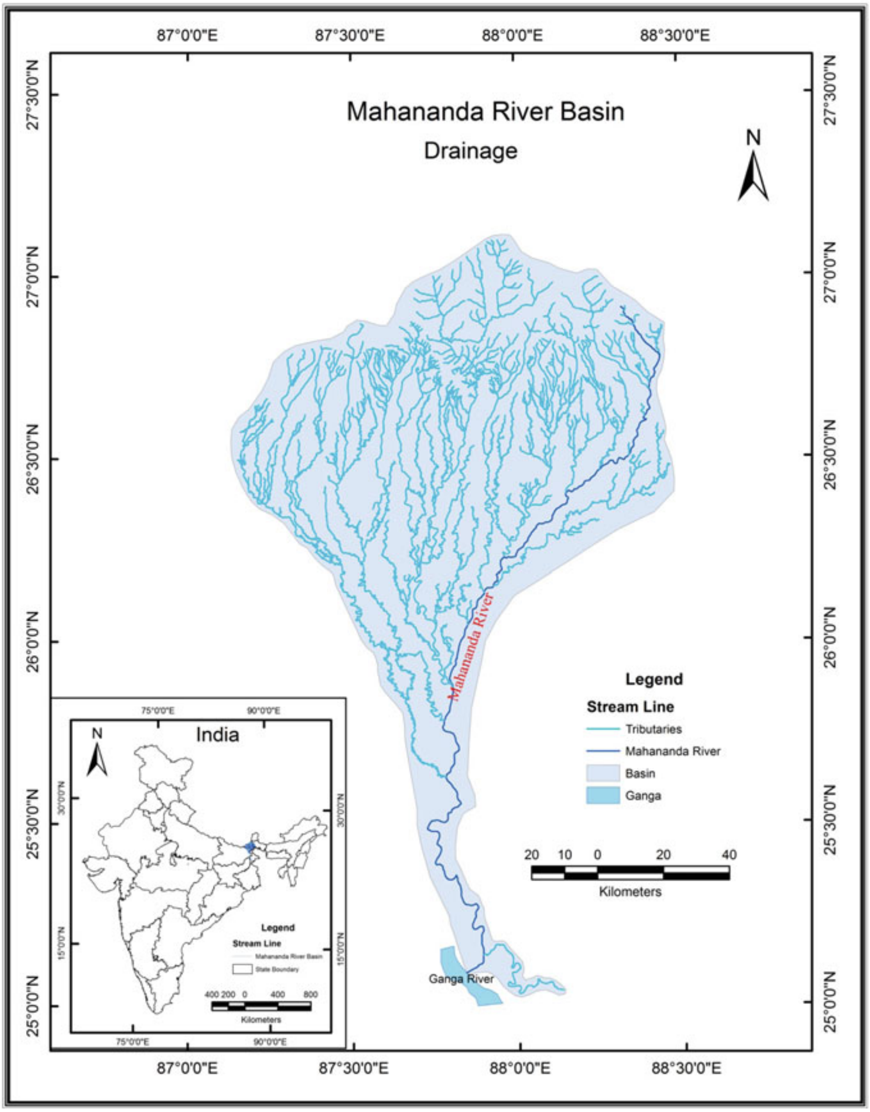

Fig. 1 Location and drainage pattern of Mahananda river basin

often dissected by old channels. The general slope of the basin as revealed by the drainage system is to the south-west. Morphologically, the basin is divided into two distinct parts: the Duars (Darjeeling Tarai) similar to the Tarai of the Upper Ganga plain and the Barind plain, a plain of older alluvium between the Kosi-Mahananda corridors. The eastern part of the basin mainly consisting of old alluvial soil, and it is less infertile as compared to other adjacent soil. It is locally referred as barind.

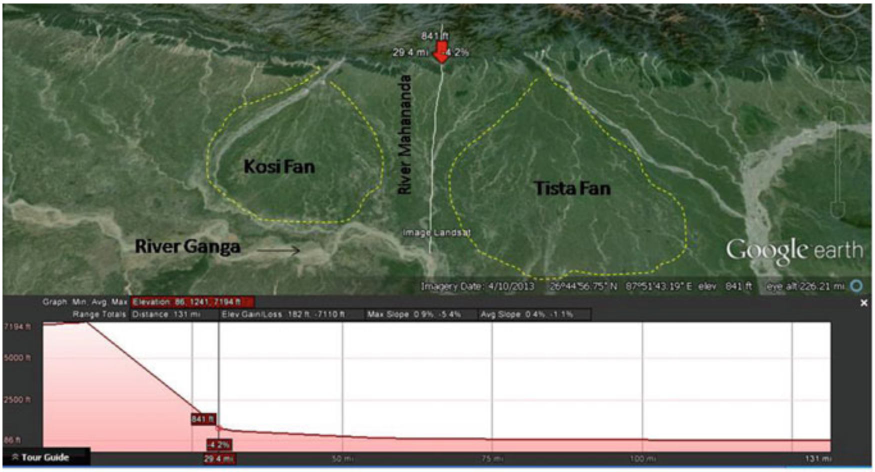

Fig. 2 Profile of the River Mahananda

The western region is further subdivided by the River Kalindri into two areas; the northern area is known as “Tal”. It is a low lying area that is often susceptible to massive inundation during rainy season. The southern area generally referred as “Diara” consists of very fertile land and is densely populated. All important streams such as the Kosi and the Mahananda make frequent swings in the area (Singh 1989).

The upper catchment area consisting of hills and mountains having considerable slopes, whereas after Siliguri, the river enters the plains and flows in the lower Gangetic plains without any appreciable slope. The longitudinal profile of the river derived from Google Earth (Fig. 2) shows that the river after descending into the plain flows considerably with little slope and exhibits extensive meandering and braiding. The presence of numerous oxbow lakes and abandoned river channels that no longer carry water (palaeo-channels) as seen in the satellite images indicates the dynamic behaviour of the river and its general movement towards the west (Chakraborty and Ghosh 2010).

3.1 *Morphometric Analysis*

The measurement of earth’s surface and its mathematical analysis of its landforms configuration notably shape, size and other dimensions are commonly referred as morphometry. It provides insight into a quantitative description of the drainage system, which in turn is an important aspect of the characterization of the basin and its drainage behaviour. In the present study, the analysis is performed in GIS environment as it enables a convenient environment and a systematic tool for the input, manipulation, retrieval and analysis of geographically referenced information. The morphometry analysis of the Mahananda basin was carried out on

Landsat TM and ASTER-DEM satellite imagery: the Landsat TM image having 30-m spatial resolution and 185-km swath acquired in March 2015 and ASTER-DEM image having 30-m spatial resolution and 60-km swath acquired in October 2015. Important parameters such as stream lengths, stream numbering, bifurcation ratio, and areas of the watersheds were calculated and analysed with the help of ArcGIS-10 software. Stream ordering is generated with the help of Strahler's methods (1953) and visualized in Arc-Hydro tool in ArcGIS-10 software. For the analysis and measurement of the linear aspects, methods given by Horton (1945), Strahler (1953), and Chorley (1972) were adopted.

4 Drainage Network

4.1 Stream Ordering (Su)

Stream ordering is the basic and fundamental step of morphometry analysis of river basin. Horton (1945) was the first person to advocate stream ordering systems, and subsequently Strahler has applied it with significant modifications. In this study, stream ordering is analysed with the method as proposed by Strahler (1953). The Mahananda river basin is found to be maximum order of stream as sixth one (Table 1; Fig. 3).

4.2 Stream Number (Nu)

Stream number refers to the total of order-wise stream segments of a river basin. Stream parameters of the present study verify Horton's first law (stream number) which shows that a simple geometric relationship exists between the order of the stream on the one hand and the number, average length, channel slope and average

Table 1 Stream order, stream number and bifurcation ratios in Mahananda basin

Stream order (Su)	No. of stream segments (Nu)	Total stream length (m)	Bifurcation ratio	Basin length (km)	Basin perimeter (km)
1	400	2,228,933		227	648
2	102	1,136,347	3.92		
3	28	645,744	3.64		
4	8	632,276	3.5		
5	2	186,447	4		
6	1	124,087	2		
Total	541	4,953,834	17.06		
Mean			3.41		

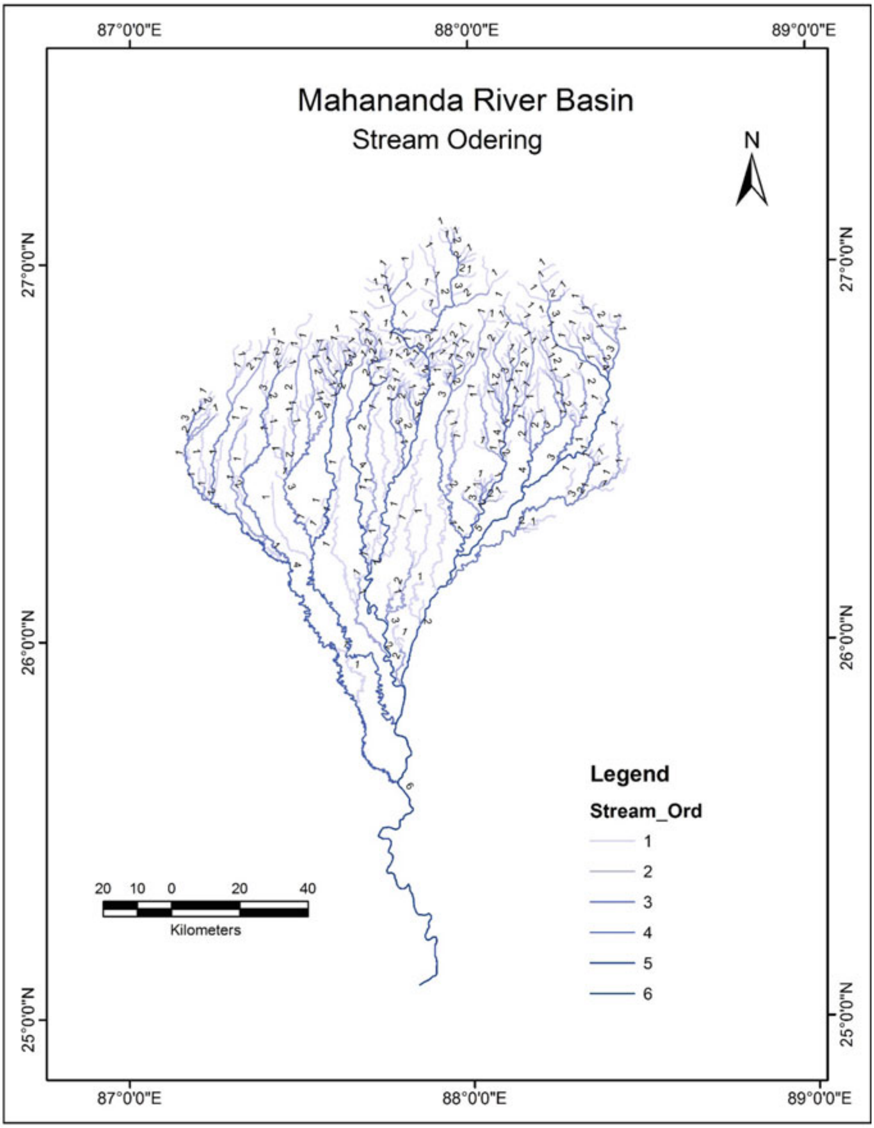

Fig. 3 Stream ordering of Mahananda river basin showing it as sixth order one

basin area of each order on the other (Singh and Awasthi 2011). The study observed that the frequency is highest in the case of first-order streams (Table 1). It is also noticed that there is an inverse relationship between stream frequency and the stream order.

4.3 Bifurcation Ratio (Rb)

The simple ratio of the number of the stream component of a particular order (Nu) to the number of streams present in the next higher order (Nu + 1) of a given river basin is referred as bifurcation ratio. Horton and Strahler measured it quantitatively. Horton (1945) advocated the bifurcation ratio as a simple ratio of relief and dissertation, whereas Strahler (1956) empirically argued that bifurcation shows a minor variation for different morphological or environmental set-ups but it differs in a significant way where there is dominance of geological controls. The present study observed that the bifurcation ratio differs among segments of different stream orders (Table 1). A formal explanation of these irregularities can be the geological and lithological developments of the drainage basin. The ratio usually varies in between 3.0 and 5.0. Lower values of the ratio are indicative of the watersheds that have under less structural upheavals, and subsequently the drainage pattern has not modified much because of the structural disturbances, whereas higher value indicative of structural control (Strahler 1964). In this study, moderate-to-high Rb values indicate influence of structural dominance on the drainage pattern of the Mahananda River, and vice versa.

5 Geometry of the Basin

5.1 Basin Length (Lb)

Basin length is referred in various methods. According to Schumm (1956), length of the basin is the longest length of the basin parallel to the main drainage system. Gregory and Walling (1968) has taken the length of the basin as the longest dimension in the basin having river mouth as the end point. In the present study, basin length (Lb) is obtained with the help of Schumm (1956) definition and it is calculated to be 227 km.

5.2 Perimeter of the Basin (P)

Perimeter of the basin is defined as the outer limit of the basin that enclosed its entire area. It is measured along the water divides between basins and it gives a general impression of watershed configurations, notably its shape and size. In the present study, basin perimeter is calculated with the help of ArcGIS-10 software and found to be 648 km (Table 1).

5.3 Elongation Ratio (Re)

Schumm (1956) defined elongation ratio (Re) as the ratio of diameter of a circle of the same area as that of the basin (*D*) to the basin length (*L*). Empirical works of Strahler suggested that this ratio varies in between 0.6 and 1.0 over a different type of climatic and geologic condition. Watersheds having varying slopes can be classified with the help of the index of elongation ratio. The ratio is indicative of elongated (0.5–0.7), more elongated (<0.5), less elongated (0.7–0.8), oval (0.8–0.9) and circular (0.9–0.10) shape with their respective value. The elongation ratio of Mahananda basin is computed to be 0.56, which represents that the watershed is elongated one (Table 2).

5.4 Circularity Ratio (Rc)

For the quantitative analysis of outline or form of watershed, Strahler (1964) used a dimensionless circularity ratio. The circularity index (Rc) is expressed as the ratio of basin area (*A*) and area of a circle with the same perimeter as that of the basin (*P*) (Singh and Awasthi 2011). The ratio is indicative of the exiting geological and lithological nature of the basin. Basin having circularity ratios that range in between 0.4 and 0.5 is highly elongated in shape and consisting mostly of permeable homogenous geologic substances. The circularity ratio value, i.e. 0.39 of the basin underlined the fact that the Mahananda basin is elongated in shape, low discharge of runoff and highly permeability of the subsoil condition (Table 2).

5.5 Form Factor (Ff)

Form factor (Ff) is defined as the ratio of basin area (Ab) to square of the length of the basin (L^2). In general, the range of form factor usually remains below 0.754 (for a basin having perfect circular shape). If the value of form factor will be less, more elongated will be the basin and vice versa. The circular basin with higher value of form factor is an indication of high peak flows of shorter duration, whereas basin having elongated shape with low form factor generates flow for a longer time

Table 2 Important morphometric characteristics of the Mahananda basin

S. No.	Parameters	Value	S. No.	Parameters	Value
1	Stream frequency	0.04	4	Form factor	0.25
2	Drainage density	0.38	5	Circularity ratio	0.39
3	Drainage texture	0.84	6	Elongation ratio	0.56

period. The form factor value of 0.25 for the present watershed indicates elongated characteristics of the Mahananda basin, thus having flow of longer duration (Table 2).

5.6 Drainage Texture (Dt)

Drainage texture represents the relative spacing of stream lines in a basin. It gives clue about the underlying lithological conditions, relief aspect and infiltration capacity of the landforms. Horton (1945) defined it as the total number of stream segments of all orders present in the basin per perimeter of that area. Similarly, Smith (1939) has further classified it into five different segments i.e. very fine (>8), fine (6–8), moderate (4–6), coarse (2–4) and very coarse (<2). In the Mahananda river basin, the drainage texture of the basin is <2 thus indicative of coarse drainage texture.

5.7 Socio-economic Importance

The River Mahananda forms lifeline of the people inhabiting the area. The river serves the socio-economic and cultural pursuits of the area, namely Darjeeling, Uttar Dinajpur and Maldah districts of West Bengal and Kishanganj, Purnia and Katihar districts of Bihar in more than one ways. It forms in its upper course an important eastward linguistic boundary between the Bengali- and Hindi-speaking areas. During the time of festival, the river plays a vital role in performing rituals. The direct economic benefit/use of the river includes river bed cultivation, irrigation and fishing. Besides, rotting of jute and maintenance of ground water are some of the other benefits often derived by the local inhabitants. Rice, wheat and jute are the stable crops grown extensively on the basin.

5.8 Fluvial Hazards

The upper catchment area of the Mahananda with a spatial extent of 26° 45′ 15″N to 26° 55′ 50″N latitude and 88° 17′ 45″E to 88° 03′ 05″E longitude has mostly been deforested, and clearing of the steep slopes has been used for the extension of settlement, agriculture, tea plantation and communication, disrupting the overall ecological balance. As a result during heavy and long spell rainfall, innumerable landslides are caused thereby transporting huge amount of sediments to the river. Most of those landslides have never been treated scientifically with proper protective measures as a result of which the affected area became enlarged during monsoon. This process led to enormous quantity of silt supply to the parent river, the Mahananda, which is incapable of transporting the loads efficiently under the existing hydrological conditions, particularly along its lower reaches. The phenomena are clearly evident during the time of lean seasonal flow, i.e. summer as size of the bars and shoals increases downstream to Siliguri. In order to avoid such numerous islands in the midst of the channel, the river in its lower reaches braided significantly. It may be attributed due to both incompetence and incapability of the river to transport the total amount of debris that is supplied to it as bed load. As a result, the bed of the river is rising at some sections in the plains, resulting in encroachment of cross-sectional areas, thereby obstructing the unusual monsoonal discharge and allowing the water to spill to cause flood hazard. Besides, the narrow road and railway bridges crossing the river channel at the foot hills often act as a barrier interrupting natural load movement behaviour of the river, causing cumulative deposition at the bottom of the bridges thereby narrowing the outlets of the channel gradually. Such hindrance to river flow became acute with the entanglement of uprooted trees thereby damaging the infrastructure, human habitations and agricultural fields.

Temporal analysis of the satellite imagery accompanied with field data from secondary sources revealed some hydro-morphological risk in the basin. Slope instability vis-a-vis slumping in the upper catchment (in and around Paglajhora area) is major area of concern. It is essentially a natural hydro-geomorphic process operating on colluvial slope under the condition of unstable equilibrium, but with human intervention, the incidence of slump became a regular feature. On the downstream side, the River Mahananda at the eastern part water often spills over their banks and causes maximum damage to the existing crops and disruption of transport and communications. The flood situation is grim in south and central part of the West Bengal and western part of Bihar. The river often causes flood havoc due to less capacity of stream channels (Planning Commission 2011). Besides, the bank erosion aggravated by local networking and re-deposition of sediments accompanied with increasing human interference. Silt deposition in the agricultural fields during the time of flood is some of the major area of morphological and societal concerns.

6 Recommendations

Morphological analysis with the help of geospatial data accompanied with GIS-based approach in morphometry analysis and their impact on stream behaviour, landforms and other characteristic parameters at watershed level is more appropriate and has comparative advantage than the conventional methods. Different morphometry parameters were identified and delineated at the watershed level based on satellite image and GIS software. The present study found that the drainage network of the Mahananda basin is dendritic with moderate drainage to low texture. The source area revealed that the River Mahananda is a hill-fed one. Due to lee slope and variable discharge, the river often exhibits the meandering and braided structure throughout its courses. The variation in stream length ratio of the Mahananda basin is possibly because of variations in slope as well as relief from upstream towards downstream. The bifurcation ratio implies that the Mahananda basin is of normal watershed type. Besides, moderate drainage density of the Mahananda basin indicating moderate-to-low permeable subsoil conditions, and moderate-to-coarse drainage texture. In addition to this, the basin is characterized by highly elongated shape. The river basin is capable of fulfilling the socio-economic and cultural pursuits of its inhabitants. However, the basin is known for frequent flood hazards accompanied with frequent changes in river bank, massive bank erosion and silting on the lower catchment area and slumping on the upper catchment area.

Based on these observations, the study suggests the followings for the ecological sustainability of the basin.

1. Massive afforestation programme along the upper catchment of the river basin comprising Mahaldiram range of the lower Himalaya. This programme not only stabilizes the slope but also reduces rate of soil erosion thereby reduction in loads supplied from upper catchment area;
2. Identification and mapping of landslides risk-prone areas and implementation of slope stability programme to prevent landslides. Promotion of appropriate land use policy to check gully erosion; and
3. Site suitability analysis for the development of infrastructure such as roads/bridge should be undertaken prior to policy implementation in the catchment area.

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Hooghly River

Prabhat Ranjan and Alagappan Ramanathan

1 Introduction

Hugli also spelt as Hooghly is a significant river in West Bengal state of north-eastern India. It formed by the junction of the Bhagirathi and Jalangi rivers at Nabadwip. From there the Hugli flows south for about 260 km to the Bay of Bengal, through a heavily industrialized area with more than half of West Bengal's population (Chugh 1961). After traversing a distance of 2705 km and crossing Uttar Pradesh, Bihar and West Bengal, River Ganga divides into two distributaries Padma and Bhagirathi at Murshidabad district of West Bengal. The river Padma flows in the south-easterly direction crossing Bangladesh and empty itself into the Bay of Bengal after meeting Brahmaputra and Meghna, whereas the other distributary, i.e., River Bhagirathi flows in India through West Bengal, It meanders for 150 km through Barampura and Katwa before it joined by a tributary River Jalangi, near Nabadwip; below the confluence of River Bhagirathi and River Jalangi, it flows by the name of River Hooghly, crossing through Kolkata and Diamond Harbour it empty itself into the Bay of Bengal (Mukhopadhyay et al. 2006; Mirza 2004).

The Ganges water is diverted by the Farakka Barrage into a canal near the town of Tildanga in Malda district which supplies the Hooghly with adequate water even in the dry season. Important cities its pass are Jiaganj, Azimganj, Murshidabad and Baharampur. It forms the border between Bardhaman and Nadia districts and then flows south past Katwa, Nabadwip and Kalna. At Kalna, it formed the boundary between Nadia and Hooghly districts, and then further south between Hooghly district and North 24 Parganas district then after passing through Halisahar, Chunchura,

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Konnagar and Kamarahati, and before entering Kolkata, it turns south-west. It joins Ganga at Nupur and turns south to empty itself into the Bay of Bengal.

Hooghly has four tributaries, the Damodar, Rupnarayan, Haldi and Rasulpur rivers, all entering from the west on the right bank of the river. The Rusulpur, however, discharges practically at the sea-face and so has no influence on the navigable channels of the Hooghly. The Damodar, which has its source west of the Ranchi and Hazaribagh, drains the Damodar River, the Chota Nagpur hills. It has one large tributary Barakar River, rising north of Hazaribagh. After passing the town of Burdwan, the Damodar, it makes a great right-angled bend above Selimabad and then flows south past Amta, the actual river channel falling into the Hooghly opposite Fulta Point at the head of the James and Mary Reach. The Rupnarayan is formed at Bunder, just east of Ghatal, by the confluence of Dalkishor and Selai rivers, both rising east of Purulia (Manbhum). After passing Tamluk, it expands into a wide basin and then enters the Hooghly through a narrow but deep neck at Geonnkhali opposite Hooghly point and the lower end of the James and Mary Reach. About 15 miles above Tamluk, the Rupnarayan is crossed by Bengal Nagpur Railway at Kola Ghat, and 10 miles further up, the Bakshi khal takes off from the left bank and connects the Rupnarayan with the Damodar through Gaighata khal. The Haldi River formed by the confluence of the Kaliaghai River, rising south-west of Midnapur, with the lower branch of the Kosai River. It enters the Hooghly through a relatively wide estuary at Sandia opposite Mud Point. The last tributary of the Hooghly is the Rasulpur River entering on the right bank at Hijli. This river has now practically no influence on the channels, though formerly it helped to maintain the western channel approach to the Hooghly (Rao 1995) (Fig. 1).

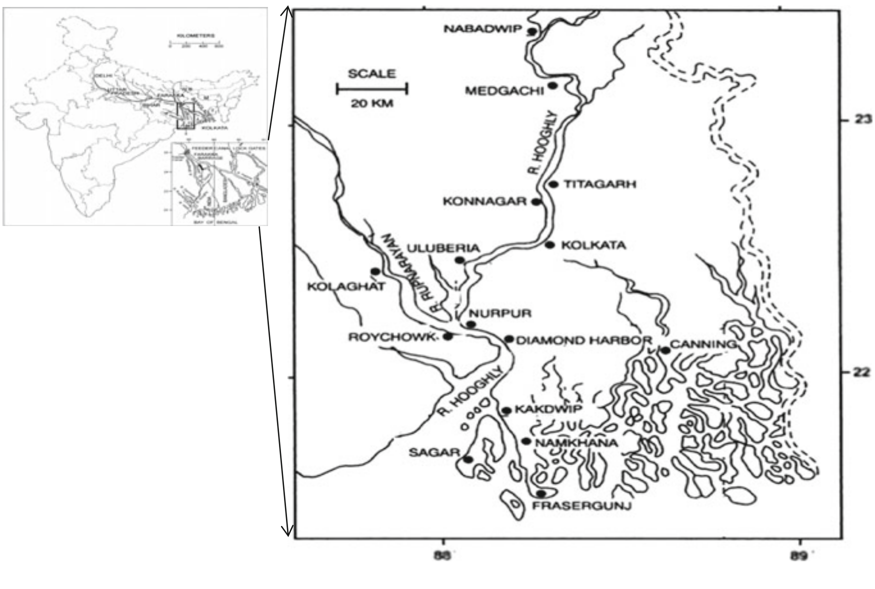

Fig. 1 Map showing Hooghly River and its tributary (Adopted from Mirza 2004)

2 Geomorphology of Hooghly River

The Hooghly River can be divided into three main parts:

(1) The Upper Hooghly from Nadia to Hooghly, a distance of 60 miles;
(2) The Lower Hooghly from Hooghly to Kantabaria at the head of the estuary, 78 miles; and
(3) The estuary from Kantabaria to Saugor, 36 miles.

Beyond Saugor, the sand project 43 miles into the sea, to the Sand heads at the Bay of Bengal and the approach channels between these sands, into the river at Saugor, may be included in a fourth section.

Upper Hooghly River from Nadia to Hooghly has an unstable course and roams through a wide strip of land continually, though gradually, changing its course, whereas the course becomes fixed in the Lower Hooghly. The Matabhanga joins the Upper Hooghly near Chakdaha on the left bank, Kharia Nadi, draining the west, north and east of Burdwan between the Damodar and Ajai rivers, enters into the Hooghly on the right bank near Mirzapur above Kalna. The old channel of Damodar, the Kunti River enters on the right bank at Noaserai and a relic of the old Saraswati River still exists in a khal at Tribeni. These two channels are dead; the Hooghly water pours into them during the rain and pouring out again as the level falls.

There are strong tidal forces in the Lower Hooghly between Chinsurah and Kantabaria; the banks are formed of the hard material, and the river has therefore fixed courses maintaining practically permanent channels. Under seasonal variation and tidal forces, the channel flow is oscillatory. The channel has been influenced by the down flowing, or ebb current, and its axes ordinarily follow a succession of connected, reverse, parabolic curves with deep water clinging to the concave bank sand shallowing at the crossings where the current swings from one bight to the next, leaving sandbanks along the convex faces of the bends.

After a severe flood of 1770 AD, Damodar changed its course and joined with Bhagirathi at 50 km south of Kolkata; due to changed confluence point, Saraswati became extinct, and Bhagirathi flowed along the present track of Hooghly River. Channel migrations are due to several interrelated effects like channel gradient, tectonic movement and compaction of fine sediments. The Bengal basin comprises three geo-tectonic provinces: (a) the stable self, (b) the central deep basin and (c) the Chittagong–Tripura fold belt. The Bengal basin located at the juncture of three plates, i.e., the Indian, Burma and Tibetan plates (Eurasian plate), and these geo-tectonic plates varied considerably in past. The two convergence plate near Bengal basin; the Himalayan plate and the Burma arcs, override on the Indian plate from the north and the east, respectively. Under a load of overriding plates, the foredeep of The Himalayan plate and Burma arcs shows bending of subducting lithosphere. Also, the influx of sediment into basin from the Himalayas to the north and Indo-Burma range to east increased the subsidence of the basin causing Indian plate to tilt towards the south-eastern direction which was a major reason for the avulsion of the river of Ganga—Brahmaputra delta like Hooghly River (Laha 2015).

The stability of the bank is the resultant of the balance between the shear stress exerted by the downslope component of the gravity (driving force) and shear strength of the bank material (resisting force) (Charlton 2008). Hooghly River, due to its curvature bank and tidal action, has high hydraulic action (driving force) which exceeds the shear strength (resisting force) as the percentage of silt (52.4%) and sand (34.08%) is too much high on the left bank of the Hooghly River which is major reason of the bank failure throughout the year, and it is more prevalent during flood period. Hooghly River's shifting nature is the fluvio-geomorphic phenomenon which is common for lower part of any river. It has the tendency to shift eastward along the left bank which is also regulated by mid-channel bar like Mangaldwip char. Channel shift and bank erosion lead to loss of land from erosional side and deposition on another side; since 1917–2012, 1.618 km^2 lands have been eroded by Hooghly River (Mongaldip et al. 2015).

3 Pollution Status of Hooghly River

In the earlier study done by Seth (1950), it was found that a total load of organic pollution into the river in the form of industrial waste has a 5-day B.O.D. of 76,000 lb which is equivalent to the sewage of a population of about 6 × 106. He found dissolve oxygen (DO) above 4 ppm and pH ranged between 7.3 and 8.1. A similar result was found by Bose (1954), for the lower part of Hooghly and Hooghly estuary complex; having pH ranged between 7.9 and 8.4, alkalinity varies from 2.0 to 7.5 millieq/l, and phosphate is low in monsoon and higher in summer due to the liberation of PO_4^{-3} from bottom mud. Hooghly River estuary complex is one of the most polluted estuaries in the world (Mukherjee and Kashen 2007), where half a billion litres of untreated waste from different industries are dumped every year.

After Farakka Barrage, i.e., 1971, there is increased freshwater discharge resulted in significant decrease in salinity. Freshwater zone extended till the mouth of the estuary, and there was the movement of estuarine zone towards seaward which resulted in the change in plankton dynamics and the sharp decrease in fisheries of marine. The plankton diversity during the pre-Farakka period was high, i.e., 79 types of species (Gopalakrishnan 1971) which decrease to 58 types in the study done by Sinha et al. (1996). This decline in the euryhaline and marine form of plankton during the post-Farraka period is due to decrease in salinity (Sinha et al. 1996).

In the study done by Mukhopadhyay et al. (2006), higher discharge of $3.0 \pm 1.0 \times 10^3\ m^3\ s^{-1}$ was found during monsoon (with maximum of 4000 $m^3\ s^{-1}$ during September) and lowest discharge found $1.0 \pm 0.08 \times 10^3\ m^3\ s^{-1}$ (minimum of the order of 900 $m^3\ s^{-1}$ in May). Flux change in the coastal zone of Hooghly River system for dissolved inorganic carbon (DIC)—2.76 × 106 t/yr.; dissolve inorganic nitrogen (DIN)—65.8 × 103 t/yr.; dissolve reactive phosphate (DRP)—12.8 × 103 t/yr.; and silicate—42.8 × 103 t/yr. Out of the total transport of nutrient, monsoonal run-off accounts for 64% of DIC, 71% of DIN and 76% of DRP and silicate both. Nitrate, phosphate and silicate value for Hooghly River varies from 15.5–34.9; 1.52–3.01 to 43.2–102.9 μM, respectively. The change in nutrient concentration since 1975–2005 was for DIN from 19.28 to 19.4 μM and DRP from 1.61 to 1.99 μM which is almost constant in these years, whereas silicate decreased from 35.6 to 102.9 μM (Mukhopadhyay et al. 2006).

4 Socio-economic Importance

The river provides the perennial supply of water to the plain of West Bengal for agriculture, industry and domestic consumption. The river is traversable and comprises the major part of the transport system in the region with a huge traffic flow. Advanced container port of Haldia, on the intersection of lower Hooghly and Haldi Rivers, carries much of the region's sea trade. The Hooghly River valley always been the most important trading and industrial area of the former state of Bengal. Many industries came up during the British time on the banks of this river, big jute and engineering factories. Earlier tradesmen like the Dutch, British, Portuguese and French used this river for trade and business transportation. Due to fall in jute industry (the principal industry of this region), it lost its glory although still it is one of the biggest industrial areas of India. Major population residing near the river area has fishing as their primary food, and it is also important for their economy.

This river was used from the historical period as the main medium of transport, trade and commerce activities. Many water sports competitions used to be held at former times by the Zamindars and the Babus. Since, the Hooghly River runs throughout Kolkata, tourism options, such as city river cruises, are the possibility for visitors also tourist boats travel and tourism hot spots on the Ganges, explore more opportunities of the job on Hooghly River.

Since ancient time, Kolkata port is the most important Indian port. Though in the past its significance had gone down, recently it had again come in top position among the list of Indian ports. The river bank filled with derelict ghats, illegal warehouses and crematorium, is essentially a vast open waste-producing zone and appears beyond redemption. There are many ghats with both historical and architectural significance, but only Princep Ghat, built in 1843, stands resplendently among the ruins. Rich in Greek and Gothic decorations, the monument was amended by the state public works department since November 2001 and has been well maintained. The river Hooghly also been used as a domestic as well as industrial sewerage system which is facing pressures related to increasing population growth, encroaching development in the wetlands, increasing industrial cluster, increases pollution and volume of the wastewater. Within the ambit of Kolkata's domestic sewage plan, it needs more wastewater treatment plants for sustainable environmental, socio-economic alternative and also to reduce the burden on the river like Hooghly. The challenge is to reduce pollution, to encourage indigenous opportunities of job and economic benefits and to build a sustainable coastal and riverine management system that will address the real needs of her people (Mishra 2004).

5 Conclusion

The channel geometry is very irregular as seen from the variation of areas and widths along the river. This is due to the existence of numerous curves and bends and sudden divergence of sections which gives rise to the divergence of flood and ebb axes with the result the crossing from one bank to the other remains shallow, necessitating dredging for the required navigable depths to be maintained. Except its importance as the navigable river, helping in transport, tourism, agriculture, Industrial use, etc., It value is degrading as its quality is declining. Waste from sewerage, untreated industrial and domestic waste, agricultural waste and increasing population pressure choking the river to death. In the study done on Hooghly river, it was found that organic pollution into the river in the form of industrial waste has a 5-day B.O.D. of 76,000 lb which is equivalent to the sewage of a population of about 6×10^6. Hooghly water pH ranged between 7.3 and 8.4 and alkalinity varies from 2.0 to 7.5 millieq/1 were found in the different study done on Hooghly river. The plankton diversity during the pre-Farakka period was high, i.e., 79 types of species which decrease to 58 types. So, to relive it we need a sensible and scientific approach towards this channel system. Firstly, the point sources of pollution need to be treated with sewage treatment plant and non-point sources need to identify and reduced. The tourism should be promoted so that even people try maintains its quality for livelihood. We need to do ecological studies, to control pollution level, providing recessional sites, investigating and monitoring of flora and fauna, control of the flow of polluted water and also dire need of vast study of this river system is required so that better decision can be taken for its rejuvenation.

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Damodar River Basin: Storehouse of Indian Coal

G.C. Mondal, Abhay Kumar Singh and T.B. Singh

1 Introduction

Damodar is a rain fed, shallow, wide and flashy river, originating near the Khamarpat Hill on Chotanagpur Plateau in the Palamau district of Jharkhand. It is a sub-basin and part of the Ganges River System, having 10% of the total length and 2.7% of the total area of the Ganga master basin. Damodar River flows through the industrial towns of Chandrapura, Ramgarh, Bokaro, Jharia, Sindri, Dhanbad, Asansol, Andal, Durgapur, Burdwan, and Howrah before joining the lower Ganga at Shayampur, 55 km downstream of Howrah (Sen 1991; Chandra 2003; Bhattacharyya 2011). Its upper reaches known as Deonad, and in some of the local Jharkhand languages, Damodar is also called as *Damuda*, '*damu*' means sacred and '*da*' means water. Damodar basin is known for its coal deposits; accounting for 46% of the country's coal reserves and commonly referred as the '*store house of Indian coal*.' It is considered as the centre of coking coal in the country (Sharma and Ram 1966). However, Damodar basin is poor in metallic minerals. It flows through one of the richest mineral belts in the world before joining the Hooghly at about 55 km downstream of Howrah. Coal mining and mine-based industrial activities are the major source of economy with low agricultural productivity in the upper part of the basin. The mining and industrial activities have made the valley vulnerable to soil erosion and pollution. The 'river of sorrow' as Damodar was known has now turned into the 'river of agony' from pollution point of view. Indian industry depends on this region heavily; out of total 91% of the coal consumed by industry in this country, a large share, i.e., 60% comes from the coal bearing belt of Damodar basin. The coal requirement for power generation in the Jharkhand and West Bengal states entirely depends on this area.

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The catchment area of Damodar River basin extends from 22° 45′N to 24° 30′N to 84° 45′E to 88° 00′E and is covering parts of Jharkhand and West Bengal which is about 11.8 and 8.6% of the total geographical areas of these two states, respectively (Fig. 1). The drainage area of Damodar River basin extends over Hazaribagh, Ramgarh, Koderma, Giridih, Dhanbad, Bokaro, and Chatra districts in Jharkhand and Burdwan and Hooghly districts in West Bengal. It partially covers Palamau, Ranchi, Lohardaga, and Dumka districts in Jharkhand and Howrah, Bankura, and Purulia districts in West Bengal. The observation reveals that three-fourth of the total basin area lies in Jharkhand and one-fourth in West Bengal. The total catchment area of basin is reported to be 25,820 km^2 (DVC 1992). However, Central Pollution Control Board (CPCB) has delineated catchment area of the Damodar basin as 23,170 km^2 only with sub-catchment areas as follows:

(i) Main Damodar River	15,280 km^2
(ii) Baraker tributary	7,025 km^2
(iii) Bokaro–Konar tributaries	865 km^2

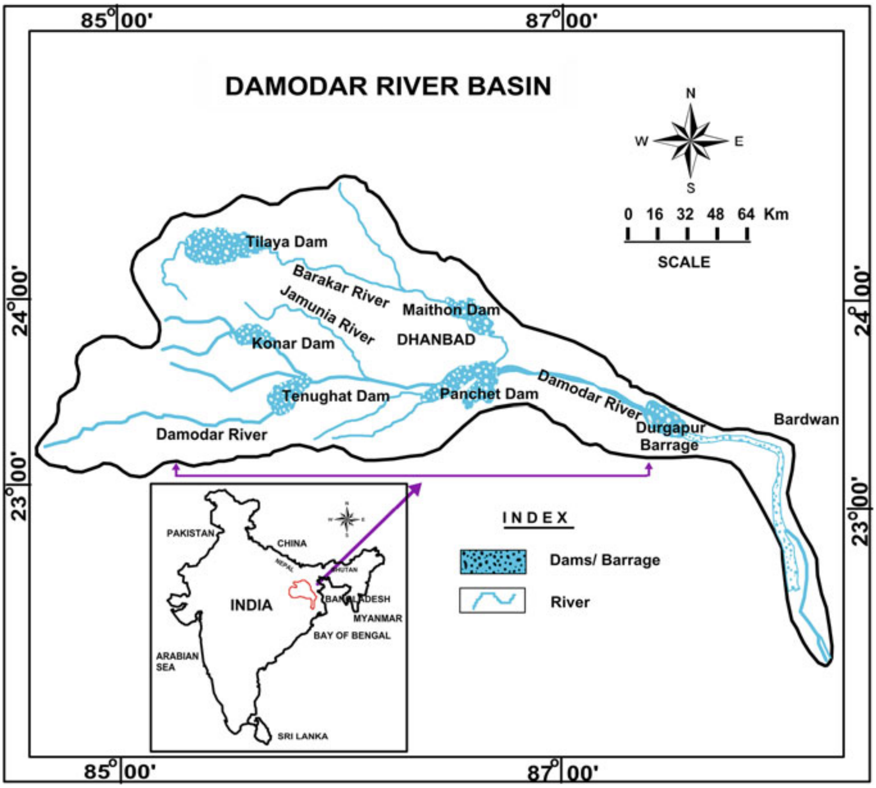

Fig. 1 Drainage map of Damodar River basin

2 River Course and Major Tributaries

Damodar River along with its major tributary Barakar constitutes the core area of the Damodar River basin. Barakar, Konar, Bokaro, Haharo, Jamnia, Ghari, Guaia, Khudia, and Bhera are the major tributaries and sub-tributaries of Damodar River (DVC 1992; CMRI 2001). The river in its upper reaches traverses through the steep slope of the pat region to descend on the gneissic flat plain of Chandwa, and flow of the river becomes sluggish over the flattop surface (Fig. 4a). The landscape around the river changes after its entry into Gondwana area and confluence with Dharamauti. Waterfalls occur abound the courses of the streams due to steeper gradient of the stream in this region. After it, the river passes through the hard sandstone and grit of Gondwana rocks in hilly and woody areas. In this part, a number of tributaries such as Saphi, Batuka, Nalkari, Barki-Garhi, and Ramghat-Haharo meet with the Damodar River both from the southern and the northern sides. Before entering the Gondwana basin, these tributaries have characteristic headword erosion and flow over the Archaean granite-gneissic surface.

The tributaries Konar and Bokaro originate over the Hazaribagh plateau near Hazaribagh town, and their combined courses meet Damodar River near Tenughat. The river Konar flows over Archaean gneiss country rocks, and a dam has been constructed near Gumea (Fig. 2). The Bokaro River flows through the Archaean gneiss and enters into the Gondwana basin near Bokaro coalfields. Damodar traverses further east after Tenughat and joined by some more tributaries both from the north and south side before reaching Panchet. The Jamunia and the Khudia which flow over the Raniganj coalfields area are the main tributaries joined the Damodar River from north side. Ijri and Gowai tributaries meet the Damodar River from the south side near the western end of the Panchet reservoir. A dam has been constructed on the Damodar River near Panchet hill, 5 km west of its confluence with the river Barakar.

The river Barakar originate from the Koderma plateau and runs for a long distance before meeting the Damodar River near Dishergarh. The Barakar River has a total catchment area of 7,025 km^2. It traverses through a steep-sided valley near its source region and drains into Tilaiya reservoir near Hazaribagh. The Barakar further emerges out of Tilaiya reservoir and meanders southeast. Barsoti and Usri are two important tributaries of river Barakar. A multipurpose dam has been constructed on the Barakar River at Maithon, which is 13 km upstream of Dishergarh.

The Damodar River passes through flat alluvial plain after its confluence with Barakar River and runs towards southeast and east up to Barsul in Burdwan (Fig. 4b). Near Durgapur, 60 km east of its confluence with the Barakar, a barrage has been constructed over the Damodar River. After that, the river turns toward south near the village Chachai. The river flow becomes very sluggish at this part, and surplus water during monsoon seasons is carried by several spill channels locally, known as *hanas*. Damodar splits into two channels, Mundeswari and Amta, after flowing further south. The Damodar further traverses over the Arambagh of

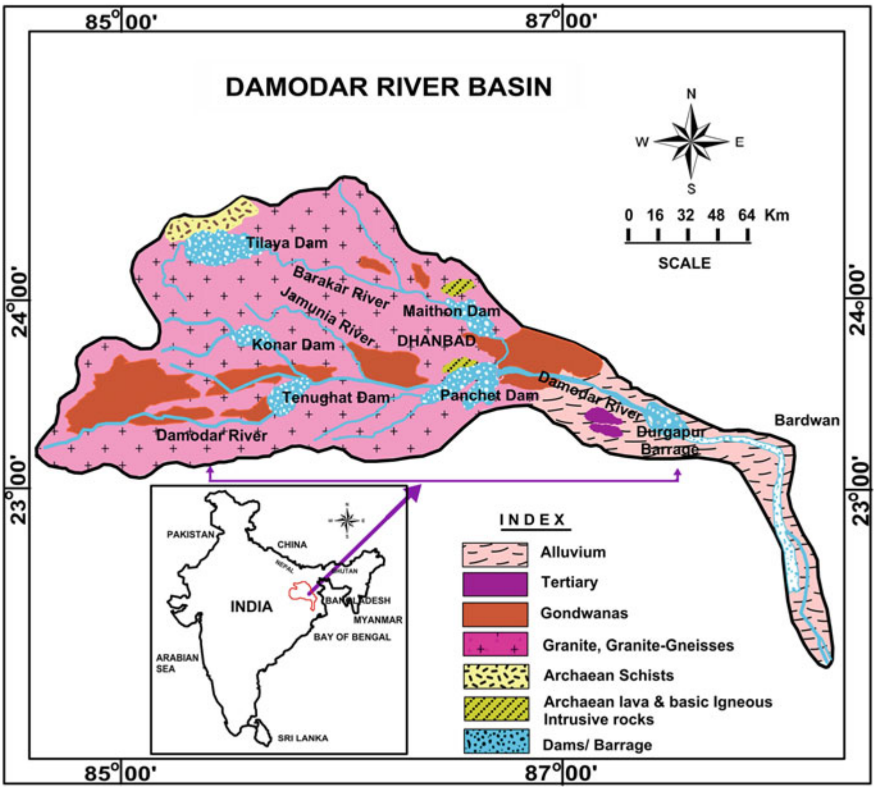

Fig. 2 Geological map of Damodar River basin

Hooghly district and Uluberia of Howrah district to join the Hooghly River at 55 km downstream of Kolkata.

3 Geomorphology

Physiographically, the upper catchment of the Damodar basin is quite different to the lower part of the basin (DVC 1992). Three major geological features of the Damodar basin are (i) Peninsular shield mainly consisting of granites and gneisses of the Archaean Age, (ii) Gondwana tract filled up by sediment during the Permo-Carboniferous period (Older Alluvium), and (iii) the Bengal basin filled with Newer Alluvium during Tertiary and Quaternary periods. Based on these geomorphological characteristics, Damodar valley may be divided into three micro-geomorphic units:

(i) **Plateaus, Hills and Ghats**: Several plateaus are identified and classified as Upper, Middle, and Lower plateaus and, respectively, named as Ranchi, Hazaribagh, and Koderma plateau in the upper Damodar region. Similar landform characteristics have been observed in these plateaus. The flat, severely gullied, isolated, low rounded hills and monadnocks are scattered all over the platform (Mahadevan 2002). On the border, plateaus are flanked by steep escarpments. Surface erosion results differential relief features on these plateaus which are considered to be formed either due to different peneplanation stages or mineralogical variation of the plateaus country rocks. The Ranchi plateau is characterized by three leveled erosional surfaces at 15–50, 50–100 and 100–200 m relative relief surface levels, respectively. Rounded isolated mass of residual hills or monadnocks are of common sight throughout the Ranchi plateau. Variation of lithological characteristics might have caused the formation of residual hill mass or buttes on peneplain surface (Ghose 1983). Due to exfoliation, the rounded forms have been carved out. As compared to the Ranchi plateau, the variation of relative relief is not so marked either in the Hazaribag plateau or in the Koderma plateau. Hazaribag plateau records a relatively higher relief, i.e., 100–200 m as compared to the Koderma plateau which has a lower relative relief of 50–100 m. The resistance of rock to erosion is nearly uniform, and the peneplanation is nearly perfect as suggested by uniformity of relief. On the Hazaribagh plateau, a few monodnocks while a fewer on the Koderma plateau are observed. Rock forms during Dharwar age are mostly found in the Koderma hills and plateaus. Hill masses are also occurred in the Gondwana trough regions of the upper and middle part of the Damodar basin. East-west trending faults running parallel to river flow delineate the northern and southern boundaries of the Damodar trough. Hilly mass of landforms has been assumed by trough region due to tectonic activities resulting into fault scarps and arching of Gondwana sediments in later periods. This hilly relief forms have become more accentuated due to differential erosion of Gondwana rocks of varying hardness and resistance to erosion.

(ii) **Dissected and Degradational Uplands**: The dissected and degradational uplands stretch over the middle part of Damodar valley. The areas fall in Purulia, Bankura Burdwan, and Birbhum districts of West Bengal and Ramgarh, Bokaro, Dhanbad, Giridih, Jamtara, and Dumka districts of Jharkhand. Major river valley is flanked from west to east by the typical landforms. These are the remnants of the older peneplains and marked by steep slope with very high relative relief around Parashnath hill. This area has highest elevation of 1345 m in the Damodar valley region. The landscape is look like a rolling upland carved out of ancient platform. Archaean crystallines schists, gneisses, and quartzite are the major rocks forming the landforms along with basic intrusive at places (Ghose 1983). The relative relief is more obvious toward north and west. The Gondwana trough includes the central block of this degradational upland. The Damodar and Barakar pass through a number of tectonic troughs. These troughs lie on Archaean basement and are filled in with Gondwana sediments. The important coal measures of the Damodar valley region are included in these sediments. The gneissic basement is completely covered by the vast expanse of laterites and lateritic soils to the eastern fringe of the degradational and dissected uplands. The poor land topography of this region has been resulted due to intense gully and sheet erosion.

(iii) **Aggradational Flat Plains**: This region is separated to the west from the degradational and dissected uplands by a line approximately joining Arambagh, Burdwan, and Bolpur. This region is characterized by monotonous flat alluvial plains of shifting rivers with less than 15 m relative relief. The altitudes vary from 15 m in the south and east to 30 m in the west. Regular shifting of river channels is commonly observed in this region. The records of ancient courses of the Damodar indicate the occurrence of change in its flow from east to south in stages. The aggradational flat plains may be divided into five units as (a) the bank plain to the north, (b) the Damodar plain to the south, (c) the Hooghly-Rupnarayan doab (d) the Hooghly levee, and (e) the marshes.

4 Geology and Soil Types

Numerous types of metamorphic, sedimentary, and igneous rocks are found in the Damodar basin (Fig. 2). Granites and granitic gneisses of Archaeans, sandstones and shales of the Gondwanas, and the recent alluvial are the major litho-units constituting the geology of the basin. The geological features of the lower catchment are quite distinct from the middle and upper part of the basin. Thick veneer of alluvium over the solid rocks of Tertiary age is dominating in the lower part of the basin. Archaean granitic gneisses, sandstones, shales, and coal measures of Gondwana age are the dominant rock types in the upper basin catchment. An approximate line joining Bankura town with Sainthia town demarcates the alluvium form the geological formations of Archaean period in Birbhum district. About two-third area of the Damodar basin is occupied by these geological formations. Some laterites and lateritic formations of Tertiary period are also exposed on the margin of the Archaean foundations to the east along the border of alluvium zone. Rocks of Gondwana and Vindhyans geological formations of later age rest over the Archaean basement and are restricted to the north of Hazaribagh plateau. Coal-bearing Gondwana formations cover considerable areas of the river basin and are of great economic importance for the country. Coal deposits are mostly exists in the tectonic trough having faulted boundaries toward north and south of the Damodar River. Damodar River flows over the faulted trough. As evidenced from different formations during Gondwana period, repeated cycles of sedimentation had been occurred. It had also been suggested that there might be repeated sinking of the basin also during sedimentation. Intrusion of mica-peridotites, dolerite or basalt occurred in coal-bearing strata of the Gondwana at many places.

In general, four types of soil are found in the Damodar River basin. Red loam soils occurred in upper and middle region and laterites and lateritic soils in the middle part of the basin, upper catchment is characterized by patches of dark gray-colored calcareous soils while riverine alluvial soils are common in the lower part of the basin. Red loam soils are developed extensively where the country rock is granite, gneiss or, schist. It is most common in the plateaus of Ranchi, Hazaribagh, Palamau, and Dhanbad districts in Jharkhand and also in Burdwan and Purulia districts of West Bengal. High temperature and moderate-to-high humid conditions of the Damodar basin area favor the decomposition of organic matter and rigorous leaching. Soils of this region acquire reddish color due to oxidation of ferrous into ferric materials under such climatic, edaphic, and vegetative environment. These soils are poor in organic matter, nitrogen and available phosphorous content and rich in potash. The soil textures range from loamy sand to sandy loam. The upland of the Ranchi and Palamau in the east and the plateau fringes of Purulia and Burdwan districts in the west show well development of laterites and lateritic soils. Organic matter, nitrogen, available phosphorous and calcium contents are poor in yellow and gray-colored soils occurred on the top and also in red color soils of below horizon.

Calcareous soils which are rich in calcium carbonate occurred as the patches in the upper catchment of Damodar basin. Such soils are originated from weathering of hornblende schist. Riverine alluvial soils are found extensively in the lower catchment of Damodar basin. Two types of alluvial soils, namely older alluvium and newer alluvium, can be identified on the basis of depositional characteristics. The older alluvium generally deposited over the levee region and on the alluvial terraces at different heights. Such soils are red in color due to iron stained and clayey in nature. The newer alluvial soils are widely distributed in the flood plains of the lower Damodar basin. These soils are extensively distributed in Birbhum, Bankura, and Burdwan districts. Marshy or swampy soils are found in the low-lying areas of Hooghly and Howrah districts.

5 Socioeconomic Importance

(i) Water Resource and Its Uses

The Damodar River was regarded as a flood-prone river due to its long history of the endemic floods and commonly known as 'Sorrow of Bengal.' History of the endemic floods in the Damodar River can be traced back from 1730 onward (Bhattacharyya 1999). Records show that during the floods, peak flow of 8496 cumec or more occurred thirty seven times between the years 1823 and 2007 (Bhattacharyya 2011). Different strategies including construction of embankments, weir, dams, and barrages were adapted to deal the caprices of this vital water resource by government agencies and local peoples. Damodar Valley Corporation (DVC), a multitask organization, was constituted in year 1948 on the model of Tennessee Valley Authority (TVA) for development and management of natural resources of Damodar River basin. Damodar Valley Corporation (DVC) constructed India's first multipurpose dams at Tilaiya (1953), Konar (1955), Maithon (1957), and Panchet (1959). A barrage was constructed on Damodar River near Durgapur for irrigation purpose in 1955. In year 1978, one more reservoir was constructed on the mainstream of Damodar at Tenughat in Jharkhand state (Chandra 2003; Bhattacharyya 2011). Dams of Damodar Valley Corporation are capable of moderating floods of 6.51 lac cusec to 2.5 lac cusec. Four reservoirs of DVC having a flood reserve capacity of 1292 mcm. This can moderate a peak flood of 18,395 cumec to a safe carrying capacity of 7076 cumec. Four DVC reservoirs store 419 mcm of water which are supplied to meet industrial, municipal, and domestic requirements in West Bengal and Jharkhand states. Durgapur barrage was mainly commissioned to supply the irrigation water especially for Burdwan, Bankura, and Hooghly districts of West Bengal. The DVC has generated irrigation capacity of 3640 km^2, besides water supply for industrial and domestic uses (Chandra 2003). Effective water management planning of Damodar Valley Corporation has turned the devastating river Damodar from a 'River of Sorrow' to a 'River of Opportunities.'

(ii) **Mineral Resources and Industrial Activities**

Damodar basin is regarded as the storehouse of Indian coal. Apart from coal, iron, limestone, bauxite, baryte, mica, fire clay, china clay, etc., are the other minerals associated with the geological formations of the Damodar valley. Coal is the most important mineral resource of the basin, and coal deposits in the Damodar River basin may be divided into seven coalfields, namely Jharia, Raniganj, East Bokaro, West Bokaro, North Karanpura, South Karanpura, and Ramgarh (Fig. 3). Out of these coalfields, Jharia and Raniganj are oldest one and it bears large number of workable coal mines. Besides coal, limestone quarries are found in Palamau and North Karanpura areas and fireclay in Jharia and Raniganj coalfields area (Chandra 1992).Damodar River basin is a highly industrialized area having a large number of coal mines and coal-based industrial establishments such as steel plants, thermal power stations, coal washeries, metal smelting plants, chemical plants, cement mills, beehive cock oven plants, metal alloy, steel re-rolling mills, refractories, mica and glass industries, as well as lime and brick kilns. There are more than 300 operating coalmines, which provide basic inputs for the other activities. Other than major industries, there are a number of small scale as well as ancillary industrial units. These units apart from providing jobs to the local population contribute significantly to the economy of the basin. The units comprise of mini workshop, tobacco processing units, textile and textile product units, petroleum and coal product units, chemical and chemical product units. There are five steel plants, eleven thermal power plants, ten cement factories, twenty-four coal washeries, sixty-four refractories, four hard coke oven plants, fourteen beehive coke oven plants, three hydroelectric power plants and number of other miscellaneous

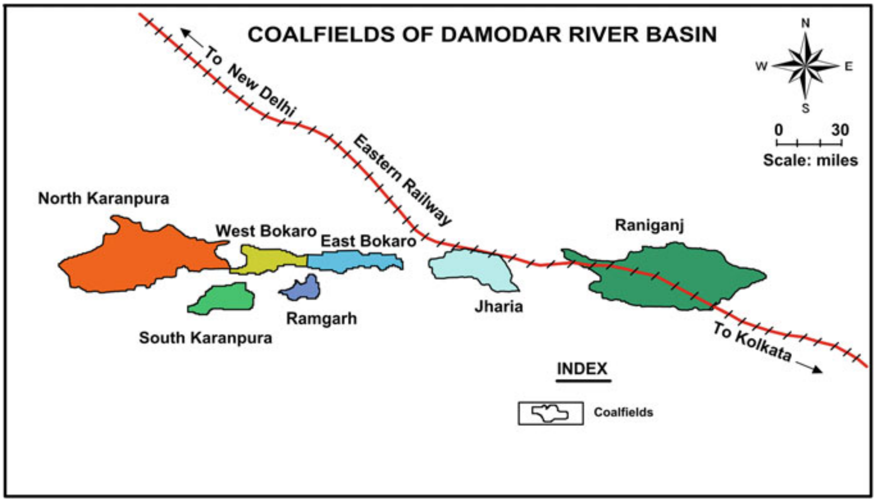

Fig. 3 Major coalfields of Damodar River basin

industries exist in the Damodar River basin. The thermal power stations of the basin having total installed capacity of 10,200 MW. Apart from these, three hydroelectric power plants having a capacity of 144 MW and one gas turbine power plant in Maithan with a capacity of 82.5 MW are also contributing toward the power generation in the basin.

(iii) **Natural and Anthropogenic Hazards**

Damodar is a rainfed river, and about 80% of the annual river discharge occurs during the four monsoon months ranging from June to September. Around 1400 mm annual rainfall occurs over the Chotanagpur plateau area, out of this more than 85% rainfall takes place in the monsoon months between June and August. The high monsoonal rainfall resulted imbalances in river flow and caused frequent flash floods in many parts of the basin. Though, floods sometimes affect the lower Damodar Valley but after construction of dams and reservoirs, the havoc it created in earlier years is now a matter of history (Ghosh 2013). The floods were virtually an annual ritual for Damodar River basin in the past. The damage was probably more in some years and of lesser magnitude in other years. The great floods of the Damodar River in pre-dam phase are recorded in the years of 1770, 1855, 1866, 1873, 1874, 1875, 1876, 1884, 1891, 1897, 1900, 1907, 1913, 1927, 1930, 1935, and 1943. The massive floods in southern West Bengal had been occurred in 1959, 1978, 1995, 1999, 2000, 2006, 2007, and 2009 in spite of flood regulation by the DVC and construction of dams and reservoirs. This signifies the vulnerability of lower valley to sudden floods even in post-dam era during monsoon season (Bhattacharyya 2011).

Damodar flows through India's richest mining and industrial belt and considered as the most polluted river in India. The river Damodar and its tributaries drain almost the entire coal mining areas of North and South Karanpura, West and East Bokaro, Ramgarh, Jharia and Raniganj coalfields. Occurrences of coal and easy availability of water and power favored the setting of coal-based industries and power plants in this area. Coal washeries, thermal power plants, coke oven plants, soft-coke batteries, steel, cement, and explosives plants are the major industrial units of the Damodar basin. These industrial units draw water from the Damodar River or its tributaries and many of them are discharging their untreated effluents into the river. The contamination of the river water is mainly due to excessive excavation and disposal of oil, fly ash, poisonous metals and coal dust. Defective and unscientific excavation operations, outmoded processing activities, and deficiency of right upkeep were intensified by insufficient pollution check measures and public ignorance toward environmental protection (Fig. 4c–f). The inhabitants residing in the valley were gradually being poisoned due to the fact that Damodar and its tributaries were the only source of drinking water for majority of inhabitants residing in the locality. Study shows that the total suspended solids (TSS) concentration at most places along the upper and middle stretches of the Damodar River is much higher than the permissible limit (Fig. 4f). Coal mining and washeries account for the bulk of pollution in terms of atmospheric dusts, suspended solids, oil, and grease. Open-cast mining accounts for 60% of the coal production in the Damodar valley. The open-cast mining and associated activities cause serious problems of land degradation, dust generation, and deterioration in environmental quality of the region (Choubey 1991; CMRI 2001; Tiwary 2001; Singh et al. 2008). The disposal and management of overburden materials and fly ash is also a serious challenge for the coal authorities. Mine fire is the other serious environmental issue associated with the coal mining areas of Damodar River basin (Fig. 4d). More than seventy coalmine fires, covering 17.32 km^2 areas are reported from the mining areas of Jharia coalfields (BCCL 2003). Jharia mine fire is one of the largest coalmine fire complexes in the world (Gupta and Prakash 1998). Mine fire gives rise to continuous and uncontrolled emission of greenhouse gases such as CO_2, NO_x, SO_2, CO, CH_4, C_2H_6, and C_3H_6 due to surface and subsurface burning of coals throughout the coalfield areas.

(iv) **Erosion and Siltation**

The fluvial environment of the lower Damodar basin has undergone gradual changes in post-dam era due to construction of dams and reservoirs and diversion of water through canals. The upper Damodar River catchment is susceptible to soil erosion, and extent of erosion depends on the slope, rainfall intensity, soil characteristics, and vegetative cover. The soil erosion problem is more severe in the catchment areas of the five reservoirs. Severe erosion in the catchment is not only causing formation of wasteland but also posing the problem of siltation and reduction in the reservoirs storage capacity (Ghosh 2014). Continuous sediment generation and its transportation to the lower part of the valley kept on raising the river bed year after year (Fig. 4b). The problem of siltation has also been

Fig. 4 Damodar River at **a** upper catchment, **b** the middle stretch, **c** an open-cast coal mine **d** mine fire in Jharia coalfield area **d** industrial activity and air pollution status in the valley, and **f** water quality status in the coal mine pit

aggravated by storing of monsoon rainwater in the dams and barrages as the annual flushing of sand–silt–clay was greatly checked. In this way, the then dynamic Damodar is now flowing very sluggishly through the braided course. The bars and islands are so stable that not only those are used for crop production due to higher fertility status but even settlements have been developed in many places as also the pathways across the river in the dry period (Ghosh 2014). Land-use alteration and natural river flows have a great impact in terms of volume and velocity of water flows and determining the relationship between dissolved and sediment load to the water discharge, river bank erosion, frequent shifts in the direction of river courses and discontinuation of some old distributaries. The reduced river flow and increased sediment load cause heavy siltation and led to the development of increasing quantum of falls channels (blind rivers), marshes, oxbow lakes, etc. Further, to save the dams from bursting due to overfilled reservoirs, the DVC authorities release huge quantity of water with a very short notice, making an avalanche of water flow over the already monsoon submerged agricultural fields and settlements. On the other hand, during the dry summer season while the farmers are hoarsely crying for irrigation water for their parched fields to save crops, the DVC remains reluctant to release adequate quantity of water as that may lower the water level in the reservoirs affecting adversely the generation of hydroelectric power which is committed for the industries in the upper catchments. Such circumstance forced the farmers to tap the groundwater more and more for irrigating their lands and overexploitation of groundwater led to lowering of water table and minimization of available annual water resource for future exploitation.

6 Conclusion

Damodar River basin is one of the richest mineralized zones of the country with a high growth potential as evident from the mining and industrial development, demographic and urban growth extending over a large area of Jharkhand and West Bengal states. The valley is the storehouse of Indian coal and considered as the prime centre of coking coal in the country. Other than coal, the non-coal minerals such as mica, fireclay, bauxite, limestone, barytes, steatite, china clay, kaolin, kynite, dolomite, graphite, magnetite, and vermiculite are also associated with the geological formations in the basin. Development activities in various sectors such as coal mining, coal washeries, power generation, steel making and other auxiliary industries and unplanned growth of urban and other settlements in the Damodar River basin have created serious environmental problems, leading to deterioration of living standard, degradation of land, scarcity of basic amenities such as safe drinking water, clean air, and infrastructure facilities. Some parts of the Damodar River basin are categorized under ‘critically air polluted zone’ notified by MoEFCC, New Delhi. The concentration of atmospheric dust and smoke is unimaginably high in some parts of the basin region. The dust generation and gaseous emission from the mining, industrial and power plant units along with the domestic coal utilization make the air dense with smoke and soot. Untreated thick black effluents are released from many coal washeries into the river Damodar at different points in along its course. The developmental activities in the basin had its own advantages and disadvantages. Though, frequent flooding became a thing of the past but establishment of new industries created many environmental problems in the basin in recent years. Forests and the agricultural operations are the major victims of the developmental activities in the Damodar valley.

The river Damodar not only serves as a source of drinking water but also fulfills the water requirement of irrigation and industries of the region. Industrial activities in this region are concentrated along the river and, which led to migration of population into some of the pockets, straining the already water resources in terms of quality and quantity, ultimately threatening Damodar's self purification capacity in its various stretches. Damodar Valley Corporation (DVC) came into the existence after independence with the primary purpose of providing power to coal mines, railway, steel plants and other small and big industries in the area. DVC had initiated the first multipurpose river valley project of the country in the year 1948. DVC has been generating, transmitting, and distributing electrical energy which not only meet the expectation of consumers but also play a major role in the development of the entire eastern region. It has also facilitated irrigation as well as industrial and domestic water supply through dams, canals and barrage and proficient management of water resources at large benefited the region.

The action plan for prevention of floods and control of water pollution in the basin must have to be taken up in an integrated manner. Besides controlling the discharge of untreated effluents from mines, industries, and urban areas, the massive programs of reforestation, soil protection, water conservation, and water storage throughout the catchment area should be of major concern. The effective measures would have to be taken to regulate the monsoon flow and maintain the non-monsoon flow to a reasonable level for balancing the river ecology and reducing the pollution load of the river. The technologic action plan has also been envisaged to reverse the decline trend in underground mining in the foreseeable future to maintain a reasonable mix between open-cast mining and underground mining. This will keep the average cost of coal production and ecological balance of the basin at an optimum level.

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Subarnarekha River: The Gold Streak of India

Abhay Kumar Singh and Soma Giri

1 Introduction

The word “Subarnarekha” literally means “*streak of gold*.” It is a combination of two words; “Subarna” meaning gold and “rekha” meaning line or streak in Indian languages. Traditionally, it is believed that gold was mined at a village named Piska near the origin of the river. This was the reason for the river being named as Subarnarekha. It has been known that gold particles were found in the Subarnarekha River bed sediments at ancient time. At some places, even today people are searching for the gold particles in the sandy beds of the river. As the tributaries of Subarnarekha flow over gold-bearing rocks of the Panch Pargana plain, they pick up particles of gold from the auriferous rocks for deposition in the bed of Subarnarekha. Still, it carries grains of the glittering metal which is often panned from its sandy bed by the local residents along the middle reaches of the river.

The Subarnarekha is a rain-fed river and ranked as the smallest river basin among fourteen major river basins of India. The Subarnarekha River originates near Nagri village (23° 18′ 02″N and 85° 11′ 04″E) in the Ranchi district and runs through some major cities and towns, i.e., Jamshedpur, Chaibasa, Ranchi, Bhadrak before joining to the Bay of Bengal near Kirtania port (21° 33′ 18″N and 87° 23′ 31″E) in Orissa. The catchment area of the Subarnarekha River basin extends over 19,296 km^2 and accounts for 0.6% of the geographical area of India (Roy et al. 2013). The total annual yield of water flowing within the basins is in the order of 7940 million m^3. The Subarnarekha River basin is bounded by north latitudes of 21° 33′ to 23°32′ and east longitudes of 85° 09′ to 87° 27′ and flows in the north-east corner of the Peninsular India (Fig. 1). Chota Nagpur plateau bounded the Subarnarekha River basin from the north-west side, while it is

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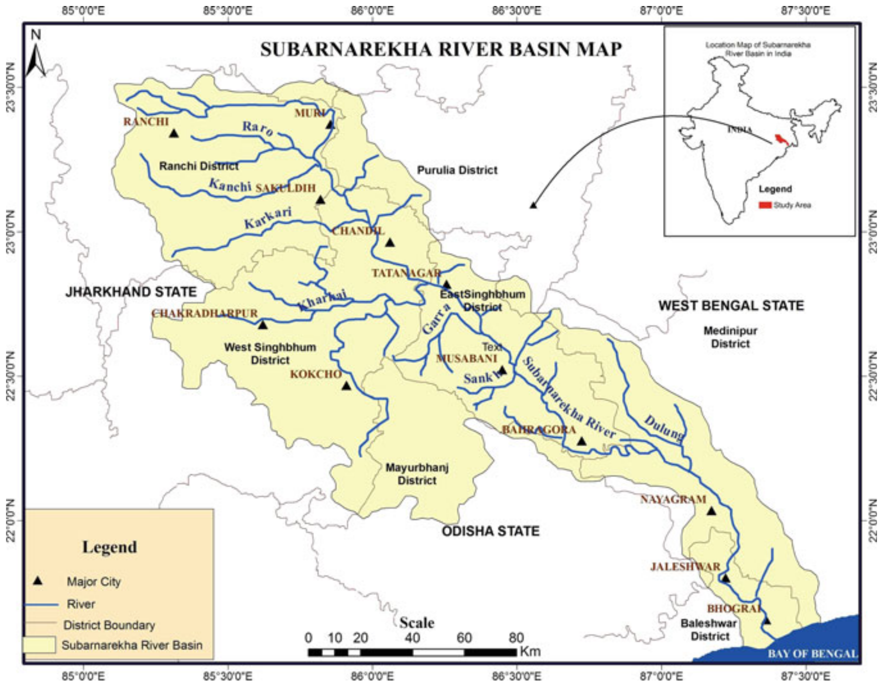

Fig. 1 Location map of Subarnarekha River basin

Table 1 State-wise distribution of the Subarnarekha drainage area

S. No.	Name of the state	Catchment area (km^2)	Percentage
1	Jharkhand	13,193	68.4
2	Orissa	3,114	16.1
3	West Bengal	2,989	15.5
	Total	19,296	100

Source Survey of India (1923–1979), Rao (1975)

restricted by the Brahmani River basin in the south-west, Burhabalang River basin in the south, and by the Bay of Bengal in the south-east side. The Subarnarekha flows through Ranchi, Saraikela, and east Singhbhum districts of Jharkhand, west Midnapore district of West Bengal, and Balasore district of Orissa. It flows a distance of about 395 km from its origin before falling into the Bay of Bengal. Out of the total travel distance of 395 km, river flows 269 km in Jharkhand, 64 km in West Bengal, and 62 km in Orissa (CBPCWP 1986; Giri and Singh 2014a). Subarnarekha is a very important river to satisfy the irrigation, industrial, and municipal water demands of these three states. The state-wise distribution of the catchment area and its percentage in respect to the total river basin drainage area are given in Table 1.

2 River Course and Major Tributaries

The River Subarnarekha is originated near the Nagri village, at a distance of about 15 km south-west of Ranchi, the capital of Jharkhand (Fig. 2a). On the Ranchi plateau, the river lazily winds its way for 60 km till its water plunge down a 74-m-high cliff, creating a scenic waterfall known as Hundru Fall (Fig. 2b). The river thereafter flows through a 25-km-long-deep gorge till it emerges out of the Ranchi plateau and debouches on the flatter piedmont plain of Panch Pargana. By now, the river swells fairly big, some 500 m wide. After having travelled through a course of 145 km over the Panch Pargana plain, the river cuts through a narrow defile across the volcanic lavas of Dalma range. After emerging from the range, the river sweeps through a fairly wide floor of the Dhalbhum valley for another 150 km till it finally leaves the rocky granitic terrain of Jharkhand and takes to a more meandering course on the unconsolidated alluvial material in the Medinipur district of West Bengal and Balasore district of Orissa (CBPCWP 1986; Jain et al. 2007). After several turns, the river eventually empties its enormous volume of water along with its rather heavy silt load into the shallow shelf of the Bay of Bengal at Kirtania near Talsari (Fig. 2c).

Fig. 2 **a** The origin place of the Subarnarekha River at Nagri village, **b** Subarnarekha plunge down a 74 m high cliff at Hundru (Hundru Fall), **c** the river near mouth at Kirtania, **d** confluence of Subarnarekha and Kharkai rivers at Sonari near Jamshedpur

Table 2 Major Tributaries of the Subarnarekha River

S. No.	Name of the tributary	Bank	Length (km)	Catchment area (km^2)	% of the total basin area	Annual yield (MCM)
1	Raru	Right	50	622	3.22	250
2	Kanchi	Right	80	1036	5.37	750
3	Karkari	Right	120	1575	8.17	950
4	Kharkai	Right	145	5825	30.19	3300
5	Garra	Right	55	483	2.50	200
6	Sankh	Right	30	196	1.02	80
7	Other streams of right bank	Right	–	4812	24.94	970
8	Jumar	Left	35	182	0.94	70
9	Dulung	Left	75	1173	6.08	500
10	Other streams of left bank	Left	–	4760	17.64	870
	Total			19,296	100	7940

Source Survey of India (1923–1979), Rao (1975)

The Subarnarekha has an asymmetrical catchment basin; the right-bank tributaries draining more than three-fourths of the total basin area, whereas the left-bank tributaries drain hardly one-fourth of the basin. On the right bank, there are four major tributaries, the Raru, the Kanchi, the Karkari, and the Kharkai, draining between them nearly half of the Subarnarekha basin, covering around 9050 km^2 area, while on the left side there is only one sizable stream, namely the Dulung, which drains an area of some 1173 km^2 (Table 2). The Kharkai is the largest tributary of the Subarnarekha originated on the slopes of the Simlipal massif in Mayurbhanj district and contributing nearly 45% of the total annual flow of the Subarnarekha River. It drains a catchment area of 5825 km^2 and flows through a course of 145 km before joining Subarnarekha at Sonari near Jamshedpur town (Fig. 2d). The Kharkai is also a gold-bearing river, some of its tributaries like the Sanjai, Sona Sanhua, and the Bonai are known to have placer gold in their beds.

3 Geomorphology and Geology

The Subarnarekha cutting across the Dalma range gives the impression of an antecedent drainage. Such a situation could arise if the main highlands and the Dalma ranges are uplifted sequentially, so that, the river emanating from the central highland is consequent but is antecedent to regions of later uplift as the Dalma ranges. Alternatively, the Subarnarekha may have eroded down its position over the then existing surface over the Dalma Range consequent upon lowering of sea level. In the latter case, it would be superposed river. Detailed work on the geomorphic controls on drainage system may address these questions. The most significant landscape element of the Subarnarekha basin in its eastern course is marked by the presence of river terraces (Mahadevan 2002). The terraces are of two to three generations and vary widely in their extent and relief. Perhaps, representing the oldest are the terraces recognized north of Tatisilwai in the Ranchi plateau region. However, more prominent are the terraces recorded in the downstream, where the river crosses the Dalma ranges. Both bedrock type and alluvial/gravel terraces occur in the tributaries of the Subarnarekha draining the western margins of the Ranchi plateau, such as the Sobha, Raro, Kanchi, Garra Sanjai, Kharkai, and Jamir. Mukhopadhyay (1973) recognizes 3-tier terraces: the upper, middle, and lower; and upper and lower flood plains in the Kharkai and the Subarnarekha near Tata Nagar. In the Sanjai basin, the two terrace levels have diverging relief from the present river floor, implying changes in plantation and deposition patterns. The Sanjai–Kharkai basin itself has features of an etch plain, offering evidences of "inversion of relief."

Prominent developments of terraces have been described from the lower Subarnarekha valley. Niyogi (1968) records 3-level terraces in the areas close to Baharagora–Jamsola on the northern bank of Subarnarekha. These are at elevations of 74, 61, and 49 m above mean sea level (amsl). The most prominent of these is the highest terrace, traceable from SW of Baharagora to near Jamsola. The terrace has a maximum width of some 2.5 km, a prominent natural levee, 2–3 m high, and about 500 m wide. The other terraces are much smaller in their dimensions. All the terraces comprise thin alluvial cover over the lateritized basement of the country rocks (Chaibasa formation).

A prominent erosion surface is described from the western bank of Subarnarekha near Dhalbhumgarh by Dunn and Dey (1942). The surface occurs 110–120 m above the river and exposes coarse gravel beds that are correlated with the Dhalbhumgarh Tertiary gravels exposed to the NE bank of the river. Dunn and Dey (1942) suggest differential warping or uplift along the western flank of the order of 100–120 m, possibly in the Pliocene or even the Miocene age. Presence of terraces was reported in the lower reaches of the river catchment at elevations of 75 m and 66 m amsl, each some of 12 m in height. In places, there are indications of a third terrace also. Niyogi (1968) also records terraces in the downstream of the river at 49 m, 34 m, 12 m, and 9 m amsl separated by modified scarp faces. The development of the terraced surfaces is generally considered to be tectonic uplift of the Chota Nagpur plateau region during the quaternary, particularly in the Holocene period. However, another important factor that may explain the relatively smaller features as the river terraces and flood plain fillings is the eustatic changes in sea levels during the Quaternary, which would have greatly influenced the dynamics of the river systems.

Indian Shield occupies the major parts of the Subarnarekha river basin, and ancient Precambrian igneous and metamorphic rocks are mainly exposed in these areas. The younger geological formation namely, Tertiary gravels, Pleistocene alluvium, and Recent alluvium are exposed only in the lower reaches of the basin at south-east of the Ghatsila. Shallow alluvial formation covers parts of the Shield area, especially in the eastern part of Ranchi district. The geological age of the rock formation of the Subarnarekha river basin is widely ranged. It ranged from 3.8 billion years old older Metamorphic Group of rocks (including tonalite gneiss) in parts of Mayurbhanj district to the most recent deltaic alluvium. Pelitic schist, calc-magnesium metasediments, ortho-amphibolites, tonalite-trondhjemite, banded iron formation, mafic lavas, phyllites, shales, metapellites, quartzite, mafic lavas, soda-granites, granitic gneiss, dolerite dyke swarms, and gravels are the major litho units associated with the geological formations of the basin. The soils in the Subarnarekha basin are derived from diverse parent materials and can be divided into three groups: (i) alluvial soils, (ii) red soils, and (iii) latosols. The red soils cover more than 83% of the basin area mainly in the upper reaches of the basin. River-born alluvial soils cover 11% of the basin area and mostly confined in the lower valleys and coastal plains. The remaining 4% of the basin area are covered by the infertile latosol (mainly laterites).

4 Socio-Economic Importance

4.1 Water Resource and Its Uses

Since the basin is located in the moderately heavy rainfall area of Peninsular India, especially along the belt of storm tracks originating in the Bay of Bengal, it receives a substantial quantity of rainwater (about 28,609 million cubic meters) every year (CBPCWP 1986). About 82% of the total annual flow actually occurs over only four wet months (June–September), while in the remaining part of the year, the Subarnarekha River and its tributaries run almost dry. If the total annual flow is taken into consideration, the mean discharge of the river would come around 250 m^3/s. At places, especially in the upper and the middle reaches, the river flow during the dry period becomes sluggish, and it behaves like a stagnant pool of water, often highly charged with pollutants. The Subarnarekha and its tributaries are sustaining a large population of Jharkhand, West Bengal, and Orissa and form the main sources of urban water supply. The water resources of the Subarnarekha River basin are summarized in Table 3.

Though Subarnarekha basin is rich in mineral and mineral-based industries, it is still dominated by its agrarian economy. Agriculture, as an economic activity, has not yet been properly developed within the Subarnarekha basin, and necessary inputs including irrigation facilities are still rather inadequate. About 62% of the basin area is classified as cultivable, and nearly 31% is devoted to forests. The forests within the basin are in poor state of maintenance and required rigorous protective measures. The net sown area occupies 40% of the basin, while 22% is left unused as fallow land or as cultivable waste (Table 4).

The Subarnarekha River basin presents a classic example of conflict among competing uses of water both sectorally and across regions. The river water has

Table 3 Water resource potential of Subarnarekha River Basin

Total renewable water resource (km^3)	12.37
Potentially utilizable surface water resource (km^3)	6.8
Potentially utilizable groundwater resource (km^3)	1.7
Total potentially utilizable water resources (km^3)	8.5
Total renewable water resource per capita availability (m^3)	829
Potentially utilizable water resources per capita availability (m^3)	568
Water withdrawal per person (m^3)	374
Net irrigated area (million hectare)	0.55
Irrigation intensity (%)	124%
Groundwater irrigated area (% of net irrigated area)	43%
Grain crop irrigated area (% of net irrigated area)	88%
Overall irrigation efficiency (%)	45%

Source CWC (2002)

Table 4 Land-use pattern of Subarnarekha River basin

Land use	Area (km^2)	Percent of the total catchment area (%)
Cultivated	7,719	40
Cultivable waste/uncultivated (Fallow)	4,338	22
Forest	5,934	31
Orchard	350	2
Other use	955	5

Source Das Gupta (1980), CBPCWP (1986)

been used by different agencies for different purposes. It is used by industry as a direct process input and as a disposal agent for the dilution of effluents; by agriculturists for irrigation; and by household sector for drinking and other domestic uses (Jain et al. 2007). A number of irrigation and multipurpose projects were initiated to fulfill the water and energy demand of the eastern region. This includes Subarnarekha Multipurpose Project, an inter-state project in Jharkhand, West Bengal, and Orissa; Kanchi Irrigation Schemes, and ten Medium Irrigation Projects of Jharkhand. The main objectives of the Subarnarekha Multipurpose Project (SMP) are (i) to provide reliable water supply to agricultural lands in Jharkhand, Orissa, and West Bengal, (ii) to supply 740 million m^3 water per year for municipal and industrial uses in Jharkhand, (iii) to reduce flood damage in Orissa and West Bengal by constructing 463 million m^3 flood-storage capacity dam at Chandil, (iv) to construct embankments by Orissa and West Bengal governments in their respective territories along the flooding reaches of the river, and (v) to generate 30 MW of hydroelectric power through medium, mini-, and micro-hydroelectric projects located at various points of the canal system.

The Subarnarekha Multipurpose Project was initiated in 1982–83 with the objective of irrigation, hydropower generation, and water supply. However, the feasibility and economic viability of the project have decreased due to the attempts to implement all project components simultaneously and the consequent delays. This Multipurpose Project envisaged the construction of two dams, one at Chandil across the Subarnarekha and the other across the Kharkai at Icha near Chaibasa, two barrages at Galudih across the Subarnarekha and the other across the Kharkai at Ganjia near Adityapur and a network of canals from these. Three small storage reservoirs at Haldia, Jambhira, and Baura and a network of canals from these reservoirs are also proposed in Orissa. However, the construction work of Chandil dam and Galudih barrage is only completed, while all other components are either delayed or still incomplete.

A multipurpose reservoir is constructed across the Subarnarekha River at Getalsud (23° 27′N and 85° 33′E), about 40 km east of Ranchi city in 1971 to meet

Table 5 Water storage/diversion structures of Subarnarekha River basin

S. No.	Dam/barrage	Completion year	River	Purpose
1	Hatia Dam	1963	Subarnarekha	Irrigation
2	Sitarampur Dam	1964	Kharkai	Irrigation
3	Getalsud Dam	1971	Subarnarekha	Hydroelectric, irrigation, water storage
4	Kakudajodi Dam	1976	Kukudajodi	Irrigation
5	Nesa Dam	1978	Nesa	Irrigation
6	Kharkai Dam	1984	Kharkai	Irrigation
7	Lorgara Dam	1985	Kharkhai	Irrigation
8	Palna Dam	1985	Ranka Jhuria	Irrigation
9	Haladia Dam	1985	Haladia	Irrigation
10	Rissia Dam	1986	Tangana nalla	Irrigation
11	Jambhira Dam	1986	Jambhira	Irrigation
12	Dimu Dam	1989		Irrigation
13	Sunei Dam	1990	Sunei River	Hydroelectric, irrigation
14	Torlow Dam	1990	Torlow	Irrigation
15	Sonua Dam	2009	Sanjay	Irrigation
16	Nakti Dam	2010	Bijay	Irrigation
17	Raisa Dam	U/C[a]	Kanchi	Irrigation
18	Chandil Dam	U/C[a]	Subarnarekha	Hydroelectric, irrigation, water storage
19	Galudih Barrage	U/C[a]	Subarnarekha	Irrigation
20	Icha Dam	U/C[a]	Kharkai	Hydroelectric, irrigation

[a]Under construction

Source Water Resources Information System of India (2014) municipal water demands of Ranchi town, industrial needs of the Heavy Engineering Corporation (HEC), and other industrial units of the adjoining areas. Getalsud dam has a catchment area of 717 km^2, dam height of 35.5 m, and water storage capacity of 288.5 Mm^3. Two powerhouses of 65 MW capacities each have been also commissioned near to dam site. Both the powerhouses have one unit of 65 MW each (Jain et al. 2007). Some of the major water storage/diversion structures of river basin are summarized in Table 5.

4.2 *Mining and Industrial Activities*

The upper part of Subarnarekha basin harbors some extensive mineral deposits, and thus, a number of industries have been established along the banks of the river. The mineral resources of Subarnarekha basin are mainly comprises of ores of Cu, Fe, U, Cr, Au, V, industrial minerals including kyanite, asbestos, barytes, apatite, china clay, talc, limestone, dolomite, and building stones (Giri et al. 2013). All these have been exploited for various purposes, some on large scale and some on small scale. The arc-shaped Singhbhum copper belt between Mayurbhanj and Singhbhum districts at the right bank of the Subarnarekha ranked as the one of the richest copper-bearing horizons of India. Rakha, Mushabani, and Surda were historically important centers for the copper mining in this region. Subarnarekha also has to bear country's richest uranium deposits, and mining activities are taking place near Jaduguda areas of Singhbhum district by the Uranium Corporation of India (UCIL). Jaduguda, Turamdih, Batin, and Narwapahar are the major centers of productive uranium mines. Deposits of chromite associated with ultramafic intrusive rocks were reported in the Chaibasa region of Jharkhand. Iron ore deposits occur at Gorumahisani, Badampahar, and Sulaipat areas. There are several deposits of kyanite occur in the Subarnarekha River basin including India's richest deposits at Lapsa Buru. The basin studded with numerous small quarries for building stones and road metals. Slabs of dolerite, Singhbhum granites, Kolhan limestone and sandstone, and Chota Nagpur granite–gneiss are extensively used in building and road constructions.

The Subarnarekha River passes through an industrial rich belt of Jharkhand and Orissa. There are four major industrial areas occur along the bank of the Subarnarekha: (i) Ranchi–Hatia industrial area, (ii) alumina processing plant at Muri, (iii) the iron and steel plant and industrial complex at Jamshedpur, and (iv) Jaduguda–Ghatsila mining and industrial complex. Heavy Engineering Corporation (HEC), Usha Martin Industries, MECON, Steel Authority of India (SAIL), Indian Aluminum Industries, Tata Steel, TELCO, Indian Tube Company, Tin Plate (of India), Tata Pigments, Hindustan Copper Ltd., and Uranium Corporation of India are the major existing industrial units in the basin. Other important small- and medium-sized industries in the basin are tobacco products in Chakradharpur; cement, asbestos sheets, glass, and ceramics at Chaibasa; locomotives and coaches, automobiles, agricultural equipments, wires and cables, iron and steel machinery, metal tubes and conduits, copper and brass, chemicals and caustics, fertilizers, and soaps are the other industries exist at Jamshedpur. Studies have indicated that the water quality of Subarnarekha River has deteriorated mainly due to discharge of untreated, domestic and industrial, and mining effluents at various river stretches (CBPCWP 1986).

4.3 Natural and Anthropogenic Hazards

The river "Subarnarekha" is the lifeline for tribal communities inhabiting the Chota Nagpur region and the people of the north Orissa. It does not merely represent a river but means a lot more than that for this region. However, it has also become the death line when it submerges major areas of Balasore such as Bhogarai, Baliapal, Basta, Jaleswar blocks, and some parts of Rasgovindpur block of Mayurbhanj every year during rainy season, causing large-scale devastation in the villages situated on both sides of the river. Every year, people suffer from the same problem; the only change is in the intensity of the flood. Annual average rainfall in the basin is in the order of 1250 mm with the maximum and minimum rainfall recorded as 1420 and 1150 mm, respectively. Out of this, about 90% of this rainfall is recorded during the south-west monsoon season, i.e., June–October (Jain et al. 2007). The water level of the Subarnarekha rose beyond its danger line due to heavy rain in July 2007, and it crossed the previous highest flood level (HFL) of 12.2 m recorded in 1997. Flash floods due to heavy rainfall in the upper catchment areas were also recorded in the Subarnarekha River in year 1973, 1974, 1977, 1978, and 2009 (Maiti et al. 2009). The floods were devastating in nature; it took many lives and submerging thousands of houses and destroyed thousands of hectare kharif crops. Severe deforestation, rapid urbanization, industrialization, and severe soil degradation in the upper catchment of the Subarnarekha basin were the main causes for such ecological disaster.

Throughout the Subarnarekha basin, the soil mantle has been subjected to heavy erosion, and the topsoil is liable to be washed down the river if adequate protection is not provided immediately. Erosion control and soil conservation in the upper catchment are therefore essential for sustainable agricultural development and conservation of the water resources of the Subarnarekha basin. Certain parts of Jumar sub-basin have also been severely affected by gully erosion. There is great fluctuation between the wet season and dry season flows if the total annual flow is taken into account. The fact is that the entire amount of annual flow is actually spread over the four wet months (June–September). During the flood stage, the Subarnarekha turns into a large, turbulent stream of highly turbid water and is charged with sediments of yellow ochre color. The silt load during the rainy season is very high, indicative of heavy soil erosion, especially in the upper catchment zone. While floods occur frequently in the wet season, during the rest eight months, the flow in the Subarnarekha drops down to a mere trickle, leaving the river as a series of fordable pools of water almost throughout its length, barring the tidal and lower estuarine stretch of the course.

Subarnarekha's rich natural resource base has proved to be disastrous for the basin. Large-scale environmental degradation of the basin owes to the unplanned and unregulated mining and mineral processing industries. Unscientific mining practices and unplanned dumping of wastes and mining tailing create many environmental problems in the region. The erosion and transportation of wastes from exposed dumps and mining tailing during the monsoon seasons increase suspended solids and heavy metal loads in the river water and caused siltation in the dams and reservoirs. Mining of construction and building materials, such as granite, basalt, quartzite, dolerite, sandstone, limestone, dolomite, gravels, and river sands, has created many environmental problems and created vast stretches of wasteland in the river basin. The copper mining around Ghatsila and Mosabani has degraded the water quality to a large extent, and in many places, concentration of toxic metals was observed above the prescribed limits. There is also apprehension about water contamination due to seepage of radioactive waste from tailing ponds of the Uranium Corporation of India near Jaduguda areas. Radioactive pollution is a serious health hazard in the water bodies of the region which necessities precautions to be taken. The mine tailing and dumps of injurious minerals must be carefully monitored for assessing their possible impact on the environment in the Subarnarekha basin.

Besides mining, the other factors responsible for pollution in the river are considerable amount of domestic and industrial wastewater generated from the towns which is discharged into the river. For mitigating pollution, proper remedial measures should be adapted in the towns and the industrial units responsible for polluting the surface water and groundwater systems. The locations around Tatisilwai, Muri, Ghatsila, Mosabani, and Jamshedpur indicate severe pollution in the Subarnarekha River (Giri and Singh 2014b). The need of stringent control of the quality of the industrial, mining, and domestic wastewater effluents discharged into the river is utmost important because the total volume of water flows in the river on the whole is on the lower side, especially during the dry season. During the long dry period, the Subarnarekha turns into stagnant brook, and at many places, it losses pollutants diluting capability and totally incapable of washing down the pollutants discharged into it from the urban and industrial centers such as Hatia, Ranchi, Muri, Jamshedpur, Jaduguda, and Ghatsila. The surface water quality in the greater part of the Subarnarekha River is graded as classes D and E on the basis of laboratory measurements of the constituents (CBPCWP 1986). Upgradation of the existing river water quality requires an appropriate treatment. It would be necessary to take up a well-planned pollution control action program not only at different towns and industries, but throughout the basin.

5 Conclusions

Subarnarekha is an important inter-state river sustaining about fifteen million people of Jharkhand, West Bengal, and Orissa. However, the environmental condition of the river is deteriorating day by day with the increase in mining and industrial activities of the basin. Considering the great endowment of natural resources in the mineral-rich basin of the Subarnarekha River, it is high time that a well-integrated plan for ecological development and natural resource management along with pollution control measures has to be formulated for the basin immediately. The action plan for prevention of floods and control of water pollution in the Subarnarekha basin must have to be carried out in an integrated manner involving massive programs of reforestation, afforestation, soil protection, water conservation, water storage, and moisture management throughout catchment area, besides controlling the discharge of pollutants from towns, industries, and agriculture fields. The Subarnarekha River which behaves like a mighty river during the monsoons dramatically turns into more or less stagnant pools of water held in hollow and potholes in the river bed during the summer season. At many places, river lost its pollutants washing down capability. To mitigate the pollution load in the river, some effective measures would have to be taken to regulate the monsoon flow and raise the dry season flow to a reasonable level for dilution of the pollutants. The distribution of available water resource in different sub-basins within the Subarnarekha River system and the consequent possible change of water regime both in the dry and wet seasons, after building of adequate number of water storage reservoirs in the upper catchment areas, have to be worked out.

Over the years, the frequency of floods is found to have increased to a considerable degree especially in the lower part of the Subarnarekha catchment. The water-holding capacity, especially in the upper parts of the catchment area, has been considerably reduced due to severe deforestation, rapid urbanization, extensive industrialization, and fast degradation of the soil mantle. Appropriate land and water resource management, massive afforestation, and corrective land-use planning are essential to abate water pollution, to control the soil erosion, and to enhance the forest cover area of the basin. There are large tracts of deforested areas, barren wasteland or inadequately used lands available within the basin for reforestation, afforestation, and effective cultivation. In the action plan for abatement of water pollution, the groundwater sources available within the basin would also have to be fully mobilized for beneficial uses, supplementing the existing surface water potential. Only through judicious conjunctive use of both surface and groundwater, the hydrological cycle can be maintained in a healthy state. Pollution control for the Subarnarekha basin should have to take into consideration the entire water resource available within the basin after making a thorough study of the water balance. If groundwater is properly harnessed and used extensively, the surface flow of the streams, especially in dry months, can be adequately augmented, thus reducing the pollution level to a considerable degree. Formulation of an integrated pollution control and resource development program for the India's smallest but potentially rich Subarnarekha River basin will not only help in pollution load reduction, but it may also serve as an ideal small-scale working model for ecological development of other basins and sub-basin in India.

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The Mahi: An Important West Flowing River of Central India

Anupam Sharma and Kamlesh Kumar

1 Introduction

Freshwater is the most important ingredient of life and is a basic natural resource, essential for various human activities. Although, the total freshwater inventory is ~3% of the total water present on our planet, and the share of freshwater present in rivers constitutes only 0.025%, which represents only about one four-thousandth of the earth's total freshwater. However, it covers and shapes nearly 75% of the earth's land surface and plays an important role in the water cycle, nutrient/sediment distribution, and controlling the earth's surface temperature by modulating the carbon dioxide concentration through weathering and erosional processes (Suttner 1974; Sharma and Rajamani 2000, 2001). Since time immemorial, it has been clearly established that rivers are essential for human growth, and therefore, rivers are called the cradles of civilizations. All the major civilizations of the world such as Indus, Egyptian, Mesopotamia, and Chinese flourished and nurtured along the river valleys. Even in modern time, it is noticed that all the large and important cities, across the globe, are situated on the banks of major rivers.

Rivers and water present in it not only cater our domestic (drinking, washing, cooking gardening, etc.), agricultural (irrigation, spraying, cleaning, etc.), and industrial (cooling, dissolving, annealing, disposing, etc.) needs but also used to fulfill our navigation, energy (water mills and hydroelectric power), additional food (fishes and other produce), construction (pebble, gravel, sand, silt, clay, etc.), and recreational (boating, water sports, fishing, etc.) requirements. In today's world with increasing population and better lifestyle, the demand for freshwater, particularly in urban areas, is increasing at an alarming rate. Similarly, contamination/pollution of rivers due to uncontrolled industrial activities, land degradation because of

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excessive use of fertilizers, pesticides and erosion, direct draining of municipal waste, etc., have posed serious threat to our rivers.

India is bestowed by a network of large and small livers receiving water mainly through glacier melt and monsoon clouds. Almost $\sim 80\%$ of the Indian rivers flow in southeast direction and finally debouching into the Bay of Bengal. Some of the major eastward flowing river systems of India are Ganges River System, Brahmaputra River System, Mahanadi River System, Krishna–Godavari River System, and Cauvery River System. The major west flowing rivers, which ultimately drain into the Arabian Sea, are the Indus, Luni, Sabarmati, Narmada, and Tapti or Tapi. Except Indus, no other west flowing river has received adequate attention as compared to the eastward flowing rivers such as the Ganges, Brahmaputra, and Cauvery because of their size and discharge and therefore, receives national and international attention, particularly in relation to the global river water budget estimation and their Himalayan connection (Sarin et al. 1989; Singh et al. 2008) or political/commercial significance (water sharing dispute between Karnataka and Tamil Nadu; petroleum and natural gas deposits in Krishna–Godavari basin and Cauvery basin). Since the above-mentioned rivers are relatively large in nature and therefore flow through variety of lithological units under a variety of climatic conditions, the behavior of natural processes is rather complex. Therefore, to understand the natural processes in relatively simplistic but comprehensive manner, a west flowing and comparatively smaller river—the Mahi River—has been identified for the present study.

The Mahi is a river flowing in central part of western India (Fig. 1). It originates in the western Vindhyan mountain ranges of the Madhya Pradesh state of central India and starts flowing northward throughout the state. Subsequently, it takes a northwestern turn and enters into the Banswara district (Vagad region) of the Rajasthan state. In Rajasthan state only, it takes a southward turn and flows through Udaipur and Dungarpur districts and then enters into the Gujarat state (western most state of India). In Gujarat state, the Mahi River flows in southwesterly trend through Panchmahal, Kheda, Vadodara, and Bharuch districts before finally debouching into the Cambay (Khambhat) Bay by making a wide estuary (Figs. 2 and 4). The name Mahi is probably derived from the Mahi Kantha hills of Vindhyachal range (from where it originates) or by the Mehwasis—a marauding highlanders as often mentioned in the Arabian chronicles. The exact origin place of the Mahi River is Minda village having latitude 22° 35′N and longitude 74° 58′E and situated just south of Sardarpur in the Dhar district of Madhya Pradesh at an elevation of 500 m amsl. Overall, the extent of the entire river basin is 21° 46′ to 24° 30′N and 72° 21′ to 75° 19′E with a total length of 583 km for the entire river course. Ratlam and Jaora districts in Madhya Pradesh, Banswara in Rajasthan, and Vadodara (Baroda), Godhra, Dabhoi, and Dohad districts of Gujarat state are the major urban centers lying close to its course. Among these urban centers, Vadodara is the metropolitan city having large industrial units of pharmaceutical and petrochemicals. Besides, relatively smaller units of caustic soda, distillery, fertilizer, dyes, and pesticides also exist in vicinity of the Vadodara city. The river Mahi is worshiped by many people and therefore has lot of temples and places of worship

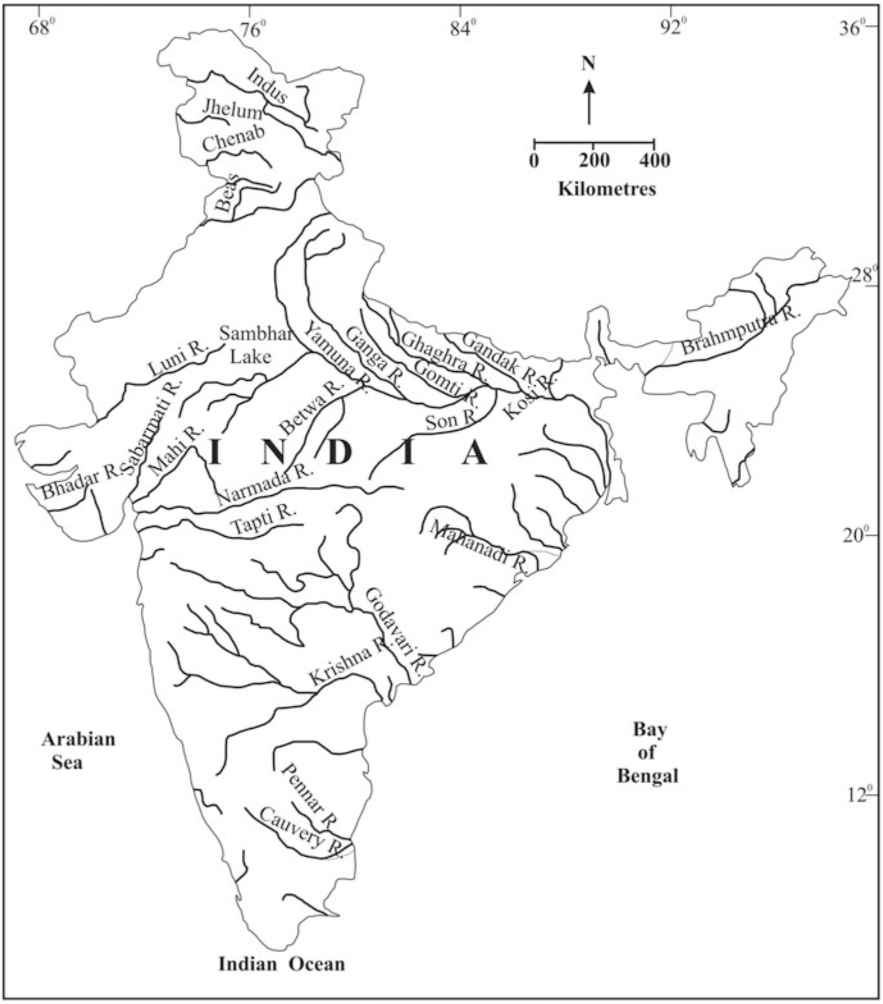

Fig. 1 Map showing major Indian rivers

along its course. Looking at its vastness, it is popularly called as Mahisagar, and the newly formed Mahisagar district in Gujarat derives its name from this pious river only (Fig. 3).

The Mahi River receives water mainly through its tributaries present on its both banks. Among many, the Som, Anas, and Panam are the important ones. The 155-km-long Som tributary having a catchment area of $\sim$8707 km^2 largely flows through the eastern slopes of the Aravalli hills and meets the Mahi river on its right bank at a place situated 63 km upstream of Paderdibadi site. The Anas tributary meets the Mahi River on its left bank in Dungarpur district of Rajasthan. The Anas originates near Kalmora of Jhabua district of Madhya Pradesh and covers a distance of

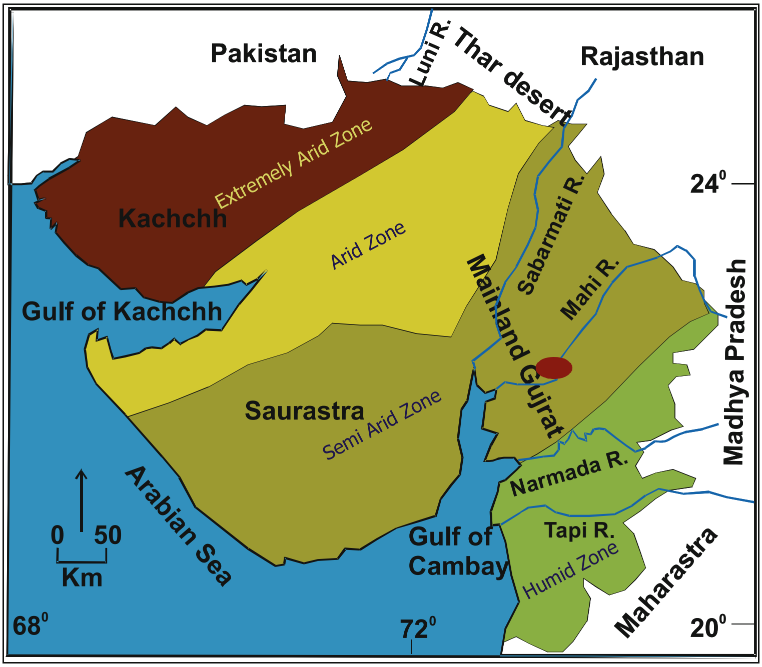

Fig. 2 Map showing different climatic zones of Gujarat (*Source* Merh, 1995)

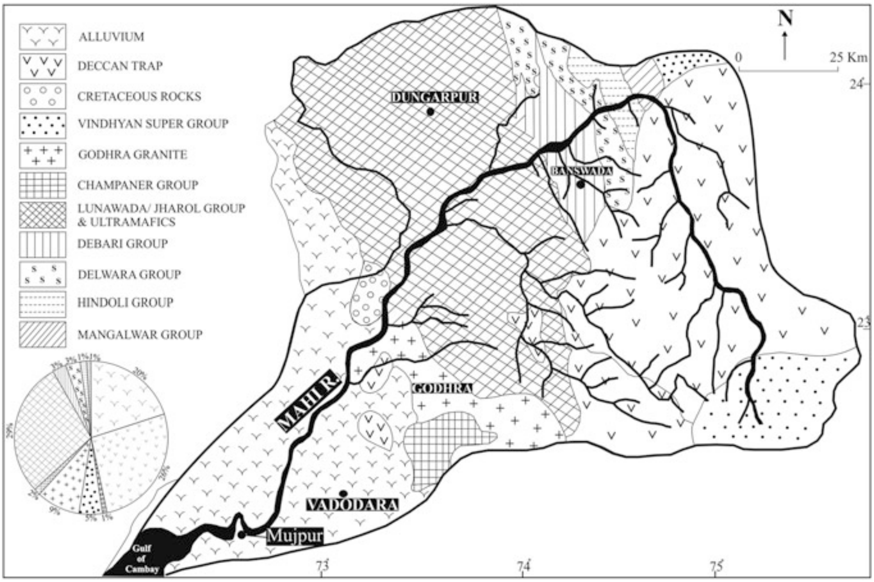

Fig. 3 Geological map of the Mahi River catchment showing exposed lithological units. The tributaries of the Mahi River mostly draining the Deccan province and the Precambrian crystallines of Rajasthan–Gujarat. The relative distribution of lithology is shown as pi diagram

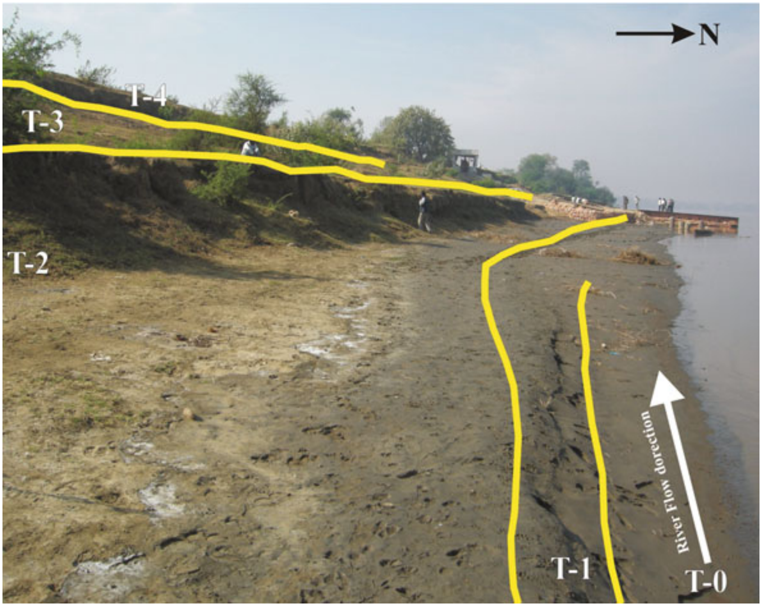

Fig. 4 The Mahi River Estuary before debouching into the Gulf of Cambay. *Yellow* lines are drawn to demarcate different river terraces formed by erosion during lateral shifting of the river course

$\sim$156 km with a total drainage area of 5604 km^2 before its confluence with the Mahi River. Similarly, Panam is also a left bank tributary of the Mahi River. It originates on the northern slopes of Vindhyan Mountain range in Jhabua district and starts flowing in northwest direction till it join the in the Panchmahal district of Gujarat state covering a distance of $\sim$127 km with the total drainage area of about 2470 km^2.

2 Geology and Geomorphology

The Mahi River is an important interstate river flowing through three west-central states of India. The basin area of the River Mahi is bounded by Aravalli hills on its north and the northwest, while Vindhyan mountains limit it in the south. On the eastern side, a ridge separates it from the Chambal basin and the river debouches in the Cambay Bay in west. The maximum width of the Mahi River basin is $\sim$250 km. The total drainage area of the Mahi River is 34,842 km^2, wherein 6695 km^2 falls in Madhya Pradesh, 16,453 km^2 in Rajasthan, and 11,694 km^2 in the Gujarat state.

Geologically, in the Mahi River basin area, the lower Vindhyan Supergroup rocks make the basement in its initial course, which otherwise forms the central Indian highland and the northern extremity of the Peninsular India (Fig. 3).

The lower Vindhyan Supergroup is largely comprised of sandstone, limestone, and shale and invariably overlain by basaltic flows of the Deccan traps (65-million-year-old rocks) giving rise to plateau-like topography. Further north, the trap rocks are unconformably overlie either the ~3.5-billion-year-old Aravalli ranges or the Vindhyan rocks, which make flat-topped hills with escarpments. In Rajasthan state, the Mahi River flows through Dilwara and Debari groups of Aravalli Supergroup rocks and then flows through the Jharol Group ultramafics. The Dilwara Group representing lower Aravalli Supergroup, which is comprised of conglomerates, mafic volcanics, clean quartzites, quartz pebbles, and minor carbonates. The litho-assemblage of middle Aravalli Debari Group has pelites sequences with coarse clastic carbonates (Sinha-Roy et al. 1998). Contrary to this, the Jharol Group has pelites with arenite bands and free from carbonates. In the Gujarat state, the river passes through the Lunavada Group, which is partly comprised of the Jharol Group and partly with the Debari Group of rocks. The dominant rock types of these groups are coarse pelitic schists, quartzites, and phosphoritic dolomite. Further downstream, in the middle and lower reaches, the river flows through a wide pediment zone across the Mainland Gujarat, which is geomorphologically divided into four broad zones—(I) upland zone in the eastern extremity, (II) shallow and buried pediment zone in the central part, (III) the alluvial zone in the central and western regions, and (IV) the coastal zone. In the lower reaches, the river forms fertile alluvial plains with frequent development of ravines. Based on sediment architecture, landscape, and other geological features, earlier workers (Merh and Chamyal 1997; Juyal et al. 2003) classified the alluvial plains into two (S1 and S2) surfaces, wherein the S1 surface is comprised of Late Pleistocene to Middle Holocene sediments and S2 is relatively much younger, representing mid-Holocene to recent sediments.

The Mahi River is classified as mixed bedrock—alluvial river, because it goes through patches of bedrock or deep alluvial cover, particularly in its upper reaches, where it flows through the Vindhyan, Aravalli, and the Deccan trap rocks, it downcuts underlying bedrock and also the modern sediments. As the region is tectonically active with hard lithological units, it is experiencing uplift and thereby steepening the river gradient. However, in the middle and lower reaches, it is largely flowing through the unconsolidated Quaternary sediments, and eroding banks and depositing material on floodplains and bars. In this part, the channel is meandering, wandering, or anastomosis at places. It is interesting to note that the sediment brought down by the river has contributed to the shallowing of the Gulf of Cambay resulting into abandonment of its once-prosperous ports. Presently, the river bed is lying considerably lower than the land level and therefore has little use for irrigation. However, with increasing population pressure and increased need-based anthropogenic activities are converting the badlands into cultivatable one.

The general climate varies from sub-humid to semiarid in the Mahi River basin (Fig. 2) as we move from south to north; average summer temperature remains between ~40 and 42 °C, which occasionally reaches up to 47 °C. During winters (December–January), the minimum average temperature remains ~15 °C, and this may drop to 3–4 °C. The average rainfall received in the river basin is ~785 mm. The SW monsoon brings rain in the basin by the middle of June and withdraws by the first week of October. About 90% of total rainfall is received during rainy season of which 50% is received during July and August months. Among all, the Vadodara district receives maximum rainfall as it lies in the windward side of the Western Ghats. Interestingly, the flat upland catchment topography due to the Deccan lava flows, the water received during the rainfall flows swiftly through the river channel, which often causes flash floods in the lower regions of the basin.

The hydrogeochemical investigation of the Mahi River basin water suggests that the water is slightly alkaline to acidic in nature. Calcium and sodium are the dominant cations, and chloride and bicarbonate are the dominant anions (Sharma et al. 2012). Overall, the hydrochemistry is primarily controlled by rock weathering, and contribution from marine and anthropogenic sources is minor only (Sharma et al. 2012). Relatively higher concentrations of total dissolved solids (TDS), Na^+, and Cl^- in samples of lower coastal vicinity indicate that more input is received from the marine sources. The saturation indices calculated for calcite (SIC) and dolomite (SID) minerals clearly indicate that most of the water samples are supersaturated with respect to these two minerals, which justify the presence of carbonate nodules (calcretes) in the alluvium. The major cation–anion distribution, particularly the dissolved silica content, larger component of Na + K in the total cations abundance with much lower ratios of Ca + Mg/Na + K (1.6), Ca/Na (1.03), HCO_3/Na (1.05), Mg/Na (0.64), and poor correlation between HCO_3 and Ca/Mg signify that silicate weathering is the most dominant contributor of ionic species, and contribution from carbonate rocks dissolution and marine sources is rather limited. The surface and subsurface water quality assessment indicates that the water quality is suitable for domestic use; however, high value of TDS, TH, Fe, F^-, and NO_3^- at few specific sites restrict the direct use of water for drinking purpose. Similarly, the calculated parameters such as SAR, %Na, and RSC show that majority of water samples are suitable for agricultural needs and only few samples where either the salinity or %Na is higher, makes the water unsuitable for irrigation, and therefore requires special management (Sharma et al. 2012).

In order to characterize the Mahi River basin sediments, it is observed that they largely fall in the litharenite category indicating that mechanical weathering is the most dominant mode of sediment generation. Mineralogically, the Mahi sediment is mainly comprised of quartz, pyroxene, basalt fragments, biotite, feldspar, minor calcite, smectite, and illite minerals (Sharma et al. 2013). The geochemical distribution of certain major and trace elements such as FeO_t ($\leq$10.9 wt%), TiO_2 ($\leq$2.41 wt%), Cr ($\leq$737 ppm), Ni (<54 ppm) suggest that mafic mineral contribution is significant in the Mahi River sediments. Based on mass balance calculations, it is proposed that ~70–75% sediments are derived from the Deccan basalts, and only ~25–30% is contributed through the biotite-rich granitoid (Banded Gneissic Complex: BGC) sources. The physical processes, which are partially supported by the winnowing of shallow sea water waves, are determining the textural characteristics of the Mahi sediments. However, mineralogical and chemical characteristics of the sediments (except for Na) are not influenced by marine action. Relatively lower CIA (37–59) values along with substantial component of basalt fragments in the sediments and also the dominance of smectite mineral in the clay fraction suggest incipient or virtually no chemical weathering in semiarid condition. Overall, the tectono-climatic conditions prevailing in the catchment region of the Mahi Basin not only supported physical erosion, but also limiting chemical weathering in the production of the Mahi sediments (Sharma et al. 2013).

In order to determine the biological productivity in the Mahi River basin, diatom distribution, both phytoplankton and phytobenthos, was studied in the water samples. It is observed that the bottom-dwelling pennate forms dominate over the centric forms of diatoms indicating profound control of physicochemical conditions in their distribution (Sharma et al. 2011). Relatively higher abundance of *Cymbeila spp.* and *Synedra. capitata* in samples of the lower reaches of the basin, where mixing through industrial effluents is significant, verifies the prevailing eutrophic conditions in this part of the river. Since, diatoms are very sensitive to the environmental conditions; it can also be used effectively as a tool for monitoring ecological/environmental including pollution conditions. In a study conducted by Sharma et al. 2011, the authors applied CCA test (a statistical tool) and found that in most cases the physicochemical components (nutrient type and their concentration) are directly controlling the nature and type of the diatom population. Therefore, the contemporary diatom assemblages of different water bodies of the upper and lower Mahi river basin provide recent analogs, which could be further applied on much older sediment successions for precise paleoenvironmental and paleoclimatic interpretations.

3 Socio-economic Importance

Rivers are very important source of water, and these caters our basic domestic, irrigation, and industrial needs. This is the reason that areas along the banks of rivers have witnessed great cultural and economic progress and aptly reflected in our folklore and folk songs. Rivers give birth to alluvial soils, which provide the most productive agricultural lands, e.g., the fertile Indo-Gangetic plain, and the Ganga–Brahmaputra, and the Cauvery delta to the country. Besides the essential water supplies, rivers also dilute the contaminants and flush them out so they act as the biggest cleaners to towns and cities. Also, rivers provide primary channels of inland waterways and the flatland formed by infilling of sediments use to make road and rail routes. Construction of dams helps in power generation and also used for recreation, tourism, and fishing activities. In the Mahi basin also, several dams have been constructed such as Jakham Reservoir, Panam Dam, Mahi Bajaj Sagar Project, and Kadana Dam (Fig. 5). Among these large dams/reservoirs, Mahi Bajaj Sagar dam and Kadana Dam also used for hydropower generation. Besides, there are several other medium- to small-scale hydro projects in the basin primarily catering the irrigation and industrial needs.

Fig. 5 *Source* WWW.sandrp.in (Based on Basin map of Ministry of Water Resources)

In the upper reaches of the basin particularly, in Madhya Pradesh and Rajasthan states, the terrain is largely comprised of hills and forests except the initial few kilometers stretch of the river course, which is fairly flat having black soil due to dominance of the Deccan traps in the region. The middle part of the river course has thin layer of alluvium derived from both felsic and mafic rocks. The lower reaches of the basin, confined to mainland Gujarat, have flat and fertile alluvial tract. The surface soil of the alluvial plains of Gujarat shows much diversity and can broadly be classified into five orders: (1) entisols, (2) inceptisols, (3) vertisols, (4) alfisols, and (5) aridisols (Merh and Chamyal 1997). The cultivable area of the basin is about 2.21 Mha, which constitutes $\sim$1.1% of the cultivable land of the country.

There are more than 15 large and medium multipurpose irrigation projects in the Mahi River basin (Fig. 5). Among all, the Jaisamund tank of Udaipur district of Rajasthan is the oldest irrigation project, which was constructed in the pre-plan period; however, all other projects in the basin were commissioned during plan period. Some of the important projects are Jakham, Panam, Mahi Bajaj Sagar, Mahi Phase-I & II comprising of Kadana dam, Wanakbori weir, and Mahi (M.P.) projects. A brief account over the two projects is given in the following section:

1. Kadana Reservoir (Dam) Project: It is lying very close to the Rajasthan–Gujarat border, where a gorge is cut by the Mahi River. The dam has composite earth fill and masonry gravity structure with a height of 58 m above the stream bed. The top length of dam is 1551 m and has two spillways; the main spillway is 406 m

in river gorge portion, while the additional spillway is 113 m long constructed on the right bank. The total catchment area of this project is ~25,520 km^2, wherein 6149 km^2 falls in the Rajasthan territory and rest lies in Gujarat state. The effective storage capacity of the Kadana reservoir is 1203 Mm^3. It provides irrigation facilities for 12,795 ha, and 240 MW of hydropower is also generated by installation of 4 reversible turbine of capacity 60 MW each.

2. Wanakbori Weir project: It is built across the Mahi River near Wanakbori village in the Balasinor Tehsil of Kheda district in Gujarat. The Weir is also known as Mahi Stage I Project. The catchment area of the project is 30,665 km^2. The maximum height above the lowest point of foundation is 25 m, and length of the dam is 796 m. It is a composite dam having a 735-m-long ogee-type spillway, and the effective storage capacity is 3624 Mm^3, which irrigates 3,15,790 ha of land.

In terms of natural hazards, floods are the major contributor, which though occasionally but adversely affect the Mahi River basin. During the SW monsoon period (June–September), very high rainfall associated with lows, depression, deep depression, and cyclonic storms causes floods in the basin regions. There are evidences that storms surge after crossing the coast brought floods in the lower reaches of the basin. For example, in July 1927, the storm moved very slowly between Mt. Abu and Jodhpur, which caused unprecedented floods in the Mahi River basin (Dhar et al. 1981). Additionally, records show that there are 7 occasions when floods occurred in the Mahi basin (between 1986 and 2001), and two of them including the one in 1990 were relatively a major flood. In tune to these, the 2006 flood was also very severe and incurred severe loss to the property.

Interestingly, the northward drift of the Indian plate is still in progress; therefore, the entire region is experiencing uplift and as some portion of middle and entire lower sections of the river has unconsolidated Quaternary sediments, so the soil erosion has become a serious threat. Similarly, the deforestation mainly to support increasing population has put further pressure and enhancing the erosional processes. As a result, the problem of siltation in dams, reservoirs, and also in the estuarine tract is reducing the water storage capacity and adversely affecting the habitat of biotic life of these areas. Several studies show that the upstream dams, which trap sediments and water, also increase the coastal erosion. Further, the increasing industrialization, particularly the paint & pigment fertilizers and pesticides, tannery, cement, and other manufacturing units in and around Vadodara city, is draining huge amounts of chemicals in the lower part of the river further compromising with the habitable conditions. The coastal pollution has severely affected the estuarine fisheries. Evidences show that the entire coastline of Gujarat state has been facing the problem of salinity ingress including the Mahi estuary According to Gujarat Water Resources Department, 7 lakh ha coastal land, 534 villages, 32,750 wells, and 10,79,733 persons are facing the problem of salinity ingress. According to the 2011 CAG report, there has been an increase of 15% in the area of salinity ingress as compared to the 1977–1984 base data. It has been observed that the TDS of groundwater is >2000 ppm in many places of coastal Gujarat (Barot 1996).

According to 2011 CAG Report, "A baseline study carried out in 1165 villages by CSPC during 2007–08 indicated that 890,753 and 337 villages reported high number of cases of kidney stones, gastric problems, and fluorosis, respectively," Therefore, it has become essential to address both natural and anthropogenic hazards so as to protect the water and associated resources for present and future generations.

4 Conclusions

River water is a basic natural resource, and therefore, the areas situated close to the river banks witnessed great cultural and economic progress since ancient times. It is essential for human, agricultural, and industrial activities. Rivers also receive a variety of wastes; however, they act as biggest cleaners of natural and anthropogenic contaminants. Besides, rivers are used in generation of electricity, and their channels provide inland waterways too. Additionally, the flatlands, formed through rivers, are utilized to construct roads, railway lines, and other routes. Rivers are also used for fishing activities, recreation, and tourist promotion. So in nutshell, rivers are of great importance for the human kind.

Floods are natural phenomenon and are responsible for the creation of fertile floodplains as well as replenish the nutrients in the soil. The increasing demand of land for various purposes and the deprived sections of the society are pushed toward the river channel and floodplain areas, and therefore, they are under constant threat of floods during the monsoon period. Since India is a flood-prone country, the Central and State governments have designed and upgraded the policies and strategies time to time to meet the challenge forced by floods. At present, the Central Water Commission (CWC) is looking after the planning, investigation, management, design of water resources, and development schemes and made valuable contributions. However, to deal the disasters in holistic, coordinated, and prompt manner, the Government of India has set up a National Disaster Management Authority (NDMA) in 2005. Besides, several expert committees were formed in the past as well to suggest measures to deal with the floods, which eventually formulated the policy document that helped in designing the flood management measures and are followed in the country. To reduce the flood losses and protect the flood plains, several measures have been adopted, and depending upon the nature of work required, these measures are broadly classified as (a) engineering structural measures and administrative/non-structural measures. Engineering measures bring relief to the flood-prone areas by reducing flood flows and also the flood levels through construction of reservoirs, embankments, channelization of rivers, channel and drainage improvement, diversion of flood water, watershed management, etc. The administrative measures include mitigation strategies of the flood damages by (1) facilitating timely evacuation and shifting to safer sites, (2) advance warning of incoming flood, (3) discourage creation of valuable assets in the areas subject to frequent flooding, and (4) enforce flood plain zoning regulation strictly, etc. Besides, there are non-governmental organizations and social groups that come forward to deal with emergent situations.

River water pollution is largely caused by the industrial units (determined by the kind of industry), farm discharge (fertilizers and pesticides), and households discharge carrying disease-causing microbes. In order to reduce the water pollution, following measures may help in reducing the water pollution such as

1. Participate in awareness-raising activities. It should also be included in the school curricula so as students learn this at initial level and can be of great help to transform the society at large.
2. Technology and monitory support by government for waste management by industries.
3. Strictly enforce the National Environmental Quality Standards (NEQS) on industrial units so as they treat their wastewater before disposal.
4. Qualitative and quantitative monitoring of river water on regular basis.
5. In areas close to contaminated water bodies, conduct epidemiological studies regularly, which would not only create a database over the effects of polluted water on human health but also help in designing the mitigation strategy to overcome the problem on a long-term basis.
6. Make arrangements to throw refuse into garbage cans. In want of these, visitors normally throw garbage into rivers and pollute as well as mar the beauty of recreational sites.
7. Construct proper sanitary landfill sites.
8. Arrangements to dispose off unwanted oils, expired drugs, paints, etc., carefully, which otherwise reach to river through drains and sewers.
9. Sensitize people to bring in water conservation at all levels, e.g., at home and at workplace.
10. Filter or better boil the drinking water to minimize the affect of disease-causing bacteria.

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Narmada: The Longest Westward Flowing River of the Peninsular India

P.K. Kathal

1 Introduction

The river Narmada (Narmadā, Sanskrit meaning 'the River of Pleasure,' also called the Rewa or Nerbudda of the 'British Raj') originates from a lake, called *Narmada Kund* (21° 39′ 3.77″N; 72° 48′ 42.8″E) at a holy place—Amarkantak, (1057 m), Maikal Hills, Anuppur District, Madhya Pradesh. Soon, it descends as a waterfall called *Kapildhara.*

2 Geomorphology

The longest among the three major 'west-flowing rivers' in the Peninsular India, the valley of river Narmada has a length of 1312 km and a basin (water shed) of 98,796 km^2 (72° 32′E to 81° 45′E and 21° 20′N to 23° 45′N, Figs. 1 and 2). Its valley covers a stretch of 1077 km length in Madhya Pradesh (86% of the basin); 74 km in Maharashtra (2% of the basin); and 161 km on the border between Madhya Pradesh and Gujarat and Gujarat states (14% of the basin) before draining the Gulf of Khambhat, Arabian Sea, 30 km west of Bharuch, Gujarat, west coast of India. Bordered by Vindhyan escarpments in the north and Satpura ranges in the south, the basin extends laying on the northern extension of the Deccan Plateau. Out of forty-one tributaries, twenty-two are from the Satpura and, the rest from the Vindhyan escarpments join the river. The main tributaries from the northern slope are, namely—Hiran, Barna, Choral, Karam, and Lohar and from the southern-slope,

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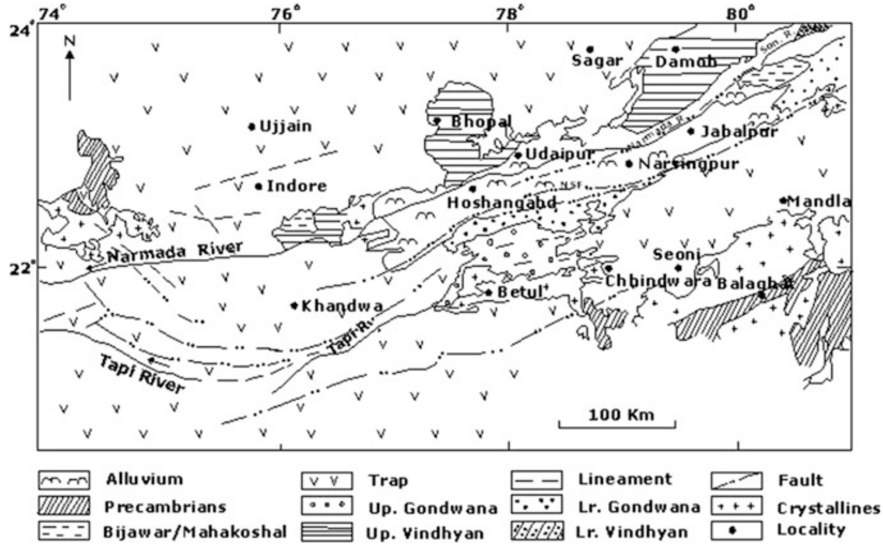

Fig. 1 Geology and tectonic features, Narmada valley, Central Indian Shield (*after*: Das et al. 2007)

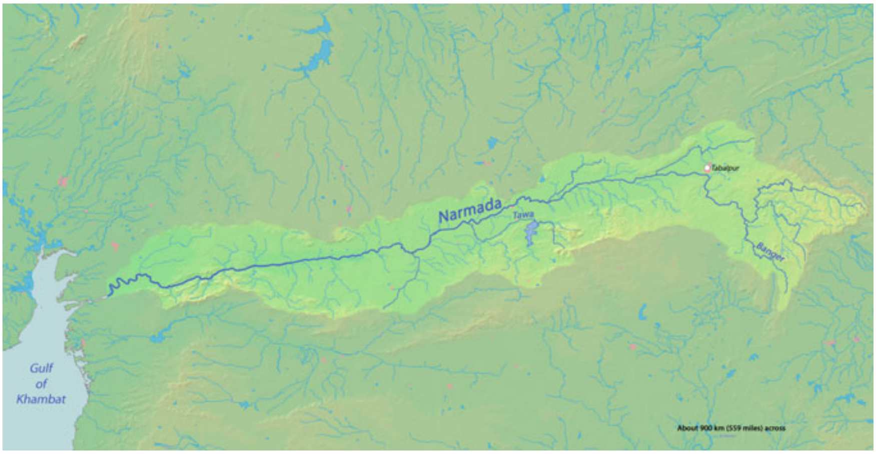

Fig. 2 Drainage basin and selected tributaries of Narmada (about 900 km across)

namely—Sher, Shakkar, Dudhi, Tawa and Ganjal, Sikta and Kaveri. Dhupgarh, Pachmarhi, is the highest point (1350 m) of the basin.

From Amarkantak, Narmada flows a meandering path before taking a turn in southeast direction up to Mandla, (25 km); a straight path with deepwater up to Banger; and a narrow loop shaped path up to Jabalpur and falls some 9 m, called the *Dhuandhara*, the 'fall of mist' flanked by 'marble rocks' (Figs. 3 and 4).

Fig. 3 Marble rocks at Bheraghat, Jabalpur

Fig. 4 Narmada riverbank near Jabalpur

From Jabalpur onward, the river crosses its first fertile basin (320 km long and 35 km wide). In the north, its valley is limited to the Barna–Bareli plain terminating at Barkhara Hills, Hoshangabad district from where onward the hills again recede in the Kannod plains flanked by 12 m high banks. A few kilometers further downstream at the crossing of the ghat of the National Highway 3, the river enters the Mandleshwar plain, the second basin (180 km in length and 65 km width in the south and 25 km in the north).

At Omkareshwar, sacred to the Lord *Shiva*, the river makes an 'island', and rushes over a barrier of rocks and makes two 12 m high waterfalls downstream (40 km from Nemawar and 40 km from Punasa, respectively. Streams of first to third orders join the river directly (Kathal 1981), showing neotectonic activity along the valley. The second valley section is broken only by *Saheshwar Dhara* fall. The early course of about 125 km up to Markari falls is met with a succession of waterfalls and rapids from the elevated table land of Malwa to the low level of Gujarat plain, where it flows between Vadodara and Narmada districts and then meanders through the rich plain of Bharuch, Gujarat.

3 Geological and Tectonic Features Related to the Narmada Valley

Narmada and Son rivers flow in a rectilinear fashion for an appreciable distance flanked by the Vindhyan escarpments and the valleys (Medlicott 1862). This lineament has controlled the geological distribution of the Vindhyan and Gondwana rocks on its north and south, respectively (West 1962), in a graben-like structure (layered block of the Earth's crust that dropped down relative to the blocks on either side due to ancient spreading of the Earth's crust, Choubey 1971). Narmada, Tapti, and Mahi rivers flow through a large tectonic feature of the Son-Narmada-Tapi (SONATA) lineament (Kale 1989; Shankar 1991; Tewari et al. 2001) characterized by neotectonism, moderate seismicity in a graben valley. Amid the tectonic graben-like structure (Map 1), Narmada River may be considered as a 'misfit river' (a river too small to have carved the valley it occupies).

3.1 Fossils

The Narmada alluvium has yielded India's first *Homo erectus* human fossil—a partial skull cap (Sonakia 1984) and collarbones of a 'pygmy-sized' man (Sankhyan et al. 2012) of early to late Pleistocene times (250–70 ka ago), showing the presence of early hominid in the Central India. Besides, several dinosaur fossils, namely —*Titanosaurus indicus* found in 1877 and *Rajasaurus narmadensis* have been found recently.

A World Heritage Site, 'Bhimbetka pre–historic rock shelter paintings', a natural art gallery of archeological importance on a dyke in Vindhyan rocks depicting is one of the oldest human habitations in India, which is located near Bhopal.

4 Hydrometeorology

Average rainfall of the Narmada basin is 1178 mm, whereas annual rainfall for the entire basin varies from 800 to 1600 mm. The valley experiences extremes of hydrometeorological and climatic conditions with the upper catchment having an annual precipitation in the range of 1000–1850 mm and with half or less in its lower regions (650–750 mm), supporting diverse nature of vegetation from lush green in the upper region to dry deciduous teak forests in the lower region.

Narmada exhibits discharges around 60,000 m^3/s, but due to reconfinement of the feeder channel resulting from tectonic reactivation of preexisting lineaments during the Late Pleistocene, this does not aggrade the fan.

Narmada at Dardi falls shows two stages of valley development: The inner gorge formed by down cutting was later filled by alluvium of the meandering palaeo-Narmada, and later exposed by the river in a second down cutting episode of post-Pleistocene age >40 ka ago (terrestrial cosmogenic radionuclide dating of the rock surface), which was then filled by Late Pleistocene alluvium followed by a Holocene excavation during which the river had enough power to remove the alluvium and excavate the inner gorge in the rock (Gupta et al. 2007).

The banks of Narmada are high on the old alluvial stretch of hardened mud, gravels of nodular limestone and sand. The width of the river spans from about 1.5 km at Makrai to 3 km near Bharuch and to an estuary of 21 km at the Gulf of Khambat. An old channel of the river, 1–2 km south from the present one, is very clear below Bharuch. The Karanjan and the Orsing are the most important tributaries in the original course. The former joins at Rundh and the latter at Vyas in Vadodara district of Gujarat, opposite to each other and form a *Triveni* (confluence of three rivers). The Amaravati and the Bhukhi are other tributaries of significance. Opposite the mouth of the Bhukhi is a large drift called Alia Bet or Kadaria Bet. There are sand bases and shoals at the mouth of the river at and at Bharuch.

The tidal rise is felt up to 32 km above Bharuch, where the neap tides rise to about a meter and spring tide 3.5 m. The lower basin, which occupies a large part in Gujarat originated in Mesozoic period (250 million years ago, Biswas 1987).

Palaeoflood analysis of a large Late Pleistocene flood on Narmada and early Holocene floods on Tapi indicates noteworthy clustering of flood events and a discernable link between palaeofloods and Holocene climatic changes (Kale et al. 2003).

5 Socioeconomic Importance

Narmada, which is the traditional boundary between North India and South India, is the lifeline to Madhya Pradesh state, the same way as Ganga is to the Uttar Pradesh state. It is navigable up to Shamlapitha or Ghangdia in Gujarat state.

From Jabalpur onward, Narmada crosses its first fertile basin, 320 km in length and 35 km in width. In the north, its valley is limited to the Barna–Bareli plain terminating at Barkhara Hills, Hoshangabad district. The futile plains of the middle basin, in Jabalpur and Narsinghpur, support fine quality pulses '*Dalhan*', groundnut earning huge export revenue.

A few kilometers further downstream, the river enters the Mandleshwar plain, the second basin (180 km in length and 65 km width in the south and 25 km in the north).

The upper, middle, and lower plains of the Narmada basin, mainly consists of black soils, broad enough and fertile, well suited for cultivation, may be divided into five physiographic regions: (i) The upper hilly areas of Shahdol, Mandla, Durg, Balaghat, and Seoni districts; (ii) the upper plains of Jabalpur, Narsinghpur, Sagar, Damoh, Chhindwara, Hoshangabad, Betul, Raisen, and Sehore districts; (iii) The middle plains of Khandwa, part of Khargone, Dewas, Indore, and Dhar districts; (iv) the lower hilly areas covering parts of the west Nimar, Jhabua, Dhulia, Narmada, and Vadodara districts; and (v) the lower plains of Narmada, Bharuch, and parts of Vadodara districts. The coastal plains in Gujarat, however, are composed of clayey alluvial covered by a layer of black soil.

Narmada exhibits discharges of up to 46 billion cubic meter (BCM) of with 22.5 is allocated to the Madhya Pradesh state (Resource Atlas 2007). The Irrigation Commission (1972) identified the Madhya Pradesh part of the basin as drought affected and a large part of North Gujarat, Saurashtra, and Kutch as semi-arid or arid regions attributable to extreme unreliable rainfall.

There are over 4000 water-related projects of various scales and purposes including irrigation for the basin. Among these, Bargi, Barna, Indira Sagar, Kolar, Omkareshwar, Maheswar, Bhagwant Sagar, and Tawa Dam are located in Madhya Pradesh and Sardar Sarovar dam in Gujarat.

Narmada having a huge water resource potential of (40.96 km^2) with an annual flow of over 90% during the monsoon months was found suitable for an ambitious multistate program of construction of hydropower and irrigation dams 30 major dams (21 irrigation dams on the Narmada and its tributaries), aims to irrigate 50,000 km^2 of drought prone and scarcity areas in the western India before 2025 by the Narmada Control Authority (NRD). The NRD has recently announced increase in the height of the Sardar Sarovar Dam from 121.92–138 m (www.Indianexpress.com 2014).

Cursory study has been conducted on the environmental aspects of Narmada, yet the river is less challenged compared to the other rivers of northern India so far the pollution is concerned. Biological oxygen demand (BOD) in the middle part of the basin is 26,535 BOD kg/day (Unni 1966).

The major sources of water pollution in the Narmada basins are may be designated to discharge of sewages; industrial effluents; agricultural runoff and annual fairs and festivals.

Turbidity from Amarkantak to Hoshangabad ranges from 0 to 0.1040 NTU. In the middle zone, 10,000 metric tons of nitrogen, 6000 tons of phosphorous, and 1500 tones of potassium are used annually for cultivation, which causes pollution in the downstream areas in the immediate vicinity of the river. Mandla, Jabalpur, Narsinghpur and Betul, Raisen, Hoshangabad districts produce 28,290 KLD industrial wastes per day (Unni 1966).

6 Conclusions

Most of the river discharge is in the monsoon months, except in some tributaries where groundwater flow to the river during non-monsoon is significant. The suspended sediment flux is significantly lowered by construction of dams and reservoirs in its course (Gupta and Chakrapani 2007). The climate of the basin is humid tropical, although at places extremes of heat and cold are often encountered (Gupta and Chakrapani 2007).

The SONATA is a neotectonically active graben and has influenced the deposition, which provided the necessary physiographic contrast, and has played an important role in the erosion of the fan, whereas climate-controlled primary and secondary processes have determined the nature of alluvial architecture (Chamyal et al. 1997). The two phases of tectonic uplift during Holocene in the Narmada basin (Biswas 1987), besides the studies on 'gravelly horizons', at Tilwara, Jabalpur show: (i) variation in climate, further attested by fining upward nature of clasts (Chamyal et al. 1994) and (ii) study of 'incisive drainage' indicates that the compressive stresses continue to accumulate along the NSF due to continued northward movement of the Indian plate (Chamyal et al. 2002) making the basin vulnerable for further tectonic activity, that may be manifested as an earthquake in the region.

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Mahanadi: The *Great River*

Raj K. Singh and Moumita Das

1 Introduction

The Indian subcontinent can be divided into Extra-Peninsular (Himalayan Region) and Peninsular region. The Extra-Peninsular region has the major perennial rivers of the country, e.g. Ganga, Brahmaputra, Indus and their tributaries, which originate from the Himalayas. On the other hand, the rivers in the Peninsular region originate from the Western Ghats and Central India, and are entirely monsoon-fed having high seasonal flow. The major peninsular rivers Mahanadi, Godavari, Krishna and Kaveri are east flowing, while Narmada and Tapti are west flowing. Majority of these peninsular rivers carry very high proportion of discharge and sediment load during the monsoon period between June and September, which may occasionally result in damaging floods. These rivers carry negligible flow during the non-monsoon season (Kale 2005) and receive water from the riverbank aquifer.

One such peninsular river, the Mahanadi, which means the '*Great River*', is a major river in East Central India. It has a total course of about 851 km and drains an area of about 1,41,589 km^2. This river drainage area comprises the states of Chhattisgarh (75,136 km^2), Odisha (65,580 km^2), Jharkhand (635 km^2) and Maharastra (238 km^2) (source: NIH). The important cities/towns located along the banks of the Mahanadi are Raipur, Sambalpur, Sonepur, Cuttack, Bhubaneswar and Puri.

The precise source of origin of the Mahanadi is not exactly known; it is a combination of many mountain streams. The farthest headwater of the river lies in a pool on a 442 m high Sihawa hill, 6 km from Pharsiya village, near Nagri town,

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in Raipur district of Chhattisgarh. The Sihawa hills are extension of the Eastern Ghats and are the source of many other streams which are tributaries of the Mahanadi. The river flows towards west for an initial 56 km; four small streams join the river near Kanker, after which it continues towards north-west. The river takes a sharp turn towards north-east after crossing Charama and is joined by the river Pairi from the right at Rajim. The Mahanadi flows a significant distance in the north-east direction and drains the Raipur district, touching the eastern portions of Raipur City. The first major tributary, Sheonath, joins the left bank of the Mahanadi near Khargahni in Bilaspur district. Beyond the confluence with Sheonath, the river takes an easterly course for almost 138 km, during which other tributaries join in. The tributary Jonk joins in from the right after 13 km near Sheorinarayan, and 17 km further down near Mahuadih, the River Hasdeo joins from the left. The River Barai joins in next, from the left while forming a 21 km long braided course. Further down, the River Mand joins the left bank of the Mahanadi at Chandrapur. The Mahanadi leaves Chhattisgarh further 28 km down and enters Sambalpur district of Odisha. In Odisha, the River Ib is the first major tributary joining the Mahanadi from the left at Bagra before the river flows into the reservoir created by the largest earthen dam,

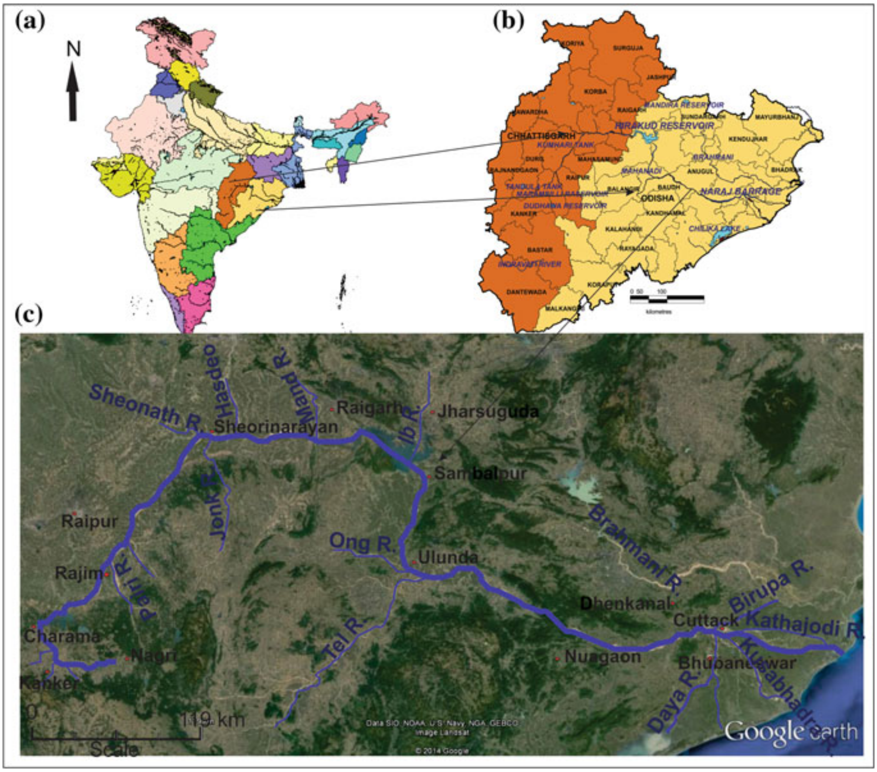

Fig. 1 **a** Map of India. **b** River Mahanadi in the states of Chhattisgarh and Odisha. **c** Course of river Mahanadi and its tributaries on google imagery

Table 1 Major tributaries of river Mahanadi, its origin, catchment area and length travel before joining Mahanadi

Name of major tributaries	Origin (elevation)	Length travel before joining Mahanadi (km)	Catchment area (km^2)
Chhattisgarh			
Seonath river	Hills near Kotgal, Chhattisgarh (533 m)	383	30,761
Hasdeo river	10 km North of Sonhat, Chhattisgarh (915 m)	333	9856
Jonk river	Khariar hills, Odisha (762 m)	196	3484
Mand river	Sarguja district, Chhattisgarh (686 m)	241	5200
Odisha			
Ib river	Hills near Pandrapat, Chhattisgarh (762 m)	251	12,447
Ong river	Northern outskirts of Khariar hills, Odisha (457 m)	204	5128
Tel river	Plain, 32 km West of Jorigam, Odisha	296	22,818

Source NIH

the Hirakud dam. This reservoir is located at a distance of 10 km from Sambalpur city. The Mahanadi turns south below Sambalpur and splits into two channels near Charpali, which unites again near Dhama. The River Ong joins the right bank of the Mahanadi about 11 km upstream of Sonepur. Near Sonepur, the Mahanadi takes a gradual south-east turn and is joined by its second biggest tributary, River Tel, as it enters into the Eastern Ghat mountain chains. The Mahanadi enters the Odisha plains at Naraj, about 11 km west of Cuttack, where it pours down between two hills that are more than a kilometre apart and emerges into the delta (Mahalik 2000). A barrage has been constructed at Naraj to regulate the river's flow. The Mahanadi splits into Birupa and Kathajodi below Naraj. The younger River Birupa, flows north-east and gets captured by Brahmani. Kathajodi further splits into various channels. The various identified paleochannels of River Mahanadi are Burdha, Alaka, Ratnachir, etc. Present active channels such as Kathajodi, Kuakhai, Bhargabi, Kushabhadra, Daya, Devi etc get debouched into the Bay of Bengal. The course of the River Mahanadi and its major tributaries can be seen in Fig. 1. The origin and length of the major tributaries before joining Mahanadi are provided in Table 1.

2 Geomorphology

The Mahanadi basin is physiographically divided into four regions, namely (i) Northern Plateau, (ii) Eastern Ghats, (iii) erosional plains of central table land and (iv) Deltaic and coastal plain. The Mahanadi originates from small hills in

Chhattisgarh and is a narrow river at its early stage. It flows through the shallow valley between low, scattered hills; the valley width ranges between 500 and 600 m. Before leaving the state Chhattisgarh, the river develops a braided course and its size also increases as the rivers Seonath, Jonk, Hasdeo and Mand join it. Before construction of Hirakud dam, the river width was about couple of kilometres at the Sambalpur district of Odisha, and it carried massive amounts of silt, especially during the monsoon. After construction of the dam, it has become rather tame as the rivers Ib, Ong and Tel join it before entering the Eastern Ghat mountains. After entering the Eastern Ghat mountains, the Mahanadi valley narrows down sharply and the river flows through extremely narrow Satkosia gorge between Jamudeli and Baramul. The gorge ends at Baramul, and the river valley becomes flat as the river passes through the scattered hillocks. Below Baramul, the river widens up to 1.6 km. It turns east-north-east at Kantilo and flows through the Kaimundi gorge. Below this gorge, the river enters the plain and widens its course and emerges into the delta at Naraj.

The Mahanadi delta, bounded by River Brahmani on the north-east and Chilka lake on the south-east, covers an area of about 9000 km^2 (Mahalik 2006). The delta is arcuate in shape which makes a fan angle of about 140° between two outermost distributaries. The evolution of Mahanadi delta was governed by the progressive shifting of river course and coastline in four different stages (Mahalik 2006). In the early stage, the Mahanadi first branched off and gave rise to its earliest distributary channel system; the number of channels increased in successive stages, while few of them were abandoned. The sediments brought by the Mahanadi are distributed by riverine and marine agents, while winds have played a supporting role in reworking of the deltaic sediments. The Mahanadi delta can be geomorphically divided into the fluvial sector and the marine marginal sector. The fluvial sector occupies the western half of the delta plain and is primarily composed of sediments of the riverine system, while the marine marginal sector runs parallel and adjacent to the present-day shoreline (Mahalik 2000). A variety of geomorphic features, e.g. channel bars, point bars, levees, flood plain, back swamps, beaches, beach ridges, tidal flats, tidal creeks, tidal swales, spits, offshore bars and enclosed lagoons, are observed along the deltaic plain of Mahanadi. Numerous paleochannels are also reported from the Mahanadi deltaic plain, which indicate that river course keeps shifting due to heavy silt load in the distributary channel. Geologically, the upstream part of the river is dominated by Proterozoic sedimentary rocks such as limestone, calcareous shales and sandstone. The downstream part of the river is dominated by silicate rocks of metamorphic origin. The river annually transports 33.59 million tons of sediments into the Bay of Bengal, out of which less than 25% is the dissolved load (Ghose and Swain 2011). The active channels of Mahanadi delta are shown in Fig. 2.

The Mahanadi and its catchment area climate are predominantly tropical with average summer temperature of 29° C and winter temperature of around 21° C. The diurnal variations in temperature are more in the river's early and middle stage catchment areas, while variations are relatively less near the deltaic area. The normal monsoon generally onset in the first week of June. The Mahanadi basin

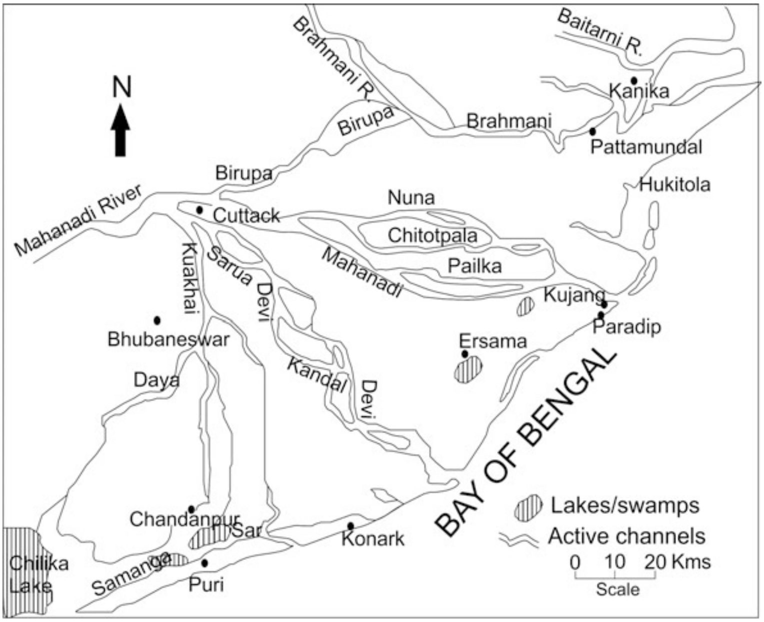

Fig. 2 Active channels and swamps in the Mahanadi Delta (after Mahalik 2006)

receives more than 84% precipitation during the summer monsoon period (July–September), while only 3% or less is received during the winter monsoon (January–February). Occasionally, the basin also receives rainfall due to onset of cyclone/depression over Bay of Bengal. Average annual rainfall in the basin is about 1400 mm.

3 Socio-economic Importance

The Mahanadi is an important river in the states of Odisha and Chhattisgarh. This river has specific values for the state of Odisha, and many important towns and religious places are located on its banks. The flow of the river is very slow, and it deposits a lot of silt (Ghose and Swain, 2011). The Mahanadi basin is famous for its fertile soil and flourishing agriculture. The Hirakud and other dams receive huge deposits of silt by River Mahanadi and its tributaries. The Mahanadi delta had highest yields per acre in India. The main soil types found in the early- and middle-stages of river, are red and yellow soils, mixed soil and black soil respectively while lateritic soil is found in the lower stages of river. The deltaic soil is dominant in the coastal and deltaic plain.

The agriculture practices in the Mahanadi basin primarily depend on a network of canals that arise from various dams and barrages. Rice, oilseeds and sugarcane are the principal crops of this basin. The average annual surface water potential assessed in this basin is 66.9 km^3, out of which 50 km^3 is utilizable water. The Mahanadi basin has assessed groundwater potential of 16.5 km^2. It has about 80,000 km^2 of cultivable areas, which is about 57% of the basin area and 4% of the total cultivable area of the country. At present, only 17 km^3 of its surface water is in use. A number of minor to major projects have already commenced or under construction to utilize the plentiful water resources available in the Mahanadi basin. These projects are used for hydropower generation and increasing the live storage capacity in the basin. After the execution of some of the major and medium projects, the live storage capacity will increase significantly and will also control the flood situation in the basin. The total live storage capacity of the completed projects is 8.5 km^3, which will increase by $\sim$5.4 km^3 on completion of the projects under construction. There are many projects under consideration which will further increase the storage capacity. The assessed hydropower potential of the basin at 60% load factor is $\sim$627MW (source: NIH). Some of the important major and medium projects on Mahanadi and its tributaries are

(i) *Hirakud Dam*: It is one of the prestigious major multipurpose river valley projects of independent India commissioned in 1957. The 1248 m long masonry dam is 61 m high with gross storage capacity of 5818 Mm^3. This is one of the biggest reservoirs of the region designed to serve three purposes: flood control, irrigation and power. The reservoir spans from the Lamdungri hills on the left to the Chandili Dungri hills on the right forming one of biggest artificial lake of Asia. The hydropower plant at the dam has 307.5 MW of installed capacity.

(ii) *Ravishankar Sagar*: This dam was constructed in 1978 and is about 92 km south of Raipur city. This multipurpose reservoir serves irrigation, hydropower generation and the industrial requirement of Bhilai Steel Plant. The storage capacity of this reservoir is 909 Mm^3 and has a maximum depth of about 32 m. The sediments of this dam are poor in nutrients and organic matter.

(iii) *Dudhawa Reservoir*: This reservoir is situated near Dudhawa village about 21 km west of Sihawa, near the origin of the Mahanadi and 29 km east of Kanker. This project was commissioned in 1963–1964 and designed to supply water to Ravishankar Sagar project complex to increase irrigation potential. The maximum height of this earthen dam is 24.53 m, and length is 2906.43 m.

(iv) *Sondur Reservoir*: This reservoir was constructed across Sondur River, a tributary of Mahanadi, in 1988. Major portion of its catchment lies in the Dhamtari district of Chhattisgarh and Koraput district of Odisha. This project is designed to increase irrigation potential and also to supply water to Ravishankar Sagar project complex through Dudhawa reservoir.

(v) *HasdeoBango*: It is a multipurpose storage reservoir on Hasdeo River, a tributary of Mahanadi, located nearly 70 km from Korba in the Korba district of Chhattisgarh. It has three powerhouse units of 40 MW each and a firm power unit of 20 MW.

Table 2 Water quality of river Mahanadi–2011

Station code	Locations	State	Temperature (°C)			D.O. (mg/l)			pH			Conductivity (μmhos/cm)			B.O.D. (mg/l)			Nitrate- N + nitrite-N (mg/l)			Faecal coliform (MPN/100 ml)			Total coliform (MPN/100 ml)		
			Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Water quality criteria						>4 mg/l			6.5–8.5						< 3 mg/l						<2500 MPN/100 ml			<5000 MPN/100 ml		
1851	Mahanadi at Sihawa	Chhattisgarh	25.0	33.0	28.5	7.3	9.3	8.2	7.7	7.8	7.7	143	590	296				0.20	2.40	0.80	220	220	220	11	11	11
1264	Mahanadi at Rudri U/S at Dhamtori Reservoir	Chhattisgarh	25.0	33.0	28.8	7.3	8.5	7.8	7.4	7.8	7.6	140	614	347				1.00	2.30	1.40				33	300	101
1099	Mahanadi at U/S of Rajim	Chhattisgarh	22.0	33.0	28.7	6.8	8.4	7.7	7.3	7.9	7.7	261	716	372				1.00	2.50	1.40				24	500	158
1852	Mahanadi at Arrang, Raipur	Chhattisgarh	26.0	34.0	30.3	6.7	8.5	7.6	7.4	7.8	7.7	242	672	392				1.30	2.30	1.60	350	350	350	33	40	37
1100	Mahanadi at Kharad	Chhattisgarh	24.0	33.0	29.0	6.4	7.5	6.9	7.5	8.5	7.7	186	366	233	1.3	1.4	1.4	1.39	2.70	2.07				12	20	15
1282	Mahanadi at Sheorinarayan Village	Chhattisgarh	25.0	33.0	29.0	7.1	7.3	7.2	7.5	7.5	7.5	265	375	320	1.4	1.4	1.4	2.33	2.69	2.51				17	18	18
1467	Mahanadi A/C with River Mand	Chhattisgarh	24.0	33.0	28.4	6.7	8.0	7.1	7.5	8.5	8.0	90	284	213	1.1	1.3	1.2	1.30	1.68	1.48				10	22	18
1101	Mahanadi at Interstate boundary	Chhattisgarh	24.0	32.0	27.2	7.1	7.4	7.3	7.4	7.7	7.5	248	301	272	0.9	1.6	1.2	1.16	1.93	1.26				43	240	127
1281	Mahanadi at Hirakud Reservoir	Odisha	24.0	32.0	27.2	5.8	9.4	7.6	7.4	8.3	7.9	120	261	189	0.9	2.0	1.4	0.03	5.71	0.92	330	1500	1015	700	4300	1937
1270	Mahanadi at Sambalpur U/S	Odisha	24.0	34.0	27.0	5.9	9.4	7.5	7.2	8.3	7.8	130	305	199	0.8	2.1	1.5	0.01	0.49	0.18	310	5400	1329	700	9200	2415
1271	Mahanadi at Sambalpur D/S	Odisha	22.0	31.0	26.6	5.3	9.6	6.8	7.2	8.2	7.8	121	333	238	0.6	3.3	2.5	0.02	1.30	0.51	2100	92000	26925	4300	160000	45192
2405	Sambhalpur Fds at Huma	Odisha	20.0	30.0	25.9	6.3	9.1	7.5	7.5	8.4	8.0	139	272	186	1.0	2.9	1.9	0.01	0.68	0.22	140	13000	3184	700	26000	5181
1272	Mahanadi D/S (after confluence with River Ong Sonepur U/S)	Odisha	20.0	31.0	26.4	5.3	9.4	7.3	7.6	8.4	7.9	148	285	203	0.7	2.1	1.3	0.02	1.58	0.39	230	2100	819	630	4300	1616
1274	Mahanadi A/C River Tel (Sonepur D/S)	Odisha	20.0	32.0	27.0	4.9	9.8	7.2	7.5	8.4	8.0	173	344	237	0.8	2.8	1.8	0.02	1.03	0.34	700	2800	1332	1100	9200	2625

(continued)

Table 2 (continued)

Station code	Locations	State	Temperature (°C)			D.O. (mg/l)			pH			Conductivity (μmhos/cm)			B.O.D. (mg/l)			Nitrate- N + nitrite-N (mg/l)			Faecal coliform (MPN/100 ml)			Total coliform (MPN/100 ml)		
			Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
1275	Mahanadi at Tikarpada	Odisha	22.0	31.0	27.0	5.6	9.3	7.3	7.1	8.4	8.0	122	261	188	0.8	2.4	1.5	0.06	0.47	0.19	460	4300	1578	580	8400	3293
1276	Mahanadi at Narsinghpur	Odisha	18.0	33.0	25.9	6.3	9.3	7.8	7.7	8.4	8.0	153	256	202	0.6	1.8	1.3	0.14	3.58	0.66	220	1500	763	260	2800	1508
1277	Mahanadi at Cuttack U/S	Odisha	20.0	32.0	28.5	5.2	10.5	8.1	7.1	8.5	8.0	142	304	198	0.7	2.4	1.4	0.01	2.06	0.49	140	1400	475	140	1700	1023
1278	Mahanadi at Cuttack D/S	Odisha	21.0	34.0	29.8	6.0	8.4	7.4	7.5	8.4	8.0	141	295	197	1.8	3.6	2.4	0.06	3.30	0.59	1100	160000	25475	1100	160000	35583
2409	Cuttack Fds (Serua) at Sankhatrasa	Odisha	19.0	32.0	27.3	5.7	9.9	7.5	7.4	8.4	8.0	143	364	210	1.3	3.3	2.2	0.06	2.11	0.48	310	7900	2846	310	13000	5018

Some of the other projects on Mahanadi and its tributaries are Tandula, Gondli, Kedar Nalla, Keshwa Nalla, Khapri, Kharkhara, Khurung Tank, Kinkari, Koncha, Kumhari, Kunaria, Madiyan, Maniyari Tank, Murrumsilli, Pairy, Paralkot, Pilosaiki, Pindrawan, Saroda, Sikasar, Surhi in Chhattisgarh state; and Budha Budhani, Damar Bahal, Lurada, Russelkonda, Saipala, Surada, Sundar dam, Upper Dahuka in Odisha state.

The Mahanadi basin is most vulnerable to climate change and variations in temperature and precipitation in the region. There are historical records of devastating floods before the construction of Hirakud dam. However, the construction of the Hirakud dam and a network of canals, barrages and check dams keep the river well in control. Heavy rain still cause large-scale flooding and flash flooding in the villages situated near the banks of the Mahanadi and its tributaries, distributaries and canals. Floods are regularly noticed along the paleo and active distributary channels of the river. Flood starts in the Mahanadi when water discharge mounts to 17,150 $m^3\ s^{-1}$. Damaging floods may result when the discharge raise to 28,580 $m^3\ s^{-1}$ (Mohanti, 2003). The years 2001, 2003, 2008 and 2011 marked very high floods in the Mahanadi, and the highest discharge recorded was above 40,868 $m^3\ s^{-1}$.

The water quality of the Mahanadi and its tributaries is regularly monitored by the Central Pollution Control Board (CPCB) at various reaches of the river and its tributaries, at different times. The water quality is quite good in upper reaches, but the quality deteriorates in the downstream reaches. The CPCB data of water quality of the Mahanadi and its tributaries for the year 2011 are given in Table 2 (Source: CPCB). Various studies on the delta area of the Mahanadi indicate deterioration of water quality due to industrialization and human activities (Panda et al. 2006; Samantray et al. 2009). The water quality is less deteriorated during the monsoon period, and deterioration is more during the non-monsoon period (Sundaray et al. 2006).

The Mahanadi and Brahmani rivers form the largest delta at the confluence with Bay of Bengal and house a variety of birds and animals. The Baisipalli and Satkosia sanctuaries are famous for its variety of wildlife and birds. The river Mahanadi is also known for freshwater turtle habitat in the country. The coastal and deltaic region around Mahanadi also hosts many migratory birds in the country which attracts tourists.

4 Conclusions

The River Mahanadi meets the requirement of water for irrigation, domestic and industrial purposes in parts of Chhattisgarh and Odisha. The Mahanadi basin has huge replenishable surface water resource 66.9 km^3, of which only 30% is abstracted. The water availability in the river undergoes large seasonal fluctuations as it is a rain-fed river. The vulnerability of the Mahanadi basin to climate change and the spatial distribution of rainfall pattern of the area enhance the chances of occurrence of flood in the downstream sub-catchments, while there are threats of drought in upstream sub-catchments. The Mahanadi basin is prone to flood and is regularly affected by catastrophic flood disasters. Further, modelling study analysis on present water use indicates a high water abstraction by the irrigation sector and increasing trend of water demand until 2050 (Asokan and Dutta 2008). The deteriorating water quality and its seasonal variability are also a cause of concern. Integrated water management policies, incorporating hydrological response of the basin to the long-term climate change, seasonal variations in rainfall, regular assessments of basin-wise water use and the anthropogenic effects, will help to develop appropriate flood and drought mitigation measures and protect water quality of the Mahanadi.

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Godavari River: Geomorphology and Socio-economic Characteristics

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1 Introduction

The Godavari river basin is expanded in the states of Maharashtra, Andhra Pradesh, Madhya Pradesh, Chhattisgarh and Odisha along with minor parts in, Karnataka state and the Union territory of Puducherry, occupying a total extent of 3,12,812 km^2, covering 9.5% of the total area of India. The length of the basin is 995 km and the width is 583 km. The longitudinal extent of the basin is 73° 24′ to 83° 4′ East and latitudes range from 16° 19′ to 22° 34′ North. The River Godavari originates at Trimbakeshwar in Nashik district of Maharashtra, which is 80 km east of the Arabian Sea, at altitude of 1067 m above mean sea level (msl). The entire lengthwise measurement of Godavari River from its source to the outlet of a river (mouth) into the Bay of Bengal is 1465 km. The Satmala and Mahadeo hills, the Ajanta ranges occur on the northern side, Eastern Ghats occur on the southern and eastern side and the Western Ghats occur on the western fringe of the basin.

The Godavari from its origin to at about 64 km is joined by the River Darna, from right side and after a small extent downstream; the River Kadana joins it from the left side. The tributaries Pravara and Mula, which rise in the hills of Akole taluka in Ahmednagar district after confluence to each other, join from the left side of River Godavari. The River Sindphana rises in the Chincholi hills at the north-western apex of the Balaghat plateau and flows in a north-easterly course past Amalner and has a fairly long easterly course up to about Majalgaon, where after it flows north-eastwards and northwards to join the Godavari at *Kshetra Manjrath*.

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Table 1 Sub-basins of Godavari river basin (after India-WRIS 2011)

S. No.	River (tributary)	Altitude of source (MSL)	Extent (km)	Catchment area (km^2)	Average annual rainfall (mm)
1	Upper Godavari (up to Pravara)	1067	675	33502	770
2	Pravara	1050	208	6537	606
3	Purna	838	373	15579	797
4	Manjira (Manjra)	823	724	30844	846
5	Manjra to Pranhita Zone	323	328	17205	955
6	Maner	533	225	13106	932
7	Penganga	686	676	23898	960
8	Wardha	777	483	24087	1055
9	Pranhita	640	721	61093	1363
10	Pranhita to sea	107	462	24869	1208
11	Indravathi	914	535	41655	1588
12	Sabari	1372	418	20427	1433

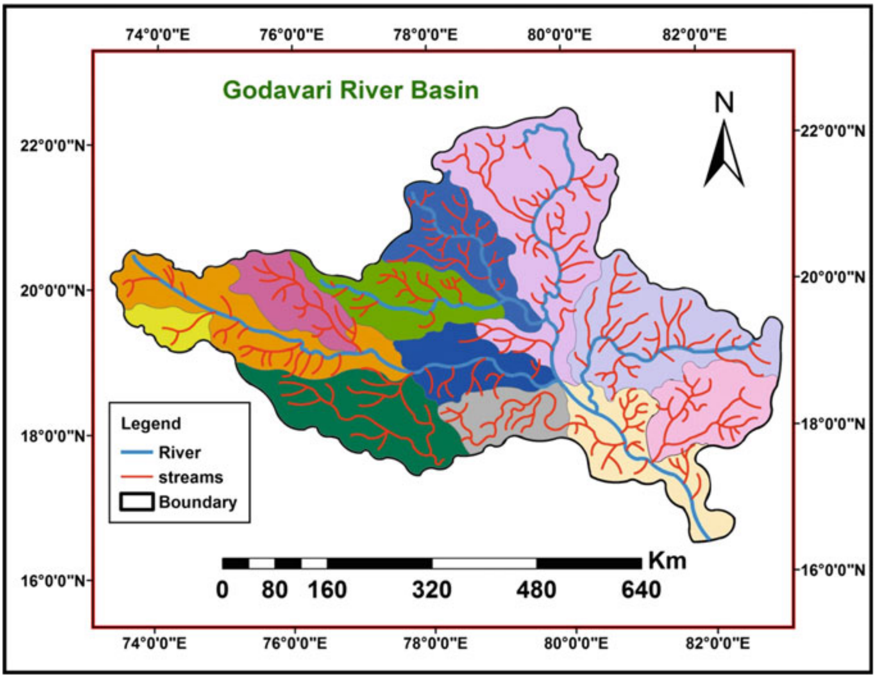

Fig. 1 Godavari river basin showing different sub-sites

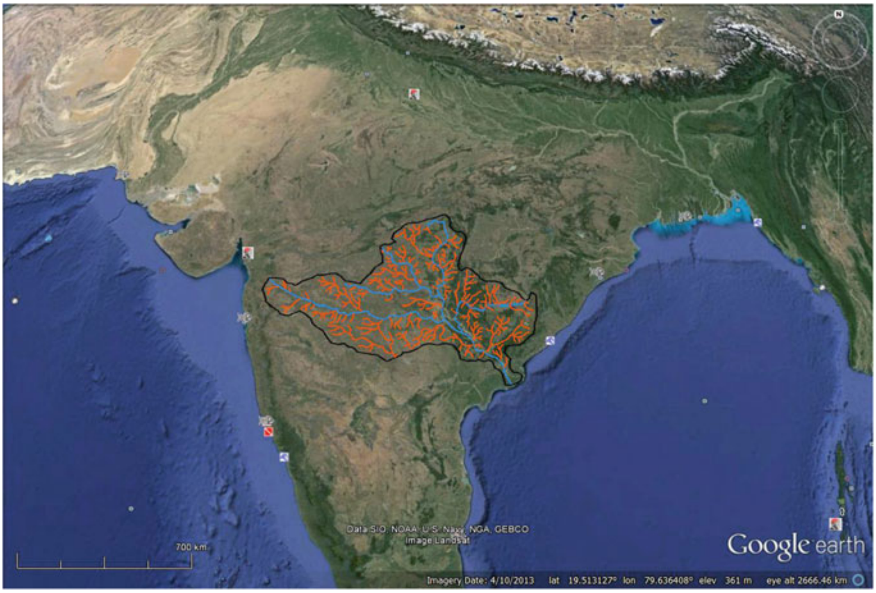

Fig. 2 Godavari river basin superimposed on the google Images

The River Godavari also receives the water from the confluence of Purna and Dudhna rivers, and in downstream after 138 km distance at the boundary of Maharashtra and Telangana, the water of the Manjra River unites it from south. The elevation of Godavari River at the confluence with Manjra River is 329 m. The River Pranhita, carrying the collective water of the Penganga, the Wardha and the Wainganga, those drains the areas of Nagpur and southern slopes of the Satpura ranges into mighty Godavari and joins at around 306 km downstream of its confluence with the Manjra River. The water of the Indravathi joins the Godavari 48 km further down. The Sabari that joins the Godavari at 100 km upstream of Rajahmundry hills is its last tributary. The biggest tributary of the Godavari is the Pranhita River covering 34.87% of total basin. Major sub-basins of the Godavari river basin are shown in Table 1 and Fig. 1, while Fig. 2 illustrates the basin superimposed on the Google Images.

2 Geology

Godavari basin comprises of unique geological setting in different areas. The basin in its initial part and the areas occupying the Pravara and Purna sub-basins chiefly consists of basalt rocks belonging Deccan Basalt Province (DBP). The lava of DBP is outpoured through fissure type of volcanic eruption for the duration of late Cretaceous to early Eocene and comprises of nearly horizontal flows. The basalt flows in the area have been assigned to the Ajanta Formation, equivalent to the upper Ratangad Formation of western Maharashtra consisting of compound (*pahoehoe* type) flows (Godbole et al. 1996). The basalt flows can be broadly classified into two main types viz., *vesicular-amygdaloidal* (compound *pahoehoe* type) and simple or compact basalt (*aa* type) flows. The *pahoehoe* flows consist of basal pipe vesicles/amygdules; middle simple part and top vesicular part with reddened and glassy nature, with or without ropy structure. Simple basalt flows are bulky and widespread having flat laying form. The average thickness of an individual flow is about 8–15 m. The top surface of simple basalt flow is rather thin vesicular and fragmentary; the middle and lower parts are thick, simple and dense. These flows show several block joints.

In vesicular-amygdaloidal basalt flows, the gas cavities (vesicles) are filled with secondary minerals eliminating its unique vesicular nature. Presence of amygdules in amygdaloidal basalt leads it to be free from joints and it develops as consistent, watertight mass (Patil et al. 1999; Babar and Kaplay 2003). The sheet joints are developed due to weathering at the contact zone of the vesicular-amygdaloidal and the simple basalt flow. Such weathered amygdaloidal basalt holds groundwater (Deolankar 1980; Lawrence 1985; Kulkarni and Deolankar 1995; Babar 2002). But the amount of groundwater is based on the depth of weathered part of the rock.

Based on hydrogeological characters, the simple basalt flows can be divided into two parts. The upper part of this flow for some extent is vesicular, without joints and impermeable when fresh, but later on it generates sheet joints after deep weathering. In simple basalt flow, the middle and lower parts are usually highly jointed. These joint patterns are closely spaced, consistent and linear along preferred orientations with the continuity perceptible over considerable distances. Such joints cut across in basaltic rocks and represent recharge conduits (Kulkarni et al. 1994).

In the Manjra river sub-basin, the main geological rock formation in the source area up to Degloor tahsil in Nanded district is Deccan trap basalt, while from Degloor onwards there is occurrence of the Peninsular Granites, Puranas and the Gondwanas.

In the middle lower part of the Godavari basin and the area occupying Maner sub-basin the rocks including the Peninsular Granites, Puranas, Dharwars and Gondwanas occur. The water-bearing characteristics of these rocks indicate that the groundwater is in confined state in joints, fissures, fractures and crevices penetrating to greater depths underneath the weathered part. The Peninsular Gneiss and Gondwanas constitute the groundwater in unconfined state where the yields are high.

The parts of basin occupied by Wardha, Penganga and Pranhita sub-basins constitute the peninsular shield area consisting of the Archaean rocks. Overlying the Archaean rocks, there are rocks of Precambrian as well as partly to the Cambrian age followed by the Gondwanas and the Deccan trap lavas. The hydrogeological evaluation revealed that the groundwater in the Vindhyan groups, Gondwanas, Deccan traps, laterites and alluvium occurs in the soil cover, weathered zone and in the jointed and fractured portions of the hard rock.

Rocks of Cuddapahs and Vindhyans comprised of sandstones, shales, limestones, quartzites and conglomerates. The Gondwanas are mainly sedimentary in origin along with occurrence of some coal seams. The lower reaches of the basin are dominated by the Khondalite rocks of Eastern Ghats and they are formed mostly from rocks containing quartz-feldspar-garnet-sillimanite gneisses, quartzites, calc-granulites and charnockites. The coastal area is dominated by the Tertiary sandstones at Rajahmundry.

Geologically, the part of Godavari basin towards its end and in the regions of Indravathi and Sabari sub-basins belongs to Archaean rocks of Peninsular India. The other rock formations found in the area are Pakhals, Sullavais and Peninsular granites, Dharwars, Khondalites and Charnockites belonging to early Precambrian to late Cretaceous age. Groundwater in these rocks is found in the fractured, weathered, sheared zones and also along the schistose planes of gneisses, schists and granites of the region. Groundwater in these rocks is developed in confined state occupied by calcareous lithounits, the argillaceous and arenaceous lithounits of the Lower Gondwanas. Alluvial deposits of the basin because of greater porosity and permeability operates as prospective aquifer.

3 Lineaments

Lineaments of Godavari basin represent a group of several mega and intermediate categories with WNW–ESE and NW–SE trends extending over the Deccan Plateau whereas Pranhita–Godavari section dominates NNW–SSE trend (Rajurkar et al. 1990; Powar 1993). The upper section of Godavari River is controlled by the Upper Godavari lineament extending for about 280 km in a WNW–ESE direction from west of Nasik to near Parbhani in the east (Fig. 3). The lineament cuts across the Deccan lava flows and is characterised by the Quaternary tectonic movements as indicated by anomalous behaviour of the river, raised terraces and thick pile of alluvium in the upper reaches (Sharma 1985; Rajurkar et al. 1990). The Godavari River in upper section shows a WNW–ESE trend of lineament, the main Godavari section passing through Nasik in the west to near Parbhani in the east and the other lineament trends like NW–SE of the Asna and Purna rivers and E–W trend of the Godavari River from Parbhani to Nanded (Fig. 3). A WNW–ESE trending structure of main Godavari River is continued into the nearly E–W lineament from Parbhani to Nanded district (Fig. 3). The most significant anomaly induced by these structures is the right angled turn of Godavari River at Dhasadi (19° 03′24″N and 76° 47′20″E, Fig. 3).

Using remote sensing data, Sarup et al. (2006) studied the tectonics of Dalvat area, Nasik district, Maharashtra, to present evidence of fault traces in Deccan trap domain near Kosurde, Dhanoli, Chikhli, Manchandar villages of Nasik district showing NNE–SSW to NS lineaments as the signature of active faulting.

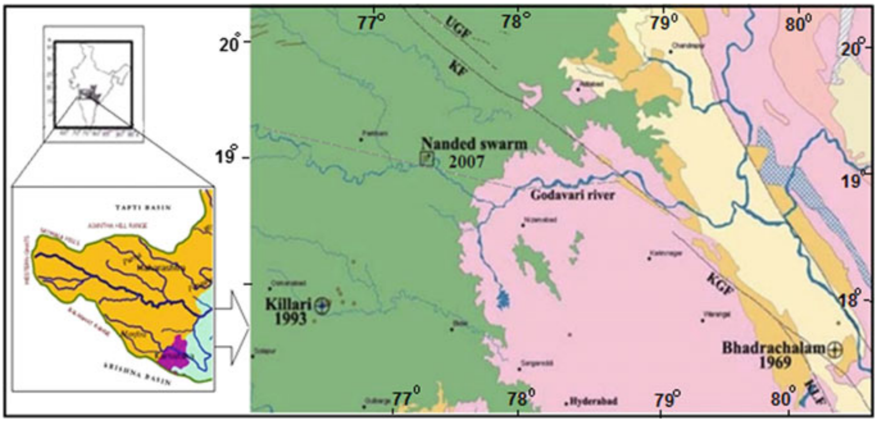

Fig. 3 Lineament and tectonic map of *Godavari basin* and south-western part of the Deccan Volcanic Province (adapted from Geological Survey of India). *KF* Kadam Fault; *UGF* Upper Godavari Fault; *KGF* Kinnerasani Godavari Fault; *KLF* Kolleru Lake Fault. Locations of *Bhadrachalam* earthquake (1969), *Killari* earthquake (1993) and *Nanded swarm* (2007) are shown (Modified after Srinagesh et al. 2012)

Srinagesh et al. (2012) have carried out microseismic study in Nanded area and suggested that the recent seismic activity is related to thrusting along a NW–SE fault lineament that coincides with a stream (Urvashi Ghat Stream) that joins the River Godavari to the south of Nanded city. The length of this newly reported lineament is about 3.5 km. Until recently, there was no detailed documentation of deformation structures in the Deccan Traps of Nanded region. Kaplay et al. (2013, 2014) carried out structural mapping in and around Nanded area and reported brittle deformation structures in the form of thrust in the Deccan basalts of microseismically active Nanded (Maharashtra), which is in the vicinity of NW–SE lineament, viz. Urvashi Ghat Lineament.

Kailasam (1975) on the basis of Bouguer gravity anomalies recognised the zones of uplift in Nasik and Sangola areas; while Power (1981) ascribed the characteristic influence of lineament pattern on regional upliftment of DBP. Leroy et al. (2008) concluded that volcanic margins of the western Indian fringe are regarded as to have 2–3 times higher uplift than the non-volcanic margins because of the breakup and rifting. In addition to this, an adjustment in relation to denudational isostatic balance and the resultant activation of faults and fractures are discussed as the main causative reasons of infrequent seismic activity in DBP over the past few decades (Mahadevan and Subbarao 1999; Widdowson and Mitchell 1999). It has been elucidated by Widdowson (1997) and Sheth (2007) that the formation of early Tertiary high-level laterites at the elevation (>1000 m ASL) in DBP is well thought out as a strong confirmation of post-Deccan uplift of the area.

4 Basin Climatic Characteristics

1. **Rainfall**

The Godavari basin gets the main portion of its rainfall for the period of the south-west monsoon. Other than south-west monsoon season, there are no well-defined and well-extended rainy seasons in the area. Rains other than south-west monsoon are about 16% of total annual rainfall in the basin.

The months of January and February are completely dry and the rainfall through these two months is generally <15 mm. But in next three months, i.e. in March to May, the rainfall varies from 20 to 50 mm in the majority areas of the basin (India-WRIS 2011).

2. **Temperature**

The Godavari basin belongs to tropical climate, in which the mean annual temperature in the areas of Western Ghats is about 24 °C and gradually raises towards the east and reaches a maximum of 29.4 °C on the east coast. In the month of January, which is a month of winter, the mean daily minimum temperature increases from west to east, i.e., from 15 °C on the Western Ghats to around 18 °C on the eastern coast, while the mean daily maximum temperature is >30 °C in the western part of the basin and it is to some extent less than 30 °C in the east (India-WRIS 2011).

3. **Relative Humidity**

South-west monsoon is the season in which the relative humidity is generally greater. After the departure of the monsoon season, the humidity steadily decreases and during summer the air becomes dry. The weather normally remains dried up for seven months (from November to May). The maximum relative humidity is normally observed in the months of July–August and minimum from April–May. The highest relative humidity in the basin is observed between 60 and 89%; the average value is 83.3%. The minimum relative humidity varies from 15 to 29.5%, with an average of 22% (India-WRIS 2011).

4. **Wind Speed**

Wind speed is normally low to medium, but ever-increasing speeds are observed in summer and at some stages in monsoon. During south-west monsoon, the wind blows predominantly from south-west to north-west. In post-monsoon time and during cold period, wind trend is from north to north-east. The wind blow during summer season is mainly in the directions of west and north. The maximum wind speed in Godavari basin varies from 10.6 to 22.5 kmph, with average speed 14.7 kmph. The minimum speed noted in the area range between 1.3 and 5 kmph with the average speed of wind is 3.2 kmph (India-WRIS 2011).

5 Geomorphology

The Godavari basin is more or less triangular in outline and the main river runs at the base of the triangle (Fig. 1). The whole Godavari basin mostly made up of undulating topography with series of ridges and valleys intermingled with low hill ranges and plateaus. The level or nearly flat areas in the basin are scanty excluding the delta flats. The western boundary of the basin is marked by the lofty Sahyadri Ranges of Western Ghats, while in the internal region of the basin there is occurrence of plateau along with numerous valleys sloping commonly towards east. The eastern margins of the basin are dominated by the Eastern Ghats. The northern frontier of the basin consists of plateaus of changing elevations. The southern margin of the basin consists of wide stretch of plain areas, scattered by hill ranges.

5.1 Major Tributaries

The major tributaries joining the Godavari are as follows: (1) Pravara, (2) Purna, (3) Sindphana, (4) Manjra, (5) Maner, (6) Pranhita, (7) Penganga, (8) Wardha, (9) Wainganga, (10) Indravathi and (11) Sabari. The Godavari basin occupied total area of 312,813 km^2, out of which Maharashtra (152,199 km^2), Karnataka (4406 km^2), Andhra Pradesh (73,201 km^2), Madhya Pradesh (26,168 km^2), Chhattisgarh (39,087 km^2) and Orissa (17,752 km^2) (India-WRIS 2011).

The River Pranhita is the largest tributary of the Godavari River covering 34.87% of the basin area. The Pravara, Sindphana, Manjira and Maner rivers are confluence of Godavari from right side, i.e., south tributaries occupying about 16.14% basin area, while the rivers Purna, Pranhita, Indravathi and Sabari are joining Godavari River from northern side, i.e., left bank and covers nearly 59.70% of the total area of the basin. The left out part of Godavari River marks the remaining 24.16% of the basin. The details of the length, elevation of the source area of the river, catchment area and various tributaries represented in Table 1.

5.2 Drainage Pattern

In the river basin, there is development of rectangular drainage patterns but within the basin the regional dendritic drainage pattern is developed. These features are observed in source region of the eastward-flowing Godavari River. Meandering channels are often followed downstream by rectilinear channels, indicating that the stream channel has entered into a structurally controlled sector, from homogeneous weathering bedrock. Abrupt and sharp-angled deflections of the linear stream channels and obtuse-angled junctions of the tributaries to the main channel are also observed at many locations along the main river. The valleys in the upland region are with broad channels, flat bottoms and steep-sided valley walls at edge of the plateau. These valleys suddenly become narrower further downstream and develop narrow linear gorges. Such sharp incision of the bedrock basalt in the downstream gorges indicates not only the change in the base level of erosion but also a strong structural control on the drainage development (Dole et al. 2002).

The Sahyadri Mountains of the Western Ghats forms the western margin of the basin having an elevation ranging from 600 to 2100 m. It receives the heaviest rainfall, and there is moistened climate in this part of the basin. About 50–60 km east of the Sahyadri Ghats the area is sparsely vegetated along with undulatory plains of the Deccan traps, having dry climate. The central part of the basin is largely covered by plateau with the elevations ranging from 300 to 600 m and the slope is towards east. The eastern margin of the basin comprising Eastern Ghats is discontinuous and not continuous like that of the Sahyadris. The Eastern Ghats rise from the plains of East Godavari and Visakhapatnam areas to nearly level areas of Jeypore. The northern edge of the basin contains a series of plateaus of changing elevation from 600 to 1200 m. These areas are subjected to the effect of denudation for years together. The southern area is occupied by the great stretches of plain having an elevation of about 300 m along with hills, some bare and rocky undulations covered with scanty forests, jungles and open scrubs. The area of Godavari delta contains the extensive belt of fluvial alluvial deposits formed at the mouth of the river. The progression of silting at the mouth of the river is still going on and the delta is steadily extending into the sea.

5.3 Channel Pattern

The western upland region of the Deccan Plateau is the source area for the eastward-flowing River Godavari and its tributaries including Pravara, Girija, Purna Sindphana, Manjra, Painganga, etc., draining the Deccan plateau. Most of the geomorphic features observed in the Deccan plateau region have been attributed to fluvial erosion by the eastward-flowing drainage system (Dikshit 1970). The development of deep valleys and canyons in the upland area is attributed to a greater relative uplift in the Nasik and surrounding area (Kale 2000). The most significant feature of the upland area at the source region of Godavari and other rivers is the anomalously broad valleys even on the edge of the Western Ghat Escarpment (Kale and Shejwalkar 2008).

The sediment study in Godavari valley in source region is found to be of 2–3 m thickness and comprises of mainly coarse-grained deposits unconformably resting on the rocky platform occurring 3–20 m above the present bed of the river. These sediments are composed of rounded to sub-rounded pebbles and cobbles of basalt, chalcedony, jasper, agate, chert and quartz placed in a matrix of granular sand and silt illustrating cross-bedding and local inverse grading structures. The cross sections along Godavari River at two places, i.e. near Paithan (Aurangabad district) and Thugaon (Nanded district) to illustrate the terrace characteristic in upper Godavari (Fig. 4a, b).

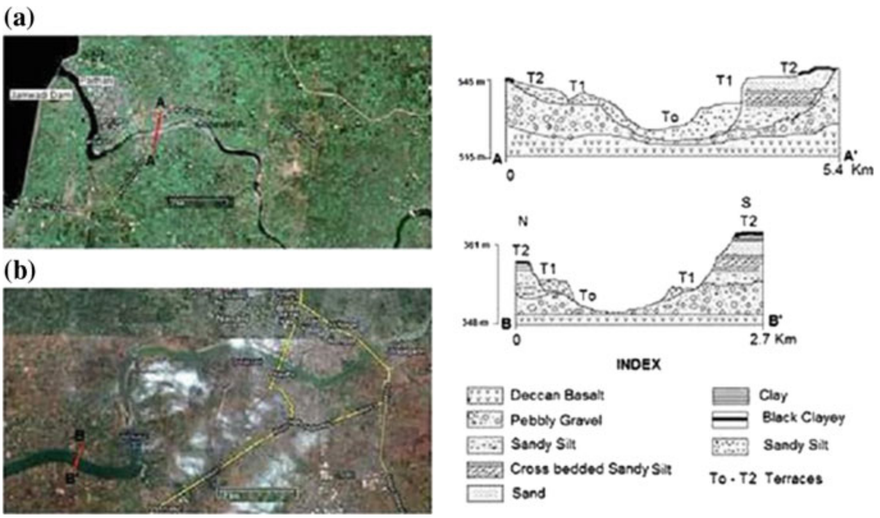

Fig. 4 Cross section along Godavari river at **a** Paithan (in Aurangabad district) at A-A and **b** Thugaon (in Nanded district) at B-B

The sediments of the Godavari basin source region to middle reaches are composite in character and might have resulted from the vertical piling and amalgamation of low-sinuosity channels consisting of thick bedded gravels. This indicates that the low-sinuosity rivers are braided (Kale 1988; Rajaguru et al. 1993). The occurrence of large amount of cobbles in these rivers points out that these rivers are of high energy with broad shallow channel and prevailing bed load transportation.

5.4 Valley Width and Channel Width

Kale and Rajaguru (1988) identified incised bedrock meanders and sequence of knick points at the gorge head occur in the Mandvi, Pravara and its tributaries Mula–Kas rivers, while Kale and Shejwalkar (2008) reported from the Malshej Ghat. Fascinatingly, the highest mountain (Kalsubai Peak; 1646 m ASL) and the deepest embayment in the Western Ghat are also observed in the western uplands. The Pravara River and its tributaries are dominated by thickest deposits of Quaternary in the DBP. Matmon et al. (1999) elucidated incised or entrenched meanders and knick points that are common phenomenon in uplifted plateaux around the world, and therefore, these features are considered as markers of regional or tectonic uplift. But in case of rivers from upland Western Ghats especially rivers Godavari and Darna, it is found that these rivers are exceptionally wide even though belonging to upland areas (Kale and Shejwalkar 2008) and no sign of deeply incised bedrock channels. This may point out that the incised meanders and knick may not always form by uplift and there may be different factors that responsible for their development, e.g. erosional disequilibrium between river systems and upstream migration (Hack 1973). Another reason proposed is, these may be formed by local or block uplifts.

The knick points in the form of waterfalls and potholes occur along Godavari River, e.g. Gangapur (Fig. 5a) and Puntamba (Fig. 5b), and the Pravara River at Randha Fall (Fig. 5c), similar kinks are also found at the Kas River near Bote and on the Mula River near Mandvi (Kale and Shejwalkar 2008).

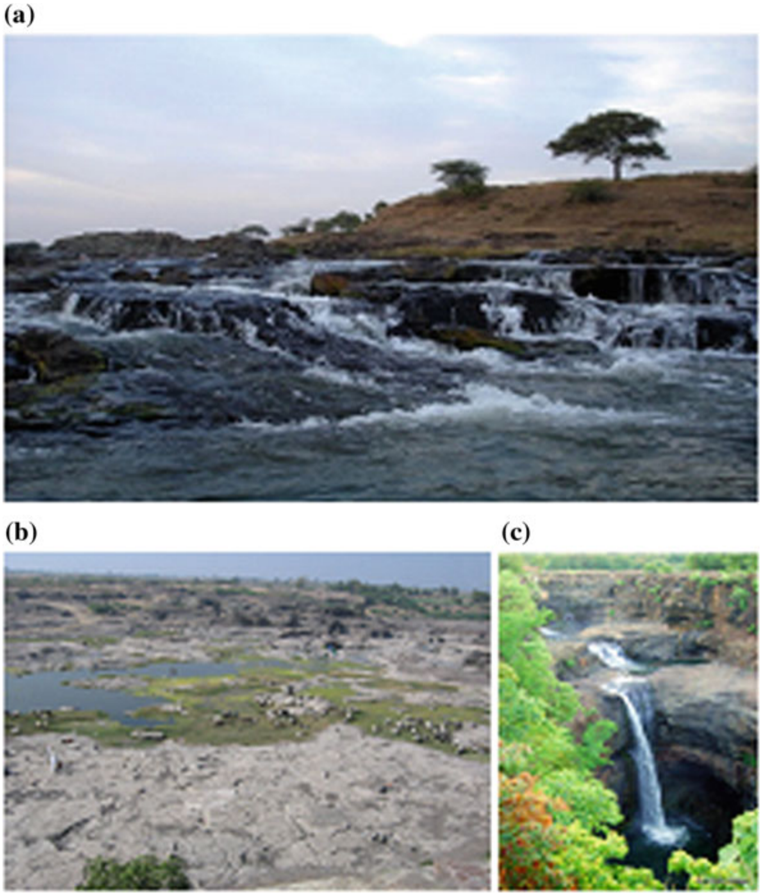

Fig. 5 **a** Kink on Godavari river at Gangapur in, Nasik district **b** Kink on Godavari river at Puntamba in Nasik district and **c** Randha fall on the Pravara river

6 Impact of Climate

Semi-arid regions of lower latitudes have strong imprints of humid tropical climate of the Neogene (Rajaguru et al. 1993). In semi-arid areas, it is observed that fluvial systems are prone to wide fluctuation in discharge. Stoddart (1969) determined the fluvial system and processes are strongly connected with the morphogenetic areas. River channels are generally classified as meandering or non-meandering or bed load or wash load dominant (Schumm 1977). The semi-arid rivers are generally composite in nature for the reason that the rivers are subjected to noticeable fluctuation in water and sediment discharge (Baker and Kochel 1988; Rajaguru et al. 1993; Kale et al. 1994).

The coarseness of sediment in semi-arid rivers is accountable for a lesser amount of stability and more mobility of sediments (Rajaguru and Kale 1985; Rajaguru et al. 1993). Because of this, the channels are unstable and dynamic, which are fascinated by regular channel shifting. In addition to this, the semi-arid rivers react fast to the changes in the hydraulic regime because of the high rate of movement of coarse sediments. The characters of sediments observed in the Godavari River illustrate the depositional environment of fluvial origin. The sediments in the upper reaches of the river consist of rounded to sub-rounded pebbles and cobbles of basalt along with varieties of quartz and zeolites occur in the granular sand and silt matrix. The sediments in lower reaches of Godavari are medium to fine grade of sandy silt and silty clay dimensions.

The sediments of the Godavari River found in the present channel deposits are sandy pebbly in nature and coarser, while the older alluvial deposits of Upper Pleistocene age are comparatively finer. This observation revealed that the rivers in the final phase of Pleistocene are comparatively of low competency. The erosional phase is related to the warm and wet climates, and the occurrence of depositional features is connected to cold and dry periods indicating the climatic control on evolution of the basin.

7 Channel Bar Deposits

Channel bars are defined as elevated masses depositional activity within channels that may be partly exposed through the stage when there is less or reduced level of the water in the river (Miall 1981; Bridge 1985; Roe and Hermansen 1993). Channel bars are broadly of two types (i) a simple bed form (Collinson 1970; Smith 1971) and (ii) a great periodic to quasi-periodic ‘macroform’ with composite history of erosion and deposition (Cant and Walker 1978; Crowley 1983). Walker and Cant (1984) classified bars of various types such as individual bed forms (two-dimensional or three-dimensional), small 'unit' bars, bar complexes, or sandflats and mature vegetated islands.

Miall (1981) presented classification of channel bars comprising of three groups:

1. Gravelly, planar or massive bedded bars;
2. Sandy, simple fore set bars; and
3. Compound bars of sand or gravel.

Identification of the earlier two groups is easy, but recognising compound bars needs restoration of the palaeomorphology of the same and requires sideward tracing of strata and quantifying the palaeocurrent pattern of structures (Bluck 1976, 1979). The 'bars' explained below are mainly of compound types.

Sediment exposure indictors:

1. The cross-bedding and current bedding structures form on the front of the depositional mounds, i.e. channel bars, which indicate accumulation of bed;
2. Scoop-shaped bounding surfaces and sets of planar cross-bedding structures are thought to be formed by stagnant water sequences;
3. The channel bar successions indicate the variable flow, flow convergence in the leeward side of the bars/bed outline and dissection of the bar tops;
4. The channels have less sinuosity, and bars are developed in the mid-part of channels;
5. Studies indicate that bar deposits can have height ranging from 5 to 10 m, e.g., Jamulbet in Godavari River (Fig. 6).

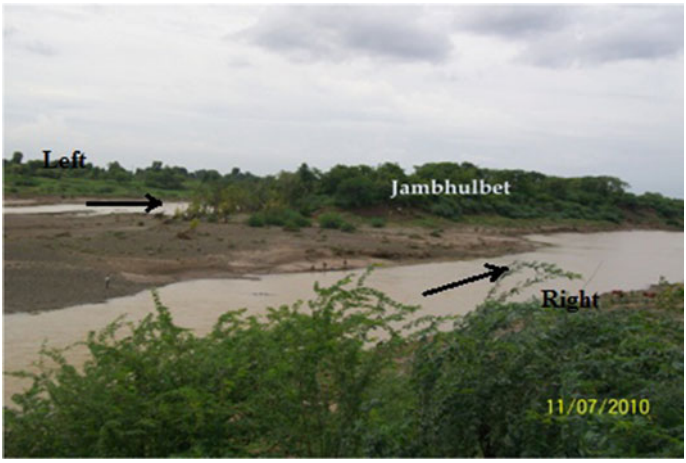

Fig. 6 Field view of the mid-channel bar deposit along Godavari river at island of Jamulbet in Palam Tahsil, Parbhani district

8 Socio-economic Importance

8.1 Important Cities Located at Its Bank

- *Trimbakeshwar*—It is famous for Jyotirlinga and very old temple of Lord Shiva.
- *Nashik*—Famous for Sinhastha Kumbh Mela along Godavari.
- *Paithan*—Famous for Saint Eknath's resident place, Jayakwadi dam and beautiful garden named as Saint Dnyaneshwar Uddyan.
- *Nanded*—Takht Hazur Sahib of Sikh Guru Shri Guru Gobind singhji.
- *Basar*—Sri Gyana Saraswati temple in Adilabad district, Telangana.
- *Bhadrachalam*—Lord Rama Temple.
- *Dharmapuri* (Telangana)—Temple of Lord Narasimha.
- *Kaleshwaram* (Sironcha)—Sri Kaleshwara Mukhteshwara Swamy Temple at border of Telangana and Maharashtra.
- *Konaseema*—Picturesque delta of Godavari River.
- *Rajahmundry*—A town known for birthplace of Telugu language.

8.2 Irrigation

The benefits of irrigation are the availability of water, increase in agriculture and raise of groundwater level. The increase in this groundwater level resulting from development of backwater areas, use of recent irrigation practices and enhancement in farm-watering techniques, the Maharashtra Irrigation Commission (1999) has envisaged the potential probable boost in irrigation in the basin areas.

Table 2 List of dams with their specifications in Godavari river basin

Sr. No.	Name of the dam/project	River	Location	Storage capacity Mcum	Purpose of project
1	Mula major project	Mula	Baragaon Nandur	28.32	Irrigation
2	Mandhol medium project	Mula	Karjule Hariya	8.12	Irrigation
3	Bhandardara major project	Pravara	Bhandardara	434.64	Hydroelectric
4	Nilwande major project	Pravara	Nilwande	351.77	Irrigation
5	Adhala medium project	Pravara	Deothan	38.73	Irrigation
6	Bhojapur medium project	Pravara	Sonewadi	10.70	Irrigation

(continued)

Table 2 (continued)

Sr. No.	Name of the dam/project	River	Location	Storage capacity Mcum	Purpose of project
7	Gangapur major project	Godavari	Gangapur	203.88	Irrigation
8	Kashyapi medium project	Tributary of Godavari	Dhandegaon	165.96	Irrigation
9	Gautami medium project	Godavari	Andharwadi	54.68	Irrigation
10	Kikwi medium project	Godavari	Bramhawade Pimpri	60.02	Irrigation
11	Bham medium project	Tributary of Darna	Kaluste	8.78	Irrigation
12	Bhavali medium	Darna	Bhavali	18.64	Irrigation
13	Waki medium	Darna	Kurnoli	12.85	Irrigation
14	Darna major project	Darna	Nandur Madhameshwar	219.82	Irrigation
15	Mukane medium project	Darna	Mukane	102.46	Irrigation
16	Kadwa major project	Tributary of Darna	Pimpalgaon Dukra	80.70	Irrigation
17	Waldevi medium project	Waldevi	Pimplad	32.09	Irrigation
18	Alandi medium project	Alandi River	Sakotiwadi (Davi)	40.67	Irrigation
19	Palkhed complex of 6 medium projects	Kaadava a tributary	Dindori tahsil of Nasik dist.	456.52	Irrigation
20	Jayakwadi major project	Godavari	Paithan	2618.59	Irrigation Hydroelectric
21	Khadakpurna major project	Khadakpurna	Buldhana dist.	259.0	Irrigation
22	Yeldari major project	Purna	Jintur	934.31	Hydroelectric
23	Siddeshwar major project	Purna	Aundha	250.84	Irrigation
24	Majalgaon major project	Sindphana	Majalgaon	3113.00	Irrigation Hydroelectric
25	Kundalika medium projects	Kundalika	Majalgaon	463.50	Irrigation
26	Sindphana medium	Sindphana	Patoda	126.00	Irrigation
27	Masooli major project	Masooli	Isad, Gangakhed	340.80	Irrigation
28	Upper Dudhna medium project	Dudhna	Jalocala	150.00	Irrigation
29	Sakla medium projects	Dudhana	Paranda	144.20	Irrigation

(continued)

Table 2 (continued)

Sr. No.	Name of the dam/project	River	Location	Storage capacity Mcum	Purpose of project
30	Galhati medium projects	Galhati	Ambad	138.40	Irrigation
31	Terna medium projects	Terna	Osmanabad	229.10	Irrigation
32	Pentakali	Penganga	Mehkar	673.55	Irrigation
33	Vishnupuri projects	Godavari	Nanded	80.79	Irrigation
34	Polavaram major project	Godavari	Polavaram	1940.00	Irrigation
35	Nizam Sagar major project	Manjara	Nizamabad	580.00	Irrigation
36	Ramagundam project	Godavari	Karimnagar	–	Hydroelectric
37	Dummugudem project	Godavari	Bhadrachalam Khammam		Irrigation hydroelectric
38	Shriram Sagar project	Godavari	Pochampadu in Nizambad	8066	Irrigation
39	Dowleswaram Barrage	Godavari	Dowleswaram in East Godavari	–	Irrigation

The catchment area of Godavari River up to Paithan dam is designated as Upper Godavari (up to Paithan dam) sub-basin. Total geographical area of this sub-basin is 21,774 km^2. Mula, Pravara, Kadwa, Darna, Kaadava, Dodni, Shivna are main tributaries in this sub-basin upstream of Paithan dam (Table 2).

The Upper Godavari sub-basin includes the entire catchment of the Godavari River from its source to Paithan dam including the catchment areas of the Pravara River, Mula River and that of all other tributaries which falls into the Godavari River in this reach. The Paithan dam is located exactly at the border of the sub-basin. Large number of major, medium, minor irrigation projects, *Kolhapuri Type* (K.T.) weirs and local sector schemes are constructed in this sub-basin. The prominent reservoir systems/complexes are Mula complex, Pravara complex, Godavari–Darna complex, Gangapur complex, Palkhed complex, remaining up to Paithan dam and Paithan dam proper (Table 2).

9 Conclusions

The second largest river in the country is Godavari, which is the largest in South India, occupying approximately 10% of the area of India. It originates in Western Ghats, flows through the Deccan basalts from west to east and further flows for a general south-eastern direction and joins the Bay of Bengal at approximately 97 km south of Rajahmundry in Andhra Pradesh.

Geologically, rocks occurring in the entire basin are Deccan Trap basalts, peninsular granites, Puranas, Dharwars and Gondwanas. The lineament cuts across the Deccan lava flows and is characterised by the Quaternary tectonic movements as indicated by anomalous behaviour of the river, raised terraces and thick pile of alluvium in the source region up to Nasik in higher reach.

The basin area is characterised by the development of rectangular drainage pattern and the regional dendritic drainage pattern is also common. The development of deep valleys and canyons in the upland area is attributed to a greater relative uplift in the Nasik and surrounding area, but the most remarkable feature of the upland area is the anomalously broad valleys in the source region of the Godavari River.

These features indicate some neotectonic activity in the area. However, the spatial variation of the neotectonic activity along the Godavari River points out that the general trend of the activity is increasing from west to east following the WNW–ESE, E–W and NW–SE lineaments.

The depositional environment of coarse gravel sediment in bottom beds of Godavari valley, e.g. at Thugaon, indicates that the streams are of relatively high energy with prevalent bed load transport; however, the formation of fine clay and silt in the upper layers reveal the streams are of lower gradient, and there is fluctuation of climatic conditions. Deposition in river channels is in the form of channel bar deposits with less sinuosity of channels, and the bar-forming deposits have height of about 5–10 m, e.g. Jamulbet, Someshwar, in the Godavari river channel.

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Krishna River Basin

Anirban Das and Meet Panchal

1 Introduction

The interconnection between river systems and human civilization is known since ages. Human settlements are established along rivers primarily because of multitude of benefits provided by rivers to humans. Natural and anthropogenic perturbations to parameters characteristics of a river (basin) have tremendous implications on humans. Because of the paramount importance of river systems on humans, they have been studied in details all over the World. In the Indian context, though Himalayan rivers carry more global significance than any other river system of India, however, the role of peninsular rivers also bears considerable significance. *Concerns have been raised on the closing of one of the important peninsular rivers, viz. the Krishna river*. Estimates show that discharge from the Krishna into the ocean had decreased rapidly from 1960 to 2003 due to irrigation expansion, even though there were no significant changes in the annual rainfall. Data show that this closure was not limited only to the downstream sections but was observed also in the in upstream tributaries. Such basin closure has resulted in interstate disputes over water. In such situation management of water resources becomes one of the critical issues, and which requires basin-scale modelling on assessment of water resources. Therefore, a better understanding of geomorphology, climate, rainfall, vegetation and hydrological resources is crucial to understanding of the river basin, and hence, the overall impact the river system has on society and vice versa.

In this chapter, the details about one of the largest rivers of the southern peninsula, the Krishna, are discussed. The details contained in the ensuing sections

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are compilation of the researches, field works, surveys and reports written, on the Krishna River Basin (KRB). Most importantly are those of the works by the International Water Management Institute (IWMI; Biggs et al. 2007), and reports/data by Central Pollution Control Board (CPCB 1990; and in their website, http://www.cpcb.nic.in).

1.1 Krishna River Basin

The Krishna is one of the major rivers of peninsular India along with the Godavari and the Kaveri (Cauvery) (Fig. 1). The Krishna originates as a small stream in the Western Ghat Mountains, near Mahabaleshwar (13°N, 73.5°E; about 64 km of the Arabian sea coast) at an elevation of ~1340 m (asl). It traverses eastwards ~25 km through the rocky terrains of the Deccan Traps, from Mahabaleshwar to the town of Wai. It then flows eastwards and finally drains into the Bay of Bengal covering a total length of ~1400 km across the states of Maharashtra, Karnataka and Andhra Pradesh. The basin is conjoined by the Godavari river basin in north, the Pennar and Cauvery/Kaveri river basins in south and is bordered by a number of small west-flowing basins of the Konkan strip originating from the Western Ghats. The basin is situated between east longitudes 73° 21′–81° 09′ and north latitudes 13° 07′–19° 25′ in the Deccan Plateau.

In terms of size, the Krishna river basin is India's fifth largest river basin covering an area of $\sim 2.6 \times 10^5$ km^2, of which 27, 44 and 29% lie in the states of Maharashtra, Karnataka and Andhra Pradesh, respectively (Fig. 2). The overall area is ~8% of total geographical area of the country. The cultivable area in the basin is about 203,000 km^2, which is 78% of the basin and 10% of the total cultivable area

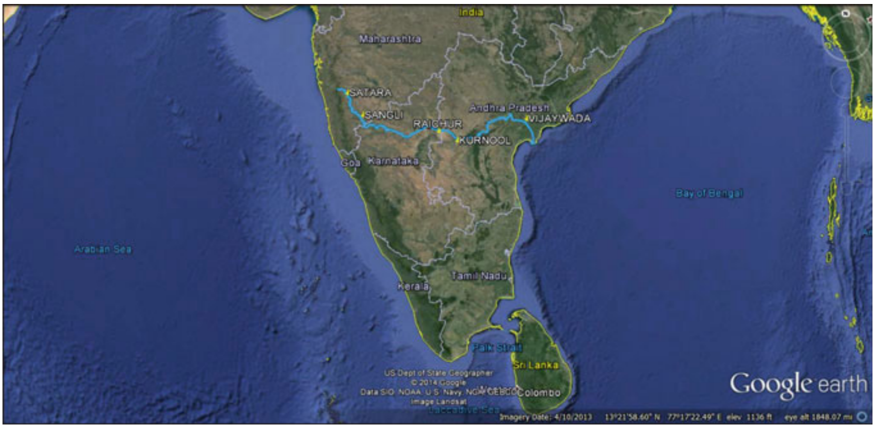

Fig. 1 Aerial view of the Krishna river and along side cities (*Source* Google Earth)

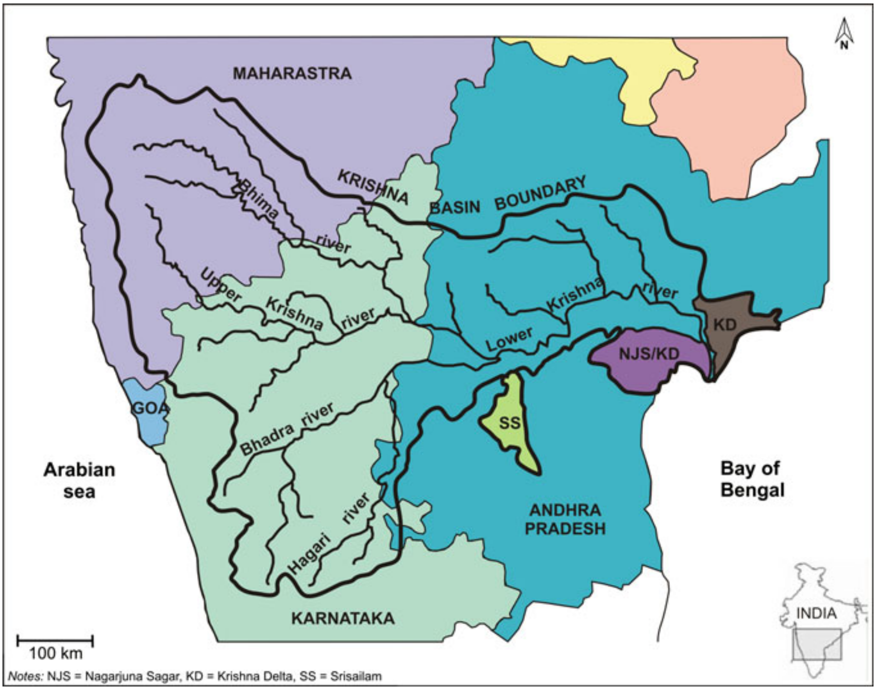

Fig. 2 Topographical map of the Krishna river basin with command areas outside the topographical boundary named as NJS/KD, KD and SS (modified from IWMI research report 111)

of the country. The delta of the river is one of the most fertile regions in the world. During its migration, the river passes through various geomorphological features and landforms, e.g. hilly terrain, plateau and plains.

1.2 Tributaries

There are thirteen major tributaries of the Krishna along its journey until mixing with the Bay of Bengal. Its first tributary, the Koyna meets the Krishna near Karad, has a drainage area of 2036 km^2, length of ~120 km, and has an elevation of ~4719 m at the source. Subsequently, the Varna and the Panchganga join the Krishna at Sangli and Kurundwad, respectively. Dudhganga joins the Krishna mainstream at a distance of ~310 km from its origin. About 201 km from the confluence of the Dudhganga-Krishna, Ghataprabha joins the river. The Bhima, largest of the tributaries of the Krishna, originates in the hills of Bhimashankar near a temple, little north of Pune. The river traverses in a south-easterly direction and joins the Krishna at Raichur (in Karnataka), at a distance of ~860 km from its origin.

The Bhima river has a drainage area of 76,614 km^2 (Rao 1975), and the water discharge of the Bhima river at Takli (in the Deccan Traps) is 7.2×10^{12} ℓ $year^{-1}$ (CPCB 1990).

1.3 Elevation

Most of the basin experiences low elevation, with ~50% of the areas under 550 m and ~90% of the areas under 750 m. The areas adjoining the Western Ghat Mountains reach up to elevation of 1900 m, whereas the plains towards the east lie at an elevation between 0 and 200 m (Biggs et al. 2007).

1.4 Geology

The lithology of the river basin in Maharashtra is almost entirely tholeiite basalts, with scattered alkaline/saline soils (Bhargava and Bhattacharjee 1982), laterites (Widdowson and Cox 1996) and calcareous tufas (Pawar et al. 1988). Downstream of Maharashtra, in the states of Karnataka and Andhra Pradesh, the Krishna basin includes granites, granitoids, green stones, schists, amphibolites and gneisses. In addition, patches of sedimentary rocks (clays, limestone, sandstone, etc.) and alluvium are also scattered in the lower and eastern parts of the basin.

1.5 Rainfall

The Indian subcontinent receives rainfall from the south-west monsoon originating in the Arabian Sea and the north-east monsoon from the Bay of Bengal. Rainout of atmospheric water/moisture during transport inland causes precipitation in the Krishna Basin, and it decreases with distance inland from both coasts. This decrease is most evident east of the Western Ghats, where precipitation decreases from over 2000–3000 mm to approximately 500–700 mm over a distance of 80 km (Gunnel 1997). The Western Ghat Mountains acts as a rain shadow region. Precipitation decreases more gradually from 850 to 1000 mm in the Krishna Delta in the east to 500–600 mm in the north-western part of the basin. The average rainfall in the basin is 840 mm, approximately 90% of which occurs during the monsoon from May to October. Figure 3 shows the typical rainfall variation in the Krishna basin (Biggs et al. 2007).

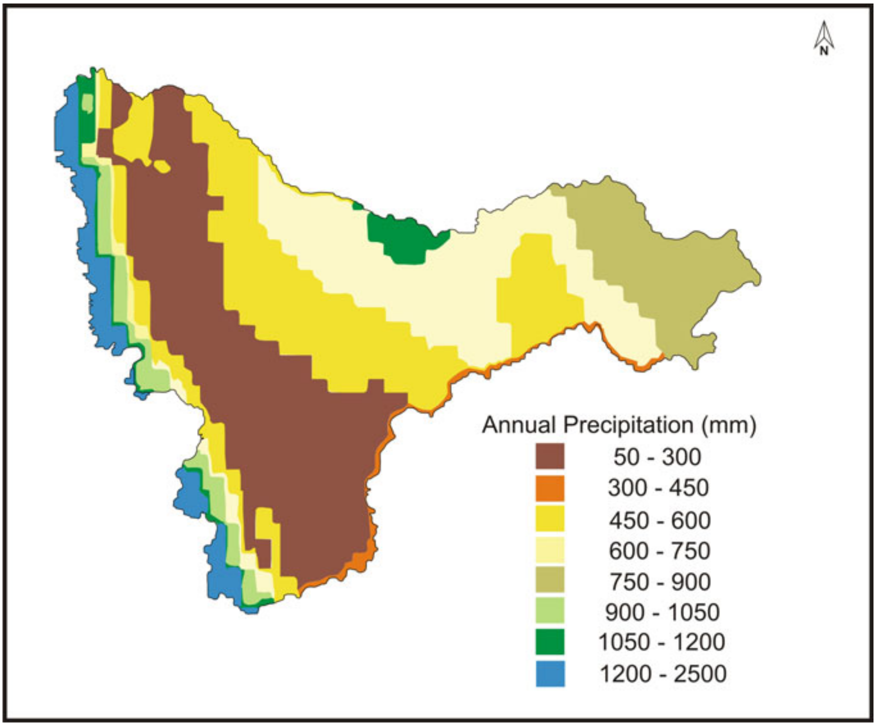

Fig. 3 Annual precipitation (mm) in the Krishna river basin (modified from IWMI research report 111)

1.6 Aridity Index

One of the parameters that characterize climate is the aridity index (AI) which is quantified as the ratio of mean annual precipitation divided by the mean potential evapotranspiration in the area. As per the recent classification (www.unep.org), AI values of 0.2–0.5 are classified as semi-arid whereas 0.5–0.65 fall in the category of dry subhumid. Most areas of the Krishna river basin typically fall in the semi-arid, dry and subhumid categories whereas some areas of the Western Ghats are humid (Biggs et al. 2007)

1.7 Surface and Groundwater Resources

The average annual surface water potential of the basin is assessed at 78,000 billion cubic metre (BCM), of which 78% is utilizable water. The storage capacity of the large reservoir is estimated to be ~42,900 MCM. The static groundwater/

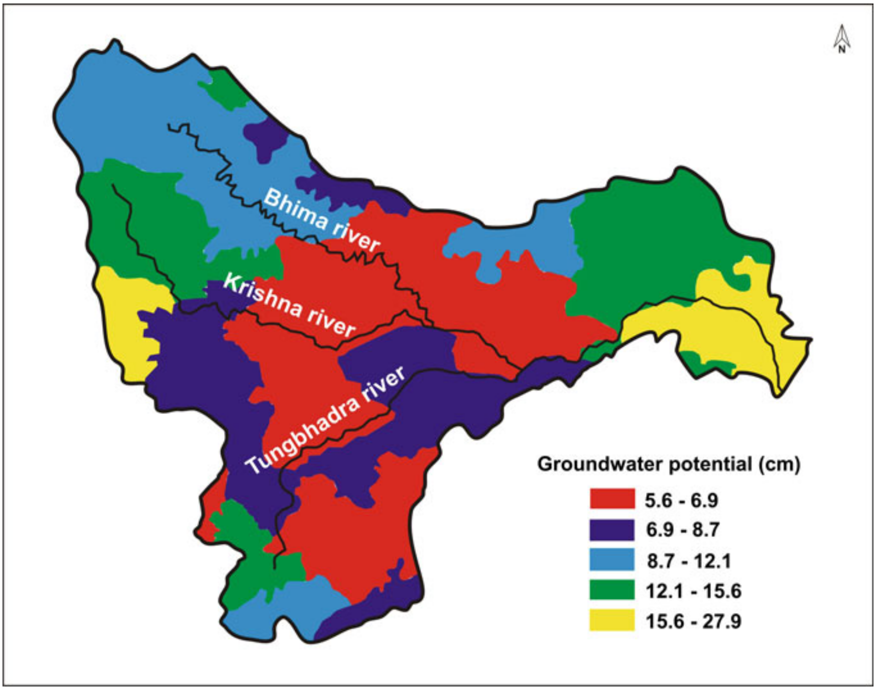

Fig. 4 Groundwater potential within the Krishna river basin (modified from IWMI research report 111)

replenishable groundwater resources for the Krishna river basin are estimated at 26.41 BCM. A map of the groundwater potential for the Krishna river basin is shown in Fig. 4.

1.8 Dams and Reservoirs

Management of river water has led to construction of dams. In case of the Krishna river, about 30 major and minor reservoirs have been constructed. These are Basava Sagar, Alamatti, Srisailam, Nagarjuna Sagar (Fig. 5), Prakasam Barrage, Jurala, Dhom, Narayanpur, Koyna, Warna, Tungabhadra, etc. Construction of dams/reservoirs/canals started as early in the sixteenth century by the Vijayanagara Empire on the Tungabhadra River in Karnataka and the Hussain Sagar in Hyderabad.

Fig. 5 Aerial view of Nagarjuna Sagar Dam built on the Krishna river (*Source* Google Earth)

1.9 Settlements

As is true with other river basins, Krishna river basin has also supported civilization and is home to 74 million habitants. The population density per km^2 is 287; population is more concentrated along the plateau and plains that mostly is dependent on agriculture for their livelihood. About 68% of the population lives in urban areas of the basin. The cities that are located in the bank of the Krishna river are Sangli, Satara and Karad in the Maharashtra; Bagalkot and Narayanpur in Karnataka; and Guntur, Kurnool, Krishna and Vijayawada in Andhra Pradesh (Biggs et al. 2007).

2 Geomorphological and Geochemical Studies

Geomorphological studies of the Krishna basin are limited. A few studies focus on the geomorphological parameters of very small catchments such as the Singnodi subwatershed in Raichur district, Karnataka (Karegoudar et al. 2006), and Nima-Wira watershed (Akbari et al. 2012). The upper and lower reaches of Singnodi watershed belong to third and fourth orders, respectively, with a dendritic pattern whereas the valley length, mainstream length and the drainage area are 15.3 km, 14.5 km and 42.25 km^2, respectively. Based on the data on bifurcation ratio (3.01–3.5), stream length ratio (1.22–1.36) and stream area ratio (2.43–2.62), the authors interpreted that the watershed has developed over a uniform geological structure. In the Nima-Wira watershed, where studies were carried out in the years of 2001 and 2009, Akbari et al. (2012) calculated several geomorphological parameters and concluded that during those eight years many stream got diminished.

Geomorphology of fluvial deposits was carried out in conjunction with archaeological, palaeontological and carbon-14 dating in the upper Krishna basin along with the Bhima and upper Godavari river basins (Rajguru and Kale 1985). In the upper part, the rivers have a dendritic pattern. The thickness of the alluvium varies from 10 to 40 m and the lateral extent of the alluvium does not exceed beyond 5 km. Based on timing of the events in the past, Rajguru and Kale (1985) inferred that these rivers were dominantly aggrading during the terminal Late Pleistocene ($\sim$40–11,000 ka) and incision predominated during the major part of Holocene. These fluvial activities were explained by the authors in terms of changes in the climate and not due to tectonics.

A detailed and systematic major ion study of the rivers draining the upper Krishna basin was undertaken with an objective to determine rates of chemical weathering rates and associated CO_2 consumption (Das et al. 2005); the sampling was mostly confined to the Deccan Traps. Chemical weathering rates (CWRs) calculated from the chemistry of rivers unaffected by major anthropogenic influences range from $\sim$3 to $\sim$60 t km^{-2} $year^{-1}$. Silicate weathering rates (SWR) in these rivers, calculated using Mg as an index, vary from $\sim$3 to $\sim$60 t km^{-2} $year^{-1}$ making up $\sim$95% of CWR; the silicate weathering rate of the Krishna at Alamatti is $\sim$14 t km^{-2} $year^{-1}$. The area-weighted average CO_2 consumption rate from silicate weathering in the Deccan Traps is 3.6×10^5 mol km^{-2} $year^{-1}$. The CO_2 drawdown by Deccan basalts is estimated to be $\sim 1.8 \times 10^{11}$ mol $year^{-1}$. This is $\sim$1.5% of CO_2 consumed by continental silicate weathering, $\sim$4 times higher than its fractional area of continental silicate exposures and reaffirms that basalts weather more rapidly and thus contribute to higher CO_2 drawdown. Comparison of the CWRs, SWR and CO_2 consumption of rivers analysed in this study from the south-west Deccan Traps is 2–4 times lower than those reported for the Narmada–Tapti–Wainganga (NTW) systems from the more northern region of Deccan. The SWR for the Deccan Traps derived in this study is comparable to that reported for the Ganga-Yamuna headwaters in the Himalayas. This suggests that weathering of granites/gneisses can be similar to those of basalts under “favourable” conditions of higher physical weathering and higher run-off.

Much earlier to the study by Das et al. (2005) and Ramesh and Subramanian (1988) had reported major ion composition of the Krishna river and a few of its major tributaries as a part of their work to determine fluxes of various elements transported by this river system to the Bay of Bengal. Their sampling was focused more on the larger tributaries and along the lower stretches of the Krishna, which predominantly drain Precambrian granites and metasediments. These results yield a chemical weathering rate of $\sim$41 t km^{-2} $year^{-1}$ for the entire basin, based on measurements at the mouth of the Krishna river at Vijayawada. This weathering rate includes basalts in the upper reaches and Archaean crystalline rocks in the lower reaches. Therefore, the data by Ramesh and Subramanian (1988) give a composite weathering rate for the Deccan Traps and the Archaean shield.

3 Socio-economic Importance

3.1 Agriculture and Aquaculture

Known from historical times, rivers have offered human with multitude of benefits. Little humans have done to the betterment of rivers compared to large amounts of socio-economic benefits they have extracted. Agriculture activities using rivers water (or reservoirs made by damming rivers) are possibly the largest benefit humans have acquired. The Krishna river basin, which encompasses the three states (Maharashtra, Karnataka and Andhra Pradesh), has diverse agriculture and crop patterns (Neena 1998). Soils in the basin are generally shallow in depth, and they belong to the type Entisols, Alfisols and Vertisols (black soils for cotton and sugarcane). The cultivation in the basin area includes rice, jowar, corn, sugarcane, millet, groundnut, grass-fodder and other horticultural crops (Fig. 6). The annual cropping cycle consists of the Kharif (June to October, monsoon season), the Rabi (November to March, the post-monsoon) and the dry season (April-May). According to the classification, the basin has five cropping regions: (1) rice grains and cash crops in the eastern basin which includes Krishna delta, Nagarjuna Sagar command areas and groundwater-irrigated ones; (2) grains, rice and sugar dominate

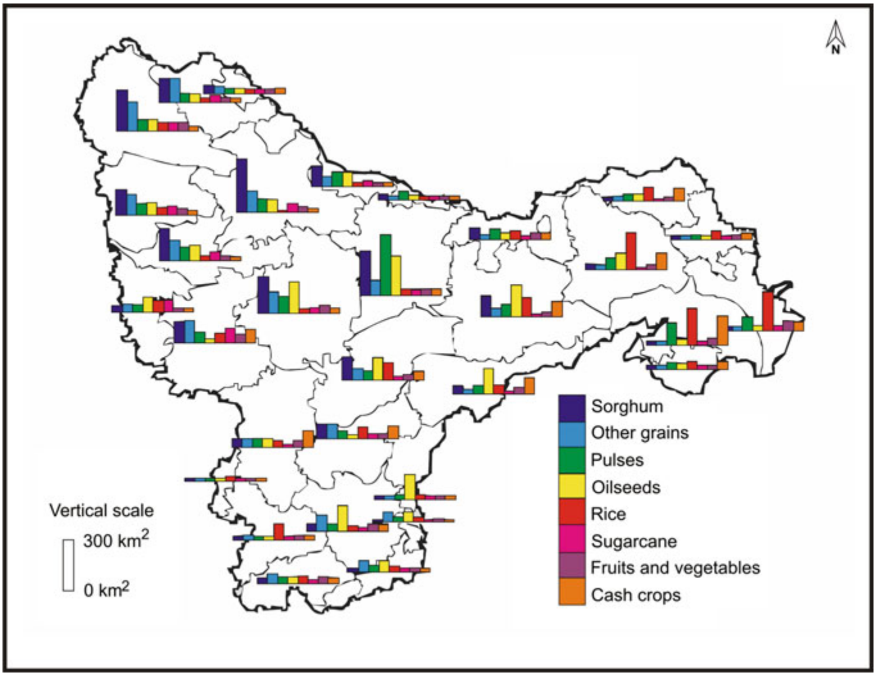

Fig. 6 Area of cultivation (district-wise) of major crops within the Krishna river basin (modified from IWMI research report 111)

the north-west; most of the rice and sugarcane are irrigated near the base of the Western Ghats; (3) grains, rice and oil seeds in the central and south-central areas of the Krishna river basin; (4) oilseed-grain in the south-west part; and (5) rainfed rice and cash crops in the Western Ghats. In addition to agriculture, aquaculture occurs in the delta at the boundary of the Krishna and Godavari Deltas.

3.2 Irrigation Projects

Projects are classified by the size of the area they irrigate, i.e. major (>10,000 ha), medium (2000–10,000 ha) and minor (<2000 ha). The first of the major irrigation project in the basin began with the Krishna Delta Project at Vijayawada in 1852, which was designed to irrigate $\sim 0.53 \times 10^6$ ha. In 1920, two reservoirs were established in Hyderabad for flood control and urban water supply. Projects for extensive irrigation and hydropower generation began in the 1950s with construction of several large reservoirs such as the Tungabhadra (1953), Nagarjuna Sagar (1974) and the Srisailam projects. Figure 7 shows different sources for

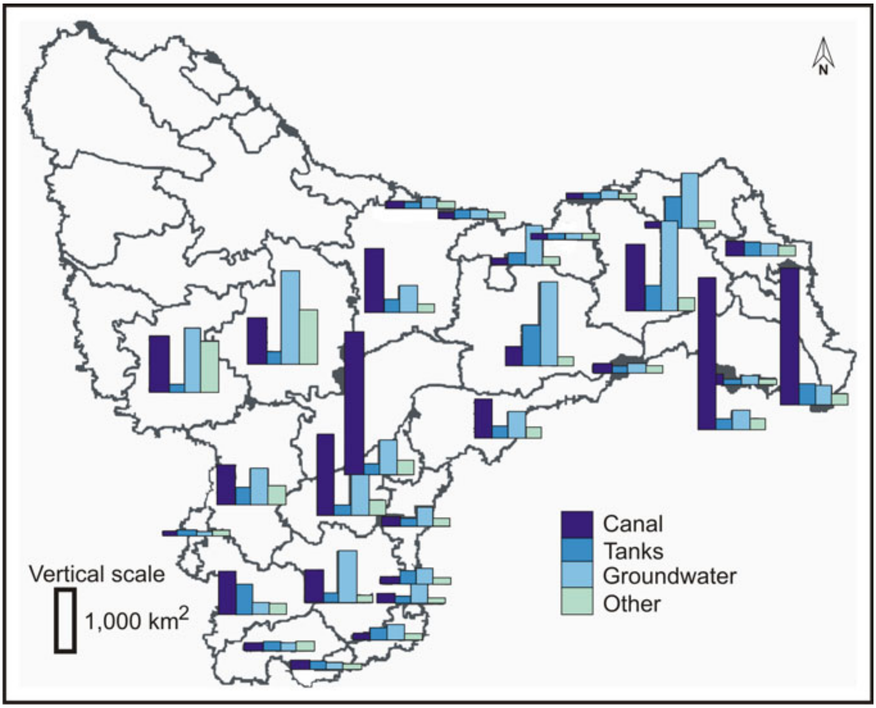

Fig. 7 Different irrigation sources in the Krishna river basin. Districts without bar chart have no data (modified from IWMI research report 111)

irrigation in the Krishna basin. Compilation of the data from Andhra Pradesh and Karnataka shows that irrigation by tanks is approximately ~11,000 km^2 similar to the area irrigated by groundwater.

3.3 Environmental Issues

Rapid population growth, urbanization coupled with depletion in water flow would impact any river basin as far as environment and water quality conditions are concerned. Sedimentation, in general, in the Krishna river is low compared to the Himalayan river as the geology, relief, tectonics and water discharges conditions are different. However, the Tungabhadra River has some issues with siltation compounded by iron and manganese mining (Shiva 1991). Soil salinity appears to be limited to command areas of Nagarjuna Sagar and some patches of the Bhima basin (Dwivedi et al. 1999; Das et al. 2005). The water quality problem in many rivers of the basin is due to effluent and wastewater from cities of Pune, Satara, Kolhapur, Hyderabad, Kurnool and Vijayawada. Groundwater in limited areas of the Bhima basin is affected by sugarcane industries (Pawar et al. 1997). River pollution has resulted in fish deaths (Kulkarni and Gupta 2001) and considerably impacted the ecosystem (Ensink et al. 2006). The biological oxygen demand in some of the rivers is high, for example, in Musi river downstream of Hyderabad (~50 mg/L) and in Bhima river downstream of Pune (~13 mg/L) (http://www.cpcb.nic.in). Some limited areas of the Krishna Delta are affected by seawater intrusion (Saxena et al. 2004). Mangroves occur in the Krishna Delta (Selvam 2003), and decreased flow of Krishna at Vijayawada has changed the mixture of fresh-to-saltwater ratio altering the mangrove community structures; however, detailed studies are lacking in these areas.

3.4 Floods

Floods are natural hazards mostly caused by unprecedented amounts of rainfall often in short duration. Sometimes release of water by dams also accounts for floods in the downstream catchment areas. Floods in Krishna river basin is related to high intensity of rainfall and/or releases of water from reservoirs in upper regions. Reason behind floods in the Krishna river basin is the improper width and depth that are unable to sustain high flow from upper catchment area which intern are due to obstructions within the flow route and siltation and heavy rain due to cyclones in the East Coast region especially in the Andhra Pradesh.

In the last ten years, three major flood events occurred during 2009, 2006 and 2005. The flood discharge recorded in the Prakasam Barrage was 1.10 million cusecs (1 cusec = 28.3 L per second) which was higher than the previous highest in 1903 (1.08 million cusecs). Within the river basin, some identified areas are flood prone such as neighbourhoods of Sangli (Maharashtra); a 60 km stretch from Audumber to Maharashtra–Karnataka border; below Bhima-Nira confluence to Pandharpur, Gopalpur and Takali; and in Karnataka, downstream areas of Alamatti and Narayanpur.

The floods of 2005 and 2006 brought major devastation. In 2005, about 1250 villages were inundated and 150 of them were fully submerged. The affected areas of southern Maharashtra and northern Karnataka include the districts of Kolhapur, Sangli, Solapur, Belgaum, Bijapur, Gulbarga and Raichur. It had destroyed crop and property worth $\sim$600 crore, standing crops of sugarcane, maize, turmeric, banana in about 10^5 ha were destroyed. During the floods of 2009, the floodwater resulted in damages to several districts of Andhra Pradesh such as Kurnool, Mehboobnagar, Guntur, Krishna and Nalgonda.

4 Conclusions

Major concerns are raised about the shrinkage of the basin (Biggs et al. 2007). During 1995–2005, water discharge by the Krishna river to the oceans was found to be significantly lower than the pre-irrigation discharge (1900–1960). The shrinkage was observed also in the upstream catchments of the basin. The basin shrinkage coupled to increasing demand of water has resulted in interstate disputes. Management of water resources is possibly the largest need for future sustainability. Researches need to focus on all aspects of hydrology. Efforts should be made to monitor the groundwater recharge especially during flooding season, and hence, a step closer towards conjunctive use of surface water and groundwater can be made. Researches should also focus on the following: (1) use of environmental isotopes in understanding the extent of groundwater–surface water interactions; (2) procuring long-term, high-resolution and reliable data on precipitation and evaporation and how they affect the affect the run-off, soil moisture, etc.; and (3) the use of GIS to extract information on geomorphological parameters that can help in understanding the hydrological behaviour of the basin.

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Cauvery River

S. Chidambaram, A.L. Ramanathan, R. Thilagavathi and N. Ganesh

1 Introduction

The Cauvery is one of the largest and great sacred Indian River. It is also known as Dakshin Ganga or Ganga of South. Talakaveri, Kodagu in Western Ghats, Karnataka, is the origin of the river which flows in south and east direction along Karnataka, Tamil Nadu, and Puducherry, through the Deccan plateau on south across the southeast lowlands, drains into the Bay of Bengal.

The Cauvery basin spreads an area of 81,155 km^2. Its lies between the coordinates of 10° 9′–13° 30′N latitude and 75° 27′–79° 54′E longitude (Fig. 1). The elevation is about 1276 amsl. Doddabetta (2637 m) is the most elevated point of the Cauvery basin. The river enters into the Bay of Bengal after flowing 800 km along SE direction, out of which 320, 416, and 64 km is in Karnataka, Tamil Nadu, and common border between Karnataka and Tamil Nadu, respectively. The basin has a rectangle shape, whose length is 360 km and breadth is 200 km. The state-wise distribution of the drainage area is 43,856 km^2 of Tamil Nadu, 34,273 km^2 of Karnataka, 2866 km^2 of Kerala, and 160 km^2 of Puducherry. It covers 24.7% geographic area of the country.

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2 Physiography

The river is surrounded by Western Ghats in west, Eastern Ghats in the east and south, and with the ridges which separate it from the Tungabhadra and Pennar basin in the north. On the basis of physiography, it has three divisions: the Western Ghats, Mysore Plateau, and Delta region. Topographic domains recognized here are two types: (i) the Mysore Plateau, on the western side, which has higher elevation and lesser relief and (ii) fluvio-deltaic plains on the eastern side (Fig. 2; Kale et al. 2014). Block Mountains, such as the Nilgiri, the Biligirirangan (BR), and the Mahadeswaramalai (MM) hill ranges (Fig. 2; Kale et al. 2014), and the Shevaroy hills of the Eastern Ghats, are found between these two topographic domains (Fig. 1).

3 Tributaries

There are 29 major tributaries flowing to this river (Table 1). The main tributaries contributing to Cauvery are the Harangi, Hemavati, Lakshmana Tirtha, Kabini, Suvarnavathi, Shimsha, Arkavati, Bhavani, Noyyal, and Amaravati. Severe tectonism represented by Arkavati, Chinnar, Dodda Halla, Thattai Halla, Palar, and Bhavani tributaries (Fig. 3; Kale et al. 2014).

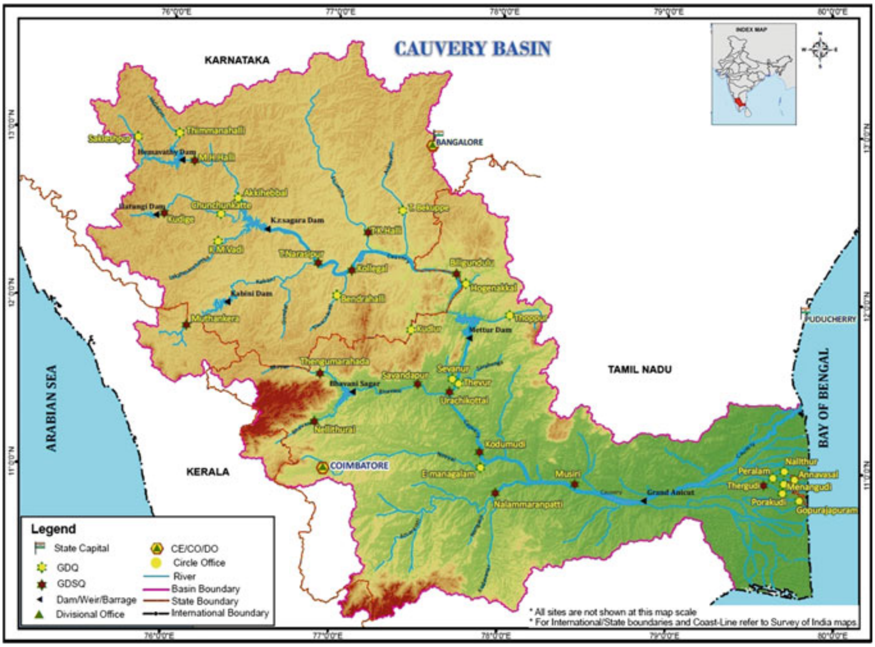

Fig. 1 Location map of the river Cauvery (not to scale) (after wris.nrsc.gov.in)

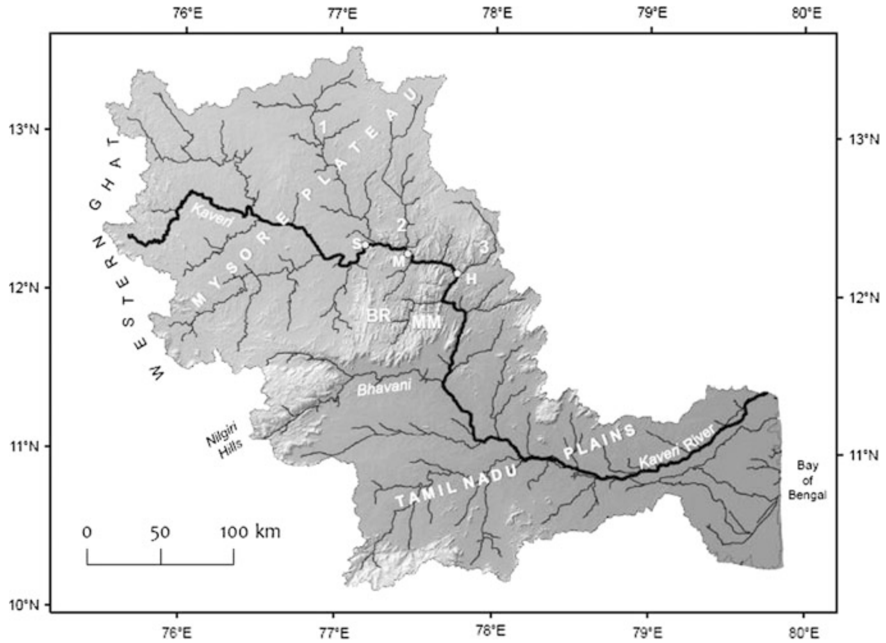

Fig. 2 Map of the Cauvery basin showing the significant physiographic features (after Kale et al. 2014) (*BR* Biligirirangan ranges; *MM* Mahadeswaramalai ranges; *S* Shivanasamudram falls; *M* Mekedatu; *H* Hogenakkal falls. *1* Shimsha river, *2* Arkavathi river, *3* Chinnar river). The figure also shows the distributaries of the river

Table 1 List of tributaries of the river Cauvery (Kale et al. 2014)

1	Dodda Halla	10	Suvarnavathy	19	G.A. Canal
2	Harangi	11	Uduthorehalla	20	Kallar
3	Hemavathy	12	Vrishabhavathi	21	Moyar
4	Kanva	13	Yagachi	22	Noyyal
5	Lakshmana Tirtha	14	Amaravati	23	Palar
6	Lokapavani	15	Aiyar	24	Ponnaiyar
7	Shimsha	16	Chinnar	25	Pungar
8	Sharabhaganadi	17	Tirumanimuthar	26	Thoppaiar
9	Uyyakondan	18	Bhavani	27	Kabini
28	Arkavati	29	Pambar		

The catchment area of the tributaries are Arkavathi (4351 km^2), Harangi (717 km^2), Hemavati (5410 km^2), Kabini (7040 km^2), Shimsha (8469 km^2) Suvarnavathi (1787 km^2). The origin of these rivers is either from BR-MM hill ranges-Nilgiri hills or it falls in the middle domain. Whereas tributaries along upper

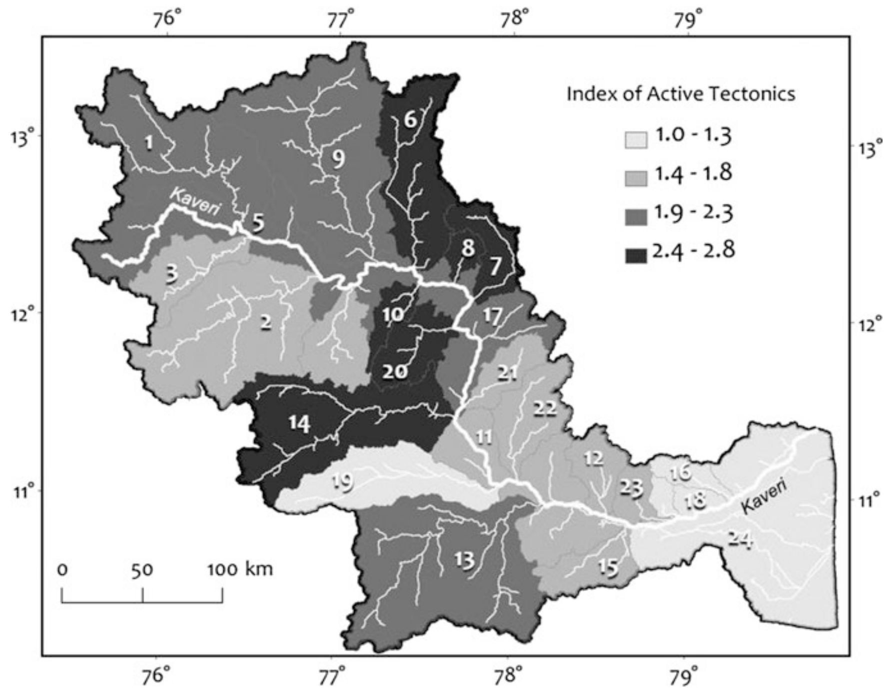

Fig. 3 Plot of indices of active tectonics. Drainage basin numbers are as follows (after Kale et al. 2014) *1* Hemavati, *2* Kabini, *3* Lakshmana Tirtha, *4* Suvarnavathi, *5* Upper Cauvery, *6* Arkavathi, *7* Chinnar, *8* Dodda Halla, *9* Shimsha, *10* Thattai Halla, *11* Middle Cauvery, *12* Aiyar, *13* Amravati, *14* Bhavani, *15* Koraiyar, *16* Marudaiyar, *17* Nagavathi, *18* Nandyar, *19* Noyyal, *20* Palar, *21* Sarabhanga, *22* Tirumanimuthar, *23* Uppar, *24* Lower Cauvery

(Kale et al. 2014) domain namely Hemavati, Lakshmana Tirtha, Suvarnavathi, Kabini and Amaravati show moderate tectonism. Again lower domain tributaries show lower-to-recent tectonism. Thus, it can be inferred that all categories of recent diastrophism are seen in the area falls along middle domain of the basin. Dendritic drainage pattern is well seen in this basin (Fig. 3).

At Shivanasamudram, the river divides into 2 branches and falls from 91 m height forming falls and rapids which are utilized in power generation. Again it joins after fall and flows through a larger gorge namely "Mekedatu" (goat's leap), and this flow continues up to a distance of 64 km to form a boundary between Karnataka and Tamil Nadu. At Hogenakkal Falls, it flows toward south direction and enters into Mettur reservoir. Below this reservoir, Bhavani tributary joins Cauvery along the right bank. Later on, it turns toward east and enters into Tamil Nadu plain.

After Tiruchirapalli district, it branches out into 2 parts, on the north called as "The Coleroon" and on the south as Cauvery. Again two branches join after 16 km flow and form Srirangam island. The Cauvery branch divides into two, namely Cauvery and Vennar below the Grand Anicut. Again these two splits into number of branches, forming a network, all over the delta.

4 Structure

The Cauvery river drains from Biligirirangan (BR) and the Mahadeswaramalai (MM) Hill Ranges falls under the control of lithological and transgresses structure which suggest that these river erosion causes rock uplift. The BR–MM terrane, in the eastern part of Mysore Plateau, is a horst mountain which has been formed in late quaternary (Kale et al. 2014). These horst mountains are formed by the strike slip and oblique slip movement in the NNE/N–SSW/S direction along the eastern side of the Dharwar Craton and in NNW/N–SSE/S direction along western part (Valdiya 2001). The faults along NNE/SSW direction or weak zones are the cause for the abrupt turns of Cauvery river at Kollegal–Shivanasamudram and at Hogenakkal (Valdiya 2001) (Fig. 4), and its lateral movements are the cause for northward deflection of Cauvery River (Kale et al. 2014). Number of recent and

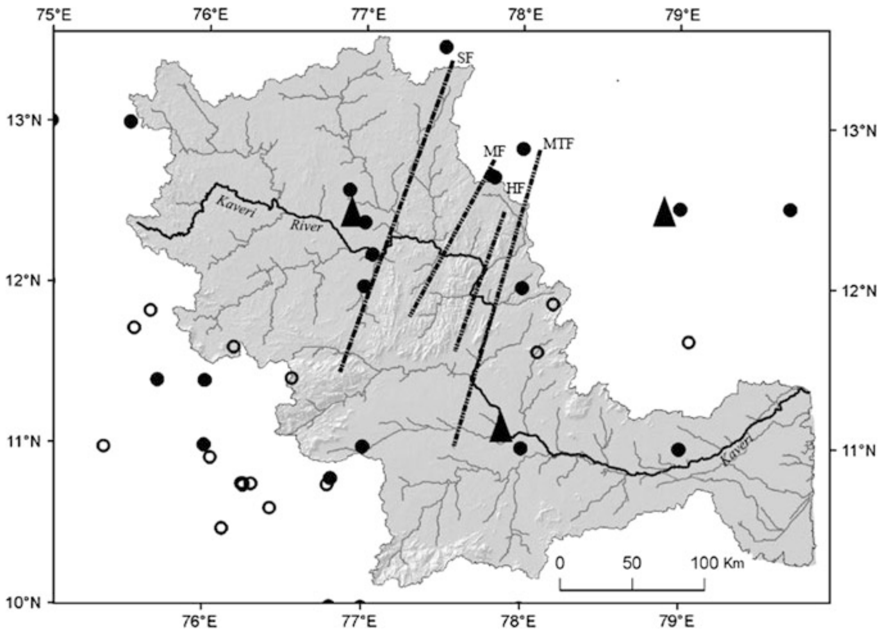

Fig. 4 Map of the Cauvery basin showing major active faults (F) and locations of historic and recent earthquakes of >4.5 (*solid circles*) and <4.5 (*hollow circles*) on the Richter scale swarm type of seismic activity (*solid triangles*) after Chopra et al. (2008). *SF* Kollegal–Shivasamudram Fault, *MF* Mekedatu Fault, *HF* Hogenakkal Fault, *MTF* Mettur Fault. Faults after Valdiya (2001) and earthquake locations after Valdiya (2001), Sitharam and Anbazhagan (2007) and Kale et al. (2014)

past earthquakes were associated with these faults (Fig. 4) (Valdiya 2001; Sitharam and Anbazhagan 2007; Chopra et al. 2008). The basin runs roughly in a NW–SE direction. This SE trend of the Cauvery River is due to the uplift of the Western Ghats and slight tilt of the Peninsular Indian mass to the east during the Miocene age (Kale et al. 2014). The River Cauvery flowing southeast has its flow across the foliation direction of rocks.

5 Geology

Metamorphic and igneous rocks are the major types of rocks in the basin among which charnockites, high-grade schists, migmatites, green stone belts, and consolidated gneisses are of archean age (Ramanathan et al. 1994) commonly found here; southern part covered with laterite and ferruginous sandstone. An area of 38.000 km^2 of the basin covered with hard rock and 11,000 km^2 with sedimentary rock. Dharwar rocks such as Peninsular granitic gneiss, charnockites and the Closepet granite of Precambrian age forming the geology of the river basin (Fig. 5).

The Dharwar metamorphic consists of phyllites, slates, schists with chlorite, biotite, garnet, and hornblende, associated with greenstone and quartzite. Peninsular granites and gneisses consisting biotite and hornblende granite gneisses are predominantly noted in the main basin. Furthermore, the long profile of the River Cauvery through terraces and knick points clearly shows the possible uplift and erosion in the geological past. The study of the distribution, transportation and mineralogy of the Cauvery river was carried out by (Ramanathan et al. 1993, 1994; Vaithiyanathan et al. 1988).

Central region of the basin mainly comprises of charnockites restricted to Nilgiri range. These charnockites are composed of gabbros, olivine norites and pyroxene,

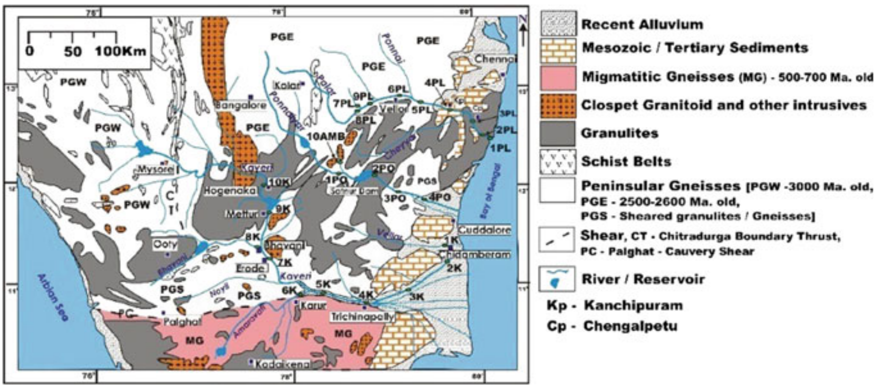

Fig. 5 Map showing the geology of the drainage basins of Cauvery rivers, (after map of Geological Survey of India, 1994), their major tributaries and monsoon sample locations are numbered along the river course

and cretaceous sediments crop out in the coastal region and consist of conglomeratic sandstone, coralline limestone, and shale (Hydrology and Water Resources Information System for India: http://pib.nic.in).

6 Land Use and Soil

Four types of land-use pattern noted in the basin arable, non-arable, forest land, and land for habitation. More than 50% of the land is arable or cultivated land, whereas 21.6% is non-arable land, 19.53% land is covered with forest, and rest area is inhabited which form rural and urban two types of habitation (Indiawaterportal.org). More than 50% people live in rural areas, and agriculture is the major occupation. Major crops cultivated here are paddy, sugarcane, ragi, and jowar, and minor crops such as coffee, pepper, banana, betel vine, gingili, onion, cotton, and black gram are also grown.

Six types of soils like black soils, red soils, laterites, alluvial soils, forest soils, and mixed soils are found here, whereas red soil occupies major portion of the basin (Figs. 6 and 7) followed by black soil. Delta region is composed of alluvial soil. The cultivable area of the basin is about 58,000 km^2 which is about 3% of the total cultivable area of the country (CPCB 1995). Laterites are found in highlands of Karnataka, which is reddish brown in color, acidic to neutral in nature, and are

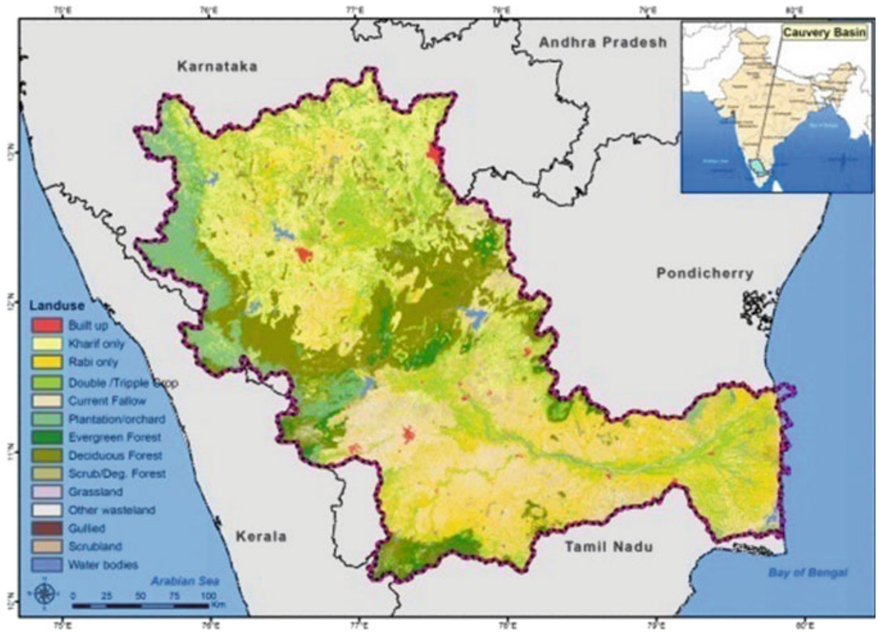

Fig. 6 Land-use map of the Cauvery basin (after support for the National Action Plan on Climate Change Support to the National Water Mission, 2011: http://pib.nic.in)

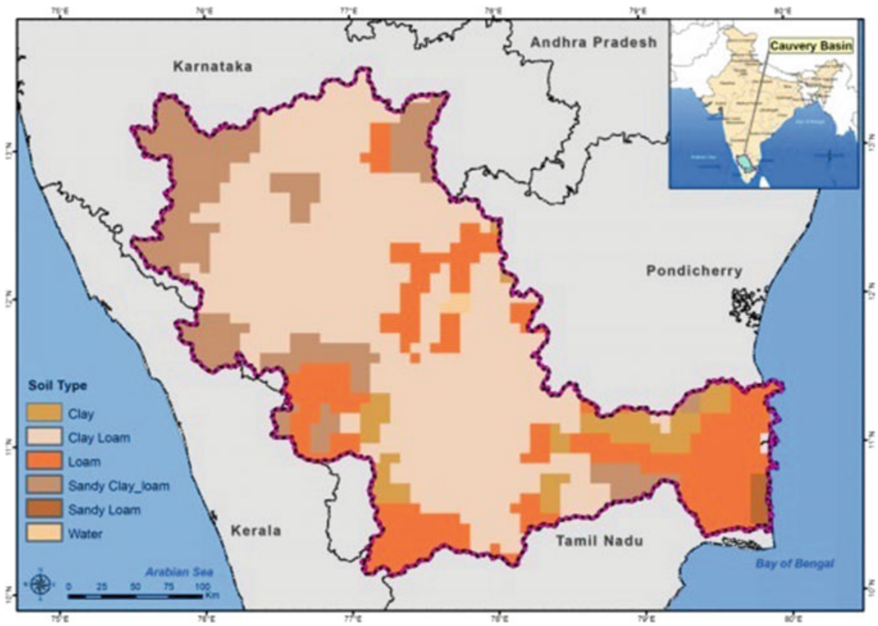

Fig. 7 Cauvery basin soil map (after National Action Plan on Climate Change Support to the National Water Mission, 2011: http://pib.nic.in)

fertile, suitable for cultivation. Red loam along with black soils is found in highlands of Kerala, which is fertile rich in organic constituents and has high nitrogen content and is very good for agriculture. Deep soils are found in Tamil Nadu whose depth increases toward coast which has higher amount of clay, lesser drainage capacity, less nitrate content, less phosphorus content, and higher potassium and lime contents.

Approximately 75, 73, and 85% of rainfall, water discharge, and sediment transport, respectively, taken place annually in Cauvery River during monsoon (Vaithiyanathan et al. 1992). Sediment transport is controlled by 2 major factors of the basin like geology and river water discharge. Presence of 2 major dams across the river is mainly influencing the sediment transport of the river. Out of total sediment transported by the river, 60% sediments have of 20 m particle size. At dam sites, coarse sediments are selectively removed from the suspended load.

7 Climate and Rainfall

Tropical climate is experienced by Cauvery basin, and monsoonal rainfall is the major climatic feature here. Out of total annual precipitation, major portion is provided by NE monsoon, and 44 and 18 °C are the maximum and minimum

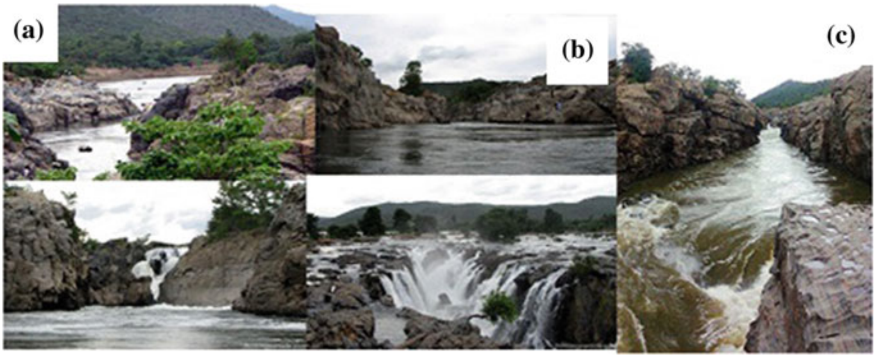

Fig. 8 Various views of the river Cauvery. **a** Coracles: distant view at Hogenakkal waterfalls and falls from the Canyon. **b** Hogenakkal falls Karnataka side. **c** Flow path of Cauvery at Mekedatu (wikipedia.org)

temperature experienced here (http://www.india-wris.nrsc.gov.in). Southeast monsoon contributes maximum rainfall, whereas northeast monsoon contributes lesser quantity of rainfall to the basin in Karnataka, but in Tamil Nadu, NE monsoon contributes significant rainfall to the basin.

During SW monsoon, the basin receives highest rainfall along its western part, whereas it receives highest rainfall at its eastern part during NE monsoon. Cyclone and heavy rainfall happen due to the depression creates in the Bay of Bengal which also affects the basin in monsoon. The various views of the River Cauvery are shown in Fig. 8.

8 Ecology and Biodiversity

The basin considered as a separate phyto-geographic unit because of its largest floristic wealth. The known flora of the basin comprise to 2037 species from 990 genera of 180 families. A total of 1050 species of 128 families are seen in this river system, out of which herbs, shrubs, trees, and other plants like climber, twinners are of 48% (504), 25.7% (270), 16.2% (170), and 10%, respectively. Land-use pattern changes are quite common in this riparian zone such as agriculture, settlements, recreation and industries because of growth of population. The river from headwater to outlet shows very good habitat heterogeneity. In headwater zone endangered fishes are found whereas along riparian zone habitat of wildlife (Sunderraj and Johnsingh 2001; Smakhtin et al. 2006; Lakra et al. 2010). Again in forest, wildlife species are found which are kept in the large protected areas like Nagarhole National Park, Talakaveri, Brahmagiri, and Pushpagiri Wildlife Sanctuaries. The river which flows along this wildlife sanctuaries provides habitat for otters, crocodiles, and many varieties of fishes along with the famous Mahseer. About 1000 elephants graze in this riparian areas.

9 Water Resource

Approximately 90% water of the basin is used for irrigation purpose in agricultural field. Water used for irrigation taken through wells, bore wells, canals, tanks, and lifts (http://www.indiawaterportal.org). Approximately 6% water of the basin is utilized for domestic needs. Demand of water used for household purpose and commercial purpose is highest in Bangalore and Mysore.

10 Groundwater Occurrence

Groundwater occurs in semi-confined-to-confined aquifer at a depth of 200 m or more as deeper fractures are noted. But the area overlying crystalline rocks is limited to fractures, joints, and weathering. Yield of weathered gneiss is 400 m^3/day (http://www.indiawaterportal.org), whereas unweathered and charnockites have 1/10th of that. Potential aquifers occur in several parts of broadly weathered and fractured hard rocks.

Western region of the river delta and in sedimentary formation potential aquifers is noted which might be the possible source of future groundwater development. But on the eastern region it is slightly mineralized. Thus, precaution is needed to protect it from other problems such as saline intrusion.

The outlet of the Cauvery River basin (CRB) is the Cauvery Delta with an area of 560,000 ha which is irrigated and drained by four main canal systems: (i) Lower Coleroon Anicut (49,000 ha), (ii) Cauvery (200,000 ha), (iii) Vennar (190,000 ha), and (iv) Grand Anicut (121,000 ha) (Subramani et al. 2014). Historically, the delta was a major agriculture production area of India having about 1.5% of the nation's cultivation area (Proposed Multitranche Financing Facility India: Climate Adaptation through Sub-Basin Development Investment Program 2012). The highly fertile soil, good rainfall, and surface water flows were well suited to rice production. Currently, the northeasterly monsoon can bring erratic but intense rains which give rise to flood and drainage problems, while there is limited surface water during the southwesterly monsoon. There are issues of saline intrusion near the coast, and low-lying land has poor drainage. Groundwater is extensively used to supplement the lack of surface water, and now there are issues of overexploitation and salinity. Climate change is expected to exacerbate these problems. There is already empirical evidence for changing rainfall patterns, both spatially and temporally. Government and communities report greater intensity and shorter duration of monsoon rains and increased frequency of cyclones. Further changes in local rainfall and sea level rise are expected. While the mean annual rainfall is expected to remain unchanged, the southwest monsoon rainfall may decline by about 10%, and the northeast monsoon rainfall will increase by about 10–20%. Sea levels are also expected to rise by about 30 cm by 2050. These phenomena will have significant impacts on the delta region, calling for holistic planning, management, and adaptation systems with community involvement: (i) groundwater depletion and saltwater intrusion, (ii) sea level rise and coastal changes, and (iii) flooding. During the dry season, farmers rely on groundwater to supplement surface water irrigation. Increased groundwater use has resulted in saline intrusion in a coastal strip of about 20 km. Attempts have been made to reduce abstraction, but saline intrusion continues and will increase under conditions of sea level rise. With no significant projected change in annual rainfall, groundwater recharge will be largely unchanged. In fact, groundwater demand will likely increase to compensate for the weakening of the southwest monsoon. The Cauvery Delta is vulnerable to the effect of rising sea levels as a result of climate change. Rising sea levels pose a number of threats including coastal erosion, increased wave energy, salinity ingress to drainage channels, and saline intrusion to groundwater (Support for the National Action Plan on Climate Change Support to the National Water Mission, 2011). The coastline was badly affected by the 2004 tsunami. Overextraction of groundwater will increase saline-affected areas and may also exacerbate natural ground settlement compounding the impact of rising sea levels. Some areas of the lower delta are already below sea level and are impacted by natural beach processes that cause waterlogging as well as salinity problems. Keeping drainage outlets open to the sea is a continuing major challenge. The expected sea level rise will increase the overall area below sea level, increasing both saline-affected areas and flood problematic areas as drainage becomes more congested. Extreme tides and storm surges may also increase coastal flooding. The northeast monsoon brings heavy rains and cyclones, and the delta becomes fully congested with inundation resulting in damage to standing crops and land salinization. The expected increased monsoon rainfall intensity and sea level rise will exacerbate flooding with an increased number of areas affected by more frequent and longer duration floods. Transportation in the area is also severely affected because riverbank protection works also serve as community roads.

A study for five years (1985–1989) has been carried out (Ramanathan et al. 1994) on the nature of solute transport in the Cauvery River. Na and HCO_3 are the major chemical constituents found in Cauvery River water which shows predominance of continental weathering and impact by atmospheric precipitation. But the river water composition is increasingly dominated by Na and Cl in the downstream region. The total dissolved material transported from the Cauvery to the Bay of Bengal is 14% of the annual flux of dissolved load from Indian rivers to the neighboring seas. Groundwater in northeastern part of the Salem districts in Tamil Nadu occurs in weathered portions of rocks along joints and fractures. Srinivasamoorthy et al. (2008) studied groundwater quality in Mettur taluk of Salem district and identified higher NO_3 and PO_4 pollution level (Srinivasamoorthy 2005).

11 Socioeconomic Importance

Cauvery water is mainly used for irrigation purpose, domestic purpose, and power generation. An estimation of five-year water flow from Cauvery was (15 km^2), of which 60% was used for irrigation. Bangalore receives 540 million liters per day of Cauvery water from Torekadanahalli pump station (www.munainstitutions.com). The river served as lively hood of the ancient kingdom as well as modern cities of South India as it is supporting the irrigated agriculture for centuries.

Monsoon rain provides water to Cauvery River. During monsoon, water is stored in the dams, constructed on its Banasura Sagar Dam project on a Kabini tributaries for providing water during dry months. During February to May, water level becomes very low and starts rising during June or July. The power plant built on the left of Shivanasamudram Falls on the Cauvery in 1902 was the first power plant in Asia. The Krishna Raja Sagara Dam has a capacity of 49 tmc ft, and the Mettur Dam which forms Stanley Reservoir has a capacity of 93.4 tmc ft. (thousand million cubic ft).

The Chola king Karikalan has built the bank of the Cauvery river from Puhar to Srirangam about 1600 years ago, which is renovated during nineteenth century (www.munainstitutions.com). Now it's named as Grand Anicut which is the main source of providing water for irrigation in the Thanjavur district. Mayiladuthurai taluk and Sirkazhi taluk are irrigated by the Manniar and Uppanai tributaries.

Cauvery River is a good example of a site where contributions of pollutants both from natural (lithogenic) sources and anthropogenic activities. The river becomes polluted by the mixing of waste from industry, cultivated land, municipal and household sewage except pedogenic waste directly into the water. A case study from Kabini River sediments where contamination of coconut trees by heavy metals released by industrial effluents soaking soils and draining into river Kabini near Nanjangud is on record (Fazeli et al. 1991). The provenance of heavy metals in Kabini River bed sediments (RBS) reveals the addition of waste from household activities is more than natural and lithogenic sources (Taghinia Hejabi et al. 2010). Fluoride concentration is greater than 1.5 ppm is noted in some regions of the river basin.

Analysis of water, plankton, fish, and sediment shows that the Cauvery River water in the downstream is polluted by certain heavy metals. Sediments accumulate at a rate of 0.4–4 mm/year. As depth increases heavy metal concentration decreases. The heavy metal concentration at certain depths is recognized to the uneven input of metals and their remobilization (Ramanathan et al. 1996). Carbonate hardness is higher in water samples. Elements and ions concentration increase toward downstream. Ions show the following order: $Na > HCO_3 > Mg > K > Ca > Cl > SO_4$ (Begum et al. 2009). But heavy metals show the following $Cr > Cu = Mn > Co > Ni > Pb > Zn$, for fish muscles $Cr > Mn > Cu > Ni > Co > Pb = Zn$, for phytoplanktons $Co > Zn > Pb > Mn > Cr$ and, for the sediments, the heavy metal concentration was $Co > Cr > Ni = Cu > Mn > Zn > Pb$. Cauvery River water falls in very good category as Zn, Pb, and Cr value exceeds the upper limit of standards which is derived from the saline and sodium content of irrigated water. Pollution is more along the downstream because of association pesticides waste from industries and household waste. For protecting the river from pollution, proper action is needed (Begum et al. 2009, Vaithiyanathan et al. 1993).

12 Conclusion

The Brahmagiri hills of the Western Ghats are the origin point of the Cauvery River with a stretch of 770 km which covers an area of 8.8 mha (56, 41, and 3% in Tamil Nadu, Karnataka, and Kerala, respectively). With three major reservoirs, a number of weirs and anicuts built across the river and its tributaries, Cauvery is the most exploited river of the country (95% abstraction of water). The shortage in rain was about 20–23% of the annual average always occurring during monsoon failure years in downstream regions. The consecutive rain-deficit years, in 2011, 2012 along with 2013, and the delayed southwest monsoon this year have created a drought-like situation in parts of the basin, presenting visuals of dried-up crops a trees. So the good rainfall in parts of upstream regions will bring relief to downstream regions with water levels improving in reservoirs and compensate the cumulative effect of deficit from previous years. In the monsoon deficient years, the water-shed management in downstream has to be augmented to improve the water availability in future. Waste from urban area, industry, and agricultural land is the major source of pollution of this river. The large quantities of fertilizers used in cultivation are discharging into the river in the form of agricultural runoff. Textile industry, paper mills, and factories of Karnataka and Tamil Nadu provide huge quantities of pollutants to the river. Thus, a large quantity of wastewater releasing from these industries is mixing with the river water.

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Trans- and Tethyan Himalayan Rivers: In Reference to Ladakh and Lahaul-Spiti, NW Himalaya

Binita Phartiyal, Randheer Singh and Debarati Nag

1 Introduction

The Himalayan system is a complex and youngest fold mountain chain, which stretches across six countries, namely Afghanistan, Pakistan, India, Nepal, Bhutan, and China. Some of the major rivers of the world rise in the Himalaya and their combined drainage basin are home to some 1.3 billion people. Among the three major rivers originating in the Mount Kailash area in Tibet, namely the Sutlej, Brahmaputra, and Indus, only river Sutlej cross-cuts the Himalayan orogen at its central part, the other two (Indus and Brahmaputra) cross the Himalaya at its west and east syntaxes. Trans-Himalaya (north of Indus Suture zone (ISZ)) and the Tethyan Himalaya (area between the Main Central Thrust (MCT) and ISZ) consist of a mountainous region about 1000 km long and 225 km wide in the center, narrowing to $\sim$32 km width at the eastern and western ends. The Trans-Himalaya, mainly composed of granites and volcanic rocks of Neogene and Paleogene age, are bounded by the Kailas (SW), Nganglong Kangri (N), and Nyainqêntanglha (SE) mountain ranges and by the River Brahmaputra (Yarlung Zangbo) (S) while the Tethyan Himalaya consists of the sedimentary rocks of Upper Proterozoic to Eocene ages. Trans-Himalaya are not divided by deep river gorges and lack a definite alignment unlike the southern sectors (Higher and Lesser Himalaya). Passes average 5,330 m in height, with the highest being Khardung La (La = pass) 5,725 m in the Ladakh region.

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Ladakh (Trans-Himalaya) and Lahaul-Spiti (Tethyan Himalaya) regions of India occupy a very important place as far as the circulatory winds and the Indian monsoon are concerned. It is the pathway of the monsoon winds to the Tibetan plateau. The area remains covered with snow for nearly six months, and the peaks above 5,000 m are permanently capped with snow throughout the year. There are many glaciers in the region which are the source of the rivers flowing in this region. The terrain is above the tree line (3,000 m), and the area has a rugged topography (lunar topography); vegetation is only confined to the villages and river valleys (Fig. 1). Thus, due to this rugged topography and high altitude (<3,000–6,000 m) and strategically hotspot (being the international boundary with Pakistan and China), not much work has been done in the area. The major rivers flowing in these areas (Fig. 1) have been discussed, and the details of their length (flowing in India) and catchment areas are given in Table 1.

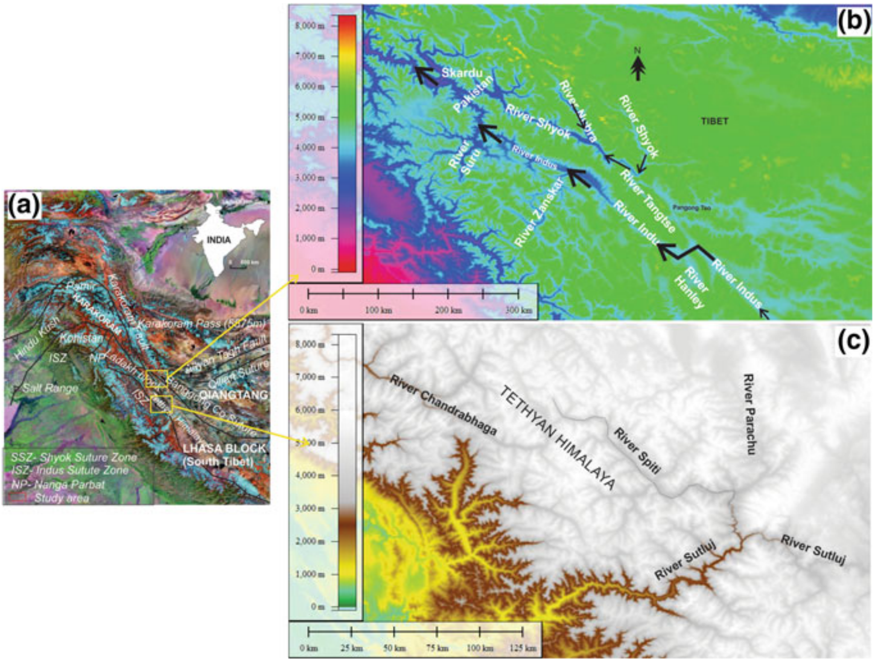

Fig. 1 **a** Location map and the SRTM DEM of **b** the Trans-Himalaya, and **c** Tethyan Himalayan regions showing details of drainage pattern with the major rivers

Table 1 Length and catchment areas of River Indus and its tributaries (in Indian side)

Name of the river	Catchment area (km^2)	Length (km)
Indus (total length) Kailash to Arabian Sea	1×10^6 25,607 (in India)	3,180
Indus (Kailash to Fukche) (China)		262
Indus (Fukche to Batalik) (India)		422
Indus (Batalik to Skardu) (border area)		129.10
Tributaries of Indus		
1. Hanley	–	125.65
2. Zanskar (Padum to Nimo)	7,656.3	133.86
Tsarap		143.72
Doda		71.87
Kurgaikh		39.33
Lungnak/Lingti		52.42
3. Yapola	662.93	48.04
4. Suru	6,876.6	173.65
5. Shyok (up to Turtuk)		386.31
Shyok (up to border)		398.86
Nubra		88.50
Tangtse (Loi Yogma)	2,170	90
Tangtse (Muglib)		40

2 Geomorphology and Socioeconomic Importance

2.1 Trans-Himalayan Rivers

2.1.1 River Indus

River Indus originates in the Tibetan plateau (from the northern slope of Mount Kailas (altitude: 6,714 m) in the Gangdise Range) near Lake Manasarovar (Allen 1984). After flowing over 1,000 km through countries from China to India and Afghanistan, it abruptly heads southward cutting through the Himalayan mountain belt around the Nanga Parbat Massif in Pakistan to merge into the Arabian Sea near Karachi. It is fed by snow and glacial melt water. The Indus derives its name from the Sanskrit word, Sindhu, which means a large water body, a sea or an ocean. In the Rig Veda, there is a reference to 'Sapta Sindhus,' where Sapta means seven and Sindhus refers to rivers. The seven rivers are the Indus, its five tributaries, and the river Saraswati.

River Indus is one of the most important rivers of the Ladakh region and flows for a length of 422 km in India (mostly in Ladakh region) (Fig. 2). It is geographically the backbone of Ladakh, flowing in a NW direction along the ISZ.

Apart from the major tributaries, Indus is fed by numerous tributaries throughout its length (Fig. 2a). The river is narrow, constricted, and meandering in most of the places except in Leh Valley region where the valley becomes wide (2–3 km)

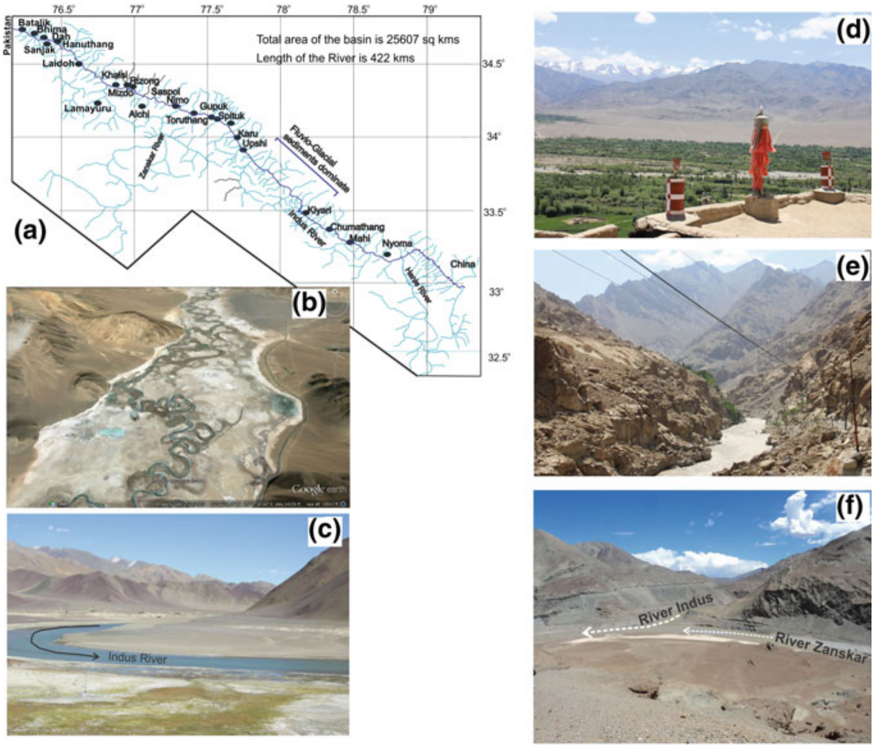

Fig. 2 **a** The drainage map of River Indus from Nyoma to Batalik, showing its major and minor tributaries, **b** Google earth image of the upper course of Indus showing spectacular development of meander loops, **c**–**d** wide Indus Valley at Nyoma and Thikse (Leh) showing the changing nature of river from meandering to braided channel, **e** the development of gorge at Bhima expresses the tectonic influence in the course of river, and (f) the confluence of Indus and its major tributary Zanskar at Nimo

changing the nature of the river to a braided stream (Fig. 2b–d). At times, it is seen flowing through narrow gorges cutting deep into the country rock (Fig. 2f). The Indus seems to not only have eroded through the overlying sediments to superimpose itself upon the rocks of the Ladakh terrain beneath but also have maintained erosion as an antecedent stream across the newly rising structure further downstream (Shroder 1993). In the upper course, the river has a gentle slope and several loops and entrenched meanders are seen (Fig. 2b). Fluvial terraces, moraines, and paleolacustrine sediments are seen scattered along the entire course of the river. The main right bank tributary is the River Shyok which joins Indus at Skardu (in Pakistan). The left bank tributaries are Hanley, Zanskar, and Suru. All these rivers are major rivers in themselves and are dealt separately.

2.1.2 River Hanley

The left bank tributaries of Indus are the River Hanley, River Zanskar, River Yapola, and River Suru. The River Hanley (~126 km) flowing in NW direction joins River Indus at Loma. Indian Astronomical Observatory (IAO) is situated at Hanley. At the confluence of Hanley and Indus, the valley is very wide in order of tens of kilometers (Fig. 2c). The topography of that region, downstream the confluence seems as though, a big lake existed there in the past. Remnants of lake sediments (buff-colored clay and silt facies) are seen scattered along the valley downstream up to Mahi Village (Phartiyal et al. 2013).

2.1.3 River Zanskar

The River Zanskar (~134 km) is a north-flowing tributary of the River Indus. In its upper reaches, the Zanskar has two main branches, i.e., the River Doda, having its source near the Pensi La and second branch River Lungnak/Lingti, is formed by two main tributaries known as River Kurgaikh and River Tsarap, with their sources near the Shingo La and Bara-lacha La, respectively. River Zanskar flows in a NE course through the gorge and joins the Indus near Nimo (Fig. 2f). Zanskar has another tributary River Markha, joining it just before the gorge. Markha Valley is a very picturesque valley with many popular trekking routes and thus has a great socioeconomic importance.

River Zanskar has a catchment area of 7,656.3 km^2 and the average channel width is ~0.08 km. Valley width varies according to the shape, 'U'-shaped (5–3 km) in the upper part, gradually narrowing and asymmetric 'V'-shaped (~1.25 km) downstream. It shows mainly meandering channel pattern; however, the upper part shows braided nature of the channel.

To the southwest is the Great Himalayan Range that separates Zanskar from the Kisthwar and Chamba basin. The topographical features make access to Zanskar difficult from all sides. Communication with the neighboring Himalayan areas is maintained across mountain passes or along the River Zanskar when frozen. The river is an ideal location for river rafting tours (Fig. 3b). The otherwise fast turgid river freezes between November to March enable the Chadar trek.

2.1.4 River Yapola

River Yapola (~48 km) is another small river joining the Indus near Khalsi. Its catchment area is 662.93 km^2. The River Yapola is also named the River Wanla. In its vicinity is the famous Moonland of Lamayuru—a paleolake deposit below Fotu La that existed from 35 to 25 ka (Fort et al. 1989; Kotlia et al. 1997, 1998; Nag and Phartiyal 2014).

Fig. 3 Pictures illustrating the socioeconomic activities of the area associated with the river; **a** horticulture of Apricot, the main fruit of the area. It is used as food and various other industries such as juice industry, cosmetics, and medicine manufacture. **b** Water sports industry is well flourished in river rafting sector at some transects. In the picture, the rafting boats near confluence at Chilling and Zanskar valleys. **c** Lamayuru, popularly known as 'Moon land,' is a most common place for tourist visit. This place is also important for earth science community as it hosts/preserves deposits of a paleolake that existed 35–25 ka BP, and **d** 32-meters-high statue of Maitreya Buddha near Diskit Monastery on the left bank of River Shyok

2.1.5 River Suru

The River Suru ($\sim$185 km) long originates from Pensi La and demarcates the western and northern boundary of the Zanskar Range. The River Suru enters the Kargil town through a deep and narrow gorge, where water influxes from other rivers (Botkul, Dras, and Shingo) also join it. In comparison with other valleys of the Ladakh region, the Suru Valley is relatively more fertile. The economy of the valley is mainly agriculture based. Two crops can be harvested each year whereas in many parts of Ladakh raising even one crop a year may not always be possible when summer starts late or there is early snowfall. The River Suru has extensive possibilities for rafting, and it is practiced during the summer. The Suru Valley is the starting point for rafting trips, and it also provides a base for mountaineering expeditions to the Nun Kun mountain massif. The catchment area is 6,876.6 km^2, and the nature of the channel is meandering.

The Indus and its tributaries mentioned above flow through an arid and dry barren land where there is an ample sediment budget (due to physical weathering of country rocks and fluvial, lacustrine, and colluvial sediments). This situation creates a havoc in the periods of intense rainfall and high melting, for example, the 2010 Leh floods (Juyal 2010; Arya 2011; Rasmussen and Houze 2012) which was a heavy toll on the life and property along the river bed. Several researchers have worked along the Indus to tackle problems related to its course, origin, and geomorphological evolution (Clift and Giosan 2013; Phartiyal et al. 2005, 2013; Phartiyal and Sharma 2009a; Sangode et al. 2011; Blöthe et al. 2014).

The main town of the Ladakh region is Leh which lies along this river. The other small villages are Fukche, Loma, Nyoma, Mahi, Chumathang, Leh, Nimo, Basgo, Saspol, Alchi, Khalsi, Dumkar, Achinathang, Bhima, Dah, and Batalik; thereafter, the river enters the territory of Pakistan. The River Indus is the backbone of the Ladakh region. The river valley is vegetated; people grow vegetables in some patches of fertile land (which is rare). The river and its tributaries are the main source of water for the residents of the area. A hydroelectric power plant in the gorge between Basgo and Alchi villages has come up recently which will cater to the needs of the local population who use to depend on the solar light source for electricity. Being one of the main centers of Buddhism, this region has several old and important monasteries (Hemis, Thikse, Spituk, and Alchi) and is a seat of his Highness Honorable Holy Dalai Lama at Leh. This place is a world famous tourist attraction offering picturesque panoramic views of the Lunar (moon) like topography. The rivers also offer rafting, kayaking as water sports along with the bike traverses throughout the river valley.

2.1.6 River Shyok

The River Shyok (tributary of the River Indus) Valley lies in the vicinity of the Karakoram Fault Zone (KFZ) (Fig. 4). River Shyok (~398.86 km length in India), the most important right bank tributary of the River Indus, flows in a wide valley (4c, d) and becomes very wide at the confluence with the River Nubra (tributary of River Shyok). The alignment of the River Shyok is very unusual; originating from the Rimo Glacier, it flows in a SE direction, and after joining the Pangong Range, it takes a NW turn and flows parallel to its previous path along the Karakoram Fault. The river, which generally flows in a wide valley, abruptly enters a narrow gorge after Chalunka and joins the Indus at Skardu, Pakistan.

This river is aligned along the Karakoram Fault Zone (KFZ). Khalsar (Fig. 4d) and Diskit are the main towns in the area, others being, Ravinagar, Shyok Village (with the highest suspension bridge of the world; Fig. 4b), Agham (Fig. 4c), Khalsar, Diskit, Hunder (sand dunes), Partappur and Thoise (airstrip), Udmaru, Chalunka, and Turtuk along the Shyok before it enters the Pakistan international boundary. Hunder Village is a famous tourist destination for its sand dunes and the double-humped (Bactrian) camel rides (Fig. 5).

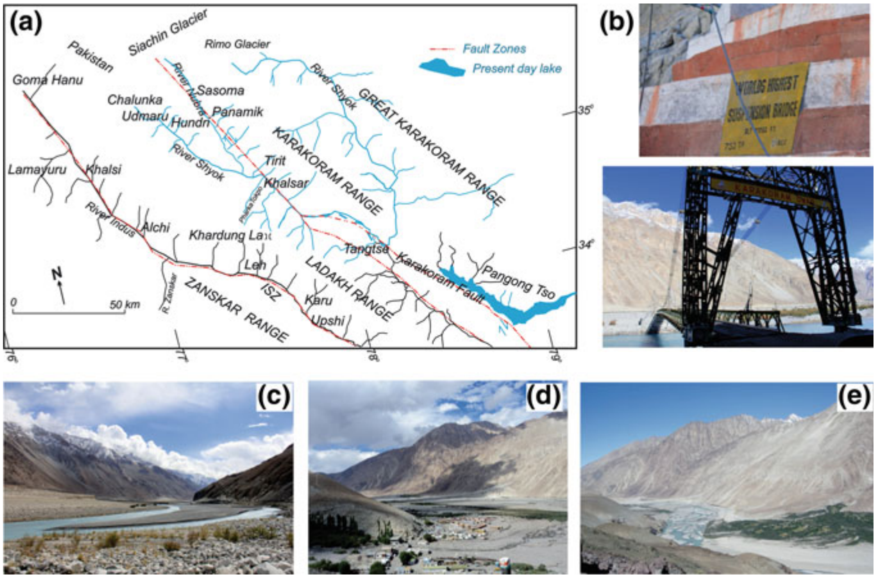

Fig. 4 One of the major tributaries of the Indus, the River Shyok; **a** drainage map of the River Shyok illustrating its major tributaries—the River Nubra and the River Tangtse; **b** world's highest (3,621 m) suspension bridge at Shyok Village, being adjacent to Indo-China border, the area's first necessity is to maintain the connectivity with the mainland; **c** the wide Shyok River Valley at Agham showing a point bar deposit; **d** Khalsar Village on the left bank of River Shyok; and **e** Sati Village, as seen while descending from Khardung La—the highest pass of the world. The braided nature of the channel has shown

Fig. 5 Tourism is the primary source of the income in the entire Ladakh area. Monasteries, high lands, passes, other natural assets of this 'roof of world' attract millions of tourist from all over the globe. **a** Bird's-eye view of braided River Nubra and Panamik Village (left bank), picture taken from a very ancient Ensa Gompa situated on the right bank; **b** the sand dune and double-humped camel in the Nubra River Valley are one of the many attractions for the tourist; and **c** Milestone-Pakistan is just 182 km away

2.1.7 River Nubra

The River Nubra originating from the Siachen Glacier (the longest glacier outside the Poles) also flows like the River Shyok; just before Tirit Village, the SE-flowing river takes a NW turn on meeting the River Shyok (Fig. 6). The Shyok River Valley is very wide (∼10 km) when River Nubra joins the River Shyok (Fig. 6e). Glacial till and moraines are seen in the Nubra Valley which is a very wide U-shaped valley. The River Nubra flows for ∼88 km before joining the River Shyok (Fig. 6a). The famous Panamik hot water springs are situated in the left bank of the river. Along the River Nubra, the main villages are Sasoma, Panamik, Tegar, and Tirit.

2.1.8 River Tangtse

Another tributary of River Shyok that drains into the River Shyok near Shyok Village is the River Tangtse. The Tangtse River Valley is situated after crossing the Chang La (La = pass; altitude of 5,258 m), one of the highest motorable passes of the world. The Karakoram Fault (KF) trends NW and bifurcates into two strands,

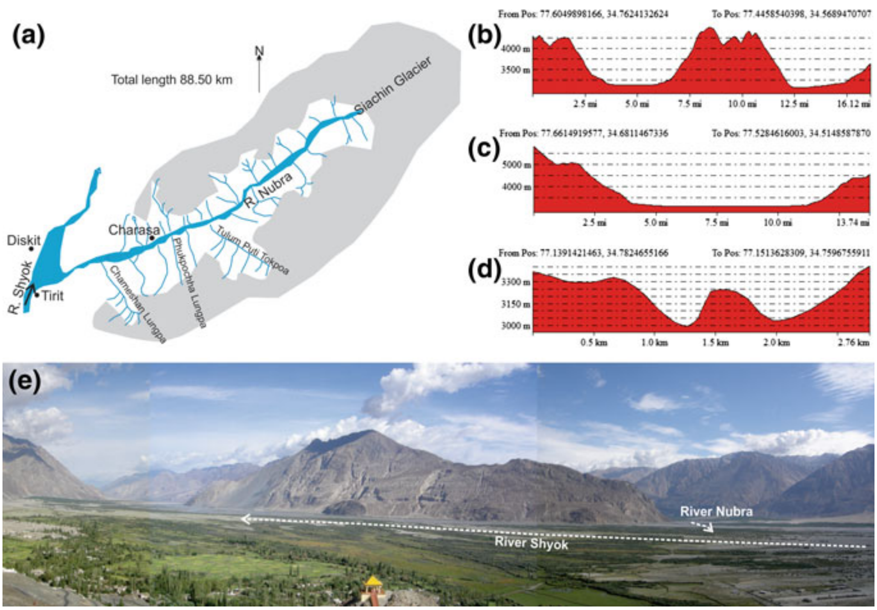

Fig. 6 **a** Drainage map of the River Nubra, a tributary of River Shyok; **b–d** cross-valley profiles showing the variation in valley width of the River Shyok before the confluence with Nubra; after the confluence and near Yaglung Village (where river flows in the gorge); and **e** panoramic view of the wide U-shaped valley (>10 km) at the confluence. The picture is taken from left bank of River Shyok at Diskit Monastery

viz. the Tangtse Strand and Pangong Strand (Dunlap et al. 1998; Rutter et al. 2007). These strands are occupied by the River Tangtse and its major tributary, respectively (Fig. 7a). It is fed by valley streams, from an altitude above 4,000 m asl. The river originates near Chushul and flows in the Loi Yogma Valley along the Tangtse strand of the KF for about 72 km. A tributary flows from near the Pangong Tso water divide in the Lukhung–Muglib Valley, for 15 km in NW direction along a wide U-shaped valley in the Pangong strand of the KF. This tributary takes a right-angle turn to join the main channel; the combined stream flows along the Tangtse-Durbuk Valley in a straight course traversing ~26 km and join the River Shyok near the Shyok Village. It covers almost 2,170-km^2 basin area. However, above the confluence with River Shyok, a 400–500-m-deep gorge has been cut by this river over a distance of about 12 km (Fig. 7b). While in the wider upstream part of the river valley, a series of flood deposits, strath terraces, fluvial fills, alluvial fans, and lacustrine deposits are well preserved (Phartiyal et al. 2015).

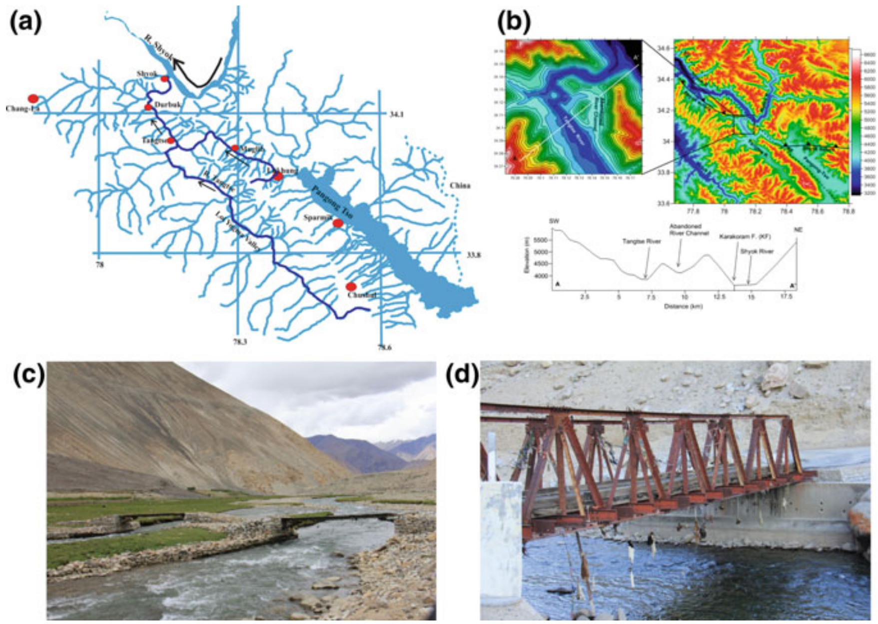

Fig. 7 **a** The drainage pattern of the River Tangtse, showing the subsidiary streams of Loi Yogma Valley and Lukhung-Muglib Valley, uniting to form the main river course, flows in the Tangtse-Durbuk Valley and, via gorge (of ~12 km), it joins the main stream River Shyok; **b** abandoned channel before the gorge area and its cross-valley profile; **c** the U-shaped valley in Loi Yogma sector; and **d** the tantric cult of Tibetan Buddhism and/or local mystical believes are the another attraction of the tourist. In this picture, the carcasses are hanged on the river through Gorkha Bridge as the offerings for local super natural powers

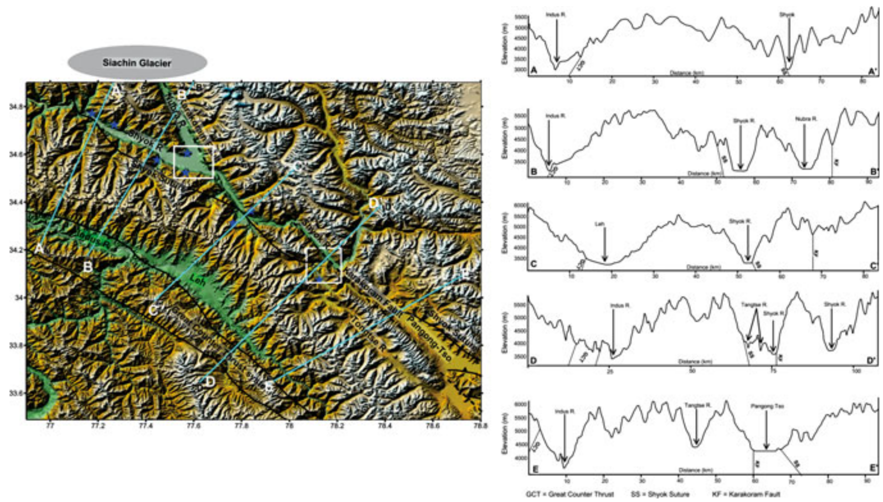

Fig. 8 The cross-valley profiles at various sections demonstrating the relation of the main rivers and their successive tributaries along with the major tectonic setup. The *boxes* indicate the location of the confluence

The relationship of rivers of the Trans-Himalayan rivers (Indus, Shyok, Tangtse), as seen in the cross valley profiles shown in Figure 8. It is seen that both Indus and Shyok flow through narrow V-shaped valley at places, occupy broad U-shaped valleys in others, and are structurally controlled rivers.

3 Tethyan Himalayan Rivers

Several small rivers originate from the Tethyan Himalayan zone and cut across the Himalayan orogen to join the famous rivers, namely Sutlej, Chenab, and Spiti. Of these, the Spiti River and the Chandrabhaga (Chenab) are discussed.

3.1 River Spiti

River Spiti is a tributary of River Sutlej, has a catchment of 66,318 with 20,793 km^2 in India and 59,385 km^2 in Tibet/China. This river originates in Western Tibet in the Kailash Mountain Range, near the source of the Indus, the Ganges, and the Brahmaputra. It flows through the Panjal and Siwalik mountain ranges and then enters the plains of India with a total length of about 1,551 km. The major tributaries, catchment areas, and the length are shown in Table 1. Spiti River Valley $\sim$185 km long (constituting of two nearly equal basins, i.e., Spiti and

Table 2 Length and catchment areas of the major tributaries of the River Sutlej

Tributary	Catchment area (km^2)	Length (km)
Spiti	9,660	185
Gambhar Nullah	550	64
Soan Nullah	797	80
Sirsa Nullah	451	51
White Bein	2,390	142
Black Bein	1,521	145
Beas River	9,978	467
Rohi Nullah	1,151	39

Parachu) is a tributary of River Sutlej (Table 2). The river originates from the Nogpo–Topko Glacier located near Kunzum La (4,551 m) as the Taktsi stream and joins the Pagnu and Kibji rivers. Thereafter, it is called the River Spiti, flows through a distance of about 150 km, and joins the River Sutlej at Khab. In the entire course, the River Spiti descends ~1,800 m with an average slope of 17 m/km. It has a catchment of 9,660 km^2, with nearly fifty percent belonging to the River Parachu, a tributary of River Spiti. Initially, the river flows as a wide braided stream in a U-shaped valley in an E–W direction, before taking a gentle right-angle turn and then flows linearly in a NW–SE direction in the axial plain of the Spiti anticline more or less parallel to the major Himalayan thrust (MBT, MCT, ISZ, etc.) before joining the River Sutlej. It has a catchment of 6,300 km^2, where Pin, Lingti, Parachu are the major tributaries. The tributaries and other first-/second-order streams joining the main river at right angle are indicative of a tectonic/structural control in their course. Based on the channel characteristics and disposition of the relict deposits, the whole valley can be subdivided into the Upper Spiti Valley and Lower Spiti Valley (Phartiyal et al. 2009a, b) (Fig. 9). In the upper valley, between Losar and Lingti, the river is braided and the valley walls are abutted by massive fluvial deposits, fans, debris cones, landslide sediments, and relict lake deposits. The lower valley, between Lingti and Khab, on the contrary, is characterized by a meandering and incised channel (Fig. 9d). This segment is characterized by incised gorges with relict lacustrine and fluvial deposits sitting on bedrock which is much above the riverbed. At places, the river has incised into the bedrock in a sinuous course (Fig. 9). The tributaries and other first-/second-order streams join the main river at right angles showing tectonic/structural control. The general NW–SE course suddenly changes to almost N–S direction along the Kaurik Chango normal fault (KCnF) all the way to junction with the River Sutlej.

3.2 River Chenab

The water of the River Chenab (960 km; Fig. 10) starts from snow melt from the Bara-lacha Pass in Himachal Pradesh. The streams flowing south from the pass are known as the River Chandra and those that flow north are called the River Bhaga.

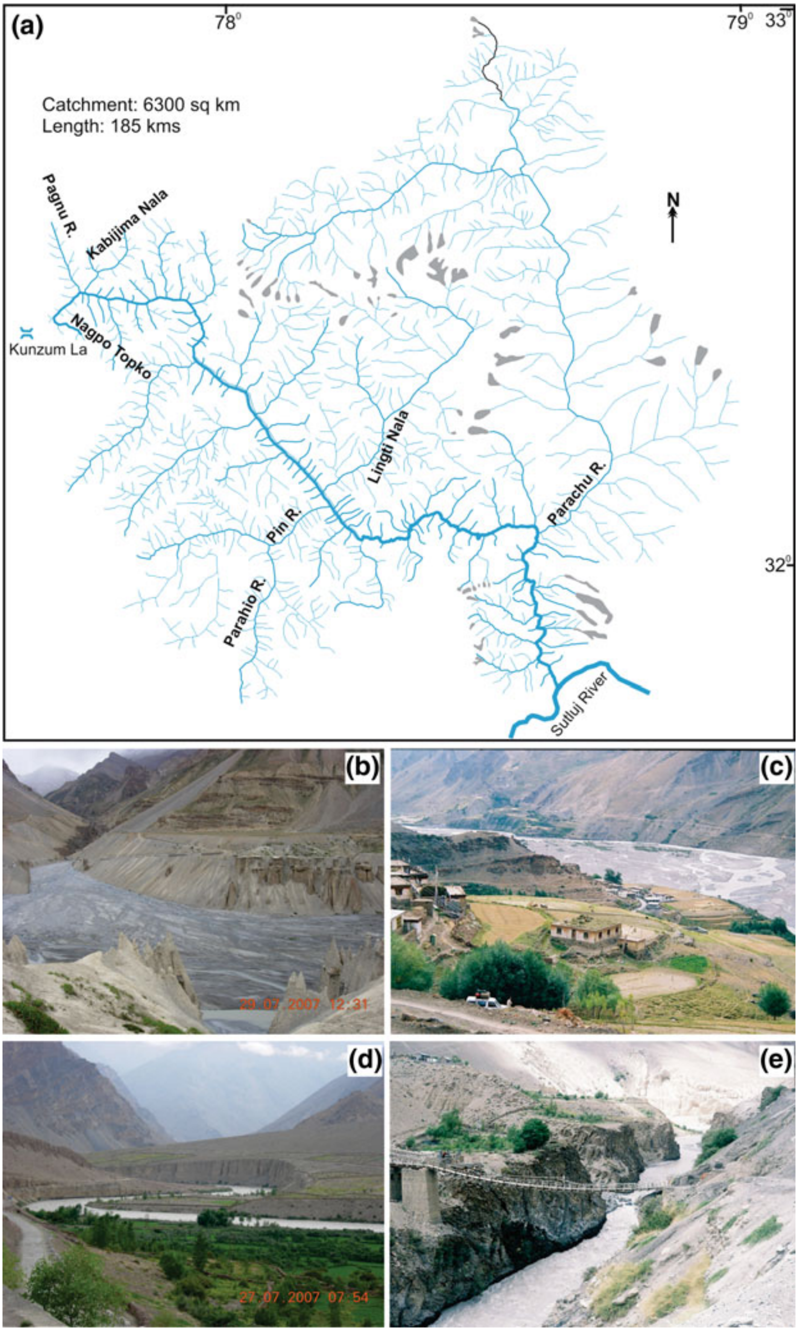

Fig. 9 **a** Drainage of River Spiti; the different views of the river **b** the braided channel, **c** cutting the terraces, **d** meandering channel, and **e** flowing in a gorge

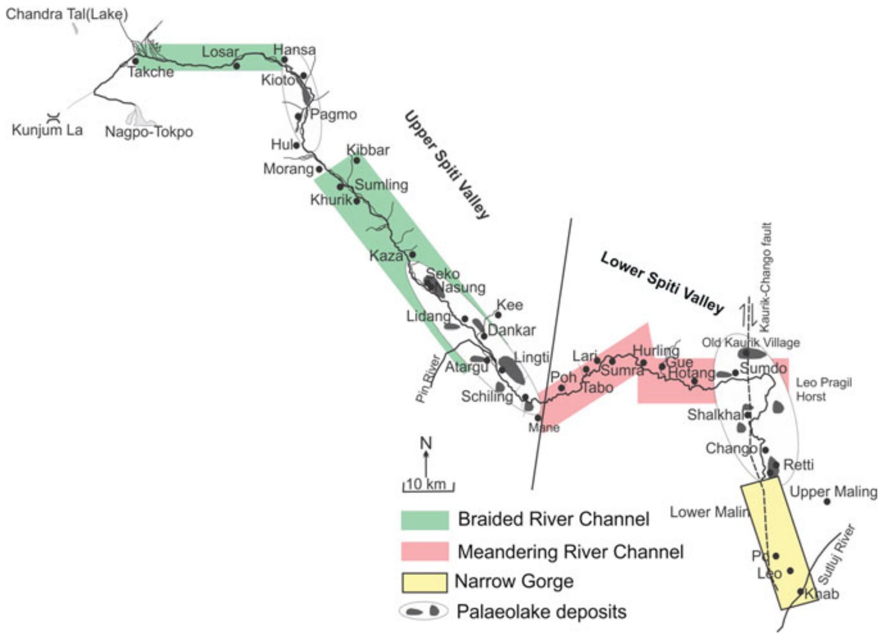

Fig. 10 Spiti River Valley showing braided river, meandering river, gorge, and the distribution of paleolake deposits in Lower and Upper Spiti River valleys

Eventually, the Bhaga flows around to the south joining the Chandra at the Tandi Village. The Chandra and Bhaga meet to form the River Chandrabhaga at Tandi. It becomes the Chenab when it joins the River Marau at Bhandera Kot in Jammu and Kashmir.

It flows from the Jammu region of Jammu and Kashmir into the plains of the Punjab, forming the boundary between the Rechna and Jech interfluves (*Doabs* in Persian). It is joined by the River Jhelum and then by the River Ravi. It then merges with the River Sutlej near Uch Sharif, Pakistan, to form 'Five Rivers,' the fifth being the River Beas which joins the Sutlej near Ferozepur, India. The Chenab then joins the Indus at Mithankot.

4 Conclusions

The rivers of the Trans- and Tethyan Himalayan terrains follow the fault lines (ISZ, KF, Spiti fault). The tributaries and other first-/second-order streams join the main river mostly at right angles showing tectonic/structural control. These rivers flow only for a certain distance in the Indian Territory. These rivers as of today are unpolluted and still away from the anthropogenic and economic impact. They have enough potential which has not been utilized properly perhaps because of its strategic location. The alarming rate of tourists that is reaching the area will certainly pose a threat to this fragile ecosystem if not dealt in an eco-friendly manner. For earth science researchers, this area is a textbook example and the vast exposures of the Quaternary sediments along the Indus (Ladakh, J&K) and Spiti rivers (Lahaul-Spiti, HP) can be helpful in generating data on paleoclimate, climate modeling, tectonics, and earth surface processes.

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Major River Systems of Jammu and Kashmir

Aparna Shukla and Iram Ali

1 Introduction

The state of Jammu and Kashmir is not only known for its picturesque beauty but also for its rich natural resources. It is the northern most state of the Indian subcontinent. The state is 640 km in length from north to south and 480 km from east to west (Annual Report 2011–2012). To its north lie Chinese and Russian Turkistan; on its east is Chinese Tibet; south and south-west lie in the states of Punjab and Himachal Pradesh; west is the North West Frontier Provinces of Pakistan, China, and Russia. The state extends between 32° 17′N and 36° 58′N and 73° 26′E and 80° 30′E longitude. It lies in northwestern Himalayas with varied relief, snow-covered peaks, antecedent drainage, complex geological structures, and rich temperate flora and fauna. It owes its distinctly rich biodiversity mainly to its unique physiography, topography, climate, soil cover, and water resources.

1.1 Administrative and Physiographic Divisions

According to 2001 census, the population of Jammu and Kashmir is 10,069,917 which constitute nearly 0.98% of the total population of the country. It is divided into three natural divisions including Jammu, Kashmir and Ladakh. However, there are two main administrative provinces, viz. Kashmir and Jammu provinces. The state with its summer and winter capitals at Srinagar and Jammu is owned by 22

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districts (10 in Kashmir, 10 in Jammu, and two in Ladakh). Area wise, Leh with a total area of 82,665 km^2 stands first, followed by Kargil, Doda, Baramulla, and Udhampur (Annual Report 2011–2012).

Physiographically, the state of Jammu and Kashmir may be divided into seven zones which are very similar with the structural components of the western Himalayas.

(i) The Plains: The plains of the Jammu region are characterized by interlocking sandy alluvial fans that have been deposited during the Pleistocene age by the streams flowing from the foothills and by a much-dissected pediment (eroded bedrock surface) covered by loams and loess (fine deposits of silt);
(ii) The Foothills: The foothills rising from 610 to 2134 m form the outer and inner zones;
(iii) The Lesser Himalayas: The Pir Panjal constitutes the first mountain range comprising mainly the western-most part of the Lesser Himalayas. It is composed of Permo-Carboniferous volcanic rocks of granite, gneisses, quartz, and slates;
(iv) The Greater Himalayas: It includes ranges above 6100 m in altitude. They act as a climatic barrier for the cold winds coming from Central Asia.
(v) Valley of Kashmir: The Vale of Kashmir is a deep asymmetrical basin which lies between the ranges of Pir Panjal and the western end of the Great Himalayas;
(vi) The Upper Indus Valley: It follows the geological strike westward, from Tibetan border to the point in Pakistan, where it gets connected to the great mountainous ranges of Nanga Parbat to run to the southward in a deep gorges cut across the strike; and
(vii) The Karakoram Range: It constitutes the highest ranges of the world like K2 (Godwin Austin), the second highest peak in the world with an altitude of 8615 m.

1.2 Climate

The climate of the state varies markedly due to its rugged topography. The southern region of the state around Jammu is typically monsoonal with an average rainfall of 40–50 mm between January and March. In summer (July and August), Jammu is very hot and the temperature may reach up to 40 °C, though erratic rainfall occurs with monthly extremes of up to 650 mm. However, in the month of September the rainfall declines and the conditions become extremely hot and dry in the month of October with minimal rainfall and temperature of around 29 °C.

Across the Pir Panjal Range, most of the precipitation falls in spring from south-west cloud bands. Due to its proximity to the Arabian Sea, Srinagar receives a maximum rainfall of 635 mm from this source, with the wettest months being March to May. Besides, there is no impact of both the South Asian monsoons and the south-west cloud bands across the main Himalayan Range due to which the climate of Ladakh and Zanskar is extremely cold and dry. The humidity of the region is very low with an annual rainfall of around 100 mm. The region is experienced by extremely cold winters with the minimum temperature of −20 to −40 °C. However, in summer, days are usually warm with an average temperature of 20 °C, but the low humidity and thin air nights can still be cold.

1.3 Soils

In the regions of Jammu and Kashmir, the soils are loamy with a little content of clay. However, the alluvium of the Kashmir valley is rich in the organic matter and the nitrogen content. The main types of the soils found in the Kashmir valley include Gurti (clay), Bahil (Loam), Sekil (Sandy), Nambaal (Peats), Surzamin, Lemb, floating garden soils, and Karewa soils. In addition, the Kandi and semi-mountainous tracts are accompanied by stony and coarse soils. In Ladakh region, the soils are bare and rocky with gravel slopes.

1.4 Water Resources of Jammu and Kashmir

The hydrological elements exercise a cumulative effect on various developmental processes. The state of Jammu and Kashmir stands apart in terms of its water wealth when considering the total runoff, overall area of the water bodies and the length of the drainage pattern. In other words, its water features are the principle component that adds to its scenic beauty. However, the distribution of the water resources is extremely uneven due to its geomorphic features. Water is mostly plentiful in the low-lying areas and is mainly categorized by a number of freshwater streams, springs, lakes, and wetlands. River Indus and its tributaries form the main river system in the state. The Indus River system includes the major rivers such as the Jhelum, the Chenab, the Ravi, the Beas, and the Sutlej (Fig. 1). The Jhelum River originates at Verinag in the Kashmir Valley, Chandra and Bhaga feeds the Chenab River in the Lahul valley (Himachal Pradesh). Similarly, the Ravi River originates from the snowy peaks of the Bara Bhangal in Chamba (Himachal Pradesh), Beas and the Sutlej Rivers are the outcome of the glacial lake near Rohtang in the Kulu valley (Himachal Pradesh), and the Manasarovar in the Trans-Himalayan region (Chandran 2009).

The main Indus River, rising in the vicinity of Manasarovar Lake, to the north of the Ladakh Range flows through the trough between the Kailas and the Ladakh ranges. The initial stream is known as the Sege Khambab up to Thangra. Beyond this place, the river pierces the mountain barrier the Ladakh Range and continues to flow in the north-westerly direction along the inner flank of the range. The river once again pierces the Ladakh Range, receiving soon after its right bank tributary, the Shyok, from across the Karakoram and the Kailasa ranges. A third and the

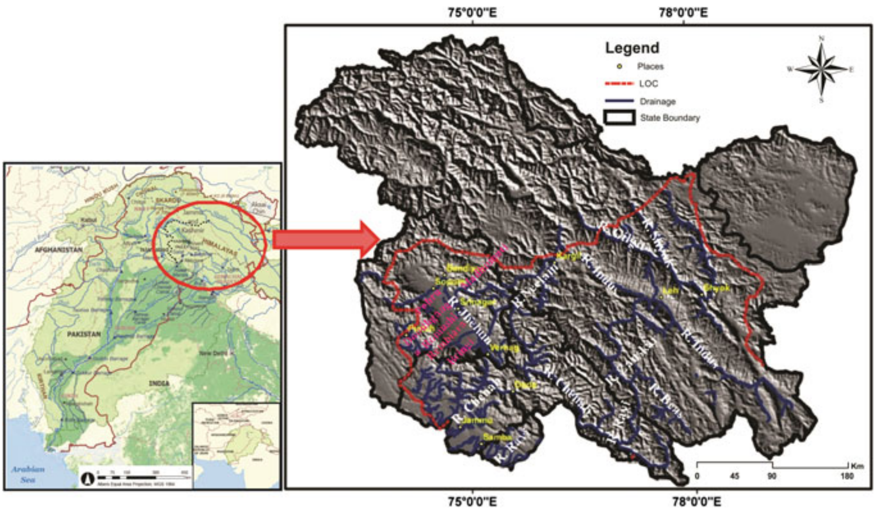

Fig. 1 River Indus and its tributaries in Jammu and Kashmir

Table 1 Catchment area of the Indus River

S. No.	Streams	Catchment area (km^2)
1	Kabul	90,600
2	Shyok	33,410
3	Gilgit	20,464
4	Zaskar	20,464
5	Shinghi	17,870
6	Dras	12,769
7	Shigar	12,769
8	Indus	2,68,907
9	Jhelum	34,747

Courtesy Hayden and Burrard, A Sketch of the Geography and Geology of the Himalaya Mountains and Tibet, first edition p. 131

another bend in the course of the river is seen 160 km downstream from Skardu where the river cuts across the Ladakh Range from the third time near Bunji. The Indus ranges between Bunji and Hazara is the typical of the Himalayan rivers, the river bed lying deep between 900 and 1400 m below the skirting mountain rim. At Bunji, the course of the river is due south, till it is diverted, by the mountain complex culminating at Nanga Parbat, to the west. The river again bends to the south near Sazin, northwest of Chilas and passes through a long and tortuous course through the Himalayan Range to debounce from the hills at Attock. Table 1 shows the major trans-Himalayan streams of the Indus along with their catchment areas (Nazir 1993).

Considering the population density of the state which is highest for the Kashmir Valley (341 persons per km^2 as compared to that of 167 and 4 persons per km^2 for

Jammu and Ladakh, respectively, in 2001), River Jhelum having a total length of 177 km becomes the most important tributary of Indus from socioeconomic point of view. Jhelum and its host of streams that drain the bordering mountain slope constitute the major drainage network of the state (Fig. 1) (Annual Report 2011–2012). Besides Jhelum, the main rivers in Jammu and Kashmir are Ravi, Chenab, Tawi, Ujh, and Kishenganga.

Apart from above, the nature has endowed the state of Jammu and Kashmir with the rich resources of springs from which these rivers mainly originate. The famous springs include the Verinag, Martand, Achhabal, Kokernag, Chirnagand Vasaknag in the Anantnag, Chashma Shahi, Vishnosar and Harmukat Ganga in the Srinagar, Tullamulla (Khir Bhawani), Vicharanag and Sukhnag in north Kashmir. Further, the state possesses a number of lakes among which most of them have the glacial origin and act as the secondary source of water. The Wular Lake which lies between Bandipora and Sopore at a distance of 75 km from Srinagar has a length of 16 km and a width of 9.6 km and forms the largest freshwater lake in India. In addition, Dal Lake with a length of 8 km and a width of 6.4 km forms the main tourist attraction in Srinagar. Other important lakes include Anchar Lake, Mansbal Lake, Harwan Lake, the Hokarsar Lake, the Konsarnag, the Gangabal Lake, the Sheshnag Lake, and the Neelang Lake. Further, the lakes such as the Tarsar and the Marsar and the two frozen lakes, namely the Sokh and Dokh which are situated in the mountainous ranges of Harmukh are also of great importance. In Ladakh region, the main lakes include the Pangong, Patlong, Thaled, Longzang, Pangor and Tsomorari (Raina 2002). The Pangong, a salty lake, is located at an altitude of 4267 m has a length of about 6.4 km and width of about 3.2–6.4 km. A picturesque view of this lake is given in Fig. 2.

Fig. 2 View of Pangong Lake (Ladakh)

Like other states of India, the role of water resources of Jammu and Kashmir in Indian economy is very important for the development of its various economical sectors. The River Jhelum and its host of tributaries supply the unending water resources and form the backbone in shaping the economy of the state. Irrigation plays a prominent role in the agriculture and other allied sectors of the state. Due to the insufficient and uncertain rainfall in the region, 25% of the total cultivated land is being irrigated by these water resources. Further, the water resources in the region have enormous potential in hydropower generation. The recent data indicates that only a small fraction of the vast potential of the River Jhelum has been harnessed for hydropower generation. The total annual power production being just 20,000 kW from all power houses. The major hydropower projects on the River Jhelum are given in detail in later section (Annual Report 2011–2012).

2 Geomorphology

2.1 Evolution and Palaeocourse of the River Indus

The remarkable fact that the Indus arises well to the north of the Himalayas and flows to the northeast, piercing through the formidable mountain chains, has puzzled many researchers. It also provides the basic clues to the unfolding of the long and circuitous process of evolution of the drainage channels. Indus has a southeast-northwest alignment in the trans-Himalayan region. According to Clift et al. (2001), the Indus River was formed shortly after the collision between the Indian and the Eurasian plates before 45 million years ago and is regarded as one of the oldest documented rivers. Further, the earliest Indus is considered older than the uplift that formed the Greater Himalayas around 25–20 million years ago in the Early Middle Miocene (Searle and Owen 1999). Since then, the river has followed a similar course along the Indus-Tsanpo Suture Zone in southern Tibet and Ladakh. Qayyum et al. (2001) stated that during the Eocene period two parallel west-flowing streams were in existence, one north and the other in south of the Himalaya. These rivers joined together and formed the Katawaz Delta at the western margin of the Katawaz Ocean which is an embayment of the Tethys Ocean. The northern stream was recognized as the palaeo-Indus. Toward the west, the sediments of the Katawaz Delta were axially fed into the Khojak submarine fan. However, it is now accreted and exposed in the ranges of the Makran accretional complex in southeast Iran and Pakistan. In spite of the tectonic events in the Early Eocene, such as the uplift of the Sulaiman Range west of Punjab, even then the main stream of the Indus River has not deviated much from its past course. According to Clift (2002), the subsequent growth of the Sulaiman Range must have pushed the course of the Indus southward by 200–300 km. In addition, Najman et al. (2003) interpreted that the palaeo-Indus first followed its modern course, cutting south through Himalaya and into the foreland basin some 18 million years ago and since then it has been flowing in approximately the same location Clift (2002). However, Shroder and Bishop (1999) opined that during the Late Cenozoic period the Indus River was flowing somewhat north and well to the west of its present location, but was captured and diverted close to the Nanga Parbat massif due to the extensional structures and down faulted topography across the Kohistan Ladakh island arc terrain. In order to trace the evolving provenance of the Indus River, Clift and Blusztajn (2005) used the isotope data and deduced that the sediment reaching the Arabian Sea changed sharply after 15 million years ago. Shortly after 15 million years ago, the sudden increase in the radiogenic sediment into the River Indus was interpreted to reflect the large-scale drainage capture of the Punjab tributaries. Further, Clift and Blusztajn (2005) opined that either the Early Miocene uplift of the Salt Range or the northeastward advance of the tributaries of the Indus which have resulted in the capture of the tributaries of the Ganga may have caused the major drainage reorganization.

Considering the restricted migration of the main channel, the Indus River differs from several other large rivers such as the Nile (Said 1981), Colorado (Elston and Young 1991), and Amazon (Hoom et al. 1995). The present course of all these rivers differs from their past locations either during the Late Miocene or later periods mainly due the regional uplift in their basins. The Indus remained pinned in the suture zone and flowing along an active strike-slip plate boundary within its foreland. However, the major changes are observed near its mouth. At about 20,000 years ago, the location of the main depositional lobe of the Indus Delta and the main channel had shifted significantly westward four times until it came to occupy its present course (Kazmi 1984). Besides, the further movement of the River Indus and its delta toward west is prevented by the uplifting ranges running north from Karachi.

2.2 Major Rivers and Their Geomorphology

2.2.1 River Jhelum

The Jhelum River emerged around 85 kyr (Inam et al. 2004) and is the important left bank tributary of Indus River and is commonly known as “The Veth.” The river originates as crystal clear water from Verinag Spring at the piedmont of Pir Panjal Range at an altitude of about 2832 m above sea level. Initially, the river flows in a north-westerly direction for about 80 km before entering Srinagar city (Fig. 1). It follows a course through the middle of Srinagar city for a length of about 23 km and then 45 km downstream of the city to empty itself in the Wular Lake. For a short distance of 32 km from Wular Lake to Baramulla, it moves along a somewhat southerly track. From Baramulla to Muzaffarabad for a distance of 129 km, it flows along the Jhelum Valley road where it is joined by Kishenganga River and bending toward the south, the river takes southward course and is joined by the River Kunar between Muzaffarabad and Kohala. Further downstream of Mangla Dam, it moves toward south and then westward up to Khushab. After Khushab, the river flows in southerly direction till confluence with river Chenab at Trimmu, Jhang (Pakistan). It serpentines over a length of about 821 km with catchment area of about 34,374 km^2 out of which 17,978 km^2 lies in Jammu and Kashmir and rest of 16,396 km^2 lies with Pakistan.

The river makes some of the finest meanders over this stretch and lays down a good deal of its suspended load along its banks. The alluvial deposits of the valley offer the best slope for such undercutting and deposition on the outside and the inside of the bends, which have grown into big meander loops. The Srinagar lakes, as one would tend to agree, may be regarded as the "enlarged old oxbows and abandoned courses of the Jhelum." This is certainly not true for the Wular, whose connections with the original deluge of Kashmir seem to be quite intimate.

The Jhelum hosts a number of streams that drain the bordering mountain slopes and together constitute the drainage network of the Kashmir Valley. Admittedly, the hydrograph complexity is of high order, yet in order to promote understanding, the following drainage basins may be identified as:

(a) Right bank drainage basins—Sandran, Lidder, Bringi, Aripat Kol, Aripal, Harwan, Sind, Erin, Madhumati, Pohru and Vij-Dakil; and
(b) Left bank drainage basins—Vishav, Rambiara-Sasara, Romushi, Dudhganga-Shaliganga, Sukhnag-Ferzepur, and Ningal.

A brief idea about the tributaries forming right bank and left bank drainage basins is as follows.

(a) ***Right bank tributaries***

The Sandran: The Sandran rises in Pir Panjal, below the Kakut peak. From its source to a point close to Verinag, the river passes through a deeply carved channel, studded with big boulders. As it debounces into the plain, the river sheds its load and divides itself into a number of channels which later unite to form a main stream. The Sandran has a perennial flow of water only in its lower reach of about 8 km before its merger with the Bringi. The combined waters of the Bringi, Sandran, and the Aripat Kol merge with the Jhelum a little above Khanbal, near Anantnag. The Sandran has a small catchment area, extensive over only 291 km^2. From source to confluence with the Bringi has a total length of 51 km only.

The Bringi: The headstreams of the Bringi catch the snowmelt from over a wide area in the Pir Panjal close to the source of the Sandran. After the Anlan and the Razparyin unite above the village of Wangom, the river after the confluence is called the Bringi. The stream then takes a west-northwest course flowing for some 25 km up to south of Anantnag where it unites with the Sandran.

The Aripat Kol: Before merging with the Sandran, the Bringi receives the waters of the mountain torrent known as the Aripat Kol. It has a small catchment area below the Niltup and Astanbal peaks in the Great Himalayan range and drains the Kutihar valley.

The Lidder: Lidder forms the major right bank tributaries of the River Jhelum. Rising at the base of Kolahoi and Sheshnag snowfields, its two main upper streams—the West and the East Lidder—unite at Pahalgam. The western branch, after having received the Lidderwat, an upland torrent from the Tarsar, flows for 30 km before its merger with the east Lidder. The latter collects the snowmelt from the Sheshnag and traverses a course of a little over 24 km before reaching Pahalgam.

Before Pahalgam, the Lidder passes through a narrow valley, studded with massive boulders and overlooked by dense forests, till it debounces into a wide alluvial fan. At the head of its delta, the main stream divides into a number of channels, braiding being a common characteristic of all the rivers in the valley, which fan out to form a wide alluvial plain and merge with the Jhelum between Khanbal and Gur.

Between Pahalgam and Gur, the Lidder falls from 2129 to 1591 m. The gradient between the source and the confluence is, however, far more steep.

The Aripal and the Harwan: The two tiny streams—the Aripal and the Harwan—are tightly interposed between the two major affluents of the Jhelum in an outer fringe of the ridges skirted by the Pambagai and the Nao Gul heights. The Aripal, besides getting its water supply from the famous Aripal Nag spring, also drains the Wustarwan before its confluence with Jhelum above Awantipora. All drainage from the slopes of the Harawar, Barzakut, Mahadeo, and Sarbal escapes into the Dal Lake through the Harwan and a number of other mountainous torrents. Some of the feeders of the Harwan originate as high up as the glacial tract west of Tarsar (3781 m).

The Sind: The Sind, with a course of 100 km and a basin area exceeding 1556 km^2, is perhaps the most well-developed side valley of the Jhelum. Its uppermost feeders rise below the lofty peaks near Zojila, as a number of the other headstreams join near the Amarnath, Kolahoi and Panjtarni snowfields. At Sonamarg, the gushing torrent flows through a narrow channel with deeply incised caves in the bordering rocks on either bank. Below Kangan, the valley widens out, although the incising tongue of the arable reaches as far up as Wangat (1989 m) in the Wangat Valley, and Gund (2437 m) in the Sind Valley. Flowing on the northern flank of a boldly projected ridge culminating in Harawar (3449 m), the river makes a knee-bend above Ganderbal, before entering into a wide floodplain. As the river sheds its load, its own channels get choked with debris and the mainstream bifurcates into a number of channels over an extensive deltaic core. One of the branches escapes into the Anchar Lake, while the others merge with Jhelum near Shadipora.

Up to Kangan, the Sind falls 3433 m in about 69 km (50 m in 1 km), and from Kangan to Shadipora the gradient is gentle, i.e., 6 m in 1 km.

The Erin and Madhumati: Both the Erin and Madhumati belong to a larger group of tiny streams which feed the Wular Lake. The Erin rises from the western flank of the Harmukh. After pursuing a course of about 24 km through a neatly cascade valley, it falls into the Wular Lake, south of Bandipora. The stream serves as an important artery of transport for timber. It is characterized by a steep gradient. Farther north, the Madhumati, or Bod Kol, drains the northern slopes of the

Harmukh precipice with its feeder streams spread over a vast area between Nagmarg in the west and Sarbal Nag in the east. From a point little above Bunakut, the valley starts opening up latterly, forming an alluvial triangle which lends itself to intensive exploitation. The Madhumati empties itself into the Wular Lake near Bandipora after traversing a course of 39 km. Like the Erin, the Madhumati also falls steeply, the average fall being 103 m in 1 km.

The Pohru: The Pohru, with a fine network of dendritic streams, occupies the northwestern corner of Kashmir Valley. Consisting a number of sizable tributaries, such as Lolab, Kahmil, Talar, and the Mawar, the Pohru has a series of palm leaf-shaped valleys with their interesting mosaic of land use. Almost all the tributaries have their origin at high elevations in the crest of the north Kashmir Range which divides the waters of the Pohru from the Kishenganga system.

From Rainpura, near the confluence of the Kahmil and the Lolab of its merger with Jhelum, the Pohru falls over 23 m in 54 km between Handwara and Suil; above a distance of about 30 km, the fall is only 4 m.

The Vij: The Vij, a tiny stream flowing from the northern slopes of the ridges culminating in Vij peak (12,111 m), merges with the Jhelum just below Dobagh, close to the confluence of Pohru. The Dakil joins the Jhelum, 5 km downstream at Ludur. The Vij and the Dakil together drain a basin area of about 140 km^2.

(b) ***Left bank tributaries***

The Vishaw: The source of the Vishaw lies in the southeastern corner of the Kashmir Valley, close to Jhelum. The river drains the entire northern face of the Pir Panjal between the Sundartop and Budil Pir and thus, has an extensive catchment area which reduces upper Jhelum to a tiny rivulet. In fact, the Jhelum draws heavily on Vishaw feeders in the initial stage. While passing through volcanic strata in the Pir Panjal range, the Vishaw forms the famous cataracts of Ahrabal. It merges with the Jhelum above 12 km below Kulgam. One of the bifurcated channels of the Vishaw, however, continues farther north merging into the Rembiara near Nyaiyun not far from the latter's confluence with the Jhelum.

The Vishaw falls from 3975 to 1568 m or 41 m in 1 km. The fall in the lower reach between the Kulgam and the confluence is, however, very gentle, i.e., 1 in 77.

The Rembiara: The Rembiara rises in the Rupri ridge of the Pir Panjal, its main feeders originating from Rupri peak and the Bhag Sar Lake, on the one hand, and the Pir Panjal and the Naba Pir passes on the other. Above Shupiyan, the river divides itself into the marshy land west of the Awantipora before finally merging into the Jhelum. The Rembiara alone has a course of 60 km; the Sasara branch flows for another 40 km.

From its source to the confluence, the Rembiara registers a fall of 2446 m or 41 m in 1 km which is smaller in gradient of the Vishaw.

The Romushi: The headwaters of Romushi (also known as Ramshii or Kachgul) draw their waters from the snowy peak of Kharmarg (4603 m) near Naba Pir pass in the Pir Panjal. The upper torrents unite near Pakharpur to give rise to a sizable stream which passes through wide sandy bed in the karewa slopes. It merges near the Jhelum near Wudipur, below Awantipura. In all, it traverses a course of 51 km and its bed below Pakharpur has an average gradient of 16 m in 1 km.

The Dudhganga: Rising below the Tatakuti Peak in the Pir Panjal Range, the Dudhganga flows north-northeast to finally merge into the marshy land west of Srinagar. Near Bagh Sahab Ram, the Shaliganga joins the Dudhganga before the united stream loses into the Nambal, a few kilometers below. A good amount of discharge from the river is never allowed into the Jhelum as it is diverted toward the west into the marshy land. The Dudhganga traverses a course of 50 km and has an average gradient of 63 m in 1 km.

The Sukhnag: The slopes of Pir Panjal Range between the Nurpur and the Chinamarg passes are drained by a multitude of torrents unifying themselves into the Sukhnag and the Ferzepur. These two streams take care of the drainage of the Toshmaidan and Gulmarg, respectively. Descending from the mountains, the Sukhnag passes through sand-choked bed across the Karewas, finally merging into the marshes of Rakh Arat, west of Hokersar. The Ferzepur empties itself through myriad channels into the Haigam Jhil and the Sultanpurach Rakh. Both the marshes are connected by a spill channel constructed to drain out the flood water. With a total length of just 41 km, the Sukhnag has a fall of 56 m in 1 km.

The Ningal: The Ningal is the last major stream in the Kashmir Valley which joins the Jhelum on the left bank. The upper feeders of the Ningal rise below the Khan Pathri (3809 m) and Apharwat (4141 m) peaks of the Pir Panjal above Khilanmarg. Flowing for about 38 km in a northeasterly direction, the Ningal pours itself into the Jhelum immediately after the latter's debounce from the Wular Lake.

The detailed information related to river Jhelum and its tributaries has already been propounded by Raza et al. (1978).

2.2.2 The Kishenganga (Neelam) River

The north catchment of Kishenganga is delimited by the Great Himalayan Range as few of its tributaries flow down the slopes of Nanga Parbat (8126 m). Its source is fed by glaciers high above the Sindh Valley. It rises from the high mountain complex of Dras along west and Deosai plateau along south. The flow in Kishenganga is contributed by a number of tiny tributaries. The waters from Vishnav Sar and Prang Sar also join it near source. At Shardi, it makes a sharp bend which is akin to the bends of the Indus at Bunji, of the Jhelum at Wular, and of the Chenab at Kishtwar. The Kishenganga has a narrow and elongated basin, the width in many places being only 20 km or so.

The Kunhar River, also flowing from the same mountain complex, merges into the Jhelum south of its great bend at the confluence of the Kishenganga and the Jhelum near Muzaffarabad (Ali 2013).

2.2.3 The Chenab River

The River Chenab is one of the largest tributaries of Indus basin. It has its origin in the Kulu and Kangra districts of Himachal Pradesh. The name Chenab appended to the combined streams coming from two sources and directions much below their confluence. One of the streams is Chandra (Moon) and another Bhaga (Luck) also Snraj Bhaga. Chandra emerges from a lake where as Bhaga joins it near Tandi. Both the rivers are of equal magnitude and are jointly called Chandra-Bhaga. These two streams confluence at Tandi in Himachal Pradesh, merge, and make a giant river known as Chenab. The river has a total length of about 1363 km and a total catchment area of about 41,899 km^2 of which 21,676 km^2 (52%) lies in Pakistan, 17,430 km^2 (42.5%) in Jammu and Kashmir state, 2792 km^2 (6.5%) in Himachal Pradesh. After the confluence at Tandi, it enters Pangi Valley of Chamba district near Bhujind and leaves the district at Sansari Nallah to enter Podar Valley of Kashmir. The river is fed by innumerable tributaries from its headwaters and gains immense power and momentum on entering the state above Kishtwar. From Kishtwar, the Chenab follows south-westerly direction for Doda, through deep gorges along the northern base of the Pir Panjal Range. Then, it pursues westerly direction toward the fort of Reasi up to Akhnoor. The total length of the river between Chandra-Bhaga confluences to Akhnoor is about 410 km. Due to the mountainous terrain of the Chenab Valley and deep gorges, the river is insignificant for irrigation and cultivation. The river enters Pakistan through Sialkot district, near Dewara village of Marala at 32° 40′N latitudes and 76° 29′E longitudes. From Pakistan border, the river pursues the south-west direction and is joined by the Jhelum River a little above Trimmu. About 64 km below Trimmu, the River Ravi joins it. Thus, meandering all along its course in Punjab with other tributaries, makes a junction with Sutlej River, the combined rivers now are called Punjnad and about 64 km below Punjnad it meets with Indus River at Mithankot (Nazir 2011).

2.2.4 The Tawi River

The Tawi River is a main left bank tributary of the Chenab River. It originates from the lapse of Kali Kundi glacier in Kalaish range, at an altitude of 4419 m above the mean sea level. In its upper course, it drains Doda Valley that penetrates deep into the east for about 64 km from Chennai. It flows to north westerly direction toward Chenani for about 45 km. In its upper part, it collects the water of some small streams. From Chennai, it turns to south-west for a distance of 24 km through a deep valley. Near Udhampur, the river pursues southerly direction. On the right bank, the river receives the waters of Burmin, Sulah Khad, and Dudar (on right bank) and Ramna Garwali Khad (on the left side) and flows through westerly direction. After flowing toward west, the river reaches the town of Jammu and finally empties into Chenab River. From source to confluence with Chenab River, the Tawi River has a total length of about 112 km and its catchment area is about 2168 km^2, falls in the district of Doda, Udhampur, and Jammu.

There are other small tributaries of Chenab River such as the Minawar Tawi, the Marao-Wardwan, and the Ans rivers which increase the volume of water in Chenab River (Ali 2013).

2.2.5 The Ravi River

The Ravi River is smallest river of the Punjab and all other transboundaries of India and Pakistan. This river is formed by three principal streams which are the Ravi Proper, the Budhil, and the Nai, which make a triple junction below Wulas in the Chamba Valley. The right bank tributaries of the Ravi include the Budhil, Tundahan, Beljedi, Saho, and Siul; the left bank tributary worth mentioning is Chirchind Nala. Flowing in north westerly direction from its source, it drains between the Pir Panjal and Dhauladhar ranges through narrow valleys and enters the Chamba district of Himachal Pradesh. After passing through the Chamba district, it leaves the Himalaya at Basoli and traverse close to Kathua. It makes a sudden westerly bend and enters the Punjab Plain near Madhopur. Some distance below Madhopur, it demarks boundary between the two Punjabs, i.e., west in Pakistan and east in India. In plain area of westerly Punjab (Pakistan), it takes a south-westerly direction passing through Lahore and Chichawatni and falls into Chenab below Sardarpur. Flowing over a length of 1059 km, it joins the Chenab River at Trimb (Pakistan). Its total catchment area is about 25,333 km^2 out of which 7094 km^2 (29%) lies in India and 18,239 km^2 (71%) lies in Pakistan (Ali 2013).

2.3 Channel and Drainage Patterns of River Indus

Considering the channel patterns of the river, it is observed that the nature of the river system is controlled by its slope and sediment load. On this basis, River Indus is braiding in the north and meandering in the south. The tributaries are multi-thread and braided in upper reaches and are characterized by large bars or islands (3–8 km long). The large bars or islands are, however, less frequent. Moreover, permanent channels are also existing which are considered as anastomosing in nature, consisting mainly of large main channel and smaller flood channels. On the other hand, single thread channels are usually meandering and are found in lower reaches particularly when the river enters lowlands and meets the Arabian Sea. At low lands, the water loss due to irrigation results in downstream change from braided to meandering. The braided upstream channels are characterized by large sediment load, high valley slope, and enormous discharge. In spite of the continuous water loss downstream, the flood depth area increases. In the middle reaches, the river channel patterns are transitional between braided and meandering and are characterized by fairly sinuous multichannels separated by macrobars. The channel pattern of the Indus River System in the Punjab Plain was classified by Abbasi (1989) into multichannel low sinuosity in the northern reaches, intermediate in the middle reaches, and single chain high sinuosity in the southern reaches. The first-order channels are usually 5 km wide and are characterized by low-sinuous channel pattern. Additionally, the second-order channels are 1–2 km wide and are separated by macroforms or large complexes. Further, these microforms are up to 10 km long and 2 km wide and dissected at many places by small third-order channels.

The river systems of the Jammu and Kashmir have disparate drainage patterns, i.e., the fluvial processes being independent on the quantum of slope and the nature of the rock material which differ from region to region (Fig. 3). The drainage of the Great Himalayan slopes is dendritic, though in certain areas, it tends to be linear and even irregular. Perhaps, the best example of a dendriform is seen in Pohru River System which makes a huge banyan tree-like canopy with its trunk attached to the Jhelum near Sopore. Another notable feature of the drainage of the northern arm of the valley and its antecedence; typical examples of this are seen in the Sindh and the Lidder valleys. There are at least two localities, in which, the streams seem to have typical diverging and converging trends. Around Kolahoi, one notices the radial nature of the drainage, while the bowl of the Wular Lake stresses the centripetal character of rivers.

The drainage of the Pir Panjal offers a sharp contrast to that of the Great Himalayan slopes. The northern flank of the Pir Panjal Range is less extensive in width and does

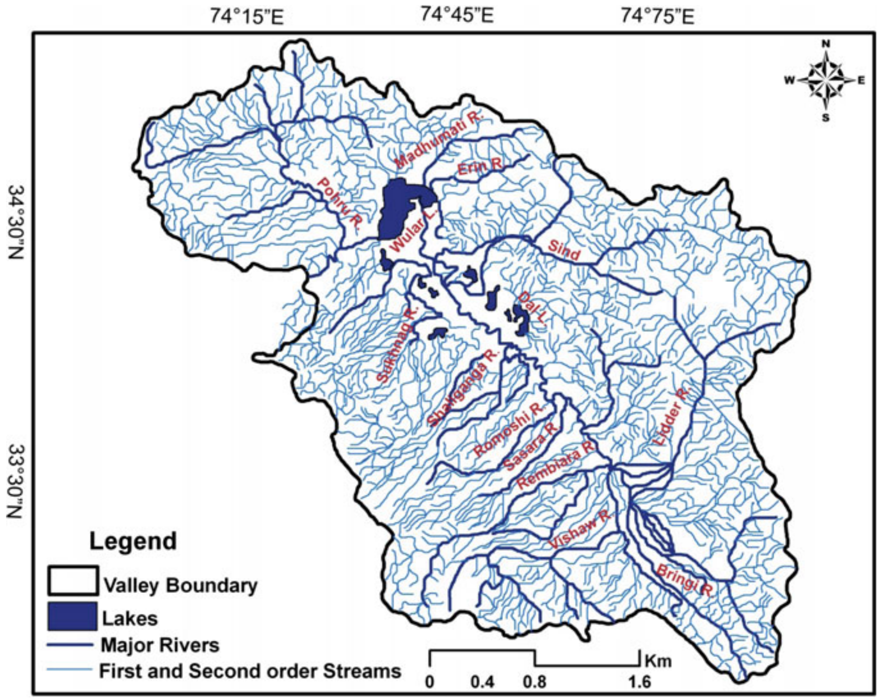

Fig. 3 Disparate drainage patterns of the tributaries of River Jhelum, draining the valley of Kashmir

not seem to promote the lateral development of stream channels, i.e., the short lateral course of the Vishaw being the only exception. The streams come down the mountains in parallel and often irregular lines. In the upper reaches, they have a dendritic pattern, lower down their courses and have aligned parallel to each other. As the streams cut across the Karewa beds, they develop braided channels, braiding and constant shifting of channels being caused by the rapid deposition of sand and gravel in the stream beds. This intertwined nature of the stream channels is most marked in the cases of the Dudhganga, Sukhnag, and Ferzepur. The uplift of the Pir Panjal Range during the Pleistocene and the later tilting and unfolding of Karewa beds have all added to the complexity of the drainage along the southern flank of the valley.

A striking feature of most of the basins is the dominance of the streams of first order and second orders. The cumulative percentage of the stream segments of the first two orders is highest in the Sindh River basin—89.435%— and lower in the Sandran river basin—50%. This proportion is above 80% in as many as eight basins; it is above 70% in another seven basins. Thus, the streams of the first two orders together account for three-fourths to nine-tenths of the cumulative channel lengths. The lower order stream segments are, however, randomly distributed, and there seems to be no direct relationship between the area of the drainage basin and the streams.

Lying in the upper part of the mountains, the streams of the first two orders generally flow only intermittently, flushing out the instant flood from the rain or the snowmelt to the third- and fourth-order streams. Their delivery role is, however, fundamental as they determine the volume of water that would flow down the higher order streams. The delivery system is such that while the first two orders are ephemeral those of the third and fourth orders flow perennially.

3 Socioeconomic Importance

Water being the elixir of life has been the driving force behind flourishing and development of new civilizations. Therefore, for availability, quantity and quality of water is still the fundamental cause of socioeconomic prosperity and well-being of any region. As already mentioned, the state of Jammu and Kashmir also relies heavily on its water resources for its multifaceted development. Main sectors of the state which are directly dependent on water resources include agriculture, irrigation, horticulture, hydroelectricity, and tourism. Water resources of Jammu and Kashmir are governed by special commandments laid down under the Indus Water Treaty (IWT).

3.1 Agriculture, Horticulture, and Irrigation in Jammu and Kashmir

Agriculture being the prominent occupation of the people of the region, hence forms an important aspect of the economy of the state. The agriculture and other allied sectors contribute as much as 25.81% to the Gross State Domestic Product (at 1999–2000 prices) for year 2008–2009. Nearly, 80% of the total population of the state is dependent on revenue generated from agriculture. The state is known for its mono-cropped and rain-fed economy with 40% area falling in the Jammu division and 60% in Kashmir. However, this sector is heavily dependent on irrigation system for its water needs. The cultivation of fruits and vegetables in the state is ideally supported by the fertile soils, sub-tropical climate, and suitable agro-climatic conditions. Horticulture has become quite popular in recent times particularly for economic reasons and occupies nearly 20% of the total cultivated land. The major fruit varieties which are grown in the state include pears, apples, cherries, mulberry, apricots, plums, peaches, almonds, and walnuts. It has been estimated that during the year 2008–2009 about 3.07 lakh hectares of land was under fruit cultivation and nearly 4.5 lakh families were directly or indirectly engaged with horticulture activities (www.hortikashmir.gov.in).

Further, the major crops of the region include rice, wheat, and maize. For the development of agriculture, irrigation plays a crucial role. Canals form the most important system of irrigation and account for about 92% of the total irrigated area. About 41% of the gross cropped area and 42% of net cropped area is under irrigation. The snow-fed Jhelum and its tributaries supply water to these canals throughout the year and never dry. About 1976 km^2 of land in Kashmir is irrigated by canals. The major canals in the valley are the Martand Canal (50 km), the Shakful Canal, the Lalkul Canal (3 km), the Zainagir Canal (47 km), the Dadikul Canal (19 km), the Nur Canal (13 km), the Sumbal Canal (35.5 km), the Zainapur Canal (32 km), the Nandikul Canal (30 km), the Parimpur Canal (8 km), the Mahind Canal (l6 km), the Avantipur Canal (36 km), the Kayal Canal (50 km), the Rishipora Canal (18 km), and the Babul Canal (22.5 km) (www.hortikashmir.gov.in).

3.2 Hydroelectric Power Projects

Development of a state is immensely dependent on the power resources. It holds a key for the sustained economic growth; commensurate growth in power supply is required to ensure that economy keeps growing. Jammu and Kashmir has immense potential for development of hydraulic power. Figure 4a gives a view of Bagliar hydropower project established on the Chenab River in the southern part of district Doda. The state has an estimated hydropower of 20,000 MW of which 16,480 MW has been identified. Out of the identified potential, only 1478.70 MW or 9% has been harnessed till the end of the 10th Five Year Plan. Table 2 shows the major hydropower projects of the state.

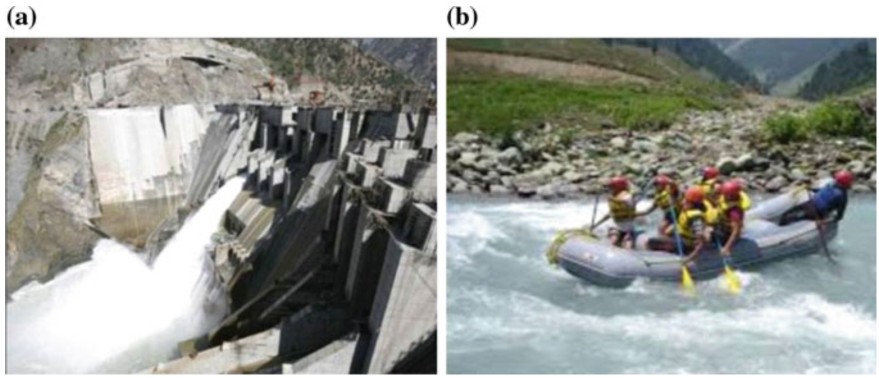

Fig. 4 **a** Bagliar hydropower project established on the Chenab River (Doda). **b** Water sport in the River Lidder, one of the greatest attractions for tourists

Table 2 Major hydropower projects on Indus Basin (Annual Report 2011–2012)

S. No.	Name of the power house	Configuration	Installed capacity in MW
Jhelum River Basin			
1	Lower Jhelum	3 × 35	105
2	Upper Sindh-I	2 × 11.3	22.6
3	Ganderbal	2 × 3 × 2 × 4.5	15
4	Upper Sindh-II	3 × 35	105
5	Pahalgam	2 × 1.5	3
6	Karnah	2 × 1	2
Chenab River Basin			
7	Chenani-I	5 × 4.66	23.30
8	Chenani-II	2 × 1	2
9	Chenani-III	3 × 2.5	7.50
10	Bhaderwah	2 × 0.5	1
11	Baglihar	3 × 150	450
Ravi Basin			
12	Sewa-III	3 × 3	9
Indus Basin			
13	Iqbal	3 × 1.25	3.75
14	Hunder	2 × 0.20	0.40
15	Sumoor	2 × 0.05	0.10
16	Igo-Mercellong	2 × 1.50	3
17	Haftal	2 × 0.50	1
18	Marpachoo	3 × 0.25	0.75
19	Barzo	2 × 0.15	0.30
20	Stakna (with J&KPDD)	2 × 2	4
21	Salal HEP	6 × 115	690
22	Uri-I	4 × 120	480
23	Dul-Hasti	3 × 130	390
		Total	*1560*

3.3 Tourism

Due to the vast resources and growing economy, the state of Jammu and Kashmir has immense potential for the sustenance of the tourism industry. One of the main reasons behind the huge tourism potential of the state rests with its pristine water resources in form of lakes, springs, and rivers. These make most indispensable part of the famous natural beauty of the state. This sector has not only generated economic activities in the tertiary sectors but also has imparted jobs to a large number of people. For example, water sport becomes the main adventure of the tourists in summer (Fig. 4b). The tourism tag has always placed the state of Jammu and Kashmir in the limelight at the national level as well international level. Between 1990 and 1996, the average flow of tourism was just 10,000 per annum. However, the tourist inflow has continuously been increasing from 6,912,000 in 2004 to 8,650,255 in 2009, which means an increase of 25.15%. There is an immense increase in the pilgrim visitors to Mata Vaishno Devi by 25.53%, domestic tourism by 53.26%, and foreign tourists by 22.58% for the same period. The overall tourist inflow in perspective of all these three categories of the state has increased by 22.58% from 2004 to 2009 (www.horti-kashmir.gov.in). Thus, conservation and maintenance of water resources of Jammu and Kashmir have a direct impact on its tourism sector.

3.4 Indus Water Treaty

The Indus water system and its well-managed network of irrigation canals were disrupted by the partition of India and Pakistan (Gulhati 1973). Many of the canals were severed from their headworks fell in India, while the land being irrigated by their waters fell in Pakistan, which led to dispute immediately after partition of 1947. The agricultural land of Pakistan was mainly irrigated by the Indus water system. However, after the partition the source of the Indus remained with India which became insecurity for Pakistan (Singh 2011). India asserted that Pakistan being a lower riparian country could not claim any property rights on the river water of the Indian Punjab. But Pakistan argued with strong principle of International Water Law that all the co-riparian countries had an equal right to the share of water in proportion to area, population, and agricultural utilizations. Thus, a strong hostility had risen over the water use after partition. To resolve this issue, an Inter-Dominion Agreement was signed between India and Pakistan in 1948 to serve as an ad hoc agreement for considering both sides' claims to share water. The negotiation process was continued for twelve years until a landmark agreement—the Indus Water Treaty (IWT)—was signed on September 19, 1960, under the auspices of the World Bank. The Treaty addressed both the technical and financial concerns of each side and included a timeline for transition. The basic aim of the Treaty is to increase the amount of water available to the both parties and to distribute the water resources equally. The salient features of IWT are as follows.

3.5 Provisions Regarding Eastern Rivers

(a) All the waters of the Eastern Rivers (Beas, Ravi, and Sutlej) shall be available for unrestricted use in India;
(b) Except for domestic and nonconsumptive uses, Pakistan shall be under an obligation to let flow and shall not permit any interference with the waters of the Sutlej Main and Ravi Main in the reaches where these rivers flow in Pakistan and have not yet finally crossed into Pakistan; and
(c) All the waters, while flowing in Pakistan, if any, tributary which, in its natural course, joins the Sutlej main or the Ravi main after these rivers, have finally crossed into Pakistan shall be available for the unrestricted use of Pakistan.

3.6 Provisions Regarding Western Rivers

(a) Pakistan shall receive for unrestricted use all those waters of the Western Rivers (Jhelum, Chenab, and Indus); and
(b) India shall be under an obligation to let flow all the waters of the Western Rivers and shall not permit any interference with these waters, except for the domestic use, agricultural use, and generation of hydroelectric power.

3.7 Provisions Regarding Eastern and Western Rivers

(a) The use of the natural channels of the rivers for the discharge of flood or other excess waters shall be free and not subject to limitation by either party or neither party shall have any claim against the other in respect of any damage caused by such use; and
(b) Each party declares its limitation to prevent, as far as practicable, undue pollution of the waters and agrees to ensure that, before any sewage or industrial waste, it will be treated, where necessary, in such manner as not materially to affect those uses.

Though the Treaty was being appreciated in different quarters, however, it has drawn flaks as it allocated Pakistan to share 80% of the Indus water and only 20% to be shared by India. Apart from this, the major issue attached to this Treaty is that it deprived the water rights of the state of Jammu and Kashmir. As a result of this, the Treaty has imposed restrictions on Jammu and Kashmir due to which the state cannot exploit its water resources with the prior approval of the Indus Commission. As a result of this, the Treaty has limited the state in its use of water resources thereby severely affecting its developmental processes. Conforming to the criteria of the Treaty, the state is unable to fully exploit the water potentialities of the rivers such as the Indus, Jhelum, and Chenab. Further, taking into consideration the currently assessed and harnessed hydro-potential, the Treaty does not allow the state to generate more than 10% of its hydropower and irrigate more than 40% land from Western Rivers (Parvaiz 2008). Detailed implications of the Treaty with reference to the hydropower development of Jammu and Kashmir have been discussed by Ali (2013).

3.8 Impact of Climate Change

The impact of climate change on the water resources of Indus has generated greater concerns since last decade. An expectation of dramatic decrease in river flow has arisen on the basis of the assessment of the given temperature changes and global climate change projections World Bank (2005). These concerns are also supported by the findings of Hasnain (1999) and Shrestha et al. (2004) according to whom there has been a significant deglaciation and recession across the Hindu Kush Himalayas including Eastern and Central Himalayas. While assessing the hydro-climatological variability and its implications on water resources in Upper Indus Basin, Archer and Fowler (2004) concluded that most of the flow in the Upper Indus is obtained from snow and glacier melting. They further reported that there is a strong correlation between the winter precipitation and summer precipitation; however, these links may operate in opposite directions glacier and snow-fed hydrological regimes. In addition, they showed that there is significant increase in winter, summer, and annual precipitations. Besides, the long-term records at Gilgit, Skardu and Srinagar showed that there is no statistically significant trend in annual or seasonal precipitation (Romshoo 2012).

During 1961–2000, Archer (2002) has shown that although the mean annual temperatures are generally rising in line with the global average, summer temperatures (July–September) have been falling at many valley stations in the Karakoram. From 1961–1999, there has been significant increase in precipitation in both winter and summer precipitation in Upper Indus Basin Archer and Fowler (2004). There has been a significant trend of increasing annual temperature from 1960 to 2007 in Lower Indus Basin Fowler and Archer (2006). Further, there is evidence that historic climatic trends in the UIB have not fallen in line with global trends with respect to seasonal trends in temperature (Fowler and Archer 2006) or precipitation (Archer and Fowler 2004). Besides, Bhutiyani (1999) used the water balance method to compute the mass balance of the Siachen Glacier in the Nubra Valley, Jammu and Kashmir, the largest glacier in the Himalayas from 1986 to 1991. Moreover, it has been concluded that on the basis of the derived climate-runoff relationships, it is predicted that the decreasing trend in summer temperature will result in decrease in seasonal runoff particularly in glacier-fed catchments such as River Hunza. However, it may increase the runoff volume on snow-fed catchments due to decreased evaporative loss.

In light of the scenario discussed above, the indicators of the climate change are quite clear and loud in the Indus Basin. The climate change is already impacting several sectors in the region and has adversely affected the cryosphere, hydrology, land system, forestry, and even the livelihood of the communities inhabiting the Upper and Lower Indus Basin (Romsho 2012).

3.9 Hazard Vulnerability of the State

The rugged mountainous terrain, climate, and the human activities have made the state of Jammu and Kashmir vulnerable to the vagaries of nature. The natural hazards which are common here include landslides, earthquakes, avalanches, and floods. Vulnerability of the state to seismic hazards is quite high owing to numerous active faults and lineaments in the region. The districts which lie in North and South of the state are categorized in Zone V. The areas like Gilgit, Chilas, Gilgit Wazarat, Muzaffarabad, Punch, Anantnag, Mirapur, Reasi, Udhampur, Jammu, Kathua, Leh, Ladakh, and Tribal Territory districts lie in Zone IV. In India, the earthquake database is still incomplete particularly before 1800 AD. In particular region, these zones thus offer a rough guide of the earthquake hazards and hence need to be regularly updated. Apart from the small routine tremors, the state has experienced moderate to large earthquakes in almost in all parts of the state. A major earthquake struck the India–Pakistan border on the morning of October 8, 2005. It had a magnitude of Mw = 7.6 and was felt strongly in the state resulting in huge damage of life and property. Besides earthquakes, tectonic and structural complexities together with slope instabilities introduced due to human interventions make landslides quite frequent and significant hazard in the state.

Considering the water-related hazards prevalent in the state, it is observed that floods, bank/soil erosion, and deterioration of water quality due to anthropogenic activities are the major cause of concern.

3.10 Floods

Unlike many other rivers of the world, the Indus and its tributaries receive practically all their water in the upper hilly parts of their catchments. Accordingly, their flow is highest when they emerge from the foothills. There is a little surface flow which is added from the relatively large but arid part of the catchment in plains. Thus, the state of Jammu and Kashmir has experienced the recurrent floods causing an enormous devastation. Through a narrow passage down the valley, the Jhelum is faced with predicament of carrying the cumulative discharge from all of its streams. The silting in the river goes on choking the channels infinitely which incapacitates it from performing its primary function. The past behavior of Jhelum shows that it has a maximum capacity of "safety" carrying only half of a high flood discharge. The other half has but to spill over the banks breaching the embankments that have been constructed to contain floods. Thus, in topographic situation, in which the Jhelum is,

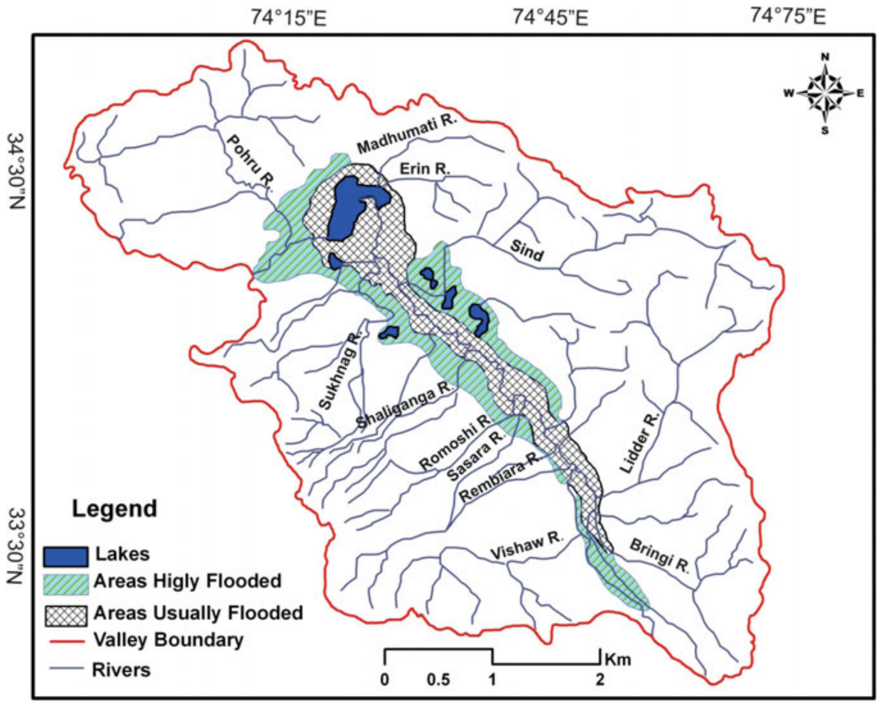

Fig. 5 Differential flood vulnerability of the Kashmir Valley

Fig. 6 **a** Flash flood 2010 in Ladakh. **b** Bank erosion along Jhelum River. **c** Anthropogenic impact on the waters of Dal Lake

the floods are but a natural phenomenon. Figure 5 shows the areas which are prone to floods.

In the twentieth century alone, of which we have a continuous record, there have been fifteen major floods up to 1965, the mean expectancy being one in 4.3 years. Among the major floods, those of 1959 and 1965 have no parallel in living history. Recently, a major flood event took place in Ladakh on August 62,010, affecting a large part of Ladakh, Jammu and Kashmir (Fig. 6a). A total of 71 towns and villages were damaged, including Leh. A cloudburst and heavy overnight rains triggered flash floods, mudslides, and debris flows. Overall, 9000 people were directly affected by the event including the death of more than 225 persons.

In the history of Kashmir extending over two millennia before Christian era, many floods have been mentioned together with the damage caused by them. A list of great floods is given in Table 3.

Table 3 Major floods in the state with their subsequent damage (*Source* Koul 1978)

S. No.	Year of occurrence	Extent of damage caused
Historical floods		
1	2082–2041 BC	A destructive earthquake occurred by which the earth in the middle of the city of Samdimatnagar rifts apart and water gushed out in a flood and soon submerged the whole city. By the same earthquake, a knoll of the hill at Baramulla near Khadanyar tumbled down which chocked the outlet of the Jhelum River and consequently the water rose high at once and drowned the whole city, together with its king and inhabitants. This submerged city is now the site occupied by the Wular Lake
2	855 AD–883 AD	Famine was caused by floods, and steps were taken to deepen the Jhelum River Khadanyar in order to accelerate the flow of the river. This measure had the effect of minimizing the chances of flood in the lower part of the valley
3	1379 AD	10,000 houses and crops were destroyed
4	1379 AD	Many houses and crops were swept away
5	1573 AD	Many houses and crops were destroyed
6	1662 AD	Many houses and crops were destroyed
7	1730 AD	10,000 houses, all the bridges on Jhelum and crops were destroyed
8	1735 AD	All the bridges on the Jhelum were swept away
9	1770 AD	Crops were destroyed
10	1787 AD	The bridges at Khanabal, Bijbihara, Pampore, and Amira Kadal were swept away
11	1836 AD	
Recorded floods		
12	July, 21, 1893 AD	The first and the only gauge setup in 1893 showed that the discharge was 61,800 cusecs, and the quantity that passed through Srinagar was estimated at 37,500 cusecs. All the bridges except Amira Kadal and many houses were destroyed. Loss of life and property was immense
13	1903	A good deal of damage was done. The water passed down the valley for its full width from hills on the right to the hills on the left of the valley
14	September 12, 1905	This flood was lower at Munshibagh by 2.5 ft. than that of 1903. The rainfall at Anantnag for a couple of days before the flood totaled 3.32 in. against 7.3 in. in 1903. The flood passed down the valley once again

(continued)

Table 3 (continued)

S. No.	Year of occurrence	Extent of damage caused
15	May 18, 1912	The rainfall was only 0.33 in. a day or too prior to the rise at Munshibagh. It is probable that the affluent above Srinagar did not add much to the Jhelum River
16	1928–1929	Along the areas between Sangam and Padshahi Bagh, a large number of breaches occurred in the bunds mostly on the left side of the river, causing heavy damage to crops and property
17	1950	The floods in the Vishaw and Rembiara synchronized with the flood in the River Jhelum allowing the nallas, such as the Arapal and the Romushi, to swell up considerably
18	4 September 2014	287 villages were affected

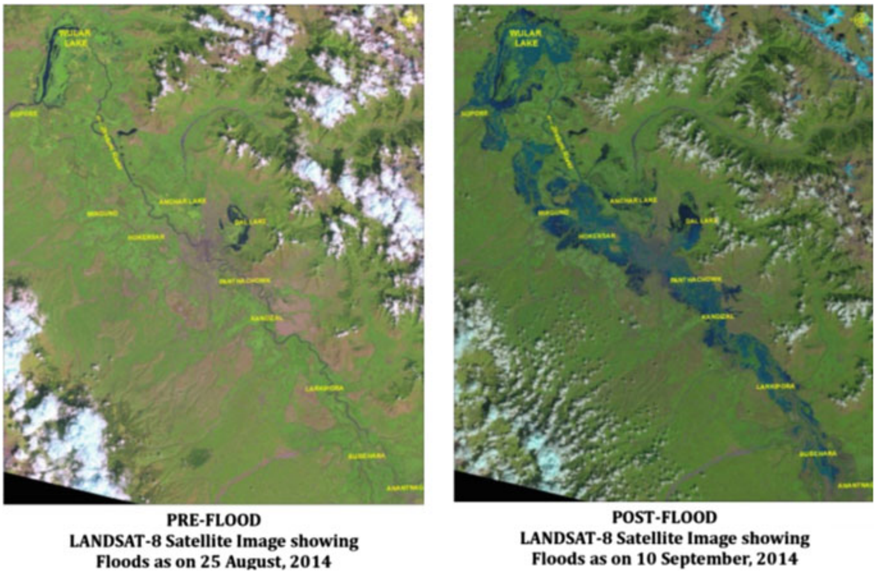

Fig. 7 Pre- and post-flood images showing inundation along the River Jhelum (Chug and Farooq 2014)

In the past 60 years, the state of Jammu and Kashmir has experienced the worst of the fields during the first week of September because of unprecedented and intense rains. Several areas in the valley were flooded, and many villages were marooned by flood water for several days (Fig. 7). Nearly, 287 villages were affected by floods. The banks of many rivers such as Jhelum, Chenab, and Tawi were breached. The districts such as Srinagar, Anantnag, Baramulla, Pulwama, Ganderbal, Kulgam, Budgam, Rajouri, Poonch, and Reasi were worst affected. The links of Kashmir Valley were totally disrupted, and the 300-km-long highway was closed for vehicular traffic from the 7 September. As many as 60 major and minor roads have been cut off and over 30 bridges washed away, hampering the relief and rescue operations. As of September 16, 2014, 190 people and 78 people have been reported dead in Jammu and Kashmir division, respectively. As per the preliminary information of government, 9814 residential houses were fully damaged and 23,763 partially in Jammu region. The preliminary information available from Kashmir says that 103,938 pucca houses are fully damaged, 64,176 pucca houses are partially damaged, 7372 kuccha houses are fully and 9220 kuccha houses are partially damaged. Over 234 relief camps were installed in the state, and 23,900 people were rehabilitated from the Jammu region only (Chug and Farooq 2014).

3.11 Bank Erosion

The possibility of erosion is found in the valley bottom along the banks of Jhelum. A view of bank erosion along the Jhelum is shown in Fig. 6b. The high-altitude rocky exposure and the glacier zone, on the other hand, have no soil cover to be eroded either. Likewise, the erodability is of a lower order in the paddy growing fringe of the Jhelum floodplain where pressure on the land is heavy and all slopes have been skillfully terraced (Table 4). It is in the dry farming of lands of the Karewas that erosion is a real hazard. The process of gullying, ravine formation, and sheet erosion, so intensive in the Karewas, offers enough evidence of the rampant affliction. The damage done to the topsoil is illustrated by the fact that in the certain areas as much as 75% of the soil cover has been eroded. The bare surface, loose structure of the soil, and absence of irrigation agriculture are some of the casual factors in this extensive devastation. Also, illegal and unprecedented degree of river bed mining in the state has also greatly added to risks of bank erosion. The intensity of erosion in various kinds of land covers is illustrated in Table 4.

Table 4 Intensity of erosion in various kinds of land covers (Raza et al. 1978)

S. No.	Altitude (m)	Topographical zone	% of topsoil depleted	Extent of erosion
1	1500–2000	Floodplain paddy belt	−25	Practically negligible erosion or slight
2	2000–2500	Dry farmland forested slopes	25−75, 75−100	Moderate to moderately heavy
3	2500–3500	Alpine pastures and margs	25−75 (subsoil)	Severe
4	Above 3500	Rocky slopes and glacial heights	Parent material exposed	Very severe

3.12 Anthropogenic Activities

Human activities commonly affect the distribution, quantity, and chemical quality of water resources. The range in human activities that affect the interaction of groundwater and surface water is broad. The impact of anthropogenic activities on water resources in Jammu and Kashmir is under tremendous stress. The input of fertilizers and pesticides to get the greater agricultural output has gone considerably high over the years. The distribution of fertilizers which stood 34,000 tonnes in 1999–2000 has gone up by estimated 237,000 tonnes in 2008–2009. Also, increased deforestation has resulted in excessive erosion in the catchment leading to immense siltation of these precious water resources. The quantification of water resources, classification on DBU, identification of most polluted river stretch, lake conservation strategy, absence of CEPTs, absence of sewage treatment of the water systems. The injudicious use of agrochemicals has resulted in degradation and contamination of the water quality and resulted in excessive growth of algal blooms. The state has to carve out an effective strategy for proper use of this very important natural resource. Agriculturalists are aware of the substantial negative effects of agriculture on water resources and have developed methods to alleviate some of these effects.

Anthropogenic activities can greatly influence the lake ecosystems and quite often disturb the ecological balance and impair the healthy ecosystem leading to hazardous problems. Dal Lake in the Kashmir valley enjoys a tremendous socioeconomic importance, but of late, its ecology has deteriorated so drastically that it exists in critical state of balance and has become one of the important ecosystems for environmental hazard impact analysis (Mukhtar 1991). Increasing population pressure of Dal dwellers is a major threat for survival of the lake. Impact of anthropogenic activities on the waters of Dal is given in (Fig. 6c). Haphazardly arranged houseboats are the most intricate problem deteriorating the lake water as they discharge the sewage directly in the lake. Adjacent agricultural land use in the catchment area is not environmental friendly. Excessive use of the fertilizers which finally move in the lake has changed its water chemistry.

Although tourism industry being an important source of state economy, however, the excessive influx of tourist pressure has caused the environmental issues. These issues are usually related to the deterioration of water resources, dumping of garbage in lakes, and pressure on drinking water resources.

The major industrial units existing in the Jammu division are contributing enormous amounts of pollutants in water every year. So, in order to have control on it, the state of Jammu and Kashmir framed a policy called Industrial Policy 2004 which has been put into action.

4 Conclusions

Rivers of Jammu and Kashmir are the lifeline of several thousands of people inhabiting their environs. Daily and basic needs of these people pertaining to freshwater for domestic, industrial, agricultural uses, and for hydropower generation make them heavily dependent on the water resources. Considering this, the government has been planning to pace-up and accelerate the development in the state. However, the growth plans should be comprehensive and consider long-term impacts of these advancements on water resources of the state. The power sector, adding of large power projects to a river system, may usher the problems, resulting in an increased and cumulative loss of natural resources, habitat quality, environmental sustainability, and ecosystem integrity. Also, construction of a series of dams may, therefore, have increasing impacts on downstream ecosystems and biodiversity. Moreover, construction of new hydropower projected in Jammu and Kashmir will invite trans-boundary concerns, interjections, and invoke water-related disputes between India and Pakistan. Further, reckless use of chemical fertilizers to enhance the crop or fruit yield undoubtedly adversely affects the water quality. Increased and unmanaged influx of tourists also builds a lot of pressure on the freshwaters of the state.

Serious concerns regarding water resources are posed by the anticipated influence of climate change on snow-ice reserves and stream flow. The records suggest that the number of exceptionally heavy monsoons over India has doubled in the last 50 years, while at the same time moderate and weak precipitation has decreased (Pal and Al-Tabbaa 2010). The effects of these changes may be manifold, far-reaching, and have many targets. Such as, an altered precipitation and temperature patterns in a scenario of changing climatic conditions will surely affect the seasonal pattern and variability of water levels in wetlands, potentially affecting valued aspects of their functioning as flood protection, carbon storage, water cleansing, and wildlife habitat.

Therefore, it is envisaged that growth plans pertaining to various sectors which are closely related to and dependent upon water resources of Jammu and Kashmir should essentially aim at sustainable development having a futuristic vision and considering their positive and negative impacts.

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Rivers of Uttarakhand Himalaya: Impact of Floods in the Pindar and Saryu Valleys

Lalit M. Joshi, Anoop K. Singh and Bahadur S. Kotlia

1 Introduction

The Himalaya fascinating due to its enveloping scenery is bountiful in its snowy peaks, river valleys, luxuriant green flora and fauna, peculiar tectonic setting and variable climatic conditions from east to north-east and also acts as monsoon barrier. The climate may affect the erosion rates and subsequently alter the mountain dynamics. The regional hydrology and climatic variations are directly influenced by the Himalayan glaciers, which are second after the polar caps and cover about 33,000 km^2 area (Dyurgerov and Meier 1997). The Himalayan range has about 15,000 glaciers, storing about 12,000 km^3 of freshwater, and there is a strong relationship between the river basins, human settlement and agricultural land. However, in recent years, increasing temperature has affected the hydrologic cycle which also influences the amount of precipitation and its intensity. The higher rainfall increases the flooding in the rivers, and after reducing the discharge, the deposition takes place and in form of the fluvial terraces which are indicators of incision, deformation, upliftment and climate change. Poor understanding of linkage between climate drivers and the processes behind formation of river terrace render a problem due to unplanned construction over the terraces.

The Himalayan orogen has four major tectono-stratigraphic units e.g. the Tethyan Himalaya, the higher Himalaya, the lesser Himalaya and the Siwalik from north to south. These are bounded by north-dipping crustal scale thrust systems that include Trans-Himadri Fault (THF), Main Central Thrust (MCT), Main Boundary Thrust (MBT) and Himalayan Frontal Fault (HFF) (Gansser 1964; Valdiya 1980; Burg and Chen 1984; Burchfiel et al. 1992; Thiede et al. 2006; Fig. 1a). Moreover, the entire Himalayan region is hazard-prone (Fig. 1b), and number of regional thrusts and faults exist within the area. Further, in Quaternary period, these

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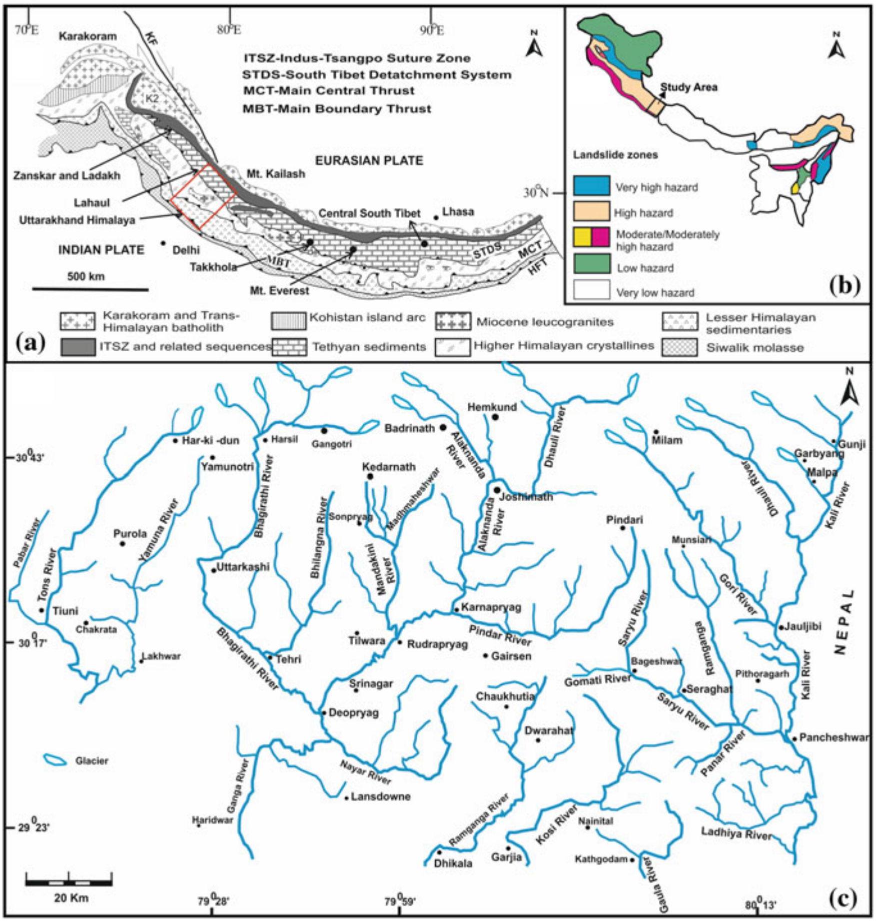

Fig. 1 **a** Litho-tectonic units of the Himalayan orogenic belt separated by major intracrustal boundary thrusts (after Godin 2003. **b** Map of Indian Himalaya showing landslide hazard zones (*source* http://www.portal.gsi.gov.in). **c** The major river networks in Uttarakhand Himalaya (after Valdiya 1980)

thrusts/faults are invariably active as suggested by various geomorphic features of neotectonic activity along most of the major river valleys e.g. paired and unpaired terraces, deflecting river course, fault scarps, immature topography, ponding of ancient drainage and development of palaeolakes, formation of cascades, straightening of river channels, series of triangular fault facets and deeps cut V-shaped valleys (Valdiya 1999, 2005, 2014; Valdiya and Kotlia 2001; Kotlia and Joshi 2013; Pathak et al. 2013; Dumka et al. 2014). Similar geomorphic evidences are also observed along studied Pindar and Saryu valleys.

Several major rivers originate from glaciers of the Uttarakhand Himalaya that feed 10.08 million population of region and nourish the millions downstream. The major rivers include Bhagirathi (also Ganga), Alaknanda, Mandkini, Bhilangana, Pindar, Kali, Gori, Saryu, Ramganga (East and West), Kosi, Gaula, Tons and Yamuna (Fig. 1c).

1.1 Bhagirathi/Ganga River

It originates from the Gomukh of the Gangotri glacier and is one of the major rivers of the region (Fig. 1) with a total length of 205 km and basinal area about 6921 km^2. The major tributaries are Kedar Ganga, Jadh Ganga, Kakora Gad, Asi Ganga and Bhilangana rivers. The river meets the Alaknanda River at Devprayag and is subsequently known as Ganga River.

1.2 Alaknanda River

The Alaknanda River originates from Satopanth and Bhagirathi Kharak glaciers (Fig. 1). The total length of the river is about 190 km and basin area is 10,882 km^2. The major tributaries of the river are Saraswati, Dhauliganga, Nandakini, Pindar, Birhi Ganga, Patalganga, Mandakini and Pushpawati rivers. The main river is famous as it forms the five mythological famous Prayag/confluences which are expressions of the Hindu religious ethos e.g. Nandprayag, Vishuprayag, Karnaprayag, Rudraparyag and Devprayag.

1.3 Bhilangana River

It is a major tributary of Bhagirathi River and emerges from the Khatling glacier and joins with the Bhagirathi River at Old Tehri (Fig. 1). The Bal Ganga is a major tributary of this river.

1.4 Mandakini River

Mandakini River is a tributary of the Alaknanda River (Fig. 1). It originates from the Chorabari glacier near Kedarnath and is later fed by Vasukiganga River at Sonprayag. The river joins the Alaknanda at Rudraprayag. One of the major tributaries of the river is Madhyamaheshwar River.

1.5 Pindar River

The Pindar River is a major tributary of the Alaknanda (Fig. 1). It originates from Pindari glacier in Bageshwar district at an elevation of 5200 m. The Pindar glacier lies between the Nanda Devi and Nanda Khet peaks having its snout at an elevation of 3627 m. The major tributaries are Pranmata Gad, Meing Gadhera, Kewar Gadhera, Chopta Gad and Ata Gad. The river travels for about 124 km from its source to confluences into the Alaknanda River at Karnaprayag in Chamoli district. Its catchment is about 1610 km^2 in which 360 km^2 areas is snow covered.

1.6 Yamuna and Tons Rivers

These are the major tributaries of Ganga which originates from the Yamunotri glacier (Fig. 1). The Giri, Rishiganga, Hanuman Ganga and Tons are the major tributaries of the river. Additionally, the Tons is the largest tributary of Yamuna River and is formed by confluence of various major rivers such as Pabar, Asan, Rupin and Supin rivers. These rivers originate from the Har-Ki-Dun valley.

1.7 Kali River

The Kali River also known as Mahakali and Sharda River originates from the Kalapani in Pithoragarh district (Fig. 1). It separates the India from Nepal and demarcates the border. The total length of Kali River is about 350 km. It flows through the rugged Himalayan terrain to Tarai via Siwalik Hills and finally meets with Ghaghara River. The Kuti, Dhauli, Gori, Saryu and Ladhiya River are the major tributaries. The average discharge of the river is about 730 m^3/s; however, even in July, its discharge is approximately 1580 m^3/s (http://en.wikipedia.org/wiki/2014).

1.8 Gori River

It is a tributary of the Kali River and originates from the Milam glacier. The major tributaries are Ralam Gad, Pachhu Gad, Burfu Gad, Laspa Gad, Pyunsani and Gonka Gad. The Gori Ganga joins the Kali River at Jauljibi, Pithoragarh district.

1.9 Ramganga River

The Ramganga (East) river is a tributary of Saryu River and originates from the Namik glacier in Pithoragarh. It finally joins the Saryu River at Rameshwar near

Pithoragarh. Another major river is Ramganga West which originates from the Doodhatoli Range of Pauri Garhwal district. It is a tributary of Ganga. It has a catchment area of about 30,641 km^2.

1.10 Kosi River

The Kosi River originates from the middle Himalaya of Kumaun region. It is a perennial river and finally meets with the Ramganga River at Ramnagar.

1.11 Saryu River

It is one of the largest tributaries of the Kali which originates from the Pindari region. Its length is about 350 km. The major tributaries of Saryu River are Revati Ganga, Kheer Ganga, Gason Gad, Dulam Gad, Gomati River, Kulur River, Panar River and Ramganga East. The river joins the Kali at Pancheswar.

2 Pindar and Saryu River Valleys: Geomorphology Aspects

Pindar and Saryu river valleys are regionally affected by the heavy rainfall inducing flooding almost every year. Both the rivers emerge from Pindari region of Bageshwar district. The Pindar River feeds the north-western part of the Bageshwar district and subsequently flow through Chamoli district; while Saryu River flows towards the south-western margin (Fig. 2). The basinal area of Pindar River is about 1942.2 km^2, whereas Saryu River accounts for 2473.6 km^2. Eventually, the entire area is affected by flood which causes loss of thousands of human life and devastation of heavy loss of property every year. In recent years, the unplanned and illegal constructions over river flood plains are responsible for degradation of river ecosystems. The increasing urbanization on fragile ecosystem increases surface run-off and also the erosion rate which causes the unpredicted havocs.

The Pindar River flows NE–SW and takes a sharp turn towards NW direction. In general, the drainage pattern in the area is largely dendritic, subtrellis to subrectangular. The river is crossed by various major thrusts e.g. Pindari Thrust (PT), Vaikrita Thrust (VT), Munsiari Thrust (MT) and Berinag Thrust (BT) (Valdiya 1980, 2014). The river is deflected at the places where it is obstructed by various thrusts and faults. The valley is characterized by various geomorphic features, e.g. two to three levels of unpaired river terraces (Fig. 3a), meandering of river (Fig. 3b), stepwise water falls (Fig. 3c), straight and V-shaped valley (Fig. 3d),

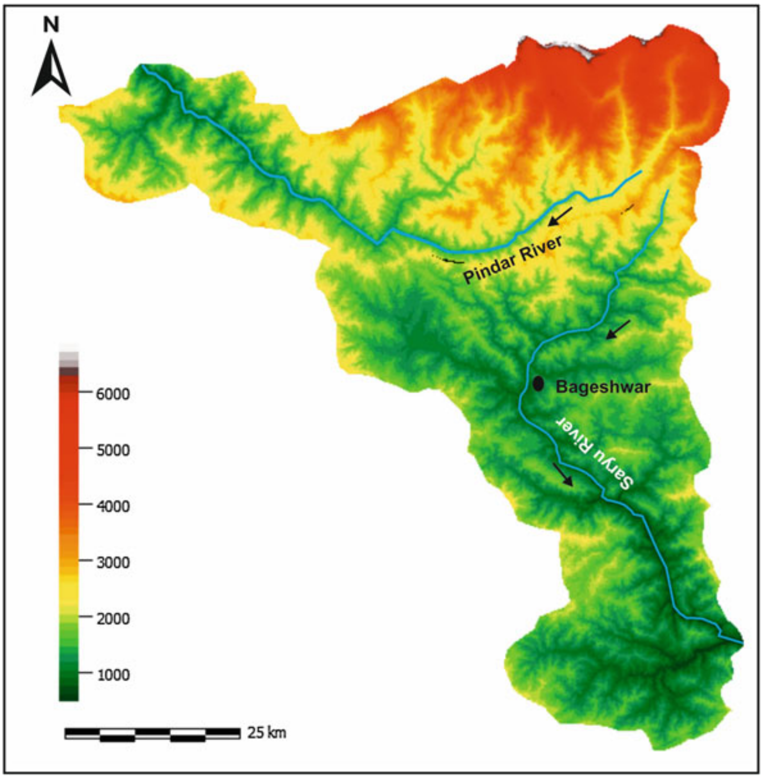

Fig. 2 Digital elevation model (DEM) of Pindar and Saryu river valleys. The Saryu river flows through Bageshwar region while Pindar river initially runs through north–western margin of Bageshwar district and afterwards flows through Chamoli district

fault facets (Fig. 3e) and hillslope instability as landslides (Fig. 3f). The geomorphic features are observed at most of the places along river valley which indicate that the area is neotectonically very active. The recent activity along these thrusts/faults may be responsible for landscape rejuvenation of the Pindar valley.

The NE–SW-trending Saryu valley is characterized by a number of thrusts/faults, e.g. Main Central Thrust (MCT), Munsiari Thrust (MT), Berinag, Thrust BT), Kausani Thrust (KT) and North Almora Thrust (NAT) with some traverses faults such as Loharkhet Fault (LF), Dulam Faults (DF), Dulam Ghadera Faults (DLF), Vongarh–Gason Fault (VGF), Girkhet Fault (GF), Mandalsera–Chhana fault (MCF) and Rantoli Fault/Saryu River Fault (RF/SRF). The valley is characterized by the development of three levels of river terraces along with river deflection (Fig. 3g), wide and straight course of river (Fig. 3h), braiding nature of river (Fig. 3i), ponding of river with deep gorge (Fig. 3j), V-shaped narrow valleys (Fig. 3k) and water falls (Fig. 3l) as well as fault facets and cones. These features further indicate that the area is under geomorphic modification along the

Fig. 3 Geomorphic features along the Pindar valley: **a** two levels of unpaired river terraces, **b** meandering course of river, **c** stepwise water falls, **d** straight and V-shaped valley, **e** fault facets and **f** hillslope instability as landslides (with wide dimension) and, geomorphic features along Saryu valley: **g** three levels of river terraces along both the banks of river; **h** straight course of Saryu river, **i** river widening, abandoned channel with braided bars, **j** river ponding with gorge (*arrow* indicate flow direction), **k** V-shaped narrowing valley (photograph looking upstream) and **l** waterfalls

thrusts/faults. A number of waterfalls along the faults/thrusts, tilting of alluvial and colluvial deposits, V-shaped valley and ponding of ancient drainage and formation of ancient lakes are clearly observed in the area. Twisting behaviour of Saryu River observed at places where the thrusts and faults run across the river. Further, a

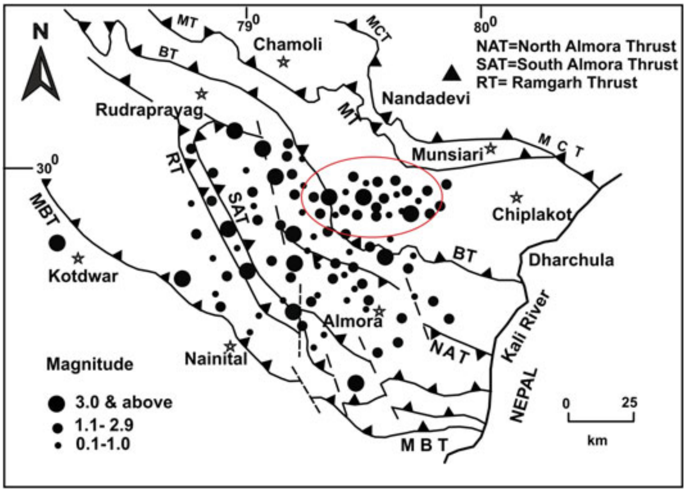

Fig. 4 Earthquake events around the study area (modified after Pathak et al. 2013), *circle* shows the area of Pindar and Saryu valley)

5-m-thick palaeolake deposit formed by blocking of the ancient drainage (Kotlia et al. 2008) clearly suggests the reactivation of the area along the younger faults, e.g. Dulam Ghadera Fault (DGF) and Dulam Fault (DF).

Geologically, the Uttarakhand Himalaya made up of the rocks of Sirmur, Massoories, Jaunsar, Tejam, Damtha, Ramgarh, Almora and Vaikrita Groups which have been separated by various thrust and subsidiary faults. Thus, the rocks along the area are highly sheared and crushed due to prevailing tectonic activity along the thrusts/faults, which make the region more fragile and prone to landslide disaster. The area is not only geologically fragile but also neotectonically and seismological quite active even today (Pathak et al. 2013; Dumka et al. 2014). The almost few epicentral distributions show that the entire Himalayan region is seismotectonically active (Fig. 4). The number of small to moderate earthquake events along most faults/thrusts (Fig. 4) suggests that the area is under the tectonic rejuvenation. The recent major earthquakes e.g. Chamoli (1999) and Uttarkashi (1991) caused enormous loss of properties and life. So, the geomorphic modification along river valley and earthquake tremors even if they are moderate can be responsible for triggering new landslides and resultant flash flood.

3 Socio-economic Significance

The rivers play a significant role throughout the human history as their waters are a basic natural resource that provides drinking water to millions of people worldwide. Mostly, the river water is used for irrigation and electricity purposes. The

Himalayan rivers are biodiversity hot spots, and people of mountainous region mostly depend on the river water. The majority of Himalayan population uses the river flood plains for agriculture activity which is major source of livelihood of the region. The river banks have attracted settlers from ancient times as it is key factor of landscape ecology. Moreover, the rivers are more important for electricity generation; these are fed by melting snow and glaciers and flow throughout the year. The Uttarakhand has 180 large and small hydroelectric stations with a capacity of generating >21,200 MW electricity (Valdiya 2014). Most of the river valleys are covered by human settlement which causes the main pressures on river systems. The higher tourist influx in recent years has intended population to increase the urbanization along lower reaches of river valleys to provide infrastructural facility in form of hotels and guest houses. When the rivers receive very heavy rainfall, it cause unprecedented flood downstream and affects the human settlement.

3.1 River Ecosystem and Human Influence

The unplanned settlement over river bed has mostly replaced the agricultural land resulting in degradation of the river ecosystem. Human population strongly affect the river ecosystem through urbanization, deforestation, building unscientific hydropower projects, mining and quarrying of rivers (Fig. 5). Most of the river areas dammed for hydropower project, cause elevated flood levels in downstream regions and river bed erosion (Valdiya 2014). Further, the blasting during

Fig. 5 Fundamental ways of anthropogenic activities resulting in degradation of the river ecosystem

engineering works also renders the problem as it can open joint spacing. Another major reason of degradation of river ecosystem is the indiscriminate quarrying and dumping of muck while construction of roads and power projects as most of the projects are implemented without proper geological investigations. The deforestation, forest fire and over grazing activities have also degraded the natural environment. All these factors result in soil erosion, aggradation and degradation of river valleys. This was experienced by Uttarakhand state while encountering a heavy flood along the Mandakini valley in June, 2013, resulting in loss of thousands of people.

3.2 Rainfall Pattern

The Intergovernmental Panel on Climate Change (IPCC 2001) estimated that the global mean surface temperature has increased 0.6 ± 0.2 °C since 1861 and projected that it will enhance between 1.4 and 5.8 °C by 2100. Under the warming trend every year, the bulk of the annual rainfall occurs during the months of June to September (e.g. Parthasarathy et al. 1992). The higher rainfall amounts in heavy erosion and flooding (Bookhagen et al. 2005; Bookhagen and Burbank 2006) that cause habitat destruction with severe changes in the flow dynamics. The peak of the south-west monsoon brings the maximum rainfall within the region.

The Chamoli and Bageshwar districts received about 80–85% rainfall during strengthening of the south-west monsoon. The annual rainfall for Bageshwar district was nearly about 1667 mm in 2013, in which 1329.7 mm rainfall was received only in monsoon months. Meanwhile, Chamoli district received an annual rainfall about 1912.2 mm, where 1563.4 mm was contributed only by monsoonal rains (Fig. 6). As a consequence, consequently most of the rivers flow up to the danger mark and carry heavy discharge and flooding in lower reaches of the valley.

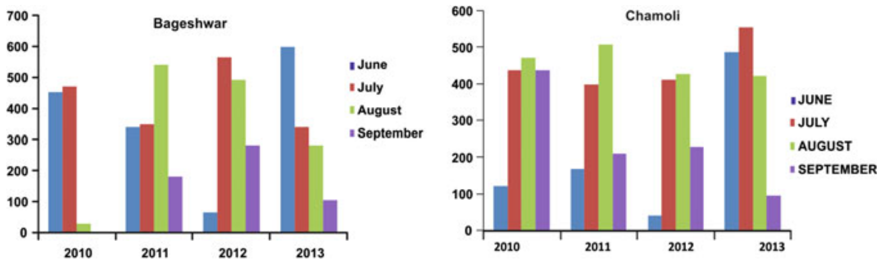

Fig. 6 Rainfall (2010–2013) during south–west monsoon for Bageshwar and Chamoli district (IMD, New Delhi)

3.3 Flood Hazards and Their Impact on the Pindar and Saryu Valleys

The Quaternary period witnessed the damming of rivers due to combined effect of climate and tectonics in Kumaun and Garhwal Himalaya (Heim and Gansser 1939; Valdiya et al. 1996; Kotlia et al. 1997, 2000, 2010; Kotlia and Rawat 2004; Basavaiah et al. 2004; Juyal et al. 2004, 2009; Pant et al. 2006) etc. Even today, the several temporary lakes are formed due to blocking of river course under excessive precipitation and when they burst often results in flash floods downstream and cause heavy loss. The people of Uttarakhand facing the problem every year as most of the area are disaster-prone. The cloud burst induced flash floods in lower reaches has badly affected human lives, caused loss of lives/injuries, damage of houses, devastation of government property in last few years. At few places, the hazards are very active and common with severe intensity. Additionally, some areas are still waiting to be hazardous, if the proper investigation will not be executed.

The Pindar River flows above the danger mark and becomes violent in monsoon months. There are flash floods due to high rainfall and were observed first during 1772 and subsequently became frequent. The majority of the settlements are located on the fluvial terraces and unstable slope along the Pindar valley e.g. Pipalsera, Wachham, Boragarh, Batunayak, Kulsari, Sinderwani, Narayanbagar, Tharalibagar, Harmoni, Dungari, Deval, Karnaprayag, Dharatalla, Chepadon, Tharali, Dungera, Kolygad, Siri, Khati, Melkhet, Paingad, Sunau, Devsar, Kunnipartha and Nand Keshari. Several villages were affected due to floods in monsoon season under enhanced rainfall in 2012 and 2013. As a result, bridges along the river valleys, road networks/footpath were washed away and taking toll of several human lives and livestock and the road networks were blocked. The lengths of landslides in the area are very wide with dimension as much as about >200 m. About 35 houses had collapsed in Narayanbagar and Tharali villages and the connecting roads in Pindar valley were almost completely damaged (http://tras.ca). A number of villages along Pindar valley are still critically facing serious problems due to prevailing tectonic setting, adverse climatic conditions with excessive rainfall such as around Narayanbagar, Harmoni, Kulsari, Deval, Boragarh and Batunayak (Fig. 7a–d). The Narayanbagar and Harmoni villages are worse hit pockets along the valley. The landslides of the area are reactivated almost every year and causing the economic loss through disrupting the traffics. The Pindar River changes its course near Narayanbagar village and washes away fields, buildings and roads. At some places, the houses are under threat due to toe cutting and erosion by the river (Fig. 7a, b). Further, the Narayanbagar village is severely affected and entire road network was washed out. Some houses were perished and some are under peril (Fig. 7c, d).

Similarly, several villagers are located on river terraces and also on the higher slopes along Saryu valley, such as Saling, Rikhari, Harkot, Dulam, Gason, Bamsera, Kapkot, Bharai, Bageli, Ason, Bhani, Utaraura, Khadgera, Rithabagar, Rainthal, Golna, Anarsa, Dwarson, Adoli, Devalchaura, Ghiroli, Joshigaon, Bageshwar, Kathayatbara, Kunara, Balagaht, Chiniya, Simrau, Balsewra, Gairkhet,

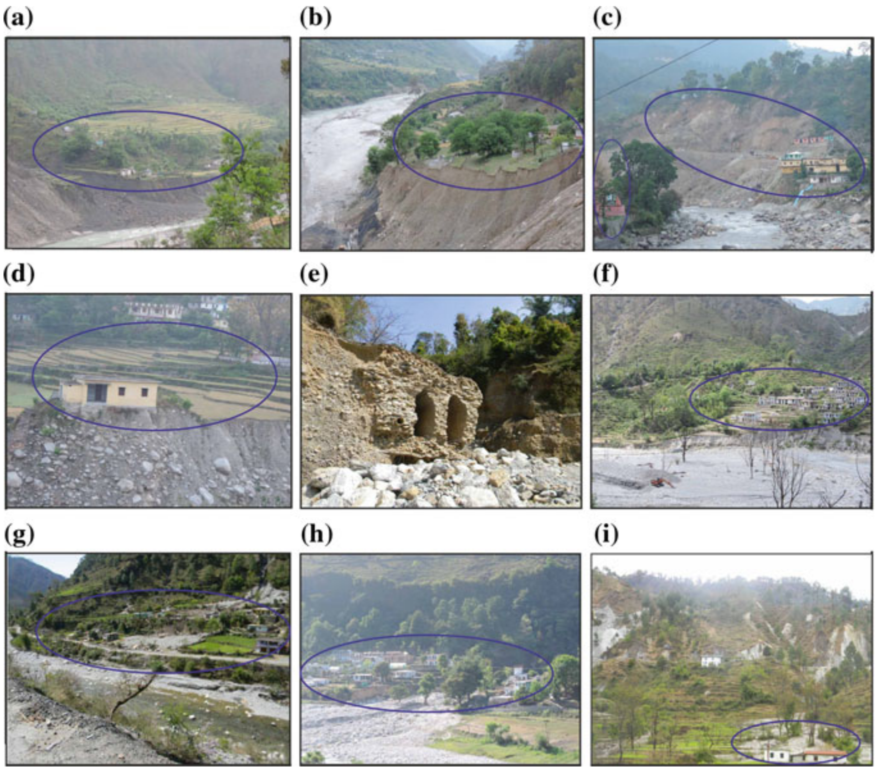

Fig. 7 **a**–**b** The houses are under threat due to excessive erosion by Pindar river between Deval to Manmati area, **c** the damaged road due to heavy landslide near Narayanbagar village, **d** the house built over the river flood deposit got damaged, **e** entire area along road side near Rithabagar was washed away, **f** the village under threat along the Revati Ganga river, **g**–**i** recent *landslides* induced channelized debris hit the houses along the Saryu valley upstream and downstream of Kapkot area

Seraghat, Lweta, Saluri, Nali, Naichun, Seri and Ara. Along Saryu valley, the road network was damaged due to flood during monsoon period in 2012 (Fig. 7e). On other hand, most of the villages were under threat near Rithabagar along Revatiganga, (Fig. 7f), Gason and Rithabagar village (Fig. 7g), Gairkhet (Fig. 7h), Dulam (Fig. 7i), Sumgarh, Chirabagar of Kapkot tehsil of Bageshwar district due to neotectonic activity, river toe cutting and bank erosion under excessive rainfall in 2012. It happened due to complete underestimation of river bed erosion and toe cutting. In Kapkot region (Sumgarh Village), 18 small school children died and nearly 30 more trapped under the rubble of a school building during 2010 due to heavy landslides triggered by torrential rains. Further, a few other casualties were reported while cloudburst hit the several villages in Kapkot subdivision. Some nearby villages are under peril and badly hit by the cloudburst not only along Saryu valley but also along the major tributaries of the river such as Revtighati, Pothing, Harsinghia Bagar and Uchat.

4 Discussion

It is clear that Pindar and Saryu valleys are under the tectonic modification along thrust/faults as evident by various geomorphic features. The fragile geology and torrential rainfall play a significant role in destabilizing of the river valleys. Thus, there is a need to build ecologically sustainable civilization through which one can secure the life of future generations. Moreover, the disaster did not or do not happen only due to tectonically controlled activities and excessive rainfall events but also due to anthropogenic disturbance along the river valley. The future hazards can be minimized through understanding of processes of landslides/flash floods and analysis of their intensity and precipitation and this can decrease the increasing pressure of urbanization on river ecosystem. The human causality in flood induced landslides are because of ignorance and poor understanding of geological structures, bad policies and unscientific construction of roads and power projects in geologically weak zone of the Himalaya. The severe hazards in the areas need proper training on disasters preparedness management involving the inhabitant and also the awareness programmes. The government should take lessen from previous year disaster and make proper guidelines to build the houses on hill region and construction of road networks and power projects. Overall attention is required on geological and geomorphological set-up, especially on slope instability along geologically fragile areas of the valleys. Further, it needs to vacate the unauthorized construction in river flood plains and shift the people in safer side on the flat and gentler slopes to save the state.

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The Major Drainage Systems in the Northeastern Region of India

Rahul Verma

1 Introduction

The drainage system of northeast Indian rivers represents the soul of faith, culture, and tradition of the seven sister states namely Sikkim, Assam, Nagaland, Meghalaya, Tripura, Manipur, and Mizoram. Most of the rivers ultimately join the 'Brahmaputra System' (Arunachal Pradesh, Assam, and Tripura), Barak (Manipur, Southern Assam), and Kolodyne (Southern Mizoram). The Barak River forms the lifeline of Manipur, Southern Assam, and it ultimately drains into Bay of Bengal as 'Meghna River.' It is interesting to know that Ganga, Brahmaputra, and Barak ultimately merge as a single river system. The merger of these three major rivers is very significant in the sense that it assimilates almost all river channels of Assam, Arunachal, Sikkim, Tripura, Meghalaya, Northern and Eastern Mizoram, Southern Manipur and Northern Nagaland. River channels running in the Southern Nagaland, Southern Mizoram, Southern and Eastern Manipur, and Southern Tripura drain into the Bay of Bengal either via Myanmar or via Bangladesh. In the next section, an account of the major rivers of the region (state wise) is presented. A composite river map of northeast India is presented in Fig. 1.

2 Physiography of Northeastern Region

The typical physiography of this region consists of flat valleys and rolling hills. The region is divided into Northeast Hills (Pataki and Lushai Hills), 'Eastern Himalayas,' the Brahmaputra, Barak, Surma, and Kolodyne Valley. The predom-

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Fig. 1 A composite river map of North East India

inant climate in the region is humid subtropical, having humid and hot summers, severe monsoons, and mild-to-cold winters. The region is endowed with rain forests with rich diversity of flora, fauna, and crop species. Tertiary sedimentary terrain consisting of sandstones and shales serves as the store house of hydrocarbon reserves of coal, petroleum, and natural gas, and these deposits account for approximately 25% of India's total reserves. The region of Assam, Arunachal and Tripura is drained by the Brahmaputra and Barak River systems and their tributaries.

About 65% of the regional terrain is hilly. Some flat lands are found interspersed with valleys and plains in the vicinity of hills of Assam, Meghalaya, and Tripura. The altitude varies from sea level to more than 23,000 ft above MSL. The average rainfall is high (more than 200 cm). The two states Arunachal Pradesh and Sikkim lie in the vicinity of higher Himalaya and fall under 'montane climate,' enjoying very cold, snowy winters and mild summers. The states Manipur and Tripura have hot summers and cold winters. Mizoram and Nagaland have subtropical climate, and the temperature remains nearly 10° in winters and rarely exceeds 35° in summers.

Under the influence of 'Indo Burmese Mobile Arc' and active plate collision between the Indian and Burmese plate, the whole region is tectonically very active and falls under Zone-V Seismicity (Nandy 1980, 1982).

Most of the region, especially in Plains of Assam and Tripura, severe floods take place. The 'Physiographic Composite' of northeastern region is shown in Fig. 2.

Fig. 2 The “Physiographic composite” of North Eastern Region

3 Rivers of Mizoram

Mizoram is located at the southernmost tip of northeastern region of India. It is sandwiched between two countries Myanmar (to its east) and Bangladesh (to its west). Mizoram shares land borders with three states—Tripura, Assam, and Manipur. Mizoram is having a rolling hills and valleys topography. Twenty-one major hills ranges or peaks of different heights strike north–south. All major rivers flow parallel to the strike of these hills and flow either northward or southwards, forming river valleys and plains (Pachau 2009).

Mizoram is divided into 23 watersheds, out of which the most important and one of the largest watershed is ‘Tlawng Watershed’ (Rao et al. 1994). All the rivers in Mizoram are monsoon-fed, and they attain maximum volume in the monsoon and post-monsoon period. The whole state experiences heavy monsoonal rainfall. The average annual rainfall in Aizawl is 208 cm, and it is 350 cm in ‘Lunglei’, Southern and eastern parts receive 290 cm of rainfall, while the northern and Western parts of the state receive 170 cm, on an average. May to August, are the rainier months and the maximum rain is received between 20th and 32nd week of the year. The average rainfall in the state is 254 cm per annum.

The main drainage system of Mizoram consists of—‘Tlawng’ (northerly flowing) and Kolodyne and Karnphuli (southerly flowing).

3.1 *Northerly Flowing Rivers from Mizoram Feeding Barak Drainage*

The Barak River system is the second largest drainage network in northeast India with a total catchment area of about 39,390 km^2 that spread over India (30,155 km^2), part of Myanmar (840), and Bangladesh (7780 km^2).

The main northerly flowing rivers of Mizoram are Tlawng, Tut, Tian, Tuichawng, Tuirial, Tuipui, Tuivawl, Teirei, Tuirini, and Serlui. The largest of these is the Tlawng (Dhaleshwari) with a length of 185.15 km. Tlawng and Tut rivers drain into the Barak River directly. All other Rivers meet the Barak River indirectly through subsidiary channels either via Tripura–Bangladesh or via Manipur.

Tlawng (Plate 1), the largest northerly flowing river, originates in ‘Zobawk’ in ‘Zopuii Hills’ in ‘Lunglei District’ and flows from south to north and finally meets the Barak River beyond the northern fringe of Mizoram, in the ‘Cachar District’ of Assam near ‘Badarpur’ town.

During its course, many rivers join it laterally. The most important tributaries of the Tlawng are the ‘Tut River’ and ‘Teirei River.’ ‘Tut’ River originates at ‘Changpui’ (in the Mid West Mizoram). It flows for 98.33 km, before joining the ‘Teirei River’ as its left bank tributary. The drainage area contributing run-off to the Tlawng watershed is 1,70,145 ha. The Tlawng watershed is a narrow and elongated watershed, and it receives an average rainfall of 240 cm in northern part and 315 cm in the southern part, mostly received through south-west monsoon. Drainage system of Mizoram is shown in Fig. 3.

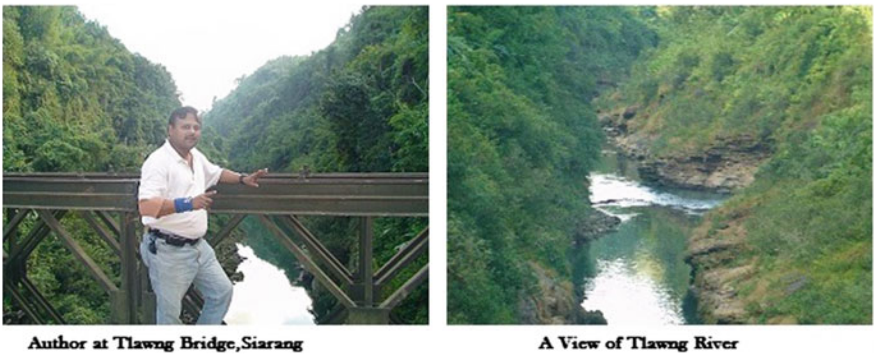


Plate 1 The largest northerly flowing river, originates in ‘Zobawk’

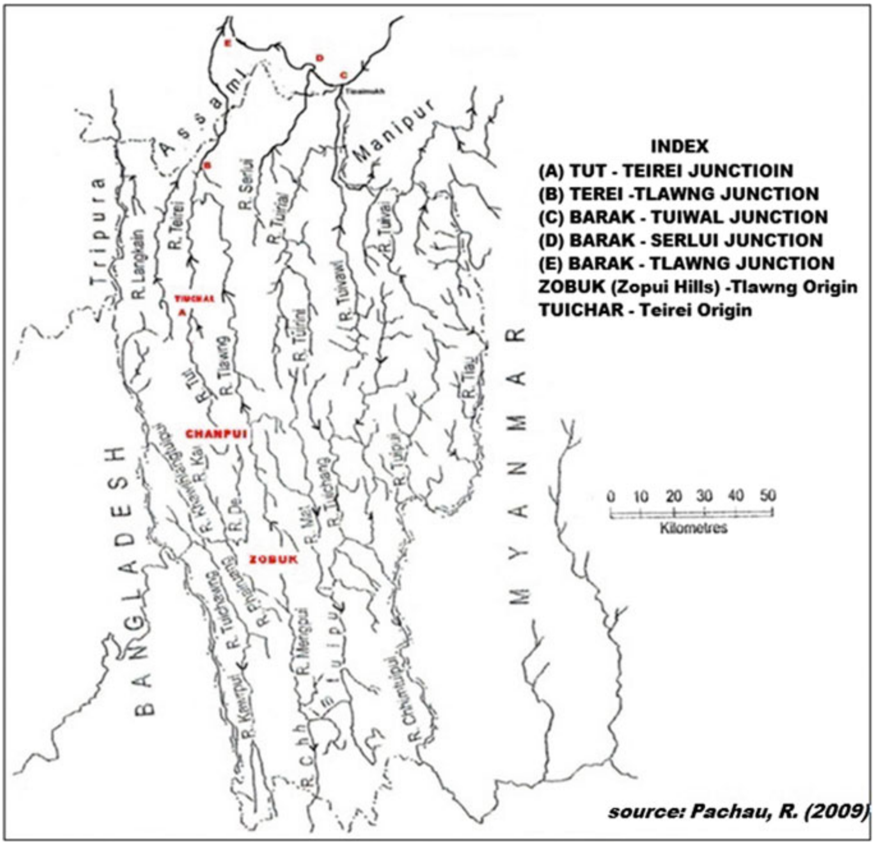


Fig. 3 Drainage system of Mizoram

3.2 *Tlawng–Barak–Meghna–Brahmaputra–Ganga System*

'Barak' River originates near 'Mao Songsang' in the Manipur Hills. Many little hill streams, namely 'Buri,' 'Balujhuri,' 'Durduria,' 'Gumti,' 'Howrah,' 'Hari,' 'Kakrai,' 'Kurulia,' 'Kagni,' 'Mangal,' 'Senai,' and 'Shonaichhari,' join Barak as tributaries. From its source, Barak flows westward in Manipur State and then turns southwest at the Manipur–Mizoram border.

At 'Tipaimukh' (located Mizoram–Assam border), 'Tuiwal' River that flows northward from Mizoram joins Barak (Fig. 4), at 24° 14′N and 93° 1.3′E approximately. After joining 'Tuiwal,' Barak takes a hairpin bend. A little upstream of Lakhipur, it flows in the Barak valley of Assam and moves into the Cachar plains of Cachar district (Assam). From Lakhipur to 'Jirimat,' Barak serves as the border between Assam and Manipur states. It is joined by another northerly flowing river from Mizoram 'Serlui' at approximately 24° 45′ 06″N and 92° 54′ 36″E.

Fig. 4 "Tuiwal" river that flows northward from Mizoram

Barak River is joined by 'Tlawng River' as its left bank tributary, approximately at 24° 04′ 06″N and 92° 54′ 38″E, at a place in Cachar District nearly 15 km west of 'Silchar' town and 8 km east of Badarpur town.

Barak then flows westward off Silchar town (Assam) where it is joined by 'Madhura River' as its right bank tributary. The principal tributaries of the Barak in India are the 'Jiri,' 'Dhaleshwari (Tlawng),' 'Singla,' 'Longai,' 'Madhura,' 'Sonai (Tuirial),' the 'Rukni,' and the 'Katakhal.'

Beyond modern 'Karimganj District' (South Assam), Barak reaches the 'Sylthet Depression' (or trough) of Bangladesh, from where it divides into two channels—The northern branch 'Surma River' and the southern 'Kushiyara River.' At this point, the river forms the 'Surma Basin.'

The 'Surma' is joined by few right bank tributaries from the 'Meghalaya Hills' (located toward north). After its merger with the south-flowing 'Someswari River,' 'Surma' gets a local name 'Baulai River.'

At northwestern fringe of Mizoram, 'Langkain' River flows northwards and it forms boundary between Mizoram ('Kahnmun' town) and Tripura ('Dhamchera' town) (Plate 2). It finally meets 'Kushiyara' as its left bank tributary, at

Plate 2 'Langkain' river flows northwards and it forms boundary between Mizoram ('Kahnmun' town) and Tripura ('Dhamchera' town)

24° 42′ 19.37″N and 91° 57′ 11.29″E., approximately 2.5 km NNE of 'Fenchuganj,' Bangladesh.

The 'Kushiyara' is joined by few right bank tributaries from the 'Sylhet Hills' (north) and Tripura Hills (south). The major tributary from Tripura Hills is the 'Manu River.' The Kushiyara is also known as a local name 'Kalni River' after its merger with a major offshoot (distributaries) from the Surma, as its right bank tributary. Surma and the Kushiyara finally rejoin in 'Kishoreganj' District near 'Bhairab Bazar' of Bangladesh. There onwards, the river is known as the 'Meghna River' (Fig. 5).

'Meghna' is joined by the great river Gumti, at 'Daudkandi,' Comilla (Bangladesh). River 'Gumti' adds immense volume to 'Meghna' and enhances the water flow considerably. The largest distributary of the Ganges in Bangladesh is known as 'Padma River.' 'Jamuna River' (largest distributary of Brahmaputra), joins 'Padma' at approximately 23° 48′ 16.88″N and 89° 43′ 38.00″E, nearly 35 west of Dhaka, the Capital of Bangladesh. Finally, Padma merges into 'Meghna' in 'Chandpur District' at 23° 15′ 14.55″N and 90° 38′ 9.73″E coordinates, nearly 55 km SE of Dhaka. After the merger of 'Padma' and 'Jamuna' into it, 'Meghna' River is known as 'Lower Meghna.'

After 'Chandpur,' 'Lower Meghna' flows toward the 'Bay of Bengal' in an almost straight line. During its course from 'Chandpur' to the Bay of Bengal, 'Lower Meghna' splits into a few little rivers, still maintaining the main flow through the 'Meghna Estuary.'

Thus, it is evident that the drainage of Tlawng River is connected to the Barak River (Verma 2011) that moves west of Silchar (Assam). Barak River bifurcates

Fig. 5 The river is known as the "Meghna River"

into Surma (north) and Kushiyara (south), and they meet again in Bangladesh to form Meghna River that finally meets the Ganga–Brahmaputra drainage system. A composite of Meghna–Padma–Jamuna is shown in Fig. 6.

3.3 The Southerly Flowing Rivers Feeding Kolodyne Drainage System

'Kolodyne River' originates in central Chin State of Myanmar, at 22° 49′ 28″N and 93° 31′ 57″E, and flows south. At the origin point, it is known as 'Timit.' It is joined by 'Chal River,' and thereafter, it is known as the 'Boinu River.' It continues to flow southwards till its merger with the 'Twe River' at 22° 08′ 40″N and 93° 34′ 30″E and from there it swings westward. After 22° 05′ 20″N and 93° 14′ 12″E coordinates, it heads northwest. At 22° 11′ 06″N and 93° 09′ 29″E, below 'Mount Phabipa,' 'Kolodyne' takes a northward turn and forms the international border between India and Myanmar. It flows north up to 22° 47′ 09″N and 93° 05′ 47″E, where it meets 'Tio' (flowing southward) as its right bank tributary (Fig. 7). After meeting Tio, Kolodyne heads northwest into Mizoram State, where it is locally known as the 'Chhimtuipui' (Plate 4). The international border between India and Myanmar continues north along the 'Tyao (Tio) River' (Plate 3).

At 22° 56′ 21″N and 92° 58′ 55″E, 'Kolodyne' touches its northern-most point in Mizoram State and then turns southwestward. 'Tuichang River' joins it as right

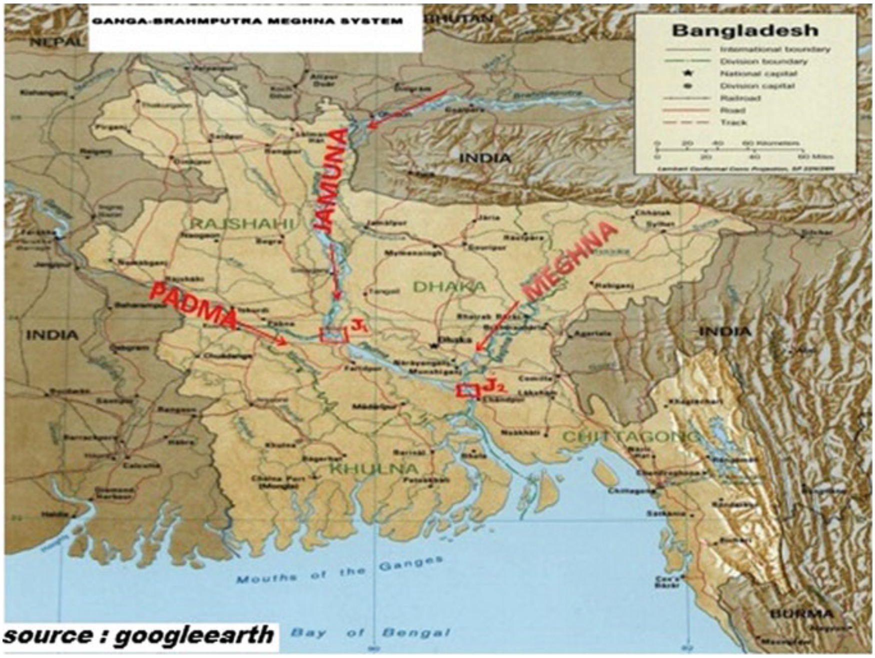


Fig. 6 A composite of Meghna–Padma–Jamuna

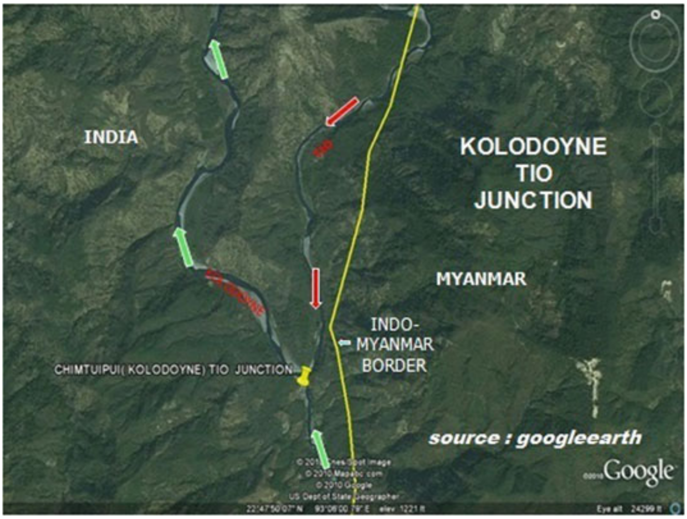


Fig. 7 "Tio" (flowing southward) as its right bank tributary

Tio River Bridge at Indo Myanmar Border, Mizoram

Plate 3 The international border between India and Myanmar continues north along the 'Tyao (Tio) river'

Bridge on Kolodyne at Saiha Entry Point

Kolodyne River off Saiha Town

Plate 4 Kolodyne heads northwest into Mizoram state, where it is locally known as the 'Chhimtuipui' bank tributary and from there onwards ‘Kolodyne’ heads south. Another right bank tributary ‘Mat River’ joins at 22° 43′ 39″N and 92° 54′ 46″E. ‘Kolodyne’ continues to flow southwards and is further joined by the ‘Kawrthingdeng River’ from the right. ‘Kolodyne’ reenters Myanmar in ‘Chin State’ at ‘Raithaw Ferry’ (22° 03′ 40″N and 92° 51′ 05″E), just northwest of ‘Khenkhar.’ The ‘Mi River’ from eastern Myanmar joins ‘Kolodyne’ as left bank tributary, at 21° 06′ 56″N and 92° 57′ 42″E. At ‘Ngame,’ ‘Kolodyne’ enters the ‘Rakhine State’ of Myanmar and continues to flow southward to ‘Sittwe’ where it drains into the Bay of Bengal (Fig. 8).

3.4 The Southerly Flowing River Karnphuli Draining Directly into Bay of Bengal

The River Karnphuli (known as ‘Khawthlangturipui’ in Mizo language) originates in ‘Mamit District of Mizoram,’ India, and flows southwards for 270 km before draining into Bay of Bengal 12 km before Chittagong Port. It flows for 128 km in Indian territory. It forms boundary between India and Bangladesh in the Eastern Mizoram. The two important tributaries of Karnphuli are ‘Tuichawng’ (Plate 5a) and ‘Chawngte’ rivers (Plate 5b), which originate in ‘Parva’ region of southwestern tip of Mizoram and both flow northward. ‘Chawngte River’ merges with Tuichawng and the latter in turn drains into Karnphuli. Another important tributary is ‘Thega River’ (locally known as ‘Thega Khāl,’ ‘Kawrpui Lui,’ or ‘Kawrpui

Fig. 8 Myanmar and continues to flow southward to ‘Sittwe’ where it drains into the Bay of Bengal

Plate 5 The two important tributaries of Karnphuli are 'Tuichawng'

River'). It also flows northwards and drains into the 'Karnphuli at 22° 52′ 43″N and 92° 26′ 52″E at Mizoram–Bangladesh border off 'Tlabung.' Karnphuli River is very important for the lifeline of Bangladesh. 'Chittagong Port' town is situated on its bank. A two-lane underground tunnel underneath Karnphuli River is being built by China Communication Construction Company (CCCC). The river is navigable by steamer up to 'Rangamati,' and it has been used for trade and transport of cotton and forest products. A large hydroelectric power plant was built on 'Karnphuli' River in the 'Kaptai' region during the 1960s. This hydroelectric power plant is vital for the power supply for Jute, Cotton, Tea and Tobacco processing plants and also for facilitating irrigation (Plate 5).

4 Rivers of Assam

The most important river of Assam is 'Brahmaputra' (Fig. 9). It forms the lifeline of the region. Its subsidiary rivers, with their length in bracket, are listed as:

Burhidihing (700), Dansiri (352), Subansiri (318), Kopili (297), Dihang (263); Disang (230), Dikhou (200), Lohit (192), Puthimari (190), Kalang (171), Manas (Main) (153), Jinjiram (143), Dikrang (134), Kulsi (122), Janji (108), Aai (103), Nonoi (97), Gangadhar (99), Dhansiri (north) (94), Ronganadi (102), Krishnai (81).

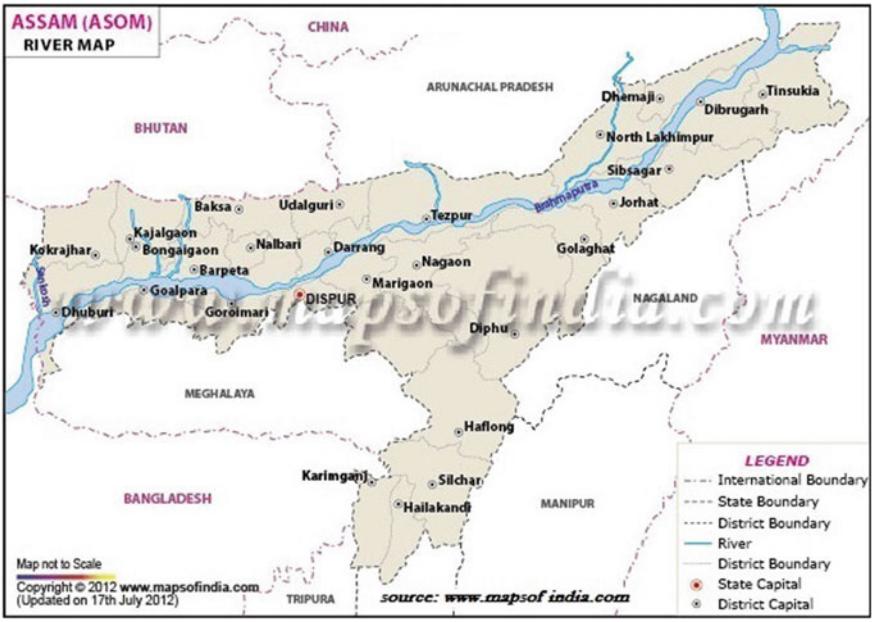


Fig. 9 The most important River of Assam is 'Brahmaputra'

4.1 The Brahmaputra River

The 'Brahmaputra' River has got different names in different languages. It is known as 'Burlung–Buthur' by the 'Bodo' people of Assam and as 'Yarlung Tsangpo in Tibetan language. It is known as 'Dihang' or 'Siang' in Arunachal Pradesh. It is called 'Jamuna' in Bangladesh (Plate 6).

It originates from the 'Angsi Glacier' of Himalayas in 'Burang County' of Tibet. Brahmaputra starts flowing eastward in southern Tibet across the 'Yarlung Tsangpo Grand Canyon,' and then, it enters into Arunachal Pradesh (India), where it flows southwestward through the Assam Valley as 'Brahmaputra' and then southwards through Bangladesh as the 'Jamuna.' In the vast Ganges Delta, it merges with the 'Padma' (the main distributary of the Ganges in Bangladesh), at 23° 48′ 16.88″N and 89° 43′ 38.00″E, nearly 35, west of Dhaka, the Capital of Bangladesh.

'Brahmaputra' is a very important river for irrigation and transportation in the northeastern region of India and Bangladesh. The average depth of 'Brahmaputra' is 124 ft and maximum depth is 380 ft. It causes catastrophic floods, in the spring, after the melting of snow. The average discharge of 'Brahmaputra' is nearly 680,000 cu ft/s, while during floods it can exceed 100,000–3,500,000 cu ft/s. Out of total area of the Brahmaputra basin (5,80,000 km^2), 1,94,413 km^2 falls in Indian territory. 'Brahmaputra' is characterized by braided river, channel migration, and avulsion and tidal bores. Its drainage area covers the Eastern Himalayan region

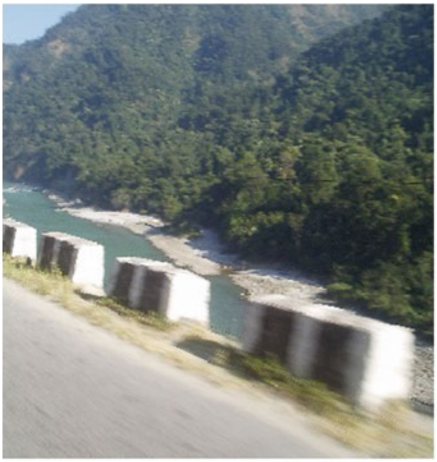
Plate 6 ‘The Subansiri River’

(east of the Indo-Nepal border), south, eastern, and central portion of Tibet plateau, ‘Patkai-Bum Hill’ (at extreme northeastern border of India and Myanmar)’, Meghalaya Hills, Assam plains, and northern region of Bangladesh. ‘Brahmaputra’ has been serving as an important mode of transportation since ancient times by virtue of the fact that most of its course is navigable. Till 1947, Brahmaputra was used as an important waterway. In 1990, the stretch between ‘Dhubri’ and ‘Sadiya’ was declared as National Waterway No. 2. Recently, the growth of river cruises has shown up. The first cruise ship ‘Charaidew’ was introduced by ‘Assam Bengal Navigation’ (Plate 7).

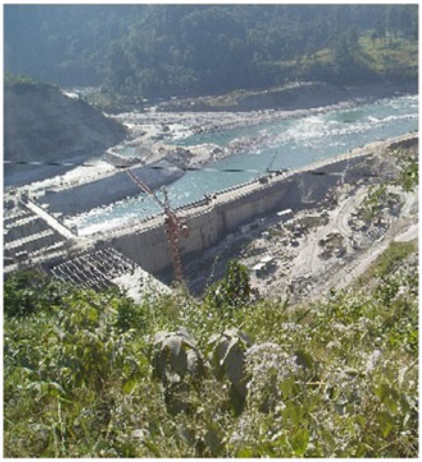
4.1.1 Brahmaputra in Assam

‘Brahmaputra’ flows at a relatively higher altitude in Tibet. It enters into India as ‘Siang River’ in Arunachal Pradesh, very rapidly descending to a much lower altitude. In the planes of Arunachal Pradesh, it is known as ‘Dihang.’ Thirty-five kilometers further, Lohit and ‘Dibang’ join ‘Brahmaputra’ as the left bank tributaries at northeastern fringe of the Assam Valley. After its merger with ‘Lohit,’ ‘Dihang’ gets the name ‘Brahmaputra.’ From this junction, ‘Brahmaputra’ suddenly attains a width of 10 km and turns toward southwest. ‘Kameng River’ (or Jia Bhoreli) joins ‘Brahmaputra’ as its right bank tributaries, near Sonitpur (Plate 8).

Between ‘Dibrugarh’ and ‘Lakhimpur,’ ‘Brahmaputra’ bifurcates into two channels namely ‘Kherkutia’ (northern channel) and Brahmaputra (southern). These two channels rejoin in the vicinity of ‘Majuli Island,’ nearly 100 km downstream, one of the world’s largest river islands. At ‘Guwahati,’ near the ancient pilgrimage center ‘Hajo,’ ‘Brahmaputra’ is narrowest (1 km), where it cuts across the rocks of the ‘Shillong Plateau.’ Most of the ‘Brahmaputra Valley’ in Assam is endowed with semi-evergreen forests eco region.



Teesta Flowing along Siliguri Gangtok Highway



Dam Site Over Teesta

Plate 7 'Teesta' can be felt as the lifeline of 'Sikkim', as it flows for almost the entire length of the state

Author in Boat Ride in Gumati River

Gumati River

Rock Sculpture on Cliffs

Sculpture of Godeess Shakti

Plate 8 Ancient stone carvings on the rocky walls of the steep gorges

4.1.2 Brahmaputra in Bangladesh

Brahmaputra is joined by its merger with ‘Teesta,’ ‘Brahmaputra’ splits into two distributaries. The western branch, containing the majority of the river’s flow, continues to flow southwards as the ‘Jamuna’ (Jomuna). Jamuna merges with the lower Ganges (known as ‘Padma River’) in Bangladesh (Fig. 10). The eastern branch (now much smaller), known as ‘Lower or Old Brahmaputra’ (Bromhoputro), curves toward southeast and joins ‘Meghna River’ near ‘Dhaka.’ ‘Padma’ and ‘Meghna’ converge near ‘Chandpur,’ and merge into ‘Lower Meghna’ and finally drains into the ‘Bay of Bengal.’

4.1.3 Flooding in Brahmaputra

During the spring season (June–October), flooding in ‘Brahmaputra’ is very common occurrence. Deforestation in the Brahmaputra watershed has resulted in increased siltation levels, flash floods, and soil erosion in critical downstream habitat. Massive flooding causes huge losses to crops, life, and property.

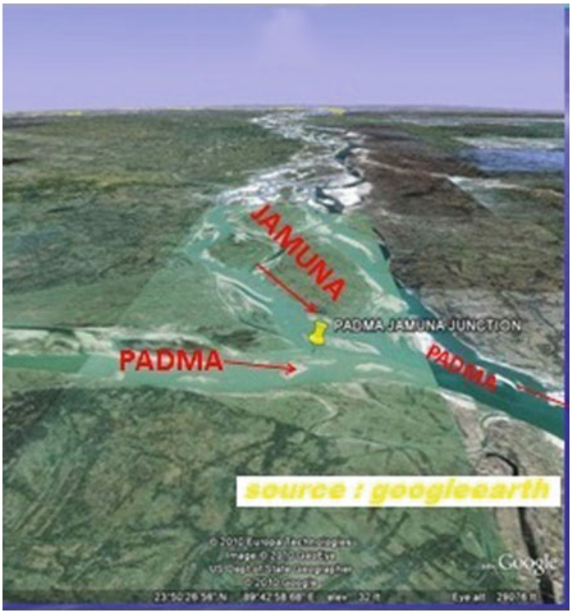


Fig. 10 Jamuna merges with the lower Ganges (known as ‘Padma River’) in Bangladesh

5 Rivers of North Bihar and Bengal

5.1 Mahananda

'Mahananda' originates in the Himalayas at 'Paglajhora Falls' on 'Mahaldiram Hill,' at an elevation of 2100 near 'Chimli' in 'East Kurseong,' Darjeeling district meters, southwest of 'Shivkhola Temple.' 'Mahananda' flows across the 'Mahananda Wildlife Sanctuary' and descends down to 'Siliguri' plains at the border of 'Jalpaiguri' district.

The 'Mahananda River' is an important trans-boundary river, flowing through the Indian states of West Bengal and Bihar and then in Bangladesh. Right bank tributary of 'Mahananda' known as 'Mechi' partly forms Indo-Nepal eastern boundary in West Bengal. Another tributary of 'Mahananda' called 'Kankai,' crosses out of Nepal.

'Mahananda' enters Bangladesh near 'Tentulia' (Panchagarh District). After flowing for 3 km in Bangladesh, near the bordering town 'Rupandighi' (West Bengal), it again returns to India off Tentulia. Further, it flows in 'Uttar Dinajpur' district of West Bengal, 'Kishanganj,' and 'Katihar' districts of Bihar. It enters 'Malda' district of West Bengal. The Mahananda divides 'Malda' district into two regions—the eastern region, consisting of old 1 and relatively infertile alluvial soil, locally known as 'Barind' (Borendrovomee), and the western region. The western region is further subdivided into two areas (northern and southern), by the river 'Kalindri.' The northern low lying area known as 'Tal' is flood-prone. The southern area consists of very fertile land and is commonly known as 'Diara.' It has thick population. River 'Kalindri' joins Ganga at 'Godagiri' in 'Nawabganj District' in Bangladesh.

Out of the total length of 360 km, 'Mahananda' flows for 324 km in India and rest 36 km in Bangladesh. The total drainage area of the 'Mahananda' is 20,600 km^2, out of which, drainage area in India is 11,530 km^2. The main tributaries of the Mahananda are 'Balason,' 'Mechi,' 'Ratwa,' and 'Kankai.' In the Siliguri area, it has three tributaries called the 'Trinai,' 'Ranochondi,' and the pair of 'Chokor and 'Dauk,' taken as a single tributary.

5.2 Kosi' (Kausiki)

The 'Kosi' has originated at 'Saptkoshi,' Tribeniganj, Nepal at a coordinate of 26° 54′ 47″N and 87° 09′ 25″E. The total length of Kosi is 720 km and its drainage area is approximately 74,500 km^2. It flows in southern parts of Tibet, Nepal, and Bihar.

Originally, Kosi flew eastward and drained into the Brahmaputra, but it is apparent that in the past 200 years, it has shifted its course from east to west to more than 130 km that comes to the tune of whole breadth of North Bengal. Nearly

200 years ago, merger of ‘Kosi,’ ‘Mahananda,’ and ‘Karatoya,’ river used to serve as an ethnic boundary between ‘Kochs’ (people living south of ‘Koshi’) and ‘Kiratas’ (people living north of the Koshi).

Its major tributaries in India are ‘Budhi Gandak,’ Bāgmati (Kareh), and ‘Kamalā.’ In addition, an important tributary is ‘Bhutahi Balān.’ In Indian territory, ‘Kosi’ (Kausiki) flows in the northeastern Bihar and drains into Ganges at ‘Muradpur’ (25° 23′ 43″N and 87° 15′ 03″E), Samastipur District, Bihar, India.

The composite of rivers of north Bihar is shown in Fig. 11.

6 Rivers of Manipur

Manipur is characterized by two distinct physical regions—(a) an outer area of rugged hills and narrow valleys and (b) the inner area of flat plain. Manipur River covers a total area about 600 km^2. The minimum altitude is 40 m at ‘Jiribam,’ and maximum altitude is 2,994 m at ‘Mt. Iso Peak’ near ‘Mao Singsong.’

There are four major river basins in Manipur, namely (1) ‘Barak River Basin’ (Barak Valley) to the west, (2)‘Manipur River Basin’ in central Manipur, (3) ‘Yu River Basin’ in the east, and (4) A part of the ‘Lanye River Basin’ in the north.

Barak originates in the Manipur Hills at ‘Mao Samsang.’ Many tributaries join ‘Barak,’ among then the important ones are ‘Irang,’ ‘Maku,’ and ‘Tuivai.’ After its junction with ‘Tuival, as the left bank tributary, ‘Barak’ turns northward forming the border between Manipur and Assam. Further, it flows through Cachar planes of Assam, traversing through Lakhipur, Silchar, and Badarpur town, before being bifurcated into two channels ‘Surma’ and ‘Kushiyara.’

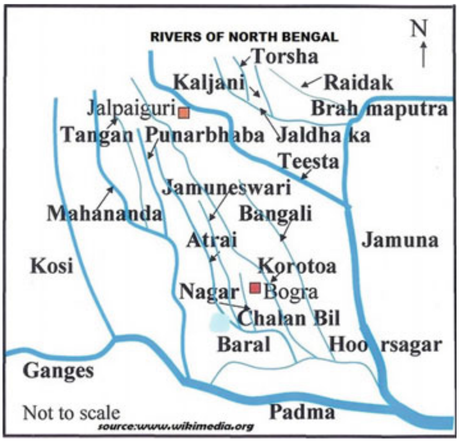


Fig. 11 The composite of rivers of North Bihar

The Manipur River drainage system contains eight major rivers originating from the surrounding hills namely ‘Chakpi,’ ‘Imphal,’ ‘Iril,’ ‘Khuga,’ ‘Manipur,’ ‘Nambul,’ ‘Sekmai,’ and ‘Thoubal.’ Most of these rivers are younger and turbulent during rainy season. Manipur River finally merges with the ‘Myittha River’ which is a right bank tributary of the ‘Chindwin River,’ in Myanmar. The Imphal River is the most important tributary of Manipur River. It originates in ‘Senapati District’ at ‘Karong Hills.’ It joins ‘Manipur River’ in ‘Thoubal district.’ Imphal River flows across ‘Loktak Lake’ and Imphal city. Finally, it joins Lilong River and drains into the Indian Ocean, flowing through Myanmar (Burma). In Myanmar, it is known as ‘Manipura River.’ It is interesting to know that Japanese soldiers used ‘Imphal River’ to reach Imphal town in World War II.

Mostly, all the rivers in the valley region are in the mature stage and deposit their sediments in the ‘Loktak Lake.’ Apart from Barak, major rivers of western of Manipur are Irang Jiri, Maku, and ‘Leimatak.’ The eastern part of the state is drained by ‘Yu River Basin.’ The main tributaries of Yu River are ‘Chamu’ and ‘Khunou.’

The River map of Manipur is presented in Fig. 12.

7 Rivers of Nagaland

Drainage system of Nagaland is characterized by a large number of seasonal and perennial rivers. The main rivers of Nagaland are ‘Doyang,’ ‘Dikhu,’ ‘Dhansiri,’ Dzu,’ ‘Dzuza,’‘Disai or Tsurang,’, ‘Lanye,’ ‘Langlong,’ ‘Likimro,’ ‘Menung,’ Manglu,’ ‘Nanung,’ ‘Tizu,’ ‘Tsurong,’ ‘Tsumok,’ and ‘Zunki.’ All these rivers show ‘dendritic’ pattern. Rivers ‘Dhansiri,’ ‘Doyang,’ and ‘Dikhu’ flow westward and drain into Brahmaputra. The ‘Tizu River’ flows toward east and joins the ‘Chindwin River’ in Burma.

7.1 Doyang

Doyang is the longest river in Nagaland. It originates from ‘Japfü Hill’ in the vicinity of the southern slope of ‘Mao’ in Manipur. From its origin, it moves southwestward and pass through ‘Kohima’ district. After ‘Kohima,’ it flows northward across ‘Zunheboto’ and ‘Wokha District.’ Further to ‘Wokha District,’ it takes a southwestward turn and reaches ‘Dhansiri’ in ‘Sibsagar’ District of Assam. ‘Chubi’ flowing southward from ‘Mokokchung District’ and ‘Nzhu,’ originating from ‘Nerhema’ area of ‘Kohima’ district, are the main tributaries of ‘Doyang.’ ‘Nzhu’ flows through ‘Miphong’ in ‘Tseminyu’ area before draining into ‘Doyang.’

Fig. 12 The river map of Manipur

7.2 Dikhu

'River Dikhu' has a total length of about 160 km. It originates from 'Nuroto Hill' in 'Zunheboto' district. 'Dikhu' flows northward, forming the border between 'Mokokchung' and 'Tuensang' districts. A major tributary of 'Dikhu' known as 'Yangyu' joins it in 'Tuensang' district while another major tributary 'Nanung' joins it in 'Langpangkong' range in 'Mokokchung' district. Further 'Dikhu' flows northward and leaves the hill and enters the Assam Valley near 'Naginimora' and finally merges with the 'Brahmaputra' River.

7.3 Dhansiri

'Dhansiri' flows across the southwestern region of Nagaland. It flows through 'Rangapahar–Dimapur Plains' of Dimapur District. Almost all the western and southern drainages of Nagaland merge into 'Dhansiri.' Its main tributaries are 'Dzuza' and 'Diphu.' At the southwestern fringe of Nagaland, 'Dhansiri' takes a northwardly turn and forms a natural boundary with 'North Cachar Hills' of Assam. Finally, it joins 'Brahmaputra' as its left bank tributary.

7.4 Tizu

The 'Tizu River' is most significant drainage system in the eastern part of Nagaland. Originating from the central region of the state, it flows toward northeast through 'Zunheboto' and 'Phek' district. Its main tributaries are 'Zunki,' 'Lanye,' and 'Likimro.' 'Tizu' finally drains into the 'Chindwin River' of Myanmar as its right bank tributary.

7.5 Milak

'Milak' is another important river flowing through 'Mokokchung District.' Its main tributary is 'Tsurong.'

7.6 Zungki

The 'Zunki River' is the largest tributary of 'Tizu.' It originates from the north-eastern region of 'Changdong forest' located to the south of 'Teku.' It flows southward, traversing 'Noklak,' 'Shamator,'and 'Kiphire,' and finally, merges into 'Tizu' below 'Kiphire.'

River Map of Nagaland is presented in Fig. 13.

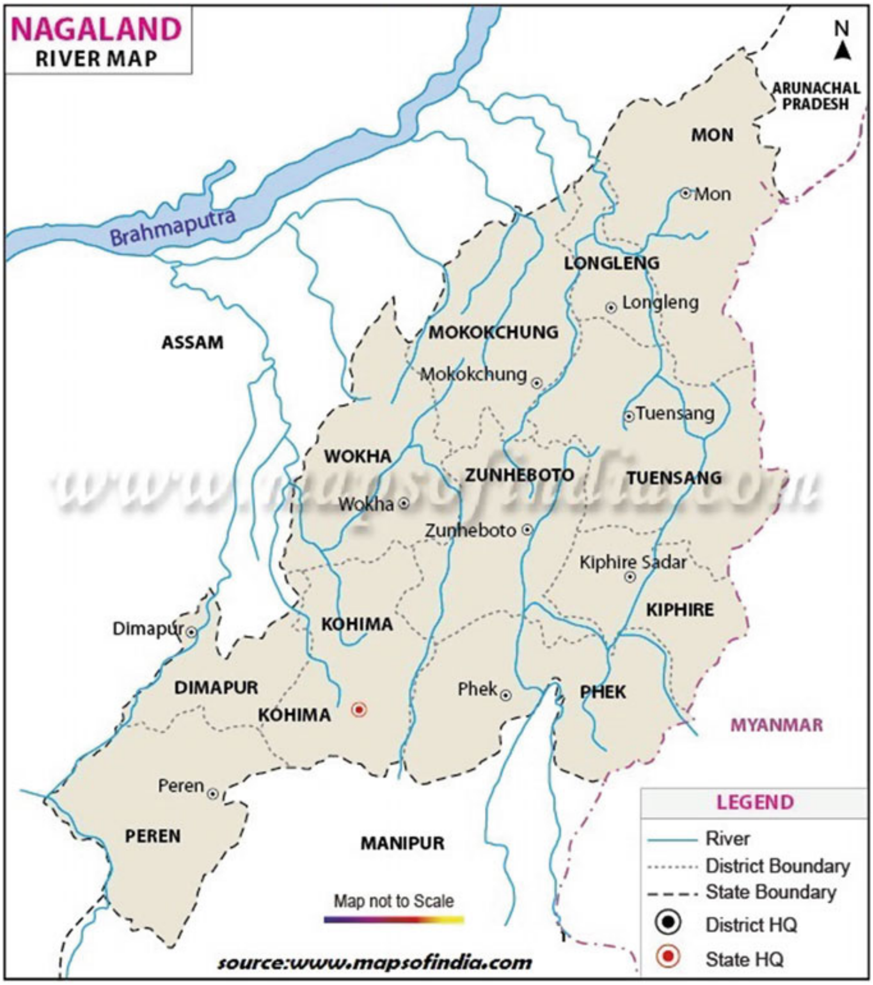


Fig. 13 River map of Nagaland

8 Rivers of Arunachal Pradesh

The main rivers of Arunachal Pradesh are 'Subhansiri,' 'Kamang,' 'Lohit,' and 'Dibang.' All of them ultimately drain into Brahmaputra.

8.1 Subansiri River

The 'Subansiri River' (Plate 6) is the largest tributary of 'Brahmaputra River.' 'Subansiri,' from its origin in Tibet, flows toward east and enters India through

Arunachal Pradesh and slightly turns southeast. From ‘West Siang,’ it starts flowing southwards and enters Assam Valley. It merges with ‘Brahmaputra’ as a right bank tributary, at ‘Sonitpur’ district of Assam. ‘Subansiri’ is a 442-km-long river, with a drainage basin 32,640 km^2 and contributes nearly 8% to ‘Brahmaputra drainage system.’

8.2 Kameng River

The ‘Kameng River’ originates from ‘Gori Chen Glacier’ on the India–Tibet border in ‘Tawang’ district. ‘Kameng River’ is also known as ‘Bhareli’ in Arunachal Pradesh and ‘Jia Bhoreli’ in Assam. It flows through ‘West Kameng’ and Sonitpur district and joins ‘Brahmaputra’ as a right bank tributary, near ‘Kolia Bhomora B in ‘Tejpur district.’ Two hundred and sixty-four-km-long ‘Kameng’ has a drainage basin of 11,843 km^2. ‘Tippi River’ joins ‘Kameng’ as a left bank tributary in the vicinity of ‘Sessa Orchid Wildlife Sanctuary,’ situated on the ‘Bhalukpong–Bomdila Highway.’ Other important tributaries of ‘Kameng’ are ‘Bichom,’ ‘Dirang Chu,’ and ‘Tenga.’

8.3 Lohit River

‘Lohit River’ originates in ‘Zayal Chu Range’ of Eastern Tibet. It flows for two hundred kilometers in Arunachal Pradesh, and then, it enters the plains of Assam. It is known as the ‘River of Blood’ because of red color imparted from lateritic soil from ‘Mishmi Hills.’ It meets ‘Brahmaputra (Siang)’ as right bank tributary, at the head of the Brahmaputra valley in ‘Tinsukia’ district.

‘Lohit River Valley’ is endowed with some of the densest subtropical and known for medicinal plant and herbs, especially ‘Mishmi teeta.’

Along the down current journey of ‘Lohit,’ interesting cultural changes from Tibetan theology to animist belief then passing on to ‘Theravada Buddhism’ and then finally to ‘Hindu’ ideology. It shows a great subcontinental mix and merge of Tibet, southeast Asia, and the Indian culture.

River Map of Arunachal Pradesh is shown in Fig. 14.

Fig. 14 River Map of Arunachal Pradesh

9 Rivers of Sikkim

‘Teesta’ and ‘Rangeet’ are the two main rivers of Sikkim. Both originate at high altitude and flow southward, until their convergence at ‘Melli.’

9.1 Teesta

‘Teesta’ originates from the pristine ‘Tso Lhamu’ glacial lake” in North Sikkim, at an altitude of 5,300 m. It moves downward and meet ‘Zemu Chu’ near ‘Lachen’ village and makes deep gorge. Further down, it meets “Lhachung Chu” at ‘Chungthang’; ‘Talung Chu’ joins ‘Teesta’ at ‘Mangan.’ After reaching ‘Singtam’ in East Sikkim, ‘Teesta’ becomes slower and it also becomes two times wider. In ‘Paykong District,’ two left bank tributaries ‘Rangpo Chuu’ and ‘Rani Khola’ join ‘Teesta’ as left bank tributaries. ‘Teesta’ then flows past the town of ‘Rangpo’ where the ‘Rangpo River’ joins, and there onwards ‘Teesta’ forms the border between ‘Sikkim’ and ‘West Bengal’ up to ‘Teesta Bazaar.’ Near the Teesta Bridge, at the ‘Kalimpong’ and ‘Darjeeling’ highway junction, ‘Teesta’ is met by its another main tributary, ‘Rangeet River.’

‘Teesta’ meets plains at ‘Sevoke,’ 22 km north of Siliguri. It then flows toward southeast through ‘Jalpaiguri’ and reached Bangladesh. ‘Teesta’ finally joins ‘Brahmaputra’ as its right bank tributary at ‘Chilmari’ in ‘Rangpur’ District of Bangladesh.

'Teesta' can be felt as the lifeline of 'Sikkim', as it flows for almost the entire length of the state (Plate 7). Teesta River flows for 315 km, draining an area of 12,540 km^2. Earlier, a large part of this was situated in Nepal. But after the 'Sugauli Treaty,' major part of 'Teesta' now falls in India.

9.2 Rangeet

'Rangeet' is the main tributary of 'Teesta.' It originates from the 'Rathong Glacier.' Important right tributaries of 'Rangeet' are 'Rangbong Khola' and 'Rathang Chu.' 'Rangeet' meets 'Teesta' as right bank tributary, at the Sikkim–West Bengal border at 'Melli.' The River then forms the border between Sikkim and West Bengal before joining the 'Brahmaputra' as a tributary in Bangladesh.

9.3 Flooding in Teesta

Rivers of Sikkim become swollen during monsoons. Being of mountain origin, the rivers of Sikkim are narrow and full of rock fragments and hence became unnavigable.

During monsoon, huge amount of water from snow melting and rain accumulates in the catchment area. In entire Sikkim, human settlements are usually made much above the flood level therefore not much damage takes place to life and property.

The River map of Sikkim is shown in Fig. 15.

9.4 Tributaries of Teesta

From Jalpaiguri, 'Teesta' bifurcates in three channels, namely 'Karatoya' (east), 'Punarbhaba'(west), and 'Atrai' (center). Because of the three channels 'Teesta River' was originally known as 'Trisrota' consisting of three streams. In due course of time, the name 'Trisrota' became corrupted to 'Teesta.' Out of these three channels, 'Punarbhaba' joins 'Mahananda.' The 'Atrai' passes through a big marshy area known as 'Chalan Beel.' 'Atrai,' 'Karatoya,' and 'Baral' join as a single stream and join the 'Padma' (Ganges) near 'Jafarganj.'

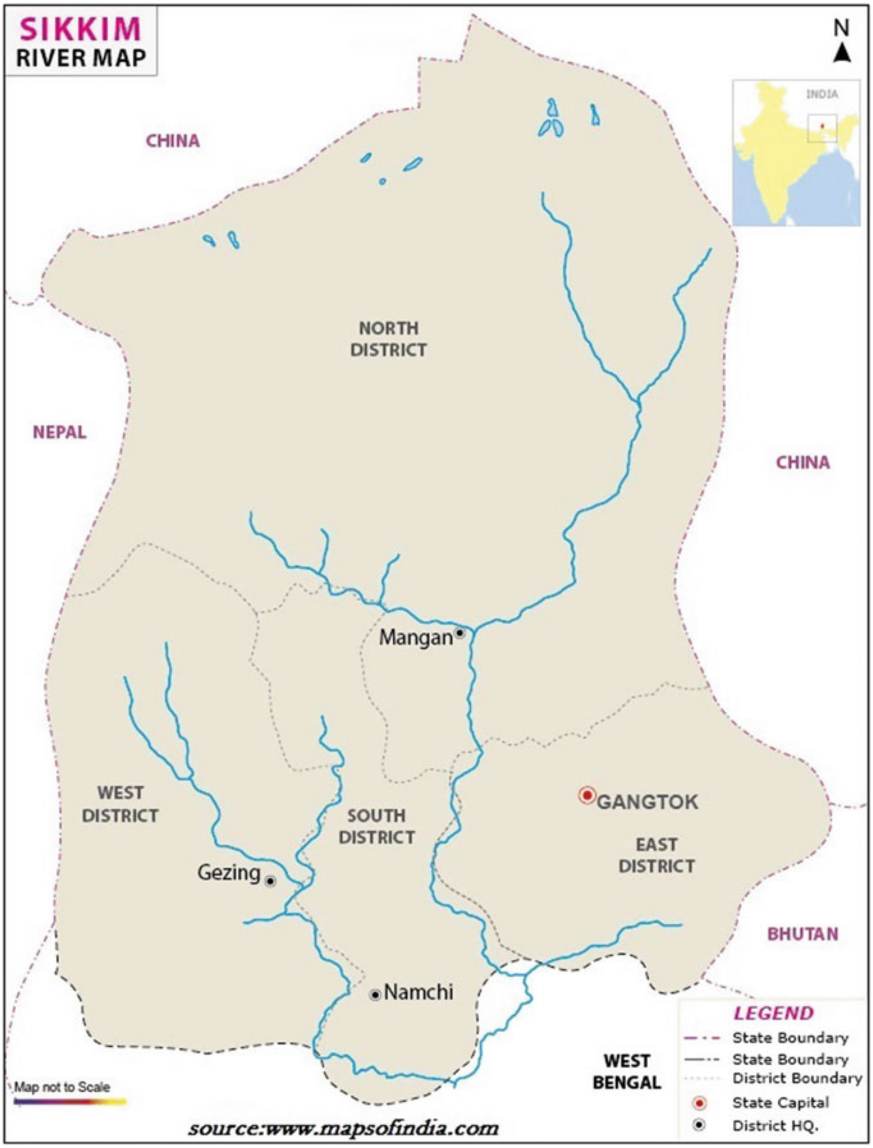


Fig. 15 The River map of Sikkim

10 Rivers of Tripura

The drainage of Tripura is characterized by 10 (ten) major ephemeral rivers, namely 'Burima,' 'Gomati,' 'Khowai,' 'Howrah,' 'Longai,' 'Dhalai,' 'Muhuri,' 'Feni,' 'Juri,' and 'Manu.'

The water becomes muddy during rainy season and bitterly polluted during lean periods. Navigation becomes impossible during rainy season due to excess mud and during dry season due to scarcity of water.

The major river of Tripura is 'Gumti.' It originates in northeastern hill region of Tripura at 'Dumbur.' 'Dumbur Dam' and reservoir (40 km^2 area) have been created on 'Gumti' to harness the water and serve as an important tourist spot.

The 'Gumti' has strong current. The catchment of Gumti is prone to flash floods during monsoon. Its width during the peak period exceeds 100 m; otherwise, it remains very narrow. During peak season, its discharge is 20,000 ft^3/s, as recorded at 'Comilla.'

'Gumti River' boat ride at 'Chabimura' offers an unforgettable thrill and adventure matching that of a 'boat ride in Amazon River,' as it passes through the densely vegetated banks with ancient stone carvings on the rocky walls of the steep gorges (Plate 8).

In addition, many small lakes and ponds are found in Tripura. 'Trishna wildlife sanctuary' has 13 lakes and 'Sepahijala wildlife Sanctuary' has 2. These lakes are house of migratory birds, which add to the tourist attraction. At the source of 'Muhuri River,' a clear water lake 'Devtapukur' has a huge potential as a beautiful tourist spot.

The river map of Tripura is shown in Fig. 16.

11 Rivers of Meghalaya

The majority of Meghalayan rivers are seasonal as they are rain-fed. These rivers form many deep canyons and waterfalls, thus add flavor and mesmerizing quality to Meghalaya Tourism. The rivers of Meghalaya can be grouped into rivers of northern, southern, central, and eastern region.

The important Rivers of the northern region are 'Ajagar,' 'Chagua,' 'Didram,' 'Dudnai,' 'Kalu,' 'Krishnai,' and 'Ringgi.' The important rivers of the southern region are 'Bandra,' 'Bhogai,' 'Bhupai,' 'Daring,' 'Dareng,' 'Nitai,' 'Simsang,' and 'Sanda.'

The main rivers of the central and eastern regions of Meghalaya are 'Digaru,' 'Umkhri,' and 'Umiam.' Most of the rivers of the eastern regions flow toward south. These are 'Barapani,' 'Mawpa,' 'Myngot,' 'Myntdu,' and 'Kynchiang.'

Important rivers of Meghalaya are as follows:

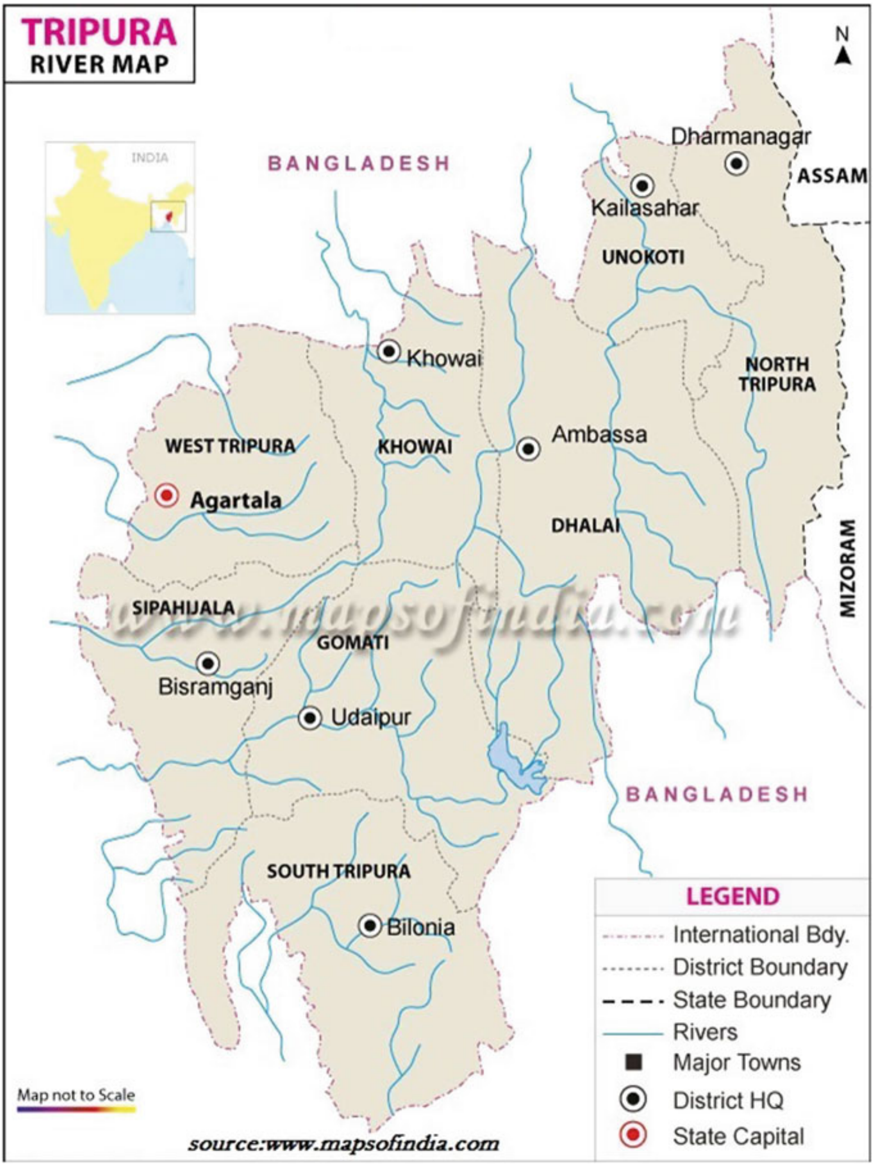


Fig. 16 The River map of Tripura

11.1 Someshwari

'Someshwari' is the biggest river in Meghalaya. It is locally known as 'Simsang.' It originates from the 'Nokrek Hills' and flows eastwards through 'Williamnagar,' 'Baghmara,' and 'Rewak' towns. After 'Baghmara,' it turns southwest ward and merges with 'Surma' as a right bank tributary at 25° 1′ 50.24″N and 92° 17′ 45.95″E.

11.2 Jinjiram

The Jinjiram River originates in 'Urpad Beel Lake' and flows eastward across 'Goalpara' district of Assam. It is a major river of the 'Garo Hills Districts.'

11.3 Kalu

'Kalu' river is locally known as 'Ganol.' It originates from 'Tura Peak' in Meghalaya and flows westwards through 'Goalpara district' in the state of Assam.

11.4 Myntdu

The 'Myntdu River' originates at Mihmyntdu, near 'Jowai.' The river streams across 'Jowai' to 'Leshka' and then to 'Borghat' village, and finally, enters into Bangladesh.

River map of Meghalaya is shown in Fig. 17.

12 Socioeconomic Importance of Northeast Rivers

12.1 Brahmaputra as the lifeline of northeastern region

Brahmaputra serves as the lifeline of Assam. It is not only navigable throughout its course but also forms numerous places of tourist attraction. A great example is the 'Majuli Island,' which is among the largest river islands of the world. Life in Guwahati (capital of Assam) cannot be imagined without 'Brahmaputra' (Plate 9), as a source of culture, traditions, communication, amusement, and tourism.

Fig. 17 River Map of Meghalaya

The Mighty Brahmaputra, Guwahati

Author in Brahmputra, with students

Plate 9 Life in Guwahati, (capital of Assam) cannot be imagined without ‘Brahmaputra’

12.2 International Relations on the Brahmaputra's Power Generation Potential

'Brahmaputra Drainage' is shared by three countries, China, India, and Bangladesh. In 2010, China initiated the construction of 'Zangmu Dam' on the Brahmaputra in Tibet. However, China assured the water rights of India.

These three countries through their trilateral cooperation and coordination have immense potential for developing hydroelectricity projects and trans-boundary water navigation in 'Brahmaputra' (Fig. 20).

12.3 Hydroelectric Projects and Dams Across Teesta

Out of India's total estimated hydroelectric power potential of 84 GW, Sikkim's share is nearly 3%, (approximately 5 GW). Having successfully completed, the major projects—Teesta—V dam, in 2007 and 'Rangeet III' hydroelectric project on Teesta, 570 MW electricity is being produced, and in addition, effective flood control has been made possible. Apart from these major projects, other minor projects on Lower 'Lagyap,' Upper 'Rongni Chhu,' and 'Mayang Chhu' are significant.

12.4 Dispute over Distribution of Teesta Water:

India and Bangladesh have inked a water-sharing arrangement through '1996 Bilateral Treaty,' subject to a review after 30 years. This treaty enabled India and Bangladesh to share 39 and 36% of the water, respectively. In the next review, which was due in 2011, an equal allocation (50:50) of the Teesta River was proposed. This treaty could not be signed due to the refusal of 'Ms. Mamata Banerjee' (Chief Minister of West Bengal) fearing water crisis in the northern region of state during drier months.

Teesta faces severe drop in flow discharge. It drops 5,000 cusecs in summers to 500 cusec during winters. The causes of this drop are the construction of dams on Teesta and its tributaries in Sikkim and diversion by the 'Gazaldoba Barrage' in India linked with 'Upper Mahananda' River. Such diversions and dams of Teesta water, surely benefits in the irrigation of nearly 100,000 ha of land in India, but they do create an acute water crisis for the Teesta irrigation project in 'Lalmonirhat' of Bangladesh (http://wikimapia.org/).

12.5 Importance of Teesta in Bangladesh

Teesta Barrage, completed in 1997–98, is located at ‘Duani’ in ‘Hatibandha Lalmonirhat’ district of Bangladesh, is very important for irrigation in Bangladesh. This barrage has a discharge capacity of 12,750 cusec of water. It is used to divert 280 cusec of water for irrigation through a canal taking off on the right bank. This project benefits an area of 750,000 ha, mostly for irrigation. The project area covers seven districts in greater Rangpur, Dinajpur, and Bogra.

12.6 Importance of Karnphuli in Bangladesh

‘Karnphuli River’ is very important for the lifeline of Bangladesh. The river is navigable by steamer up to Rangamati, and it has been used for trade and transport of cotton and forest products for a long time. ‘Chittagong Port’ town is situated on its bank. A 950-m-long, ‘Shah Amanat Bridge’ (Fig. 21a, b) is constructed across the ‘Karnphuli River’ in Bangladesh, by China Communication Construction Company (CCCC). It is the first major cable-supported bridge in the country. It connects the Southern Chittagong, ‘Cox’s Bazar’ with the hill district ‘Banderban.’ A two-lane underground tunnel underneath Karnphuli River is also under construction.

A large hydroelectric power plant was built as a part of ‘Karnphuli Multipurpose Project,’ on ‘Karnphuli’ River in the ‘Kaptai’ region in 1962. The generation capacity of this plant is 230 MW. This plant is vital for the power supply for Jute, Cotton, tea, and tobacco processing plants and also for irrigation purpose.

‘Kaptai dam’ (Fig. 21c, d) is the only dam of Bangladesh, generating hydroelectric power. It has the water storage capacity of 11,000 km^2. This hydropower plant constructed in 1962 is located at ‘Kaptai,’ nearly 50 km from the port city of ‘Chittagong’ (http://didar-physics.blogspot.in/).

12.7 Kaladon Multi-Modal Transport Network

India’s serious initiatives, under the ‘Look East Policy’ (LEP), focused on strong infrastructural development impetus with ASEAN, have been documented in form of ‘Kaladon Multi-Modal Transport Network Project.’ Under this project, Indian government is developing the ‘Sittwe’ port on the mouth of ‘Kolodyne River’ in Myanmar at a ‘Revised Cost Estimate (RCE) of approximately Rs. 2900 Crores. After completion, this project will not only immensely beneficial to the land-locked northeast region of the country but also serve as the gateway for Southeast Asia.

Presently, the distance between Mizoram and Kolkata is 1600 km, through the narrow ‘Chicken Neck’ or the ‘Siliguri Corridor.’ This 1600-km-long stretch is infested with geological hazards such as landslides, floods, and also security threats.

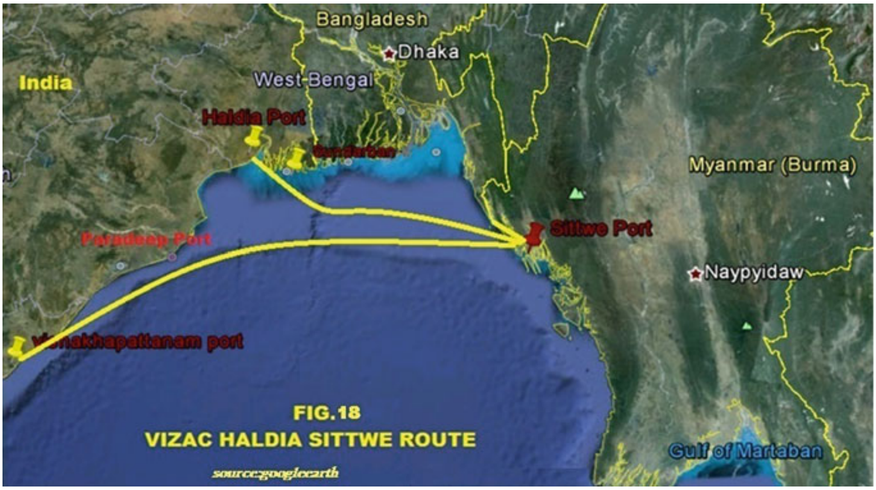


Fig. 18 ‘Chicken Neck Corridor’ and more importantly, this route will be free of geo hazards

After the completion of ‘Sittwe Port,’ the distance between ‘Kolkata’ and ‘Sittwe’ will drastically reduce to 600 km (Verma 2013). Importantly, the journey between these two points will be possible in 12 h only as compared to nearly 2000 km via ‘Chicken Neck Corridor,’ and more importantly, this route will be free of geo-hazards (Fig. 18).

In addition to the development of the ‘Sittwe Port,’ inland water transport from ‘Sittwe’ to ‘Lashio’ and ‘Paletwa’ (160 km), ‘Paletwa’ to Indo–Myanmar border road (110 km), and Indo–Myanmar border to ‘Lawngtlai’ road (100 km) are under construction. The ‘Kolodyne Multi-Modal Transport Project’ was expected to be commissioned by the end of 2012, but due to complex issues of compensation and cultural assimilation, it is still incomplete and is likely to be complete by the end of 2016.

12.8 Barak River as the National Waterway 6

The Barak River is the lifeline of the Manipur, Southern Assam, and Bangladesh (where it flows as Meghna). Barak River can significantly serve as the river interlinking channel in the region. All the northerly flowing rivers of Mizoram and Manipur drain into Barak. Barak as Meghna, in turn, assimilates the Ganga–Brahmaputra rivers in Bangladesh, before draining into Bay of Bengal. Government of India, realizing the significance of Barak, has proposed the National Waterway 6 between ‘Lakhipur’ and ‘Bagha’ (Fig. 19).

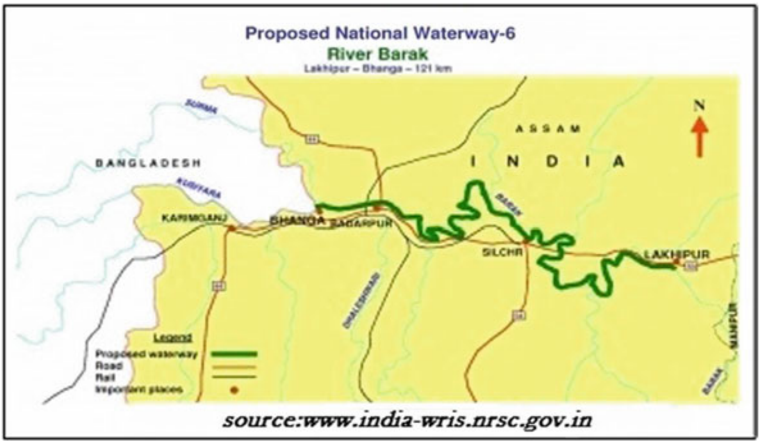


Fig. 19 The National Waterway 6 between ‘Lakhipur’ and ‘Bagha’

Fig. 20 Manipuri people in the affected area

12.9 Tipaimukh Dam on Barak

At Mizoram–Manipur border, an embankment dam on Barak at ‘Barak–Tuiwal’ junction, at Tipaimukh is proposed with a purpose of flood control and hydro-electric power generation. Though, it was commissioned in 1984, the project is facing repeated delay because of the water the rights issues between India and Bangladesh. Moreover, the people of Manipur are also protesting against the construction of ‘Tipaimukh Dam’ on the ground of adverse environmental effects and rehabilitation concern of Manipuri people in the affected area (Figs. 20 and 21).

Fig. 21 A 950 m long, 'Shah Amanat Bridge'

13 Conclusion

The rivers of northeast India not only serve as the lifeline of the 'seven sister states' but have immense potential as effective mode of transport and power generation capacity. Strategically also, many of them serve as the state and international borders. A clear balance in the international policy has to be maintained in relationship with China on the issue of sharing of 'Brahmaputra' water and with Bangladesh on the sharing of 'Teesta' water. The ambitious 'Kaladon Multi-modal Transit Transport Project' will not only facilitate the alternative sea route between India main land and the northeastern state, but also boost the international trade with the southeast Asian nations.

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Rivers of Mainland Gujarat: Physical Environment and Socio-economic Perspectives

Alpa Sridhar and L.S. Chamyal

1 Introduction

Mainland Gujarat refers to the region of Gujarat state stretching between the Aravalli mountain ranges in the north and the Satpura ranges in the south, separated from the Kachchh and the Saurashtra Peninsula to the east. The Mainland Gujarat encompasses two physiographic divisions, the Eastern Rocky Highlands and the Western Alluvial Plains (Merh and Chamyal 1997) (Fig. 1). These highlands, with an elevation range of 300–1100 m, are the extensions of the Aravalli, Satpura and the Sahyadri mountain ranges. The alluvial plains on the other hand comprise a huge thickness of unconsolidated sediments deposited mainly by the rivers during the Quaternary (the most recent period of geological time; ~2.5 million years to present). A major part of the Mainland Gujarat is occupied by these gradually sloping (25–150 m elevation range) alluvial plains called the Gujarat Alluvial Plains. A number of rivers that drain these plains are constantly modifying the landscape causing natural hazards. However, these rivers also serve as major water resources for the agricultural and the industrial needs and hence have a profound socio-economic influence. The major rivers that flow through Mainland Gujarat are the Sabarmati, the Mahi, the Narmada and the Tapi, all of which originate in the neighbouring states and flow from east to the west, debouching into the Arabian Sea. Whereas the Sabarmati and the Mahi Basins are situated in the semi-arid climatic zone, the Narmada and Tapi fall in the sub-humid climate zone (Fig. 1). Owing to such diverse physiographic and climatic conditions, these rivers possess distinct hydrologic and geomorphologic characters.

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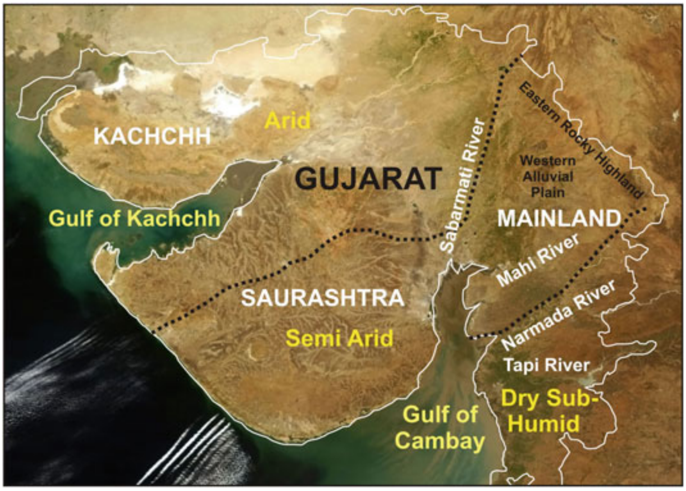

Fig. 1 Satellite image showing the physiographic divisions of Gujarat—the Mainland, Saurashtra and Kachchh. Also marked are the climatic zones in the state and the major rivers and urban centres of mainland Gujarat

The northernmost major river basin of Mainland Gujarat, the Sabarmati basin extends over states of Rajasthan and Gujarat having an area of 21,674 km^2 (IWRIS). It lies between 70° 58′–73° 51′E longitudes and 22° 15′–24° 47′N latitudes. Sabarmati River originates from Aravalli Hills at an elevation of 762 m from Mewar hills in Udaipur district of Rajasthan. The total length of river from origin to outfall into the Arabian Sea is 371 km, and its principal tributaries joining from left are the Wakal, the Hathmati and the Vatrak whereas the Sei joins from right. The basin is bounded by Aravalli Hills on the north and north-east, by Rann of Kutch on the west and by Gulf of Cambay on the south. The basin is roughly triangular in shape with the Sabarmati River as the base and the source of the Vatrak River as the apex point. Agriculture is the major land use in the basin accounting for 74.68% of the total area. The river catchment comprises of the metamorphic rocks of the Aravalli Supergroup, the Vindhyans and the expansive alluvial plains. It is a seasonal river receiving varied rainfall (450–800 mm) and has been frequented by floods in the past. Gandhinagar and Ahmedabad are the important urban centres in the basin.

The Mahi River is the third largest river in Gujarat having a drainage basin area of ~34,842 km^2 after the Narmada and Tapi rivers. The Mahi Basin extends over states of Madhya Pradesh, Rajasthan and Gujarat and lies between 72° 21′–75° 19′ E longitudes and 21° 46′–24° 30′N latitudes. The basin is enclosed by Aravalli Hills on the north and the north-west, the Malwa Plateau to the east, the Vindhyan hill ranges to the south and the Gulf of Khambhat on the west. The origin of the Mahi River is in the Mahi Kanta Hills, Madhya Pradesh, at an altitude of 500 m. The total length of Mahi is 583 km. The Som, the Anas, the Panam, the Goma and the Mesri are the major tributaries. It flows through the metamorphics of the Aravalli Supergroup, the Deccan Traps and the vast alluvial plains and debouches into the Gulf of Cambay. The mean annual monsoonal rain ranges from 850 mm in the headwaters to 600 mm in the lower reaches. Mean annual run-off is $\sim$135 mm and the mean annual discharge is 384 m^3 s^{-1}. Vadodara is the only important urban centre in the basin.

The Narmada River basin, largest on the Mainland Gujarat, extends over states of Madhya Pradesh, Gujarat, Maharashtra and Chhattisgarh having an area of 98,796 km^2. It lies between 72° 38′–81° 43′E longitudes and 21° 27′–23° 37′N latitudes. The Vindhyas, the Maikala range, the Satpuras and the Arabian Sea mark the basin boundary to the north, east, south and west, respectively. It rises from Maikala range near Amarkantak in Anuppur district of Madhya Pradesh, at an elevation of about 1057 m and flows for a total length of 1312 km (IWRIS). The Burhner, the Banjar, the Sher, the Shakkar, the Dudhi, the Tawa, the Ganjal, the Kundi, the Goi and the Karjan, the Hiran, the Tendoni, the Barna, the Kolar, the Men, the Uri, the Hatni and the Orsang are the major tributaries. It flows for a major distance through a rocky terrain comprising predominantly of the Palaeocene basaltic flows, Cretaceous sedimentary rocks, Vindhyan sedimentaries and the Quaternary sediments before draining into the Arabian Sea through the Gulf of Khambhat. The Narmada, also a seasonal river, receives an annual rainfall of 1250 mm and is located in the zone of severe rainstorms. Large floods occur on the Narmada during the monsoon, and a number of such floods have been recorded in the historical past. Jabalpur is the only important urban centre, and Khandwa and Bharuch are other towns situated in the basin.

The Tapi is the second largest westward draining river of the Peninsula. The Tapi basin lies between 72° 33′–78° 17′E longitudes and 20° 9′–21° 50′N latitudes and extends over states of Madhya Pradesh, Maharashtra and Gujarat having an area of 65,145 km^2. It originates near Multai reserve forest in Betul district of Madhya Pradesh at an elevation of 752 m. The total length of the river is 724 km and its important tributaries are the Suki, the Gomai, the Arunavati, the Aner, the Vaghur, the Amravati, the Buray, the Panjhra, the Bori, the Girna, the Purna, the Mona and the Sipna. The average annual rainfall is 830 mm and the basin is located within the zone of severe rainstorms. The river is characterized by one of the most intense flood regimes in the monsoonal tropics (Kale et al. 1994), and a number of floods have been recorded during the historical past. Surat is the only urban centre in the basin.

2 Geomorphology

The river valleys of the Mainland Gujarat were formed during the early Holocene-enhanced monsoon conditions (Gupta et al. 1999). Since then, the geomorphology of these river basins has been controlled by the factors of physiography, lithology, tectonics and climate (present and past) and thus showcases a variety

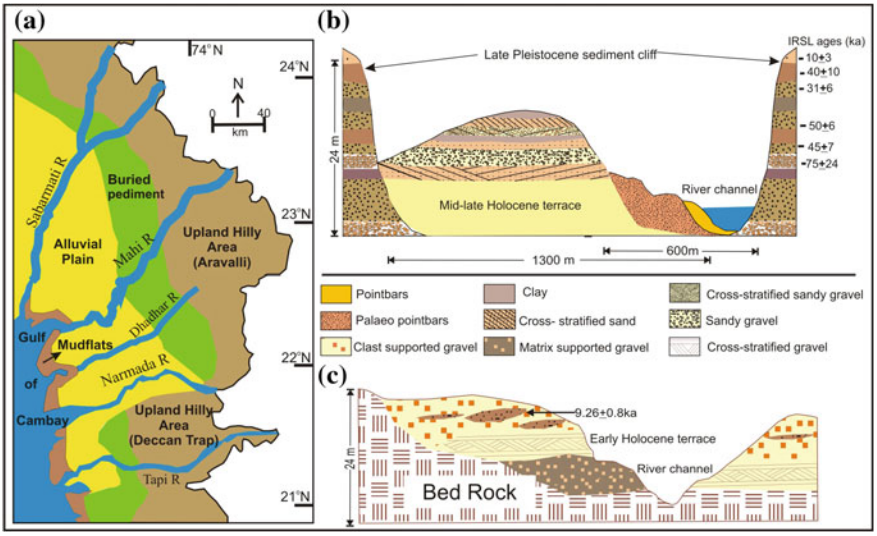

Fig. 2 **a** Geomorphic diversity across Mainland Gujarat. **b** A section across the Mahi river in the alluvial zone showcasing the juxtaposition of the various geomorphic features. **c** A section across the Mahi River in the pediment zone showing the relation between the bedrock and the terrace deposits (Sridhar, 2007)

of landform features that have evolved through time. A typical river profile of this region exhibits higher topography to the east and a flat terrain towards the west with a major slope towards the southwest and is thus divided into four geomorphic zones, viz. the upland, the pediment, the alluvial and the estuarine zones (Fig. 2a). The alluvial and the estuarine zones on the other hand comprise of the huge fluvial deposits in the form of alluvial terraces, point bars, channel bars, meander cut-offs and floodplains as an evidence of climatic changes (Fig. 2b) (Sridhar and Chamyal 2010). Features such as the uplifted planation surfaces, terraces (Fig. 2c), escarpments and entrenched meanders observed in the upland and pediment zones are a testimony to the tectonic activity during the Quaternary (Maurya et al. 2000). Further, in the alluvial zone, the geomorphic features form three lateral surfaces, viz. the valley-fill terraces, the ravine surface and the alluvial plain surface (Maurya et al. 2000) extending from the present-day channel towards the banks (Fig. 3). However, the extent and complexity of these surfaces as well as other geomorphic features vary in an individual river basin as is discussed below.

2.1 The Sabarmati Basin

The Sabarmati River Basin can be categorized into three geomorphic zones, viz. the eastern hilly highlands, the alluvial zone and the estuarine zone. The river originates

Fig. 3 A view of the geomorphic surfaces (alluvial plains, ravines and terrace surfaces) abutting against the trappean offset ridge in a tributary of Narmada

in the highlands comprising of rock formations of Aravalli and Delhi Supergroups and granitic intrusions. The terrain is moderately rugged with low hill ranges separated by extensive shallow valleys through which the streams flow. The granitic hills form a number of prominent peaks and massifs. In the alluvial zone, the surface topography is generally very flat but become increasingly undulating with numerous dunal mounds in the northern part of the basin. The present-day course of the river is slope deviatory and highly incised. The dunal hills rise up to 70 m above the ground level (Sridhar et al. 1994). These dunes are stabilized and dissected by ill-defined stream courses.

The alluvial zone is also characterized by the terraces, point bars and scroll plains seen exposed along the river channel due to incision. The channel is wide and shallow with high width–depth ratio and is highly meandering in the alluvial and estuarine zones with a number of abandoned palaeochannels and meander cut-offs. The alluvial plain surface comprises the gravel deposits at the base followed by the sandy-silty sediments deposited during the late Quaternary and covered by the dunal deposits. This has been deeply incised by the Sabarmati River, giving rise to cliffed banks up to 40 m elevation during the early Holocene (Fig. 4). In the middle reaches, this surface has been highly dissected by the tributaries giving rise to high drainage density and a ravenous topography. The present-day alluvium and scroll plains occur along the modern meander bends of the Sabarmati (Srivastava et al. 2001). The channel is seen to shift its course frequently in the alluvial zone leaving behind a number of palaeochannels and meander loops. In the estuarine zone, features such as mud flats and palaeobars are observed.

2.2 The Mahi Basin

The major geomorphic zones of the Mahi Basin include the rocky upland, pediment zone, alluvial zone and estuarine zone (Raj et al. 1999). The Mahi River valley is $\sim$10 m deep and 200 m wide in the upland zone whereas in the pediment zone, the channel is $\sim$6 m deep and 500 m wide with exposed bed rock, active floodplains, and terraces. The terraces are about 160 m amsl and mainly comprise gravels on both river banks. In the alluvial zone, the river exhibits meandering giving rise to

Fig. 4 A view of the exposed high cliffs (geomorphic surface S2) along the middle reaches of the Sabarmati comprising of the late Quaternary fluvial and aeolian sediments

Fig. 5 A photograph showing the various geomorphic features such as the cliffs, ravines, terraces and point bars in the alluvial zone of Mahi Basin

point bars, channel bars and alluvial terraces (Fig. 5). The sediment succession comprises of coarse point bar facies at the base overlain by fine flood plain facies. The Mahi River has wide estuarine mouth with marine and estuarine valley-fill deposits forming terraces. Typically, these terraces are observed exposed along the river at lower elevations (5–12 m).

2.3 The Narmada Basin

The Narmada River is the longest of the west flowing rivers of western India and flows through a hard rock terrain for most of its course. The river follows a constricted course in the upper and the middle reaches, alternates between stretches of bedrock gorges and patches of alluvium and is characterized by waterfalls, rapids and scablands (Rajaguru et al. 1995). The channel cuts through the hills and table lands in a series of gorges in the upper reaches. The lower Narmada basin in Gujarat is the sink of sediments and comprises alluvium (Bhandari et al. 2005).

The presence of young mountain-front scarps marking the Narmada–Son fault suggests that the area is tectonically very active(Fig. 6). Apart from the three geomorphic surfaces as seen in the Mahi and the Sabarmati river basins, the lower Narmada valley is also characterized by a fourth distinct geomorphic surface, the early Holocene fan surface. A major part of the drainage basin is covered by the alluvium forming a gently sloping alluvial plain surface. This surface is extremely dissected near the river and forms 20–30-m-deep gullies. These sediments are said to have been deposited initially in an alluvial fan environment and subsequently in an alluvial plain environment (Chamyal et al. 2002). The early Holocene fan surface is bounded by faults on either side and comprises a number of fans that have been deposited along the scarps of the Narmada–Son Fault (Chamyal et al. 2002). The alluvial-estuarine zone is marked by wide and flat terraces, 5–10 m in elevation. This surface occupies a highly incised valley and is devoid of deep ravines. According to Chamyal et al. 2002, these valley-fill terraces are comprised of tidal estuarine and sandy fluvial facies .

2.4 *The Tapi Basin*

The Tapi River flows through both bedrock that is predominantly basalt and alluvial reach comprising sand and silt deposits. The hilly region of the catchment shows geomorphic features such as the escarpments, piedmont-plains, colluvial plains, plateaus and valleys. In the alluvial reach, the channel is cut into cohesive alluvial deposits and exhibits a channel-in-channel physiography (Gupta et al. 1999), with high alluvial banks enclosing a large channel, point bars, a smaller low-flow

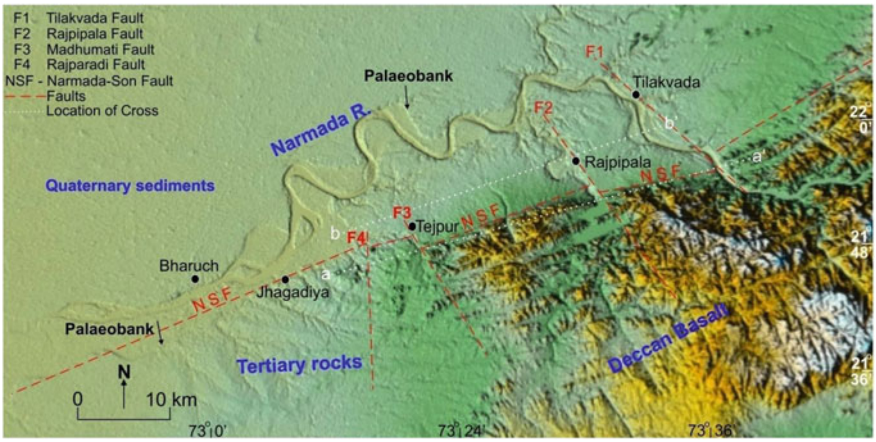

Fig. 6 DEM-derived topographic image of the lower Narmada valley after (Joshi et al. 2013). Note the fault controlled linear contact of the alluvial plain with upland terrain

channel and patches of floodplain. The channel width ranges between 240 and 703 m and the gradient is about 0.0006 (Kale and Hire 2004). The river bed is sandy and gravelly with terraces and gullied high banks.

3 Socio-economic Importance

River is an important corridor along which water, sediments and organisms are distributed through the landscape and thus is directly related to the socio-economic changes. The increased demand of water, food and shelter has resulted into embankments, dams, channelization and diversion of river systems for agriculture, flood mitigation, navigation, power production, etc. Such human interventions have resulted in drastic modification of the physical structure of river systems, directly or indirectly as a result of changed discharge regime leading to degradation of water resources and ecosystems. The river basins of the Mainland Gujarat are endowed with a wide range of microclimates, physiography, landforms, geology and vegetation that have an influence on their physical environments. The alluvial areas of these river basins are very fertile and house large-scale agricultural practices. Irrigation practices both surface as well as groundwater have also been in force in these basins since the last fifty years. Major cities located in the basins are industrial hubs that contribute to the water pollution in the rivers as well as groundwater. The changes in the land use have also led to degradation of soil and water resources in the river basins of Mainland Gujarat.

3.1 Soil Type, Agricultural Practices and Soil Erosion

In Mainland Gujarat, the Sabarmati basin includes parts of Sabarkantha, Ahmedabad, Banaskantha, Mehsana, Surendranagar, Kheda and Anand districts. The important soil types in the Sabarmati River basin are medium black, alluvial and sandy loam to sandy soils formed mainly due to the weathering of basalts/granite-gneiss and the deposition of the alluvium by the river, respectively. The medium black soil as well as the sandy soil has low fertility; however, the sandy loam soils are very fertile. The soils in the hilly area of the upper reaches are shallow and excessively drained leading to high soil erosion. Agriculture is the dominant land use in the basin, both rain fed and irrigated in almost equal measure. Cropping intensity varies greatly among basin districts. Besides the field crops such as wheat, paddy, jowar (sorghum), maize, cotton, tobacco, pulses, oil seeds and groundnut (peanut), in some areas, particularly near urban settlements, fodder crops and vegetables are commonly grown. Fruits orchards and banana plantations are also found in some parts, especially the Kheda and Anand districts. The Sabarmati basin is one of the most intensively irrigated regions and irrigation continues to be a major user of water in the basin in spite of the fact that most part of the basin falls in water stressed region. The major dam reservoirs in the basin are Dharoi, Hathmati and Watrak and a number of small- and medium-size projects do exist. The area under irrigation has shown dramatic increase over the years due to the construction of storage and diversion structures on the river and its tributaries and easy access to groundwater abstraction because of wide-scale use of electric pumps and easy availability of institutional financing (ICID, 2005).

The Mahi Basin includes parts of Sabarkantha, Panchmahals, Vadodara, Kheda, Anand and Bharuch districts in Mainland Gujarat. The upper part of the basin in Rajasthan and Madhya Pradesh comprises mostly hills and forests whereas the lower reach is totally plains. The soils here are shallow and medium black with poor fertility. The lower part of the basin lying in Gujarat is flat and fertile with well-developed alluvial tract. Important soil types in the basin are red-black soils and sandy loam to sandy (Goradu) soils. The major crop types include wheat, maize, cotton, tobacco, pulses and oil seeds, and in some areas, particularly near urban settlements, vegetables are commonly grown. Banana plantations are also found in some parts, especially the Kheda and Anand districts. The Mahi Basin is a highly irrigated region deriving water from the Jakham, Mahi Bajaj Sagar, Kadana, Panam, Wanakbori reservoirs. The excessive irrigation in the lower reaches of the basin (Anand and Khambhat districts) for water intensive cash crops caused problems of water logging and soil salinity. The medium black soils here have poor drainage and inherent soil salinity which resulted into water levels above the ground surface and salt encrustations.

The Narmada basin includes parts of Bharuch, Narmada and Vadodara districts of the Mainland Gujarat. The black smectitic soils with high water-holding capacities are predominant in the basin. In the upper basin, the black soils are accompanied by the red sandy or lateritic soils. The soil profile covering the hilltops and the plateaus is very shallow. Shallow black to medium black soils that are poor in drainage and fertility occur in the Vindhyan and Satpura plateau. Whereas the black soils are widely spread in the lower stretches of the basin, mixed red and black soils occur in the northern plateau. The major part of basin is covered with agriculture accounting to 56.90%, and sugarcane, cotton, pulses, wheat and oil seeds are the common crops taken here. Tawa, Barna, Sukha, Indira Sagar, Omkareshwar and the Sardar Sarovar are the major surface water development projects in the basin that provide water for irrigation.

Tapi River supports a large population as the soil around the Tapi River is good for agriculture. In the valley, by and large the soils are deep black and extremely fertile. However, in areas near the main river and its tributaries, extensive badlands have developed due to soil erosion. The soils grade from the deep fertile soils to coarse shallow to stony soils away from the river. The major part of basin is covered with agriculture accounting to 66.19% of the total area and is well irrigated by the canals from Kakrapar, Ukai, Upper Tapi and Girna projects.

3.2 Water Resources

The multiple water demands for irrigation, domestic and industrial usage are being met through groundwater mining, over-appropriation of surface flows and water import, threatening the hydrologic and ecological integrity of the river basins in Mainland Gujarat (Sridhar and Chamyal 2014). Water scarcity and conflicts over water use are widespread in the basins. The demographic and socio-economic processes are increasing the demand for water in the basin, thereby deepening the crisis.

Out of the four major river basins in Mainland Gujarat, the Sabarmati is one of the most water stressed river basins. It supports a population of nearly 10 million persons, 50% living in urban areas, several small, medium and large industries and nearly 2.9 million livestock. The total mean annual surface water resources of the Sabarmati basin are estimated as 3769 million cubic metres. Out of the 4.8 km^3 total utilizable water resources, 1.9 km^3 is surface water and 2.9 km^3 is groundwater resources. Almost about 90% of the irrigation is done through the groundwater resource that has caused depletion of the water levels in the aquifers. The increase in the salts due to over pumping and low recharge has made the groundwater unsafe for drinking purposes.

The Mahi Basin supports a population of about seven million, 70% of which are in rural areas. Of the total potential utilizable resources of 6.6, 3.5 km^3 is ground water and 3.1 km^3 is surface water. The total renewable resources amount to about 11 km^3. About 66% of the irrigated land draws water from the groundwater aquifers. Excessive irrigation and repeated cropping has lead to serious problems such as water logging and salinity of soils in the flat alluvial areas. The availability of groundwater for irrigation in the hilly areas with shallow soils has promoted the clearance of forests for agricultural practices ultimately causing heavy soil erosion in these areas. The quality of water is by and large good in the Mahi Basin apart from a few pockets with high sulphate and phosphorous content. The surface water quality has deteriorated by the disposal of chemical waste in the Mahi River and its tributary, the Mini near Vadodara.

The Narmada Basin has a surface water surplus though a number of development projects such as the Indira Sagar, Omkareshwar, Maheshwar, Burna, Tawa are in place. The basin has a total renewable water resource of 45 km^3 off which 35 km^3 is surface water. The ground water potential is comparatively low and only 40% of the total irrigated area draws water from the aquifers. The major development project of the Narmada River is the Sardar Sarovar Project, one of the largest in the world. It provides water for irrigation to huge areas in Rajasthan and Gujarat and provides drinking water to the water scarce Saurashtra and Kachchh regions. The Narmada Canal is functioning as a linking corridor and the water from the Narmada is being flown into the Mahi and the Sabarmati rivers providing drinking water to the city of Ahmedabad.

The Tapi Basin also is characterized by high surface water potential due to higher precipitation. The total utilizable water resources amount to about 21, 15 km^3 surface water and 6 km^3 groundwater. However, 65% of the irrigated land draws water from the groundwater aquifers. The water resources have been developed through the Ukai, Kakrapar, Girna and other medium and minor irrigation projects. The groundwater resource is limited due to hard rock terrain and water is available only in the weathered and fractured zones, joint planes, etc. The water quality is good with TDS less than 500 ppm.

3.3 Industries and Pollution

The major industries in the Sabarmati Basin include textiles, leather goods, plastic, paper, automobile, drugs and pharmaceuticals. Mahi Basin also has some industries such as cotton textile, paper, newsprint, drugs and pharmaceuticals. Whereas the Narmada basin has only few industries such as textiles, drugs and pharmaceuticals, tobacco products, machine tools, glass and ceramics, the important industries in the Tapi basin are textile, news print, machine tools, drugs and pharmaceuticals, plastic and allied products. In the Sabarmati River, the effluents are released from the industrial estates around Ahmedabad making the water highly polluted with high COD and TDS. Large amount of hazardous chemicals are being released into the Mahi River and the Gulf of Cambay. The severe coastal pollution has almost destroyed estuarine fisheries like in Amlakhadi where there has been a 75.76% fish catch reduction noted in five years in Bharuch district (ICID). According to Central Pollution Control Board (2010), three of the five most polluted river stretches in the country are in Gujarat which are the Amlakhadi at Ankleshwar (714 mg/L), Khari at Lali village, Ahmedabad (320 mg/L), and Sabarmati at Ahmedabad (207 mg/L). A very high volume of faecal coliform (FC) a bacteria present in human and animal excreta in the country has been reported in Sabarmati (CPCB 2010).

3.4 Natural Hazards

The major natural hazards associated with the fluvial activity in these river basins are the soil and bank erosion and floods. Floods are common in all the four river basins; however, the intensity and frequency of flooding vary owing to the diverse precipitation and geomorphic conditions. The Narmada and Tapi are more prone to high-magnitude floods as compared to the Sabarmati and Mahi and the lower reaches suffer heavy loss. Sediment records of palaeoflood events during the last 2 ka are available in the bedrock upper reaches as well as the alluvial reaches of these rivers (Kale et al. 2003; Sridhar et al. 2014). However, the flow of these rivers has been restricted by the construction of a series of dams that has helped in reducing the number and intensity of the flood events. Since these flood events are directly related to the rainfall conditions, they respond to the climatic changes in terms of increase or decrease in the flood frequency and magnitude.

Soil erosion is another major hazard that has great socio-economic relevance. For example, the Mahi Basin has a high density of trees and is characterized by rich biodiversity; however, an undulating topography coupled with loose and sandy to sandy loam soil renders the area highly susceptible to land degradation and erosion. Due to the loss of vegetation cover, deep gullies and ravines are formed on the land area adjacent to the channel. Ravines not only impact the ecosystem and food, fuel wood, fibre and water regulation services but also cause a loss of arable land which in turn threatens the livelihoods of the poorest farmers with marginal landholdings.

The banks of the Sabarmati, Mahi, Narmada and the Tapi are very high and more or less stable but severe bank erosion is observed in the lower reaches of these rivers. The alluvial banks 5–10 m high are being intensely cut and eroded by the high discharge flows in the rivers, especially the Narmada, Mahi and the Sabarmati. Lateral shifting of the river channel is also commonly observed leading to a loss of fertile agricultural land.

4 Conclusions

The river basins of Mainland Gujarat possess distinct hydrologic and geomorphologic characters owing to the diverse physiographic and climatic conditions. These river basins are broadly divisible into four distinct geomorphic zones from its origin to the mouth, viz. the upland zone, the pediment zone, alluvial zone and the estuarine zone. The geomorphology of these river basins can be viewed as a landscape response to both, tectonic activity and climate change. The major geomorphic features in the upland and pediment zones include scarps, badlands, waterfalls, rapids, planation surfaces and entrenched meanders suggesting tectonic activity during the late Quaternary. The features such as the alluvial terraces, point bars, channel bars, meander cut-offs and floodplains indicate the role of climatic changes in the evolution of these river basins. The socio-economic development in the Mainland Gujarat has been river centric and all these river basins have played a significant role in the overall growth of the region. There are major environmental issues that loom large over these basins. On the one hand where there is excess run-off in the rivers such as Narmada and Tapi, the population in the Sabarmati basin faces water scarcity. The agricultural growth in these basins has been exceptionally high and all fall in the food surplus zone. However, unplanned irrigation activities have put the surface as well as the groundwater resources under severe stress. To add up to this, the industrial effluents are being discharged into the main rivers or the tributaries leading to water contamination in the downstream areas. Soil and bank erosion, though common, are still within the limit where conservation methods can be applied. Thus, the socio-economic relevance of these river basins is very high.

A large potential exists to further improve upon the conditions of water supply, agriculture, soil erosion as well as the pollution. Major and minor projects are already in place on most of the rivers but still most of the rivers do not augment to the available capacity. The rich groundwater resource and advent of tube wells have led to neglect of surface water bodies in these basins. As a result, the surface water resources are not well managed, but the groundwater resources are now overexploited. In its present state of governance, resources such as land and water are managed by various local, state, and central agencies. The resource availability can be improved through a basin perspective, managing resources in a holistic and integrated manner. Nonetheless, each geomorphic unit has a unique resource potential and a scientific evaluation of the potential is a must for effective river basin management.

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Purna River, Maharashtra

Ashok K. Srivastava and Vivek M. Kale

1 Introduction

The Purna River is one among the major rivers of Maharashtra and considered as a significant geological unit of central India because of its scientific as well as social aspects. It originates in the Satpura region at Chincholi village (77° 38′ 39″E–21° 40′ 11″N, +760 m msl) in Betul district of Madhya Pradesh. The river with south-easterly flow enters to Maharashtra at Brahmanwada Thadi (77° 46′ 03″E–21° 23′ 08″N, +450 m msl) after covering a distance of about 35 km from the origin that further continues for about 75 km up to village Pingla (77° 27′ 21″E–20° 51′ 03″N, +280 m msl) in Murtizapur taluka (tehsil). This entire course of river falls in high terrain of basalt (Figs. 1 and 2a). From this point, the river takes an abrupt westerly flow, which continues for a distance of about 160 km mostly in alluvial zone (Fig. 2b), before its confluence with Tapi River at Changdev village (76° 0′ 26″E–21° 5′ 25″N, +210 m msl) of Muktainagar taluka as a major tributary (Fig. 2c). The river basin covers 38 talukas belonging to five districts of Maharashtra, viz. Amravati (11 talukas; 4958.59 km^2 area), Akola (7; 5424.46 km^2), Buldhana (10; 5658.40 km^2), Jalgaon (3; 671.47 km^2) and Washim (5; 1061.87 km^2); and two of Madhya Pradesh, i.e. Betul (2; 695.39 km^2) and Nimar (1; 44.69 km^2). A total of twenty-four towns are under the geographical extent of the basin. A few major towns are Amravati, Akola, Akot, Achalpur, Daryapur, Chikhaldara, Buldhana, Shegaon and Khamgaon, which together incorporate a total of 2583 villages.

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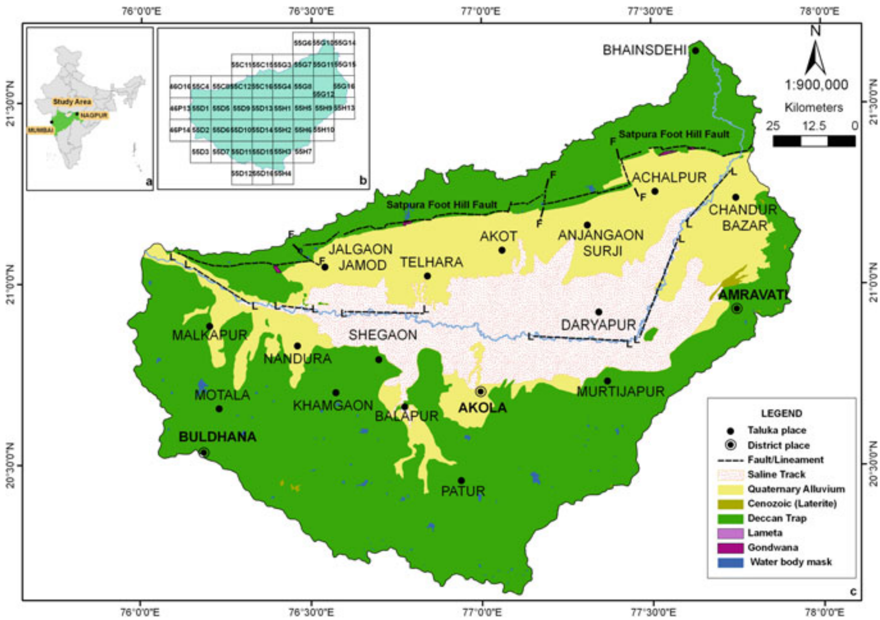

Fig. 1 Entire course of river falls in high terrain of basalt

The basin has many significant and interesting features which are as follows:

(i) Vast alluvial tract of Quaternary sediments covering an area of 6522 km^2 that shows a variable lithological set-up in both vertical and lateral profiles.
(ii) Structural set-up of the basin has a close relationship with the major tectonic feature of central India, viz. Son-Narmada-Tapi lineament zone.
(iii) Occurrences of ash beds at 7–8 localities as small, lenticular, pockets or discontinuous beds in the Quaternary successions of the basin having a significance in precise inter- and intra-basinal correlations, interpretation of palaeoclimate, nature of volcanic eruption, etc. (Fig. 2d).
(iv) Presence of skeletal remains of *Elephas namadicus*, *Equus*, *Antilope*, etc., in the alluvial sediments having a key role in reconstructions of palaeofaunal and vegetational scenario (Fig. 2e).
(v) Prevalence of saline groundwater in 2900 km^2 area of the central alluvial zone of the basin, commonly known as saline track.
(vi) Overexploitation and rapid lowering of the groundwater table affecting adversely to the production of main cash crops, i.e. cotton, pulses and orange.

The river has twelve major tributaries forming together an east–west trending river basin with total catchment area of about 18,514 km^2. Peripheral part of the basin is the basaltic terrain of the Deccan Trap, whereas the central area is covered by sediments carried out by the river in reference and its tributaries, i.e. Purna

Fig. 2 Muktainagar taluka as a major tributary

alluvial basin. The alluvial sediments, ranging in age from Quaternary to Recent, cover a large area of the basin, i.e. 6522 km^2. These sediments exhibit vast lateral and vertical extents and represent varied lithological characteristics. Major part of this zone covering central 2900 km^2 area experiences groundwater salinity that happens to be a matter of concern to the earth scientists and contributes a major share of the available literature from decades back (Wynne 1869; Adyalkar 1963; Muthuraman et al. 1992; Muthuraman and Padhi 1996; Khare and Kale 2001; Siddiqui 2004; Parimal 2012).

Rainfall precipitation in the basin area, in general, is moderate and observed during the months of mid-June to mid-September, with an average of 770 mm. The area experiences moderate drought condition when the rainfall is below the average for consecutive 2–3 years. The summer period is prolonged, with a temperature up to 48 °C in the months of May–June.

2 Physiography

The east–west elongated basin exhibiting slight convexity towards the south and broad, easterly edge tapering towards the west, constitutes a part of Narmada-Tapi rift zone. It is bounded by Satpura Hill Range (Melghat Hill Range) in north and Ajanta Hill Range in the south. The central part is a gently sloping alluvial plain, deposited by Purna River and its tributaries (Fig. 3). The highest elevation of +1180 m msl is recorded in the high hills of Satpura, whereas lowest of +210 m msl is recorded at the confluence point of Purna and Tapi rivers. The overall slope for entire basin is from north to south, however, fairly steep in northern sector of the basin, whereas reverse, i.e., from south to north but gentle in southern sector (Kale 2010).

Physiographically, from north to south, the basin can be subdivided in four major regions: (i) Melghat Hills, (ii) gently sloping alluvial plain, (iii) undulating to rolling plateau plain and (iv) Ajanta Hill Range. The Melghat Hill, an east–west trending range with an average elevation of about +1150 m msl, constitutes a part

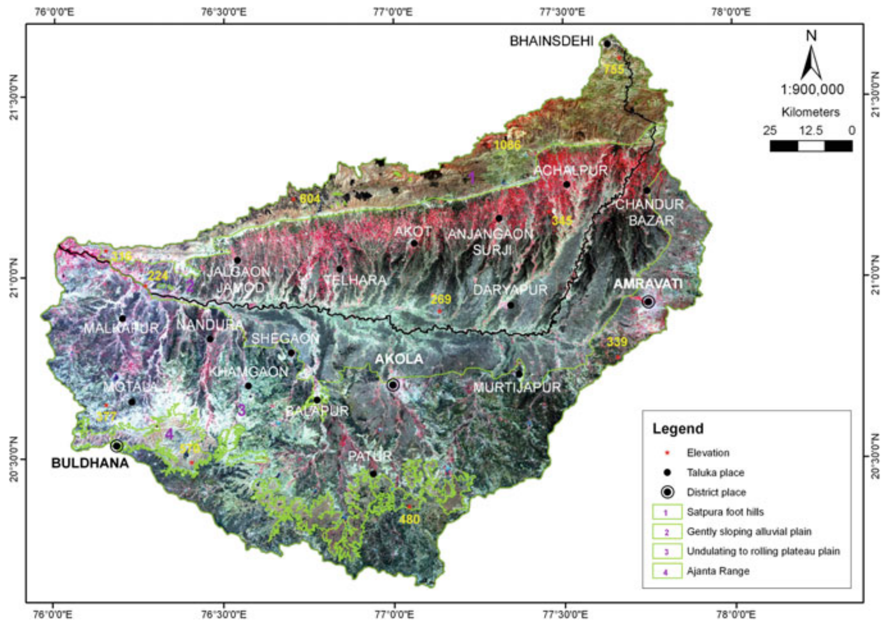

Fig. 3 Gentle slope towards the southwest

of the southern flank of the major Satpura orogenic belt. It extends from Betul district of Madhya Pradesh in the east, up to the vicinity of Purna and Tapi river confluence in the west. The alluvial plain constituting central part of the basin, ranges between the altitudes of 250 and 300 m above msl and shows a gentle slope towards the south-west (Fig. 3). Undulating to rolling plateau plains, a country of black cotton soil lies in the eastern and south-eastern parts of the basin, which is interrupted by mesa, buttes and residual hills. The Ajanta Hill Range having average elevation of +400 m msl, lying in the southern part, exhibits a curving trend from west to east. It has a steep northerly down slope towards the Purna River.

3 Geology

Thematic mapping of the basin reveals five major geological units: (i) unconsolidated sediments, (ii) semiconsolidated sediments, (iii) residual cappings, (iv) volcanic flows including intertrapeans and (v) water body mask. The unconsolidated sediments, covering 7811.55 km^2 area on either sides of the Purna River and its major tributaries, are mainly the alluvial sediments of Quaternary to Recent age. The semiconsolidated sediments consisting of arenaceous and argillaceous rocks of Gondwana Supergroup, cover 10.63 km^2 area on extreme northern boundary of the basin.

The residual cappings constituting an area of 33.07 km^2 are the laterites formed by leaching process of basalt. The volcanic flows along with the intertrapeans, together constitute maximum area of the basin, i.e. 10,599.58 km^2. It is mainly represented by Deccan basalt having small pockets of calcareous, marl and argillaceous sediments of intertrapeans ranging in age from Cretaceous to Eocene (Fig. 4). Water body mask with an extent of 60.03 km^2 is mainly represented by the Purna River and its tributaries along with a few reservoirs such as Wan, Shahanur and Katepurna.

Lithologically, the basin area is dominantly represented by the alluvium and basalt of the Deccan Trap. The previous is represented by a thick pile of Quaternary sediments on the basement of Deccan basalt and restricted by faults on the northern side. The alluvial plain occupies about 28% of the basin with a spread over of 6522 km^2 area. These sediments, ranging in age from Lower Pleistocene to Recent, vary considerably in grain size and nature, i.e. boulders, sand, silt and clay. In general, a decreasing trend of grain size from north to south is noticed in the lateral profile of the basin. The borehole data reveal that the thickness of alluvial deposit has a decreasing trend from north to south with a maximum of 426 m at Akot in the north whereas 40 m at Walgaon in south. Lithostratigraphically, the succession has been classified into four formations, viz. (i) the Vaghoi Formation, (ii) the Kodori Formation, (iii) the Kural Formation and (iv) the Purna Formation, respectively, having their deposition in lacustrine, older to younger flood plains (Tiwari et al. 2010). Chakrabarti and Roy (2007) studied the sedimentary processes by establishing the facies architecture at three different locations in the alluvial basin and

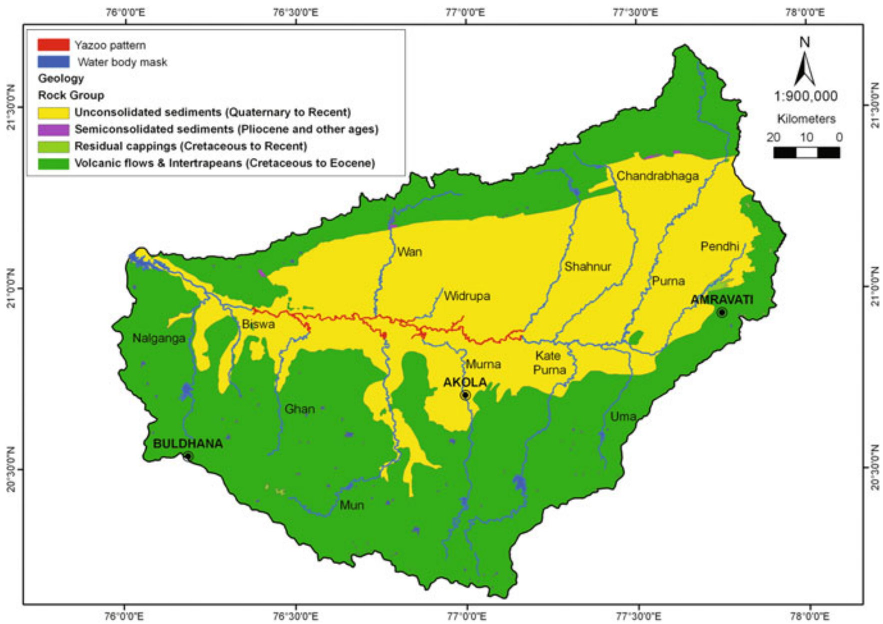

Fig. 4 Map showing spatial distribution of rock groups and yazoo pattern

interpreted that the alluvial fan sedimentation has taken place through debris, sheet and stream flows. Recently, Srivastava and Kale (2010) studied sedimentological characteristics of ten river-cut sections exposed along the main channel of Purna and interpreted that the depositional environment of the alluvium ranges from alluvial fan, braided stream to flood plain of a meandering river of semiarid climate.

The Deccan Trap complex of Early Cretaceous–Eocene age is represented by fine-grained, melanocratic, hard and compact basalt. The basalt is represented by both Aa and Pahoehoe types of lava flows. The Aa lava flows are characterized by fragment surfaces, rough and spiny, with a ‘cindery’ appearance (Jay and Widdowson 2008). Fine-grained, dark basaltic flows constitute the high country, whereas the weathered vesicular variety predominates in the basin areas (Siddiqui 2004). It covers 11,990 km^2 peripheral area of the basin, having an elevation range of 210 to +1180 m (Kale 2010). Often, the rocks show weathering which may form a laterally extended zone, ranging from 50 to 300 cm in thickness.

4 Lateral Distribution of Alluvial Facies

Lateral distribution of alluvial sediments is also heterogeneous in nature which is controlled by basin geomorphology, lithology, drainage pattern, slope and relief. Here, the term ‘facies’ is used which is limited to horizontal dimension of lithounit represented surfacially by similar characteristics. It is based primarily on FCC image characteristics, refined by high-resolution (6 M) panchromatic satellite data. Certain part of the area exhibits a very low density of dug wells because of high thickness of clay; therefore, the irrigation in that area is mostly done by tube wells. These dug well and tube well data have also been considered to classify the lithounits as per the quality of groundwater. Similarly, the absence or presence of the summer-irrigated crops has proved to be a potential geo-botanical indicator in the delineation of boundary. It also forms a key factor in understanding lateral distribution of facies, particularly on the imageries of summer season. On the basis of above parameters, a total of five facies have been identified: (i) boulder-pebbly facies (BPF), (ii) sandy-gravel facies (SGF), (iii) sandy-clay facies (SCF), (iv) silty facies (SF) and (v) clay facies (CF) (Fig. 5).

The boulder-pebbly facies (BPF) is restricted at the foothill zone of steeply sloping Satpura Range, extending from Jalgaon Jamod in the west up to little beyond Chandurbazar towards east. The width of the zone is very narrow and ranges from 3 to 5 km. It is represented by a brighter tone on the imagery. Since, the zone is lying immediately at the foothills, therefore, considered as piedmont or bajada zone. The area is mainly represented by boulders and pebbles embedded in loosely packed sandy-clay matrix. The aerial extent of the facies is 341.26 km^2. The zone is almost devoid of well irrigation, which corroborates that it acts as a run-off zone, where most of the water drains out. The groundwater is very deep, making the zone unfit for dug well or even tube well development. The sandy-gravel facies

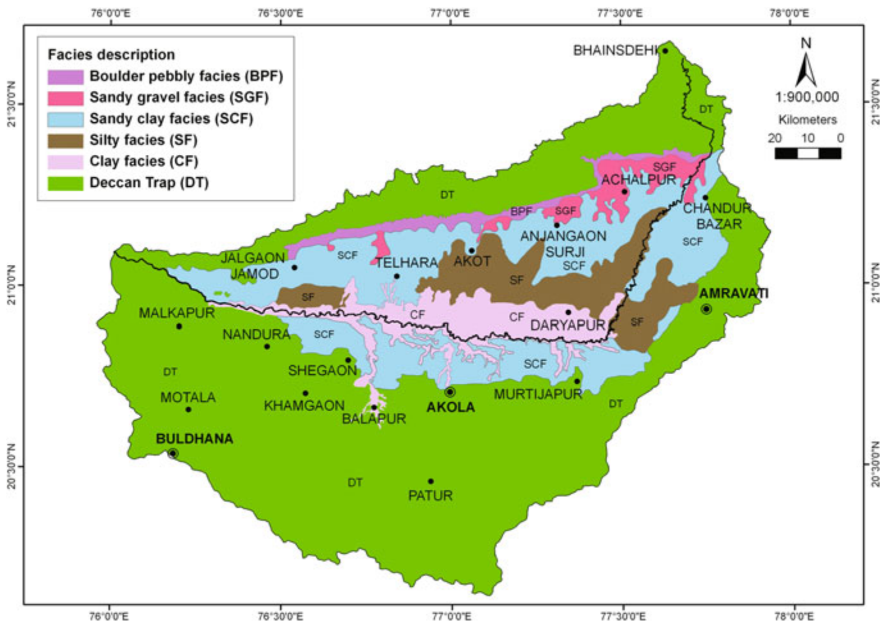

Fig. 5 Spatial distribution of various lithofacies in alluvial part of the basin

(SGF) lies adjacent to the southern margin of boulder-pebbly facies, in the form of isolated patches. The aerial extent of this facies is about 443.45 km^2. The zone shows almost uniform image characteristics because of the land use practice. Dominance of well irrigation in this area indicates the presence of sandy, water bearing horizons, in the subsurface strata. The dominance of well irrigation also indicates that the area is suitable for local shallow aquifer-based irrigation or domestic needs. The yield of the tube wells is reported to be between 5 and 10 LPS.

The sandy-clay facies (SCF) extends in a vast track on either sides of the river Purna, covering an area of about 3634.78 km^2. It is composed of mainly fine to medium sand and clay, which is identifiable due to its smooth tone and texture, though, locally show little darker tone due to high content of soil moisture. The well irrigation is very less indicating limited sandy horizons in subsurface column. The silty facies (SF) is characterized by its little brighter tone on panchromatic image with a smooth texture. Its spread over is a narrow belt, which is more prominent in the north of Daryapur town. Lithologically, the area is represented by fine-grained sediments, in which the sand proportion is comparatively low. The aerial extent of this area is about 1375.18 km^2. Well irrigation is almost absent, owing to the fact, that the area has silty horizons in subsurface deposit. The quality of groundwater is brackish as inferred by the discussions with local people during field visits, rendering the zone unfit for well irrigation. The clay facies (CF) indicates darker tone on image and covers a vast narrow belt, all along the Purna River course for about 110 km length. It is exposed on either sides of the river, which is known as inner saline zone in the hydrogeological context of the basin. The spread of this facies is very large making a total of about 1266.32 km^2. Remarkably, this zone shows absence of well irrigation, indicating unsuitable quality of water. It is marked as 'saline track' where total dissolved solids in groundwater are very high. The absence of well irrigation is presumed because of lack of prominent sandy horizons in the subsurface column.

It is observed that in lateral profile, these facies show a gradation in the size of sediments, i.e. from Satpura foothill region in the north towards the river Purna in south. The boulder-pebbly facies, represented by larger grain size, is confined to foothill region, which grades to sandy-gravel facies towards the south. The later further grades to sandy-clay facies and onwards to silty and clayey alluvium in south up to Purna River course.

5 Drainage

The main channel of Purna River, exhibiting perennial nature, initially flows in SSW direction and covers a distance of about 110 km in the elevation range of +760 m msl at originating point to +280 m msl at other extreme end at Pingla. This south-easterly course of river falls in basaltic terrain which is devoid of any major tributary, as well as the recognizable alluvium, due to high slope gradient of the terrain. Afterwards, the further flow of the river takes an abrupt turn towards west, which continues, for 160 km, till its confluence with Tapi. This westerly course falls in the central part of the alluvial zone. This east–west trending river course shows comparatively more tendency of meandering than the south-westerly course. It is deep and wide along with the dissected banks of broad alluvial cover on both the sides. It has many tributaries developing a subparallel drainage along with the main river before their confluence, sometimes forming Yazoo pattern (Fig. 6). The Yazoo tributaries appear to have been developed because the levees of the main channel, which act as a barrier at the confluence of tributaries and main river.

The aggraded basin of Purna has twelve major tributaries, which develop a subparallel drainage pattern before their confluences with the main river (Fig. 6). Based on the flow directions and position with respect to Purna main channel, the tributaries are classified into two categories: (i) tributaries of northern sector having roughly southward flow and (ii) tributaries of southern sector having roughly northward flow. The southerly flowing streams originate in the foot of the Gawilgarh Range. The major tributaries falling in the northern sector, from east to west are Pedhi, Chandrabhaga, Shahnur, Widrupa and Wan. The NNE–SSW main course of Purna River of this sector is the only channel, which maintains a good constantly running stream throughout the year while the other streams become dry or very sluggish. The southern sector is characterized by north flowing streams, having their origins from the Ajanta Hill Range as well as undulating to rolling

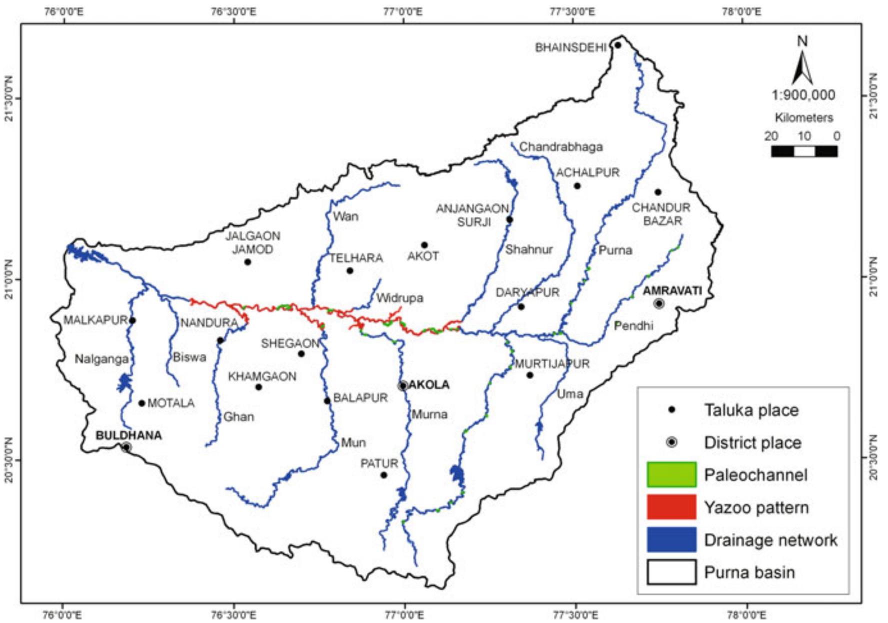

Fig. 6 Map showing major drainages of the basin

plateau plains. The major tributaries, from east to west in successive order, are Uma, Katepurna, Murna, Mun, Ghan, Biswa, and Nalganga. The courses of most of the streams are roughly south to north. Conspicuously, these tributaries run parallel for a short distance before meeting to the main channel.

All the tributaries of the basin are entirely rain-fed. Most of the southern tributaries hold water throughout the year, along with the Purna main channel, which maintains a good constant flow. The other tributaries falling in the north of main channel are either dry or very sluggish during the lean months of the year. The annual flow regime is similar to the other rivers of tropical monsoon climate zone. The south-west monsoon dominates the basin area in the months of June, July, August and September, which account for roughly 80–90% of the mean annual rainfall. Consequently, with the onset of the monsoon, most of the streams suddenly snap from trickle to torrent.

The present-day river system distinctly shows that their courses and patterns are mostly governed by the surface slope gradients and structural features of the basin. The east–west trending course of Purna River is almost a linear zone which is a termination zone of the northern and southern sectors of the basin having southerly and northerly slope directions, respectively. In most of the cases, the flow directions and drainage pattern of the tributaries are in accordance with the slope gradients. Structurally, the linear features are the major controlling factor of the river course. The NNE–SSW trend of the main channel in the northern half abruptly changes to east-west for almost rest of the course is because of three major lineaments which controls the river course. Some of the tributaries are also governed by local faults, e.g. southern parts of Chandrabhaga and Wan tributaries which have almost straight and sharp contact with the main channel of Purna. The lithological control on drainage pattern especially on the tributaries is clearly evident. The portions of the tributaries falling in peripheral basaltic terrain show dendritic pattern, whereas the rests have a tendency of subparallel to parallel belonging to the central alluvial zone. The southern tributaries shows a striking feature marked by their short distance parallel to sub parallel flows along with the main river course of Purna before the confluence with the same. It is because of the cumulative result of very less slope gradient and flat alluvial terrain of the southern region that also restrict the flow velocity of the tributaries in the area.

On the basis of origin of streams, elevation and slope pattern of the region, the tributaries of the basin can be classified into three: (i) mountain-fed, (ii) foothill-fed and (iii) plain-fed tributaries. The first category includes the streams have their origin at high altitudes in Satpuras. The slope gradient of the region is very high. The tributaries falling in this category are Chandrabhaga, Shahanur and Wan in the northern sector of the basin, whereas Katepurna, Murna and Mun in the south. The foothill-fed tributaries are Pedhi in the east and Uma, Ghan and Nalganga in the south. This zone borders the central alluvial plains and shows comparatively moderate slope gradient as well as relief. The plain-fed tributaries are because of run-off from the plains or subsurface water of the alluvium and include Widrupa and Biswa in northern and southern parts of the basin, respectively.

6 Watersheds and Drainage Morphometry

On the basis of various parameters proposed by AIS & LUS (1990), the basin is divisible into twenty watersheds. Considering the main channel of Purna as a dividing line, these watersheds can be divided into two groups: (i) northern sector watersheds and (ii) southern sector watersheds. The previous includes nine watersheds, viz. Pendhi, Upper Purna, Sapan, Chandrabhaga, Bodli, Shahanur, Widrupa, Ban, and Purna. These watersheds are mainly catchments of tributaries which have southerly flows, except the westerly flowing Purna River. The southern sector is constituted by eleven watersheds, i.e. Uma, Katepurna, Main Purna, Murna, Nirgana, Mun, Mas, Ghan, Biswa, Nalganga and Bhogavati (Fig. 7). All the tributaries are northerly flowing except Main Purna River having the westerly flow.

Various quantitative measurements obtained through modern techniques such as remote sensing and GIS, belonging to linear, aerial and relief aspects of the watersheds, have been summarized in Table 1. The boundaries of the watersheds and various aspects of their drainages are marked from the Survey of India topographic maps on 1:50,000 scale, incorporating significant changes in the drainage pattern during the recent past through latest IRS-1C, LISS-III geocoded satellite data. Salient features of the drainage morphometry are as follows:

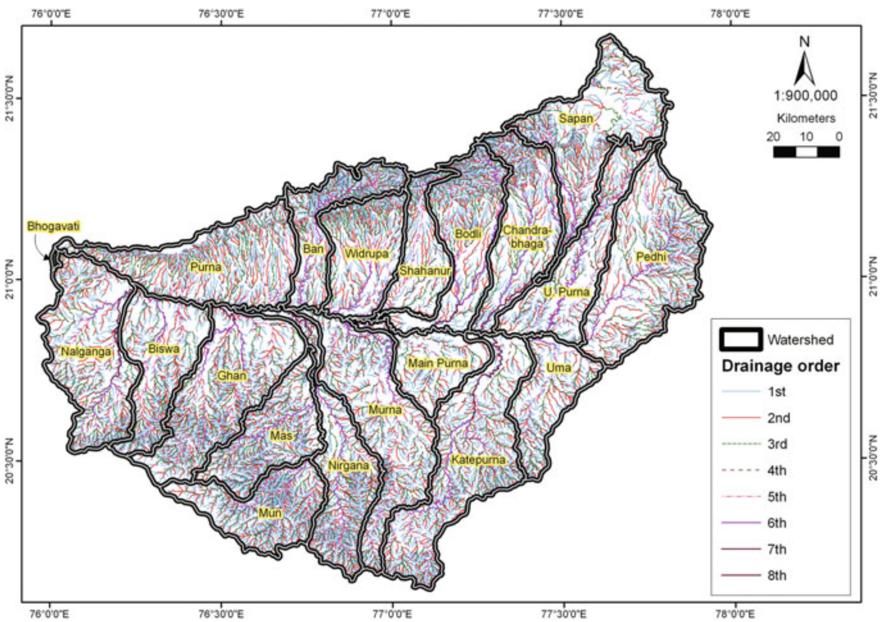

Fig. 7 Map showing various watersheds of the basin along with their drainage order

Table 1 Result of morphometric analysis of Purna basin

Sr. No.	Name of Watershed	Area (km^2)	Perimeter (km)	Basin order	Length (Lu)	Order (Nu)	Mean length (Lsm)	Bifurc. ratio (Rb)	Basin relief (Bh)	Rugged. number (Rn)	Drainage density (Dd)	Stream frequency (Fs)	Drainage intensity (Di)	Texture ratio (T)	Form factor (Rf)	Circul. ratio (Rc)	Constant channel maintenance (C)
1	Ban	630.76	197.01	6	1706	2742	0.62	5.33	600	1622.60	2.70	4.35	11.76	9.14	0.16	0.20	0.37
2	Bhogavati	10.70	18.29	3	29	30	0.98	6.00	80	219.35	2.74	2.80	7.69	1.20	0.25	0.40	0.36
3	Biswa	854.66	172.89	6	1402	2205	0.64	7.12	410	672.59	1.64	2.58	4.23	7.06	0.32	0.36	0.61
4	Bodli	959.06	225.28	7	2020	2574	0.78	4.37	830	1748.39	2.11	2.68	5.65	7.50	0.16	0.24	0.47
5	Chandrabhaga	931.38	189.22	7	1781	2040	0.87	4.07	900	1720.89	1.91	2.19	4.19	7.19	0.17	0.33	0.52
6	Ghan	1298.57	203.35	7	2723	3819	0.71	4.51	410	859.64	2.10	2.94	6.17	12.24	0.35	0.39	0.48
7	Katapurna	1489.45	262.79	7	2741	3319	0.83	4.10	310	570.57	1.84	2.23	4.10	8.18	0.21	0.27	0.54
8	Main Purna	558.51	147.93	8	612	507	1.21	7.37	100	109.51	1.10	0.91	0.99	1.95	0.30	0.32	0.91
9	Mas	789.91	164.50	7	2034	3484	0.58	5.14	330	849.85	2.58	4.41	11.36	14.97	0.23	0.37	0.39
10	Mun	777.48	157.67	6	2044	3617	0.57	6.23	260	683.47	2.63	4.65	12.23	15.63	0.25	0.39	0.38
11	Murna	1309.98	258.40	6	2317	2637	0.88	6.06	320	565.92	1.77	2.01	3.56	6.70	0.13	0.25	0.57
12	Nalganga	1233.67	191.00	7	1918	3227	0.59	5.22	440	684.21	1.56	2.62	4.07	9.38	0.31	0.42	0.64
13	Nirgana	901.91	267.17	7	2094	3267	0.64	5.40	320	742.94	2.32	3.62	8.41	7.95	0.08	0.16	0.43
14	Pedhi	1439.25	195.70	6	2324	2498	0.93	5.75	200	322.91	1.61	1.74	2.80	8.38	0.27	0.47	0.62
15	Purna	1251.43	215.10	8	2575	2645	0.97	5.92	580	1193.21	2.06	2.11	4.35	8.06	0.22	0.34	0.49
16	Sapan	1219.00	263.93	6	2043	2210	0.92	6.81	830	1390.73	1.68	1.81	3.04	5.54	0.18	0.22	0.60
17	Shahanur	555.31	169.53	7	943	941	1.00	4.76	850	1443.31	1.70	1.69	2.88	3.67	0.15	0.24	0.59
18	U. Purna	895.57	217.21	7	1388	1401	0.99	4.04	380	588.78	1.55	1.56	2.42	4.31	0.19	0.24	0.65
19	Uma	632.60	136.11	6	981	947	1.04	4.05	140	217.11	1.55	1.50	2.32	4.68	0.30	0.43	0.64
20	Widrupa	775.66	135.89	6	1584	1417	1.12	4.67	540	1102.52	2.04	1.83	3.73	6.87	0.46	0.53	0.49
	Total	18,514.87															

(i) The Katepurna watershed is the largest, covering an area of 1489.45 km^2, followed by Pendhi (1439.25 km^2), Murna (1309.98 km^2), whereas Bhogavati watershed is smallest having only 10.07 km^2 area, next to Shahanur (555.31 km^2).

(ii) Perimeter of Nirgana watershed is the maximum, i.e. 267.17 km followed by Sapan and Katepurna, which are almost equal, i.e. 263.93 and 262.79 km, respectively. Bhogavati being the smallest has only 18.29 km next to Widura (135.89 km). The decreasing order of stream length is Katepurna (2741.43 km) > Ghan (2723 km) > Purna (2575 km), whereas Bhogavati is the smallest one, i.e. 29 km next to Main Purna (612 km). The extremes of the higher values of mean length, i.e. 1.21, followed by 1.12, respectively, for the Main Purna and Widrupa watersheds are because of their alluvial topography. These are clearly distinguishable from the Mun (0.57) and Mas (0.58) watersheds, falling in basaltic zone showing low values. This difference of value is because of comparatively more number of streams present in the basaltic zone as compared to the alluvium.

(iii) The bifurcation ratio is highest for the Main Purna watershed, i.e. 7.37, followed by Biswa and Sapan, i.e. 7.12 and 6.81, respectively. It is because of highly permeable alluvial terrain of Main Purna, whereas medium to high slopes and dissected nature of Deccan plateau may be responsible for Biswa and Sapan watersheds. The Upper Purna and Uma watersheds show lowest bifurcation ratio, i.e. 4.04 and 4.05, respectively, which are of basaltic terrain having medium dissections.

(iv) The basin relief and ruggedness number of watershed are mainly related with the relief aspects of the basin and considered as the determining factors for the estimation of run-off rate, drainage pattern, infiltration, etc. The higher basin relief >800 m is noticed in the watersheds of NE-quadrant of the basin, viz. Chandrabhaga (900 m), Shahanur (850 m) Sapan and Bodli (830 m each). Among these, the Bodli and Chandrabhaga watersheds lying in the northern central sector are characterized by higher ruggedness numbers, i.e. 1748.39 and 1720.89, respectively.

(v) The low basin relief of >140 m is represented by Bhogavati, Main Purna and Uma watersheds which also have comparatively low values of ruggedness number, i.e. <219.35. These watersheds fall either in flat alluvial topographic region, i.e. Bhogavati and Main Purna or in basaltic terrain of very less surface slope gradient, i.e. Uma.

(vi) The drainage density is comparatively higher in the watersheds of Bhogavati (2.74), Ban (2.70), Mun (2.63) and Mas (2.58), of which the later three have comparatively higher stream frequency, i.e. Mun (4.65) followed by Mas (4.41) and Ban (4.35). The lowest limits of both the parameters are revealed by Katepurna watershed, next to Uma.

(vii) The main channel of Purna River, falling in the upper Purna watershed, is of 6th order, before the joining of Pendhi river. After this confluence, the river upgrades to 7th order and continues up to the Katepurna confluence. The Katepurna tributary, being a 7th order stream, makes Purna one unit higher after its discharge. The further course of Purna channel remains the same, i.e. 8th order.

7 Landforms

On the basis of origin, three types of landforms have been identified: (i) structural, (ii) denudational and (iii) fluvial (NRSA 1995) (Fig. 8 and Table 2).

The landforms of structural origin are mainly represented by (A) structural hills and (B) low relief plateau. Structural hills consist mainly of low-lying hills, which are generally elongated and structurally controlled. The scrub is the major land cover of this region. Plateaus essentially formed over horizontally layered rocks and are marked by extensive flat top. They may show low to high dissections and accordingly divisible into three: (a) highly dissected basaltic plateau (HDP), (b) moderately dissected basaltic plateau (MDP) and (c) slightly dissected plateau (SDP). The HDP landforms occupy mostly the elevated parts in the central,

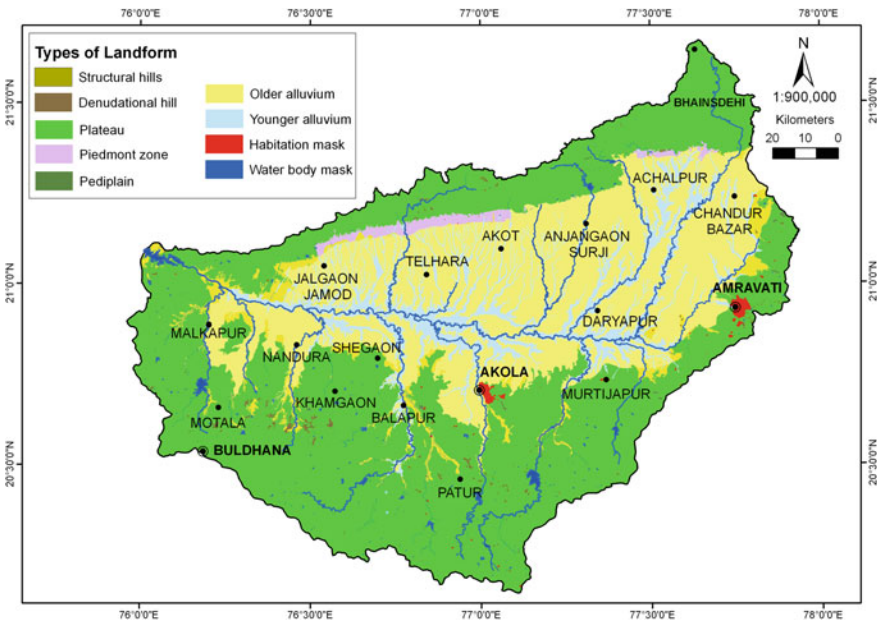

Fig. 8 On the basis of origin, three types of landforms have been identified

Table 2 Various types of landforms and their geographical extents in the basin area

S. No.	Description-1	Description-2	Description-3	Area km^2
1	Alluvial plain	Older alluvial plain	Deep alluvial plain (older)	5438.53
2			Shallow alluvial plain (older)	0.21
3			Buried channel (older alluvial plain)	0.34
4			Eroded land	454.25
5		Younger alluvial plain	Deep alluvial plain (younger)	84.35
6			Eroded land	716.89
7			Palaeo-/abandoned channel (younger plain)	0.14
8			Shallow alluvial plain (younger)	207.37
9	Pediplain	Pediplain weathered/buried	Deeply weathered/deeply buried pediplain	0.1
10	Piedmont zone	Bazada	Upper Bazada—shallow	343.38
11	Plateau	Plateau top	Plateau top	275.67
12		Upper plateau	HDP-A, with exposed rock, negligible soil cover	2722.76
13			HDP-B, with thin soil cover and weathering	79.35
14			HDP-C, moderately thick soil cover and moderate weathering	0.66
15			MDP-A, with exposed rock and thin soil cover	2184.98
16			MDP-B, with moderate soil cover	4669.74
17			MDP-C, with thick soil cover and thick weathered zone	752.51
18			Outer fringe of Upper plateau (denudational slopes)	143.99
19		Slightly dissected plateau	SDP-B, with thick soil cover and thick weathered zone	9.64
20	Denudational hill	Denudational hills (small)	Massive type denudational hills (small)	38.96
21		Residual hill	Massive type residual hills	10.25
22	Structural hills	Structural hills (small)	Intermontane valley/structural valley (small)	0.71
23		Structural hills (small)	Linear ridge/dyke	2.8
24		Structural hills (small)	Ridge-type structural hills (small)	5.14
25	Water body mask			278.19
26	Habitation mask			103.57
			Total area	18,514.84

south-western, southern and the eastern parts of the basin. Shallow soil cover and higher dissection of the terrain characterize the area. The land acts as a run-off zone, of which forest is main land use. The MDP landforms occupy mostly the fringe area of highly dissected basaltic plateau. It has an undulating topography and thin to moderate soil cover. The SDP landforms having gentle undulations occupy valley areas and plains. Moderate to thick soil cover and fewer dissections favour extensive agricultural activity.

The denudational landforms are mostly characterized by low relief and lack of vegetation. Based on the occurrences, these can be subdivided into two: (A) denudational hills and (B) residual hills. The previous consisting basalt of Deccan Traps are identified in south-eastern part of the basin which are characterized by low relief, isolated hills with scrub as the major cover of the land. Steep slope, thin soil cover and weathered mantle are the characteristic features of this unit. Residual hills are isolated, low relief units formed due to differential erosion. These are scattered over the basaltic terrain of the basin.

The landforms of fluvial origin are basically represented by loose to consolidated sediment cover of the area, due to the depositional activity of the Purna River and its tributaries. On the image, the landforms are mostly represented by light tone. Three distinct landforms have been identified: (i) alluvial plain, (ii) pediplain, and (iii) piedmont. Alluvial plains, fairly extensive in geographical extents, are the areas along the major river and its tributaries that consist mainly of gravel, sand, silt and clays. On the basis of mode of deposition, this unit is further subdivided into two: (a) older alluvium and (b) younger alluvium. Older alluvial plains are mostly noticed along the Purna River which are flat surfaces having gentle slopes towards the main channel. It consists of clay, sands and gravel representing earlier cycle of deposition. It is marked with thick soil cover, very gentle slope and with intensive agricultural activity. The younger alluvium mainly differs from the previous in the cycle of deposition and occurs relatively at lower levels. It represents a landscape of badland topography resulting due to severe soil erosion.

The pediplain is gently sloping, smooth surfaces of erosional bedrock between hills and plains with veneer of detritus and coalescence of pediments marked by a large area. Piedmont zone is formed on gently sloping foothills of Satpura by coalescence of several alluvial fans structured by the streams. It is also known as 'Bazada zone'.

8 Land Use/Land Cover, Palaeochannels and Lineaments

Land use/land cover map, prepared by using the satellite data of three seasons, viz. Kharif, Rabi and Zaid, and following the standard land use classification as proposed by NRSA (1995) denotes five major units: (i) built-up land (282.47 km^2), (ii) agricultural land (12,438.35 km^2), (iii) forest land (3068.05 km^2), (iv) wastelands (2409.35 km^2) and (v) water bodies (316.64 km^2) (Fig. 9). The delineation and identification of palaeochannels in the basin are significant and necessary

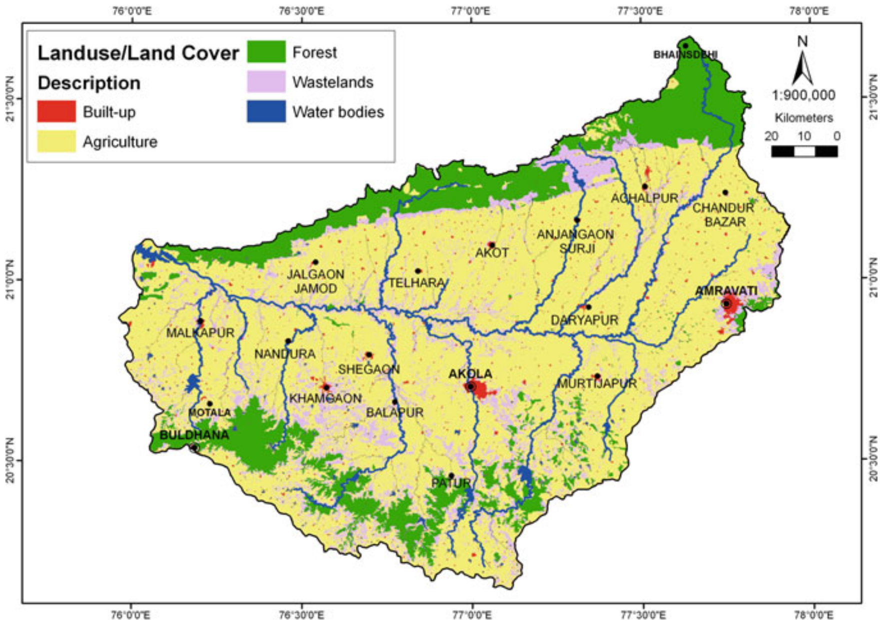

Fig. 9 Land use/land cover description

aspects in the present-day scenario as a major part of the basin experiences groundwater salinity. These palaeochannels may act as source of normal groundwater and also the possible locales for artificial recharge. Palaeochannels are considered as the lost drainage which are still having under flows of groundwater as evidenced by abnormally high plumage discharge, fresh to low saline quality in comparison with the water occurring in adjoining non-riverine environment, and are also comparatively older in character. Thirty-eight palaeochannels covering an area of 4.17 km^2 and perimeter of 81.46 km have been identified in the basin, lying mostly along the main channel of the Purna River, e.g. south of Khallar village, near Rohana village, north of Gandhigram village (Fig. 10), north of Akot town and near Runmochan. Interestingly, the palaeochannels are associated with brick cline industries because of availability of both water and clay.

The lineament map of the basin clearly shows that the Satpura region, lying towards the north, is marked by high density of the same (Fig. 11). These are mostly oriented in the ENE–SWS directions and at places intersected by N–S trending short lineaments; the entire feature is comparable with the fault pattern as the main fault is also intersected by two strike-slip faults at Achalpur and Garpeth. The density is comparatively less in the southern part of the basin. The map also shows that a few lineaments are cutting across the main alluvium, which indicates that the tectonic activity was probably remains active even after the deposition of the alluvium. The second-level classification as proposed by NRSA (1995) shows four categories of lineaments: (i) axial trace of anticline (7.64 km.), (ii) confirmed

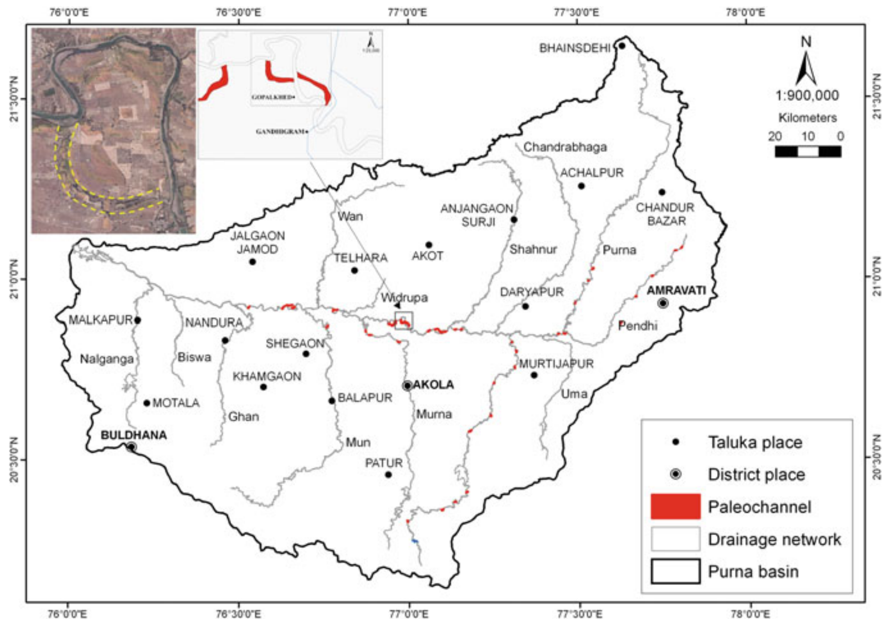

Fig. 10 South of Khallar village, near Rohana village, north of Ghandigram village

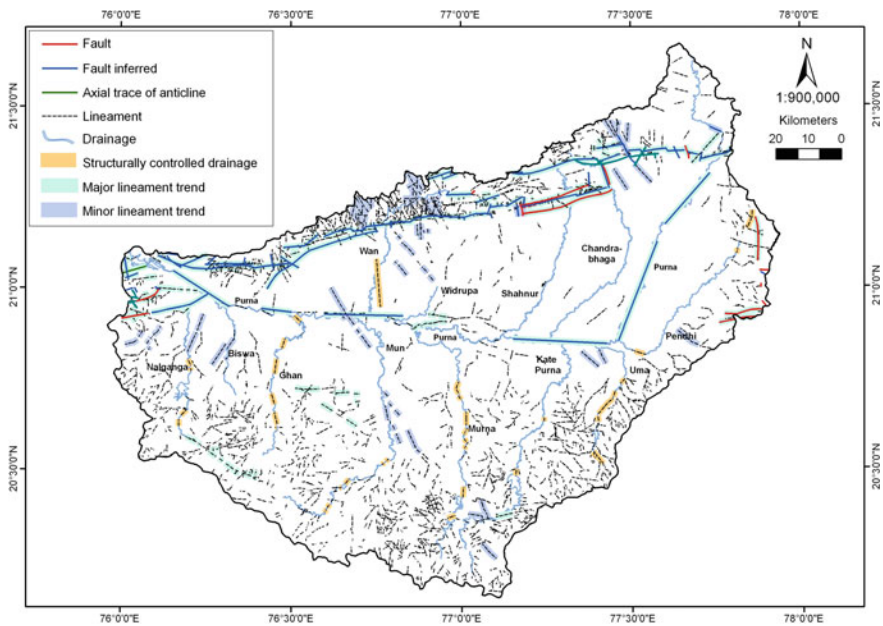

Fig. 11 The lineament map of the basin clearly

fault with displacement of rock formations (143.39 km), (iii) displacement of rock formations inferred (where evidences are not very clear) (246.34 km) and (iv) fault/fractures (3697.54 km). It indicates that the lineaments falling in the category of fault/fracture are very high in the basin. It is well evident that the basin is heavily criss-crossed by a major fault and several minor faults. Because of these faults, the lineaments of above-referred category are comparatively very high.

Watershed-wise analyses of the lineaments are provided in Table 3. The analysis shows that there are 2833 lineaments having a total length of 4100.88 km. Their density ranges from 0.04 to 0.75. The area of good infiltration capacity generally shows higher lineament density values and vice versa (Obi Reddy and Maji 2003). The lineament frequency ranges from 0.03 to 0.37, which indicates degree of dissection of plateau. In general, the alluvial area has low frequency as compared to basaltic terrain.

Table 3 Watershed-wise statistics of lineaments

S. No.	Name of watershed	Number of lineament	Length (km)	Lineament density	Lineament frequency	Lineament intensity
1	Pedhi	95	224.94	0.16	0.07	0.01
2	Upper Purna	25	35.91	0.04	0.03	0.00
3	Sapan	96	152.46	0.13	0.08	0.01
4	Chandrabhaga	77	155.68	0.17	0.08	0.01
5	Bodli	123	177.43	0.18	0.13	0.02
6	Shahanur	77	112.29	0.20	0.14	0.03
7	Widrupa	190	199.68	0.26	0.24	0.06
8	Ban	212	298.99	0.47	0.34	0.16
9	Purna	291	428.31	0.34	0.23	0.08
10	Uma	150	220.40	0.35	0.24	0.08
11	Katepurna	325	441.67	0.30	0.22	0.06
12	Main Purna	61	69.74	0.12	0.11	0.01
13	Murna	158	235.98	0.18	0.12	0.02
14	Nirgana	179	264.44	0.29	0.20	0.06
15	Mun	147	157.70	0.20	0.19	0.04
16	Mas	114	149.66	0.19	0.14	0.03
17	Ghan	154	233.88	0.18	0.12	0.02
18	Biswa	109	185.02	0.22	0.13	0.03
19	Nalganga	246	348.70	0.28	0.20	0.06
20	Bhogavati	4	8.00	0.75	0.37	0.28
Total		2833	4100.88			

9 Soils

In general, the soils in the area are clayey, sticky and poorly permeable in nature. They have an excellent soil moisture retention capacity. Because of these physical properties, leaching of excess water does not take place causing water logging and deposition of salts. The chemical analysis of soils from this depth has shown that the soils are alkaline in nature and sodic. The alkalinity in the soil goes on increasing in depth. The pH value in the soil profile thickness of up to 6 cm ranges in between 7.5 and 8.5. The soils of the basin are mostly alkaline with exchangeable sodium percentage in surface, i.e. ESP < 8, while the subsurface has higher values of the salinity and sodicity being ECe > 2.7 and ESP > 17 (Singh and Sharma 1996). The interfluvial zones of the northern and southern alluvial plains are covered with thick to very thick black soils. Owing good fertility, it supports the growth of important crops in the region, viz. cotton, jawar, tur, soyabean, safflower, gram and groundnut. Pal et al. (2001) reported that in the north-eastern and south-western parts of the basin, surface-oriented plasma separation indicates a high degree of clay activity and shrink–swell phenomena; however, the plasmic fabric is not uniform throughout. In the southern part of the basin, the soil is strongly alkaline with exchangeable sodium percentage ranging from 5 to 26, whereas moderately alkaline with ESP < 5 in the north-eastern part (Pal et al. 2001).

10 Inland Groundwater Salinity

Groundwater condition of the basin is mainly controlled by geomorphology and host rock lithology. The northern part of the basin, particularly the Bazada zone, acts as a recharge zone having fresh groundwater in the area, whereas the central part acts as a discharge zone along the depressions of the area (Sharma et al. 2003). Rainwater is the only source for recharge; however, most of the rainwater collected in the tributaries is short lived and drains out as run-off due to high slopes. The alluvial part is a multiaquifer system, in which the clay lenses at various depth levels hinder the water percolation. On the basis of borewell data, three types of aquifers have been reported: (i) boulder-pebbly units having sandy matrix in the north, (ii) coarse sandy horizons with pebbles in peripheral areas of Purna main channel drained by tributaries, and (iii) graded sand with clays in central part along main channel (Adyalkar 1996; Siddique 2004). In general, the shallow aquifers are represented by coarse-grained sands and gravels of unconfined nature, whereas the deep aquifers consist mostly of medium sand and clay admixture which are confined to semiconfined in nature (Siddiqui 2004).

The major problem of the basin is inland groundwater salinity in the central alluvial part covering significant parts of districts Amravati, Akola and Buldhana. The salinity is recorded in both shallow and deep aquifers as revealed by the dug well and borewell data. It has also been experienced that there is an irregular trend in the magnitude of salinity both in lateral and vertical profiles of the basin. Because of it, the groundwater of the area is unsuitable for both drinking and agricultural purposes. More than 400 villages falling in saline area are continuously facing severe problem of drinking water, which becomes more acute in summer months. The magnitude of the problem is so high that in some of the area it is directly affecting the socio-economic set-up, i.e. desertification of villages, reduction of crop yield, infertility of soil. The area is also deprived of well irrigation; hence, only rain-fed crops are cultivated.

Adyalkar (1996) identified four different zones in the alluvial area: (i) freshwater-assorted sediments, (ii) marginal thickness of freshwater, (iii) marginal saline zone and (iv) hard-core saline zone. The first is confined to northern part of basin and simulates a mélange of Bazada or flowing artesian condition. This has perennial source both in the phreatic and confined zones. Next to this towards the centre is the second zone having sorted sandy patches in the alluvium. The marginal saline zone is the lower reaches along the Purna River and its tributaries which is totally devoid of irrigation. The soil of this zone is also saline. The hard-core saline zone is gullied and ravenous landform with mostly clayey alluvium, occupying the central part of basin.

The prevailing groundwater salinity of Purna Basin is a natural problem, which is multiplied due to continuous lowering of the water table particularly in normal water zone. Many common reasons have been put to justify the presently deteriorated situation of the area, e.g., salinity is due to the remnant water of transgressive phase of Arabian Sea during Cretaceous period (Adyalkar 1963), wall rock alteration due to long stay of groundwater at a particular place (Muthuraman and Padhi 1996), unwise and excessive exploitation of the groundwater, increased number of tube wells, exploitation of the sweet water pockets lying within the saline tract area, less recharge due to clayey soil, no feasibility for large scale water conservation, etc. The authors are of the opinion that the groundwater salinity, especially in the central part, is because of unique geomorphological and structural set-up on the western end. Various thematic maps and borewell data show that the alluvial basin gradually narrows down towards the west that continues up to the confluence of Purna and Tapi rivers. At the western end, the basement rocks are of shallow depth and affected by tear faulting. This weak zone acts as a barrier and restricts the thickness of alluvial deposit at outlet of the Purna basin affecting the groundwater flow from Purna alluvial tract to adjacent Tapi basin. This structurally controlled barrier for the outflow of groundwater and stagnation of the same from a long time within the alluvial sediments gave rise to salinity problem. The absence of SO_4 type of groundwater further suggests that the salinity of groundwater is a natural phenomenon.

11 Socio-economic Status

Agriculture is the main land use in the basin area. Maximum agriculture is unirrigated followed by the non-cultivable area and grazing land. Cotton (*Gossypium*) is major crop in Kharif season followed by jowar (*Sorgum*), mung (*Vigna*), tur

(*Pisum*) and soybean (*Glycine*), whereas some farmers also crop the gram (*Cicer*), wheat (*Triticum*), groundnut (*Arachis*) and kardi (*Carthamus*) in Rabi season. In the saline tract area, the well water is moderately to highly saline and unsuitable for irrigation; therefore, the agriculture is mainly rain-fed. Majority of farmers in the village of the basin own the land <2 ha of land that indicates the higher percentage of marginal farmers. The major occupation of the households is agriculture.

The northern Melghat and southern Ajanta fringes of the basin are covered with the deciduous type of forest. The forest in rugged and hilly area of Melghat is typical southern dry deciduous forest. This consists mainly the important tree species of Teak (*Tectona grandis*), Ain (*Terminalia*), Tiwas (*Desmodium*), Amla (*Phyllanthus*), Lendia (*Lagerstroemia*), Dhawada (*Anogeissus*) and Kusum (*Schleichera*). Bamboo is widely spread in the forests. The area, particularly the Melghat forest, is rich in medicinal plants. The fauna is also very rich and includes wild mammals such as tiger, panther, sloth bear, wild dog, jackal, hyena, chausinga, sambar (largest deer on earth), gaur, barking deer, ratel, flying squirrel, cheetal (a type of deer), nilgai, wild boar, langur, rhesus monkey, and macaque. Also, about 25 types of fishes and many species of butterflies are the characteristics of area.

Melghat Tiger Reserve is located in Chikhaldara and Dharni talukas of Amravati district, on the Satpura hill range. It spreads over an area of 1676.93 km^2. It is one of the last remaining habitats of Indian tiger in Maharashtra. The Narnala Wildlife Sanctuary is located around 40 km ahead of Akola which spreads over 12 km^2 of land and is one of the densely populated wildlife sanctuaries in the state of Maharashtra.

Almost all major tributaries of Purna River are harness by the major, medium and minor reservoirs. The major reservoirs of the basin are Wan (76° 46′ 21″E–21°N near Wari Bhairaogad in Telhara taluka, Akola district); Shahanur (77° 19′ 12″ E–21° 15′ 30″N in Achalpur taluka, Amravati district); Chandrabhaga (77° 23′ 37″ E–21° 20′ 9″N in Chikhaldara taluka, Amravati district); Purna (77° 45′ 52″ E–21° 22′ 3″N near Vishroli in Chandurbazar taluka, Amravati district); Pedhi an ongoing project (77° 37′ 45″E–20° 55′ 47″N near Nimbha in Bhatkuli taluka, Amravati district); Uma (77° 23′ 38″E–20° 36′ 14″N in Murtizapur taluka, Akola district); Katepurna (77° 9′ 23″E–20° 28′ 54″N near Satali, Barshitakli taluka, Akola district); Murna (76° 59′ 56″E–20° 25′ 10″N, Patur taluka, Akola district); and Nalganga (76° 11′ 4″E–20° 44′ 3″N, Motala taluka, Buldhana district). Irrigation is possible using the potential generated by these reservoirs and dams in the basin area. The Shahanur regional rural water supply scheme in Anjangaon and Daryapur talukas of Amravati district acts as a main source of drinking water for 156 + 79 villages in the saline tract.

Flash flood is a regular phenomenon of the area. Large areas of cultivated land get devastated and eroded by flash floods. These floods also cause damage to houses and cattle, as well as erode the soil and rendered it barren. Extensively hazardous flood during September 1959 due to heavy rains is still remembered, which affected 179 villages in the Amravati district. Damage was caused to villages along the banks of the Pendhi tributary in Amravati, Belmandi the Kholat sub-tributaries in Chandurbazar, Chandrabhaga and Shahanur tributaries in Daryapur talukas. Houses were washed away and an area of about 74 km^2 with standing crops was also completely swept away by floods. Thousands of acres of standing crops were submerged in water for a number of days.

The basin also bears archaeological significance. Three sites, namely Bhon, Paturda and Kholapur, have been identified having remains of manmade structures, potteries, grains, etc. (Deotare 2006). Bhon site (76° 39′E, 20° 55′N) is located at about 30 km north-west of Shegaon, Buldhana district. Glass, shell bangles, different varieties of terracotta, beads, pendants and amulets, crucibles, coins and pieces of iron and copper belonging to third–fourth century BCE of Pre-Satavahana and second century of Satavahana are recovered from this area. Animal bones are also recovered. Rice (*Oryza sp*.), wheat (*Triticum sp.*), jowar (*Sorghum sp*.), green gram/black gram (*Vigna sp*.), pigeon pea (*Cajanus sp*.), grass pea (*Lathyrus sp*.) common pea (*Pisum sp.*) as well as Indian jujube (*Zizyphus sp.*), hyacinth bean and lentils are recovered. Availability of 50% rice indicates heavy rainfall, i.e. abundance of water. Paturda site (76° 44′E, 20° 57′N) lies at the bank of Wan tributary covering an area of one hectare. It indicates the presence of Post Gupta of fifth to ninth century CE. The evidences include terracotta and glass beads, pieces of glass and shell bangles, red ware pottery with little black and red colours. The grains recovered in abundance are of Jowar (*Sorghum sp*.) at about 30% along with rice (*Oryza sp*.), wheat (*Tritium sp*.), green gram/black gram (*Vigina sp*.), pigeon pea (*Cajanus sp*.), gram (*Cicer sp*.), common pea (*Pisum sp.*) as well as Indian jujube (*Zizyphus sp*.). Minimum recovery of grains and pulses indicates worst climatic condition. Chauhan (2004) reported low rainfall at Paturda. The Kholapur site (77° 31′E, 20° 57′N) lies 30 km west of Amravati on the bank of Purna River basin. The archaeological evidences include black and red ware in pottery, terracotta antiquities such as beads, pendants, amulets, bangles as well as iron and copper. Two ring wells are significant at this site.

Some of the pilgrimage places in the Purna basin are Ashtamashidhi, Runmochan, Ridhapur and Muktagiri. Ashtamashidhi, a holy place near Achalpur in Amravati district, is famous for sulphur water which is having medicinal importance for skin diseases. Runmochan village of Bhatkuli taluka is the work place (locally known as *karmabhumi*) of great Saint Gadge Baba. Ridhapur is a holy centre for the *Mahanubhav* cult. Muktagiri is a well-known religious palace of Jains. The Balapur Fort is situated in Balapur which is about 26 km from Akola.

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Saraswati River: It's Past and Present

G.S. Srivastava

1 Introduction

The vast Indo-Gangetic plain, an active foreland basin, forms a significant physiographic unit of the Indian subcontinent. Indo-Gangetic Plain is drained essentially by two major river systems, namely Indus System which drains into the Arabian Sea and Ganga System which drains into the Bay of Bengal. The buffer area between Satluj River in the west and Yamuna River in the east, designated as Punjab-Haryana Plain (Singh 1987, 1996; Singh and Ghosh 1994) occupies a unique position, located in the water divide area of these two systems. Interestingly, Punjab-Haryana Plain does not contribute any sediment or water to the systems; instead it makes an independent system between the two (Srivastava et al. 2006, 2013). Further, Punjab-Haryana Plain exhibits several unique features, such as diverging, ephemeral rivers and terminal fans and does not have any perennial stream at present. However, the situation was not like the same about 6000 year BP when the rainfall was higher than at present (Saini et al. 2009; Saini and Mujtaba 2010).

2 The Past

In the present context, the term 'Vedic Saraswati' is used, to connote the ancient and mighty river, once supposed to have existed in the northern and western India. In the *Rig Veda*, it has been described as 'supreme amongst all the rivers, swift and violent river that possessed enormous discharge, responsible for causing floods on a massive scale' (Bharadwaj 1999). It emanated from the Himalayas and joined the sea as an independent river system. The Saraswati River was supposed to be located

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east of Shatadru (modern Satluj River) and west of Yamuna River, along with other Punjab rivers, as mentioned in the *Nadi-stutisukta* of *Rigveda* (Chauhan 1999; Lal 2002). The relevant verses run as follows:

> *Imam me Gange**Yamune Sarasvati Satudri*** stomam sachata *Parusnya*
>
> *Asiknya Marudvridhe Vitastaya Arjikiye srinuhya Susomaya*//5//.

O Ganga, **Yamuna Sarasvati Sutudri** (**Satluj**) and Parusni (Ravi), O Marudvridha with Asikni (Chenab), O Arjikiya with Vitasta (Jhelum) and Susoma (Sohan), please listen to and accept this hymn of mine//5//.

In Epic *Mahabharata*, the Saraswati River has been described to follow an independent course to 'Saraswat sea' (modern Arabian Sea), but it subsequently got disrupted and 'lost in the sands (of Thar Desert), near a place called 'Vinasana' (Sridhar et al. 1999).

The existence and desiccation of Saraswati River, mentioned in the *Rigveda* and associated texts, engaged attention of geologists, geographers and archaeologists of the world, ever since the first report of a 'lost river' of the Indian Desert in (1874) was made by Oldham of Geological Survey of India (GSI). It was followed by more detailed account of the same in (1886) by Oldham published in the Journal of Asiatic Society of Bengal. Sir Aurel Stein's archaeological expeditions (1940–1941) and Wilhelmy's (1969) findings about the Old course of Saraswati River kept the interest alive. With the advent of satellite data, various facets of the problem were highlighted by Yashpal et al. (1980), Valdiya (2002), Gupta et al. (2004) and others. Geological Society of India published a memoir (eds. Radhakrishna and Merh 1999) on the subject of Vedic Saraswati.

Oldham (1874) has given a preliminary account about the traces of a lost river in the Great Indian Desert (Thar Desert). He, later on (1893), came out with a detailed paper stating therein that the existing Saraswati meets Ghaggar, another small Himalayan stream, at a point (near Shatrana), beyond which the river continues to be referred today as Ghaggar, which was the ancient Saraswati. During the Vedic times, this river, after receiving waters from a number of tributaries such as the present-day Saraswati and Markanda, continued to flow as a major river westward. This ancient Saraswati (Ghaggar) is seen to lose itself in the sands of the desert near a place referred to in literature as Vinasana. The dry bed of Ghaggar River thus indicates the ancient course of Saraswati. He further reported a dry bed course of a great river and referred to it as Hakra which flowed through Bikaner and Bahawalpur into the Rann of Kachchh. This river, according to him, represented the former course of Shatadru (Satluj) and the Saraswati was a major tributary joining it. At some point of time, when the Satluj River changed its course westward to meet Beas River and finally Indus River, its abandoned eastern arm (Hakra) was left as a deserted channel. Interestingly he also envisaged the possibility of Yamuna River at some very remote period, following a westerly course and joining the Saraswati. Oldham (1886), on the basis of historical and geographical evidences, envisaged the former existence of a river, which flowed into Rann of Kachchh, the lower course of which flowed through eastern Nara, in Sind.

Ruling out that the eastern Nara was a deserted channel of Indus River, he asserted that it was Satluj River, but not Saraswati, which flowed in its lower course along Hakra, Sankra, Wandan, Wahind and Nara. In his map (Fig. 1), an ancient channel can be traced with the dry bed of Hakra, following through Bikaner, Bahawalpur to Nara. According to him, Hakra was the old bed of Satluj, which joined up with the Nara till the eleventh century. Prior to eleventh century, it did not join the Beas River as it does today, but, instead, pursued an independent course to

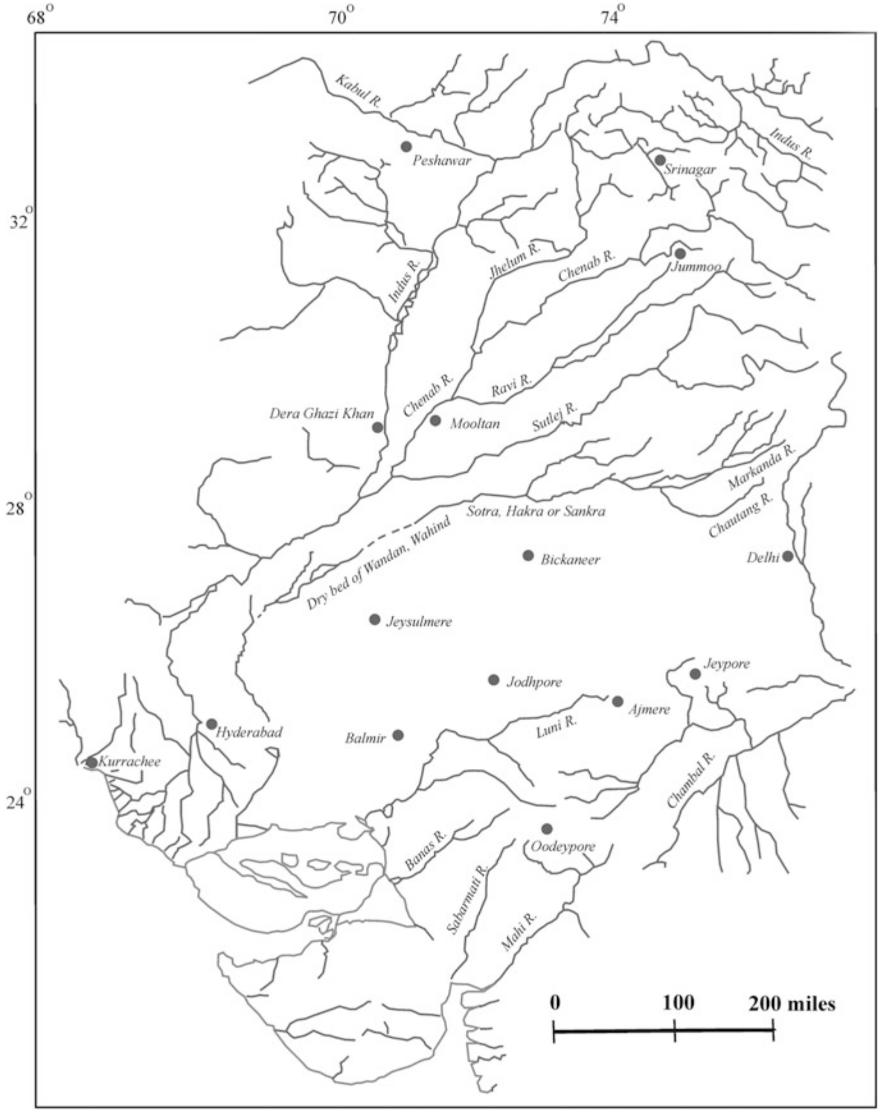

Fig. 1 Map showing present and ancient courses of the Punjab Rivers (after Oldham 1886)

the sea. He concluded that the legendary lost river of the Indian desert was none other than the ancient Satluj River and it was lost when the river turned west to join the Beas River.

Subsequent to the works of C.F. Oldham and R.D. Oldham, this subject did not receive attention from geologists and archaeologists for several decades. The debate was revived by Marshall (1931), an archaeologist, who located various pre- and post-Harappan cultural sites along major ancient river valleys, particularly a large number of sites along the dry bed of Ghaggar River. Subsequently another archaeologist, Stein (1942) linked all the Harappan sites, discovered along the old palaeochannel of Ghaggar River, to the ancient Saraswati. According to him, the palaeochannels of Ghaggar and Hakra represented the ancient Saraswati River.

Krishnan (1952), on the basis of Vedic literature, described the ancient Saraswati River as a mighty and great river that existed around 5000 BC or even earlier. He postulated that earlier west-flowing Yamuna River was connected to Saraswati River and between Vedic period and Mahabharata period, and the upper course of Saraswati River dried up due to the easterly diversion of the Yamuna waters.

Bhargava (1964) gave a description of various ancient rivers as mentioned in the Vedas and Sanskrit classics. He has provided valuable information on the Saraswati and its tributary Drishdwati, which flowed south of it. According to him, the present-day Chautang Nala is a relict of ancient Drishdwati River, and the area between the two rivers, called Brahmavarta, was the homeland of the Aryans.

Welhelmy (1969), who studied the palaeodrainage of western Indian subcontinent, concentrated on the upper reaches of various rivers of the north-western part of Indo-Gangetic Plain and tried to establish the chronology of their shift and capture. He maintained that prior to Alexander's invasion (in 326 BCE), there prevailed two independent river systems, in this part of the subcontinent; one comprised the frequently changing Hakra-Nara course, and the other Indus system, progressively shifting to the west (Fig. 2).

The advent of satellite data facilitated synoptic viewing of a large area and deciphering soil moisture, particularly along the palaeochannels. Ghose et al. (1979) studied aerial photographs, Landsat imagery and the archaeological sites associated with old river courses, envisaged that a major river stemming from the same source as Satluj, flowed through northern Rajasthan, Bahawalpur and Sind, to the southeast of present Satluj and Indus rivers. He also stated that this river, in its upper reaches, was ancient Saraswati River. These workers subsequently (Ghose et al. 1980) attributed the westward shift of the rivers to the increasing aridity and advancement of the desert, though they did not rule out mild tectonic activity during the late Quaternary period, causing such shifts. These workers believed that ancient Satluj River contributed water to Saraswati River and the alluvium in the extreme western part of the Thar Desert was deposited by the Saraswati River.

Yashpal et al. (1980), using Landsat imagery, stated that the present dry bed of Ghaggar River was that of the ancient Saraswati River, which flowed westward through Hakra-Nara River to the Rann of Kachchh. They further stated that the Satluj River once flowed into Ghaggar River and the west-flowing Yamuna River

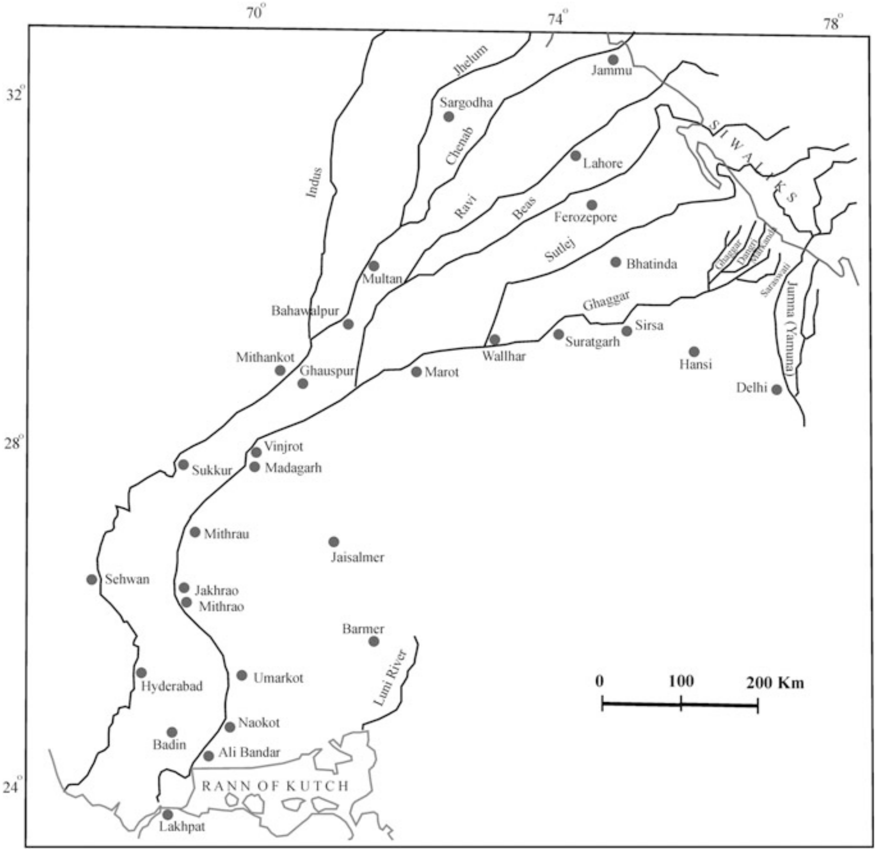

Fig. 2 Drainage of north-western India (after Welhelmy 1969)

also debouched into Ghaggar River. Tectonic events were considered to have diverted Satluj River westward and Yamuna River south-eastward to their present position. This tectonic activity was also responsible for the subsidence of the middle reaches, causing Ghaggar River to disappear near Anupgarh.

Bakliwal and Sharma (1980) studied eastward migration of Yamuna River. Deriving evidences from the archaeological sites, they stated that in the last 5000 years due to tectonism, the Yamuna River shifted its course from west to the present position. Bakliwal and Grover (1988), relating numerous relict palaeochannels, envisaged a migratory pattern of the Saraswati River and traced its various courses from Aravalli to the dry bed of Ghaggar River. They implied that Yamuna River fed the Saraswati River and the former's piracy by Ganga was responsible for drying up of the Saraswati River.

Contrary to the trend of focusing attention on the Saraswati River, Kar and Ghose (1984) investigated the Drishdwati River as another important Vedic river. Using Landsat data, they traced the river from the Siwalik Range of the Himalaya, through present Markanda and Chautang rivers flowing south-westward to join Saraswati River as its major tributary. Satluj River was another important tributary of Saraswati River in the west (Kar 1995).

Valdiya (1996, 2002), while discussing overall drainage changes of Indian subcontinent, stated that the legendary Saraswati River rose in the Great Himalaya and was joined by Shatadru (Satluj) River. The Saraswati Valley was clustered with Harappan settlements dating back to 4600–4100 BP. Around 3700 BP, there was an upstream migration of these settlements, as the climate became drier and salinity set in the lakes of Rajasthan. He postulated that the rise of Aravalli and concomitant subsidence of the land to the west deflected a number of rivers of this region. Due to this tectonic uplift, the Shatadru River joined the Indus River and the Saraswati River, was left high and dry.

Based on conspicuous signatures of palaeochannels on satellite imagery and supported by archaeological data, Sahai (1999) averred that the main course of Vedic Saraswati River during the proto-historical times was from the Himalaya to the Arabian Sea through the Ghaggar-Hakra-Nara river system with Satluj and Yamuna rivers contributing their waters at some stage/times. He also postulated shifting of the course of these rivers in different stages.

Sridhar et al. (1999), synthesizing the early works, described various ancient rivers such as Drishdwati, Saraswati, Shatadru and Luni from their place of origin to the likely locations where they met the sea. All these rivers flowed into a gulf, associated with Arabian Sea. Their mouths came quite close to one another in the northern part of the great Rann of Kachchh, which today represents the delta complex comprising deposits of these rivers. Late Quaternary tectonism in combination with the sudden increase in aridity-related aeolian activity disrupted and obliterated the courses of these rivers, which lie buried beneath the sands of Thar Desert and are presently seen only in fragmentary relicts. On the basis of archaeological evidences, studies on geological and climate changes and geochronological information, they envisaged that the tectonic changes began around 3700 BP and continued right up to eleventh/thirteenth century AD.

Thussu (1995) attempted to build the stratigraphy of the Quaternary sedimentation in Haryana area of the Indo-Gangetic Plain, on the basis of extensive borehole data. He identified various geomorphic units, represented by piedmont zone, fans and central alluvial plain, consisting of Ambala Older Alluvium, Newer Alluvium and Aeolian Deposits. He concluded that the sedimentation in the Haryana-Punjab Basin has been controlled by tectonic processes through activation of WNW–ESE and N–S lineaments present in the basement, during Quaternary period. Subsequently, Thussu (1999) discussed migration of rivers in Haryana area and argued that the alteration in drainage pattern has been due to basement uplift, recognized as Gula-Ladwa, Samrala and Karnal highs. He postulated that Somb and Boli rivers, which are present-day tributaries of Yamuna, were the main streams contributing to the Vedic Saraswati River, along with the streams such as Markanda, Dangri and Ghaggar rivers (Thussu 2006). Satluj River, flowing in a southerly direction, in the past, through Hakra channel, poured into the Saraswati

River. The courses of these rivers have changed, since the pre-Alexandrian times, as evident from historical records.

Kochhar (2000) synthesized data from a wide variety of field's, viz. linguistics, literature, natural history, archaeology, history of technology and astronomy. He argued that a major part of *Rigveda* was composed in south Afghanistan (after c.1700 BCE) before Rigvedic people entered the plains of Punjab. He asserts that, during their migration, the Indo-Aryans not only carried their rituals and hymns but also place and river names, which they selectively reused. He suggested that the Vedic Saraswati River can be equated with Helmand River of south Afghanistan, and its tributary Arghandab River with Drishdwati River. Other rivers can likewise fit with it. The Helmand River, though emerges from high mountains, does not debouch in the sea, instead it terminates in a lake (Lake Kasaoya). The works of Kochhar (2000) is strongly refuted by Lal (2002), on the basis of tropical fauna and flora associated with the Rigvedic people in their homeland. By implication, the Vedic Saraswati River was located, as described in the Sanskrit texts, between Shatadru and Yamuna rivers (Lal 2002).

Other significant publications on the subject are from Puri (2001) and Gupta et al. (2004). Puri and Verma (1998) and Puri (2001) carried out study of palaeoglaciation, glacial inventory parameters, basin identification and terraces in the Himalayas. They postulated that the Vedic Saraswati River had originated as melt water channel from a group of glaciers in Tons fifth order basin in Garhwal Himalaya. In early stages, Vedic Saraswati River had occupied the present-day Tons River up to Paonta Doon and took almost a westerly swing after receiving nourishment from Algar, Yamuna and Giri rivers. Thereafter, it followed Bata valley and entered the plains across the Siwalik Hills at Adh (Adi) Badri. Subsequent tectonic movements resulted in Yamuna Tear and reversal of drainage, and Saraswati River abandoned its Adh Badri course and took the Drishdwati course.

Taking advantage of development of satellite sensors and better processing techniques, Gupta et al. (2004) and Bhadra et al. (2009) attempted to rediscover the course of Saraswati River in the sand-covered Thar region. According to these authors, the Saraswati River had its course through Ghaggar River and flowed thereafter parallel to Indus as an independent river system. The River did not follow the present Nara River course, instead took an easterly course to Rann of Kachchh. They feel that rise of the Himalayan foothills and consequent displacement along Yamuna and Satluj (Ropar) tears are the main cause of drainage desiccation and disappearance of Saraswati River.

In some more recent literature on Saraswati, Saini et al. (2009) recorded subsurface sand bodies belonging to two separate phases of fluvial activity on the basis of well log data and OSL dating, The older phase between 20 and 30 ka time interval had an integrated drainage network in south-western Haryana; while the younger phase of fluvial activity between 6.0 and 2.9 ka pertains to Vedic Saraswati River system. Saini and Mujtaba (2010) further delineate this subsurface palaeochannel from Tohana-Fatehabad to Sirsa and suggest that it is part of Vedic Saraswati River. Danino (2010), in his book 'The Lost River: On the trail of the Sarasvati' gives a good account of Vedic Saraswati River, especially in its lower reaches, including parts of Pakistan. Kshektrimayum and Bajpai (2011) established missing stream link between the Markanda River and the Vedic Saraswati River in Haryana, through geoelectrical resistivity method. Giosan et al. (2012) studied the fluvial landscape of Harappan civilization areas and contended that the ‘mythical’ Saraswati River was a monsoon-fed river emanating from Himalayan foothills and did not water the heartland of Harappan civilization. The size of population decreased with decreasing monsoon after 3900 BP, and the Harappan people moved north and eastward where water was still available to sustain their agriculture activities. Valdiya (2013) strongly refuted the same on the evidences generated by many Indian workers.

3 The Present

The present author has carried out extensive work in Haryana-Punjab Plain and dealt with the problem of Saraswati in his published thesis (Srivastava 2012). In this article, the geomorphology of Haryana-Punjab Plain has been dealt in more detail, while other related studies on surface profiles, drainage morphometry and the nature of Ganga-Indus water divide have been described in brief.

The Haryana-Punjab Plain is essentially drained by three independent river systems, namely Yamuna, Satluj and Ghaggar. Yamuna River is a perennial stream rising from the central Himalaya, while its tributaries such as Somb and Boli draining the interfluve area originate in the Siwalik Hills of Outer Himalaya and are ephemeral type. Satluj River, which originates from Masarovar Lake in Trans-Himalayan area, is perennial type and has the largest catchment. Ghaggar River and its tributaries such as Patiali Rao, Markanda, Fandi Rao, Chautang and Saraswati originate in the Siwalik Hills or from the Himalayan Piedmont Zone. Ghaggar River is the most important drainage of Haryana-Punjab Plain. It has an ephemeral type of trunk stream and has relatively small catchment area. The minor streams contributing to the Ghaggar drainage system miss out at the distal end of Himalayan Piedmont Zone. Larger streams such as Dangri Nadi, Patiali Rao, Choa Nala and Jainta Devi Ki Rao miss at the distal end of Older Piedmont Zone. Further still larger streams such as Chautang Nala, Markanda River, Ghaggar River, Choa Nala and Sirhind Nala miss out at the distal end of their terminal fans.

The streams of Ghaggar drainage system flow southward and show divergent trend, missing out at places and re-emerge to join the trunk stream. These channels in segments are also called Saraswati River/Nadi. The Ghaggar-Saraswati River takes a westerly course near Kurukshetra and flows towards WSW up to Sirsa. From there onwards, it takes a south-westerly course which is traceable up to Anupgarh in Rajasthan. It is further traceable as high moisture area supporting good cultivation to Fort Abbas and beyond up to Fort Derawar, where it is completely missing out in the aeolian sand of Cholistan Desert of Pakistan. At present, the Ghaggar-Saraswati drainage system, as such, does not contribute directly to the Indus System.

4 Geomorphology of Haryana-Punjab Plain

The Haryana-Punjab Plain is a vast alluvial plain, bounded by Siwalik Hills of Himalaya in the north and Aravalli-Delhi Massif in the south, formed by essentially fluvial processes. Several distinct regional geomorphic surfaces have been identified (Srivastava et al. 2014). They are characterized by their location, type of sediment, slope and pattern of drainage. These surfaces were formed during changing climatic conditions in late Quaternary; however, they have been partly modified later and are undergoing changes in the present day. The following geomorphic surfaces have been identified (Fig. 3).

4.1 Himalayan Piedmont Zone

The Himalayan Piedmont Zone is located at the base of Siwalik Hills and has developed due to coalescing of fans near the hill front. The zone is generally confined to the altitudes between 300 and 350 m and makes a 10–15 km wide belt along the Siwalik Hills. The Siwalik rocks are exposed at about 350 m altitude and above. The piedmont surface has a slope of 3–5° (50–85 m/km) towards south. The Himalayan Piedmont Zone forms a continuous surface drained by parallel and radiating drainage where the individual channels are ephemeral, shallow and

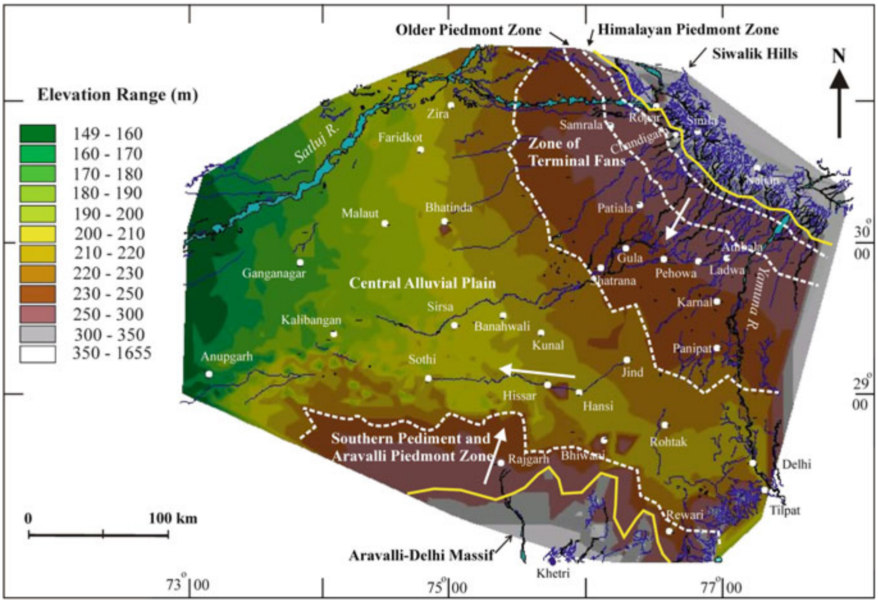

Fig. 3 Geomorphological map of Punjab-Haryana Plain; *white arrows* indicate general slopes

braided. The drainage density is poor in this zone due to high permeability of the coarse clastic material, consisting of pebbly horizons and medium-to-fine sand. It is considered the youngest surface of the area and formed during period of reduced water and sediment supply in recent times.

4.2 Older Piedmont Zone

Southward of the Himalayan, the Piedmont Zone is about 20 km wide belt with gradient of about 1.3–1.5 m/km. This surface is often covered with muddy to sandy sediments, but shows gravel and coarse sand below. It extends between 270 and 300 m altitude and exhibits numerous ephemeral streams. This surface was formed during period of higher sediment and water budget than at present, when piedmont fans were larger that today. At present, fine-grained sediment is accumulating on this surface. The southern margin of this zone shows a prominent break in slope, often associated with a bluff of 2–7 m. This feature has been observed in several field traverses.

4.3 Zone of Terminal Fans

This is the most prominent feature of the Punjab-Haryana Plain and marks about 80 km wide belt south of the Older Piedmont Zone. Generally, it shows a break in slope at the contact with the Older Piedmont Zone and merges southwards into Central Alluvial Plain. It has been formed by amalgamation of terminal fans, extending from 270 to 200 m altitude. In the proximal part, the gradient is 70–85 cm/km, in the middle part it is 30–35 cm/km. In the distal part, the gradient is 20–30 cm/km and generally shows relict anastomosing channels (Parkash et al. 1983; Singh and Ghosh 1994).

Few prominent terminal fans have been identified in this zone, namely Markanda Terminal Fan which has been studied in detail (Mukerji 1975, 1976; Parkash et al. 1983). The terminal fans are characterized by fan morphology, diverging channel system and multifurcation of distributaries channels on a gentle slope (Mukerji 1976). The channels of terminal fans lack alluvial incision and show down-flow decrease in channel dimensions (Friend 1978; Kelly and Olsen 1993; Nichols and Fisher 2007).

Most of the channels disappear in the distal part of this Zone, namely Raksi Nadi, Chautang Nala, Saraswati Nadi, Markanda River, Amri Choa and Dangri Nadi. Only Ghaggar River and Saraswati Nadi flow beyond this zone after a short distance of disappearance (Fig. 4). In the distal part of the Zone of Terminal Fans, a number of surface water bodies are seen, namely in the areas of Sangrur-Shatrana-Akalgarh and Karnal-Pehowa-Panipat-Sonipat (Fig. 5). In the area of Ropar (at the apex) and Ferozpur-Bhatinda, a triangular-shaped area exhibits many

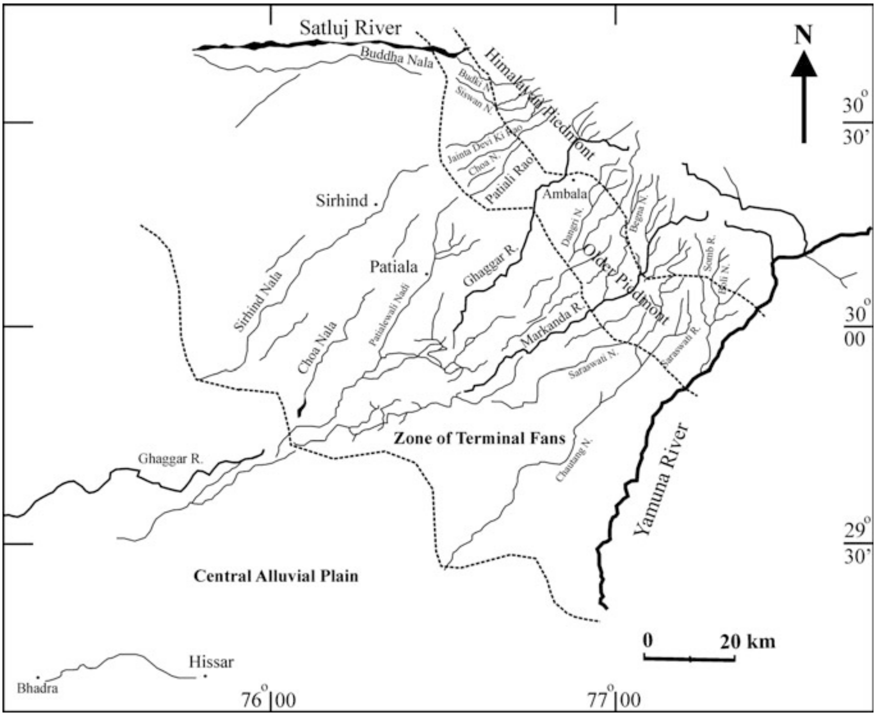

Fig. 4 Drainage in northern part of Punjab-Haryana Plain. Minor streams disappear at the distal end of Himalayan Piedmont Zone while larger streams miss at the distal end of Older Piedmont Zone. Still larger streams disappear at the distal end of Zone of Terminal Fans. Only Ghaggar River and Saraswati Nadi flow further westward, after a short distance of disappearance

relict stream scars and few ephemeral drainage. Some streams emanate in the distal part of the Zone of Terminal Fans, flow southward and terminate mostly at 200 m altitude. It is postulated that neotectonic activity along subsurface Gula-Ladwa High and Zira-Faridkot-Bhatinda Ridge (Samrala High, Thussu 1999) is responsible for the termination of streams and formation of water bodies at the distal end of the Zone of Terminal Fans.

4.4 Central Alluvial Plain

The Central Alluvial Plain is low-lying area south of the Zone of Terminal Fans, developed between the altitudes 228 m in the northeast and 180 m in the southwest. It is a flat surface having a narrow zone of westward gentle slope occupied by the dry alluvial low area extending towards Sirsa, Suratgarh and Anupgarh. The surface exhibits prominent undulations, small areas of centripetal drainage and a number

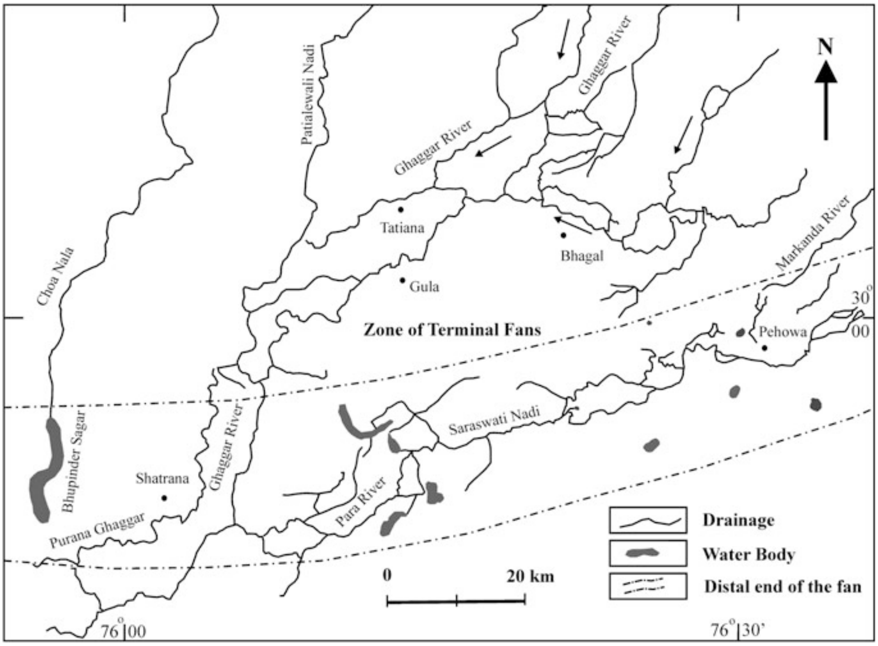

Fig. 5 Water bodies at distal end of the Zone of Terminal Fans in Shatrana-Pehowa area

of lakes, ponds and wetlands. The plain is about 50–80 km wide, in NE–SW direction, with a gentle slope of about 25 cm/km, towards the south.

The reversal of slope towards north, close to the Southern Pediplain surface is gentle.

4.5 Southern Pediplain

This surface is confined between Aravalli Piedmont Zone and the Central Alluvial Plain with a slope between 17 and 35 m/km towards the north. The surface is made up of sediment derived from the Aravalli mountain front and consists of brownish mud and silt, with granules of pedogenic calcrete.

4.6 Aravalli Piedmont Zone

This forms a narrow belt along the Aravalli-Delhi Massif and comprises of brownish coloured clays, silts and sand. The slope of the Aravalli Piedmont Zone varies between 50 and 85 m/km towards north.

4.7 Surface Profiles

Five surface profiles were drawn along N50°W–S50°E direction, parallel to the Himalayan trend, in the northern part of Haryana-Punjab Plain, spaced about 15 km apart. Out of these, the northernmost two profiles cover areas from Yamuna valley in the southeast to Satluj valley in the northwest. In the southern part of Haryana-Punjab Plain, four profiles were drawn across the Aravalli-Delhi Massif. Yet four more profiles were drawn across the Himalayan trend (N40°E–S40°W), running from the Himalayan foothills in the northeast to the tip of Aravalli-Delhi Massif in the southwest. These profiles indicate that:

1. The abnormal ratio of valley width to channel width of the streams draining Yamuna–Satluj interfluve indicates that the water supply and energy regime of these streams were much higher in the past (latest Pleistocene-Holocene) due to better precipitation. Subsequent deterioration in precipitation and neotectonic activities desiccated and disrupted the drainage in this area (Srivastava et al. 2013). Also they continued flowing further south-westward, as indicated by the presence of Bhur ridges.
2. The contact between Older Piedmont Zone and Zone of Terminal Fans is marked by a prominent bluff of 2–7 m and may represent trace of a blind thrust (Srivastava et al. 2014).

4.8 Nature of Ganga-Indus Water Divide and Drainage Morphometry

Ganga-Upland Interfluve water divide does not always coincide with the highest altitude of the surface profiles drawn parallel to the Himalayan trend in Haryana-Punjab Plain. In the northern and central part of the plain, the distance between the water divide and the highest point of the surface profile varies from 15 to 93 km. The Haryana-Punjab Plain has been identified into Eastern Interfluve and Western Interfluve. The area between Ganga-Upland Interfluve water divide and the line connecting highest points of the profiles, designated as Eastern Interfluve, is drained by Chautang Nala, Saraswati Nadi and Markanda River. These streams cross over to the Western Interfluve successively, as one moves from north to south. The water divide coincides with the highest point of the surface profiles in the southern part of Punjab-Haryana Plain, close to the Aravalli Massiff.

The water divide between Ganga and Upland Interfluves drainage systems has developed due to movement along Delhi-Ambala basement high related to the northward movement of Indian plate and crustal adjustment. The uplift imparted eastward tilt, causing Yamuna channel to migrate eastward within its valley; while the westward tilt to the western side of the water divide caused westward movement of Chautang, Saraswati and Markanda rivers (Srivastava et al. 2013).

This detailed study of drainage basins on the both sides of the Ganga-Indus water divide shows several abnormalities and features indicating strong maturity level and certain features of rejuvenation and immaturity. Rejuvenation is also indicated by gullying in some of the western basins. These features strongly suggest that the basins have existed in their present form for a long time to develop reasonably mature basin features. However, later neotectonic activity in the form of uplift and some tilt rejuvenated the basins to develop several features of immature basin. There has been distinct eastward tilt and westward tilt in the areas located on either side of the water divide. Moreover, the region witnessed differential uplift and tilting of different blocks influencing individual river basins. This neotectonic activity is related to the movement along Delhi-Ambala basement high of the northward moving Indian lithosphere (Srivastava et al. 2011).

4.9 Harappan Settlements in Saraswati Basin

After the discovery of Mohenjodaro and Harappa in Pakistan and contemporary site at Kalibangan in northern Rajasthan, India, there was tremendous impetus for studying archaeological sites of Harappan Civilization (Lal 1979). Joshi et al. (1984) have compiled data on early, mature and late Harappan stages of nearly 400 archaeological sites in Saraswati valley located in the northern states of India. A large number of sites of Harappan culture which later termed as Indus-Saraswati Civilization have been found in the Saraswati basin. These were compiled by Mughal (1997), Kayanraman (1999), Possehl (2003). The data are given in Table 1 (modified after Danino 2010). It may be noted that the migration of settlements, in general, has been towards the north and east due to availability of more water in the upper reaches of Ghaggar-Saraswati basin. The locations of some important sites are shown in Fig. 6.

Table 1 Distribution of Harappan sites in the Saraswati basin (adapted from a list compiled by S. P. Gupta, with Inputs from G. Possehl and M. Rafique Mughal)

Saraswati basin (east to west)	Early Harappan (4600–4300 year BP)	Mature Harappan (4300–3800 year BP)	Late Harappan (3800–3100 year BP)	Total
Haryana	558	114	1168	1840
Indian Punjab	24	41	160	225
Rajasthan	18	31	0	49
Cholistan (Pakistan)	40	174	50	264
Total	640	360	1378	2378

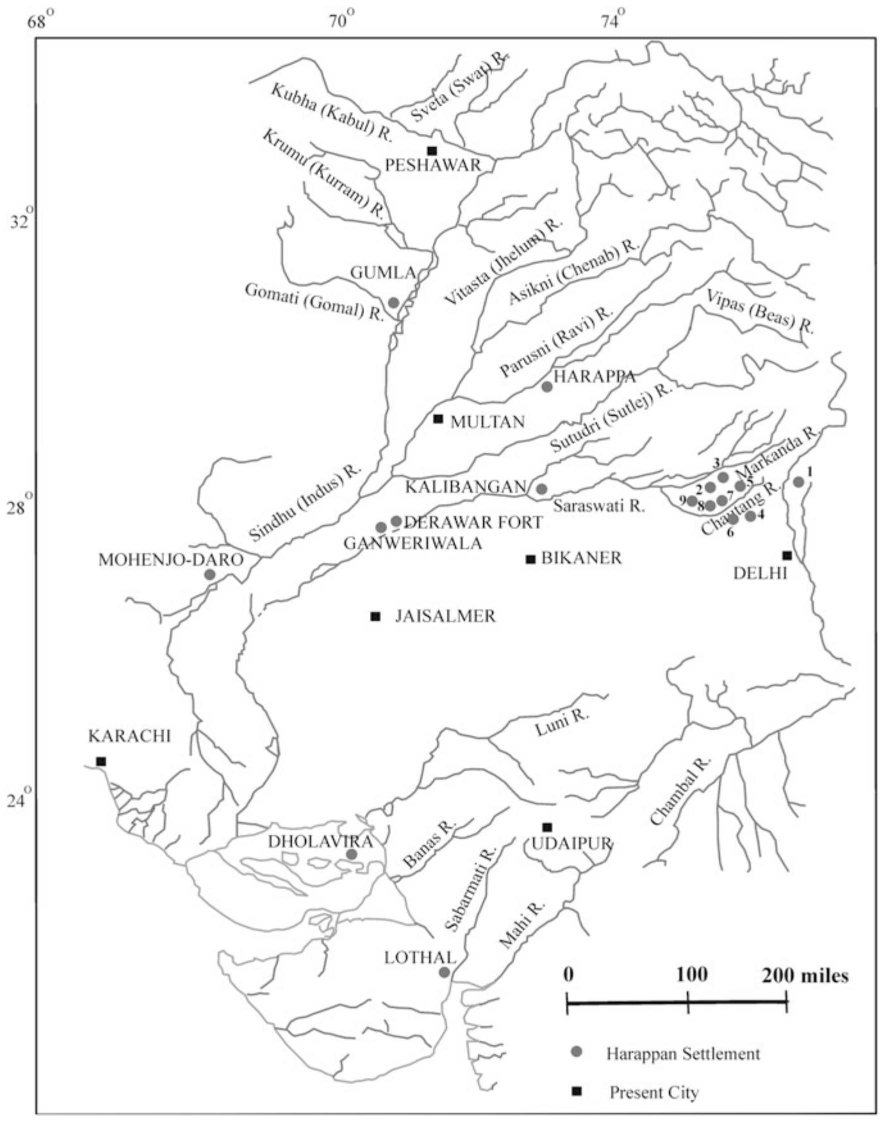

Fig. 6 Map showing Harappan settlements along present and ancient river courses. *1* Alamgirpur, *2* Banawali, *3* Bhirrana, *4* Farmana, *5* Kunal, *6* Mitathal, *7* Rakhigarhi, *8* Siswal and *9* Sothi

5 Discussion and Conclusions

The Saraswati River of past had its origin in Himalaya in the Tons fifth order basin, as postulated by Puri and Verma (1998). They have assumed Tons River as Vedic Saraswati River and named the trunk glacier of Tons fifth order basin as Saraswati

Glacier. The two assumptions, however, need to be validated by more scientific evidences. Virdi and Philip (2006) have recorded a former course of Tons River in its lower reaches before its confluence with Yamuna. However, this former channel of Tons River makes a northerly swing instead of a southerly diversion supposed by Puri and Verma (1998). The lower reaches of Tons River need further examination from this point of view.

The change in the course of Giri River is well documented by Virdi and Philips (2006) near Dadahu. The former course is represented by Parashuram and Renuka lakes. The block tilting, which caused this change in course, is further evidenced by the deeper part located in the upstream side of Renuka Lake, while it is shallower on the downstream side. Further downstream an abandoned channel of Giri River is seen which is presently occupied by Jambu Khala, joining Bata River. Giri River was previously flowing west of Garibnath hill, taking Bata-Markanda course. It is presently flowing to the east of Garibnath hill before joining Yamuna.

Bata-Markanda drainage basins are highly asymmetrical (Virdi et al. 2006). Bata-Markanda water divide is very subtle in nature. The two rivers share a common river terrace extending from Kolar westwards till Katasan Devi and beyond. The water divide at Uttamwala is so flat that it supports paddy cultivation. The Bata-Markanda water divide has come up syngenitically with Yamuna Tear which is constrained to about 5000 year BP. A similar water divide with a wind gap is seen in the adjoining Sukh Rao drainage basin to the south (Srivastava et al. 2012 online). It is, therefore, logical to assume that before 5000 year BP Giri and Tons(?) (cf. Saraswati River) rivers were flowing through Bata-Markanda valley to emerge out of the Siwalik Hills around Adh Badri (Adi Badri). The pebbles of quartzite and metamorphic rock in Kolar and adjoining Sudanwala river terraces also indicate that they must have been brought through a river emanating from Lesser/Central Himalaya (Puri and Verma 1998). Both Bata and Markanda rivers presently originate from Siwalik Hills.

Haryana-Punjab Plain has an independent drainage system (Srivastava et al. 2013). It had an integrated drainage system (Proto-Saraswati) between 20 and 30 ka BP time interval (Saini et al. 2009). Yamuna and Satluj might have contributed to this Proto-Saraswati at that time. Vedic Saraswati River belongs to the younger fluvial activity of Haryana-Punjab Plain between 5.9 and 4.3 ka BP. It was a wet phase in Rajasthan as well (Saini and Mujtaba 2010). During this time frame, Yamuna River had well settled in its valley, although its channel migrated eastwards within its valley in response to the tectonic upheaval creating Ganga-Upland water divide (Srivastava et al. 2011, 2013).

Satluj River was flowing southwards after emerging out from the Siwalik Hills near the apex of Ropar fan. It continued feeding Saraswati River at different times through Eastern Naiwal, Naiwal and Western Naiwal rivers successively (Sahai 1999). Satluj River took a westerly course due to block movement related to Ropar Tear (coeval with Yamuna Tear).

Ghaggar River is the main tributary of Saraswati River which joins the latter near Rasula in Patiala district. A major subsurface palaeochannels of Saraswati River has been deciphered from Tohana-Fatehabad-Sirsa tract (Saini and Mujtaba 2010).

After Sirsa, the Vedic Saraswati River took the present course of Ghaggar River through Hanumangarh, Suratgarh and Anupgarh in Rajasthan to Fort Abbas, Marot and Fort Derawar in Cholistan Desert in Pakistan. It took Hakra-Nara course to Rann of Kachchh to meet the Arabian Sea (Sridhar et al. 1999). A large number of important Harappan settlements proliferating Saraswati basin provide ample proof of a flourishing Indus-Saraswati Civilization.

After the Mahabharata war, Balram went for pilgrimage along Saraswati River which was already degenerated and desiccated, especially in lower reaches. He tells King Janmejaya (Mahabharata, Shalya Parva, **63**: 90):

Snigdhtwadoshdhinam cha bhumeshcha Janmejaya

Jananti siddhah Rajendra nashtamapi Saraswatim translated in English as:

'Looking to the vigour of vegetation (including medicinal) and soil moisture, learned people can make out the lost course of Saraswati'.

It is true at many places when one sees a spiralling course of a river valley supporting lush green cultivation within the dry expanses of Thar Desert.

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Subansiri: Largest Tributary of Brahmaputra River, Northeast India

Manish Kumar Goyal, Shivam, Arup K. Sarma and Dhruv Sen Singh

1 Introduction

Indian subcontinent is drained by several perennial rivers, which makes this subcontinent a fertile land for agriculture. The river systems in India play important role in the energy, industry, agriculture, and health sector. Brahmaputra River, which originates near Manasarovar in Tibet Plateau, is considered as the lifeline for the northeastern region of India. Brahmaputra River enters in the state of Arunachal Pradesh at Gelling (Upper Siang district) where it is known as Siang River. After entering in India and traveling across the Arunachal Pradesh, the river enters the fertile plains of Assam at Pasighat and joins river Ganga in Bangladesh; further, it merges in the Bay of Bengal. Several tributaries contribute to Brahmaputra River along its path. In this chapter, Subansiri River, the largest tributary of Brahmaputra River, has been discussed.

Subansiri River is the right northern bank and longest tributary of Brahmaputra River (Sarkar et al. 2012). The name Subansiri originates from the fact that this river was a potential site for gold mining in the past. The name Subansiri is derived from the Sanskrit word 'Swarn' which means 'gold.' Subansiri River is a

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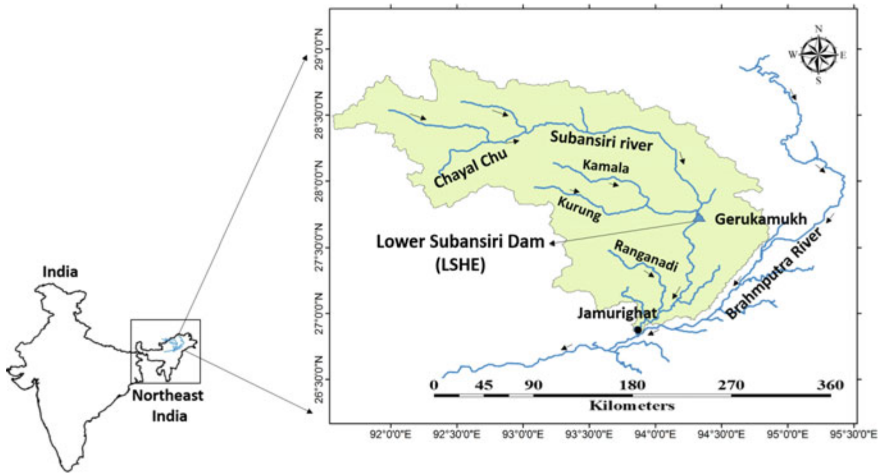

Fig. 1 Subansiri River map and its tributaries

trans-Himalayan river, which originates in the Tibetan Plateau in the western part of Mount Porom (Goswami et al. 1999) at an elevation of 5340 m. It is formed by joining of three small streams namely Lokong Chu (Char Chu), Chayal Chu, and Tsari Chu in Tibet. After traveling through the Himalaya, this river enters India through Miri Hills in Arunachal Pradesh. The total length of Subansiri River from origin up to the confluence to the Brahmaputra is 337 km. The 208 km of the river flows in the mountainous terrain of Himalaya and the remaining length in the Assam plain. Subansiri River joins Brahmaputra River at Jamurighat in Lakhimpur district of Assam.

Total area of the river basin is about 35,771 km^2 [calculated from the basin delineated from the Shuttle Radar Topography Mission (SRTM) digital elevation map], out of which 21,066 km^2 area lies in Arunachal Pradesh, 4360 km^2 lies in Assam, and remaining 10,345 km^2 lies in Tibet region (Ray and Sarma 2011). The maximum observed discharge of the river is about 18,500 m^3/s and the minimum is about 131 m^3/s. Subansiri River contributes 7.92% of total discharge of the Brahmaputra River as observed near Pandu Port (Singh et al. 2004). Several small tributaries such as Ranganadi, Dikrong, Kamala, Ghagar, and Sampara contribute to the Subansiri River (Fig. 1).

The districts located in Subansiri River basin are shown in Fig. 2. Lower Subansiri, Upper Subansiri, Papum Pare, and West Siang are located in Arunachal Pradesh while Dhemaji, Lakhimpur, and Jorhat are in Assam state. The Lower Subansiri hydroelectric (LSHE) power plant was established at the foothill near

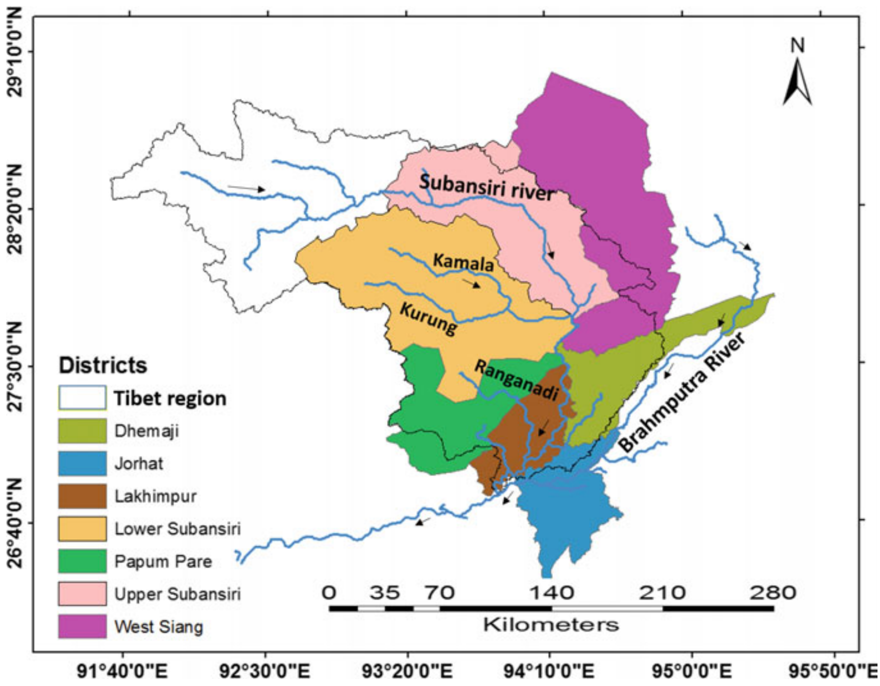

Fig. 2 Regions covered by Subansiri River basin

Gerukamukh in Dhemaji district of Assam. The main objectives of the LSHE project is electricity production (capacity of the power plant is 2000 MW) and flood control (Ray and Sarma 2011).

2 Geological and Morphometric Characteristics

Subansiri River covers a very diverse topography from its origin point to the confluence of the Brahmaputra River. Shuttle Radar Topography Mission (SRTM) data analysis of the Subansiri River basin shows high relief in the upper catchment with sharp mountain tops, which is indicative of the hard rock terrain with low erosion rate, whereas the southern part of the basin has the low hill topography and flat hill tops (Goswami et al. 1999). Floodplain of the Subansiri River extends about 63 km in an east–west direction and 40–58 km in north–south direction. Thus, the geomorphic units of the Subansiri River basin can be broadly classified as dissected piedmont plain and dissected flood plain (Ray and Sarma 2011). The terrain in the foothills to the south is mainly composed of alluvial deposits of Brahmaputra River. The Siwalik Hills are located in the northern part of the area. Subansiri River's alluvial plain has more than 6-km-thick sedimentary sequence with very low gravity anomaly indicating thick mass of low-density material. Subansiri River in the foothills follows a braided course (Gogoi and Goswami 2014), whereas the river is typically meandering in nature with drastic channel shift. In the Assam plain, Subansiri River shows a very sinuous character and creates bar of different sizes. The Subansiri River exhibits point bars, natural levees, channel bars, and back swamps. During flood season, river flows above the natural bank of the river, which reduces the flow velocity and deposits the coarse sediments on its bank, which leads to the formation of natural levees. Due to heavy sediments from the upper mountainous areas, the river forms very broad levees in the plain areas.

3 Socioeconomic Status

The major population lives downstream of the LSHE in this river basin. This area is geographically remote and infrastructurally not very good. The literacy is low and large portion of the population depends upon the agricultural practices and fishing. The river basin covers seven districts of Assam and Arunachal Pradesh, among these Lakhimpur of Assam has the highest population (approximately 1 Million) (Census 2011), whereas the population of Dhemaji district is approximately 0.7 Million. The population of districts of Arunachal Pradesh is comparatively low as compared to the districts of Assam. Papum Pare district has a total population of 0.1 Million (Census 2011). Agriculture and livestock are the backbones of the economy of these villages, and rice cultivation is practiced by the major part of the population.

4 Land Use and Land Cover (LULC)

Upstream of Subansiri River basin (above LSHE project) is dominated by the forest cover with 5–10% snow and glaciers. However, some parts, which come under the Tibet Plateau, are rain shadow zones and mostly cold desert with barren land and grasses. Downstream of the Subansiri River basin, 50% of the area comes under agricultural land. Village houses, huts, and residential plots account for 18% of the total area whereas 16% area is swamp or marshy land. Figure 3 shows the land use and land cover classification map prepared using Moderate-Resolution Imaging Spectroradiometer (MODIS) Land Cover Institute (LCI) datasets with spatial resolution of 0.5 km.

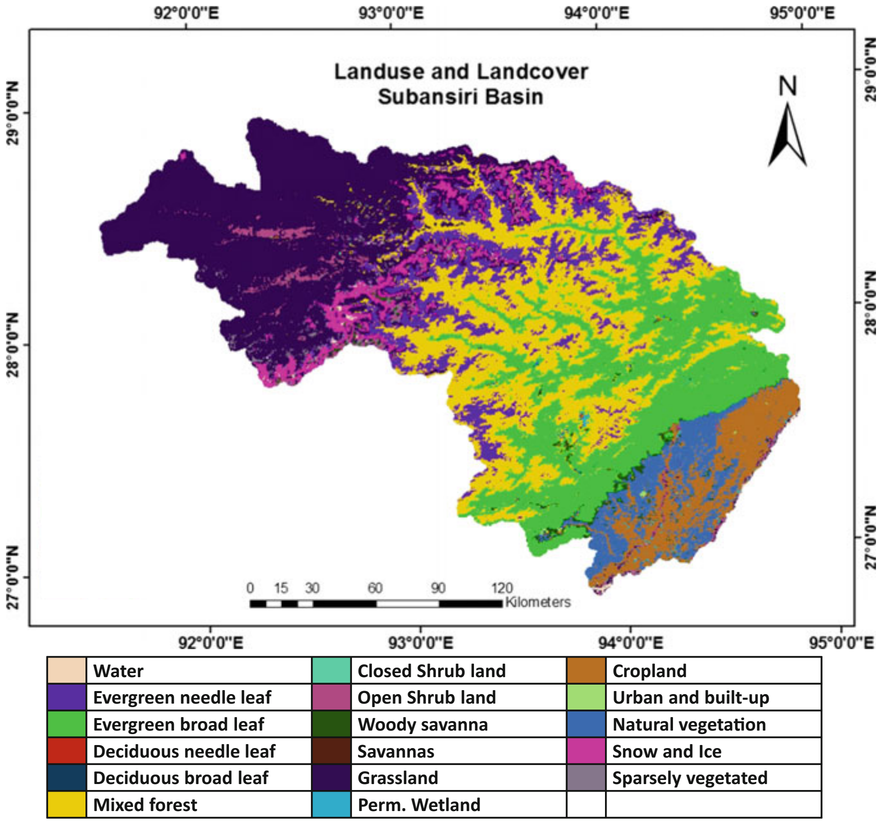

Fig. 3 Land use and land cover map of Subansiri River basin

5 Soil Type

Soil map obtained from Food and Agriculture Organization (FAO) shows seven dominant soil classes in the basin (Fig. 4). In the downstream area on the flood plain, major soil class at top layer is orthicacrisol (3651) with lepticpodzols and humicacrisol at secondary and lower layers. In the upstream of the river where the river passes through the hilly terrain, major soil types at the top layer are orthicacrisol (3650) with ferric luvisols and gleyicacrisols as secondary and lower layers. In North Lakhimpur area, thickness of silt and silty clay zone is about 2 m and below this medium coarse sand is present. Near confluence of Brahmaputra and Subansiri River, soil type is eutriccambisol (3683) at the top layer along with orthicluvisol and chromicluvisol at the second and third layer. Some parts of the basin are permanently covered with glaciers (6998) and waterbodies (6997).

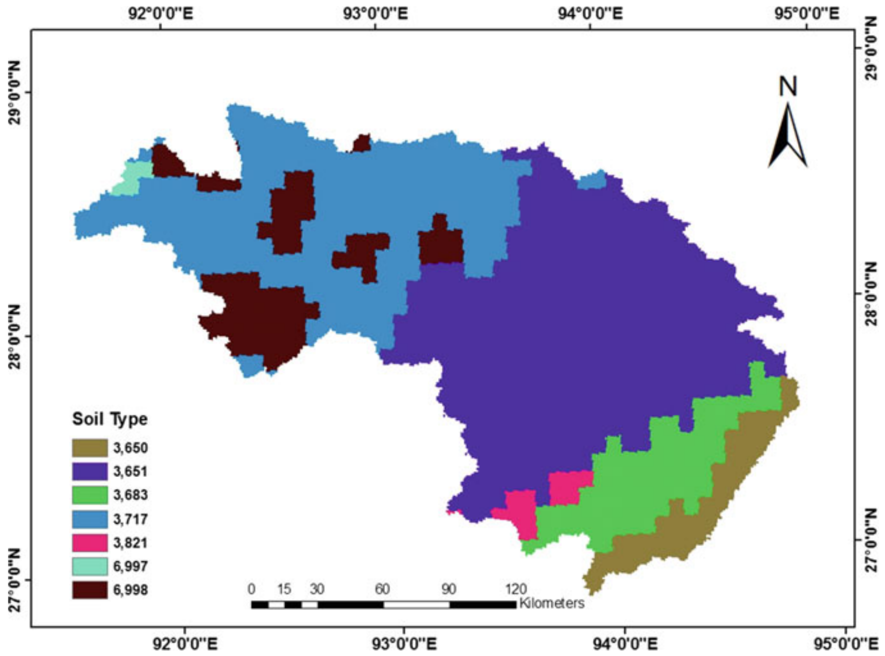

Fig. 4 Soil map of the Subansiri River

6 Meteorological Characteristics of Subansiri River Basin

Subansiri River basin shows significant variability in rainfall characteristics because of its areal extents from tropical to temperate zones (Sarkar et al. 2012). Relative humidity remains high throughout the year. Average annual maximum temperature varies from 2 to 25 °C whereas average annual minimum temperature varies from −7 to 5 °C. Variation of temperature in the upper part of the basin is very low because of the high elevation zone which remains covered with snow and glacier throughout the year (Shivam et al. 2016). Temperature variation in the basin can be explained separately for the upstream and downstream part. The upstream part is mostly hilly terrain so the temperature is not high whereas in the downstream part temperature can rise up to 35 °C during summer. Monthly variations of maximum and minimum temperatures along with the monthly precipitation are shown in Fig. 5.

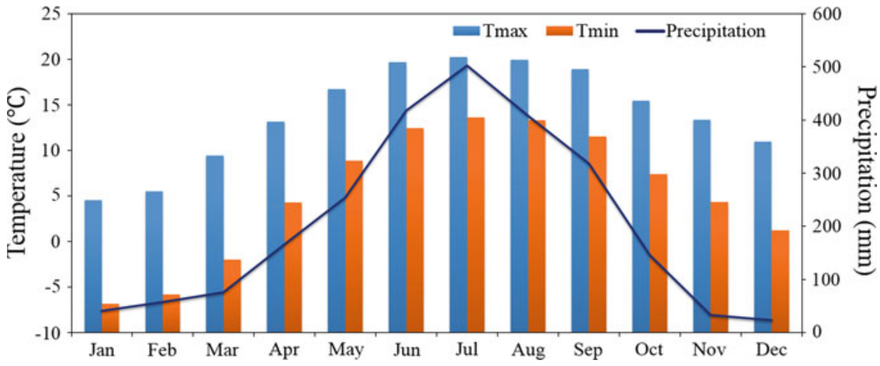

Fig. 5 Average monthly precipitation, minimum and maximum temperature variations in Subansiri River basin

7 Impact of Climate Change on the Precipitation, Temperature, and Hydrology of Subansiri River Basin

Climate change impacts on the precipitation and temperature in Himalayan belt are unequivocal and have been addressed in several previous studies (Singh and Goyal 2016a; Goyal 2014). Rise of temperatures in the Himalayan range has affected the glacial melt rate (Singh et al. 2016). Previous studies in the Northeastern India have reported the increase in precipitation and temperature (Singh and Goyal 2016b). Changes in temperature and precipitation affect the hydrology of the rivers which increases the runoff of rivers because of the enhanced glacier melt and precipitation (Khadka et al. 2014). Shivam et al. (2016) analyzed the temperature and reported the increasing trend in the diurnal temperature range within the river basin. Hydrology of the river basin anticipated to change because of the increased temperature and precipitation, which is affecting the hydrological process such as evapotranspiration and runoff.

8 History of Natural Hazards in Subansiri River Basin

The river basins having high density of population and rapid unplanned urbanization are prone to natural hazards (Singh and Awasthi 2011). The situation becomes more critical when flood takes place in the hilly region of Assam and other states of Northeast India. Northeastern part is prone to earthquake and heavy rainfall, which makes this region vulnerable to natural hazards. The known biggest natural hazard in the Subansiri River basin happened in August 1950, when a massive earthquake struck the Assam state, which caused landslides in the hilly region. This landslide choked the path of Subansiri River at the gorge near Gerukamukh where the Lower Subansiri hydroelectric project is situated.

The amount of water stored in this ephemeral lake formed by the blocking of river was equal to the present capacity of the constructed hydropower dam. After three days, due to the pressure of stored water, the ephemeral lake was broken which resulted in catastrophic flood (cf. Singh 2013, 2014). This flood caused a massive deposition of sediment and changed the morphology of the Subansiri River.

Apart from this catastrophic flood event, frequent floods are quite common in the Subansiri River basin. Northeast region receives more than 2000 mm annual rainfall, which makes this region prone to frequent flood events. Districts such as Dhemaji and Lakhimpur are affected by severe flood problems in monsoon season. Extreme events like heavy precipitation are very common in the region which causes flash floods and landslides (Das et al. 2009). In June 2004, a flash flood occurred due to heavy rain in North Lakhimpur district, which inundated approximately 50 villages and caused loss of lives. Another event occurred in the same year 2004 in the month of October when flash flood due to heavy rainfall caused inundation of several villages and loss of properties in the Subansiri River basin (Das et al. 2009).

9 Hydrological Modeling of Subansiri River Basin

Hydrology of the Subansiri River basin is complex because topographic variation and being fed by snow/glacier melt and rain. A detailed hydrological modeling analysis of the river basin could provide a clear understanding of several hydrological processes, which can be helpful for water resource planning, management, and flood control measures. An effort was made for hydrological modeling of the river using soil and water assessment tool (SWAT). The data are available at the Gerukamukh Lower Subansiri dam site so the modeling was carried out for the same place.

Hydrological modeling can be defined as the mathematical representation of the physical processes of each component of the hydrological cycle (Jayakrishnan et al. 2005). Hydrological modeling helps to understand the physical processes responsible for the observed variables such as streamflow, evapotranspiration, and runoff. Water resource planning and management requires a modeling framework of any river basin. Various planning strategies are based on the modeling framework.

Hydrological modeling of the Subansiri River was performed using the Soil and Water Assessment Tool (SWAT), which is a semi-distributed, deterministic model (Abbaspour et al. 2007). SWAT works on the principle of water balance equation (Eq. 1), which computes all the hydrological components (Arnold et al. 2012).

$$SW_t = SW_0 + \sum_{i=1}^{n} \left(R_{day} + Q_{surf} + E_a + W_{seep} - Q_{gw} \right) \tag{1}$$

where SW_t denotes the soil water content (mm) at the end of the time period, SW_0 refers to the initial soil water content (mm), t is time in days, R_{day} denotes precipitation (mm), Q_{surf} is the surface runoff (mm), E_a is the evapotranspiration (mm), W_{seep} is the percolation exiting the soil profile bottom (mm), and Q_{gw} is the return flow (mm).

Runoff calculation is performed using soil conservation services (SCS) curve number (CN) method as shown in Eq. (2).

$$S = 25.4\left(\frac{1000}{\text{CN}} - 10\right) \tag{2}$$

where S is water retention parameter in mm, CN represents Curve number, which depends on land use class, antecedent moisture content, and soil hydrological group.

10 Model Input for Hydrological Modeling

10.1 Weather Data

Precipitation and temperature data series are used as a primary weather data input in SWAT model. Precipitation, minimum and maximum temperature data were obtained from the India Meteorological Department (IMD) grid datasets of 0.25° × 0.25° (Rajeevan et al. 2006).

10.2 Soil Map and Land Use Land Cover Data

SWAT model works on the SCS-CN number equation to calculate the runoff; SCS curve number depends on the soil type, LULC, and antecedent moisture content. Soil map was obtained from the Food and Agricultural Organization (FAO) world soil map, LULC was obtained from the MODIS land cover facility portal (www.glcf.umd.edu/data/lc).

Figure 6a represents the elevation map obtained from the SRTM Digital Elevation Model (DEM). Figure 6b shows the four major soil classes of the Subansiri River and Fig. 6c shows the slope map presented in percentage.

Land use and land cover maps are shown in Fig. 6, the upper portion of the basin which falls in Tibet region is a rain shadow zone and grasses are the dominant land cover class in this region, whereas glaciers are also present in the Himalayan range. Different types of forest are the dominant land cover classes in the Arunachal Pradesh part.

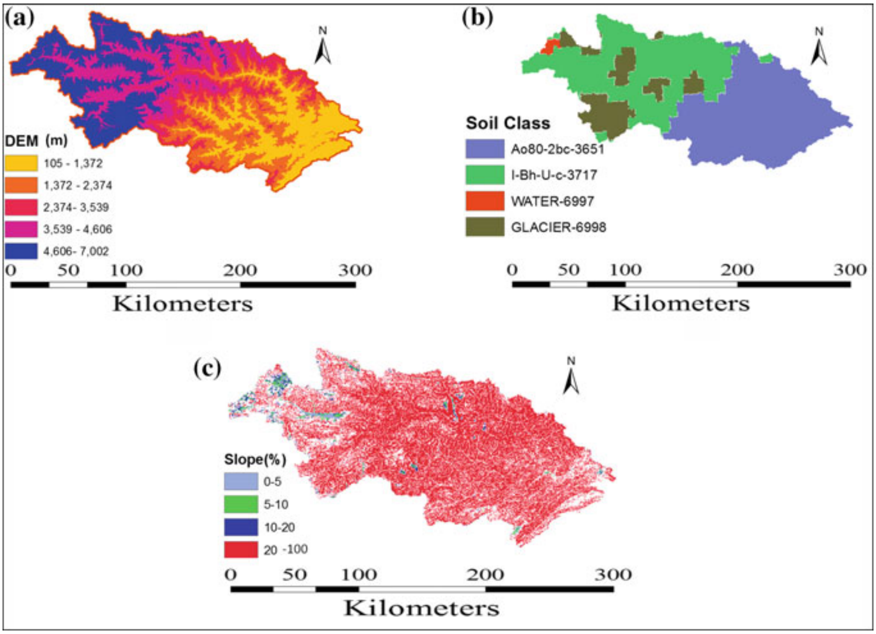

Fig. 6 **a** Elevation map, **b** soil map, and **c** slope map of Subansiri River basin (up to LSHE)

11 Model Performance Metrics

Model performance was evaluated by the coefficient of determination (R^2) which can be calculated as

$$R^2 = \left(\frac{\sum_{i=1}^{n} \left(T_{O_i} - \overline{T_O}\right)\left(T_{P_i} - \overline{T_P}\right)}{\sqrt{\sum_{i=1}^{n} \left(T_{O_i} - \overline{T_O}\right)^2} \sqrt{\sum_{i=1}^{n} \left(T_{P_i} - \overline{T_P}\right)^2}} \right)^2 \tag{3}$$

where T_{O_i} and T_{P_i} are the values of ith observed and simulated data points, respectively, and $\overline{T_O}$ and $\overline{T_P}$ are the mean values of observed and simulated time series, respectively.

12 Calibration and Validation of Subansiri River Streamflow

Streamflow calibration and validation of the hydrological model for Subansiri River basin was performed for the observed streamflow series from 2008 to 2013. Figure 7 shows the calibration and validation scatter plot for monthly streamflow model, Fig. 7a shows the coefficient of determination (R^2) for the calibration period which was found to be 0.88 whereas Fig. 7b shows the R^2 for validation period which was 0.83.

Parameters, as shown in Table 1, were selected for calibration of the model. CN2 represents the curve number coefficient for antecedent moisture content (AMC) class 2 conditions, Alpha_BF represents the base flow factor, GW_Delay shows the groundwater delay, and GWQMN shows the water level in the aquifer. Prefix R_ and V_ represents the method of updating the values of parameters, R means the relative value, and V represents the complete value. For calibration, initially an acceptable range of parameters was provided to calibrate the model.

The sensitivity of the parameters was checked using *t*-stat, and significance of parameters was tested using *P* value. Table 1 shows the upper and lower limits of the parameters, their final value with *t*-stats and *P* value. Calibration and validation of the streamflow show an acceptable range for physical-based modeling (Fig. 8). This hydrological model in combination with the future projected temperature and precipitation series for different climate change scenarios could be utilized for assessment of the future change in river discharge and water availability for

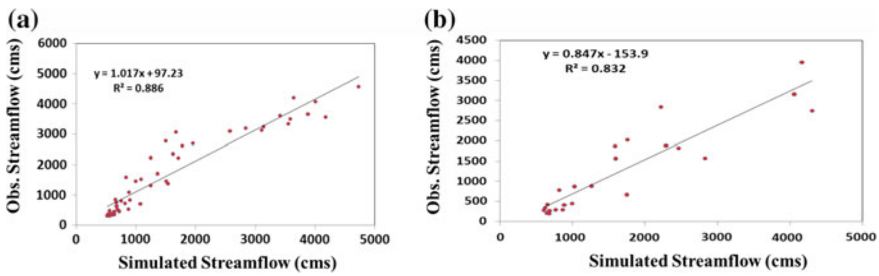

Fig. 7 **a** Calibration and **b** validation results of streamflow simulation

Table 1 List of selected parameters for calibration and validation

Parameter name	Min value	Max value	Fitted value	*t*-stat	*P* value
1:R__CN2.mgt	−0.25	0.25	0.21	6.94	0.000
2:V__ALPHA_BF.gw	0	1	0.51	1.23	0.220
3:V__GW_DELAY.gw	10	250	136.36	−3.32	0.001
4:V__GWQMN.gw	0	1000	234.50	−2.17	0.030

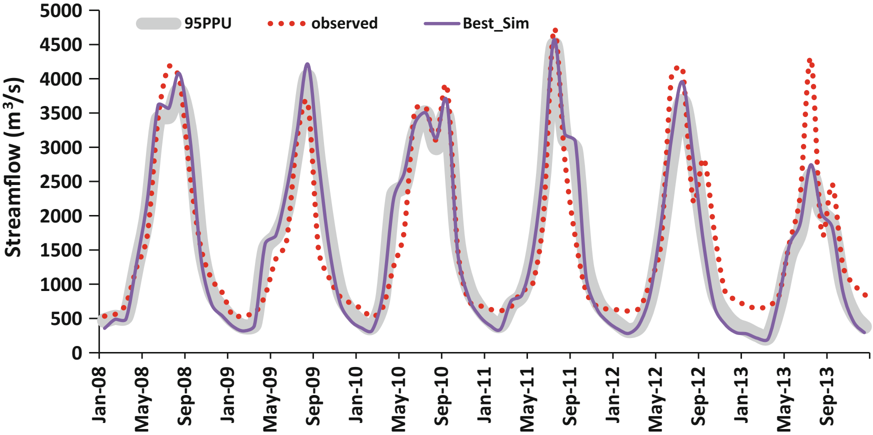

Fig. 8 Observed and simulated streamflow plot with 95 ppu band

the different greenhouse gas emission scenario. These hydrological projections could be helpful for deciding the water management plan and flood mitigation strategies.

13 Summary and Conclusions

This chapter focuses on the detailed description of the Subansiri River, which is the largest tributary of Brahmaputra River. This study encompasses the geology, morphology, and meteorological descriptions of the Subansiri River basin. Subansiri River is a potential site for harnessing the hydropower because of the perennial nature of the river and high discharge even during the lean season. This river causes severe flood problems in downstream districts during monsoon. Moreover, Subansiri River carries huge amount of sediments and deposits it within the river valley in the Assam plain, which causes diversion of the river course. Hydrological modeling of the Subansiri River was performed to understand the various processes involved in streamflow generation process. A hydrological model is a useful tool for planning and management of available water resources in the river basin. Flood in the rainy season and water scarcity in the lean season is the major problem in the Subansiri River basin, which can be solved through the hydrological modeling approach.

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Teesta River and Its Ecosystem

Manish Kumar Goyal and Uttam Puri Goswami

1 Introduction

In India, most major rivers originate from Himalayan glaciers such as Ganga, Brahmaputra, Jhelum, Sutlej, and Teesta. Himalayan glaciers are the largest sources of major rivers system in Asia, which serves water to more than 1.3 billion people living in the downstream (Singh et al. 2016; Bajracharya et al. 2007). The river Teesta originates from the TsoLhamo Lake, North Sikkim, at 5033-m elevation. Pahunri glacier, Khangse glacier and ChhoLhamo Lake are also considered the sources of Teesta River (Meetei et al. 2007; Singh and Goyal 2016). It is a right-bank major tributary of Brahmaputra River. The river is formed by two glacier-fed streams, LachenChhu and LachungChhu, meeting at Chungthang in North Sikkim. After Chungthang junction, it increases its width with wide loop glowing down to Singhik with elevation which drops from 1550 to 750. At Singhik, TalungChhu River joins the Teesta River as its tributary which originates from Talung glacier in the Khangchendzonga range. The RongniChhu joins at Singtam, and RangpoChhu River joins at Rangpo. After this, Teesta River gradually increases in width and joins major tributary Rangeet at the border of West Bengal. Then river moves across the Rangpo town where it creates the boundary between West Bengal and Sikkim until it reaches Teesta Bazaar.

The Teesta River system, Ganga's major tributary in the historical past, must be controlled by climatic forcing (Meetei et al. 2007). The major tributary of Teesta and Rangeet rivers which originate from Rathong Glacier, West Sikkim, meets at the border of Sikkim and West Bengal. The major tributaries of Rangeet River are RathongChhu, KalejKhola, and RimbiKhola originates from Talung Glacier, West Bengal. The major left and right-bank tributaries of Teesta river basin are listed in

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Table 1 Major left and right-bank tributaries of Teesta river

S. No.	Tributaries	
	Left-bank tributaries	Right-bank tributaries
1	LachungChhu	Rangeet River
2	ChakungChhu	RangyongChhu
3	DikChhu	ZemuChhu
4	Rani Khola	
5	RangpoChhu	

Table 1. The total stretch of Teesta River is about 309 km long, out of which 115 km is in Bangladesh, joins the Brahmaputra River at Fulchori, Rangpur district, Bangladesh. The catchment area of the river is about 12,500 km^2. It is the major source for the lifeline of many fishermen, farmers, and boatmen, etc.

2 Geography of the Teesta River

The upper portion of the catchment area of Teesta River is mostly covered with snow and glaciers and lower portion covered with forest. The Teesta River exhibits large variability in geography such as undulating elevated profile. The glacial and peri-glacial deposition, uneven elevation dissected valleys, undulating plains and floodplains, valley-side slopes and landslide slopes, forest, rich fauna and flora (Nag et al. 2016; Singh et al. 2016; Meetei et al. 2007; Mukhopadhyay 1982).

The Teesta River has formed canyons and narrow valley in Sikkim and highlands with Kalimponghill. Along the river course vegetation cover changes from high elevation zone alpine vegetation to lower elevation zone with tropical deciduous vegetation. The Teesta and its major tributary Rangeet are the perfect places for river.

The landforms in the Teesta river basin is the result of continuous denudation and deposition processes that are constantly modifying the newly formed land forms in the upper reaches existing land forms in the lower reaches (NDMA 2013). Based upon the geo-morphological ecological and climatic regimes, Teesta basin in Sikkim can be demarcated into five distinct geo-eco-climaticzones such as (Carrying capacity study of Teesta Basin in Sikkim 2005a, b, c).

1. Sub-tropic zone up to 1000-m elevation (fluvial processes).
2. Warm temperate zone in between 1000 and 2000 m (fluvial processes).
3. Cold temperate zone in between 2000 and 2500 m (fluvioglacial and fluvial processes).
4. Cold zone between 2500 and 4000 m (periglacial, fluvial processes).
5. Frigid Zone above 4000 m (glacial, periglacial and fluvioglacial processes).

The upper Teesta River basin is characterized by glacial, accumulation of debris, debris avalanches and rock glaciers. The middle and lower parts of the basin is relatively less slope and relatively subdued relief. Teesta and most of its tributaries

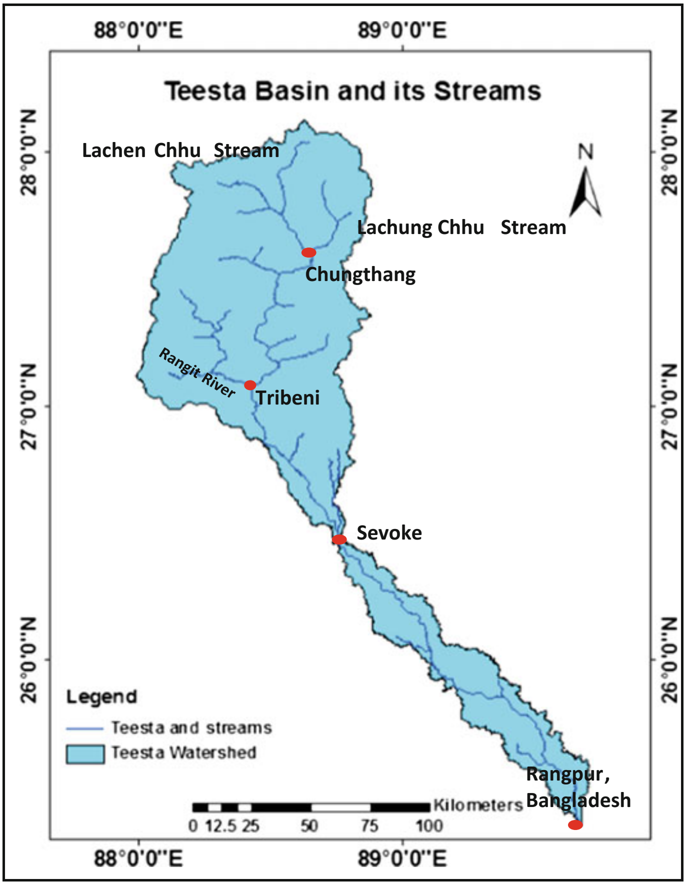

Fig. 1 Teesta river basin and its tributaries

flow with high velocity and carry boulders and suspended sediment. The flow is turbulent and characterized by high velocities throughout Sikkim. Figure 1 shows the Teesta river basin and its streams with location points.

3 Hydro-climatology

Teesta River basin is characterized by heavy rainfall and floods in monsoon season. In north Sikkim region, due to steep slope and uneven elevation, these extreme events lead slope transformation, landslides, and erosion. These events are responsible for the deposition of suspended sediment in river channel.

3.1 Climate and Rainfall

The northeastern part is one of the most vulnerable regions in response to precipitation (Shivam et al. 2016; Goyal 2014). The huge variation in the elevation from 8598 to 213 m in a stretch of about 100 km is the main cause for abrupt change in the climatic variables. The average annual rainfall varies from 2000 to 5000 mm over the river basin. Due to steeper elevation profile and high rainfall, it generates the runoff and soil erosion and landslides occurs over the Teesta river catchment. Here, the rainfall varies with elevation, i.e., rainfall in Chungthang is 2650 mm at 1600 m elevation, in Lachen 1680 mm at 2730 m elevation and in Thangu 840 mm at 3800-m elevation (carrying capacity study of Teesta Basin in Sikkim 2005a, b, c). The variation in rainfall in different seasons are as given: winter 0.7%, summer 13.6%, monsoon 80.2% and post-monsoon 5.5%, and average annual rainy days are 110.5 days (Ranade et al. 2007). The northern parts of Teesta river basins are dry and cold, whereas southern and middle parts are hot humid and wet. The temperature varies with elevation and increases with a decrease in altitude. The average seasonal temperature in summer is 25 °C, winter is 3 °C, and humidity of catchment remain above 70% throughout the year (Carrying capacity study of Teesta Basin in Sikkim 2005a, b, c).

4 Geomorphological Profile of Teesta River Basin

Climate change and global warming further affects the precipitation and temperature (Singh 2015; Singh and Agnihotri 2016) especially in the Himalayan region which affect the geomorphology of Himalayan Rivers. The ten broad landforms in the Teesta river basin are ridge, rocky cliff, escarpment, landslide zone, moraine zone, low mountain (less than 1000 m), narrow valley, middle mountain (between 1000 and 2000 m), high mountain (between 2000 and 3000 m), very high mountain (between 3000 and 4000 m) and extremely high mountain (higher than 4000 m) with glaciers (Carrying capacity study of Teesta Basin in Sikkim 2005a, b, c). Most of the Teesta river basin areas are situated at the high altitude. About 59% of the catchment area lies at 3000 m, 16% area lies in between 2000 and 3000 m, and only 25% area lies below the 2000 m, whereas sub-tropical elevation is found only 6% of the basin.

4.1 Slope Variation

The elevation profile varies from 8598 m to 213 m with in the short aerial stretch; subsequently, the steep and very steep slopes have been characterized in the Teesta river catchment. About 52% area lies in the above 27 slope class, and 10.32% area

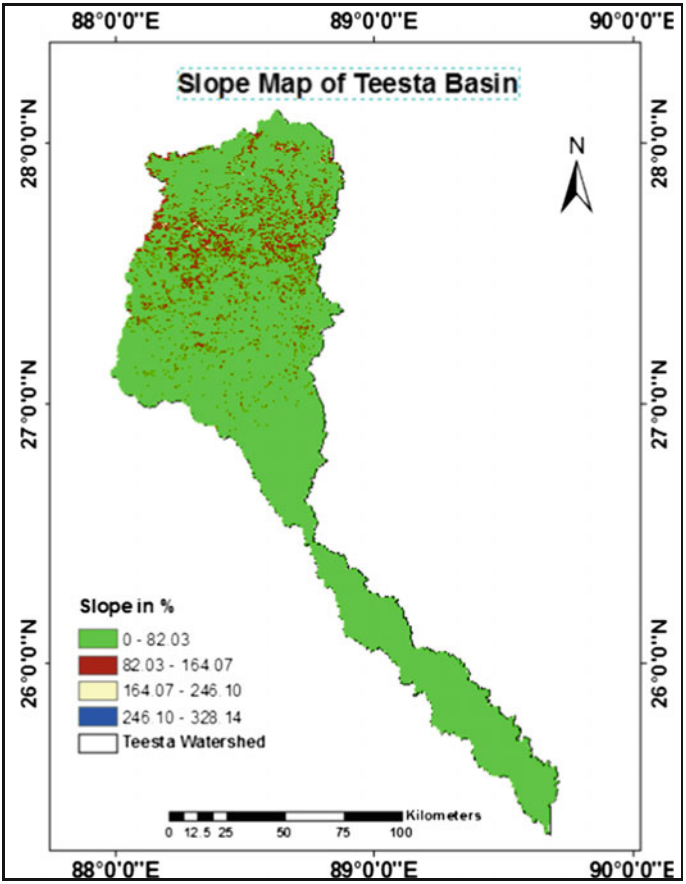

Fig. 2 Slope variation over the Teesta River catchments

lies in 65 and above slope category, while only 8.61% area comes under moderate slope class. Figure 2 represents the slope map of Teesta river basin and clearly indicates that Teesta River flows through high slope classes. The slope variation is obtained from the CARTOSAT DEM of 30-m spatial resolution.

4.2 Soil Characteristics

The Teesta basin having large diversity related to soil type and biological activities is shown in Fig. 3. In the hilly terrain, extensive deforestation, random construction, slope cultivation, random use of land and improper drainage system are the common issues. The soil and water conservation practices and/or measures are the most important for mountainous regions (Teesta River catchment) to keep safe

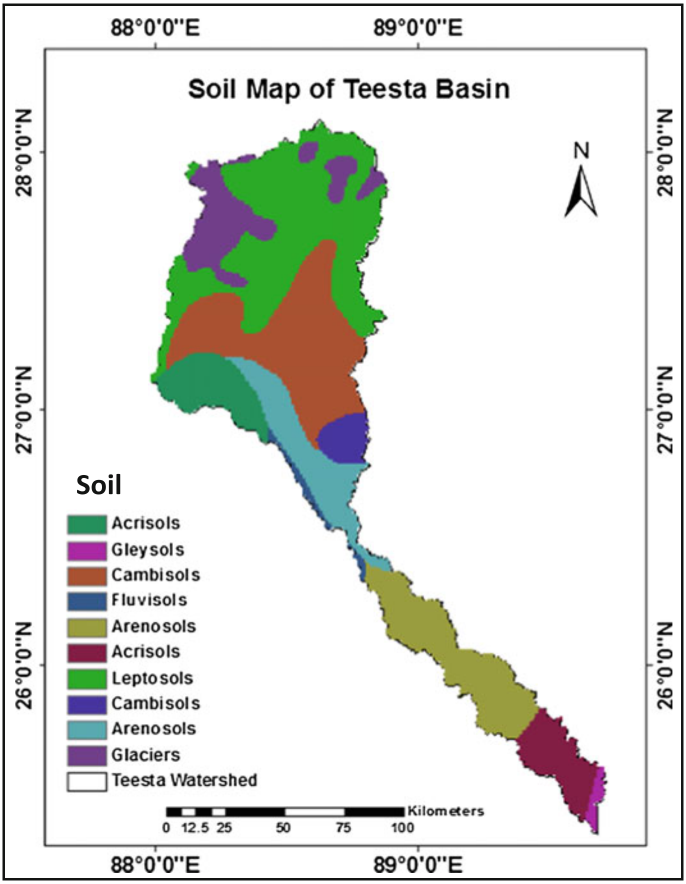

Fig. 3 Soil map of Teesta River catchment

valuable natural resources. Figure 3 presents the different types of soil over the river catchment, and large variation has been observed. This soil map is obtained from Food and Agricultural Organization (FAO) world soil map.

4.3 Land Use Land Cover (LULC) of Teesta River Basin

Land use land cover of a river system is an important characteristic. The runoff capacity of any stream is different with different land use land cover (Prakash and Abhisek 2016). Land use land cover of a river is characterized in terms of soil properties and land use.

5 Hydroelectric Power Projects

A hydro-power project mostly depends on the ecosystem quality of the catchment of its river and reservoir, biological health (which controls not only the water quantity and quality but also reservoir life). Maintenance of natural ecosystem of a catchment is the only way to generate the hydro-power on sustainable basis. It provides the direct benefit to functioning of natural ecosystem, which is controlled by its biodiversity.

Teesta River has steep slopes which are relatively appropriate for hydropower potential, with construction of storage structures depending up on the geography of the study area. Accordingly, numbers of power projects already have been proposed across the Teesta River catchment by Indian government and public sectors. In the Teesta River, power is generated in six stages as shown in Table 2 (Environmental impact assessment of Ting Ting H.E. Project Sikkim, 2010).

5.1 Project Schemes

5.1.1 Teesta Hydro-electric Project Stage-I

The Teesta hydro-electric project Stage-I has been constructed with diverting structure and interlinked tunnels to generate the power. It is located at an elevation of 3300 m. The power generation capacity of structure is 280 MW.

5.1.2 Teesta Hydro-electric Project Stage-II

The project is a run-of-the-river scheme to generate the hydropower. The combined diverted water from LachenChhu at Chhatten and LachungChhu at Lachung through tunnel is used for power generation. The installed power generation capacity of this structure is 480 MW.

Table 2 Name of the hydro-power project with its capacity

S. No.	Name of project	Capacity (MW)
1	Teesta Hydro-electric Project Stage-I	280
2	Teesta Hydro-electric Project Stage-II	480
3	Teesta Hydro-electric Project Stage-III	1200
4	Teesta Hydro-electric Project Stage-IV	495
5	Teesta Hydro-electric Project Stage-V	510
6	Teesta Hydro-electric Project Stage-VI	440

5.1.3 Teesta Hydro-electric Project Stage-III

For power generation, Teesta river water is diverted through a 12.93-km-long tunnel by constructing a reservoir at Chungthang. The proposed power project is located at an elevation of about 780 m. The installing capacity of project is 1200 MW.

5.1.4 Teesta Hydro-electric Project Stage-IV

The power produces through tailrace water of Teesta Hydro-electric Project Stage-III by diverting structure near DikChhu. The installing power capacity is 495 MW. This water is diverted through 11.3-km-long tunnel.

5.1.5 Teesta Hydro-electric Project Stage-V

The Teesta hydroelectric project stage-V is a run-of-the-river scheme with a gravity dam at Dikchu near Balutar. This project started in 1999 and is due to be completed by 2006. The project constructed by National Hydroelectric Power Corporation (NHPC) is expected to generate 510 MW.

5.1.6 Teesta Hydro-electric Project Stage-VI

This project is proposed to use the water between Singtam and Rangpo by diverting river through 4.3-km-long tunnel. The expected installing power capacity is 440 MW.

5.2 Socio-economic and Environmental Effects

The developing countries face different types of positive and negative impacts on socioeconomic and environmental effects when it comes to large infrastructure development projects. For example, dam and/or hydro-power projects are large infrastructure projects which shows the economic development, environmental changes which affects the socio and economic values for downstream communities (Saxena and Singh 2016; Bird 2012). The hydro-power projects and other reservoirs have the potential to produce unfavorable and favorable impacts on environment and surrounding communities.

There are some favorable/unfavorable impacts as follows:

1. During the construction, soil erosion increases, and after completion it changes the landuse.
2. Water quality degrades with disposal of construction material.
3. Disturbance of hydrologic regime, sedimentation and siltation.
4. Increasing pressure on aquatic ecology as a result of indiscriminate fishing and migrant fish species.
5. Increase in employment and revenue from power generation.

To get the optimum benefits from the hydro-power projects, the relation between river network, surrounding communities, livelihoods, ecosystem and environmental aspects is important to take into account.

6 Natural Hazards

A natural disaster is a major adverse event cause from natural processes such as floods (urban flood, flash flood, river, coastal and many), earthquakes, volcanic action, and others. These natural disaster events cause loss of life or property damage. In the last two decades, frequently observed in the India (World Disasters Report—1999, International Federation of Red Cross and Red Crescent Societies). For example, a number of flood hazards in Sikkim Himalaya (Starkel et al. 1998), Ghaghra River (Singh and Awasthi 2011), and Brahmaputra River (Apurv et al. 2015) have been analyzed (Singh et al. 2015a, b).

Climate change and global warming are further expected to affect the hydro-climatological processes and patterns over the eastern Himalaya (Goyal and Sharma 2016; Singh and Goyal 2016) which produce number of natural hazards such as flood, GLOF, landslides and drought. Sikkim is the most vulnerable zone for natural hazards, as it is situated at the high elevation which is earthquake-prone and a landslide zone based on the UNDP map (map no. 3) of hazard. Recently on the May 17 and 18, 2016, due to a bridge collapse at Ritchu on the way of Mangan to Chungthang caused by heavy rainfall, four people died. On March 18, 2015, a big landslide occurred on the way to Yungthang Valley from Lachung, and that event has been observed by our research team during field visit (March 17–21, 2015) as shown in Fig. 4. In Sikkim Himalaya, a number of landslides occurred which affects the river morphology and hydrology.

In the Sikkim Himalaya, a number of glacial lakes and waterbodies are present, and some of them are vulnerable for outburst (Fujita et al. 2013; Kumar and Prabhu 2011). These lakes are continuously changing its size due to retreating of glaciers which can create disaster in terms of glacial lake outburst floods (GLOFs), i.e., Kedarnath flash flood due to Chorabari glacial lake outburst. Consequently, it can disturb the geomorphology and hydrology of river system. Such type of events generates huge amount of water with debris cover and has the erosive potential. Thus, it changes the river morphology and the surrounding system.

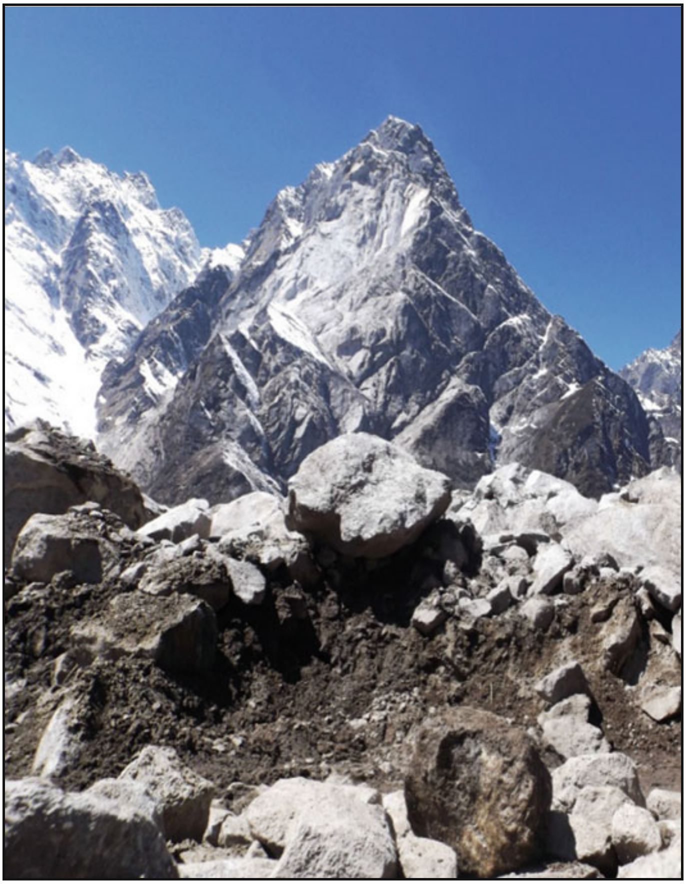

Fig. 4 Landslide image during our field visit from 17 to 21 March 2015

7 Case Study

Hydrology of the Teesta River basin is very complex because of its topographic variation and being spread by snow/glacier melt and rainfall. The hydrological modeling is an important feature to simulate the hydrological processes of any river system. The modeling mechanism controls the river flow characteristics and flow time (Prakash and Abhisek 2016). The hydrological modeling analysis of river basin can provide understanding over the hydrological components. These analyses may help in water resources planning and management, flood forecasting, suspended sediment transport, and flood control policies (Supiah and Hashim 2002).

The Teesta River catchment up to Chungthang has been taken for this case study using hydrological model (MIKE11 NAM). The purpose of this study is to estimate the hydrological characteristics of Teesta river catchment.

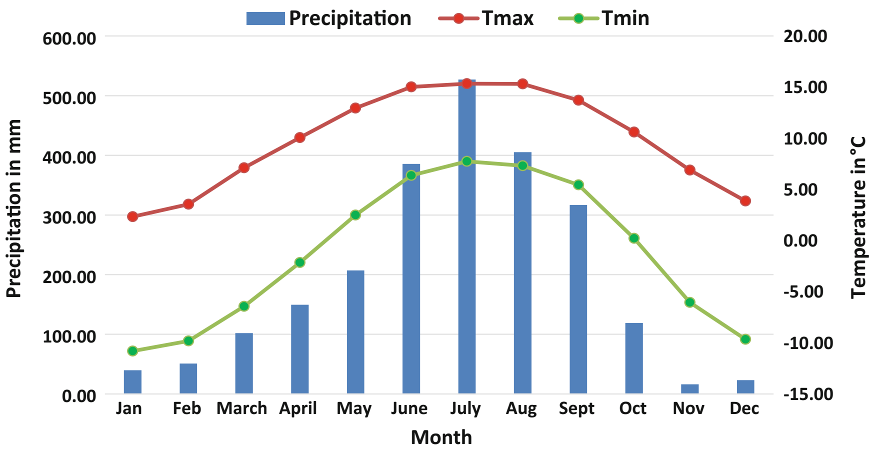

Fig. 5 Observed meteorological parameters over the Teesta River catchment

Precipitation and temperature data series are used as main data into the MIKE11 NAM model. The India Meteorological Department (IMD) is the main source of precipitation and temperature (maximum and minimum) data time series. The IMD is in the form of gridded datasets of 0.25 × 0.25. The daily observed meteorological (precipitation and temperature) parameters are shown in Fig. 5.

The Teesta River catchment up to Chungthang is selected for hydrological modeling. It covers the two glacial-fed streams, LachenChhu and LachungChhu, meeting at Chungthang, North Sikkim, as shown in Fig. 6. The selected study is divided into seven sub-basins (SB).

The soil and LULC map are used for hydrological modeling as input parameters. In the soil map, soil is divided into the three classes as shown in Fig. 7a, and soil map is obtained from the Food and Agricultural Organization (FAO) world soil map. LULC map classified and observed eight classes as shown in Fig. 7b, and LUCLC map is collected from the MODIS land cover facility portal (www.glcf.umd.edu/data/lc).

The streamflow calibrated and validated from 1991 to 2005 time series. The simulated streamflow calibrated with observed streamflow from 1991 to 2000 and validation from 2000 to 2005. Figure 8a presents the calibration results for daily time series of streamflow, and Fig. 8b shows the validation plot for daily streamflow time series at Chungthang. In the calibration, the coefficient of determination (R^2) is about 0.56 and for validation is about 0.44.

The hydrological modeling is required to prepare the water planning and management, flood forecasting and flood planning strategies. In the hydrological real-time simulation, the peak discharge and volume of discharge can be predicted, and inundated area can be assessed. Therefore, people can get aware before the water reach the area. Loss of life and property can be minimized using this process.

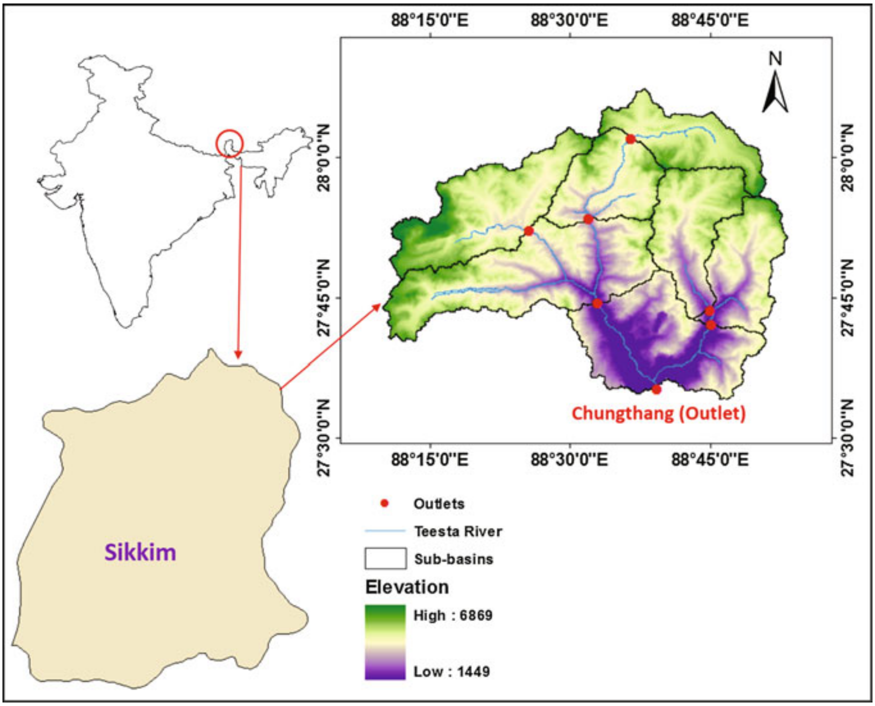

Fig. 6 Study area for hydrological modeling of Teesta River catchment

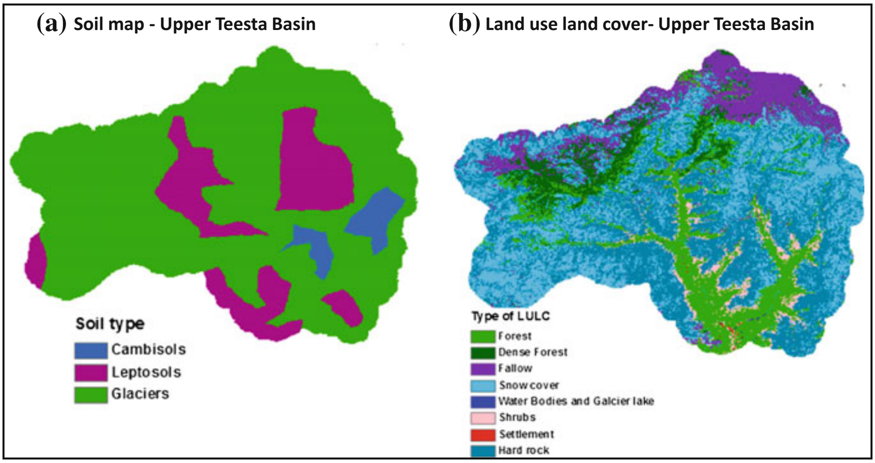

Fig. 7 **a** Soil map study area and **b** land use and land cove map of study area

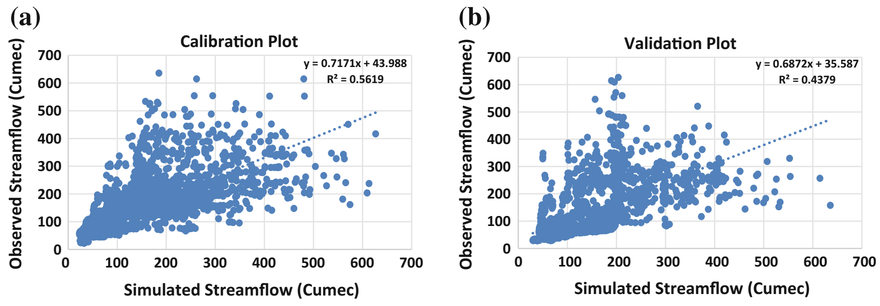

Fig. 8 Calibration and validation plots **a** streamflow calibration from 1991 to 2000 and **b** streamflow validation from 2001 to 2005

8 Summary

The Teesta River is the right-bank tributary of Brahmaputra River. The Teesta River having the hydroelectric power production potential because it originates with high altitude (5033 m) and drain with vary steep slope. Six hydroelectric projects are proposed in the Teesta River, and some are completed. The total installed capacity of these power projects is about 3405 MW. The Teesta stage III hydropower project is the largest power generation project in the Sikkim. This will generate about 1200 MW, that is much more than demand of Sikkim. Thus, water resources management and planning and understanding of hydrological process are required. The hydrological modeling is useful for water resources management and planning and hydrological processes.

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Correction to: Cauvery River

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Correction to:
Chapter "Cauvery River" in: D.S. Singh (ed.), *The Indian Rivers*, Springer Hydrogeology, https://doi.org/10.1007/978-981-10-2984-4_28

The original version of Chapter 28 was revised, a reference to an earlier paper was omitted. This has now been rectified and the reference has been added.

The updated version of this chapter can be found at
https://doi.org/10.1007/978-981-10-2984-4_28

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