S. P. Sinha Ray *Editor*

Ground Water Development - Issues and Sustainable Solutions

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ISBN 978-981-13-1770-5 ISBN 978-981-13-1771-2 (eBook)
https://doi.org/10.1007/978-981-13-1771-2

Library of Congress Control Number: 2018961560

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

The Members of Centre for Ground Water Studies, Kolkata

Foreword

India is facing a perfect storm in terms of managing water, both surface and underground. Decades of continued mismanagement by central, state and municipal authorities, private sector and general public as well as political apathy and interference, institutional incompetence, rapid industrialization and urbanization, a steadily increasing population aspiring and demanding a better quality of life, poor implementation of existing environmental laws, pervasive corruption, poor adoption of currently available cost-effective technologies and absence of good policies at all levels of government are only some factors which have contributed to the development of this perfect storm. All the indications are that unless the current water management practices all over the country are significantly improved, the situations will get progressively worse.

In spite of this sad current state of affairs, there are no real signs that politicians are waking up to address effectively the rapidly deteriorating water situations all over the country and are willing to take hard decisions to improve the existing conditions. Policies have been mostly ad hoc, incoherent, short term, often incorrect and at best incremental. Even these policies are rarely implemented properly. It really has not mattered which political parties have been in power at central and state levels; net results have been steadily deteriorating water conditions all over the country both in terms of quantity and quality.

At the central level, the last competent water minister who stayed in the position for a reasonable period of time was Dr. K. L. Rao. It was more than half a century ago. During the past 20 years, India has had ten water ministers. One even lasted all of one day! During the same period, the Ministry has had 14 secretaries. Not surprisingly, this revolving door has ensured that not one minister nor one secretary has had any lasting impact on water management of the country.

Surface water conditions in the country are bad, but groundwater situation is even worse.

Groundwater abstractions in the country are increasing steadily and significantly. It has become progressively more and more unsustainable over the past six decades. Consequently, in many parts of the country, groundwater levels have been declining by more than 1 metre per year. Lack of proper wastewater management from domestic, industrial, agricultural and mining sources has ensured progressive deterioration of groundwater quality by known and unknown contaminants. This is already endangering the health of both humans and ecosystems.

Monitoring of surface water quality is poor. However, monitoring of groundwater quality is truly dismal!

During the past three decades, there has been an explosive growth of private tubewells in agricultural farms because of the absence of reliable surface water supply for irrigation. This is compounded by Indian laws which guarantee exclusive rights to landowners over groundwater. These factors, plus free electricity to farmers for pumping, have ensured groundwater use in the country has been unsustainable for decades.

Consider monitoring of groundwater quantity and quality uses. Despite having four separate central bodies regulating groundwater, there is no single groundwater database for the country. In 2016, the Standing Committee of Water Resources of the Indian Parliament finally recommended the need for having a central groundwater database. However, when this will happen is anybody's guess.

Data on groundwater availability, use and quality are patchy and often unreliable. The best estimate now is India is using 230–250 km^3 of groundwater each year. More than 60% of irrigated agriculture and 85% of domestic water use now depend on groundwater. Because of prolonged and poor groundwater governance, India alone now accounts for one-quarter of the global groundwater use. The country currently uses more groundwater than China and the USA combined.

In 2009, NASA reported that the Indus Basin is the second most overstressed aquifer in the world. The Basin includes Punjab and Haryana, the two main granaries of the country. NASA also noted that groundwater depletion rate in North India is about 1 metre every 3 years. This is 20% higher than an earlier assessment of the Indian Water Ministry.

The extent and gravity of the Indian groundwater situation is not in doubt. With increasing population, urbanization and industrialization, the situation will get progressively worse. Nearly half of India's employments are now in the agricultural sector. This means groundwater management in India needs urgent attention from all the levels of government, private sector, academia, research institutions and general public.

I am thus heartened to see Dr. Syama Prasad Sinha Ray, one of the India's leading groundwater experts, writing an authoritative and objective book on the groundwater problems of the country and their sustainable solutions. There is absolutely no question that this book was long needed. I not only wish the book much success but earnestly hope that India's policymakers and academics will make a determined attempt to implement many of the solutions recommended in this book. The country has simply no other choice.

Distinguished Professor, Lee Kuan Yew School of Public Policy
National University of Singapore, Singapore, Singapore
Co-founder, International Water Resources Association,
World Water Council, and Third World Centre for Water Management
Mexico City, Mexico
Stockholm Water Prize Laureate

Asit K. Biswas

Preface

Major groundwater development problems in India and adjoining South Asian countries are over-exploitation, chemical contamination, seawater intrusion and uneven distribution in time and space. A precise understanding of the complex groundwater regimes in different hydrogeological settings and under different socio-economic conditions in this part of the world is a primary necessity for planning sustainable and equitable management of these precious resources. Deterioration of groundwater quality consequent to large-scale groundwater development to support agricultural and industrial activities has already emerged as a threat to sustainability of groundwater development schemes already in progress. The problem of drinking water supply, especially in rural areas which rely 90% on groundwater sources, has been aggravated, and in some places, availability of safe and adequate drinking water supply to the communities has become a matter of great concern. It was therefore felt necessary to review such groundwater development issues which are so similar in nature in India and other South Asian countries.

The majority of the scientific papers included in this book were submitted in the International Seminar on "Challenges to Ground Water Management: Vision 2050" organized by the Centre for Ground Water Studies at ITC Sonar Hotel, Kolkata, on 13–14 November, 2015. Prof. P. K. Sikdar, member, Centre for Ground Water Studies, made painstaking efforts to review the papers as per the format prescribed. Mrs. Pampa Bhattacharya, member, Centre for Ground Water Studies, assisted Prof. Sikdar in his effort. Their valuable contributions made at the initial stage are gratefully acknowledged. Subsequently, when it was contemplated by Springer IN to publish the book on our request, the selected papers were sent to the authors for revision and updating. The individual authors whose contribution in this field of hydrogeology is well known took considerable pains in revising the manuscripts. It is needless to emphasize, only due to their sincere and timely efforts that it has been possible to bring out the publication.

It is my proud privilege that Prof. Asit Kumar Biswas, distinguished visiting professor of Lee Kuan Yew School of Public Policy and co-founder of Third World Centre for Water Management, Mexico, who is well recognized universally because of his highly illustrious work in the field of Water Development and Management, has kindly written the "Foreword" of the book. I have no words to acknowledge such kindness.

I am deeply obliged by the active cooperation of my colleagues in CGWS, especially Shri. Abhijit Ray, president, and Dr. Sandhya Bhadhury, assistant secretary, whose encouragement at every stage made it possible to go ahead with the publication in spite of my ailing conditions. Shri. Saheb Das, technical assistant, CGWS, offered most useful secretarial assistances in making correspondences with the authors and Springer IN which is deeply acknowledged.

My special thanks are due to the editorial groups of Springer IN, specially Dr. Mamta Kapila, Mr. Daniel Ignatius Jagadisan and Ms. Raman Shukla who have continuously provided guidance in making out the publication.

Kolkata, India S. P. Sinha Ray

Thoughts from Abroad: Communication Received from Prof. Asit Kumar Biswas

Regrettably groundwater management has not received adequate attention in India for decades. How much groundwater the country has, how much of it is being withdrawn every day and how much is being replenished annually are not reliably known. In the absence of reliable estimates and public apathy and lack of sustained political and bureaucratic will to manage groundwater efficiency and equitably on long-term basis, serious mismanagement is continuing to take place.

The problem was compounded by poor advice the country received from the development banks in the 1970s and 1980s, which equally, unfortunately, the Indian Government accepted without any serious scrutiny. Thus, for the World Bank/IFAD Project on UP Groundwater Irrigation of the 1980s had to have dedicated electrical transmission lines so that the farmers would have 24-h free electricity for pumping. This was in spite of the fact that the inhabitants of major cities like Lucknow did not even have continuous electricity supply. This was a necessary condition for the World Bank/IFAD loan for the project.

Not surprisingly, food production did increase for several years, but no one, neither the World Bank nor the Indian Government, anticipated the long-term economic and social costs to the country of such ill-conceived policies. It created many vicious circles. As farmers pumped water indiscriminately, groundwater levels started to decline. Consequently, the farmers had to install higher horsepower pumps for pumping water from greater depths. Thus, groundwater levels have continued to decline precipitously in many parts of the country for decades. Free, or highly subsidized, electricity for pumping has ensured that nearly all Indian utilities are nearly bankrupt. It has thus been a lose-lose situation for the country as a whole, both in terms of water and electricity.

In drought years, pumping by the farmers intensifies further because of surface water shortages. A major problem is likely to be that continuation of such unsustainable practices may soon reach tipping points during future drought years. This could deplete groundwater to such levels in the coming years that pumping becomes impossible or seriously uneconomic. In addition, this would contribute to serious environmental problems, including land subsidence.

This is *only* one of the numerous groundwater management problems the country is facing at present.

I sincerely hope that the seminar will discuss these types of complex and real issues and come out with a roadmap for sustainable development and management of groundwater in India for the coming years.

Dated: June 16, 2017

India's Wells Are Running Dry, Fast

Ratanpura Lake, on the outskirts of Ahmedabad, Gujarat, has almost completely dried up. Amit Dave/Reuters

Over the past 3 years, the monsoon – the rainy season that runs from June through September, depending on the region – has been weak or delayed across much of India, causing widespread water shortages.

With the onset of summer this year, southern India, particularly Karnataka, Kerala and Tamil Nadu states, are already wilting under a blistering sun and repeated heatwaves. Drought is expected to affect at least 8 states in 2017, which is a devastating possibility in a country where agriculture accounted for 17.5% of GDP in 2015 and provides the livelihood for nearly half the population.

Across rural India, water bodies, including man-made lakes and reservoirs, are fast disappearing after decades of neglect and pollution.

"They have drained out the water and converted the land into a plot for schools, dispensaries, and other construction activities", Manoj Misra of NGO Yamuna Jiye Abhiyan warned in *The Hindu* newspaper as far back as 2012.

Residents wait for the government-run water tanker in Masurdi village, Maharashtra. Danish Siddiqui/Reuters

Not a Drop to Drink

It was not always this way. For the past 2500 years, India has managed its water needs by increasing supply.

Prior to industrialization and the accompanying global "Green Revolution" in the 1960s, which saw the development of high-yield variety crops using new technologies, India's water availability was plentiful. Households, industries and farmers freely extracted groundwater and dumped untreated waste into waterways without a second thought.

But such practices are now increasingly untenable in this rapidly growing country. Per capita availability of water has been steadily falling for over a decade, dropping from 1816 cubic metres per person in 2001 to 1545 cubic metres in 2011.

The decline is projected to deepen in the coming years as the population grows. India, which currently has 1.3 billion people, is set to overtake China by 2022 and reach 1.7 billion in 2050.

Water scarcity is also exacerbated by a growth in water-intensive industries, such as thermal power production, extraction and mining, as India seeks to feed and power its growing population. In addition to affecting biodiversity, these activities also alter natural water systems.

Still, successive governments have pursued the same old supply-centric policies, paying little heed to the country's waning clean water supplies.

For nearly 50 years, a misguided groundwater policy has sucked India dry; water tables have declined by an average of 1 metre every 3 years in some parts of the Indus basin, turning it into the second most overstressed aquifer in the world, according to NASA.

Across nearly the whole country, basic sewage management is also lacking. According to the Third World Centre for Water Management, only about 10% of wastewater in the country is collected and properly treated. As a result, all water bodies in and around urban centres are seriously polluted.

Today, the country is struggling to provide safe drinking water to every citizen.

Sugarcane production is highly water-consuming and should be managed more efficiently. Kolkata, 2015. Rupak De Chowdhuri/Reuters

What Conservation?

Even so, residents of New Delhi or Kolkata today use more than twice as much water, on average, than people in Singapore, Leipzig, Barcelona or Zaragoza, according to data compiled by the Third World Research Centre.

The water use in Delhi is 220 litres per capita per day (lpcd), while some European cities boast figures of 95 to 120 lpcd.

Excess consumption is attributable in part to citizen indifference about conserving water after so many years of plentiful supply. Since large swaths of many Indian megacities lack piped supply of clean water, leaks and theft are common. Cities in India lose 40% to 50% due to leakages and non-authorized connections.

At this point, the only viable option for India would seem to be managing demand and using water more efficiently.

The country is making tentative steps in that direction. The 2016 new National Water Framework, passed, emphasizes the need for conservation and more efficient water use.

But under India's Constitution, states are responsible for managing water, so central policies have little resonance. Neither the 1987 nor 2012 National Water Policy documents, which contained similar recommendations to the 2016 policy, had any real impact on water use.

And after millennia of exclusive focus on expanding the water supply, the idea of curbing water consumption and increase reuse remains a mostly alien concept in India.

Water Wars

Consistent supply-centric thinking has also resulted in competition for water as states negotiate the allocation of river water based on local needs.

The century-long conflict over the Cauvery River, for example, involves Andhra Pradesh, Tamil Nadu and Karnataka – three major south Indian states. With each state demanding ever more water, the river simply cannot keep up.

In Karnataka, where agricultural policies are heavily skewed towards water-guzzling commercial crops, such as sugarcane, mismanaged ground and surface water are dying a slow death. Still the state continues to petition the Cauvery Water Dispute Tribunal for an increase in its share.

Water scarcity in Karnataka is aggravated by non-existent water quality management. Its rivers are choked with toxic pollutants, and oil-suffused lakes in Bengaluru, the capital, are reportedly catching fire.

Meanwhile, in the northern part of the country, the Ravi-Beas River is causing conflict between Punjab and Haryana states.

In India's water wars, rivers are a resource to be harnessed and extracted for each riparian party's maximum benefit. Very little emphasis has been placed on conserving and protecting existing water sources. And not one interstate negotiation has prioritized pollution abatement or demand management.

Even policies from the national government, which claims to target water conservation and demand management, remain reliant on supply-side solutions. Big infrastructure programmes, such as the Indian river-linking plan, envision large-scale water transfer from one river basin to another, again seeking to augment supply rather than conserve water and reduce consumption.

Sand mining on the Cauvery river in 2017. Prashanth NS/Flickr, CC BY-SA

For inspiration on managing demand, India could look to Berlin in Germany, Singapore and California, all of which have designed and implemented such policies in recent years. Successful measures include raising public awareness, recycling water, fixing leaks, preventing theft and implementing conservation measures such as water harvesting and storm water management.

Between rapidly disappearing freshwater, unchecked pollution and so many thirsty citizens, India is facing an impending water crisis unlike anything prior generations have seen. If the nation does not begin aggressively conserving water, the faucets will run soon dry. There is simply no more supply to misuse.

Asit K. Biswas, distinguished visiting professor, Lee Kuan Yew School of Public Policy, National University of Singapore; Cecilia Tortajada, senior research fellow, Lee Kuan Yew School of Public Policy, National University of Singapore; and Udisha Saklani, independent policy researcher

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National University of Singapore
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Mexico City, Mexico
October 6, 2015

Asit K. Biswas

Communication Received from John M. Mc Arthur

A good understanding of groundwater resources – their amount and quality – is essential for the planning and development of any nation that wishes to avoid the mistakes of the past. Those mistakes have left a global legacy of both polluted water on the surface and underground and over-abstraction that impedes sustainable development and reduces the quality of life for many peoples.

Through 30 years of working in India and with Indian colleagues, I know that Indian scientists and engineers currently have much of the knowledge necessary to formulate an excellent management plan for groundwater in India and could rapidly complete their understanding were they given the right conditions in which to do so. Principal amongst those conditions is an increased willingness to share data and understanding between the numerous institutions that are involved in groundwater management and to do so especially at the level of junior staff. In a federated country, that means that states and the centre should work together better. Let me list the organizations involved at present:

1. Central Ground Water Board, Ministry of Water Resources, River Development and Ganga Rejuvenation
2. Ministry of Drinking Water and Sanitation
3. State Ground Water Boards (in West Bengal the State Water Investigation Department)
4. Public Health Engineering Departments
5. The Departments of Science and Technology
6. IITs, IISWBM and universities and research organizations such as NGRI, CWRDM, BARC
7. Municipal corporations in urban areas and Panchayats in rural areas

An enduring management plan for groundwater in India, and I emphasize the word *enduring*, can only be achieved if all relevant organizations buy in to the plan, and that means working together and sharing data and information. Junior staff, in particular, should be freed to exchange and discuss information with less restraint than now from bureaucratic impediment. I hope the seminar succeeds in bringing together relevant people to help achieve those aims.

Earth Sciences
University College London
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John M. McArthur j.mcarthur@ucl.ac.uk
20th October, 2015

Communication Received from Prof. K. M. Ahmed

Challenges of Groundwater Management in Bangladesh in 2050: Mission Impossible Vis-a-Vis Visions for Sustainable Development

Groundwater in the Context of Bangladesh

Groundwater has been the backbone of Bangladesh's remarkable achievements in the fields of access to safe water and food security. Despite being a delta country crisscrossed by numerous rivers including the Ganges-Brahmaputra-Meghna, dependence of groundwater is increasing every day to meet the demands of various sectors.

Current Challenges of Groundwater Management: Mission Impossible?

The ever-increasing demands along with natural stressors result into major challenges for management of the vital natural resource in the country. Increasing population is the major challenge where groundwater is the main source of safe water for drinking and domestic purposes in rural and urban areas. Meeting the demand for increasing food production is another major challenge for the world's most densely populated country. Significant increase in dry season rice production through groundwater irrigation has made the country self-sufficient in rice, and production of all major crops has also increased. Demand for water is also increasing due to faster rate of urbanization and industrializations; groundwater is the major source of supply of municipal and industrial waters. The scenario of too much and too little surface water compels to use more and more groundwater all over the country, and large groundwater is fresh and free from pathogenic contaminants over most of the country, and switching to this source for drinking saved millions of lives over the year. Occurrences of natural arsenic and salinity are the two most severe water quality issues of the current time. Millions of people are still drinking arsenic above national and international standards, whereas people living in the coastal areas are exposed to high salinity. Also, pollution of groundwater due to municipal, agricultural and industrial sources is becoming widespread. People living in the slums in the big cities and adjacent to industrial towns suffer from safe water scarcity.

Groundwater abstraction is increasing every day without a proper management and monitoring plan. Conventional water pumps are becoming inoperative in many areas due to declining water levels and need to be replaced by alternative expensive pumping technologies. Groundwater governance is almost nonexistence in the country due to mainly lack of proper institutional arrangements. There are rules, regulations and policies to ensure proper management, but enforcement is lacking.

Bangladesh in 2050: Water Challenges for the Emerging Tiger

Bangladesh economy is growing fast and will become the 23rd largest economy in 2050. Water for agricultural and industrial sectors will be much needed to sustain this growth. Bangladesh population will reach 202 million in 2050, and about half of the people would live in urban areas. Dhaka is the fastest growing megacity and will be joined by other megacities in 2050, resulting in a very high demand of municipal water supply. Intensification of agriculture would continue, and production has to be increased by 97.4% to ensure food security. Groundwater irrigation would play the major role here, but at the same time, agricultural pollution will become a major issue. Industrial development would surpass many western economies which would lead to more abstraction and more contamination. Emerging contaminants like pharmaceutical by-products and personal care products can be a major source of groundwater pollution. Intra-sectoral conflict would increase particularly between domestic water supply and irrigation sectors. Transboundary groundwater issues will emerge, and sharing both surface and groundwater resources with neighbouring countries will pose a major challenge. Climate change may have significant impacts on the hydrologic cycle, and hydro-disasters may become more frequent, resulting in quality- and quantity-related issues for the groundwater resources.

Visions for Sustainable Groundwater Management

Better governance has to be the main agenda for meeting the challenges of groundwater management in 2050. A national institute empowered with necessary technical, financial and legal resources is crucial for ensuring sustainable use of the vital natural resource. Full commitment towards adaptation to integrated water resource management has to be ensured at all levels. Decentralized water management at planning area or basin scales has to be introduced. Managed aquifer recharge has to be adopted at all levels to augment the declining water levels. Water-sensitive urban designs have to be adopted and implemented for major urban areas and urban conglomerates for reducing impacts of urbanization on groundwater. Recycle and reuse of wastewater has to be promoted by combining technical options and awareness of stakeholders. Regional cooperation on water has to be increased for basin-wide management by conjunctive management. Bangladesh will have to adapt various water purifying technologies including reverse osmosis for salinity removal. Paradigm shift in people's perception about groundwater, which is now undervalued by users, is necessary for proper evaluation of the resource. Groundwater management has to be placed high in the political agenda in order to make it everybody's business. Courses on groundwater sciences have to be introduced at tertiary levels to produce more water experts. The research institutes have to be equipped with state-of-the-art laboratory facilities. Predictive groundwater modelling can aid better in decision-making. National monitoring system has to be updated along with open access to data for all users and interested parties. Groundwater has to be protected from overexploitation and degradation by introducing abstraction controls and licensing.

Groundwater: Vital Resource for a Better Bangladesh in 2050

Like today, groundwater shall remain one of the main sources of water for various uses in 2050 as well. However, ensuring sustainability of groundwater development shall become a mammoth challenge. Various natural and anthropogenic stressors will make the sustainable management extremely difficult.

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About the Editor

S. P. Sinha Ray has been a member of Central Ground Water Board and Central Ground Water Authority, Ministry of Water Resources, Government of India. He has more than 40 years of experience in groundwater exploration, development and management. By virtue of his long association with the country's apex organization dealing with groundwater resources, he has acquired substantial expertise in the field. Besides having a vast knowledge of the subject within the country, he has also gained insights and know-how in other countries like Algeria, Bangladesh, the USA, Korea, Zimbabwe and Japan. He is a Fellow of West Bengal Academy of Science, a Member, International Association of Hydrogeologists and Emeritus President, Centre for Ground Water Studies, Kolkata.

Part I
Major Ground Water Development Issues in South Asia

Major Ground Water Development Issues in South Asia: An Overview

S. P. Sinha Ray and Abhijit Ray

Abstract The complex nature of ground water problems in South Asia, i.e., India, Pakistan, Nepal, Bangladesh, Sri Lanka, and Myanmar, requires an in-depth analysis of the ground water regimes in different hydrogeological framework including ground water quality. Major ground water problems which require effective management include overexploitation, chemical contamination, seawater intrusion, and uneven distribution in time and space. Suitable policy framework for ground water utilization by individual countries and implementation of measures underlined in the policy need to be taken up.

Keywords Ground water · Overexploitation · Chemical contamination · Policy framework · South Asia

1 Introduction

Ground water resources play a major role in ensuring livelihood security across the world. The ground water crisis is acquiring alarming proportion in many parts of South Asia. Ground water contribution to poverty alleviation is very high in South Asia. The complex nature of ground water problems in South Asia implies that a precise understanding of the ground water regimes in different hydrogeological settings and socioeconomic conditions is a primary necessity for sustainable and equitable management. Major countries in South Asia, considered for this paper, are India, Pakistan, Nepal, Sri Lanka, Bangladesh, and Myanmar. The present deterioration of ground water sources on which people rely for their livelihoods, drinking and sanitation, and daily domestic needs means that water and sanitation pressures will simply grow from bad to worse. South Asian countries are characterized by wide variation of ground water levels in shallow aquifers, associated with monsoon rainfall. Rapid urbanization has resulted in important changes to ground water both by modifying preexisting recharge and discharge patterns.

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S. P. S. Ray (ed.), *Ground Water Development - Issues and Sustainable Solutions*, https://doi.org/10.1007/978-981-13-1771-2_1

Ground water is vulnerable due to its relatively limited circulation, ability to transport pollutants originating from geogenic and anthropogenic stresses. Strategies to respond to ground water overexploitation and deteriorating water quality must be based on a new approach, considering ground water as a common property and redefining the institutional structure governing ground water. Development of practical policy and management options needs to be formulated and implemented at the earliest.

2 Ground Water Resources in South Asian Countries

Country-wise description is given below.

2.1 India

Ground water in India occurs in diversified geological formations with significant variation in lithological composition, in complex tectonic framework, and within different climatological conditions. Although country-wise aquifer mapping has been taken up by the Central Ground Water Board recently, from the existing knowledge, aquifers are available from the two principal geological formations, i.e., fissured formations and porous formations. The fissured formations are available in almost two-thirds of the country and include igneous and metamorphic rocks, volcanic rocks, consolidated sedimentary rocks, and carbonate rocks where ground water is available in near-surface weathered zone and deeper fracture zones in which secondary porosities have been developed due to weathering action and fracturing by tectonic activities. Volcanic rocks represented by Deccan Traps, Rajmahal Traps, etc. having low permeability have limited ground water potentialities. Carbonate rocks characterized by karstification in Vindhyans are promising aquifers due to the presence of saturated solution cavities and channels. However, vesicular lava has primary porosity. Igneous and metamorphic rocks like granite gneiss, charnockites, khondalites, schists, etc. have limited ground water potentialities.

The unconsolidated sediments deposited by riverine alluvium in major and minor river systems together with coastal and deltaic sediments constitute the major potential aquifers in the country. The hydrogeological setup of Ganga-Brahmaputra river valleys contains by far the most prolific aquifer system in the country.

The semi-consolidated Gondwana System of rocks also contains ground water in fissures, joints, and bedding planes under favorable hydrogeological environment. Older alluvium sediments of Plio-Pleistocene age also have moderately potential aquifers in porous zones.

The annual ground water recharge from rainfall in India is 342.43 km^3 and that of canal recharge is about 89.46 km^3. Thus the total replenishable ground water resources of the country is 431.89 km^3. CGWB has estimated state-wise fresh ground water resources also (Gandhi and Bhamoriya 2011). When considered basin-wise, Ganga basin is by far, the most ground water worthy (170.99 km^3/year). Although ground water utilization in domestic and industrial sector is within 15% of the total ground water resource, major share of the resource is allotted for irrigation sector.

The chemical quality of ground water in the country shows wide variation. While arsenic contamination in ground water is the most devastating menace in Ganga-Brahmaputra Plains having major impacts in the states of West Bengal, Bihar, Jharkhand, Assam, and Uttar Pradesh, high fluoride in ground water has been detected in 22 states of the country. Again, high concentration of uranium occurs in Andhra Pradesh, Jharkhand, Odisha, Rajasthan, Telangana, and Punjab. Besides these, industrial discharges, urban activities, disposal of sewage waters, and application of fertilizers and pesticides cause various pollution like excess nitrate in ground water. In some localized pockets, ground water is polluted by chromium, manganese, and selenium. Both inland and coastal salinity in ground water within 100 m depth are also very common.

The Central Ground Water Authority has been formed in 1996 to address various issues related to ground water protection. Overexploitation of ground water due to excessive ground water withdrawal has been identified through ground water monitoring system designed to address ground water level variation and the chemical quality change in ground water regime.

Ground water legislation based on the reformed Model Bill advocated by the Central Ground Water Authority has been adopted in some of the states of the country. To determine precisely the quantity and quality of India's ground water, Central Ground Water Board has launched the Aquifer Mapping Programme. Managed Aquifer Recharge Programme is also being taken up in the areas of high ground water stress.

2.2 Bangladesh

Unconsolidated sedimentary aquifers, belonging to Pleistocene and Holocene age, formed by alluvial sediments of Ganga-Brahmaputra-Meghna (GBM) delta system occur in major parts of the country. The country can be broadly divided into six major hydrogeological units (Ahmed et al. 1994) such as Zone I (Holocene piedmont plains), Zone II (Holocene Deltaic and Floodplains), Zone III (Pleistocene Terraces), Zone IV (Holocene depressions), Zone V (Tertiary Hills), and Zone VI (Holocene Coastal plains). Hydrogeological conditions vary significantly from unit to unit.

Ground water levels of the shallow aquifers fluctuate with annual recharge from monsoon rains. However, information regarding behavior of the water level in deeper aquifers are vary little and scanty. Jones (1987) considered that fresh ground water may be available from older Tertiary rocks from the depth of 1800 m. The regional flow of ground water is, by and large, from north to south.

The ground water recharge, under the studies of National Water Plan Phase-2, 1991, can be described as 9786 million m^3, 6594 million m^3, 1498 million m^3, 1249 million m^3, and 1961 million m^3 for NW, NE, SE, SC, and SW regions, respectively. The total ground water resource available in the country has been estimated as 21,088 million m^3, of which only 946 million m^3 is balance left for further development. The deep aquifer from Barisal and Patuakhali districts occurs within the depth range of 238–328 m, separated from the upper aquifer system by a 65–165 m thick clay layer.

Although 90% of rural drinking water is supplied from ground water, the principal use of ground water in Bangladesh like India is for irrigation.

Arsenic contamination of ground water in shallow aquifers was detected in the southwest part in 1993, but subsequently it has been found in central and northeastern regions also. Forty-four out of sixty-four districts in Bangladesh are affected by high arsenic in ground water.

The problems associated with the development of ground water in Bangladesh include unplanned process of expanding irrigation coverage, overexploitation of ground water, excessive use of ground water for summer paddy (Boro) cultivation, creation of ground water for markets, etc. However, ground water pollution due to excess arsenic content in ground water has posed considerable concern.

2.3 Pakistan

The Indus Basin, formed by alluvial deposits, is having unconfined aquifer system at shallow depth. About 79% of the Punjab province is having fresh ground water with less than 1000 mg/l TDS, whereas in Sindh province fresh ground water is available within 28% of area from 20 to 25 m depth. Indiscriminate use of ground water has caused enhanced level of salinity. In Tharparkar and Umarkot, the situation is further complicated by the occurrence of high fluoride in ground water. In North-West Frontier Province, abstraction in excess of recharge especially in Karak, Bannu, Kohat, and D.I. Khan has lowered water table and caused contamination from underlying saline water. In Balochistan, the Makran coastal zone and Kharan contain highly brackish (as high as 3000 mg/l) ground water which is being used for drinking water sources. In Mastung Valley as also in Makran coast and Kharan, ground water also contains high fluoride.

A ground water recharge of 56 billion cubic meters for the country has been estimated. The potential storage is the aquifer system of the Indus Plain and mountainous valley of NWFP and Balochistan. It has been established that ground water withdrawal exceeds annual average recharge in areas outside the Indus Basin. In Balochistan water table is receding 0.6–0.9 m annually on average. In one estimate, it has been observed that out of the total 68 billion cubic meters ground water, 60 billion cubic meters is already being extracted, leaving a balance of 8 billion cubic meters for exploitation.

Salinity of ground water shows wide variation from 1000 to 3000 mg/l and above. In many areas mining of ground water has set in causing intrusion of saline water and seepage of polluted water from agricultural field. The net addition of salts to the Indus Basin irrigation system is around 33 million tons, contributed by the canal water annually. Ground water in Pakistan which occurs under varying conditions is affected largely by changes in the prevailing climatic conditions. Above 50 ppb As has been detected in cities like Multan, Sheikhupura, Lahore, Kasur, Gujranwala, and Bhawalpur. It was found that in some districts of Sindh (Ahmed et al. 2004), As level exceeds 200 ppb in shallow depths. Under the arid condition, high fluoride and high salinity are quite widespread water-related problems.

In order to streamline the ground water exploitation, extraction, and management practices, each province in Pakistan has formulated its own laws to manage ground water resources. The key issues of ground water development are resource degradation, resource depletion, and equity deficiency and industrial policies (Qureshi 2004 and Qureshi et al. 2009).

2.4 Sri Lanka

The geology of Colombo represents the geology of Western Coast having sediments of Quaternary age comprising of high-level gravel formation embedded in a matrix of laterite and pebble-free layers of laterite. The floodplain deposit of Kelani River consists mainly of alluvium deposits. The geology of Kandy and surrounding areas is characterized by a thick band of marble and coarse crystalline rock with intruded calcsilicate gneiss. Other crystalline rocks prevalent in the area are hornblende-biotite gneiss, garnet-biotite gneiss, granulite gneiss, etc.

Six types of aquifers have been identified (Srimanne 1952, 1968; Arumugam 1966, 1974): These are the following: Shallow Karstic Aquifer of Jaffna Peninsula, Deep Confined Aquifers, Coastal Sand Aquifers, Alluvial Aquifers, Shallow Regolith Aquifer of the Hard Rock Region, and Southwestern Laterite (Cabook) Aquifer. Hydrogeological setting of all these aquifers has been adequately studied. In the Jaffna Peninsula, 100–150 m thick Miocene limestone, Karstic in nature, occurs in a form of solution channels and cavities. Annual rainwater recharge has been estimated between 10 and 20×10^7 cum., 50% of which drains out to sea (Balendran 1968). About 80% of this ground water is being used for agriculture and 20% for domestic purposes. Enhanced level of nitrate around the municipal area of the Peninsula has been reported. A number of deep confined aquifers occur within the sedimentary limestone and sandstone formations of the northwestern and northern coastal plains. The average depth of the wells reaching the artesian aquifers in the well-defined basins is from 30 to 50 m having yield potentialities 3–10 l/s (Wijesinghe 1973). High ground water use for agriculture in Vanathavilluwa basin has caused leaching of salts which increased the conductivity of the water.

The coastal sand aquifers are represented by shallow aquifers on coastal spits and bars in the Kalpitiya Peninsula and Mannar Island in the Northwest region and shallow aquifers on raised beaches in Nilaveli-Kuchchaweli, Pulmoddai, and Kalkuda in the northeastern region. Ground water is very limited but has precious resources in this aquifer. The Alluvial Aquifers occur in coastal and inland floodplains, dissected and depositional river deposits, and inland valleys of different shapes, forms, and sizes. Old buried riverbeds with high ground water yields are present in the lower Kelani River Basin.

The alluvial thickness varies between 10 and 15 m, and moderate quantity of ground water is extracted throughout the year. Because of low storage capacity, weathered zone or regolith of the Hard Rock Region contains limited ground water. The regolith layer is only 2–10 m in thickness. However, ground water also occurs at depth in the Hard Rock Region in the fracture zones restricted to 30–40 m depth which has been tapped by bore wells to support domestic water needs of the Dry Zone. Southwestern laterite, generally called "Cabook," has good water-holding capacity within the vesicular laterites which are developed by dug wells as well as shallow tube wells. In the outer Colombo and surrounding area due to rapid urbanization and setting up of industrial estates, these vesicular laterites face overexploitation situation and enhanced nitrate levels in ground water.

Shallow Karstic Aquifer in Jaffna Peninsula is the most intensively utilized. The aquifer gets recharged by November–December rains of the northeast monsoon. Monitoring of ground water has confirmed a significant imbalance between ground water recharge and discharge situation. In the Deep Confined Aquifer safe abstraction rates have been estimated as 3 MCM/year for the Vanathavillu aquifer basin to 8 MCM/year for the Paranthan aquifer basin. Yield of the artesian wells within 50 m depth ranges from 0.5 to 25 l/s. The study conducted in Shallow Coastal Sand Aquifer indicated that Nilaveli-type Aquifer has more recharge than Kalpitiya Aquifer. The Alluvial Aquifer of the larger river systems in the southwestern part of the country does not show reduction in quantity even in drought months. Shallow Regolith Aquifer, restricted mainly in the North Central and northwestern provinces, has an estimated recharge of 100 mm during the Maha season. During severe drought conditions, this aquifer having limited ground water resources causes depletion. Southwestern Laterite (Cabook) Aquifer gets recharge during first rains after the dry period in February to March and gets recharge several times during the year.

It has been established that tank irrigation is having an important impact to sustainable ground water use in Sri Lanka. Water Resources Board set up in 1966 with a vision to adequate access to clean and safe water for all is subsequently from 1999 looking after the management of ground water resources with adequate emphasis.

2.5 Nepal

The high mountains of the Himalayas and central hill regions are dominated by ancient crystalline rocks comprising mainly granites, metamorphic rocks, and old indurated sediments. The southern lower-lying parts of Nepal and isolated intermountain basins (e.g., Kathmandu Valley, Mugu Karnali Valley) are occupied by Mesozoic to Quaternary sediments. Recent Alluvial Sediments constitute the low-lying Terai plains along the Indian border.

Ground water availability is very limited in hilly regions. However, in Kathmandu Valley, ground water occurs in thick alluvium sequence. Both shallow (within 10 m depth) and deep (310–370 m) aquifers occur in the valley in which the shallow one is under unconfined and deep one is under confined state. A large quantity of ground water is being withdrawn in Kathmandu Valley through shallow and deep tube wells (Pandey and Kazma 2011). However, development of deep aquifer has caused a recession of piezometric surface to the tune of 15–20 m (Khadka 1993). Kastric limestone aquifer occurs beneath the alluvial sequence of Kathmandu Valley, which, however, has not been exploited. Throughout the Terai region, shallow and deep aquifer of varying thicknesses occupy except in Kapilavastu and Nawalparasi (Upadhyay 1993). However, the deeper aquifer shows artesian condition.

Although ground water quality data is not available adequately, it has been seen that shallow ground waters are at risk from contamination of pathogenic bacteria, pesticides, nitrates, and industrial effluents. In some parts of the Terai region, anaerobic conditions are observed with high concentrations of arsenic and iron. The deep aquifer in Kathmandu Valley and Terai region shows higher values of iron, manganese, etc. However no high arsenic deep ground water has been reported so far. Springs from the Karstic limestone aquifer is reportedly calcium-bicarbonate type with good chemical quality. In deep aquifer high concentration of ammonium (<3–35 mg/l N), possibly of natural origin, has been observed. From the available data, it has been found that higher concentrations of arsenic occur within shallow aquifers (restricted to 50 m) in the Terai region. Areas of crystalline basement with sulfide mineral veins may also contain contaminated ground water with trace elements like zinc, copper, cobalt, lead, and cadmium.

2.6 Myanmar

Myanmar can be divided into four geological regions: Central Lowland, a vast alluvial plain with intermittent outcrops of hills and mountains containing Dry Zone, Sham Highland in the East, Western Fold Belt, and Rakhine Coastal Belt. The Irrawaddy group comprising mostly loosely cemented sand and sandstone beds occupies about 38% of the Dry Zone. In the Central Basin, Irrawaddy sands comprise a large proportion of quartz pebbles, gravels, conglomerate, and red earth beds. Irrawaddy group aquifers consisting mainly of sands occur within maximum depth of 350 m in which ground water occurs in semi-confined to confined state. Shallow tube wells occurring within 40–70 m depth in Magwe and Monywa districts can yield 270–4700 m^3/day. Ground water is available throughout the Dry Zone. While alluvial and Irrawaddy groups are usually freshwater bearing, Pegu (marine sandstone) units are mostly brackish or saline (Tun 2003).

Available ground water varies considerably both in quantity and quality in four major aquifer groups in the Dry Zone due to their depositional environments, lithology, and mineralogy. Quality deterioration is associated with the occurrence of various trace elements like iron, manganese, and arsenic. In Irrawaddy delta region within an area of 3000 km^2, higher level of arsenic has been detected, and the World Bank (2005) has estimated that about 3.4 million people are at risk of arsenic hazards.

District level figures estimated on the ground water recharge are around 4777 MCM/year. Ground water is mainly used for domestic purposes, while in agriculture sector also, its contribution is significant in the Dry Zone area. However, in some areas ground water shows underdevelopment.

The major ground water development issues include unrestricted ground water withdrawal which may cause overexploitation syndrome, water quality deterioration, decline of ground water level due to excessive withdrawal from confined artesian aquifers, etc. A well-knit ground water data monitoring system and precise ground water assessment are to be made.

3 Key Issues of Ground Water Problems in South Asia

- Overexploitation of ground water
- Contamination of ground water contained in shallow aquifers due to geogenic stresses
- Seawater intrusions in coastal area
- Anthropogenic activities polluting the ground water
- Participation of stakeholders in water management
- Proper policy framework regulating the water utilization
- Implementation of measures underlined in the policy
- Coordination among the agencies entrusted with supplying water and maintaining hygiene considering health impacts

4 Conclusions

A review of hydrogeological situation in the megacities of South Asia reveals several alarming trends of overexploitation of ground water causing long-term decline of ground water level, ingress of saline water, and deterioration of ground water quality. This calls for a new approach to ground water governance and sound management plan. There is a dire need to evolve workable methods and approaches to synchronize the demand and supply gap. In order to improve the water supply in urban areas, the installation of water meters needs to be encouraged. Building a near social framework including community participation at all levels of water system is necessary. The community participation in water pumping policies, incentives of efficient use, affordability by low-income users and other vulnerable grumps, and water awareness, especially among women and children, are prime factors for success of any domestic water project. The shift policy for the permission of safe, adequate, equitable, suitable, and affordable water is critical for the health and the project of the region.

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Part II
Groundwater Development Problems in Arid and Semi-Arid & Hilly Areas

Water Management in Arid and Semiarid Areas of India

Subhajyoti Das

Abstract The arid and semiarid areas of the country, a major part of which suffers from recurrent drought, are under increasing economic and environmental strain mainly because of water scarcity. Due to paucity of surface water, groundwater has emerged as the sole sustainable source for water supply and irrigation in this terrain. But its widely variable occurrence and potential in time and space necessitate its delineation, development, conservation, and protection from overexploitation and pollution. Studies and experiences have shown that integrated water resource management involving conjunctive use and rainwater harvesting as part of watershed development can ensure water security and equity. Science and technology has a big role in water resource management which holds key to the economic growth of the region. This article narrates and analyzes some recent efforts in augmenting and conserving scarce water resources with community participation to achieve this objective in this terrain.

Keywords Aquifer · Arid and semiarid area · Groundwater · Hydrogeology · Water management · Watershed

1 Introduction

Since the dawn of civilization, man has acknowledged the value of water in life. Being an agrarian community, humans did not fail to understand the virtues of water as essential for cultivation, healthy crop growth, and food and nonfood grain production, apart from metabolic function and sanitation for hygiene. Thus, ancient civilizations sprang up on the river sides. All activities of the agrarian society were oriented toward rainfall occurrence and its seasonal distribution. But unwanted rainfall vagaries like droughts and floods played havoc to their life. Since the industrial revolution in the sixteenth and seventeenth centuries, the role of water has evolved manifold as invaluable inputs in advanced lifestyle, industrial processes, and related technology-driven fields.

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S. P. S. Ray (ed.), *Ground Water Development - Issues and Sustainable Solutions*, https://doi.org/10.1007/978-981-13-1771-2_2

Worldwide 97% of total water resources is saline in sea, leaving only 3% as freshwater, out of which 0.4% is groundwater, while 0.009% is surface water in lakes and rivers; the balance remaining is locked in glaciers. Our country shares 17% of world population but 4% of its geographical area and 2.5% of water resources (Black and King 2009). This clearly points to a severe anomaly in the distribution and availability of water in the country vis-à-vis global water resources, though despite this anomaly, India is the largest consumer of groundwater in the world. Because of multitude of advantages of groundwater over surface water, it is much in use and even overexploited.

India has nearly 33% of its geographical area in the semiarid and arid category. Further out of its total arable area, nearly 60% is rainfed without benefits of surface water irrigation. But it contributes only about 40% of the total food grain production in the country. Paradoxically the irrigation facilities developed, i.e., dams and barrages such as DVC, Hirakud, Bhakra, etc., cater to the valley areas, leaving vast catchment areas parched and unirrigated generally raising only one crop in a year. Also these areas reeling under recurrent droughts chronically suffer from acute drinking water scarcity and miserable state of hygiene due to poor sanitation. With surface water in short supply, these areas are mainly dependent on groundwater which is, therefore, under severe strain. This has resulted in low agricultural output, stunted rural growth, and overall economy. Thus, the management of scarce water resources is of vital importance in the arid and semiarid areas. The latter has been the focus of intensive study since the last three decades as crucial for country's economic development. However, water resources are dependent on a variety of interrelated factors like rainfall, climate, topography, soil, and geology which in turn determine the land and water endowments of an area.

2 Arid and Semiarid Areas: Rainfall and Drought

Rainfall is the source of all waters on earth. As India receives most of its precipitation from southwesterly monsoon lasting from June to September, and occurring within a span of 90–100 days in a year, the rainfall varies widely in space and time (Fig. 1). It is the highest (2500–3000 mm or more) in the northeastern parts of the country and in the Western Ghats. It declines to 750–1000 mm in the Gangetic and coastal plains, but to less than 750 mm westward, and even 300–100 mm or less in the northwestern parts in the deserts of Rajasthan and adjoining areas of Haryana, Punjab, and Gujarat. The areas receiving rainfall less than 650 mm are designated as "semiarid and arid" which forms a roughly N-S belt. A major part of this tract frequently suffers from deficient rainfall or droughts, while whatever precipitation that occurs is often concentrated in a short span of time and lost as flash floods – a not so uncommon phenomenon. The nonuniform incidences of precipitation cause flood havocs too. Reportedly about 12% of total geographical area is flood-prone. A total of 74 districts encompassing 55.12 M Ha are in the drought-prone category, i.e., 1/6 of the geographical area of India. The states of Rajasthan, Haryana (part), and Gujarat (part) are chronically under severe drought syndrome receiving an

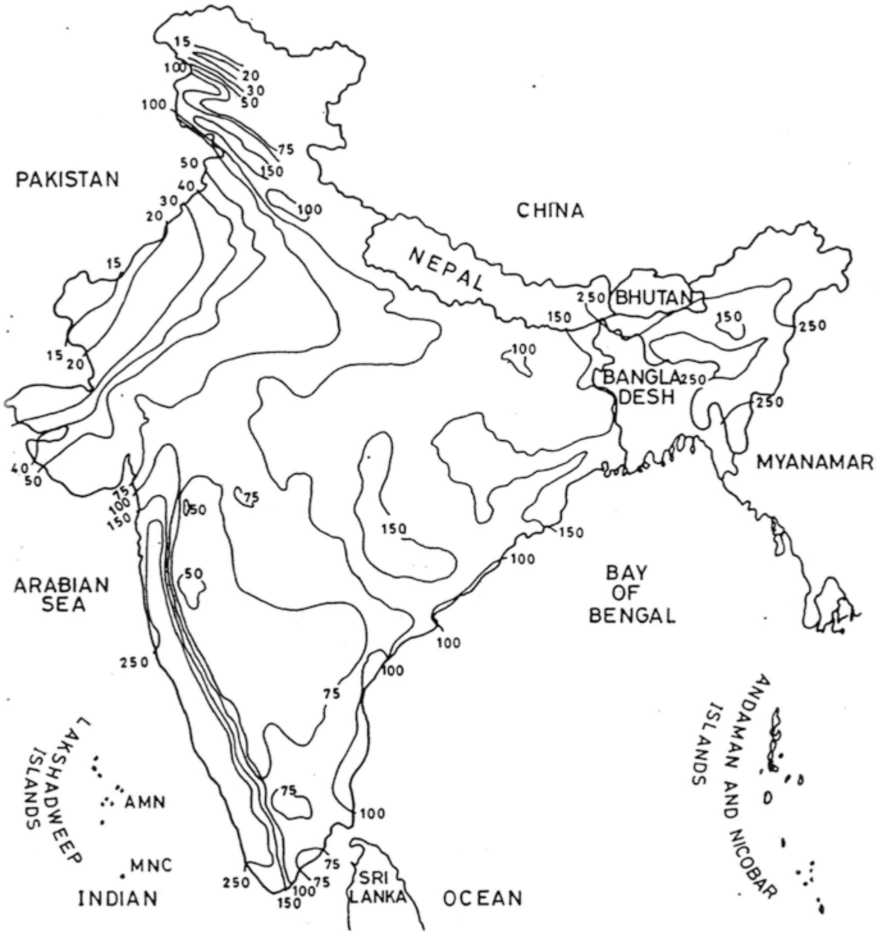

Fig. 1 Map of India showing average annual rainfall (cms)

average annual rainfall of <100–400 mm, while Haryana (part), Punjab, West Uttar Pradesh, West Madhya Pradesh, Maharashtra (part), Karnataka, and parts of other Peninsular states with an annual mean rainfall of 400–600 mm suffer from moderate drought once in 2–3 years (Central Water Commission 2012).

3 Geomorphic and Hydrogeologic Setup

While rainfall and its pattern of distribution in time and space are the principal determinants of groundwater recharge, geomorphic, geologic, and tectonic setup of the country primarily control groundwater condition of the country – occurrence, movement, and development potential. Broadly two main hydrogeological zones are generally recognized in the arid and semiarid areas (Pathak 1988; Central Ground Water Board 2002; Das 2011).

a) The Indo-Gangetic Plains and Narmada-Tapi uplands with a variable thickness of unconsolidated porous alluvium of Pleistocene to recent age, overlying older geological formations of Archaean to Cenozoic age, endowed with high rainfall and regionally extensive highly potential groundwater reservoirs and intensively developed. Yield medium to high (15- >30 lps). Sand and gravel layers constitute both shallow and deep aquifers and are thick and regionally extensive, under both unconfined and confined conditions. The depth to water level is of the order of <2–10 m below ground level (bgl).

   Aeolian sands occur in Western Rajasthan, adjoining Haryana and Gujarat containing discontinuous aquifers. However, as rainfall dwindles westward in the arid and semiarid climate in Rajasthan, Haryana, Punjab, and Gujarat, groundwater potentials drop sharply with increase in salinity and yield of medium to low (>10–25 LPS).The depth to water level is in places as deep as 40–100 m bgl.
b) Peninsular shield, composed of Archaean/Precambrian to Mesozoic, consolidated formations like igneous, volcanic, and metamorphic rocks and compact sedimentaries, folded and faulted, Deccan trap basalts, and semi-consolidated Gondwana coaliferous sedimentaries. Fractures, fissures, and weathered residuum form aquifers holding limited, discontinuous, unevenly distributed groundwater storages. Yield potentials: low to medium (<1–25 LPS).The depth to water level is of the order of <3–20 m or more below ground level.

This widely variable hydrogeological setup has led to spectacularly varying groundwater situations, e.g., occurrence, movement, storage, and development potentials (Fig. 2). Climate and rainfall, topography, and soil conditions decide rainfall infiltration and recharge, while lithology and structure control weathering and soil characteristics, storage, and transmissivity of the aquifers. Groundwater development needs a thorough knowledge of these terrain conditions. But lack of adequate knowledge of subsurface geology and structure, saturated alluvial thickness, facies variations in alluvium, weathering phenomenon of consolidated or hard rocks, distribution and extension of water-bearing fractures in hard rocks, as also groundwater movement and barrier render delineation and exploitation of groundwater in these areas rather complex, being a major hindrance in resource management.

4 Status of Water Resources

The country receives annually 4000 billion cubic meters (BCM) of precipitation, out of which 1869 BCM is lost as surface runoff; 432.72 BCM accounts for accretion of groundwater storage, a part of which is used by humans and the rest flows out to rivers and sea. The remaining part is locked in soil moisture for use by plants and later return to the atmosphere through evapotranspiration. According to Central

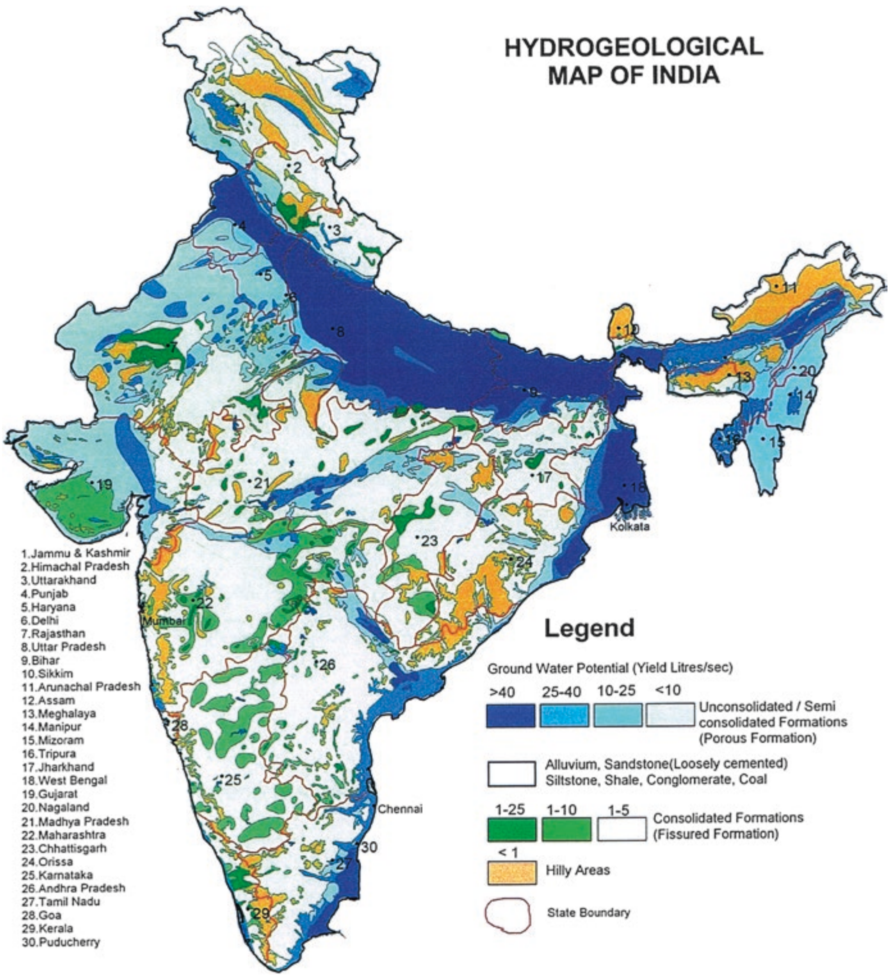

Fig. 2 Hydrogeological map of India

Water Commission (2012), out of 1869 BCM of estimated surface runoff, only 690 BCM can be stored/utilized in major, medium, and minor storage reservoirs constructed for irrigation or power generation because of technical, environmental, and ecological constraints. Surface water storage so far created is 17.3 million hectare meter (Mham), and another 8.3 Mham is under construction (Source: Ministry of Water Resources, GOI, In; Aswathanarayana 2012). Further, out of 432.72 BCM of estimated annual dynamic groundwater resource as of March 2011, 398.16 BCM is utilizable after accounting for natural discharge (Central Ground Water Board 2014). The total groundwater draft for all uses is 245.05 BCM. Besides dynamic resource, a part of the static resource occurring below the zone of water table fluctuation is also accessed in times of necessity such as droughts, to be replenished in succeeding years of above normal rainfall. Since 1950 groundwater development in the country has seen steady growth reaching a stage of 62% with many parts of the country overdeveloped as in Punjab, Haryana, Rajasthan, and NCT Delhi where draft exceeds annual recharge, so also are the states of Tamil Nadu and Uttar Pradesh reaching stages of 74–77%. Out of 6584 blocks/taluks in the country, nearly 20% fall under overexploited or critical category. The arid and semiarid areas are the worst hit. With low and uncertain surface water availability, these areas depend solely on groundwater leading to its mining in many areas.

The total groundwater-irrigated areas in India account for more than 60% of the total irrigated area in the country. But more than 60% of the cultivated area in the country is rainfed occurring mostly in arid/semiarid areas. Groundwater had been key to the Green Revolution of the 1970s, though mostly in water-rich northern plains. Uncontrolled development has led to desaturation of aquifers, declining water levels, rising cost of water lifting and power consumption, declining well yields and agricultural production, and also acute scarcity of drinking water, triggering migration of people. As per World Bank reports (1998), 37 million people lived in areas classified as dark or overexploited in 1995 which might have reached a staggering figure by now. This has led to social, economic, and environmental strains. But with increasing water demands, groundwater extraction is poised for steep escalation in the coming decades, foreboding a crisis situation, and hence careful ecofriendly management of this vital resource of the country is a necessity (Das 2006, 2011).

Presently groundwater is a major source of water for drinking and sanitation and a sustainable source for irrigation too.

4.1 Groundwater Quality and Pollution

Groundwater in the semiarid areas with rainfall less than 650 mm annually is generally fresh and useful for all purposes with EC 1000–1500 μs/cm at 25° C. But with rise in aridity, saline groundwater with an electrical conductivity of more than 2500–10,000 μs/cm is encountered in Western Rajasthan, Southern Haryana, NCT Delhi, Southern Punjab, Western Uttar Pradesh, and parts of Gujarat and in scattered areas of other states in Peninsular India like Maharashtra, Madhya Pradesh, Andhra Pradesh, Karnataka, etc. Some estimates indicate that 1.93 lakh km^2 area in the country is affected by inland salinity (Central Ground Water Board 1997; Kapoor 2000).

Over the years groundwater pollution has been emerging as a major concern due to both anthropogenic and natural causes, for example, high nitrate derived from leachates of chemical fertilizers, landfills, and soak pits and high fluoride and iron from geogenic sources apart from heavy metal contamination due to untreated industrial effluents. Pollution is acute in arid and semiarid areas, exacerbated by overexploitation. Reportedly 0.217 million villages in India are facing critical problems of contamination of their drinking water sources with fluoride contamination affecting 23,107 villages, iron contamination affecting 118,088 villages, and nitrate contamination affecting 13,958 villages (Anon 2013). Fluoride pollution of groundwater is rampant in semiarid and arid areas of Rajasthan (5.0–20 mg/L) and quite

Table 1 Projected water demands

Purpose	Annual water demand in cubic kilometer (km^3)	
Year	2025	2050
Total	1050	1180
Availability of utilizable surface water	690	690
Availability of utilizable groundwater	396	396

Source: Ministry of Water Resources (Quoted in Reddy 2001)

common in Southern Punjab (up to 11.7 mg/L), Southern Haryana (up to 15 mg/L), parts of Gujarat (up to 11 mg/L), Uttar Pradesh (10–12 mg/L), Karnataka (up to 4.7 mg/L), Odisha (up to 8 mg/L), Telangana (2–5 mg/L), and several other states (Das 2011). Climate change and global warming scenario are likely to intensify the problems, as groundwater recharge declines and degree of mineralization increases, but its consumption increases due to rising temperatures and fall in surface water availability. The pollution of groundwater is threatening its very sustainability.

4.2 Projected Water Demands

Table 1 below gives a tentative assessment of water requirement vis-à-vis availability of utilizable freshwater resources in the country as projected for 2025 and 2050.

Reportedly the present status of water utilization is 634 km^3 (Aswathanarayana 2012) leaving a balance of 443 km^3 foreboding a crisis situation in not so distant future.

5 Water Management: Some Recent Initiatives

Reportedly in India 221 million people do not have access to food. A large section of these people in India reside in arid and semiarid areas. The population of India is projected to escalate to 1390 million by the year 2025 and 1640 million by the year 2050. By 2050 the per capita annual availability of water may dip below 1000 m^3 resulting in a crisis situation. The requirement of food grains too will reach a staggering figure of 450–500 million tons annually. This may be achieved only through expansion of irrigated agriculture and enhancing productivity per unit water. The rainfed areas, a substantial part of which is arid and semiarid, account for 60% of net cultivable area of the country but provide 40% of total food grain output in the country. These are the areas which hold key to the achievement of the food grain production target. In the coming years, groundwater the most sustainable water source in the rainfed areas will play a crucial role in this scenario. Commensurate with this, the requirement of drinking water and also water needs for developmental activities will escalate. According to the survey of WHO/UNICEF (2015), 75.8 million people in India have no access to safe potable water sources. The country is poised to face acute water scarcity by 2025 itself as all known sources of water including aquifers may be harnessed or exhausted by then. This necessitates scientific development and management of water resources and integrated use of all available water resources – groundwater, surface water, and rainwater – for maximizing yield per unit of water or in other words increasing its use efficiency. This should be based on three primary guiding principles:

1. Conservation and optimal use of all water resources
2. Protection of water from pollution and overexploitation
3. Stakeholders' participation in groundwater development, management, and monitoring

Conjunctive use and artificial recharge are the two modern technological innovations for optimal use and conservation of available water resources for water security in arid and semiarid areas.

5.1 Conjunctive Use

Conjunctive use or integrated use of surface water and groundwater is the most efficient method of water conservation, which allows optimal use of total available water resources, rectifies aberrations in canal irrigation between head reaches and tail ends, ameliorates waterlogging through vertical drainage, increases irrigation intensity and agricultural production, and maximizes yields per unit volume of water. This calls for assessment of geological and hydrological setup and periodic availability of water resources commensurate with crop water requirement vis-à-vis other uses (Bhamra 1996; Prasad 1995; Anon 1995). Based on this analysis, alternate conjunctive use scenarios are generated through mathematical modeling and simulation studies. The Central Ground Water Board (CGWB) carried out detailed studies in the command area of Indira Gandhi Nahar Project (IGNP) in Rajasthan as a pilot project to develop conjunctive use model in a typical arid, drought-prone area (CGWB 1999). The IGNP canal command is suffering from rampant waterlogging and falling soil fertility. The study area falling in the parts of Sri Ganganagar and Bikaner districts is underlain by older flood plains and aeolian sands. The groundwater and surface water resources in the study area were computed to be 992 and 4215 million m^3 per annum, respectively. Modeling and simulation studies were carried out to maximize irrigation intensity and effectively control waterlogging and soil salinity. When only canal water is used and no groundwater for 110% cropping intensity, mass balance studies indicating 10,567 million m^3 is added to groundwater within 15 years causing waterlogging of 4264 km^2 area. But alongside canal water, if groundwater too is developed and used at 18% of canal water used, the recharge will reduce to 6982 million m^3, and the waterlogged area will reduce to 785 km^2 in 15 years, and an area of 2400 km^2 will be saved from waterlogging with consequent socioeconomic benefits. The irrigation intensity will be enhanced to 12% (Fig. 3).

In Punjab waterlogged areas of 9.71 lac hectares in canal-irrigated areas reduced to 1.69 lac hectares over a period of 10 years through irrigation from shallow tube wells which allowed vertical drainage of seepage waters.

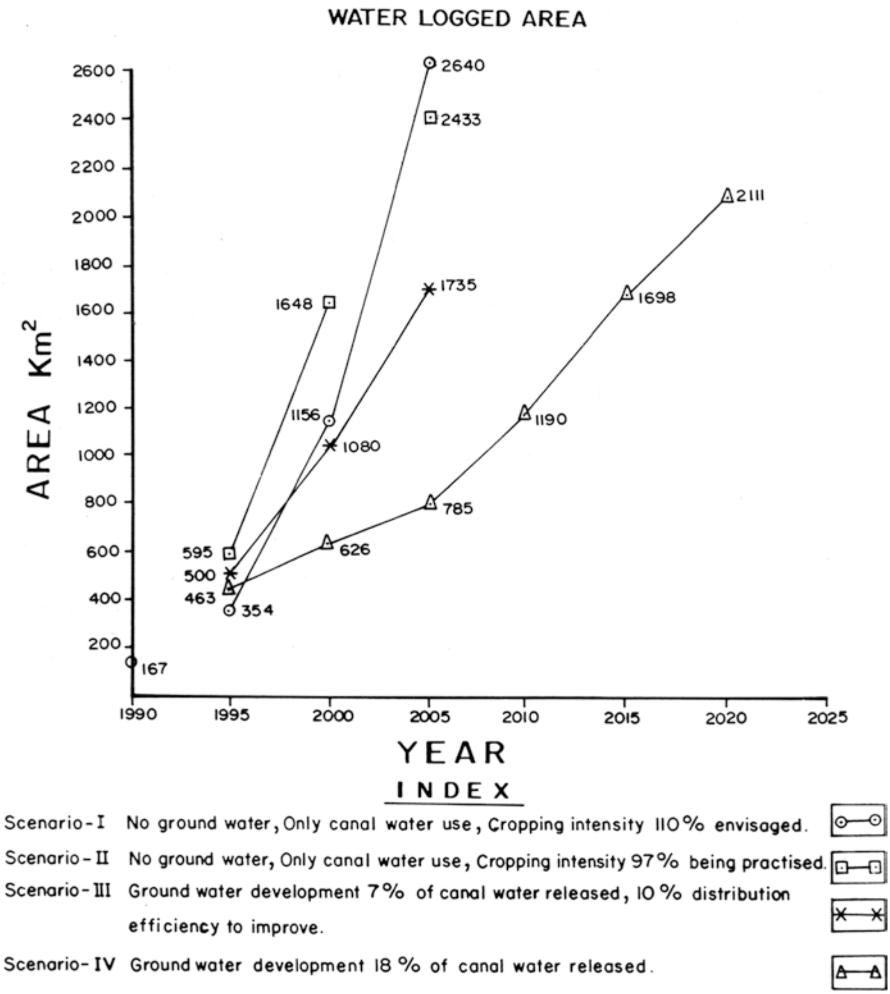

Fig. 3 Conjunctive use in Indira Gandhi Nahar Project (IGNP), Rajasthan. (Source: Bhujal News 1999)

5.2 Rainwater Harvesting and Artificial Recharge

Rainwater harvesting and artificial recharge are two recent innovations in order to enhance natural recharge rate replenishing depleted aquifers or creating subsurface storage under favorable hydrogeological conditions (Anon 1996, 2002; Das et al. 1996, 1998; Das 2006) to be accessed at times of need. The harvested rainwater may also be stored in small surface reservoirs. These may be implemented through technically simple, cost-effective water harvesting and moisture conservation measures and structures as part of integrated watershed management (Table 2) for which materials, designs, and skill are indigenously available.

Table 2 Types of water harvesting structures and methods (Sinha 1987; Das 2004)

Surface practices	1st–2nd order streams	Contour bunding, gully plugging, trenching, soil conservation, afforestation.
	2nd–3rd order streams	Cement plugging, nalla bunding, percolation tanks.
Subsurface practices	Throughout watershed	Injection well, recharge shaft, trench, dug well recharge.
Water conservation		
Surface water	To arrest base flow	Weirs.
Groundwater	In discharge area where base flow is generated	Groundwater dams/subsurface dykes.

Hydrogeologists and agricultural scientists/engineers have a big role in the selection of suitable sites and designs of water harvesting structures and crop water planning. Experiments have been successfully conducted by CGWB in the rain-short areas of Maharashtra (Jalgaon district), Andhra Pradesh (Kadapa and Ranga Reddy districts), Karnataka (Kolar district), and Tamil Nadu proving efficacy of percolation tanks, check dams, and gully plugs in recharging desaturated aquifers (Jain and Sharma 1999; Mehta and Jain 1994; Farooqi et al. 2016; Ramasesha et al. 2002). Groundwater dams or subsurface bandhara can effectively conserve groundwater runoff as experimented in Kerala (Sinha and Sharma 1990). The Demonstrative Artificial Recharge Projects helped in developing models for replication in other areas.

6 Selected Case Studies in Dryland Areas

Watershed development in drought-prone water-short areas (rainfall <100–400 mm annually) reveals that drinking water and food security are possible through rainwater harvesting and integrated use of rainwater, surface water, and groundwater with scientific crop water planning and multi-cropping which should depend solely on water endowments and land capability. Soil conservation, dryland agriculture, and other water conservation measures, including alternate livelihoods, support optimal use of available water resources leading to equity and sustainability (Aswathanarayana 2008; Das 2008).

6.1 Arvari Watershed in Alwar District, Arid Rajasthan

A shining example of community-driven integrated water management using traditional knowledge of rainwater harvesting is Arvari watershed of Alwar district in Rajasthan. Under the leadership of Tarun Bharat Sangh, nearly 8600 water harvesting structures (johads) have been constructed in the watershed along with water conservation measures through people's participation reviving flows in dying rivers, agriculture, and economy. The dead river Arvari was restored to life through rainwater harvesting relevant in water management. Arvari also set a new model of water governance of the newly created resource through setting up River Basin Parliament making their own rules and laws for water management, water allocation, crop selection, dispute resolution, etc. (Singh 2008; Rathore 2013). Thus, this is a new model of development in rural areas where Panchayati Raj institutions are not strong or where government departments suffer from bureaucratic red tapism. However, technical and financial institutions not being linked with the programs (due to noninvolvement of gram panchayats or block development offices) may prove to be a bottleneck in the long run. Johads are mud and rubble barrier structures built across contour slope to arrest runoff. The geological setup comprises Precambrian granites, marbles, amphibolites, quartzites, schists, and phyllites. Quartzites form ridges, while schists and phyllites occupy valleys (Das 2013).

Through community efforts rainwater harvesting converted dry parched lands of Alwar deserts in Rajasthan to lush green fields, transforming a desert to a hub of agricultural and economic activities even in drought years. The financial investments, labor, and materials all came from the people in the beneficiary villages. Designs and skills were based on traditional knowledge. No government agency was involved in the process. The UN Inter-Agency Working Group on Water and Environmental Sanitation in its report (1998) cited it as a unique example of self-help, worthy of emulation in all water-starved areas of Southeast Asia for food and drinking water security. It also underlined the point that the age-old traditional knowledge of the people is still relevant in water management. Arvari also set a new model of water governance of the newly created resource through setting up River Basin Parliament making their own rules and laws for water management, water allocation, crop selection, dispute resolution, etc. (Singh 2008; Rathore 2013). Thus, this is a new model of development in rural areas where Panchayati Raj institutions are not strong or where government departments suffer from bureaucratic red tapism. However, technical and financial institutions not being linked with the programs (due to noninvolvement of gram panchayats or block development offices) may prove to be a bottleneck in the long run.

6.2 Ichelahalla Watershed in Drought-Prone Gadag District, Karnataka

In the Ichalahalla watershed of drought-prone Gadag district in Karnataka, rainwater harvesting and drought proofing as part of watershed management through stakeholder's participation have changed the rural scenario from intense poverty to prosperity (Hiregoudar et al. 2008, 2016). Krishi Vigyan Kendra (KVK) at Hulkoti organized marginal and small farmers and landless laborers to harness social capital to cross poverty line in the quickest possible time. A total of 844 check dams, 2756 farm ponds, 1654 loose boulder structures, 3 nala bunds, and 6 water tanks and

Fig. 4 Top row: (**a**) Rain water harvesting structures: farm ponds and stone checks across primary streams in Ichalahalla watershed. Bottom row: (**b**) Rejuvenation of open wells and bore wells in Ichalahalla watershed. (Source: Hiregoudar et al. 2016)

percolation tanks were constructed in Gadag district (Fig. 4a, b). Nearly 36 crore liters of water have been annually harvested through these structures. In the last 11 years, 27,000 trained farmers participated in watershed treatment programs treating 1, 06,809 ha of land. The programs included soil moisture conservation technologies, especially compartment bunding, cultivation across slopes, maintenance of waste weirs, water harvesting structures, planting of various species, etc. These processes were aimed at not only soil moisture conservation but also enhancing soil moisture holding capacity, so that long dry spells of 30–35 days during the crop growth period do not affect the crops adversely. In view of frequent droughts, KVK also popularized the use of organic manures, bio-fertilizers, compost, etc., in lieu of chemical fertilizers.

After adoption of rainwater harvesting, commercial crops have been introduced, and suitable alternate land use systems have also been developed to drought-proof the area like agro-horticulture systems. Between 2003–2004 (pretreatment period) and 2007–2008 (posttreatment period), cropping intensity has changed: single cropping, 285–130 ha; double cropping, 98–172 ha; and relay cropping, 55–136 ha. The productivity of major crops increased by 3–25 Qt/ha. The employment potentials for men increased from 58 to 105 man-days/annum and for women from the 72 to 278 man-days/annum. The annual income levels of families significantly increased water availability has helped in solving the endemic drinking water shortage. Thus, artificial groundwater recharge through rainwater harvesting has remarkable effect on the irrigation sources. Due to artificial recharge, nonfunctional dug wells and bore wells got reduced in number. Many new bore wells were also drilled. The stream flow duration changed from 6 to 7 months in pre-rejuvenation to 10–12 months in post-rejuvenation periods along with availability of drinking water.

Two important aspects of the rainwater harvesting and watershed development were (1) mobilizing the village community, mostly poor farmers and landless agricultural laborers, into self-help groups (SHGs) and apprising them about the measures to mitigate adverse effects of recurring droughts. The capacity building programs helped the watershed development associations and village watershed development committees to plan watershed development of their villages in a proper manner with enhanced participation of beneficiary farmers. (2) Linkage of the programs with financial and technical institutions and various government schemes made implementation and maintenance free from hindrances. Technical institutions too were brought within this linkage. Panchayats being involved, managing the new resource was not a problem.

Thus, these examples reveal five vital inputs in the success of watershed development (Srikantia 2008; Das 2015):

1. Inspiring leadership.
2. Community participation or self-help.
3. Vital role of village panchayats.
4. Traditional knowledge with S&T inputs can make water harvesting an eco-friendly program and easy to implement.
5. Technical and research institutions have a major role to play, bringing science to the grassroot level to improve our living standards. Geological inputs are major necessities. Geologists and geomorphologists should develop area-wise thumb rules which may serve as "best practices" for the people.
6. Linkage with financial institutions for successful implementation of the programs without fund crunch.

7 Discussions and Conclusions

The water resources of the arid and semiarid areas so far neglected hold key to the country's economic development in the coming decades, water being an indispensable input in the overall development and all-inclusive growth. But in the wake of rainfall uncertainties and limited water resource potentiality in the terrain, what is needed is disciplined development and management of all available water resources. This involves water conservation and augmentation measures through integrated water resource management, conjunctive use, rainwater harvesting, and artificial recharge, application of drip or micro-irrigation and also other water-saving measures, and monitoring and protection of resource from overexploitation and pollution. Groundwater is the core element in the management of the water cycle in the arid/semiarid areas. Some of the strategic actions needed in groundwater management in the arid and semiarid, drought-prone areas may be highlighted below.

7.1 Water Conservation and Augmentation

1. Conjunctive use of surface water and groundwater, along with crop water management and water economy, is the most efficient means of water conservation in the canal commands.
2. Rainwater harvesting and artificial recharge constitute a vital cog in water conservation in arid and semiarid areas providing for harnessing surplus rainwater in monsoon which is lost as runoff and storing the same in porous subsurface geological formations under favorable circumstances.
3. Age-old traditional practices of water harvesting should be revived blended with modern inputs of science and technology. These small and simple cost-effective water harvesting/recharge structures like gully plugs, small dams, check dams, percolation tanks, ponds, tanks, groundwater dams, and soil conservation measures like terracing, trenching, contour bunding, afforestation, etc. as part of watershed development will alleviate water scarcity and mitigate drinking water problems.
4. Integrated use of rainwater, surface water, and groundwater aided by micro-irrigation or drip irrigation, coupled with land use changes and alternate livelihoods, will unlock potentials of the vast rainfed areas (60% of the country's cultivable area), improve the environment and ecology, and ensure food and drinking water security.
5. Large tanks and water bodies, both man-made and natural which dotted the country, particularly in arid and semiarid areas and peninsular states, which historically served as water harvesting structures and effective drought proofing measures even in the arid territory of Rajasthan but now defunct due to neglect should be rehabilitated. Desiltation and rejuvenation of these 1.5 million village tanks and ponds in the country will insure 6,60,000 villages against recurrent droughts and enhance groundwater recharge. Almost every settlement in the Thar Desert has water collection pond or earthworks to harvest rainwater, a system developed over thousand years reflecting adaptation to climate change.
6. Pricing of water in a rational tariff regime will induce the people in water economy and conservation. Pricing should cover the cost of O&M and also of upgradation of the water services system. However, the pricing tariff should be in a slab system with the economically weaker sections paying less than the affluent consumers. Drinking water should be free of cost. Also tariff for water consumption more than the allocation norm should be highly charged. The issue needs wider debate (Damle 2006; Kurien and Sinha 2006).
7. Demand and supply management is the bedrock of water conservation.
8. Wholehearted participation of the community and stakeholders is a must for the success of water management programs.

7.2 S&T in Aquifer Management

1. The water management efforts need to be supported by an adequate knowledge of subsurface water regime, geology, and structures, which give vital clues to the water-saturated zones and groundwater flows, gained through integrated and multidisciplinary scientific exploration aided by remote sensing, GIS, and geophysics. The use of space technology and GIS with ground truthing helps in demarcating areas favorable for groundwater development and artificial recharge. Subsurface imaging through geophysical surveys will help in locating yet unknown aquifers in unexplored terrains to be developed, and also drilling sites, as also demarcating potential artificial recharge areas.
2. Mathematical modeling of groundwater flow should be undertaken to understand groundwater flow systems in hard rocks, to develop conjunctive use and artificial recharge models in varied terrains, and to generate alternate strategies of optimal groundwater development and management in critical and overexploited areas.
3. Groundwater monitoring system along with stream gauging needs to be strengthened as an essential management tool.
4. Refinement of groundwater resource estimation is required taking into account complexities of water cycle specific to the watershed.
5. More and more involvement of academic institutions including engineering colleges, agricultural universities, university geology departments, and IITs in hydrogeological research in a meaningful way.

7.3 Groundwater Legislation: Disciplined Development

For disciplined development of the resource and its protection from overexploitation, draft should not exceed recharge potential, and safe spacing norm should be strictly adhered to. In the wake of overexploitation and water scarcity situation, it is the poor who suffer most. Groundwater legislation will curb uncontrolled overdraft and ensure sustainability and equity of the resource. It has been enacted in most of the states but with limited scope or implemented half-heartedly.

However, existing laws of the country entitle the land owners' unrestricted rights to withdraw groundwater leading to overexploitation of the resource. Hence, some believe that groundwater use rights should be vested with the state or the community as it is a common pool resource.

In the overexploited areas, groundwater should be reserved only for drinking water use.

7.4 Protection from Pollution

In the arid and semiarid areas, although groundwater quality is generally good, incidences of high fluoride, iron, nitrate, lead, chromium, and cyanide contents and bacterial pollution are not uncommon, thereby squeezing its utilizability. Wholehearted measures should be undertaken for remediation of adverse water quality due to these alien chemicals introduced through geogenic sources or by human activities, patently hazardous to the health of the ecosystem. Defluoridation is a must before use of fluoride-rich groundwater for drinking purposes. Municipal and industrial wastewaters should be properly treated before discharge. SAT (soil aquifer treatment) is a very effective technique to remove pathogens, dirts, and alien chemicals from the used wastewaters. Engineered landfills can also preempt groundwater pollution. Artificial recharge, too, helps in dilution of contaminants in the aquifer. To minimize nitrate pollution, organic manures should be used in lieu of chemical fertilizers, or release of irrigation water and fertilizer application should be controlled. Bioremediation, too, is a cost-effective tool. Zones vulnerable to groundwater pollution should be delineated using DRASTIC technique for corrective actions well in time (Aller et al.1987). Also solute transport modeling may enable understanding of pollutant movement to decide on preemptive or remedial options. Periodical groundwater monitoring and time series analysis are fundamental to pollution control of groundwater.

7.5 Climate Change Mitigation

India may face the major impacts of climate change and global warming. The mean surface temperature may rise by 3 °C by 2050 and 3.5–5.5 °C by 2080, with increase in annual precipitation by 5.36–9.34% by 2050 and 7.48–9.9% by 2080. Winter precipitation may decrease by 5–25%, and average monsoon rainfall may increase by 10–15%. Also the monsoon may weaken (Ameer Ahmed 2009; Thakkar 2009). The frequency of extreme events like droughts and floods will increase, and the number of rainy fays will decrease. Such changes will impact water resources and agricultural productivity. Drinking water will be scarce. Rising temperature will reduce soil moisture, increase energy flux for evapotranspiration and crop water requirement, and cut down yields of primary food crops like rice and maize by 20–40% (Financial Express 2009). Groundwater recharge will be increased in places but reduced in others. This coupled with increase in draft will spell doom to water regime. It assumes significance as the food basket in the country is in the irrigated tracts of Punjab, Haryana, and Uttar Pradesh. Anticipated melting of glacier river flows may dry up. The water resources will be the worst sufferer. Water conservation and augmentation, rainwater harvesting, protection from overexploitation and pollution, enforcing water economy and enhancing use efficiency, and dryland agriculture are some of the measures to be adopted at micro-level for mitigation of climate change fallouts. Integrated water resource management and watershed development are the two most important climate change mitigation technologies (Jain 2011; Das 2012).

Lastly, as the National Water Policy dwells at length on the management of water resources, groundwater in particular, it falls short of adequate stress on groundwater conservation specific to arid and semiarid areas, and the critical role of groundwater as the core element of the water cycle in the terrain, which is pivotal for integrated watershed development. Groundwater being an unseen resource, technology and rules of its conservation are essentially different from those of surface water. Hopefully, the crucial issues raised in the preceding paragraphs may find place in the National Policy in the wake of climate change and global warming impacts.

Acknowledgments The author is grateful to Dr. S. P. Sinha Ray of the Centre for Groundwater Studies, Kolkata, for his constant encouragement in preparing this write-up. The article draws extensively from various seminar and workshop proceedings of the Geological Society of India, edited by the author, and also from the author's keynote address in the National Seminar on Green Earth (2012) organized by the Wadia Institute of Himalayan Geology and Indian Geological Congress and various other publications, which are gratefully acknowledged.

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Frontiers of Hard Rock Hydrogeology in India

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Abstract Hard rocks are consolidated and fissured formations occupying nearly two-thirds of the geographical area of the country and comprising a wide variety of igneous, volcanic, sedimentary, and metamorphic rocks of Archaean and Precambrian age. In this terrain the aquifers are characteristically thin, discontinuous, of irregular occurrence, and hence of low to moderate yield potentials. The latter depends mainly on the distribution of porosity, imparted by weathering and fracturing, and interconnection of weathered zone with fractured massive layers. Distribution of interconnected fracture systems, openness of fractures, and porosity of vesicular lava flows are the other important factors determining aquifer potentials. Study of long-term groundwater monitoring data reveals declining trend of groundwater levels, increasing overexploitation due to uncontrolled groundwater draft, and deteriorating groundwater quality in several parts of the terrain. Meteorological factors and anthropogenic activities influence the groundwater regime. But the stress on groundwater exploitation is ever-increasing with mounting demand for water calling for scientific management of the resource. The paper highlights the overall status of knowledge of groundwater in the hard rock terrain of the country and the role of science and technology in groundwater exploration, development, and conservation, presenting a few case studies and setting the agenda for better understanding of the groundwater regime and its management.

Keywords Aquifer productivity · Artificial recharge · Basement complex · Conjunctive use · Deccan Traps · Flow model · Fractured rock aquifer · Morphogenetic classification · Stress field · Water level trend

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S. P. S. Ray (ed.), *Ground Water Development - Issues and Sustainable Solutions*, https://doi.org/10.1007/978-981-13-1771-2_3

1 Introduction

In the mid-twentieth century as per prevailing knowledge of the time, the country used to be subdivided into groundwater provinces based on aerial extent of important water-bearing geological formations or grouping together of formations of similar hydrogeological environments which hold significant and usable groundwater potential. Thus the less potential hard rock terrains – Precambrian crystalline, Precambrian sedimentary, and Mesozoic Deccan Trap provinces – were distinguished from the more potential Cenozoic and Quaternary alluvial and Gondwana sedimentary provinces. Till mid-twentieth century whatever meager groundwater development occurred, it was mainly confined to the highly potential alluvial terrains through dug wells and shallow tube wells. However large-diameter dug wells were not uncommon in hard rock areas to be use for drinking water. But with the progress of time, availability of more and more information on aquifer lithology, continuity and boundary, stratigraphic position, aquifer geometry, parameters, aquifer yields, flow behavior, confined or unconfined conditions gained through extensive hydrogeological surveys, investigations, exploration and pilot project studies prompted a more precise and scientific definition of aquifer groups as:

1. Hard rocks: Consolidated, also called fissured, formations – Precambrian crystallines, Proterozoic sedimentaries as also Mesozoic Deccan volcanics, and igneous intrusives. Devoid of primary porosity, but possesses secondary porosity due to weathering and fracturing. Aquifers of limited to moderate potentials.
2. Soft rocks or porous formations: (a) Semi-consolidated formations – Paleozoic and Mesozoic sedimentaries. (b) Unconsolidated formations – Cenozoic sedimentaries, older and younger alluvium. Possesses primary porosity. Highly potential aquifers.

The Peninsular shield forms the major hard rock terrain, comprising two-thirds of the geographical area of the country (nearly 22 lakh km^2), a major part of which is under arid-semiarid drought climatic condition and drought prone, suffering from chronic water scarcity. Since the 1970s as studies enabled better understanding of hard rock aquifers and revealed their moderate potentials, and pressed by the urgent need of drought-proofing the country through more and more use of groundwater, focus has been directed toward groundwater development in the hard rocks. But these fractured rock aquifers are characteristically thin, discontinuous, and irregular in occurrence and distribution riddled with uncertainties of aquifer yields and hence leading to frequent well failures. Unregulated development of groundwater and its contamination, too, haunt its sustainability. Therefore, development and management of this precious resource in this terrain calls for expert handling. The following chapters present in brief an overview of the status of knowledge and the vital role of science and technology in addressing the challenges in the field.

2 Nature and Productivity of Hard rock Aquifers

A wide variety of rock types of different ages constitute the hard rocks, namely, Archaean basement complex and Dharwarian metamorphics comprising granites, gneisses, schists, amphibolites, phyllites, granulites, ultrabasics, intrusives, metamorphics, charnockites, khondalites; Precambrian sedimentaries like sandstones, quartzites, slates, limestones (Cuddapahs and Vindhyans); and Mesozoic Deccan Trap basalts and intertrappeans.

2.1 Basement Complex and Precambrians

These are hard, consolidated formations with primary porosity weeded out through metamorphism, induration, and tectonic deformation in the geological past but rendered porous through weathering, fissuring, and fracturing forming aquifers. A typical profile of the weathered mantle shows a top weathered zone followed by alternating poorly weathered and unweathered zones of fractured or unfractured rocks before imperceptibly grading into massive rock at depth. The weathered zone plays an important role in groundwater occurrence and movement in this terrain. The degree of weathering depends upon the topography, climate, vegetative cover, texture, mineralogy, and fracture distribution in the host rocks. Thick weathered zone develops in humid or subhumid tropical climate with good vegetative cover and rainfall. It is thickest and extensive in erosional peneplains with low relief as in Peninsular India. Other favorable hydrogeomorphic features are deep and moderately deep buried pediments, intermontane valleys, structural valleys, and lineaments. Coarse-grained granitic rocks have commonly thick weathered layers and contain permeable layers. Finer-grained rocks are less susceptible to weathering. In mafic rocks such as diorites, gabbros, and dolerites, the weathered and altered products are clayey and poorly permeable. In intensely fractured granites and other salic rocks, weathering is generally deep and forms thick weathered layers with permeable zones. Massive and poorly fractured granites resist weathering. The near-surface weathered zone which attains a thickness of 15–30 m (but generally 5–10 m) forms the repository of groundwater in the hard rock terrain and groundwater circulation through deep fractures and fissures. The weathered residuum and the fracture porosity are the two most important components controlling storage and transmission of groundwater in fissured formations (Fig. 1).

Fractures may be of tectonic or nontectonic origin. Long deep-seated vertical to subvertical, narrow fracture zones in the Precambrian crystalline rocks are the results of ruptural deformation. Tensile fractures develop parallel to the direction of compression. Sheer fractures develop at an acute angle to the direction of maximum compression. Open tensile fractures persisting over long distances act as potential groundwater reservoir. Sheer fractures are relatively compact. Sheet joints are

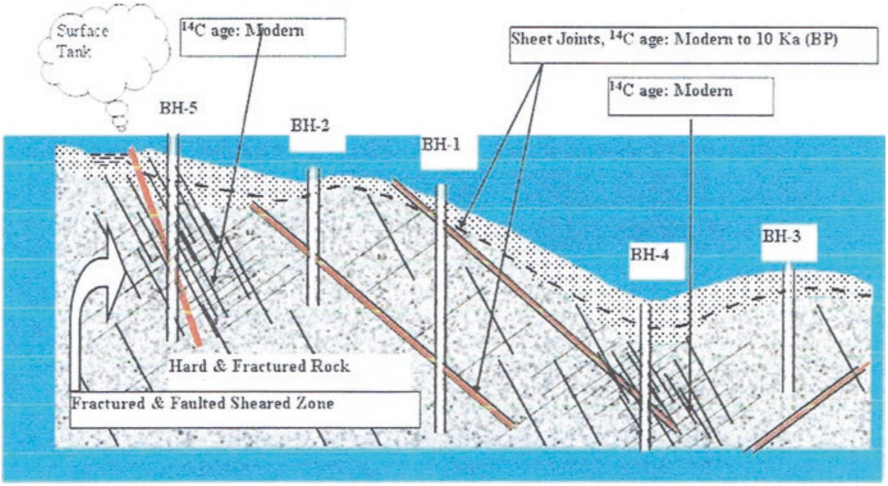


Fig. 1 Conceptual model of hard rock hydrogeology based on radiocarbon data for delineation of potential deeper fracture zones. (After Sukhija et al. 2005. **In**: Jaroslav and Verhagen (ED) 2006)

horizontal fractures developed in hard rocks due to load release and change of temperature. In coarse-grained rocks like granites, fractures are long and widely spaced.

Precambrian crystalline rocks are usually made up of irregular plinths of massive rock, separated by intensively fractured and highly permeable rock material on the sides and weakly fractured, moderately permeable rock material on the top and at bottom. A hydraulic continuity exists between weathered zone and underlying fractured zone. Generally a fracture system consists of two or more sets of syntectonic fractures which together form one hydraulic system. Similarly interconnected fracture systems of two different phases of deformation may also form one hydraulic system.

2.1.1 Tectonic Model and Fracture Analysis

Fracture geometry and their hydraulic properties depend upon stress distribution, palaeo-stress, and in situ stress analysis. As geometry of fractures influence flow characteristics, structural analysis in hard rocks is significant. Based on the results of field studies, exploratory drilling, and analysis of the data, the tectonic model is evolved which enables evaluation of different generation of fractures in terms of its groundwater potential. Detailed studies have been undertaken in Noyil river basin and coastal Kerala (Baweja and Raju 1980; CGWB 1992). The structural analysis vis a vis hydraulic behavior of fracture aquifers is well illustrated by Nandakumaran et al. (2017) in Bharathapuzha river basin of Kerala. The rocks have undergone several phases of tectonic deformation, including ruptural deformations creating open tensile (T) as also shear fractures (S). Table 1 and Fig. 2 summarize the stress fields and ruptural history in the hard rock areas of Kerala.

Table 1 Stress fields in hard rocks in Kerala during different deformation stages

Deformation stage	E-W	WNW-ESE	NW-SE	NNW-SSE	N-S	NNE-SSW	NE-SW	ENE-WSW
First ruptural	T	S						
Second ruptural		S	T	S				
Third ruptural			S	T	S			
Present compression						S	T	S

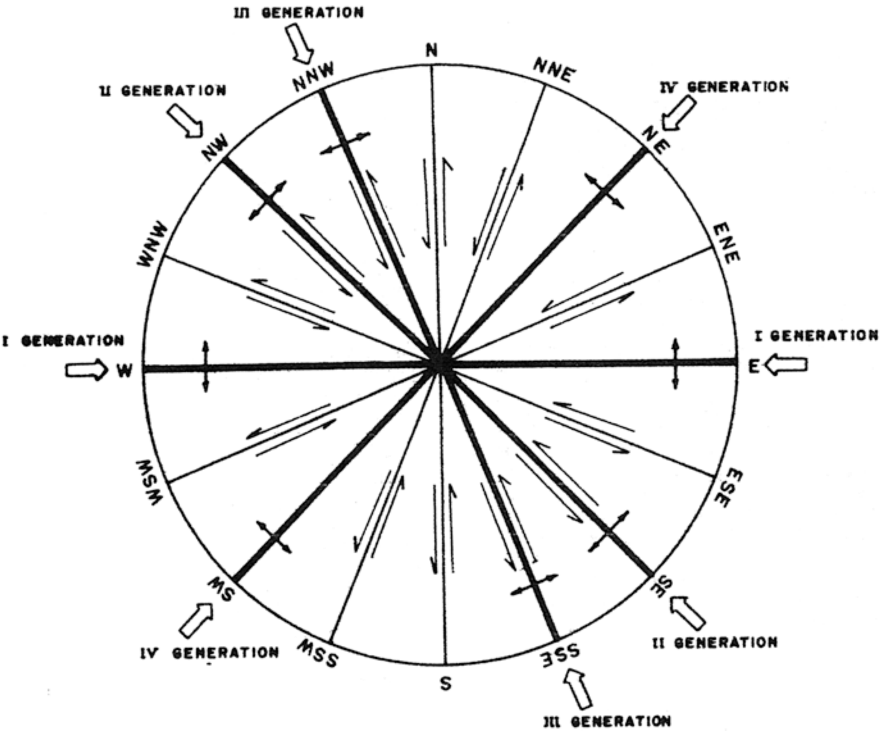


Fig. 2 Ruptural deformation history of hard rocks in Kerala. (CGWB 1992)

The stress fields have changed several times. Usually the younger set of fractures are more productive than the other sets as in Bargarh and Keonjhar districts (Das et al. 1997; Das 2000). The fractures originally developed as tensile and open and later might have become shears on compression, thereby closing up the fractures or resulting in tight fractures. Some of the original shear zones might have been dilated as tensile, thereby opening the fractures. Lineaments are surficial manifestations of these fractures. A lineament map was prepared based on satellite imageries. A rose diagram of lineament trends in the study area was drawn. Analysis of yield data of bore wells with respect to lineament orientations shows that bore wells drilled along N-S and NW-SE lineaments are the most productive with mean well yields of 9.3–16.5 lps.

2.2 Deccan Traps

The traps include basalts, tuffs, breccias, ash beds, and intertrappean sedimentaries. The trap flows generally have two distinct units, namely, a lower dense and massive unit passing upward into a vesicular horizon, full of cavities. The upper and lower surfaces of each flow are traversed by cooling joints. The massive horizon may be traversed by both sheet joints and columnar joints. The thickness of vesicular layers may range from a few meters to 10 m. Red bole layers formed by weathering of trappean materials often separate the flows.

A characteristic feature of Deccan basalts is the contrast in their water-bearing properties. The massive traps with their fracture porosities, vesicular traps with their minutely interconnected and partly filled vesicles, and the intertrappean sediments with their primary porosities influence the groundwater regime. The weathering too produces lateritic capping with vesicular structures which attains a thickness of 30 m. Topography, nature and extent of weathering, jointing and fracture pattern, thickness, and depth of occurrence of vesicular basalts are the controlling factors for groundwater occurrence and movement in these rocks. Weathered, vesicular, or fragmented upper parts of the flows, the interface between the flows, and jointed and fractured parts of the flows facilitate the movement and accumulation of groundwater. The near-surface weathered and jointed zones of massive trap units and vesicular zones together form the main water table. A hydraulic continuity exists between the consecutive massive and vesicular units. The weathered and jointed zones in massive units act as leaking aquitards to the lower vesicular units, and in case the massive unit is dense, it may act as confining bed, and groundwater in the underlying vesicular zones may occur under semi-confined to confined conditions.

2.2.1 Lithological and Morphogenetic Classification

In the classical concept, the Deccan Traps have been regarded as a layered complex of multi-aquifer system including both productive and nonproductive zones. This follows the model of trappean lava flows of Snake River Valley plains in the United States. The aquifers act as unconfined, semi-confined, or confined zones depending on their interconnection through fracture networks and with weathered residuum. Hawaiian nomenclature of compound pahoehoe flows as distinct from simple flows is also popular among workers. The former is typically of hummocky and sheet flow type. Sheets show a vesicular zone (crust), followed by non-vesicular zone (core) and a lower vesicular zone (basal). Simple flows have greater thickness, broad flow fronts, and rather flat upper surface capped by discontinuous flow-top breccia (Fig. 3).

A simpler classification of vesicular and massive units has also been used by workers for field mapping of the inhomogeneities of the trappean flows. Kulkarni and Deolankar (1995) proposed a lithological model of amygdaloidal flows at the top followed downward by compact flows.

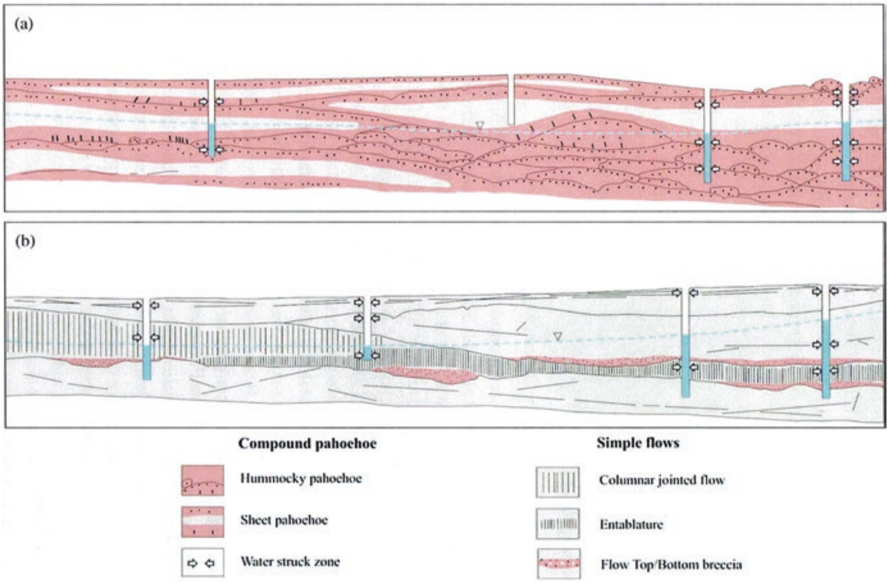


Fig. 3 Conceptual model illustrating (**a**) compound flows and (**b**) simple flows of the Deccan Traps. (After Duraiswami et al. 2000)

The above models only partially described the groundwater flow characteristics in the heterogeneous Deccan Trap aquifers. Rather there were many anomalous observations. Duraiswami and others (2012) have recently introduced a more dynamic concept of sixfold morphogenetic classification of the traps as illustrated in Fig. 4 to better understand the morphology and internal structure of the basaltic flows which constitute the framework of the aquifers for proper utilization and development of groundwater in basalts, as also improving their sustainability through artificial recharge measures:

Scenario 1: Compound sheet pahoehoe aquifers
Scenario 2: Compound lobate pahoehoe aquifers
Scenario 3: Compound sheet-lobate pahoehoe aquifers
Scenario 4: Simple unconfined aquifer
Scenario 5: Simple semi-confined aquifer
Scenario 6: Simple confined aquifer

Any combination of Scenarios 5 or 4 existing above Scenarios 1, 2, or 3 is possible.

The combination of Scenario 4 above Scenario 3 is responsible for the success of water conservation in Ahmednagar district, Maharashtra.

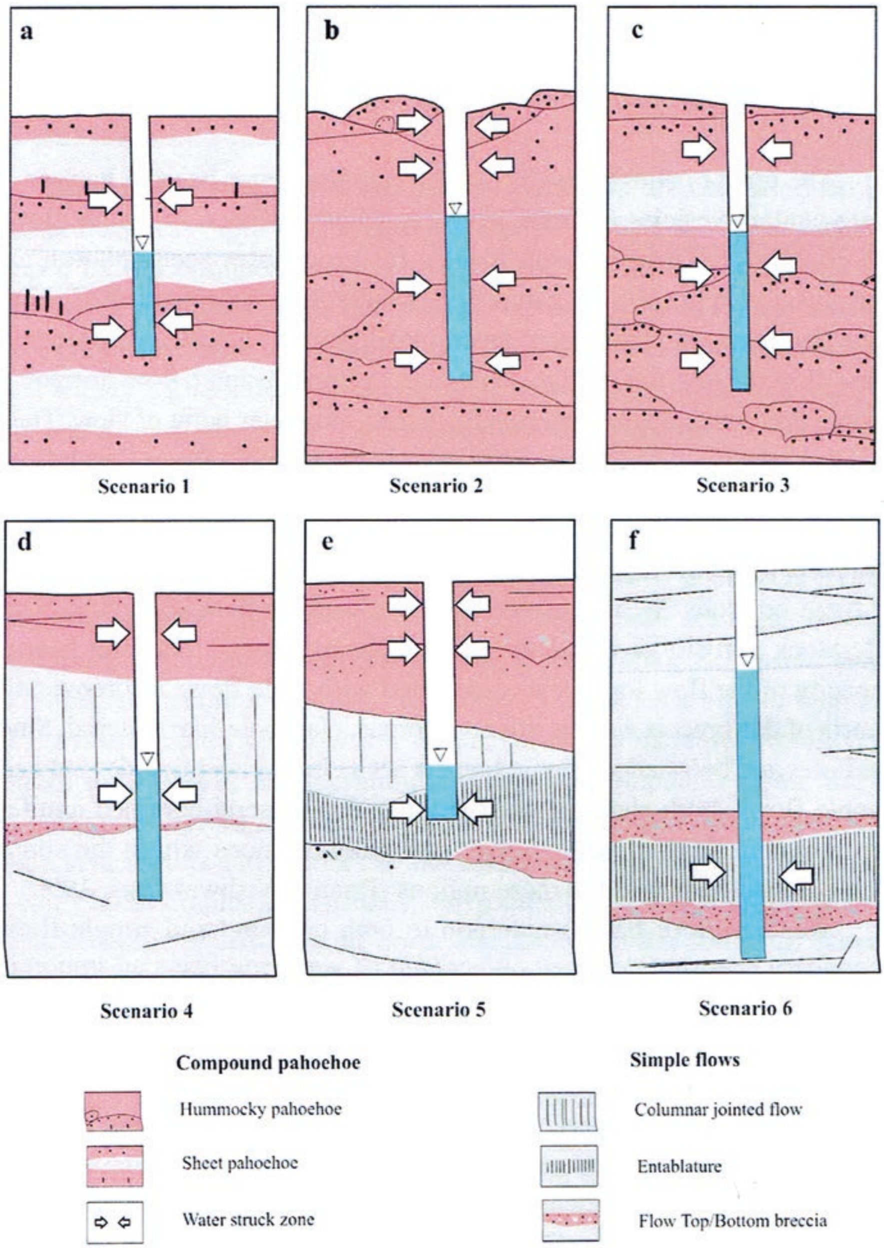


Fig. 4 Conceptual ground water system scenarios in Deccan Traps. Pink represents vesicular basalts/flow-top breccias. Gray denotes massive basalts. (After Duraiswami et al. 2012)

2.3 Flow Models in Fractured Rocks

Because of the heterogeneity of fracture distribution, interconnectivity of different fracture systems and weathered residuum, fracture spacing and aperture size which together determine fracture permeability and porosity, and groundwater flow through fracture systems in hard rocks is complex and difficult to predict through conventional flow equations (such as Theis equation), which are developed for homogeneous, isotropic, and infinitely extending porous aquifers. However use of flow models makes it easier to understand the system and flow characteristics. The commonly used flow models in fracture aquifers are double-porosity model, equivalent porous medium model, and discrete fracture network model (Singhal 2007). The first one, widely in use in fractured rock aquifers, assumes a matrix of low permeability and high storage capacity (porous rock) intersected by fractures of high permeability and low storage capacity. The difference in pressures between porous block and fractures leads to the flow of fluid from porous to adjacent fractures. Due to difference in permeability between the two, flow mechanism is different in the early, intermediate, and later time of pumping (Larsson 1984).

2.3.1 Storativity and Hydraulic Conductivity

Storativity and hydraulic conductivity are the two factors determining productivity of aquifers. Karanth (1987), Das et al. (1996), and Das and Chatterjee (1997) studied the hydraulic characters and depth-wise variations of hydraulic properties of granitic aquifers based on pumping tests of exploratory wells (Tables 2, 3, and 4) illustrated in Figs. 5 and 6.

Their studies further show that the average specific yield values of weathered/fractured granitic rocks in Peninsular India and in Orissa state are of the order of 0.4–3.0%. Further, unconfined to semiconfined condition prevails down to a depth of 100 m. The storativity values of deeper aquifers in Orissa are generally in the range of 10^{-3}–10^{-4}, same as in Peninsular India (Karanth 1986; Das et al. 1997).

Table 2 Hydraulic characters and productivity of shallow aquifers (dug wells)

	Yield factor (lpm/m/m)			Unit area-specific capacity (lpm/m/m^2)			Permeability (m/day)		
Lithology	Range	Mean	Median	Range	Mean	Median	Range	Mean	Median
Granitic rocks (n 195)	0.035–147.465	9.749	4.881	0.049–11.54	1.839	1.174	0.06–42.07	3.448	2.05
High-grade metamorphics (n 20)	0.302–18.182	7.314	6.054	0.134–4.88	1.798	1.51	1.983–3.42	2.794	2.98
Schists and phyllites (n 15)	0.311–35.56	8.967	2.306	0.244–12	2.052	1.150	0.576–0.75	0.652	0.649

Source: Das et al. (1997) and Das (2000)

Table 3 Hydraulic characters and productivity of deeper aquifers

Lithology	Depth range of saturated fractures (m bgl)	Piezometric head (m bgl)		Yield (Lps)		Permeability (m/day)	
		Pre-monsoon	Post-monsoon	Range	Average	Range	Average
Granitic rocks (n 192)	10–190	3.51–14.74	2.42–9.26	<1–25	4–31	0.0004–25.95	0.76
High-grade metamorphics (n 7)	14–142	7.25–11.58	5.37–7.85	<1–5.5	1.56	0.007–0.27	0.055
Basic and meta basic rocks (n 9)	19–87	4.92–7.10	3.25–6.51	<1–9.0	3.94	0.003–0.468	0.149
Schists and phyllites (n 13)	14–179	4.65–8.42	2.42–6.82	<1–7.1	2.32	0.0004–0.052	0.024

Table 4 Depth wise variation of hydraulic characters of granitic aquifers

Depth range (m bgl)	Yield (Lps)			Transmissivity (m^2/day)			Hydraulic conductivity (m/day)		
	Range	Mean	Median	Range	Mean	Median	Range	Mean	Median
0–76	0.10–25 (n 12)	11.64	10	1.93–6.59	191.62	104.57	0.0037–25.95	6.88	2,5
76–100	1.30–23.5	11.38	9.5	3.12–225.86	66.45	21.0	0.04–12.92	1.85	0.74
100–150	0.1–12.94	4.72	4.3	0.63–96.6	19.49	7.73	0.001–2.55	0.27	0.071
150–180	0.1–9.52	3.12	2.42	0.18–163.64	16.29	4.60	0.001–1.2	0.16	0.04
180–200	0–25	2.54	1.02	0.07–116.34	13.78	2.20	0.0004–2.83	0.17	0.028

Source: Das (2000)
Bgl below ground level

There is also a sharp decline in the values of hydraulic properties and aquifer productivity below this depth which is attributed to the decrease in intensity of weathering, as also tight and less frequent fractures (Fig. 7).

In contrast, the Deccan Trap volcanic rocks possess significant porosity in the form of interstices in the vesicular layers, pillow lavas, lava tubes, and occasional tunnels. Secondary porosity in these rocks result from weathering, brecciation, shrinkage, cracks, and joints and also from fracture systems created through tectonic disturbances. As a result there are wide variations in porosity of volcanic rocks. The massive traps with their fracture porosities, vesicular traps with minutely interconnected and partly filled vesicles, and intertrappean sediments with primary porosity influence the groundwater regime. The following Table 5 gives porosity and specific yield values of basaltic rocks as studied in Betwa basin of Madhya

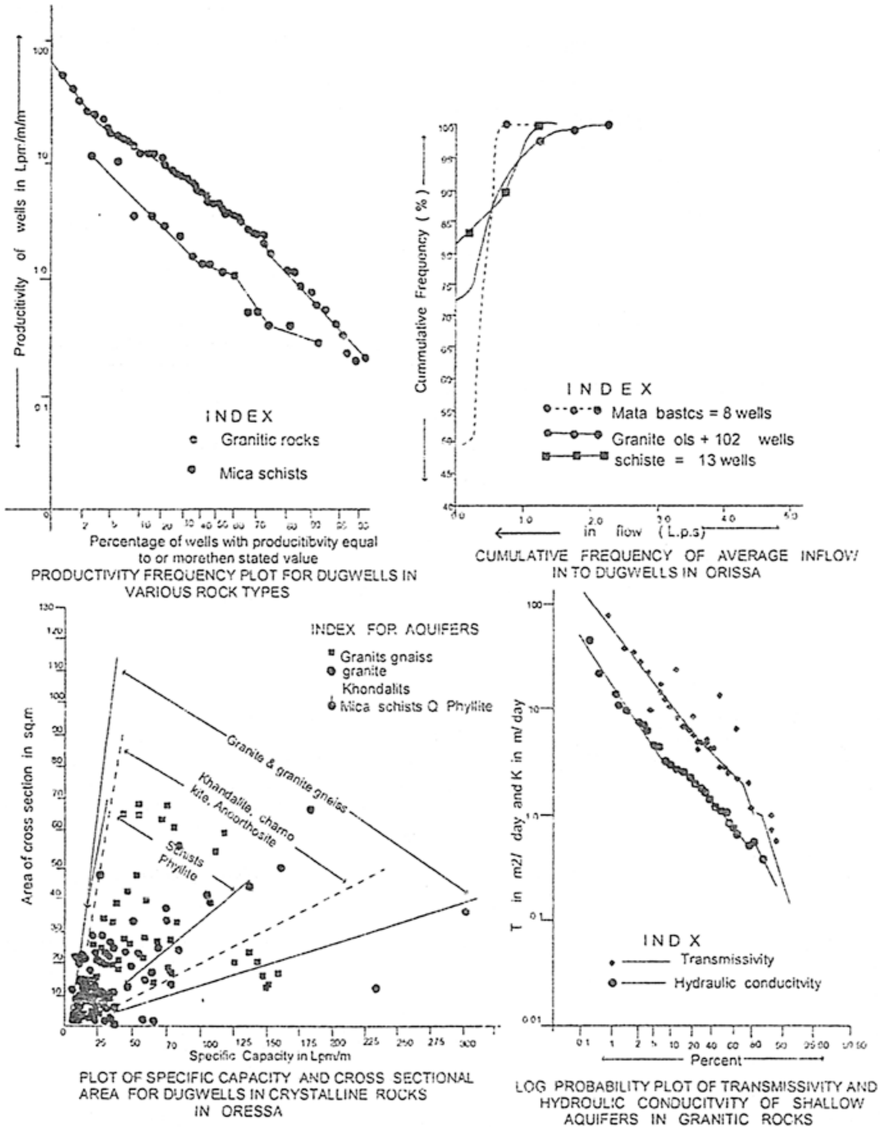
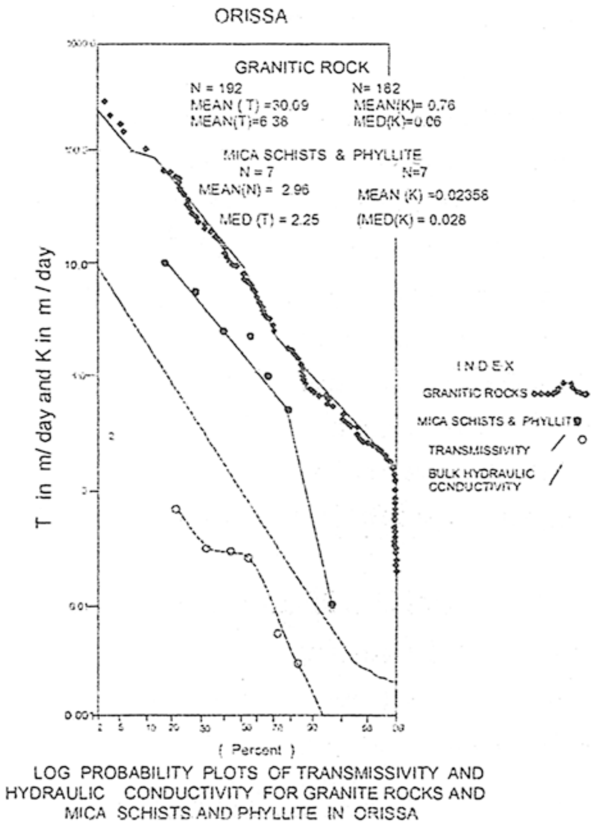


Fig. 5 Hydraulic characters of shallow aquifers in basement complex. (After Das and Chatterjee 1997)

Pradesh (CGWB 1982). Permeability is imparted by interconnected primary and secondary openings in the volcanic rocks and varies widely. The highest permeability is along the flow contacts. The permeability barriers developed due to variations in the nature and intensity of joints, fissures and weathering give rise to many irregularly shaped mini basins.

Fig. 6 Hydraulic characters of shallow aquifers in basement complex. (After Das and Chatterjee 1997)



2.3.2 Aquifer Productivity

Weathered and fractured granites and gneisses form the most potential water yielders under favorable geomorphic setups. Fractured metabasics and volcanics too form potential aquifers. While dug wells and dug-cum-bore wells yield 1–10 Lps, bore wells may yield up to 20 Lps or more. The contact zones of country rocks and basic intrusives, normally denoting tensile fractures, also yield copious water. In contrast, massive granites and charnockites do not form aquifers. The productivity of fractured sandstones and shales is almost similar ranging from <1 to 5 Lps. The yield depends upon the number of fractures tapped in the well, thickness of weathered residuum, and interconnection of the two. Quartz and pegmatite veins may yield up to 10 Lps. Bore wells in cavernous limestones in Belgaum district in Karnataka yield up to even 15 Lps. Well yields in Deccan Traps vary widely because of anisotropic and heterogeneous nature of the aquifers. Dug wells are the most favored structures sustaining yield of 100–150 m^3/day, while deep bore wells may yield 0.25–2 Lps.

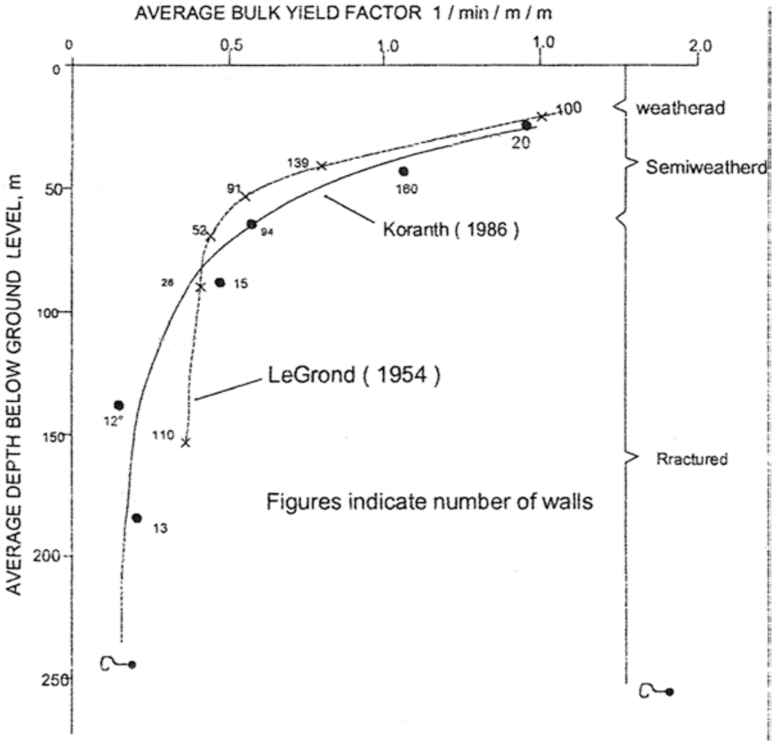


Fig. 7 Depth wise variation in productivity (yield factors) of saturated zones of granitic rocks in Peninsular India. (In: Karanth 1987)

Table 5 Porosity and specific yield of basaltic rock in Betwa River basin, Madhya Pradesh

Lithological type	Porosity range	Specific yield range and average
Weathered	0.10–0.34	0.02–0.26(av.0.03)
Fractured	0.005–0.15	0.008–0.10
Vesicular	0.10–0.50	0.01–0.03
Amygdaloidal	0.01–0.04	Insignificant
Compact	0.0–0.06	Almost nil

2.3.3 Response of Fractured Rock Aquifers to Pumping

In fractured rock aquifers, well productivity depends on fracture porosity both in the vicinity and away from the pumping well. The complexity of aquifer geometry which influences flow characteristics produces varied responses to well pumping as reflected in the time-drawdown curves of pumping tests. Kukilaya (2007) has studied the various characteristic responses to pumping in hard rock fracture aquifers of Thrissur, Kerala (Fig.8):

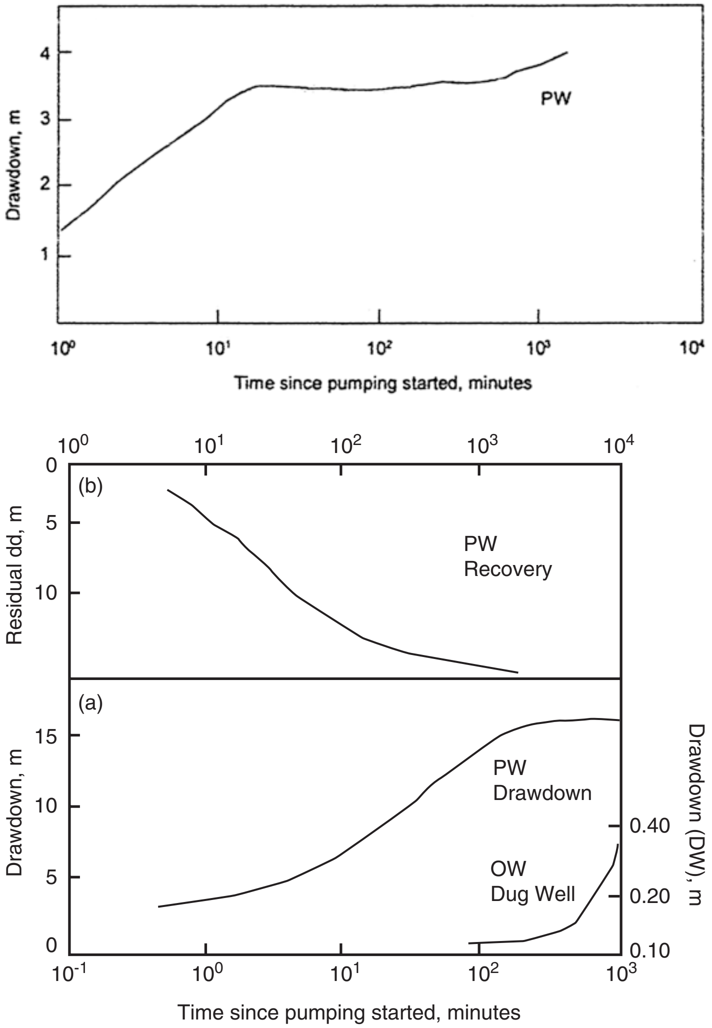


Fig. 8 (**a**) The drawdown curve of well no. 1 showing rising segments at intervals. (**b**) Drawdown/recovery curves of well No. 5 and OW (observation well). (**c**) Drawdown curve of well no. 6 showing cusps in late segments. (**d**) Continuous increase in slopes of drawdown curve of well no. 2 and OW indicating outer regions off lesser permeability. (After Kukilaya 2007)

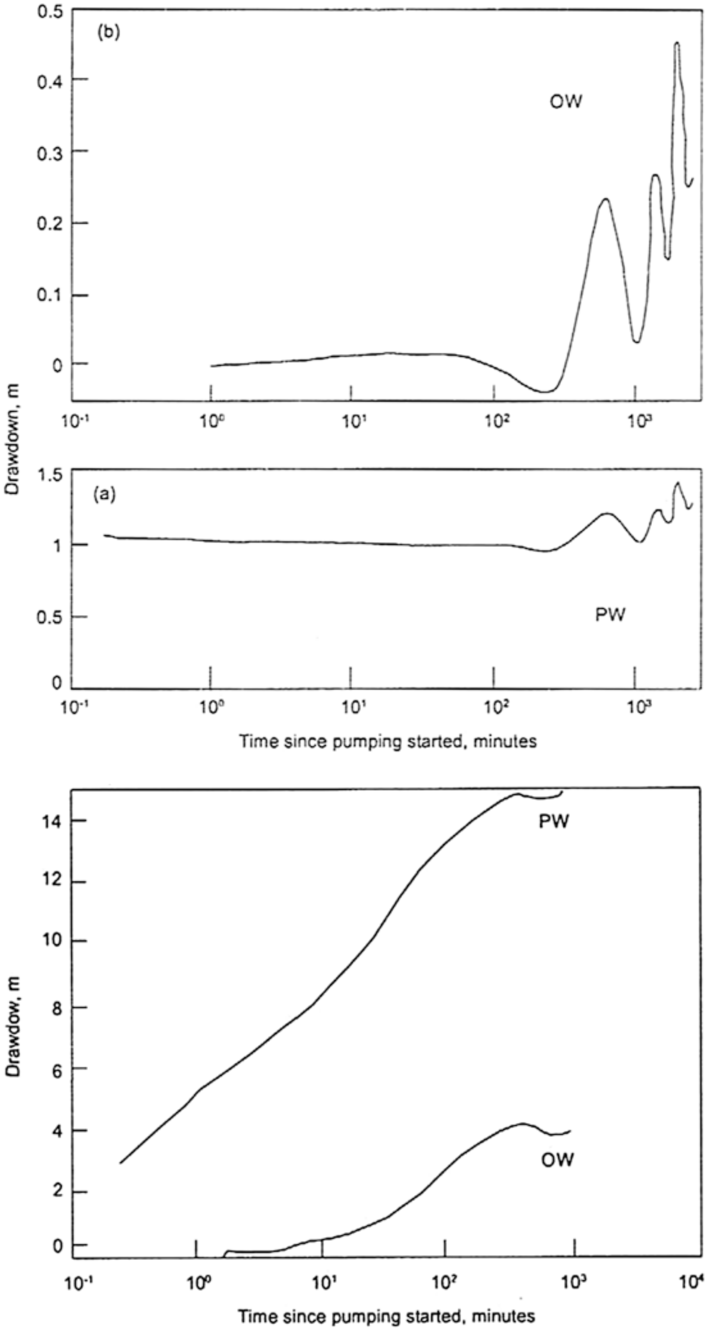


Fig. 8 (continued)

(a) Connectivity of fracture aquifer to phreatic aquifer. If the interconnection is high, the effects are noted in the nearby dug well.
(b) Heterogeneous aquifer-drawdown curves with different slopes at different times as the cone of influence spreads to regions with contrast in storativity of the regions.
(c) Response similar to double-porosity model. Transition limb develops within 20 min of commencement of pumping, followed by a second rising limb at a later time.
(d) Linear fracture zone with barrier (no flow) boundary on both sides. Bore well located along a lineament. The fracture zone with massive or slightly fractured rock on either side at distances less than 300 m. Boundary effect is seen when the area of influence reaches the massive/poorly fractured rock of low transmissivity. OW (observation well) curve shows continuous slope. In case of recharge boundary, drawdown stabilizes as the cone of depression reaches a surface water body and starts drawing from it.
(e) Complexities of fracture network may cause ambiguous responses in rocks with double porosities. The initial rising limb may be absent or very short if fracture porosity is negligible. Or the late-time segment may be negligible within the time period of test. The late rising segment may be punctuated by small cusps showing short spells of water level stabilization and/or rise during pumping.
(f) Drawdown curves of observation wells located at various distances, trend parallel to each other for more than 1000 min of pumping. It shows homogeneous behavior of fracture aquifer over a large area.

It is a common experience that in wells drawing from fracture systems, the initial high or moderate yield decreases or increases with time. Usually after 4–5 h of pumping, steady-state condition is achieved in most of the cases which indicates that the weathered and semi-weathered zones are regionally extensive notwithstanding local inhomogeneities. In the hard rock terrain, only long-term-specific capacity gives optimum well yield (Larsson 1984; Karanth 1987; Das 2000).

3 Stratigraphic and Geographic Distribution

The hard rocks composed of consolidated and fractured igneous, volcanic, metamorphic, and sedimentary formations are vestiges of ancient cratons and depositional basins. These are widely distributed in Peninsular shield areas occupying nearly 22 lakh km^2 area. Deccan Trap volcanics extend over 5 lakh km^2. The following Table 6 presents in a nutshell the hydrostratigraphy and distribution of hard rocks in India. Figure 9 presents the hydrogeological map of Peninsular India.

The following are some of the states where the hard rock formations are the dominant hydrogeological units having maximum aerial coverages: Karnataka 98.44%, Kerala 88%, Tamil Nadu 73.33%, Andhra Pradesh 83%, Maharashtra 91.71%, Jharkhand 93%, Orissa 80%, Rajasthan 45%, Madhya Pradesh, and

Table 6 Hydrostratigraphy of hard rock formations and state-wise distribution

Geological age	Formation	Lithology	(a) States, (b) hydrogeological characters
Jurassic to Eocene	Deccan Traps/ Rajmahal Traps	Basalts, dolerites, diorites and other acidic derivatives of basaltic magma	(a) W. Bengal, Jharkhand, Madhya Pradesh, Gujarat, Maharashtra, Andhra Pradesh, Karnataka. (b) Almost same as Archaeans/ Precambrians. Fractured and vesicular basaltic layers are productive. Yield <5 Lps. Unconfined shallow aquifers, leaky confined/confined deeper aquifers
Precambrian to lower Cambrian	Cuddapahs/ Delhis/ Vindhyans and equivalents	Sandstones, shales, conglomerates, limestones, dolomites, quartzites, marbles, intrusive granites and Malani volcanics	(a) Rajasthan, Delhi, Uttar Pradesh, Gujarat, Odisha, Andhra Pradesh, Karnataka, Chhattisgarh. (b) Devoid of primary porosity. Weathering, denudation, structural weak planes, fractures impart secondary porosity/ permeability in rocks. Solution cavities in carbonate rocks give rise to large groundwater storage/circulation, limited to 100 m depth. Generally Yield <1–4 Lps. Leaky confined/ confined aquifers in layered formations. Groundwater Potentials limited
Archaean	Basement complex, Dharwar, Aravalli and equivalents	Granites, gneisses, charnockites, khondalites, schists, slates, phyllites, banded hematite quartzites (Iron Ore Series)	(a) All states. (b) Weathered residuum and fractured zones form aquifers. Both unconfined and semiconfined/ confined aquifers. Granites/granite gneisses most productive aquifers. Limited within 90–100 m depth. Yield 2–10 Lps, more in exceptional cases

Chhattisgarh. These are also some of the most drought-prone areas of the country. This underlines the importance of in-depth study of the nature, behavior, occurrence and flow characteristics of these fractured rock aquifers, and their yield potentials for groundwater development and management. The state-wise distribution of hard rock aquifers are as follows:

Andhra Pradesh Hard rocks include Peninsular gneisses, charnockites, khondalites, amphibolites, schists, and quartzites. The dug wells in granites and gneisses yield 68–227 m^3/day and in khondalites 45–136 m^3/day which dwindles in summer. The bore well yield ranges from 1 to 10 Lps or more. The open wells in amphibolites and schists yield 5–125 m^3/day, and bore well yield is limited. While bore wells in Kurnool formation of shales, limestones, slates, quartzites, and limestones yield 0.41–13.88 Lps, bore wells in vesicular traps (Deccan Traps), 40–120 m deep, yield 3–146 m^3/h for a drawdown of 6 m.

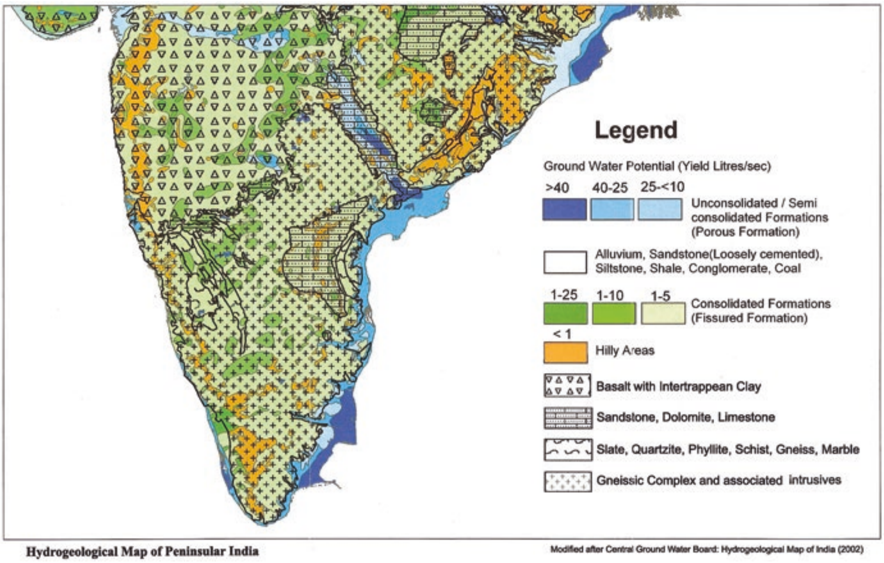


Fig. 9 Hydrogeology of Peninsular India. (Modified after CGWB: Hydrogeological Map of India 2002)

Assam In the highland plateaus of Shillong-Mikir Hills, the yield of the weathered, fractured/fissured Archaean and Precambrian metamorphic rocks is of the order of 5–30 m^3/h.

Gujarat The yields of wells tapping gneisses, schists, phyllites, quartzites, and metamorphosed igneous rocks vary from a few cubic meters to 100 m^3/day. However tube wells in Deccan Traps at favorable locales yield up to 10 Lps. Dug well yields though generally low are sometimes reported to be as high as 500 m^3/day.

Jharkhand Gneisses and granitic rocks with associated schists and quartzites constitute the hard rock terrain. Bore wells, 100–180 m deep, yield 2–70 m^3/h while bore wells in Rajmahal Traps, 99 m deep, yield in the range of 6–51 m^3/h.

Karnataka The Archaean crystallines occupying 75% of the state are composed of composite gneisses, migmatites, granites, quartz veins, and also charnockites in a limited tract. Dug wells in granitic rocks yield 50–250 m^3/day, while reportedly bore wells yield up to 481 m^3/h for 10 m drawdown. The schistose rocks which occur widespread may yield up to 15 Lps in bore wells. Proterozoic limestones with karstification and solution cavities occurring in a wide area between Lokapur and Bagalkot also form a potential aquifer, bore wells yielding 12 m^3/h for 20 m drawdown.

Kerala The crystalline formations occupying eastern upland tract include gneisses, granites, charnockites, khondalites, amphibolites and schistose rocks. Bore wells drilled in gneisses yield <1–20 Lps or more but generally 1–5 Lps. Bore wells in charnockites may yield up to 10 Lps or more.

Madhya Pradesh Crystalline formations are comprised of granites, charnockites, granulites, basic and ultrabasic rocks, schists, gneisses, and quartzites. The yield of dug wells varies from negligible to 500 m^3/day for drawdown of 4 m while that of drilled wells (45 m deep) up to 10 m^3/h for a drawdown of 15 m. Proterozoic cavernous limestones yield up to 1000 m^3/day for 4 m drawdown in dug wells and up to 1 m^3/h for 15 m drawdown in bore wells. The other Proterozoic rocks like sandstones and shales are not good water yielders. Fissured and vesicular members of trappean basalts are the productive aquifers. Dug wells yield 200–450 m^3/day for 4 m drawdown, but bore wells may yield up to 40 m^3/h for 15 m drawdown.

Maharashtra Dug wells and dug-cum-bore wells in granites, gneisses, schists, marbles, granulites, quartzites, and phyllites may yield 45–100 m^3/day and, in favorable locations, 150–250 m^3/day. Dug wells and dug-cum-bore wells are common in these formations. Weathering, fracturing, jointing, and solution cavities render quartzites, shales, and limestones that are porous and permeable. While dug wells in these formations yield 25–75 m^3/day, bore wells or deep dug-cum-bore wells tapping karstic zones in limestones may yield in the range of 250–350 m^3/day. Deccan Traps, the most dominant geological formation in the state, have poor water-yielding potential. But bore wells, 20–150 m deep, may yield 0.5–5 Lps though yield up to 10–25 Lps is not uncommon.

Odisha Consolidated formations are comprised of granites, gneisses, schists, khondalites, charnockites, and Precambrian sandstones, shales, and limestones. Weathered and fractured granites and granite gneisses form productive aquifers yielding 2–10 Lps, but the others yield 1–5 Lps. Bore wells in granites and granite gneisses, 100–150 m deep, may yield up to 30 Lps under favorable geomorphic setup.

Rajasthan Crystalline rocks are poor water yielders. Vindhyan sandstones and limestones in parts of Kota, Jhalwar, Bundi, Chittorgarh, Jodhpur, and Nagaur districts yield copious water due to locally pervious nature. The yield ranges of wells in these hard rocks are 5–25 m^3/h but more in fractured crystallines and limestones.

Tamil Nadu Hard rock aquifers including gneisses, charnockites, khondalites, and ultramafics are generally low yielding except in isolated patches. However folded quartzite bands and cavernous limestones form potential aquifers. Yields of open wells may range from 10 to 256 m^3/day. Bore well yields in Madurai and Coimbatore districts, 25–305 m deep, may range from 13 to 363 m^3/h.

West Bengal Yield potentials of granitic and basaltic aquifers in Purulia, Bankura, and Birbhum districts are in the range of 1–6 Lps.

Table 7 State-wise groundwater resources and development stage

States	Total[a] annual recharge	Total[a] annual draft	Critical blocks/ mandals /taluks[b]	Overexploited blocks/ mandals /taluks[b]
Andhra Pradesh	35.89	14.51	15	83
Chhattisgarh	12.42	4.05	2	1
Delhi	0.31	0.39	2	18
Goa	0.24	0.04	0	0
Gujarat	18.57	11.86	5	24
Jharkhand	6.31	1.86	0	6
Karnataka	17.03	9.41	21	63
Kerala	6.69	2.84	2	1
Madhya Pradesh	35.04	18.83	4	24
Maharashtra	33.95	17.18	2	10
Odisha	17.78	4.73	0	0
Rajasthan	11.94	14.84	24	172
Tamil Nadu	21.53	14.93	48	372

[a]In billion cubic meters.cm
[b]Nos

The following Table 7 presents the status of the estimated groundwater resources and their development in the major hard rock states of the country. The groundwater development is uneven being rather subnormal in many parts of the hard rock terrain. The highest stage of development is in Rajasthan, Delhi, and Tamil Nadu, followed by Karnataka and Gujarat.

4 Changing Geohydrological Scenario

Since 1950 with the appreciation of groundwater as a sustainable source for irrigation and drinking water capable of withstanding 2–3 seasons of consecutive droughts, easy to develop with small individual investments, ubiquitous in occurrence, groundwater exploitation has been steeply on the rise, emerging as major rather than supplemental source of irrigation (more than 60% of total irrigation), sole source of potable water in rural India, and a vital source of urban water supplies. But with millions of groundwater users and its unregulated withdrawal, it has eventually led to overexploitation, wastage of resource, and pollution impacting the ecology and environment. The abstraction structures for irrigation increased from 5,875,909 in 1983 to 18,503,267 in 2001 as the irrigation potential from groundwater jumped from 22 mha in 1980 to 50.34 mha in2012. Mining and other industrial activities, too, have left profound adverse impact on the groundwater regime. Number of overexploited blocks or talukas is on the rise. Wells dry up, cost of water lifting increases due to declining water levels, well yield decreases and so also baseflows in rivers, agriculture output decreases as well as command shrinks, and drinking water becomes scarce. Plants and wetlands which sustain on shallow water table are destroyed. Overall economy is adversely affected leading to rural unemployment and migration of people. A few case studies of long-term changes in groundwater regime over the last few decades in the hard rock-dominated Peninsular shield areas as carried out by several workers are briefly narrated below (In: Das ed. 2008) which gives a glimpse of the emerging situation of groundwater depletion. But the scenario is not overwhelmingly the same across the entire terrain as the groundwater development is subnormal in many parts. In the canal commands, water logging is widespread due to rising water table because of the excess of recharge from the return flow of irrigation waters combined with limited groundwater exploitation. The rainfall pattern, too, influences the water levels. Even falling or rising trends of water levels in a decade may be reversed in consecutive seasons of excess or deficient rainfall respectively. The water table trend being resultant of interaction between recharge and discharge processes is influenced by cumulative rainfall departure (Das et al. 1990, 1998a).

Further, quality monitoring through permanent observation wells (Network Hydrograph Stations) has brought to light rising incidences of deterioration of groundwater quality with its progressive development in many parts of the terrain either from geogenic sources or due to anthropogenic activities. High fluoride (>1.5 mg/L) and nitrate (>45 mg/L) are common contaminants of groundwater in this terrain which have crippling effects on health. High iron too is a deterrent to groundwater usage in places.

Andhra Pradesh Since the 1950s Andhra Pradesh has *seen a steady* escalation in groundwater development to meet the ever-increasing need for irrigation and food grain production and demand for drinking water of the rising population and for drought-proofing the country and its economy. As a consequence, during the last five decades, the irrigation potential due to groundwater as percentage of gross area irrigated increased from 11% to 49%. Paradoxically dug well irrigation declined by 52.86%, but bore well or tube well irrigation increased by 376% in the last 20 years. The number of dug wells recorded a fall from 9.63 (1982) to 9.20 lakhs (2004), as bore wells registered a rise from 0.63 (1982) to 8.72 lakhs (2004). Phreatic aquifer has been desaturated in major part of the state as revealed by groundwater monitoring data. The impacts have been perceptible (Sudarshan et al. 2008). Table 8 summarizes the changes in the resource status in the state since 1993. Figure 10 depicts the decadal water level trend in Andhra Pradesh for comprehending the impact.

Table 8 Status of groundwater resources of Andhra Pradesh

Particulars	1993	2001	2004
Net groundwater availability (bcm)	29.99	32.20	32.95
Annual draft (bcm)	7.09	15.57	15.30
Stage of development (%)	25	40	45
No. and percent of dark/critical mandals	12 (1.06%)	79 (7.0%)	77 (6.8%)
No. and percent of overexploited mandals	8 (0.7%)	118(10.48%)	219 (19.46%)

Source: Sudarshan et al. (2000)

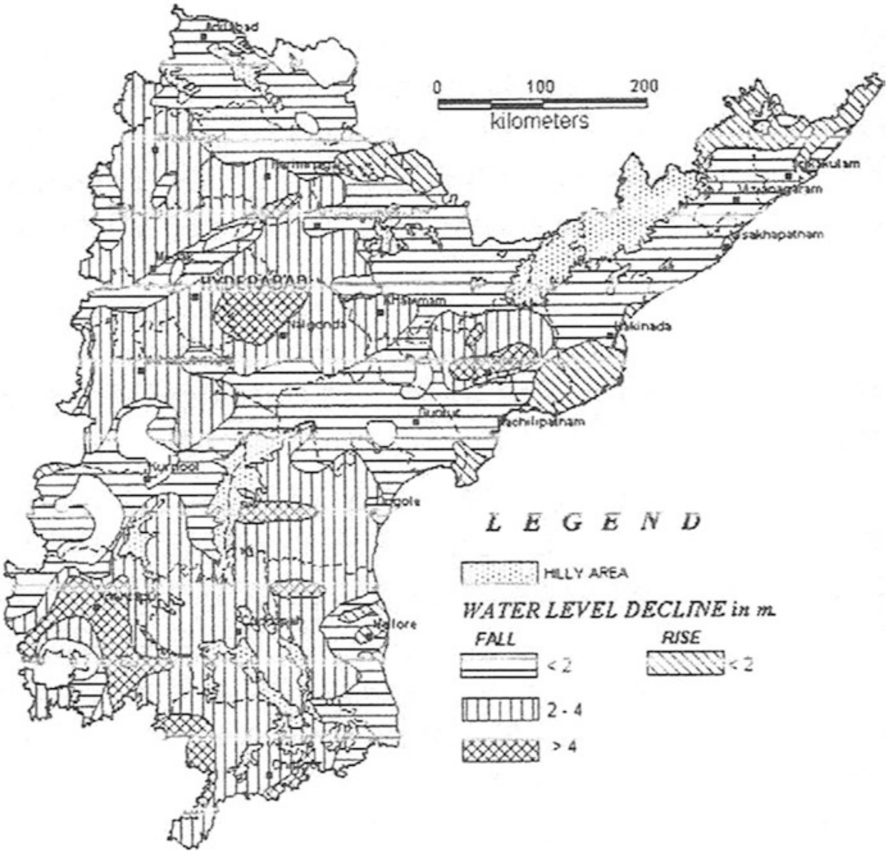


Fig. 10 Decadal trend of pre-monsoon water level (1996–2005) in Andhra Pradesh

Bore well depths nosedived from 30 - 60 m to more than 100 m and in some areas more than 200 m in 1990 onward with fall in bore well yields (Table 9), shrinkage of command area of individual bore well (from 1–3 to 0.5–1.5 ha), and drying up of many lower- or middle-order streams resulting from falling baseflows.

Historical hydrograph data point toward a sharp pre-monsoon decadal water level fall of 0.02–19.7 m and post-monsoon water level fall of 0.01–13.57 m, clearly as a result of indiscriminate groundwater withdrawal and overexploitation (Fig.11). The groundwater levels which were within 3–7 m in the mid-1970s have now dropped to more than 20 m in several parts of the state. The decadal water levels show an overall declining trend all over the state, with 32.6% wells recording a decline of 2–4 m and 20.6% 2–4 m and more.

Groundwater quality too deteriorates with growing contamination due to high salinity, fluoride, many alien chemicals like heavy metals caused by geogenic sources/reasons, or unregulated anthropogenic activities like discharge of untreated sewage or industrial waste waters, excessive use of chemical fertilizers/pesticides, and aquaculture practices.

Table 9 Change in groundwater structures and yields in Andhra Pradesh

Year	Type of well	Depth range (m)[a]	Well density[b]	Yield (range)
1982	Dug wells	8–12	<5	50–150 m^3
1983–1994	Dug wells/	8–12	5–10	50–150 m^3
	Dug-cum-bore wells	20–30		
	Bore wells	30–50		150–600 lpm
1994–1998	Bore wells	50–100	10–15	50–400 lpm
1998–2004	Bore wells	50–100	15–20	50–150 lpm

Source: Sudarshan et al. (2007)
[a]Meters below ground level
[b]No/km

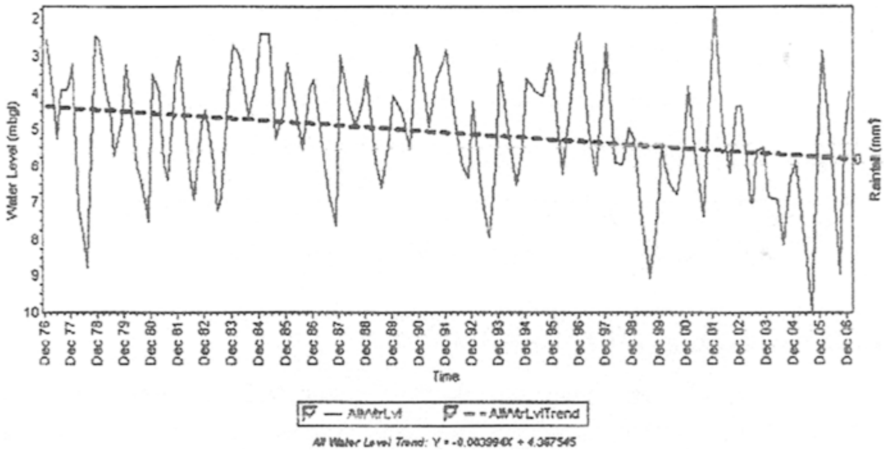


Fig. 11 A typical hydrograph of monitoring well at Srikalahasti in Andhra Pradesh. (Sudarshan et al. 2008)

Karnataka The situation in Karnataka is no different from Andhra Pradesh. Indiscriminate exploitation of groundwater has led to drying up of phreatic aquifers in most parts of the state along with deterioration in water quality, fall in well yields, and extinction of dug wells in most parts of the state (Najeeb et al. 2008). Figure 12 depicts increase in number of critical and overexploited blocks in the state and the severity of the situation.

Though the total area under irrigation has increased manifold, the area under surface water irrigation has dropped, but the same underground irrigation has phenomenally increased during the same period. The gross groundwater draft has increased from 5.68 BCM in 1992 to 9.41 BCM in 2011. In the last two decades, groundwater levels in several parts of the state are continuously declining. About 25% of monitoring wells have gone dry indicating a magnitude of the problem. Further 28% monitoring wells record a fall of 2–4 m and more in post-monsoon water level with reference to decadal mean showing thereby overexploitation. The

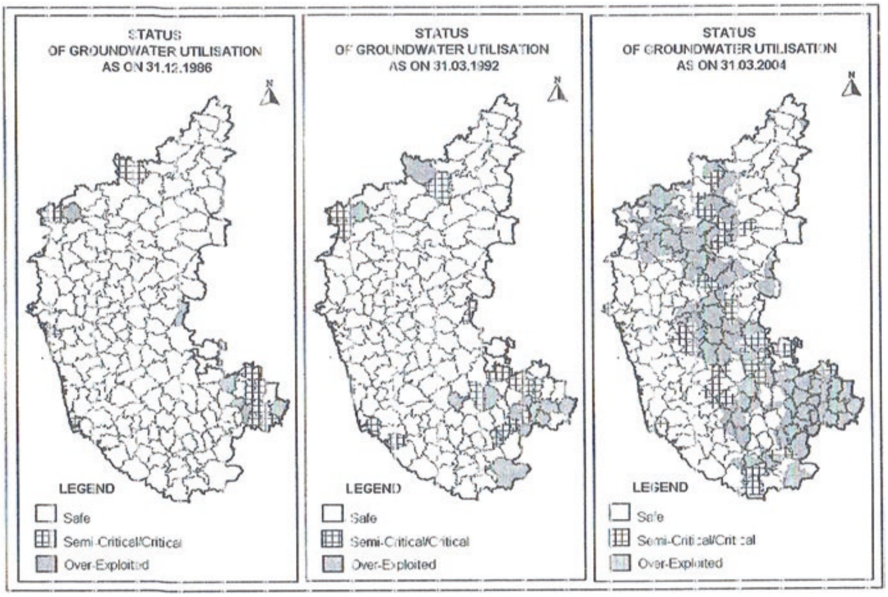


Fig. 12 Status of groundwater utilization in Karnataka (1986–2004). (Source: Report of CGWB on Dynamic Ground Water Resource of Karnataka 2004)

groundwater quality too is showing concurrent deterioration. While in 1992, 33% monitoring wells showed high nitrate (>45 mg/L) and 9% high fluoride (>1.5 mg/L), the numbers increased to 45% and 17%, respectively, in 2004. This alarming trend is seen all over the state.

Kolar Gold Mining Areas in Southwestern Karnataka An interesting study has been conducted on long-term changes of groundwater regime from 1909 to 2004 recording overwhelming depletion of pre-monsoon groundwater levels, deepest being in three areas, namely, Gubbi (49.91 m), Hosur (26.39 m), and Lakkur (33.2 m). Based on data of dewatering in the KGF mines, Ravindra and Sharma (2007) calculated that 0.3–0.4 MCM of water accumulated annually per square kilometers of the fractured zone of the mines area, while annual dynamic recharge was 0.09 MCM/Km^2. Thus dewatering in the mines, about 3000 m deep, was four times the annual recharge, entailing enhanced lateral flows from the surrounding region, thereby causing an annual drawdown of roughly 3 m over 4 km^2 of the area. They also observed that while groundwater depletion was mainly due to overexploitation, several major fractures connecting Kolar terrain at higher altitudes with the Palar valley region might have been conduits of gravity drainage of groundwater to lower altitudes of the river valleys. Figure 13 presents water level decline in the area from 1909 to 2004.

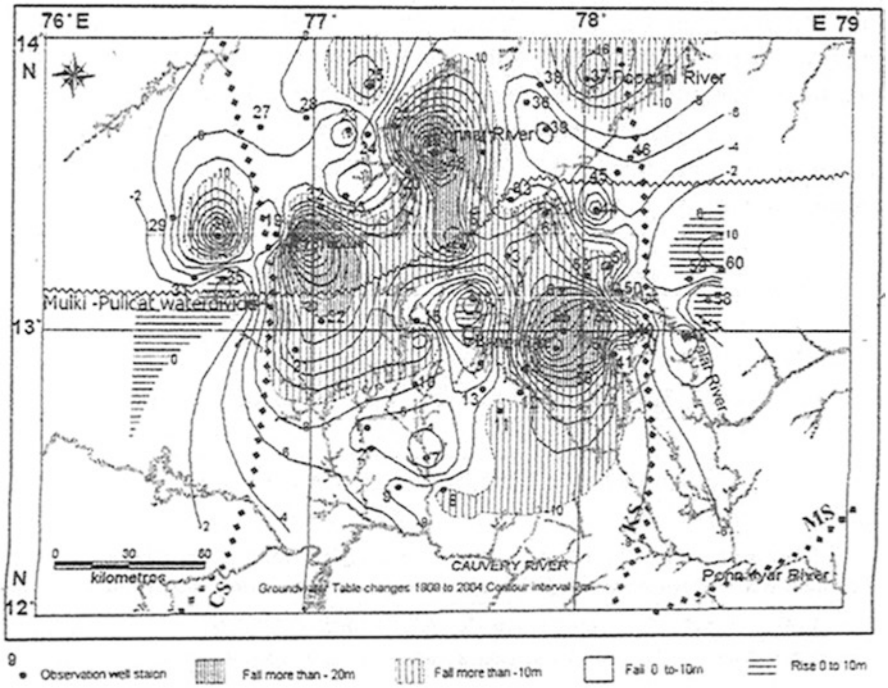


Fig. 13 Vertical water table fluctuation from 1999 to 2004 in southeastern Karnataka. Contour interval 2 m. Groundwater depletion (fall) contour values more than −20 m (vertical lines) shown as depletion nadirs. Contour values representing less than −10 m contours shaded with sparse vertical lines. Overall depletion zone (−8 m contour) mainly opens southeastward toward Ponnaiyar and Palar basins. (Ravindra and Nagaraaj Sharma 2007)

Financial Implications The economy of the rural population has been severely impacted by falling water levels. The farmers have been compelled to alter the cropping patter. Financial crisis has led to many farmers in debt trap committing suicides. Keerthiseelan et al. (2006) have attempted to estimate the loss of command area in Karnataka due to drying of tanks and wells (Tables 10 and 11). The financial cost has been a colossal loss of 323 crores.

The computation was based on data of dried up groundwater structures as on 2001. Afterward there have been consecutive drought years, and 80% of the wells in the overexploited districts have gone dry with severe financial implications. As on 2008, 71% of groundwater monitoring stations in pre-monsoon and 75% in post-monsoon seasons show declining trend of water levels.

Maharashtra Extensive studies have been conducted by Duraiswami and others (2008) on long-term changes in geohydrological regime of Maharashtra. The groundwater scenario in the state has undergone a sea change over the last three decades – from “surplus’” to “deficit” and “safe” to “polluted.” Over the last three

Table 10 Irrigation potential lost due to declining water level in Karnataka

Structure defunct	Unit draft (ham/annum)	Total water potential lost (ham/annum)	Crop water requirement (m)	Irrigation potential lost (ham/annum)
Dug well	0.6	28,810	0.79	36,468
Shallow bore well	1.1	2983	0.79	3776
Tank/pond	0.6		0.79	
Deep bore well	1.1	2186	0.79	2767

Source: Najeeb et al. (2007)

Table 11 Cost of defunct groundwater structures in Karnataka

Structure	Average unit cost (Rs)	Number of wells dried as on 2001	Loss of investment (Crore Rs)
Deep bore wells	3,1000	1987	6.16
Shallow bore wells	20,000[a]	2712	5.42
Dug wells	65,000[a]	48,016	312.10

Source: Najeeb et al. (2007)
[a]As per NABARD norm

decades with increasing water demands, the groundwater draft nearly doubled from 7, 73, 968 to15,08, 513 ham, while the water table declined from 4 to >50 m in some parts of the state, and the stage of groundwater development rose from 30% to 48% between 1985 and 2004, respectively. The depth of dug wells too increased commensurate with water table decline and increasing draft. An examination of number of wells and total groundwater draft shows that there is a general lowering of unit draft from 1.57 ham in 1974 to 0.97 ham n 2004, as the density of dug wells increases which tap the same finite resource. In the early 1970s, mohots were used in dug wells for water lifting which were gradually replaced by oil engines and power pumps with declining water table and deepening of dug wells leading to further exploitation and deepening of wells. With the induction of mechanized bore well rigs, the depth and number of bore wells increased sharply resulting in rapid increase in groundwater level especially during rainfall deficient years. Consequently dug wells in basaltic areas reached a depth of 20–30 m (Fig. 13), and these are the areas designated as critical or overexploited.

Similarly there are cases of deepening of wells in response to mine dewatering in eastern Maharashtra. Over the period there is also a gradual increase in the number of water-stressed areas – from 57 gray and 34 dark watersheds in 1985 to 87 gray and 26 dark watersheds in 1998, while in 2000 163 watersheds declared as semicritical, 20 critical, and 76 overexploited watersheds. Table 12 presents changes in resource status between 1985 and 2004.

The impact has been serious in some pockets with continuous increase in overexploitation and decline of water level. Over the years the area under well irrigation has increased from 19.62 in 1998 to 28.75 lakh ha in 2004 which accounts for 71%

Table 12 Comparison of groundwater assessments between 1985, 1998, and 2004 in Maharashtra

Division	No. of watershed	1985 Recharge (ham)	1985 Draft (ham)	1998 Recharge (ham)	1998 Draft (ham)	2004 Recharge (ham)	2004 Draft (ham)
Konkan	82	136,711	14,384	120,978	9219	84,678	27,270
Nashik	291	420,381	229,642	571,353	250,967	659,327	201,856
Pune	263	510,808	212,417	598,151	243,544	574,801	391,511
Aurangabad	332	712,595	165,934	788,018	214,396	892,541	392,087
Amravati	249	397,508	83,281	430,198	91,363	365,012	174,244,288
Nagpur	288	369,029	68,310	645,765	74,219	515,044	121,551
State total	1505	2,647,932	773,968	3,154,461	883,707	3,121,404	1,508,515

of the total irrigation in the state. Further there is a link between groundwater exploitation and cropping patter. The sugarcane, which accounts for only 4% of the state's well-irrigated area, consumes about 27% of the groundwater; the main sugarcane-growing areas coincide with low rainfall, arid megathermal and drought-prone region and hence the main critical and overexploited areas in the drought-prone region. Further cash crops like banana and orange too have adverse effect on groundwater regime in the northern and northeastern parts of the state. Thus there is a need for synchronizing cropping pattern, crop water requirement, and water availability.

Duraiswami and others (2008) have studied the spatial changes in groundwater quality and their trend. Large areas in Maharashtra have been affected by saline groundwater. The Konkan belt is characterized by the presence of creeks and estuaries of fast westerly flowing rivers. Ever-growing demands of agriculture and industries, high surface runoff, lack of major surface water projects, poor infiltration rates and storativity of hard rocks, and indiscriminate drilling have led to increasing dependence on groundwater and subsequent heavy groundwater withdrawal. This has caused reversal of hydraulic gradient along the coast, widespread saltwater intrusion damaging shallow and deeper aquifers of the region. Further there are inland saline hotspots in the upland drought-prone western Maharashtra around Dhule-Jalgaon, Nasik-Ahmednagar, Pune-Satara, and Sangli where along the banks of rivers, basaltic aquifers have shallow water table and calcretized soils which are susceptible to natural in situ salinity due to weathering and arid climate and the application of inorganic fertilizers. Change in land use and agricultural practices have increased the natural salinity. There are also fluoride hotspots in Precambrian metamorphic belt of Chandrapur-Nagpur-Yavatmal and Sindhudurg-Ratnagiri tracts, as also in Precambrian gneisses of Nanded district (up to 10 mg/L in groundwater) affecting deeper aquifers more, fluoride being sourced from weathering of fluorine-bearing minerals like muscovite, biotite, tourmaline, and apatite. Occurrence of high fluoride in groundwater of the Deccan Traps is being increasingly reported from the districts of Aurangabad, Jalna, Sangli, and Solapur. Excess iron in groundwater has also been reported from several parts of the state from lateritic aquifers of Konkan coast, from Precambrian terrains associated with banded-haematite-quartzites, as also from Deccan Trap basalts. Increasing incidences of nitrate contamination of groundwater from agricultural practices are reported from several parts of the state being a matter of concern since high concentration of nitrate causes eutrophication of water bodies and serious ecological and environmental damage. Thus groundwater pollution has been reaching alarming proportion in several parts of the state since the last several decades.

Tamil Nadu Based on the data of groundwater monitoring wells, Varadarajan et al. (2008) have analyzed the impact of excess rainfall in 2005 and normal rainfall in 2006 on the declining trend of the groundwater levels in the entire state during the period 1996–2005 mainly due to progressive groundwater development. All over the state, the depth to water level has been distinctly shallow in 2006. The situation may be visualized from the following Table 13.

Ninety percent of the monitoring wells recorded either rise or insignificant fall (0- <2 m), thus reversing the earlier trend of decline.

Varadarajan has also reported gradual deterioration of groundwater quality in Salem urban area due to infiltration of sewage water based on water quality analysis of surveillance wells from 2003 to 2006 (Table 14).

Table 13 Depth to water table status in selected wells in hard rock areas of Tamil Nadu

	Depth to water table (meters below ground level)					
	April 1978		May 1996		May 2006	
Districts	Min	Max	Min	Max	Min	Max
Coimbatore	2.88	10.70	2.20	49.36	1.28	39.03
Dharampuri	5.37	5.37	2.82	18.99	1.59	12.55
Dindigul	4.30	5.49	2.80	21.44	0.12	13.1
Madurai	2.35	6.82	1.18	12.27	3.13	7.66
Salem	9.44	9.44	2.37	19.63	2.3	11.46

Source: Varadarajan et al. (2008)

Table 14 Range of chemical constituents in surveillance wells in Salem urban area

Parameter	May 2003	May 2005	May 2006
pH	7.5–8.5	7.33–8.08	7.31–7.97
EC(μS/cm at 25 0 cm	520–7000	1448–9740	1922–10,630
TH as CaCo3	245–1500	270–2230	525–2650
Ca	47–336	12–164	88–440
Mg	31–294	58–472	61–377
Na	14–840	190–1280	198–1461
K	1–250	5–310	8–282
CO3	0–36		
HCO3	207–848	116–555	342–866
Cl	35–2113	241–3039	688–3261
SO4	23–512	38–680	50–2232
NO3	0–19.4	5–298	38–662
F	0.54–1.74	0.49–1.54	0.42–1.76

Source: Varadarajan et al. (2008)
Ionic concentrations in mg/L

Thus the groundwater resources are at risk from both quantity and quality aspects calling from protection through appropriate preventive and remedial actions.

5 Management Issues: Science and Technology

India is the highest consumer of groundwater in the hard rock terrains of the world, but still our knowledge of this valuable resource of the terrain lacks depth which is constraining its exploitation and management. This is because, so far, the stress has been laid on groundwater development in the more potential inland and coastal alluvial basins of the country, and the hard rock areas were neglected as rather barren of groundwater potential. Hard and compact nature of rocks, unpredictability of groundwater occurrence, and want of suitable deep well-drilling machines were the formidable constraints. Chronic water shortage is severe in the hard rock terrain especially in the arid and semiarid areas of the country. Scarcity of water had been mainly responsible for the stunted development and economic backwardness in the terrain. Since the 1970s the pressing need of expanding irrigated agriculture for boosting food grain production and the need for sustainable, safe potable water supplies, apart from insuring economy against recurrent droughts, led to stepping up of groundwater investigations, surveys, and exploration in the terrain. In addition, a number of pilot project studies on groundwater, both indigenous and also with foreign aid, were launched, namely, Canadian-aided Project (Telangana), UK-aided Betwa River basin Project (Madhya Pradesh), Sina-Man Project (Maharashtra), SIDA Project I in Noyil and Ponnani river basins (Tamil Nadu, Karnataka), SIDA Project II in Coastal Kerala and Vedavati river basin Project (Karnataka), UN-aided Kasai Subarnarekha basin Project (Jharkhand, West Bengal, Odisha), and a number of pilot projects on Conjunctive Use and Artificial Recharge studies in drought-prone hard rock areas of the country. Our knowledge of the complex hydrogeological setup of this terrain was boosted but still lags behind management needs. With exponential growth of population and ever-increasing demand of food and drinking water security combined with uncertainties of rainfall, climate change impacts, and surface water availability, management of groundwater being the only dependable source in this terrain has justifiably assumed the center stage.

The key issues in the groundwater management in the hard rock terrain are as follows: (1) heterogeneities in aquifer characteristics and distribution, (2) uneven and subnormal groundwater development in many parts of the terrain, (3) overdevelopment due to unregulated draft, (4) rising pollution of groundwater, and (5) lack of public awareness of hard rock hydrogeology. Hence, the guiding principles in addressing these challenges are as follows: (1) exploration and mapping of aquifers, (2) precise estimation of groundwater resources, (3) regulated development without exceeding recharge potentials, (4) conservation and augmentation of this finite resource, (5) protection from pollution and remediation of contaminated groundwater, and (6) public participation in groundwater development and management (Fig. 14).

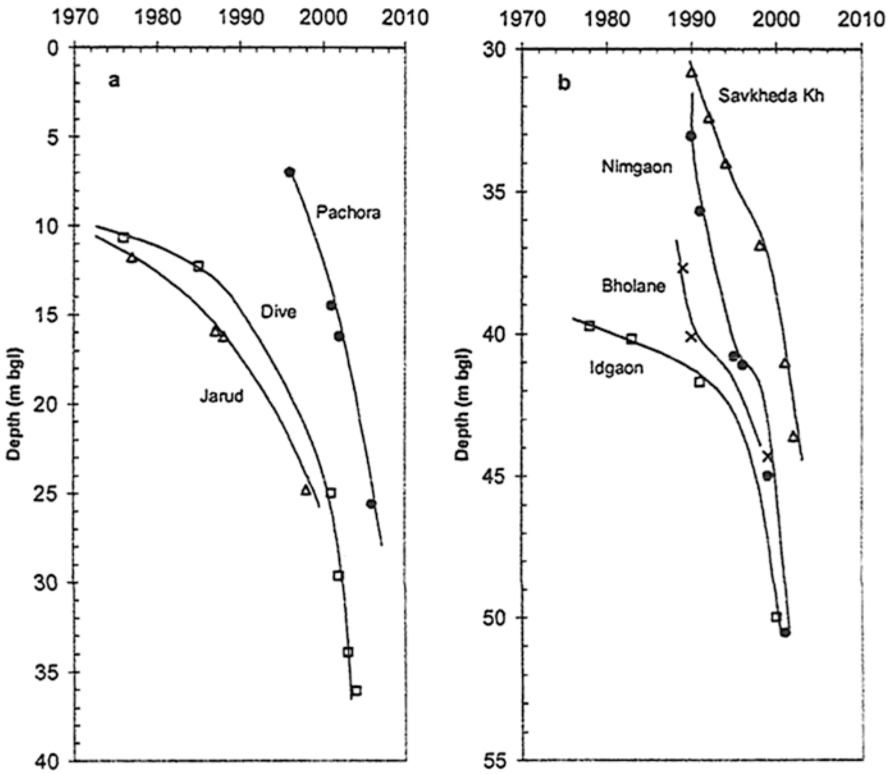


Fig. 14 Increase in depth of wells due to overexploitation and decline in water levels from 1974 to 2007 in Maharashtra

Large tracts of the hard rock terrain still remain unexplored resulting in meager development of groundwater. Exploration should be stepped up adopting a multidisciplinary approach including remote sensing, geophysics, and modeling aiding hydrogeological mapping of unknown aquifers, their potentials, and quality. Remote sensing is a powerful modern tool. Scanning of satellite imageries can demarcate hydrogeomorphic units and delineate fracture lineaments favorable for groundwater storage. This helps in the speedy coverage by hydrogeological surveys delineating the potential aquifers, groundwater movement, recharge-discharge areas, and their boundary conditions. Hydrogeological mapping invariably includes structural analysis in tectonically disturbed basement complex, and delineation or study of compound pahoehoe and simple flows, and their morphogenetic combinations. Geophysics is another useful tool as a cheap alternative to costly and time-consuming exploratory drilling. The commonly used methods are electrical resistivity soundings and profiling, electromagnetic surveys, VLF, and seismic refraction surveys which can help in subsurface imaging of the formations/structures holding possible groundwater storages based on variations in physical properties of the formations (Chandra et al. 2016). Heliborne ERT survey is the latest in geophysical methods

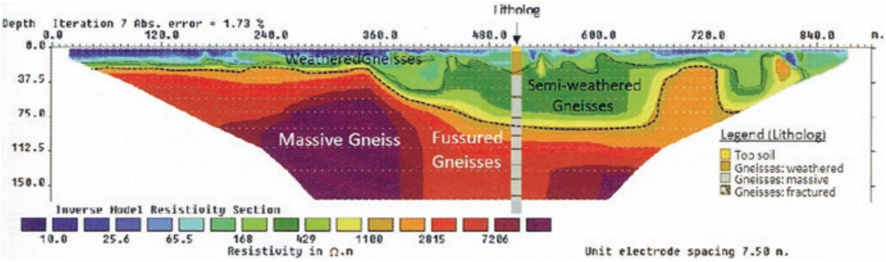


Fig. 15 High-resolution aquifer mapping-ERT image traversing from west (left end) to east direction in Sasalu village, Ankasandra watershed, Tumkur district, and Karnataka. (After Chandra et al. 2016)

effectively in use in regional hydrogeological mapping for 3D imaging supported by ground-based hydrogeological data (Chandra et al. 2016) (Fig. 15).

This should be followed by exploratory drilling, borehole logging, and pumping tests to identify the compute water-saturated zones, compute yield potentials and safe well spacing, and assess water quality.

Modeling studies should be undertaken to understand the flow dynamics in fractured rock aquifers, between weathered saturated zone and fractured media, as also between unsaturated and saturated zones. It also helps in understanding the system better and in generating the flow equations.

Precise estimation of the resource is basic to optimal development of the resource. But the norms used for recharge estimation in the hard rocks known for characteristic heterogeneities need to be precisely evaluated and computed. The current methodology of water table fluctuation method is not comprehensive enough for microlevel planning. Specific yield values and other recharge norms used in the estimation are mostly ad hoc, which should be refined intensive microlevel field studies and experiments. Other methods used in the estimation are water balance, soil moisture balance, and chloride balance which require detailed area-specific information. Tracer technique is an advanced method of groundwater estimation which should be promoted (Sukhija et al. 1983). More and more flow modeling will help in realistic assessment of the resource, and in generating its optimal development and management scenarios.

Optimal development and management of resource involves conservation and augmentation of the resource. Water conservation means fruitful use of water without wastage through measures of economizing water consumption in all sectors. Drip and sprinkler irrigations are two modern techniques for water economy in irrigation, the largest consumer of water in the country, which should be promoted. There is much scope of water saving in domestic usage and industries through adoption of water-efficient processes.

Conjunctive use of surface water and groundwater is the most efficient method of water conservation and promotes optimal development of all water resources in canal commands as established in the pilot project studies on conjunctive use by the Central Ground Water Board in Hirakud Irrigation Project (Odisha), Tungabhadra

Irrigation Project (Telangana and Karnataka), and Nagarjun Sagar Irrigation Project (Telangana) (Rao et al. 2016). It rectifies the aberration of water allocation in canal commands between head- and tail-end reaches, and rampant water logging in the irrigation commands, and enhances agricultural output and productivity of per unit water used.

Artificial recharge is another modern innovation for saturating overexploited aquifers by artificially increasing recharge rate. It also enables harvesting surplus monsoon runoff and conserving the same in the subsurface formations for usage at times of need. The structures required for the purpose are technically simple and cost-effective like gully plugging, check dams, percolation tanks, and subsurface dykes combined with soil moisture conservation techniques and watershed treatment (CGWB 1994; Anon 2002; Das et al. 1998b). Researches have revealed that artificial recharge and water conservation in arid and semiarid areas can be successfully implemented as part of integrated watershed management through community participation (Aswathanarayana 2012). Rainwater harvesting and conservation in drought-prone Arwari river basin in Rajasthan (Proterozoic sandstones, shales, quartzites, gneisses), Jain watershed in Jalgaon district, Maharashtra (Deccan Traps), and Ichalahalla watershed in Gadag district, Karnataka (granite gneisses), are shining examples (Singh 2007; Hiregoudar 2007; Das 2015). However, this essentially needs community participation and linkage with technical institutes for the success of the program. It is also a cost-effective means of diluting pollution load of contaminated groundwater.

Overexploitation should be scrupulously avoided. Groundwater exploitation needs to be regulated and restricted to annual recharge potential. Groundwater legislation may be enacted to enforce regulation of groundwater draft.

Periodical reappraisal hydrogeological surveys and groundwater monitoring through Network Hydrograph Stations will go a long way in the appraisal of long-term changes in groundwater regime with progressive development or climate changes to take timely remedial measures.

Fluoride and nitrate pollution of groundwater is an emerging menace. There are well-known people-friendly methods of defluoridation and denitrification of contaminated water which should be promptly applied as soon as the incidence of pollution comes to the notice. All-out measures are to be taken to protect the aquifers from pollution. Periodical groundwater quality monitoring, DRASTIC method of mapping vulnerable zones, and solute transport modeling to study pollutant movement and management options are three efficient modern tools for timely preventive actions.

Lastly, as groundwater is the people's resource used by millions, its management needs wholehearted participation of all sections of society and stakeholders, mostly unaware of the causes and aftereffects of overexploitation and pollution of groundwater. Hence mass awareness campaigns should be organized through print and electronic media and through training courses for the success of scientific development and management of groundwater. Modern science and technology plays a crucial role in groundwater management in hard rock terrain.

Acknowledgments The author expresses his deep gratitude to Dr. S.P. Sinha Ray for his constant encouragement in writing paper. The paper draws extensively from various published and unpublished sources which are duly acknowledged.

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Characterization of a Deep Saline Aquifer Using Oil Exploration Data in an Arid Region of Rajasthan, India

Ranjan Sinha and Ashok Kumar

Abstract Finding large volume of saline water to support oil field developments in an arid region of the Barmer Basin, Rajasthan, India, was a challenge. Prior to this study, very limited information was available about aquifers deeper below 150 m below ground level (bgl). The present paper describes the characterization of a deep aquifer system using oil field data acquired during hydrocarbon exploration and development. The objective of the study was aimed to identify saline water that has no practical use for domestic or irrigation purposes at economically viable cost without any adverse effect on freshwater system. Detailed regional hydrogeological study has been carried out using oil exploration data, i.e. seismic, geophysical logs, etc. followed by aquifer well drilling and testing to understand the hydrogeology of the southern part of the Barmer Basin. It has been found that extensive confined multiaquifer systems exist between 150 and 1000 mbgl. Aquifers were identified by using oil field well logs and cores of exploration and development wells. Four distinct groups of permeable granular zones separated by impermeable zones have been identified. The spatial extent of the aquifer has also been mapped with the help of seismic reflection data. Finally, geometry and thickness of the aquifer have been defined of each layer with reasonable accuracy. The salinity data of drilled wells indicate that groundwater salinity increases with depth. Brackish (2500 mg/L) groundwater occurs at the top and becomes highly saline (~17,500 mg/L) at the bottom. An extensive deep confined saline aquifer has been identified in Jagadia (Miocene) formation. Aquifer test has been conducted to understand the hydraulic characteristics and water quality of this aquifer. The results indicate that hydraulic conductivity is in range of 20–25 m/day in the Jagadia formation. Salinity of groundwater is ~17,500 mg/L. The aquifer is shallower in the north and gradually deepens southwards where aquifer top is ~1500 mbgl. The gross thickness of sand in the Jagadia formation varies from 25 m to a maximum of 600 m (south-east). The total gross calculated volume of the aquifer is ~2.6×10^9 m^3. The aquifer contains unconsolidated to poorly consolidated, medium- to coarse-grained, moderate to well-sorted, subrounded sands. Quartzose with carbonaceous claystone and clay

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S. P. S. Ray (ed.), *Ground Water Development - Issues and Sustainable Solutions*, https://doi.org/10.1007/978-981-13-1771-2_4

interbeds and minor lignite are also present. Grain size analyses indicate a mostly uniform formation with the majority of samples having a uniformity coefficient of 4 or less. The effective porosity has also been derived from petrophysical logs, and it is ~20% in the northeast and increases to ~30% in the southeastern boundary. This large static groundwater resource within the Jagadia formation below ~250 m depth has been identified as suitable aquifer for saline water abstraction to meet the long-term saline water requirement of oil fields in the southern area of the Barmer Basin. This aquifer is not in use for domestic and irrigation purposes due to salinity and its depth of occurrence. Saline water abstraction is not likely to deplete the limited dynamic shallow groundwater resources.

Keywords Groundwater · Hydrogeology · Deep confined aquifer · Salinity · Arid · Miocene

1 Introduction

1.1 Scope of the Study

Cairn needs saline groundwater supply for its southern field development located in Barmer District. The saline groundwater supply is required to optimize the oil production as well as for various operational activities for the entire field life. The lack of other sources for water in the area makes locally available deep saline groundwater, the only suitable option to meet water requirement for oil field development. Cairn is committed not to use fresh water for field operations. Instead, Cairn will utilize saline water from the deep confined aquifer of Miocene formation. The saline water of the deep confined parts of the Miocene formation is not in use for domestic and irrigation purposes. The objective of this study is to provide a detailed assessment of the aquifer's potential as a source for oil field water requirement.

1.2 Location of the Study Area

The study area is a part of Luni river basin and falls under parts of Barmer and Jalore District. The site is located close to the river (Fig. 1). In some part of the study area, the Central Ground Water Authority (CGWA) has categorized shallow aquifer as overexploited. Study has been carried out to explore the deeper saline aquifer without affecting the shallow aquifer system for oil field development.

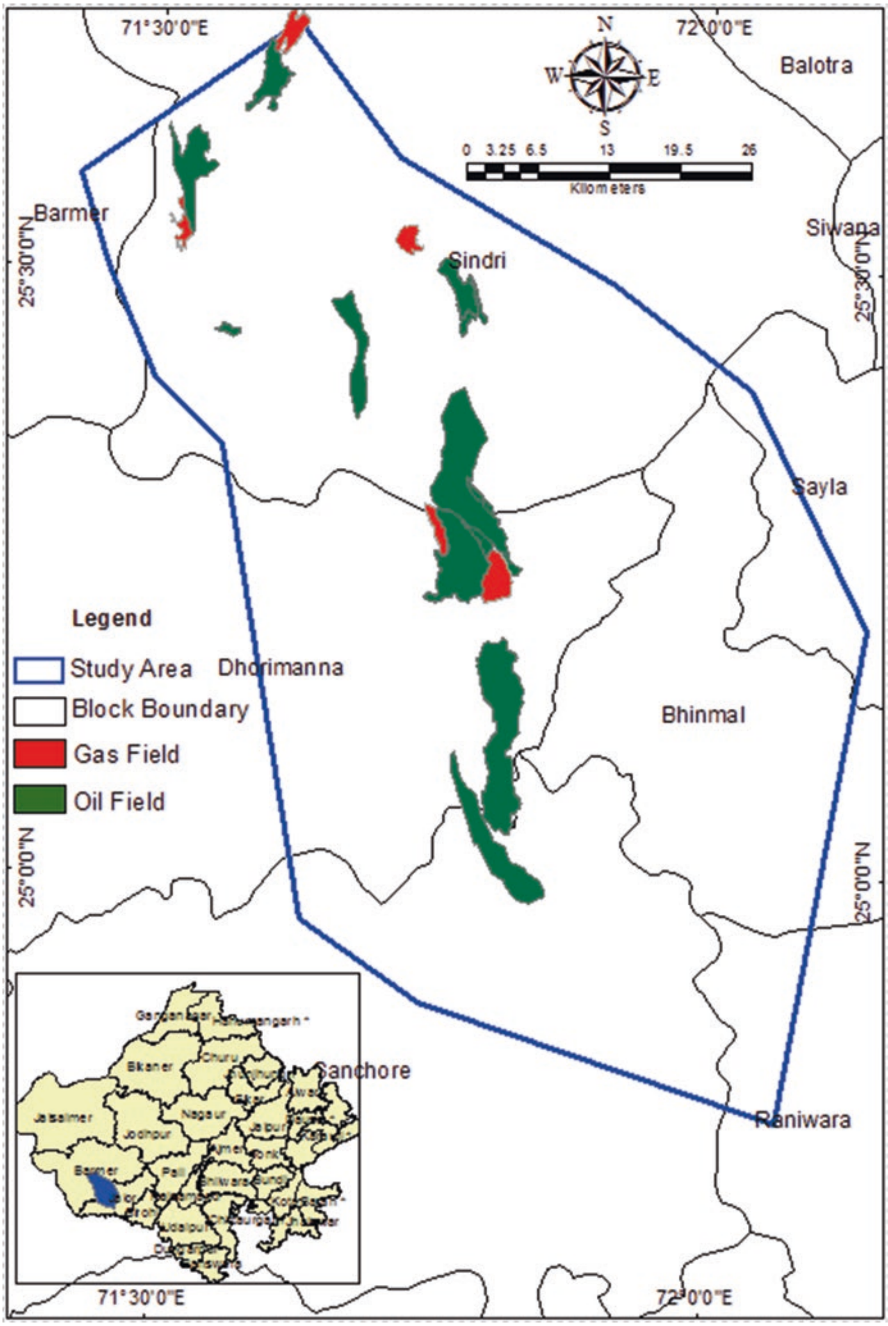

Fig. 1 Location map

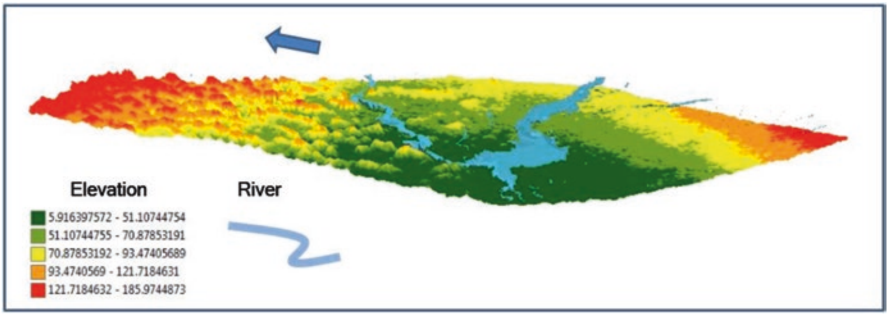

Fig. 2 3D view of topography of the area

1.3 Topography, Drainage and Climatic Condition

The regional topography of the area is shown in Fig. 2. High and low sand dunes, elongated inter-dune depressions, sandy plains and other arid landforms characterize the landscape of the area. The area receives annual rainfall of 250 mm or less. The maximum rainfall occurs from July to September. No significant surface run-off enters or leaves the study area. There is no major check dam/dam to collect the rainfall run-off. The closest significant watercourse is the Luni and Sukri Rivers to the south-southeast. Rainfall run-off mostly drains into the River Luni which is not perennial in this area. However, base flow is available throughout the year.

2 Geology of the Area

The Barmer Basin in western Rajasthan is a northern extension of the hydrocarbon-productive Cambay Rift with sedimentary fills that are primarily early Tertiary in age. It trends roughly NNW-SSE, is fault-bounded on both flanks and was initiated as a rift basin during the late Cretaceous-early Tertiary.

Within the Barmer Basin, in the southern area, the Base Miocene Unconformity (BMU) is overlain by a thick (up to 1200 m) sequence of gravels, sands, silts, clays and shales. From detailed biostratigraphy and sequence stratigraphy investigations, these sediments are recognized as probably being mostly Miocene, ranging to Recent in age (25–0 MYa). The predominantly arenaceous nature of the sediments and the recovery of sparse but exclusively terrestrially derived palynomorphs from the biostratigraphical analyses suggest a relatively high-energy, fluvio-deltaic palaeoenvironment. Braided stream gravel deposits, floodplain clays and meandering channel sands are the likely depositional products. Limestone is sometimes evident as small stringers, perhaps as an indicator of occasional marine influence and particularly so at the BMU itself.

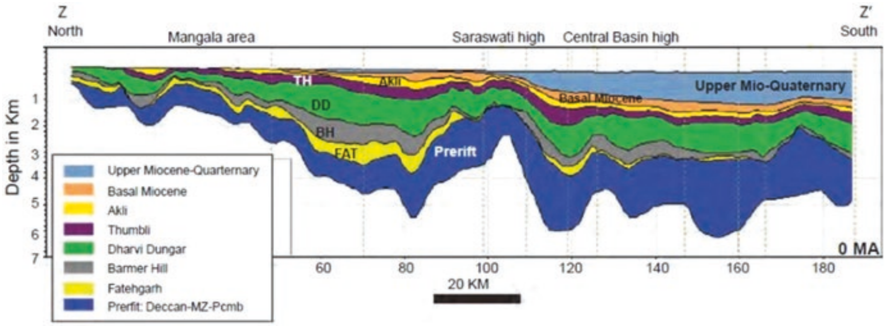

Fig. 3 North-south cross-section based on sonic travel times, apatite analysis, vitrinite reflectance, spore colouration and apatite fission track analysis (AFTA) studies together with seismic and calibration to the regional maturation model

The axis of the Miocene subbasin is approximately NNW-SSE with a pronounced southerly plunge, such that the Miocene thickness in the southernmost part of the area is greater than 1200 m. The basin is contained in a WSW-ENE direction either by faulting or the reduction of the Miocene through erosion onto the BMU which, whilst still the same unconformity, is overlain by Quaternary sediments as one moves eastwards.

A north-south cross-section (Dolson et al. 2015) based on sonic velocities, surface geology to seismic ties is shown in Fig. 3. The section shows that the northern part of the basin has not been buried as deeply as the southern part.

3 Geological and Geophysical Interpretations

3.1 Geological Interpretations

The hydrological mapping of the basin showing different potential aquifer groups was done using well data of exploratory wells. The lithologies are commonly described in all boreholes that have penetrated the Miocene formations as loose or poorly consolidated (Parkinson 2003). The mud logs, lithologs and geophysical logs were used to prepare the composite logs. All porous beds are regarded as water-bearing.

3.1.1 Log Picks and Demarcation of Marker Horizons

The geological interpretation of the area was done with the help of lithological logs and geophysical logs of the available boreholes. The principal log marker is the Miocene coal and Akli coal. Groups of strata having similar lithology were identified on the basis of marker coal horizons (Russel and Thickpenny 2004). Each such

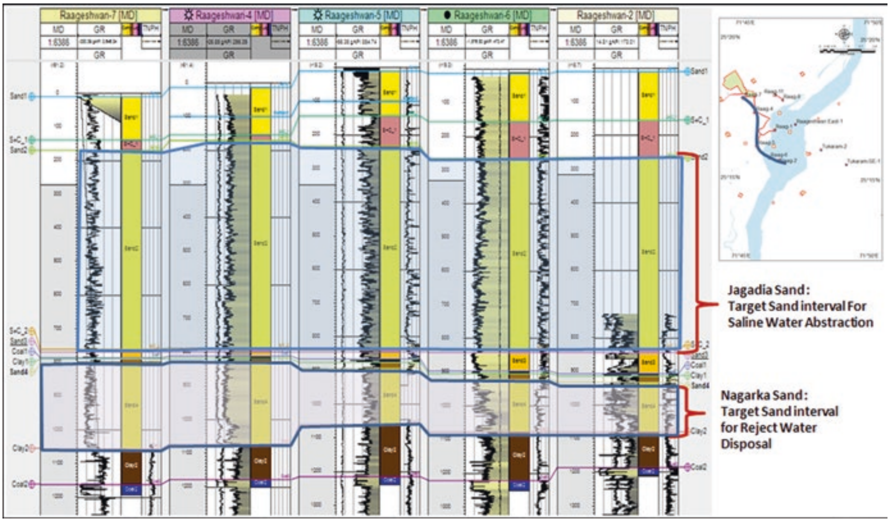

Fig. 4 Lithostratigraphic well correlation with the Akli coal displayed as the datum

group comprised of a number of individual sandy or clayey layers. But an individual group had diagnostic characteristics by which it was separated from others. The regional clay or coal which is extensive in the whole area is used for marking the major aquifer groups. Lithostratigraphically, the BMU is delineated in most wells by an underlying interval that is shaly and marly with thin lignite beds and by an overlying interval where the first of the series of sandstones are represented (CEIL 2004). Figure 4 shows the lithostratigraphic well correlation along N-S section extending from Raag-7 to Raag-2. The correlation sections help in visualizing the number, disposition and extension of aquifer groups in the study area as a whole.

3.2 Geophysical Interpretations

The 3D seismic data and the log data were tied at a number of wells distributed evenly across the study area. Synthetics were generated using wavelets extracted from the seismic. Bulk shifts of less than 30 ms were applied in different wells (CEIL 2002). The synthetic versus seismic match is generally good at most well locations. Coal-1, Sand-4 and Coal-2 horizons are seismically resolvable and hence picked throughout the project area. The seismic section showing the extent of sand and clay is shown in Fig. 5.

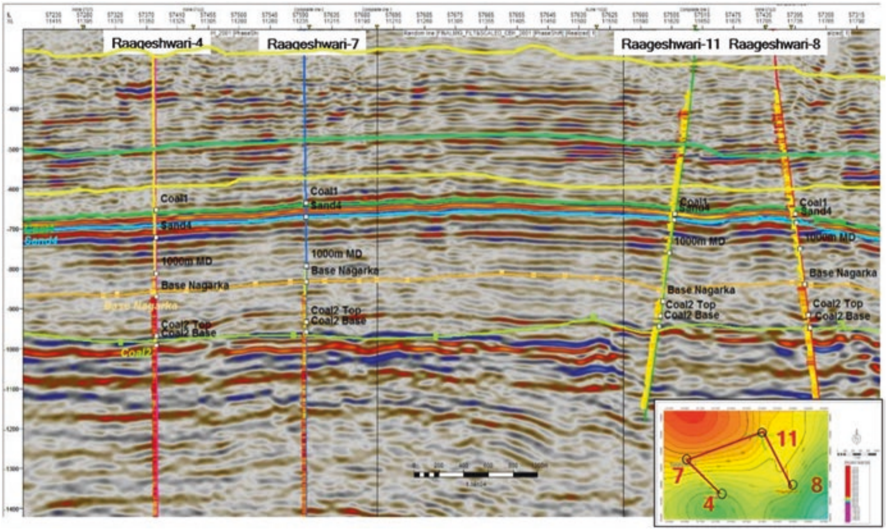

Fig. 5 The seismic section showing the extent of sand and clay

4 Mapping of Major Aquifer Systems

The aquifer mapping of the study area showing different potential aquifer groups was done for a depth up to ~1200 m by interpretation of lithological logs of the available boreholes. Further, with the help of these marker horizons, subsurface geological sections in the form of fence diagram connecting several exploratory sites (Fig. 6) were prepared. The regional picture of subsurface geology which emerges from the study is that four distinct aquifers (Aquifer-I, Aquifer-II, Aquifer-III and Aquifer-IV) of permeable granular sand separated by three different poorly permeable/impermeable horizons were identified. It is inferred that Aquifer-I is underlain by a clayey horizon 30–165 m thick which is regionally extensive and completely separated from Aquifer-II and spread over 30 km radius (Sinha and Kumar 2015a, b).

5 Grain Size Analysis

The degree of sorting and size of grains of sediments are of considerable importance in groundwater studies. Porosity and hydraulic conductivity are the hydrogeological parameters that generally depend on the size of sediment grains and the percentage of various sediment fractions. These were determined by mechanical analysis, which consist of separation of grains of various size groups by passing through standard sieves. The cuttings collected during exploratory and development drilling of oil well against the depth ranges of Jagadia aquifer were mechanically analysed

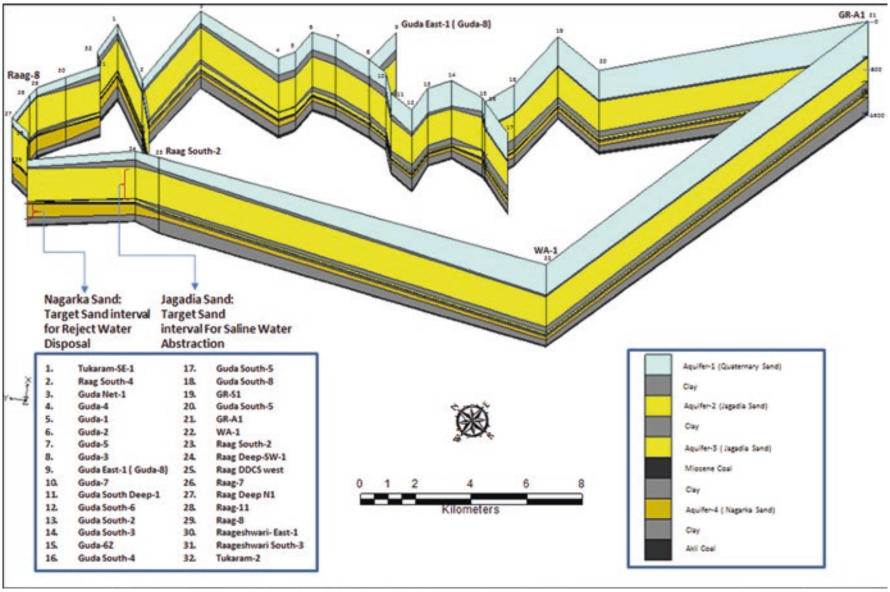

Fig. 6 Fence diagram connecting several exploratory sites of the study area

using sieves of 10, 4.75, 2.36, 1.18, 0.6, 0.3, 0.15 and 0.075 mm. The grain size distribution plot is also plotted on semilogarithmic scale (Fig. 7). The uniformity coefficient is found to be less than four in most of the cuttings which infers that the sediment is well sorted. The average effective grain size (d10) is 0.26 mm. The grain sizes of respective sites were used in empirical relations to determine the hydraulic conductivity variation of the area. Based on grain size analysis, slot size of screen and filter pack was also designed (Sinha and Kumar 2015).

6 Mapping of Aquifer's Salinity

Shallow freshwater unconfined aquifer system is available within the Quaternary deposit. The fresher water (TDS <3000 mg/L) lens within unconfined aquifer is mostly distributed in the proximity of River Luni and its interfluvial land (Fig. 8). Aquifer is recharged on annual basis, and salinity improvement depends on the yearly quantity of rainfall in the area. The field data has indicated rise in water level in the area after the major rainfall event in the year 2006. The average recharge depth to the unconfined aquifer has been estimated to be in range between 1.0 and 1.5 m. Prior to major rainfall event of 2006, there was constant deterioration in the quality of the groundwater, but after rainfall improvement in water quality has been observed. This is the aquifer which is mostly tapped for drinking and other domestic purposes. Majority of the area has saline groundwater. This is well explained in

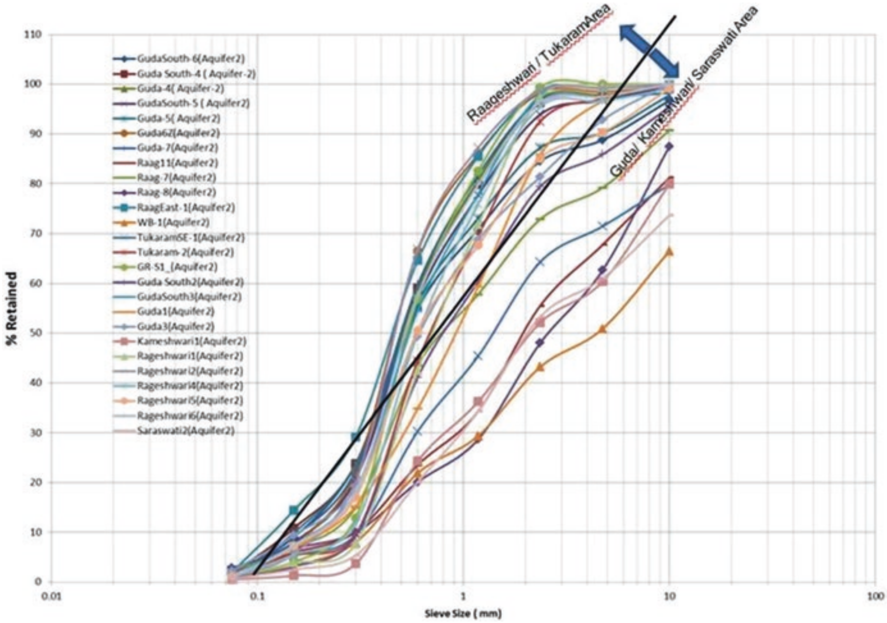

Fig. 7 Grain size distribution curve for Jagadia aquifer

salinity map. The salinity at the top of the formation is 3000 mg/L. The salinity increases gradually with depth to approximately 20,000 mg/L at the base. The aquifer geometry and variation of salinity profile along Raageshwari and Guda field area are shown in Figs. 9 and 10, respectively (Sinha and Kumar 2015).

7 Aquifer Characteristics

7.1 Aquifer Test and Analysis

The hydraulic conductivity of unconfined aquifer is ~30 m/day. The yield of most of the wells is between 100 and 200 m^3/day. To understand the aquifer characteristics of confined Miocene aquifer, a production well and an observation well were drilled in Raageshwari campus and tested for aquifer characteristics and well performance. The purpose of this test was threefold: Firstly to provide estimates of well performance which is an important feedback to well design, for completion effectiveness to decide the pump setting and to know the hydraulic properties of the aquifer. The pumping test data was analysed and the aquifer hydraulic parameters have been evaluated. Although the area is a multilayered system, pumping test has been done tapping the Jagadia (Miocene) formation (Aquifer-II) for evaluating hydraulic parameters. The well test data reveals that the aquifer is confined aquifer. The

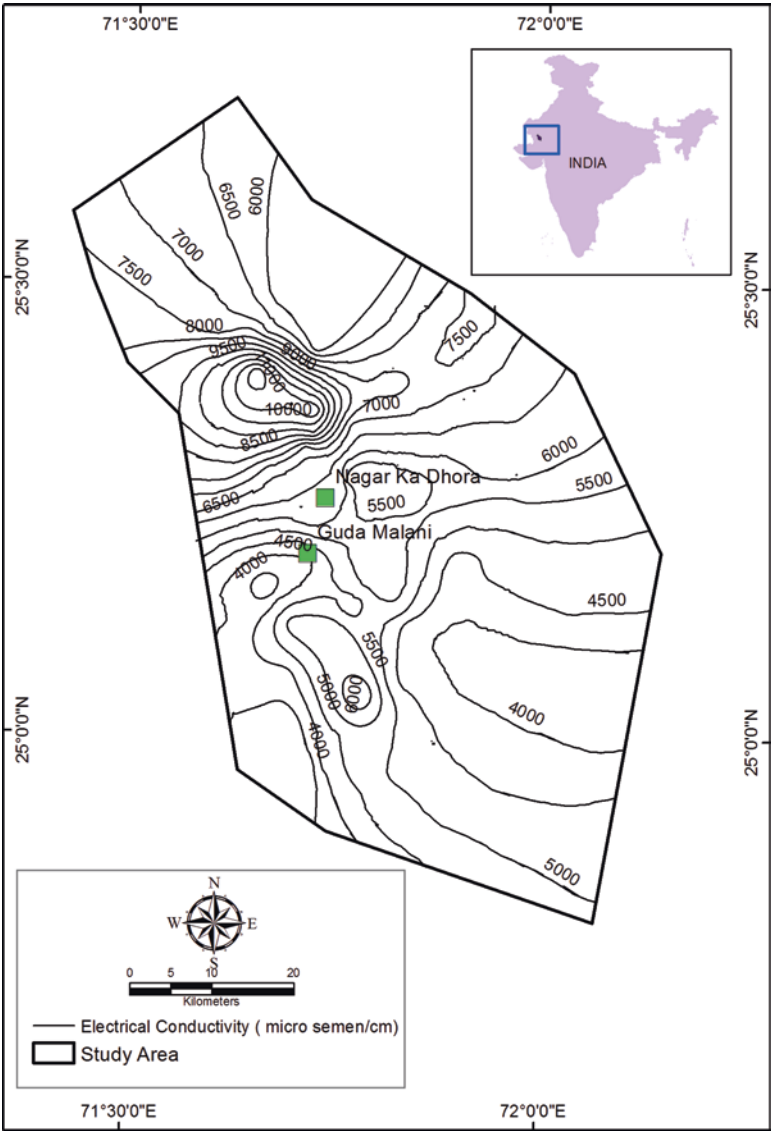

Fig. 8 Spatial distribution of electrical conductivity during the post-monsoon season in the area

analysis/interpretation of pumping test result (Fig. 11) has indicated hydraulic conductivity of aquifer as 20 m/day aquifer appears to be regional in nature because the formation encountered at this site is present in all the existing oil wells. Aquifer pressure is also quite high.

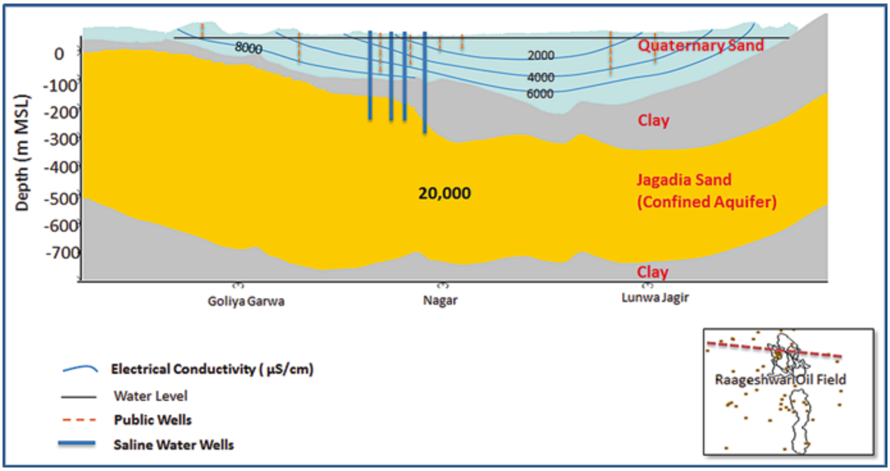

Fig. 9 Aquifer geometry and variation of salinity profile along Raageshwari field area

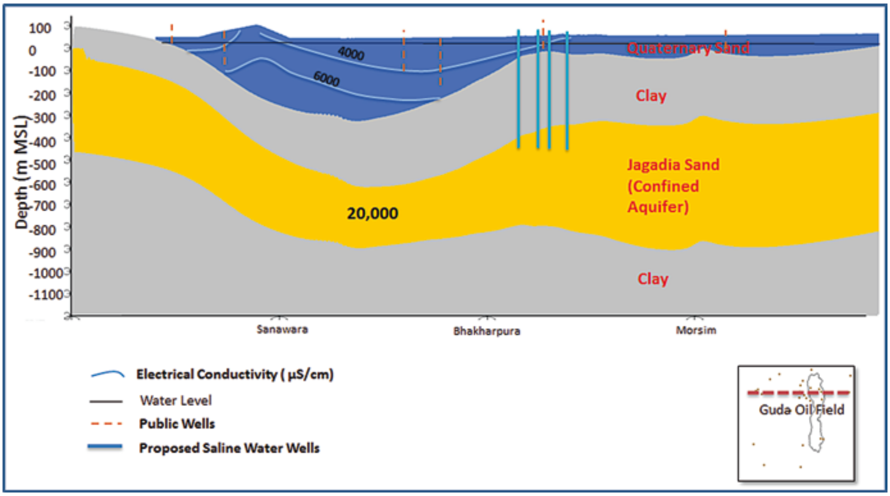

Fig. 10 Aquifer geometry and variation of salinity profile along Guda field area

7.2 Hydrogeological Interpretation

The collation of representative and suitably accurate water levels in wells is an extremely important aspect of characterizing the aquifer: first, in terms of the changes in storage that may be occurring seasonally (fluctuation in pre- and post-monsoon) or as a result of groundwater abstraction and secondly for knowledge of regional groundwater movement.

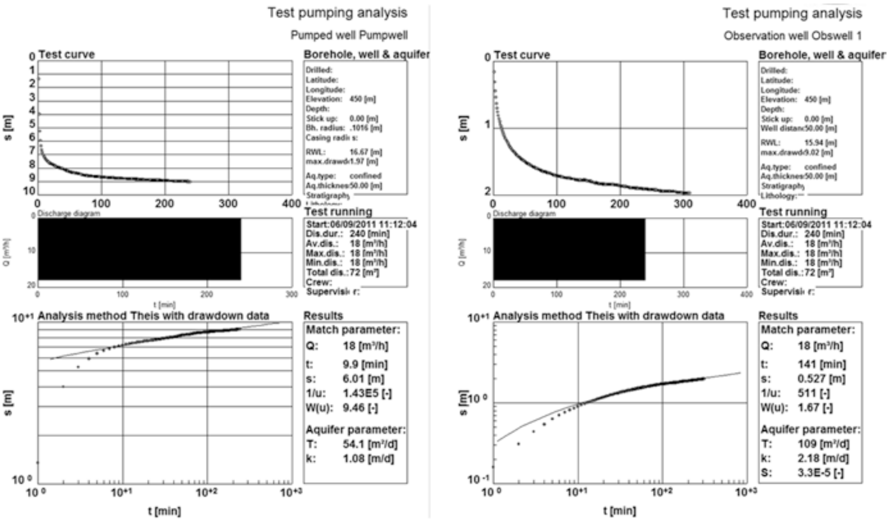

Fig. 11 Plot of pumping test data of Raageshwari production and observation wells

7.2.1 Water Table Variation of Unconfined Aquifer

The available field data indicates that groundwater is being abstracted from shallow depth (<150 m bgl) through tube wells, dugwells or dug-cum-borewell. The hydraulic head contour map (Fig. 12) of the unconfined aquifer has been prepared with the pre-monsoon data. The map indicates hydraulic head of upper aquifer is generally controlled by the depression of River Luni. Water table is shallow along the river channel. In normal condition groundwater flow direction is towards the river (depression area). Isolated groundwater mounds are also present in the areas which are representing the perched aquifer. Inter-depression area is represented by high hydraulic head.

The hydraulic head of unconfined aquifer in Raageshwari oil field area is ~40 m above mean sea level (amsl), whereas surface topographic level is ~50–55 m amsl. Therefore, water level is in range of 10–15 m bgl during pre-monsoon period. The oil field area is characterized by shallow water table zone compared to adjoining area.

7.2.2 Water Table Variation of Confined Aquifer

A monitoring well at Raageshwari Terminal campus is drilled up to a depth of ~250 m bgl, and it taps Jagadia (Miocene) confined aquifer. The static water level of the confined aquifer is ~18 m bgl. Since this aquifer is separated from the unconfined shallow aquifer by a thick layer of clay and under confined condition, there will be no impact either on water level or on the salinity of the top Aquifer-I. Since

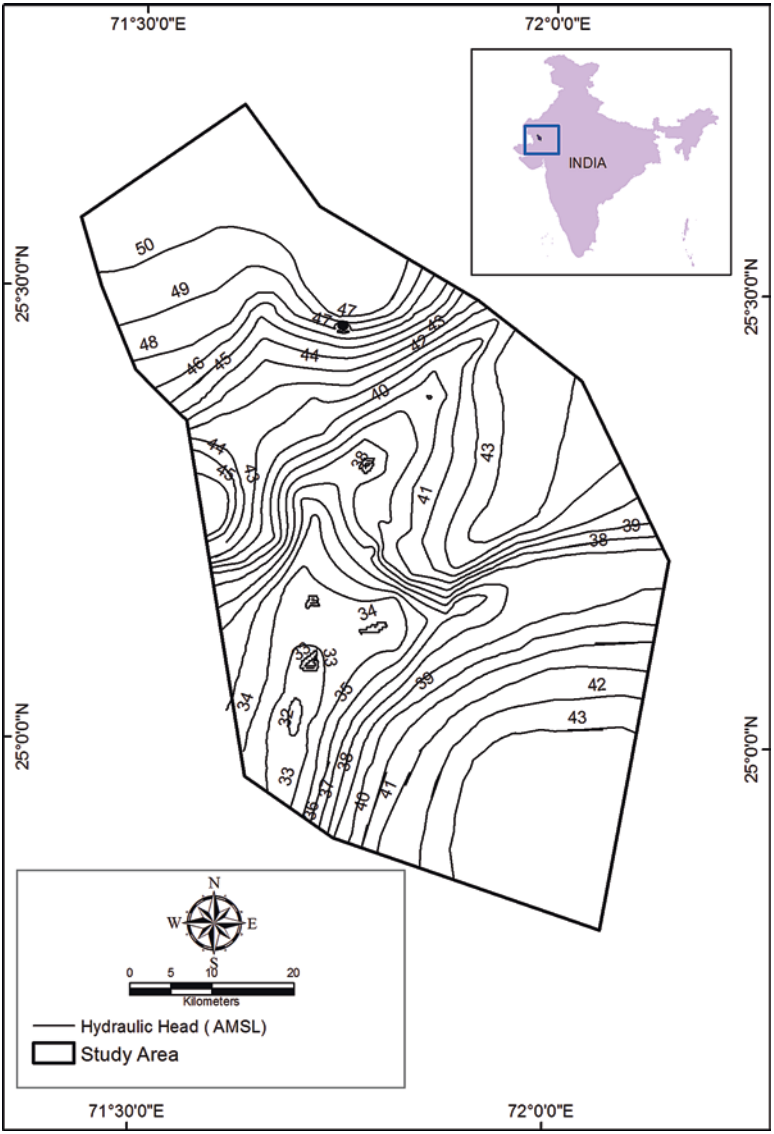

Fig. 12 Variation of hydraulic head of unconfined aquifer

there is no freshwater aquifer inventoried, hence there is no possibility of interface with freshwater system.

8 Conclusion

Saline water is required to optimize oil production in Rajasthan oil field. The detailed aquifer mapping has helped in identifying potential aquifer groups to depth up to ~1000 m bgl with the help of oil exploratory and development well lithological logs along with correlation and interpretation of seismic data. The regional subsurface geology that emerged from this study indicates four distinct groups of permeable granular zones separated by three different poorly permeable/impermeable horizons. Out of the four aquifers group mapped, an extensive deep Jagadia aquifer has been identified as the most suitable saline water source in the vicinity of the oil field. The sediments of this aquifer consist of well-sorted sand with uniformity coefficient less than 4 and average effective grain size (d10) of ~0.26 mm.

The data collected during exploratory and development drilling of oil wells along with regular pre- and post-monsoon hydrogeological data have helped to characterize the aquifer. The yield from unconfined aquifer ranges between 50 and 150 m^3/day in dugwells and between 80 and 550 m^3/day in tube wells. Transmissivity varies from 350 to 500 m^2/day. The hydraulic properties of the deep (>300 m bgl) confined Jagadia aquifer have been obtained from detailed aquifer tests conducted in wells near Raageshwari Gas Terminal. The depth to piezometric surface of the confined aquifer is ~20 m bgl, hydraulic conductivity is ~20 m/day, and groundwater salinity is ~17,500 mg/L. This deep confined aquifer is most suitable aquifer for groundwater development for industrial purpose. Since the deep aquifer is separated from the shallow unconfined aquifer by a thick layer of clay, there will be no adverse impact on the shallow unconfined aquifer used for drinking and domestic purposes.

Acknowledgments The authors are thankful to Cairn oil & Gas, Vedanta Ltd for the technical support tendered for the present study.

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Sustainable Management of Groundwater in Hard Rock Aquifers of South Andaman and Rutland Islands, India

Amlanjyoti Kar

Abstract South Andaman and Rutland Islands in India are underlain mostly by hard rocks of ophiolite igneous suite. Ophiolites are incipiently weathered and water-bearing fractures occur up to 100–120 m depth. During the study, potential springs in ophiolite were discovered in Rutland Island. This has enabled to formulate a plan for interisland transfer of spring water to the water-scarce capital town of Port Blair. More than 200 borewells are operative since the 1990s in South Andaman for various purposes. The mega earthquake ($M = 9.3$) of December 26, 2004, had stupendously influenced the hard rock aquifer whose effects are still persisting. After the disaster, in higher elevations, both groundwater and surface water were either dried up or yields declined. At lower reaches, springs were generated. Studies were undertaken to resolve the water scarcity in elevated areas applying artificial recharge. Surveys pinpointed fractures for water well construction and grouting. Highlights of work are focused in the paper.

Keywords Hard rock aquifer · Over-exploitation · Fracture · Mega earthquake ($M = 9.3$) · Artificial recharge · Grouting · Drinking and irrigation water

1 Introduction

The study area (12°38′30″–12°28′30″N and 92°37′30″–92°45′30″E) spans for about 200 km^2 and is located at the outskirt of Port Blair town in the South Andaman Island and includes the contiguous Rutland Island. The area falls under the jurisdiction of newly created South Andaman District of the Union Territory of the Andaman and Nicobar (A&N) Islands in the Republic of India (Fig. 1). Andaman and Nicobar group of Islands form an arcuate chain of about 720 km length and 24 km width in the Bay of Bengal. The cordillera is composed of 532 picturesque small to large islands, few of which are important tourist destination. The capital town of the

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S. P. S. Ray (ed.), *Ground Water Development - Issues and Sustainable Solutions*, https://doi.org/10.1007/978-981-13-1771-2_5

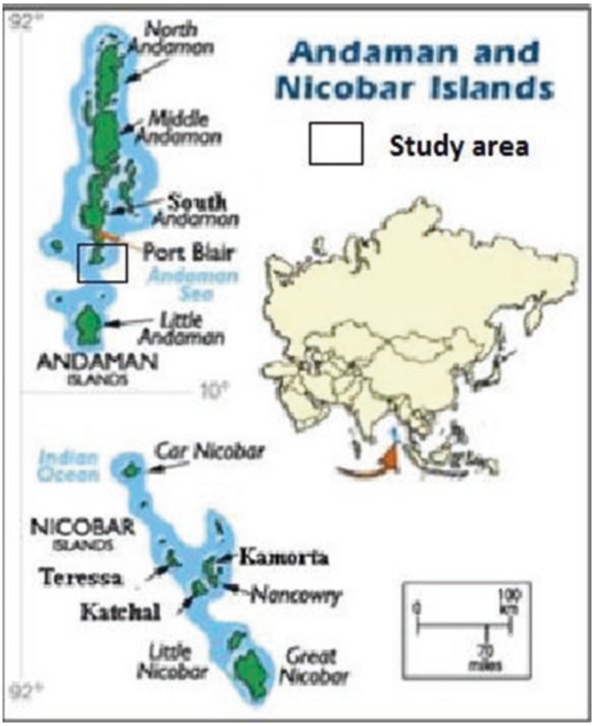


Fig. 1 Location map

island territory is Port Blair (11°40″N, 92°46″E). The location of the islands is highly interesting in matter of collision tectonics. The Andaman and Nicobar Islands form the outer arc ridge of the subduction zone, where the Indian plate collides with the Eurasian plate. Besides generating the killer tsunami, the great Indian Ocean earthquake of magnitude 9.3 in the Richter scale on December 26, 2004, caused significant vertical changes in its rupture zone. About 800 km of the rupture is created due to coseismic deformation along the exposed land and could be observed as upliftment/subsidence. During the mega disaster as also in its aftermath, many significant changes on land and especially in the water resources of the islands occurred whose case studies are forming invaluable evidences in the literature (Jain et al. 2005; Kar et al. 2005; IGRAC 2006).

The islands were devastated by both mega earthquake (M = 9.3) and tsunami. The islands in the Nicobar group as also in the Andaman group up to Rangat (12°30′25″N, 92°55′01″E) in Middle Andaman were subsided, while the rest part in Middle and North Andaman were uplifted (Jain et al. 2005; Kar et al. 2005). Tsunami could not damage the study area, because of its topographical height barring the low-lying coastal stretches in the south near Chidiya Tapu. However, earthquake had severely battered the area which had influenced the water resources to a great extent. Pre- and post-tsunami geological studies of the Andaman and Nicobar Islands were carried out by various workers of the Geological Survey of India.

Hydrogeological and geophysical studies of the islands were carried out by many workers of the erstwhile groundwater wing of the Geological Survey of India and subsequently by the Central Ground Water Board of the Union Ministry of the Government of India (Kar 2001, 2002a, b, c, 2003, 2004a, b). Groundwater resources of the entire Andaman and Nicobar Islands as also in the study area have been thoroughly investigated in the Post-tsunami period (Kar et al. 2005). During 1984–1991, deep groundwater exploration activities were undertaken by CGWB in South, Middle and North Andaman including Great Nicobar islands which had unravelled the groundwater potential of the deeper aquifers of the geological formations in the island territory for the first time.

2 Climate and Rainfall

The overall temperature in the islands remains almost identical throughout the year, while the mean maximum and minimum temperature range from 23 to 30 °C. Relative humidity remains high in the rainy season ranging from 79% to 89%. Mean humidity varies from 77% to 82%. The islands receive copious rainfall both from northwest and southeast monsoons, and the average cumulative rainfall is 3180 mm per annum. The monsoon generally sets in May and continues till November. In the month of December, a good amount of rainfall occurs in the area. During the last two decades, highly erratic behaviour of rainfall has been observed (Fig. 2) in the islands. In 13 years, there has been negative departure from the normal rainfall which has disturbed the water supply recurrently, leading owing to the miseries of rural and urban population in the South Andaman Islands. In the post-tsunami period, there was positive departure of rainfall from normal in 2005 and 2008 and was almost identical in 2006, while a negative departure of 20% was recorded in 2007 (Fig. 3). The rate of evaporation (Fig. 3) in the islands as recorded in Port Blair

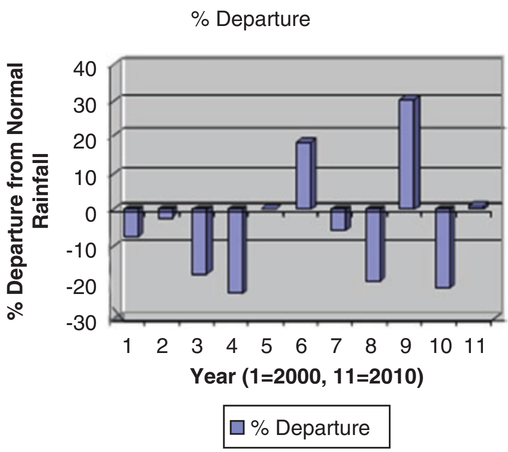
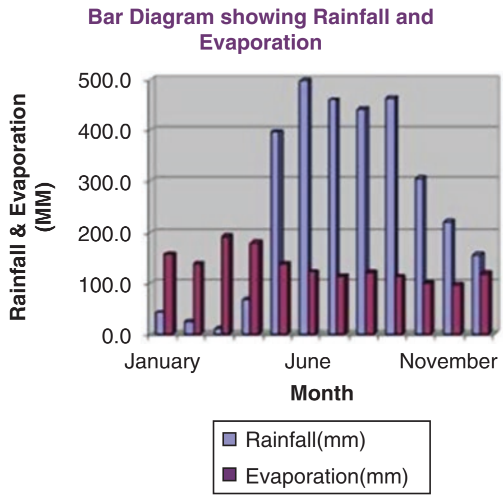


Fig. 2 Percent deviation of rainfall from normal

Fig. 3 Monthly evaporation versus rainfall



is on an average of 1400–1500 mm per year because of the geographical location of the islands in the tropical zone. Because of high evaporation rate, the effective rainfall is relatively less which warrants judicious conservation.

3 Geomorphology and Drainage

The topography of the study area is highly undulating. The area is characterized by low conical hills and deep slender valleys which occur within the elevation range of 60–100 m from mean sea level. Relatively high topographic position saved the area from the invasion of tsunami waves barring the low-lying fringe along coastline in the east and in the southern tip near Chidiya Tapu and near Bimblitan and Sippighat in the west. Drainage pattern is dendritic and immature and it is fully controlled by the structural weak planes. Small streams, locally called *nalas*, like Burma *Nala*, Kodiaghat *Nala*, Brichgunj *Nala*, Bimblitan *Nala*, Barakhari *Nala*, Chain *Nala*, etc., drain the area and show meagre to significant flow even in dry period.

4 Geology

Late Cretaceous igneous ophiolite suite of rocks, marine sedimentary classic rocks of the Palaeocene to Oligocene age and Recent to Sub Recent beach sand, mangrove clay, alluvium and coral rags underlie the areas in South Andaman and Rutland Islands (Fig. 4). While a lion's share of the South Andaman Island (more than 80%

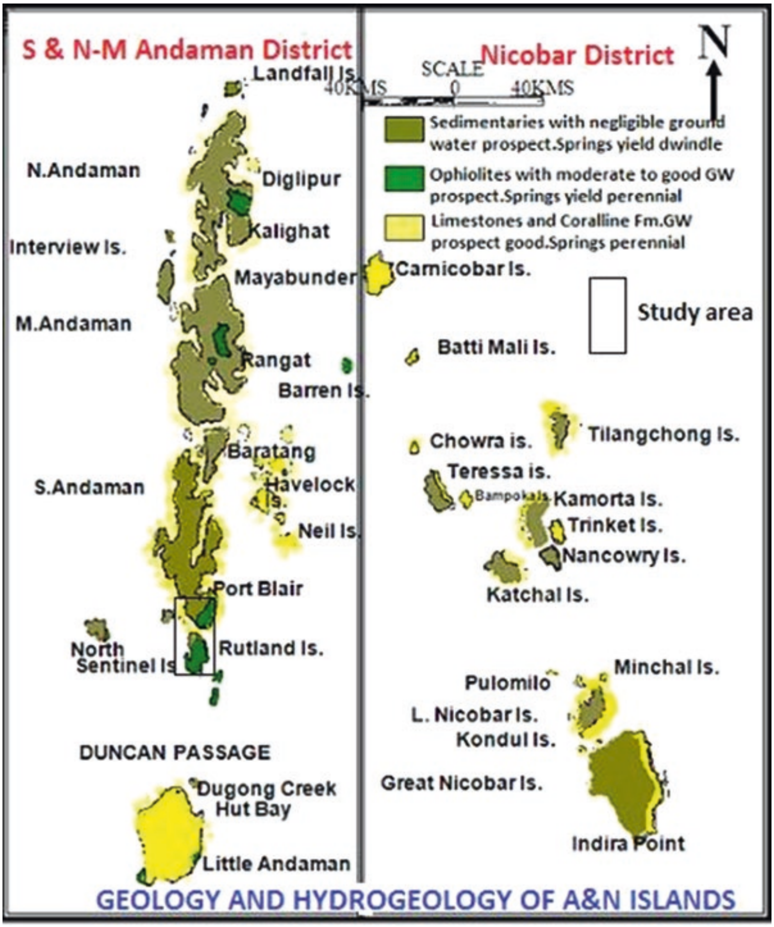


Fig. 4 Geology and hydrogeology of Andaman Islands

of the total geographical area) is occupied by the sedimentaries, an area of about 200 km^2, that is, the study area, in South Andaman and Rutland Islands is underlain by hard rocks comprising mafic-ultramafic cumulates, plagiogranite and thick pillow lava sequence of ophiolite igneous suite. These ophiolitic rocks are exposed in the tract of Brookshabad-Brichgunj to Calicut-Macca Pahar-Chidiya Tapu sector and extended in the west up to Teylerabad-Bimblitan areas. In further west, ophiolites crop out at Sippighat-Lalpahar-Chouldari-Badmaspahar areas. Since the islands are located in a tectonic zone, the rocks are highly disturbed and intensely fractured and sheared.

5 Hydrogeology

The availability of groundwater in hard rock is unubiquitous, and if it is in an island, certainly the occurrence of fresh groundwater is to be ascertained more cautiously keeping in view of its scientific withdrawal to avoid seawater intrusion. Several published literatures are available on hydrogeological studies in the islands underlain by mafic and ultramafic igneous rocks. The ophiolite suite of rocks in the study area are characterized by shallow weathering down to a depth of 1–12 m, and potential water-bearing fractures occur up to a depth of 100–120 m. The potentiality of the hard rock aquifer in the study area was first discovered through the exploration made by the Central Ground Water Board (CGWB) in 1984 at Calicut village (11°36′N 92°42′30″E). Groundwater occurs under unconfined condition in the weathered mantle, while confined to semi-confined conditions exist in the deeper fractured mantle as evident from the occurrence of the auto-flowing wells in the area. The weathered and fissured horizons in ophiolite are tapped by dug well and borewells with moderate yield (Table 1).

The intermontane valleys are underlain by the porous colluvial materials as also alluvial valley fill materials of various size fractions borne by the streams carry a good amount of base flow even in the summer. The thickness of the valley fill varies from 1 to 18 m below ground level (bgl) as revealed from the detailed hydrogeological studies coupled with electrical resistivity sounding and exploratory drilling carried out in the area in the pre-tsunami period. Hydrogeological studies revealed that the valley fills form potential aquifers at shallow depth which can be intercepted by tube wells and collector wells with subsurface dams. At places where potential fractures are available at shallow depths, dug-cum-borewells can also be constructed with subsurface dams. The depth to water levels in various geomorphic settings is shown in Table 2. The hydrogeological situation of the area has been thoroughly changed after the mega earthquake (M = 9.3) on December 26, 2004 (Kar et al. 2005). Pumping and slug tests were conducted in dug wells and borewells tapping both shallow and deeper aquifers in the ophiolites to adjudge the aquifer potential and to determine the aquifer parameters. A good number of slug tests were also conducted in the shallow experimental pits to verify the transmissivity of the valley fills for construction of subsurface dams and check dams (especially in areas where good surface flow exists during dry season). Computation of hydrologic parameters was done following various methods opined by Slichter, Hvorslev and Cooper. The results are summarized in Table 3. The thickness of weathered horizon generally tapped by the dug wells varies in depth from 3 to 6 m bgl.

Besides tapping groundwater from wells, the other mode of availability of groundwater through natural gravitational flow is the spring water. Spring water forms a dependable source of water supply in the islands since the establishment of these islands by Britishers. These springs are tapped for water supply in the rural areas of South Andaman Island by the Andaman Public Works Department (APWD). A number of such topographic and fracture springs originated in the forest clad hills of South Andaman and Rutland Islands. Studies carried out by the CGWB (Kar et al. 2002, 2004) have proved that the springs originating in the fractured ophiolites

Table 1 Hydrological parameters of shallow colluvial-regolithic and deeper fractured aquifers in the hard rock areas of South Andaman

Sl. no	Location	Aquifer	Type of structure	Depth (mbgl)	Dia (m)	SWL (mbgl)	Yield (LPD)	Duration of pumping (min) during test	Recovery (m)	Sp. capacity (m^3/min)	Transmissivity (m^2/day)
1	Corbyn's Cove	W.PL	Dug well	5.42	1.43	3.02	2500	15	0.73 m in 1225 min	0.0458	19.05
2	Brookshabad on the way to quarry	W.P	Dug well	2.68	2.55	1.72	3000	16	0.55 m in 1320 min	0.0058	44.46
4	Chidiya Tapu	W. PL	Dug well	5.75	1.46	3.95	6000	50	1.20 m in 350 min	0.0095	271.6
5	Brichgunj	W.PL	Dug well	4.17	1.88	2.57	2500	15	0.128 m in 438 min	0.0079	23.64
6	Calicut junction near mosque	WF. PL	Borewell	80.2	0.203	1.30	375 × 103 (500 min pumping)	500	4.05 m in 650 min	0.090	163.79
7	Beadnabad near culvert	Coll. and W.PL	Tube well	17.0	0.203	3.28	3729 × 102 (500 min pumping)	500	4.67 m in 484 min	0.131	127.03

m - metre, *m bgl* - metre below ground level, *min* - minute, *sp. capacity* - specific capacity, *W* - weathered, *PL* - pillow lava, *Coll.* - colluvium, *Dia.* - diameter, *LPD* - litres per day

Table 2 Seasonal fluctuations and depth to water levels in different physiographic settings

Sl. no	Physiography	Depth to water level (m bgl)		Fluctuation (m)	Remarks
		Pre-monsoon	Post-monsoon		
1	Intermontane valley	0.6–3.66	0.47–2.69	0.31–0.97	At places, auto-flowing conditions were noted. Good springs are developed in ophiolites. The water level situation was changed after the mega ($M = 9.3$) earthquake
2	Hill slope	3.16–7.58	0.98–5.95	1.63–2.18	

Table 3 Result of slug tests carried out in the streams flowing through the areas underlain by hard rocks in South Andaman Island, India

Sl. no	Location of the stream section	Depth of the alluvium/colluvium above the massive/fractured basement (m)	Average width of the stream section (m)	Nature of the stream and flow condition in lean period	Transmissivity (m^2/day)	Conservation and recharge structures proposed to harvest the flow
1	Beadnabad near pump house	3–5	10–15	P, MF	159.23	Check dam
2	Near culvert of Maratha Rifle, Brichgunj Cant.	3–4	12–15	P, SF	779.93	SSD, DCB
3	EME Workshop, Brichgunj Cant.	2–3	5–8	P, MF	6.33	SSD, DCB
4	Teylerabad near quarry	5–6	5–8	NP, BF	381.97	SSD, DW
5	CSD Depot, Brichgunj Cant.	5–8	8–10	P, SF	112.75	SSD, DCB
6	Spring zone of Badmas Pahar	3–5	2–3	NP, BF	1.74	SSD, DW
7	Bird line near explosive godown	5–8	5–8	P, SF	679.27	SSD, CD, SH, DCB
8	Lalpahar Nala near pump house	3–5	5–8	P, MF	120.78	SSD, DW
9	Brookshabad on the way to quarry	3–5	15–20	P, SF	57.81	SSD, DW
10	Near J&K Rifles, Brichgunj Cant.	5–8	5–8	P, SF	81.66	SSD, DCB
11	Near Brichgunj Cant. canteen	5–6	8–10	P, SF	91.67	SSD, DCB

are more potential and sustainable than the springs in sedimentary formations. The entire South Andaman Island including Port Blair urban area suffers from acute drinking water crisis in the years with deficit of rainfall (Fig. 2). During 2002, in the wake of acute drinking water crisis in Port Blair and environs, a reconnaitory study on the yield potential of the springs of Rutland Island and their feasibility for inter-island transfer to Port Blair City was carried out by the author, and a recommendation was put forward to A&N Administration for implementation (Kar et al. 2002). The study revealed that nearly 36,54,722 gal of water per day was unabatedly flowing to the sea (Table 4). A short-term option was immediately implemented by the island administration in 2002 by transporting spring water from the Chain *Nala* by ships and barges. The implementation of the project of interisland transfer of spring water from Rutland Island through pipeline work has been deferred in view of its environmental clearance and expenditure sanction. Recent severe water scarcity in the summer of 2007 was instrumental for final approval of the project by Government of India in 2009. Pipeline work in both sides of the two islands is over, and the undersea pipeline connection is yet to be started.

5.1 Status of Groundwater Development in the Pre-Tsunami Period

After the establishment of the villages in the past in the study area, only dug wells were constructed by the local inhabitants tapping the weathered regolithic aquifers to meet the drinking and domestic water requirements. However, perennial springs were tapped by the Andaman PWD for rural piped water supply.

Large-scale exploitation of the hard rock aquifers in parts of the study area located at Brichgunj, Kamrajnagar, Calicut, Macca Pahar, Teylerabad, Bimblitan and New Bimblitan was started after the maiden groundwater exploration done by the Central Ground Water Board in 1984 at Calicut village and at Beadnabad. Since then, the groundwater in the fractured ophiolite aquifers in the area was continuously developed through private borewells, and gradually 200 private borewells were constructed in the area for irrigation, drinking and poultry business. The first irrigation well in the entire islands was constructed in the study area. Thereafter, unscientific use of groundwater has led to its over-exploitation as envisaged from the information supplied by the APWD. As per the data, the static water level (SWL) of the borewell constructed by the Central Ground Water Board (CGWB) was 1.30 m bgl during March–April 1985. In April 2002, the SWL dropped to 5.34 m bgl, while in April 2004, the SWL was recorded as 7.01 m bgl. The borewell yield was 2, 95,000 litres per day (LPD) in April 2000, while in April 2002, it was 95,000 LPD. During the survey in 2004, it was reported by the local villagers that the SWL and the discharge of their respective borewell have significantly dropped in the last 2–3 years. Based upon the studies carried out by the author, the Andaman and Nicobar Islands Administration was informed by the CGWB, and it was decided to stop further drilling of borewells in the area and to notify the area under the

Table 4 Details of springs in Rutland Island

Sl. no	Date of study	Name of spring	Location of place of origin of the spring from sea coast (km)	Reading through 900 V-notch plate (cm)	Discharge (gallons per day, GPD)	Electrical conductivity (microsiemens/cm)
1	6.2.02	Bada Khadi Nala	2.5	20	460,320	270
			5	20		270
2	9.2.02	Kendi Nala no-I	2.5	20	460,320	320
			3.5	21.5	555,200	310
3	9.2.02	Kendi Nala no-II	2.5	14	189,760	350
			3.0	14		330
4	9.2.02	Kumda Nala	2.5	14	189,760	350
5	12.2.02	Bet Nala-I	2.5	Dry	Negligible	290
6	12.2.02	Bet Nala-II	2.5	Dry	Negligible	300
7	12.2.02	Grass Nala	2.5	Dry	Negligible	340
8	12.2.02	Nimboo Nala	2.5	Dry	Negligible	320
9	12.2.09	Kichedy Nala	2.0	8	45,120	350
10	12.2.09	Bamboo Nala	3.0	13	156,800	340
11	11.2.02	Chain Nala	0.75	23	657,600	240
12	11.2.02	Meetha Nala	1.0	11	104,320	280
13	11.2.02	Purana Nala-I	0.5	3	4038	310
14	11.2.02	Purana Nala-II	0.75	12	126,400	330
15	11.2.02	Purana Nala-III	0.75	9	63,630	320
16	11.2.02	Komio Nala	0.5	23	657,600	240
Cumulative discharge from all springs in Rutland Island (GPD)					32,10,278	
Subsurface discharge as base flow along all spring locations (GPD)					4,44,444	
Total groundwater availability for interisland transfer to Port Blair [(GPD)]					36,54,722	

Abbreviations used in Table -3: Cant. - cantonment, *P* - perennial, *NP* - non-perennial, *MF* - meagre flow, *SF* - scanty flow, *SSD* - subsurface dam, *DCB* - dug-cum-borewell, *DW* - dug well

Central Ground Water Authority. Accordingly for creating public awareness before notification, regular publication in local print media regarding the scientific observation on over-exploitation of groundwater in the area and its after-effects was initiated along with telecasting and broadcasting of scientific programmes on groundwater development status in the islands. However, before enacting the regulatory measure and initiation of large-scale artificial recharge and conservation of groundwater, the area was rocked by the mega ($M = 9.3$) earthquake on December 26, 2004, which was also responsible for the killer Indian Ocean tsunami.

Besides exploitation of groundwater through borewells, dug well and springs, detailed studies were carried out by the CGWB (Kar 2001, 2003) on the conservation and recharge of perennial subsurface flow (base flow) along stream channel flowing unabatedly towards the sea and also on the conservation of surplus monsoon run-off. From the studies, models were prepared for augmentation of drinking and irrigation water in the entire Andaman and Nicobar Islands including the study area. Studies revealed that a good amount of groundwater flows along the stream (*nala*) sections as base flow even in dry season when the islands suffer from severe crisis of drinking and irrigation water.

While the formation materials in the islands at many places are impervious and unproductive in terms of groundwater, the stream sections are underlain by appreciable thickness of porous alluvium/colluviums which can yield a good amount of water if the base flow is intercepted through subsurface barrier or subsurface dams. Profuse annual and intermittent rainfall even in dry spell gives ample scope for recharge of the subsurface reservoir in succession if recharging structures like check dams and shafts are constructed. The subsurface perennial flow (base flow) is required to be obstructed by subsurface dams, which can be tapped fully through properly designed dug wells or collector wells. The yield of these wells could be estimated using the following formula derived from the modification of Darcy’s law. Q= TIL where Q= flow along any stream section in m^3 or litres per day, T= transmissivity in m^2/day, I= hydraulic gradient and L= width of the stream section in metre.

To assess the lateral flow through subsurface aquifers, a good number of slug tests were conducted in test pits, in the streambeds, and the transmissivity of the formations was ascertained. Accordingly after finding out the hydraulic gradient and stream width, sectional flow in each study area was determined (Table 5). Tables 6 and 7 show the recommendations made and the status of implementation.

Similarly, to tap the spring flow in dry season, base flow and optimal conservation of surplus run-off and construction of check dams with intermittent subsurface dam and wells, all along the length of the stream, from hill to sea were advocated by the author (Kar 2003). The recommendation was fully accepted by the island administration for implementation to augment irrigated agriculture. In 2003–2004, 101 check dams were constructed in the entire Andaman group of islands, while 17 check dams were constructed in the study area during the first phase (Table 5). This also marked the beginning of irrigation from surface water in the islands.

In addition to all the above recommendations, for optimal conservation of rainwater in the island watersheds along with recharging of groundwater, construction of ponds was advocated. Accordingly, ten ponds were constructed in the area.

Table 5 Impact assessment of check dams in the study area during the second week of December 2004

Sl. no	Location	Width (m)	Depth of water (in m)	Volume of water impounded (M^3)	Irrigation potential created (hectare)	Cropping pattern
1	Beadnabad-I	4.46	0.9	137.68	6.0	Betel vine, ladies finger, pumpkin, ridge gourd, cowpea, radish
2	Kodiyaghat	4.50	0.55	24.85	5.0	Cowpea, betel gourd, ladies finger, radish, bean, French bean, bottle gourd, pumpkin
3	Macca Pahar-I	3.8	0.88	26.51	3.0	Drumstick, betel vine, areca nut
4	Macca Pahar-II	4.0	0.7	34.66	4.0	Coconut, areca nut, cowpea, ladies finger, ginger
5	Macca Pahar-III	6.02	1.2	40.47	4.0	Coconut, areca nut, cowpea, ladies finger
6	New Bimblitan-2	2.10	1.0	11.52	2.5	Coconut, areca nut, cowpea, ladies finger
7	Calicut-II	8.5	1.0	119.98	10.0	Coconut, areca nut

5.2 Hydrogeological Changes in the Post-Tsunami Period

It is already explained in the preceding paragraph that barring the devastation from the mega earthquake of December 26, 2004, the study area was spared by the tsunami invasion because of topographic elevations, except the fringe areas. However, one notable hydrogeological event occurred in Calicut area during the progression of tsunami. Highly mineralized water with electrical conductivity of 14,500 microsiemens per cm had pushed through the fractures and reached uplands (103 m above mean sea level) by dint of the thunderous pressure generated by the propagating tsunami. The water had pungent smell continuing various volatile compounds. The upcoming highly mineralized saline water was detected at Baratang Island, and it was also reported from Little Andaman Island in the uplands during tsunami event (Kar et al. 2005). The aquifer system in the study area was highly influenced by the mega earthquake ($M = 9.3$) of December 26, 2004, and its impact on the brittle hard rock formation, i.e. ophiolite suite of rock in the study area, was grave. On the other hand, the pervasive sedimentary formations in the islands were also highly disturbed during the earthquake. Deep fractures were produced in the comparatively more elastic sedimentaries comprising mainly shale, siltstone and fine-grained sandstone. In many places, groundwater levels in the highland fell, while in lowlands, it rose. The water in the ponds moved out through the newly developed fissures. But interestingly after a gap of 4 years, these cracks and voids in the sedimentary terrain have been infilled with the weathered clay minerals. The

Table 6 List of recommendations of artificial recharge and base flow conservation structures in hard rock areas of South Andaman during pre- and post-tsunami

Sl. no	Location	Structures proposed	Remarks
1	Austinabad near Mariamman Temple	15 M long, 1 m width, 3.5 m deep SSD, DW one no, 5–6 m dia, 6 m depth (pumping device with pipelines)	Status – completed in the pre-tsunami estimated yield (Pre-project) – 40,000 LPD
			Post-project yield (observed) – 50,000 LPD
2	Bird line near explosive godown	15 M long, 1 m width, 3–4 m deep SSD, DCB one no, 5–6 m dia, 6 m depth, five check dams 3–5 m long as per required engineering design, 3 to5 nos, concentric shaft 1.5–2 m depth, 1.5 m dia in between two check dams, one borewell, 4″ dia, 25–30 m deep inside the well (pumping device with pipelines)	Status – completed in the pre-tsunami
			Estimated yield (Pre-project) – 40,000 LPD
			Post-project yield (observed) – 50,000 LPD
3	Brookshabad on the way to quarry	50 M long arcuate, 1 m width, 3.5 m deep SSD, DCB one no, 5–6 m dia, 6 m depth, 2 check weirs (dam), 20 m long as per engineering design, 3 borewells, 4″ dia, 15–20 m deep inside the well (pumping device with pipelines)	Status – completed in the post-tsunami
			Estimated yield (Pre-project) – 40,000 LPD
			Post-project yield (observed) – 50,000 LPD
4	Teylerabad near quarry	15 M long, 1 m width, 3.5 m deep SSD, DW one no, 5–6 m dia, 6 m depth (pumping device with pipelines)	Status – sanctioned
			Estimated yield (Pre-project) – 40,000 LPD
5	Lalpahar Nala	30 M long, 1 m width, 3.5 m deep SSD, DW one no, 5–6 m dia, 6 m depth (pumping device with pipelines)	Status – completed in the pre-tsunami
			Estimated yield (Pre-project) – 40,000 LPD
			Post-project yield (observed) – 50,000 LPD
6	Sippighat near agriculture farm	10 M long, 1 m width, 3.5 m deep SSD, DW one no, 5–6 m dia, 6 m depth (pumping device with pipelines)	Status – completed in the post-tsunami Estimated yield (Pre-project) – 60,000 LPD
			Post-project yield (observed) – 80,000 LPD

SSD - subsurface dam, *DCB* - dug-cum-borewell, *DW* - dug well, *LPD* - litres per day, *Dia* - diameter, *m* - metre

Table 7 List of recommendations of construction of check dam in hard rock areas of South Andaman during pre- and Post-tsunami

Sl. no	Location	Structures proposed	Remarks
1	New Bimblitan village	Cement concrete (C.C) check dam 10 m width with wing wall and appropriate foundation as per engineering design to tap the base flow, spring discharge and surface water flow	Status – completed in the Pre-tsunami The structure was highly successful but it dried up at the aftermath of the mega earthquake (*M* = 9.3) on 26.12.04
2	Calicut village at the upstream of Supari Bagicha stream	Cement concrete (C.C) check dam 10 m width with wing wall and appropriate foundation as per engineering design to tap the base flow, spring discharge and surface water flow	Status – completed in the Pre-tsunami The structure was highly successful but a crack was developed during the mega earthquake (*M* = 9.3) on 26.12.04
3	Supari Bagicha stream, Calicut village	Cement concrete (C.C) check dam 40 M width with wing wall and appropriate foundation as per engineering design to tap the base flow, spring discharge and surface water flow	Status – completed in the Post-tsunami
4	Beadnabad stream close to the main road and the pump	Cement concrete (C.C) check dam 30 M width with wing wall and appropriate foundation as per engineering design to tap the base flow, spring discharge and surface water flow	Status – completed in the Post-tsunami
5	Chidiya Tapu stream For water supply	Cement concrete (C.C) check dam 30 M width with wing wall and appropriate foundation as per engineering design to tap the base flow, spring discharge and surface water flow	Status – completed in the Post-tsunami

gradual natural revival of the aquifer characteristics is evident through continuous groundwater monitoring in the islands.

As in the case of sedimentaries, the earthquake movement caused the development of new fractures in the brittle ophiolite, and groundwater movement occurred towards the topographic lows. After the event, in the higher topographical parts of the study area in the villages of New Bimblitan, Macca Pahar, Calicut, Teylerabad, Brichgunj, Brookshabad, Burmanala, etc., groundwater and surface water sources either dried up or their discharges dwindled. Cracks developed in the check dam at Calicut, borewells in many cases dried up, and auto-flowing wells ceased to flow. Water levels in wells fell down alarmingly (Table 8a and 8b). A pond in Macca Pahar village was full of water just before the tsunami, and about 25,000 gallons per day of water was supplied from this pond to Arvind International, a local hotel used

Table 8a Change in water levels of borewells in and around Macca Pahar village, South Andaman District, before and after the earthquake (M = 9.3) of December 26, 2004

Village name	Name of the owner	District and subdivision	Type	Total depth (m)	Static water level (m)		Affected irrigable area after the earthquake (hectare)
					Pre-earthquake	Post-earthquake	
Macca Pahar	Sunder Raj	South Andaman (SA)	Borewell (BW)	45.75	1.5	15.00	0.62
Macca Pahar	Ramaswamy	SA	do	34.00	3.0	12.00	0.6
Macca Pahar	Bal Murugan	SA	do	54.00	0.6	24.00	0.70
Macca Pahar	Arumugam	SA	do	40.00	7.6	12.19	0.54
Macca Pahar	Rajendran	SA	do	33.50	3.0	15.00	0.60
Macca Pahar	N. Hamza	SA	do	33.50	7.6	12.19	2.10
Macca Pahar	R. Manoharan	SA	do	30.48	Auto-flow	6.00	0.55
Macca Pahar	R. Veluswamy	SA	do	30.48	1.2	9.14	0.65
	R. Ramaswamy	SA	do	33.50	3.0	12.19	0.56
Macca Pahar	Muthuswamy	SA	do	44.20	3.0	6.00	Not available (NA)
Macca Pahar	Ganeshan	SA	do	33.50	3.0	12.19	NA
Macca Pahar	Arunachalam	SA	do	33.50	Auto-flow	6.00	NA
Macca Pahar	GunaSekaran	SA	do	22.86	Auto-flow	7.62	NA
Macca Pahar	Masala Muthu	SA	do	33.50	6.0	12.19	NA
Macca Pahar	S. Muthaiah	SA	do	30.48	3.35	15.00	NA

Table 8b Change in water levels of borewells in and around Calicut-Teylerabad villages, South Andaman District, before and after the earthquake ($M = 9.3$) of December 26, 2004

Village name	Name of the owner	District and subdivision	Type	Total depth (m)	Static water level (m)		Affected irrigable area after the earthquake (hectare)
					Pre-earthquake	Post-earthquake	
Calicut	V. Subramanium	South Andaman (SA)	Borewell (BW)	30.48	2.43	18.29	Not available (NA)
							9
Calicut	K. Ali	SA	BW	30.48	2.74	19.80	0.50
Calicut	M. Mohammed	SA	BW	42.68	3.00	15.24	0.50
Calicut	P. Moideen	SA	BW	30.48	3.0	Dried up	NA
Calicut	P. Moideen	SA	BW	45.73	24.0	Dried up	2.10
Teylerabad	Vellakanu	SA	BW	30.48	6.0	15.00	NA

to exist at Bathu Basti, Port Blair till 2014 or so, for its daily need. Just after the mega earthquake, the pond completely dried up, and till very recent time, the situation has not improved much.

The area is suffering from severe drinking water crisis, irrigation system has collapsed, and agriculture has turned rainfed after the mega disaster. While the groundwater situation in higher altitudes deteriorated, discharge of the springs increased in the lower altitudes. New springs also developed in the topographic lows. The discharge of the stream in the upper part near New Bimblitan decreased sharply; the same stream in the lower stretches, near the teak plantation area at Macca Pahar close to Burma Nala, was found to discharge copiously (75,000 gal per hour). Similarly, the stream near Beadnabad started discharging heavily (more than 50,000 gal per hour) even in the lean period. Many private water tanker owners earned easy money through carrying water from the free-flowing stream at the former location to the water-scarce Port Blair town in the post-tsunami period at least till February 2009. The springs in the Rutland Island did not show much variation in discharge.

6 Studies Carried Out in the Post-Tsunami Period, Recommendations and Their Implementation

After the disaster, there was an adverse effect on the groundwater condition. The drinking water supply and irrigation systems failed in the area. The acute scarcity of water invited detailed hydrogeological studies to find out the root cause of the change and to recommend at least some remedial measures to restore first the drinking water supply followed by irrigation water supply. Consequently, no action was taken to tackle over-exploitation which occurred before the tsunami took place as contemplated in the notification of the Central Ground Water Authority, but intensive hydrogeological and geophysical studies (Table 9) were carried out to find out the solution of the newly developed problems. Detailed surveys by the author have delineated the existence of subsurface water bearing which can be tapped for water supply and dry fractures which may be grouted. From the hydrogeological investigation and resistivity surveys, it is clear that the formation of shallow fractures at high altitudes is responsible for the flow of groundwater from higher altitudes to lower altitudes and loss of surface water from the ponds, check dams, dug wells and borewells. This is also corroborated by the fact that in many places, the water level has gone down to a much deeper level and auto-flow condition has stopped due to lowering of the piezometric surface.

Grouting of the water-losing fractures at strategic locations will rejuvenate springs in the upstream which in turn will revitalize groundwater in dug wells, borewells and ponds located in the highland. Grouting is yet to be implemented by the island administration. To meet the acute scarcity of drinking water, the construction of two borewells at Lalmitty area and two wells at Teylerabad was recommended by

Table 9 Subsurface information from VES in hard rock areas of South Andaman Island

	Resistivity (Ohm-m)				Thickness (m)			
VES no	P1	P2	P3	P4	H1	H2	H3	Fracture zones (m bgl)
1	12.82	39.36	V.H	–	1.76	35.6	–	10–15, 25–40, 60–100
2	4.70	12.66	V.H	–	0.39	16.86	–	10–20
3	11.44	54.99	–	–	3.06	–	–	25–30, 40–60
4	11.19	138.89	–	–	4.60	–	–	30–40, 60–70
5	8.08	112.87	–	–	6.54	–	–	–
6	11.83	127.88	–	–	3.66	–	–	90–100
7	115.85	11.93	V.H	–	4.72	50.87	–	40–50, 80–100
8	87.07	High	–	–	10.77	–	–	70–80, 90–100
9	12.72	V.H	–	–	6.60	–	–	–
10	34.10	98.06	–	–	4.68	–	–	30–40, 60–70, 80–100
11	11.11	50	V.L	–	7.0	53.0	–	–
12	8.45	276.53	400.00	–	1.66	28.34	–	–
13	8.34	511.22	–	–	4.76	–	–	–
14	20.66	123.03	–	–	4.0	–	–	15–20, 60–80
15	77.80	26.35	133.56	–	0.77	9.84	–	40–50,80–90
16	4.0	70.0	20.0	100.0	1.0	15.0	39.0	60–70, 80–100
17	15.6	V.H	–	–	7.21	–	–	80–90
18	9.66	293.25	–	–	3.72	–	–	20–30
19	5.63	32.75	V.H	–	0.30	13.64	–	–
20	5.62	36.07	V.H	–	0.30	23.21	–	30–40, 80–90
21	50.43	5.20	V.H	–	11.23	8.88	–	20–50, 80–90
22	31.9	537.49	–	–	7.71	–	–	–
23	39.04	254.65	–	–	14.65	–	–	–
24	22.0	300.0	40.0	–	6.0	14.0	–	20–30, 40–90
25	22.45	48.84	V.H	–	3.47	55.60	–	80–100
26	6.04	51.51	V.H	–	0.75	46.41	–	15–25, 70–80, 90–100

the author. The Lalmitty wells (80 m deep, 6″ diameter) have been constructed, and these are yielding cumulatively 25,000 gal per day of water. Following the research and development studies during the pre-tsunami undertaken by the author on artificial recharge and conservation of water, a major water supply project near the teak plantation area had been recommended considering the base flow, surface flow and potential fractured basement aquifer. The project envisages construction of an 8–10 m diameter collector well with 3–5 shallow borewells, feeder wells with infiltration gallery, check dams and a subsurface dam. The well will be capable to supply 1 million litres of potable drinking water per day (Fig. 5). For conjunctive use of surface water and groundwater and their conservation, two dam projects have been also recommended, one at Superi Bagicha, Calicut village, and the other at Beadnabad. It is contemplated that with the completion of this project, the water scarcity in the entire southern part of South Andaman will be solved.

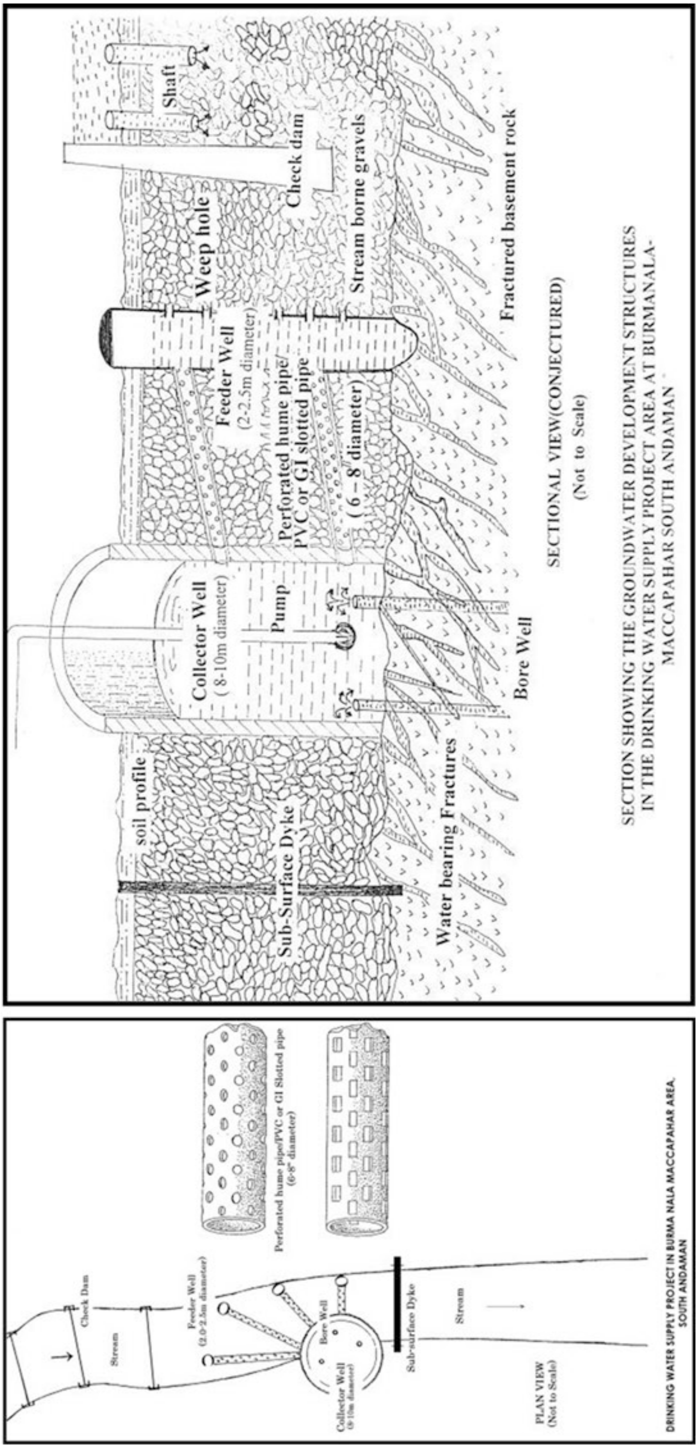


Fig. 5 Plan and section of Macca Pahar-Burma Nala water supply project in the Post-tsunami

The two projects have been approved by the island administration and implemented. The former one is completed and the latter one is under completion. In addition to the new recommendations, the old recommendations as advocated by the author in the Pre-tsunami period (Kar et al. 2002, 2004) have been approved by the Andaman and Nicobar Island Administration and are under implementation (Table 6).

In addition to these projects, detailed groundwater investigation was also carried out to undertake an artificial recharge project in the defence establishment at Brichgunj. The cantonment is located in the comparatively lower topographic locales. After a thorough study, a sum total of fifteen (15) borewells, six (6) dug-cum-borewells with subsurface dam and seven (7) recharge borewells with recharge shafts from the rooftops were advocated by the author. As per the information of Army engineering authority received, six borewells were constructed immediately to tide over the extreme water-scarce situation, and all were successful, yielding water to the tune of 30,000–50,000 gal per day. Other recommendations are yet to be implemented.

7 Conclusion

Detailed hydrogeological studies encompassing an area of 200 km^2 in the South Andaman and Rutland Islands were carried out. The area underlain by ophiolite suite of rocks comprising mafic and ultramafic igneous rocks fractured down to 70–80 m from ground level. Regoliths and the fractured hard rock aquifers in the igneous complex are suitable for the construction of dug well, borewell and dug-cum-borewell. Besides the availability of groundwater in the subsurface, perennial springs are also present in the ophiolite which can supply copious amount of water for various uses. Base flow along the streams could be tapped through subsurface dams and properly designed dug well, collector well with or without infiltration gallery, dug-cum-borewells, etc. Furthermore, the subsurface reservoirs could be recharged if check dams are constructed with recharge shafts. Conjunctive use of surface water, groundwater and rainwater is possible in the study area through check dams and ponds. The deep aquifers were being continuously pumped by more than 200 borewells during the pre-tsunami period leading to their over-exploitation as revealed from the survey carried out by the author in 2004. Extensive hydrogeological studies were carried out in the pre-tsunami times by the author for optimum development of groundwater, surface water and rainwater through wells, borewells, dug-cum-borewells, check dams, subsurface dams and ponds and by harvesting of spring water from Rutland Island for interisland transfer of water to Port Blair town. Many of the recommendations were implemented by the island administration to meet the drinking and also irrigation needs of the study area.

Acknowledgements The author expresses his sincere gratitude to Shri K.B. Biswas, chairman of the CGWB, for his permission and enthusiasm to publish the paper in the International Conference. The author is indebted to Dr. D. Saha, Member (SAM) of the CGWB, for his inspiration during the preparation of the manuscript. Regional directors of Eastern Region Kolkata office of the CGWB are acknowledged for providing infrastructural facilities. The author expresses his gratitude to the Lt. Governors of the Andaman and Nicobar Islands; Chief secretaries, Development commissioners and Secretaries of the APWD; A&N Administration; Chief engineers of the Andaman Public Works Department, Military Engineering Service and Andaman & Lakshadweep Harbour Works; and Director of Agriculture of A&N Administration, for their constant enthusiasm and needful logistics during the long course of work in the remote islands. Their keen attention to implement the projects had enhanced the working experience and spirit of the author. The author gratefully acknowledges the inspiration received from Dr. S. P. Sinha Ray, former Member of the CGWB, President of the CGWS and organizer of the International Conference. Constructive suggestions from him were pivotal for improvement of the manuscript.

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Part III
Ground Water Management in Alluvial and Coastal Areas

Groundwater Management in Alluvial, Coastal and Hilly Areas

M. Thirumurugan, L. Elango, M. Senthilkumar, S. Sathish, and L. Kalpana

Abstract Groundwater plays a major role in the modern world being used for drinking, irrigation and industrial development. The increasing population and developments in agricultural and industrial sectors depends on groundwater as it is a reliable source, and so it leads to overexploitation of groundwater without due regard to the recharging capacity of the aquifers. Groundwater extraction from most of the aquifers around the world has exceeded its recharge capacity, and hence the water table has gone down drastically leading to adverse environmental consequences like land subsidence and water quality deterioration. A proper assessment of groundwater resource should be undertaken to ensure sustainable management of groundwater. Hence, the present study proposes empirical methods for the sustainable groundwater resource management in alluvial, coastal and hilly regions.

Keywords Groundwater management · Alluvial aquifers · Coastal aquifers · Weathered rock aquifers · Groundwater modelling

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S. P. S. Ray (ed.), *Ground Water Development - Issues and Sustainable Solutions*, https://doi.org/10.1007/978-981-13-1771-2_6

1 Introduction

Groundwater is known as a replenishable resource for the nation, which also plays a major role in human health, economic development, ecological diversity and also maintains environmental sustainability. The growth of human population, development of agriculture and industrial activities in the regions of coastal, alluvial and hilly areas have led to overexploitation of groundwater. In India, Central Ground Water Board (CGWB 2009; Chatterjee and Purohit 2009) has categorized 4078 units as safe, 839 units as overexploited, 226 units as critical and 550 units as the semi-critical, and the remaining 30 units were totally underlain by saline groundwater out of 5723 units (Blocks/Mandals/Taluks). It has also been estimated that about 60% of groundwater sources in India will be in a critical state of degradation within the next few years (World Bank 2010). Therefore, to avoid overexploitation of groundwater, it is recommended to study the long-term behaviour of an aquifer and the management policies that needs to be adopted for a successful groundwater resource management. The present paper deals with the protection strategies to be adopted for mitigating the groundwater-related management issues in different types of the aquifers.

2 Alluvial Aquifers

In general, alluvial aquifers are mainly composed of thick piles of sediments formed by river action, which comprises predominantly of gravel, sand, silt and clay that are deposited in river channels or on floodplains. This vast and thick alluvial fill acts as the most potential and productive groundwater reservoir system, which are characterized by regionally extensive and highly productive multi-aquifer system. Groundwater from this type of aquifers occurs under unconfined condition at shallow depth and confined condition at deeper depth with good yield. Groundwater flow in these aquifers is mainly controlled by the interaction between the aquifers and streams. Due to rapid urbanization in the alluvial aquifer regions, pumping of groundwater has increased. On the other hand, climate change has also affected the recharge/infiltration rate that leads to groundwater scarcity over these regions.

3 Coastal Aquifers

The coastal aquifers are an important groundwater resource in coastal zones. The aquifers in these areas generally comprise of alluvial and rock materials. In the coastal aquifers, there is a hydraulic connection between saline and freshwater which are characterized by the behaviour of coastal transition zone with respect to space and time. Coastal aquifers are comprised of freshwater lens overlying a saltwater wedge on land with the saline groundwater below the seafloor (Hubbert 1940). This may rise up during overexploitation of freshwater by forming cone of depression and resluting into seawater intrusion. The rapid growth of urbanization, industrial and agricultural activities in coastal regions leads to overexploitation of groundwater, which causes land subsidence and seawater intrusion into the freshwater aquifer.

4 Weathered Rock Aquifers

Weathered rock aquifers are commonly found in many areas of the world. These aquifers are formed due to weathering of crystalline rocks such as granite, gneisses and schist. Due to the presence of high heterogeneity in the hard rock regions, especially in terms of fracture system, the aquifer characteristics may vary from place to place and therefore the water holding capacity of these rocks varies drastically (Chandra et al. 2006, 2008). In weathered rock aquifers, the groundwater occurs in the pore spaces between the mineral crystals, fractures and joints of crystalline rocks, which are based on the rate of weathering. The groundwater movement in these aquifers are dependent on the fracture network which allows the groundwater to move faster and so the storage capacity of these aquifers is very much lower.

5 Groundwater Management Strategies

The groundwater development in an aquifer must involve management strategies which demands both good quality and adequate quantity of groundwater. Hence, the sustainable management of groundwater poses greater importance, especially in the overexploited aquifers.

Groundwater management in an alluvial aquifer involves the setting of two conditions, which will induce recharge from the river to aquifer. First is the setting up of hydraulic connection between river and aquifer which would maintain groundwater flow even away from the river. Second is the construction of check dam across the river, so as to trap the surface water and allow it to recharge (Parimalarenganayaki et al. 2014), into the space, created by overexploitation of groundwater in an alluvial aquifer. Riverbank infiltration is a planned management methodology to induce groundwater recharge along the river, which when adopted near the check dams maximizes the well yield and will achieve natural infiltration (Parimalarenganayaki et al. 2014).

In coastal aquifers, the management strategies must consider seawater intrusion, sea-level rise due to climate change impacts, land subsidence and other hydrogeological processes including the density-dependent solute transport in heterogeneous systems (Kashef 1971; Post 2005; Werner et al. 2011). Based on the above constraints, the management activities should involve injecting freshwater through borewells as artificial recharge, reducing the pumping rate to prevent up-coning of saltwater, and safeguarding the aquifer for future needs (Melloul and Collin 2000). It is recommended to install a denser monitoring system to monitor the saltwater intrusion (Melloul and Collin 2000). Studies pertaining to seawater intrusion and density-dependent solute transport using predictive modelling was carried out by Sivakumar and Elango (2010).

In weathered aquifers, the pumping rate and rate of weathering is relatively high when compared to others. Hence, the management strategies should focus on increasing the groundwater recharge. This can be achieved through contour bunding, hillslope trenching, gully plugging and construction of MAR structures. It is also recommended to set up a network of piezometers and observation wells for monitoring the water table to estimate the recharge rate and to measure the impact (Sikka 2002).

6 Groundwater Modelling

During the past several decades, mathematical groundwater models are playing a major role in the evaluation of alternative approaches for groundwater resource management. Groundwater models represent the actual groundwater system through the model cells and boundaries. A groundwater flow model can provide an accurate and quantitative relation between groundwater flow system, pumpage and groundwater level decline. This enables to forecast changes in groundwater flow system under future hydrologeologic conditions in the time scale of decades or more (USGS 2013). The reliability of groundwater models is dependent on the quality and extent of historical data (rainfall and pumpage) used for calibration. A number of groundwater modelling software like FEFLOW, MODFLOW, GMS, GW Vista, etc. are widely used to model the groundwater flow and are used to outline groundwater resource management plans (Rejani et al. 2008; Kushwaha et al. 2008; Kumar et al. 2011).

7 Case Studies

There are several case studies available in the literature on groundwater resource management. Some of the studies on these three different kinds of aquifers in different regions of India (Fig. 1) were studied by us and are given below.

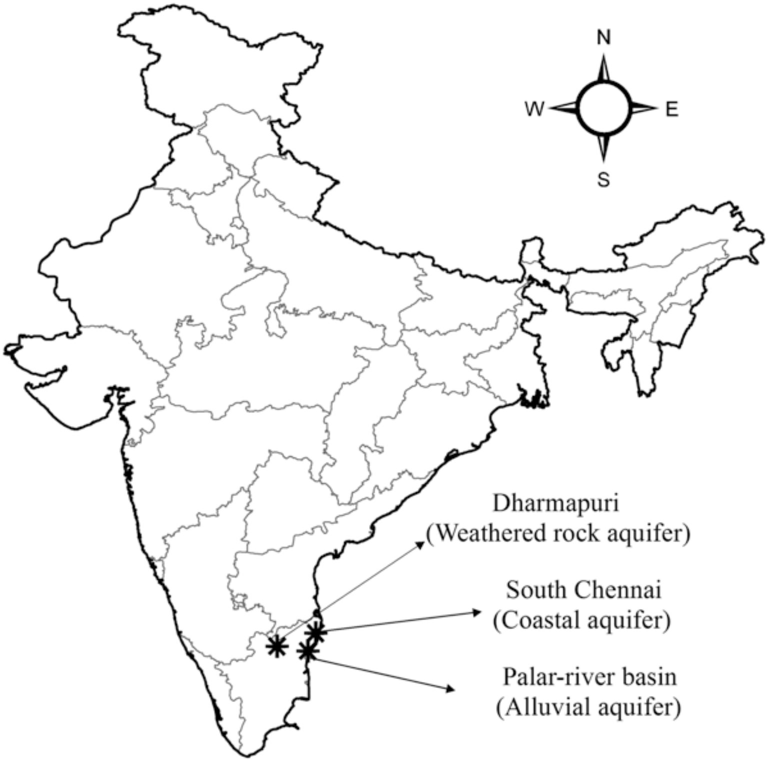

Fig. 1 Study locations of three different aquifers

7.1 Alluvial Aquifers

Senthilkumar and Elango (2004) used 3D mathematical models as a tool to simulate regional groundwater flow of the alluvial aquifers of the Palar river basin (Fig. 2). The area is characterized by heavy abstraction of groundwater for agricultural, industrial and drinking water supplies. An area of 392 km^2 was modelled and simulated under steady and transient state conditions. Under transient state, the model was simulated for a period of 20 years to forecast groundwater flow under various scenarios of overpumping and less recharge. It was suggested that the aquifer system is stable at present rate of pumping, except at few locations. The study also indicated that the groundwater head would decline by about 0.9–2.4 m below sea level for a groundwater withdrawal of about 2 million gallons per day (Fig. 3).

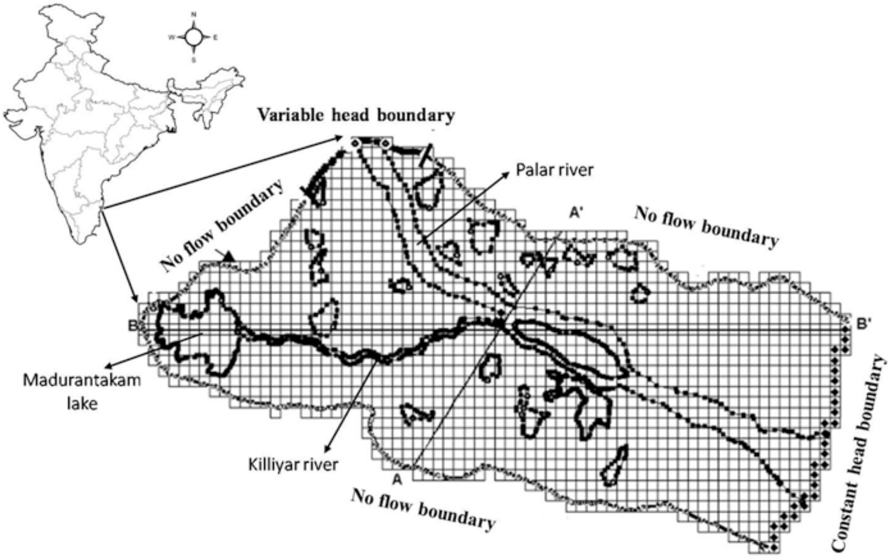

Fig. 2 Alluvial aquifer of Palar river basin

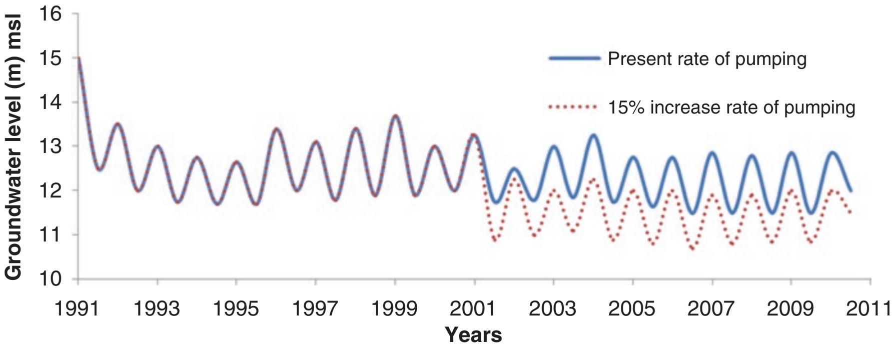

Fig. 3 Simulated groundwater head in Palar river basin with increased rate of pumping

7.2 *Coastal Aquifers*

The rapid urbanization and industrialization in the south of Chennai (Fig. 4) have resulted in groundwater depletion and/or degradation, which calls for development and adaptation of new management strategies. Sathish and Elango (2015) have simulated the groundwater head using 3D groundwater flow models to predict the groundwater flow in coastal aquifer at decreased recharge and increased discharge rates. The discharge rate is comparatively less than the recent past, but still the recharge and discharge of present trend leads to the decline in groundwater head of

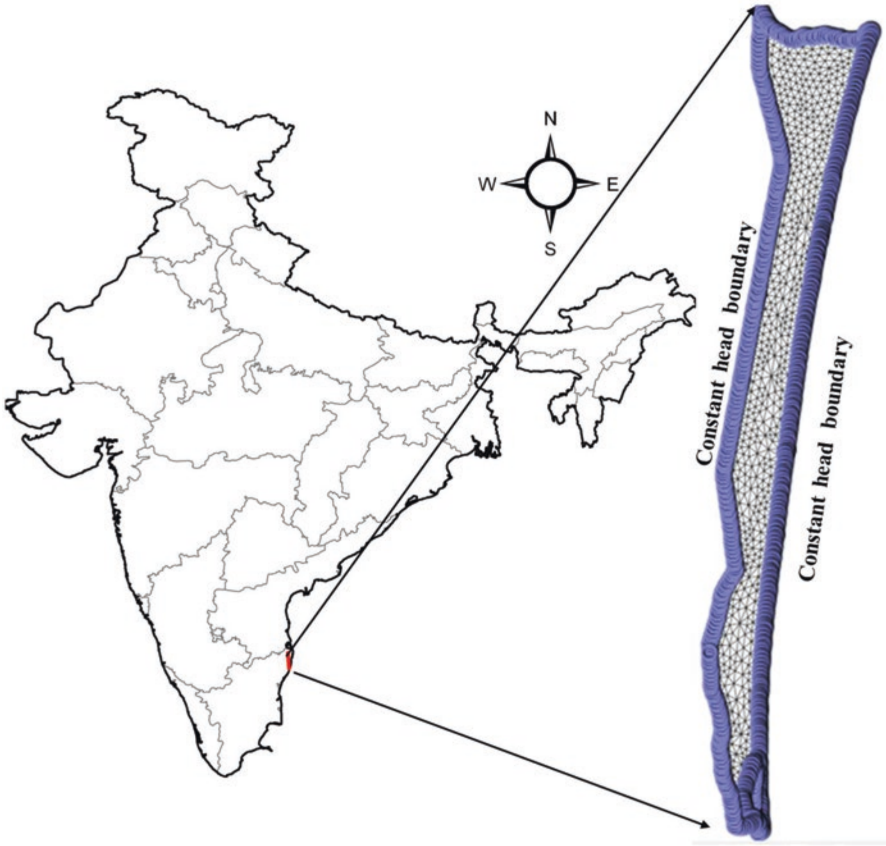

Fig. 4 Coastal aquifer of south Chennai, India

0.32 m at the end of 2020. The land use and land cover map from 2004 to 2012 of Chennai shows the rise in settlements which impose high pumping rate. The 5% and 10% increase in discharge makes the decline of groundwater head of about 0.60 m and 1 m at the end of 2020 (Fig. 5). The fall in 10% of recharge rate from normal suggested rainfall recharge range; the groundwater level will be lowered below the sea level.

7.3 *Weathered Rock Aquifer*

The 3D groundwater flow model was used by Kalpana (2014) to predict the possibility of reducing the concentration of fluoride in groundwater by managed aquifer recharge in the hard rock region of Dharmapuri district, Tamil Nadu, India (Fig. 6). The long-term analysis of rainfall and groundwater level over the region has resulted

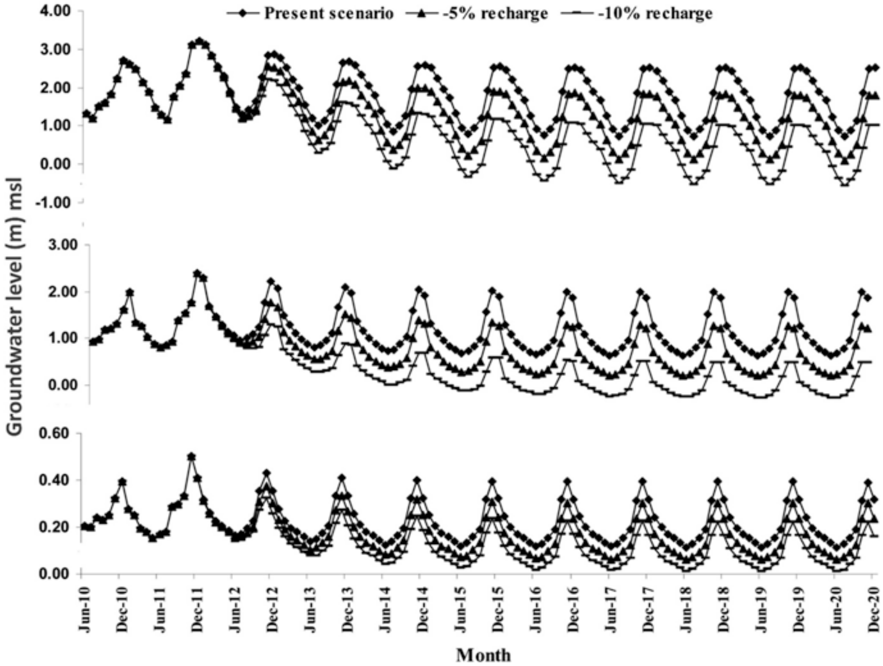

Fig. 5 Simulation of groundwater head with reduced recharge rate in south Chennai

in drastic reduction of the number of water bodies. It was recommended to rejuvenate the water bodies to reduce the concentration of fluoride. The range of groundwater level fluctuation was 2.5 m, and the maximum concentration of fluoride in groundwater is 4.3 mg/l. The geochemical studies which are carried out in this area indicate a rise of groundwater level about 2.5 m, which results in a reduction in about 1 mg/l of fluoride. The simulated groundwater model indicates the groundwater level increase by about 5 m with the practice of managed aquifer recharge through the MAR (Fig. 7). With the observed groundwater level and fluoride concentration variation in the well, it is predicted that about 2 mg/l of fluoride will be reduced for the 5 m increase in the groundwater level after MAR. Hence the effect of increased groundwater recharge will make groundwater in the well suitable for drinking purposes with respect to fluoride.

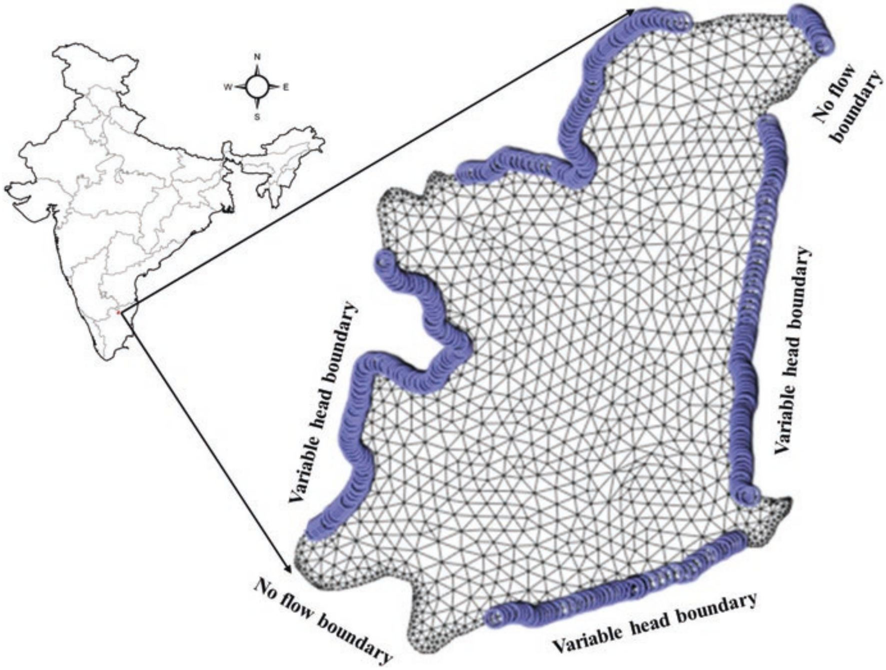

Fig. 6 Weathered rock aquifer in the part of Dharmapuri district, India

8 Conclusion

Applications of groundwater models to estimate the groundwater resources management at the three different kinds of aquifers, viz. alluvial, coastal and weathered rock aquifers, were put forth in this chapter. The groundwater models were helpful in estimating the pumping and recharge rate and to predict the saltwater intrusion. It is also used to estimate the impact of the construction of MAR structures in terms of improvisation in groundwater level and quality. Apart from these, the groundwater models were used as an efficient tool to resolve other groundwater-related problems and proper groundwater resource management. This chapter provides an idea of employing groundwater models for diverse groundwater Scenarios.

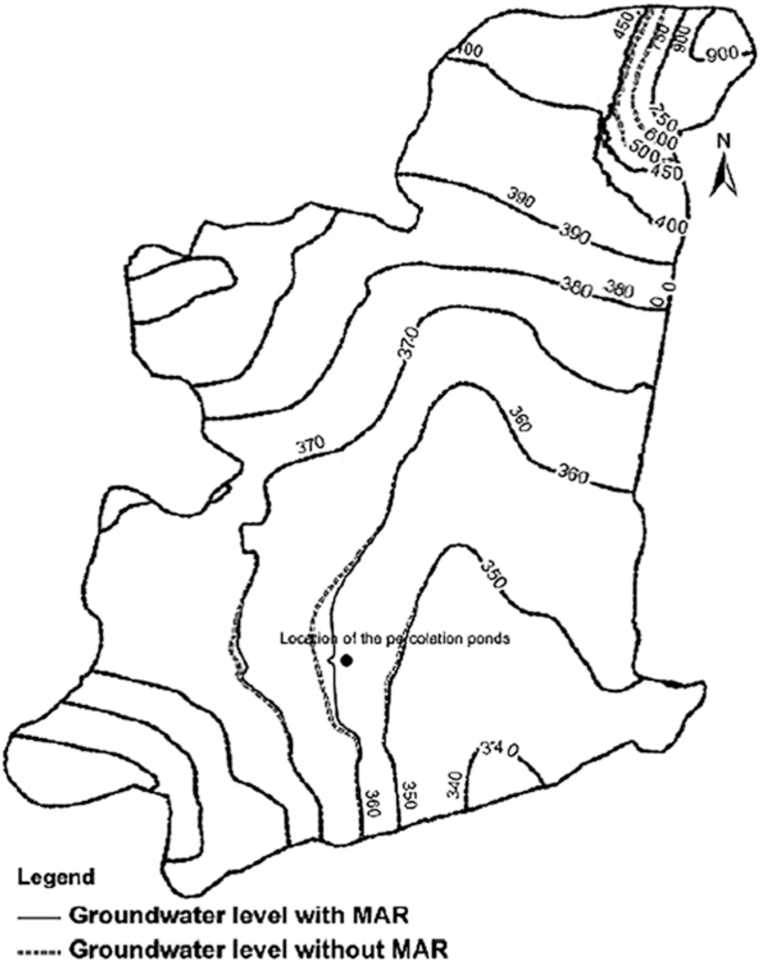

Fig. 7 Effect of MAR on spatial improvement of groundwater level

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Findings of Large Groundwater Development Potential in Deeper Aquifers in Karnaphuli–Feni Interfluve, Chittagong, Bangladesh: A New Scientific Initiative

Ranajit Saha

Abstract A group of steel industries situated in the district of Chittagong, Bangladesh, has engaged NRIEMT of Kolkata, India, to study the entire area in and around of their proposed plant areas stretching from Chittagong town in the south to Mirsarai (latitude 22°45′01″ N and longitude 91°35′15″ E) in the north up to the Feni River, Chittagong, Bangladesh, with a length of 70 km (approx) and width varying from 3 to 12 km. This study is essential for obtaining a clear picture of the prospects of groundwater and surface water, and this paper deals with various problems of groundwater.

The present study has thrown light considerably to the fresh groundwater regime which occupies underneath Karnaphuli–Feni interfluve. Being an extension of Sitapahar, the eastern part of the area is characterized by somewhat rugged and irregular topography.

The study area comprises a continuous succession of sandstone and shale. A clear picture about the subsurface deposition of different lithological strata has been revealed from both VES and electrical logging report as well as from a number of drilling of production tube wells at different locations. The entire investigated area has been categorized in 3 (three) segments, namely, north, central and south. The sediments of Tipam group comprise medium- to fine-grained and semi-consolidated sand and form the main aquifer system of the area (equivalent to Tripura of India extension).

The chemical quality of groundwater is overall good, but there is an indication of salinity in the aquifers that exist at a depth of approximately 85.00–125.00 m from north to south. The iron content is also high beyond permissible limit.

This systematic scientific approach has established the existence of a moderate to large potential of groundwater resources in the Karnaphuli–Feni interfluve area. These precious resources will go a long way in supporting industrialization in this otherwise underdeveloped tract of land which will ultimately usher to a new socio-economic horizon in coming years.

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S. P. S. Ray (ed.), *Ground Water Development - Issues and Sustainable Solutions*, https://doi.org/10.1007/978-981-13-1771-2_7

Keywords Groundwater reservoir · Rainwater harvesting · Geophysical resistivity survey · Tipam group of sediments · Tapping zones · Step drawdown test

1 Introduction

A number of steel industries and proposed power plants having their offices at Chittagong, Bangladesh are planning to set up a billet making melt shop, and thereafter, a coal-based power plant has engaged the “Natural Resources Investigation, Evaluation and Management Technologies” (NRIEMT), an International Water Resources Management Consultant having its office at Kolkata, India, to study the entire area *stretching from Chittagong town in the south to Mirsarai (latitude 22°45′01″ N and longitude 91°35′15″ E) in the north up to the Feni River, Chittagong, Bangladesh, with a length of 70 km (approx) and width varying from 3 to 12 km, covering mouzas* Mirsarai (N22°45′01.0″/E91°35′ 15.0″), Sonapahar, Bansberia, Chota Kumira (N22°31′05.0″/E91°43′47.1″), Masjiddah, Bara Kumira (N22°26′37.4″/E91°44′14.7″), Baraulia (N22°28′39.6”and E91°43′17.6″), Fauzdarhat (N22°22′47.0″/E91°46′03.0″) and Nasirabad in the district of Chittagong, Bangladesh, with a view to finding out the water availability (both groundwater and surface water) to cope up with the water requirements for both steel and power plants.

2 Purpose and Scope of Study

The mainstay of economy of an area depends on industrialization, though agricultural development also plays a major role. This study is essentially for obtaining a clear picture of the prospects of groundwater and surface water of the area. However, this paper deals with various problems of groundwater development only. During these studies, detailed quantitative information on the groundwater resources available for utilization, annual recharge to the groundwater reservoirs, present stage of development and utilization of groundwater including its chemical quality were collected and analysed. The present study has thrown considerable insight to the freshwater and groundwater regimes occurring underneath Karnaphuli–Feni interfluve area.

3 Methodology

The following steps were taken to address the problem:

1. Reconnaissance hydrogeological investigation in and around of the project area
2. Reduced level survey by total station
3. Geophysical resistivity survey (VES) and geophysical electrical logging

4. Construction of test wells and carrying out aquifer performance tests on existing borewells and selected test wells
5. Preparation of different thematic maps and lithological correlation map based on available borewell data as well as newly constructed test borewell data and production tube well data
6. Preparation of design of rainwater harvesting structures for storage of rainwater in suitable location within plant area
7. Preparation of design of rooftop rainwater harvesting structures as well as groundwater recharge structures within plant area/outside plant area
8. Formulation of a total comprehensive water sourcing and management plan required for the project (steel plant and power plant)

4 Location and Accessibility

The specified studied area lies from Chittagong town (Nasirabad) in the south and on the extreme northern part of Chittagong district under Mirsarai Upazila of Bangladesh with a border of the Feni River covering an area of approximately 300 km^2. This area is included in Survey of Bangladesh Toposheet No.79 M/9. It is bounded by Feni district of Bangladesh and Tripura of India towards north; Chittagong City on the south; Sitakundu pahar, Khagrachari and Ranga Mati district towards east; and floodplain valley and Bay of Bengal towards west. The study area with a linear stretch of about 70 Km in a north–south direction is traversed by Dhaka–Chittagong National Highway and metre-gauge railway track of Dhaka–Chittagong. The extreme northern part of the study area is about 207 km from Dhaka, the country capital, and 70 km from Chittagong City (Plate 1).

5 Previous Study

The area has been studied by the Geological Survey of Bangladesh for geological mapping. Some research scholars studied the adjacent hilly terrain Sitapahar periodically. In addition, short-term water availability investigations have been carried out by the Bangladesh University of Engineering and Technology (BUET) for assessment of water availability in the study area (Plates 2 and 3).

6 Geomorphology

The Sonapahar and adjoining areas show well-defined physiographic as well as geomorphic units. The existing landforms have emerged as a result of long-term subaerial denudation and subsequent infilling of the basins (micro watershed) by

Plate 1 Map showing the areas of investigation, Chittagong, Bangladesh

sediment derived by the principal nalas (streams) and charras and its tributaries. The area, as a whole, exhibits more or less matured peneplain topography with hillocks towards east.

Being an extension of Sitapahar, the eastern part of the area is characterized by somewhat rugged and irregular topography. In the central part of the study area, from east to west, landforms gradually lose its height, and undulating topography diminishes moderate to low in order which passes to the railway track and national highway (Dhaka–Chittagong). This undulating characteristic of the northern and central part of the area dies out towards west, and the lands become more or less flat and finally merge to the alluvial plains of Padma–Yamuna river systems.

The principal drainage is controlled by the Feni River and Hingoli River which originated from Sitapahar area north–south and merges towards west to the Bay of Bengal.

There are a few number of nalas called “charras”, which originated from Sitapahar areas flowing east–west direction surrounding the study area. The “Sonacharra” flows encircling the project area towards east with a direction of flow south to north, crossing the project area, and flows towards east. This “Sonacharra” meets with Kanail at the south-eastern part of the project area and forms a wide valley towards north-east of the project area. A map showing the drainage pattern of the surrounding areas has been shown in Plate 4.

The other nalas are named as Mitti Charra and Phuljhari Nala which fed the area in dry weather. The chief characteristics of all the nalas are that they flow with tremendous velocity in the monsoon months, carrying substantial volume of sand and

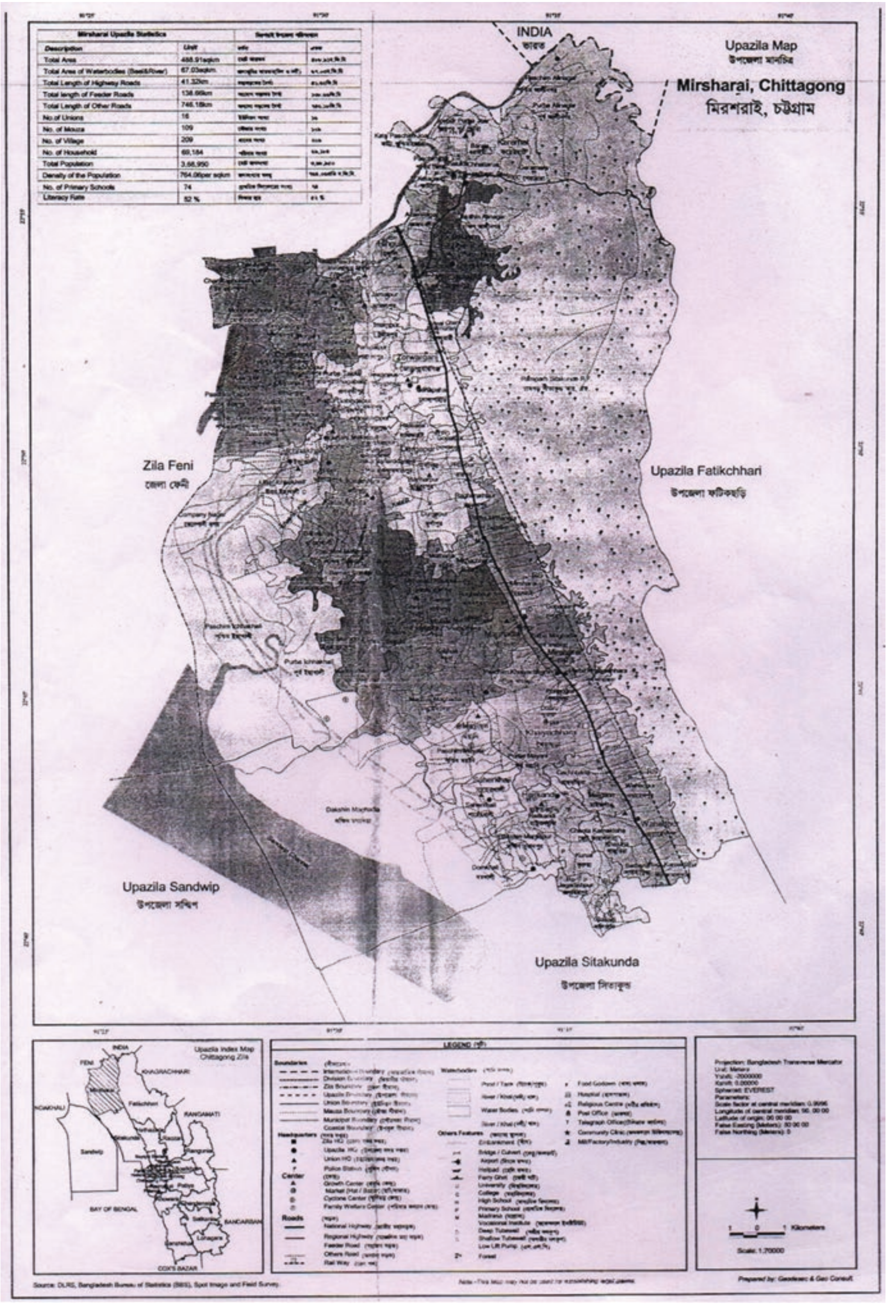


Plate 2 Map showing the areas of Mirsarai Upazilla, Chittagong, Bangladesh

Plate 3 Satellite imagery of Sitakunda area

silt with them. Flash flood is quite common to these nalas in rainy season, followed by dry courses (only seepage water) in summer period.

7 Geomorphic Evolution

The geomorphic evolution of an area is the result of interaction between the different elements like lithology, structure, climate, etc. involved in the various endogenic and exogenic processes. Broadly, the area can be grouped into the following geomorphic units:

Plate 4 Map showing drainage system in Mirsarai Pourashava, Chittagong, Bangladesh

1. Zone of resistant structural hill ranges. They form the crests of various hill ranges. This unit shows high-relief ridges of sandstone belonging to Bhuban series of Surma group of rocks. This is the run-off zone with springs.
2. Moderately dissected, low-relief area with parallel ridges represented by Bokabil shales and siltstone of Surma group of rocks. This is also mainly run-off area with occasional springs.
3. Low-lying, highly dissected, moderately round crested low hills with broad bad land topography. This unit is also mainly run-off zone.
4. Moderately dissected, round crested to nearly flat-topped denudational hills in Bokabil shale-siltstone. This is partially the recharge area where shale, alternating with siltstone, forms the run-off zone.
5. Low round to flat-topped moderately dissected residual sandstone hills occupy synclinal valleys of Tipam sandstone of Mio-Pliocene age. This is the main recharge area, having moderate prospects for groundwater structures.
6. Undulating plains with very low-lying flat-topped mounds and narrow to wide valley fills (Lunga Land) in Dupitila sandstone. This is also the recharge area forming shallow to moderately deep aquifers with good groundwater potentiality. This unit is mostly found in West Tripura district.
7. Floodplain areas of Feni River and its tributaries. The floodplain is mostly restricted to within the river valley only (Plate 5).
8. The prevailing temperature and rainfall indicate that it experiences a tropical humid to subhumid climate. There are three seasons which can be prominently visualized, viz., summer, rainy and winter seasons. Summer extends from March to May, when the rains set in under the influence of monsoon which lasts till September. Winter starts from the middle of November and continues up to February. The temperature varies from 32.3 to 44.5 °C in summer and 12.10 to

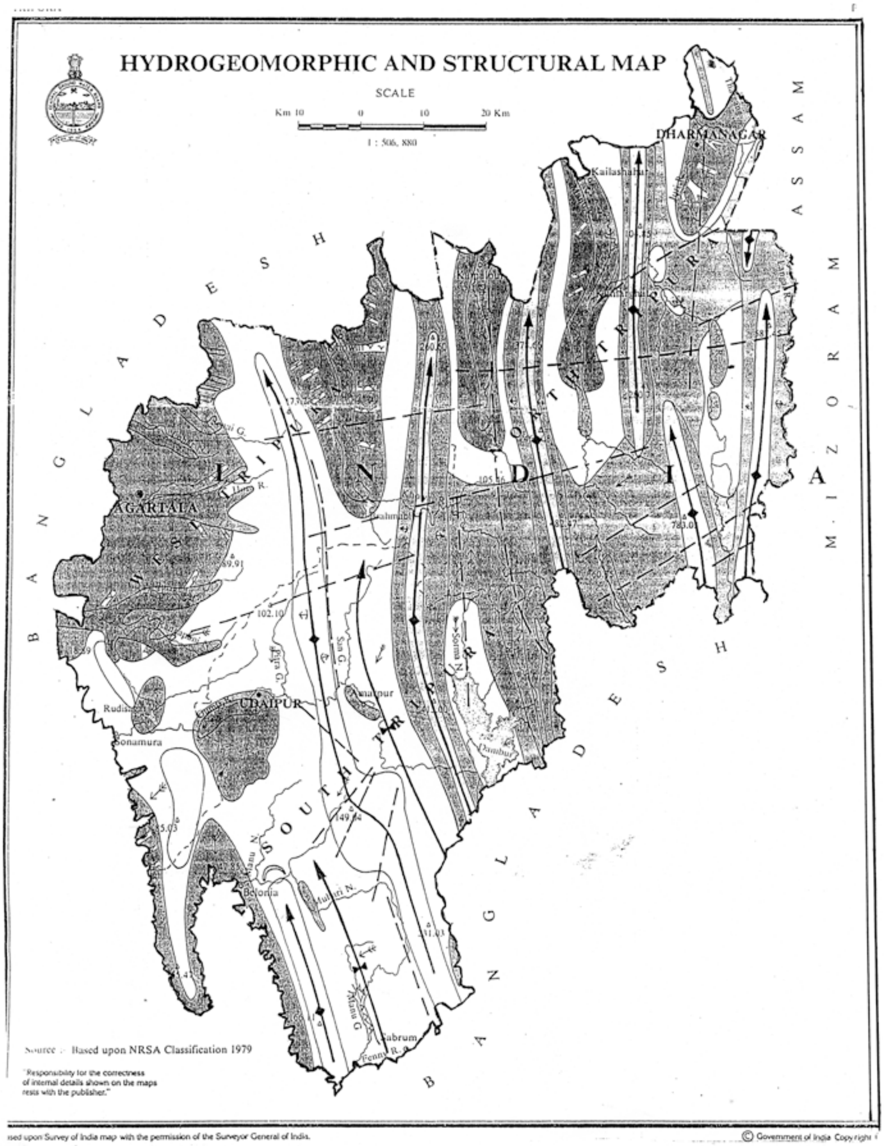


Plate 5 Hydrogeomorphic and structural map

9.52 °C in winter. The annual rainfall varies from 3200 to 4600 mm; rainfall in monsoon months constitutes about 80% of total rainfall. The monthly rainfall data shows that downpouring set under the influence of monsoon is maximum in July–August and it ranges from 1352 to 3293 mm with an average annual monsoon rainfall of 2194 mm. Flash rain is common and even more than 100 mm in a day or two.

8 Geological Setup

8.1 Surface Geology

A considerable thickness of clastic sediments of Miocene age is exposed on the eastern flank of Sitapahar Hill Range. A comprehensive study was undertaken which includes overall geology, subsurface geology, where multidisciplinary approaches involving geomorphology, geophysical resistivity survey and detailed hydrogeological studies (Plate 6).

Structurally, the Sitapahar Hill Range is situated within the eastern subzone of the folded flank of the Arakan–Yoma geoanticline.

The tectonic evolution of this region ranges from Cretaceous through Tertiary to Quaternary. Sedimentary features found in the area suggest that deposition took place under shallow marine to continental fluviatile environment.

The study area comprises a continuous succession of sandstone, siltstone and shale. The rock sections are derived into three lithostratigraphic units, mainly on the basis of gross lithology. These units are equivalent to upper Bhuban, Bokabil and alluvium formations, respectively.

Grain size analysis of the samples ascertains that the sediments were carried in and deposited by the river.

The coarsening-upward sequence suggests basinward progradation of deltaic sedimentation. A clear picture about the subsurface deposition of different lithological strata has been revealed both from geophysical resistivity surveys from 52

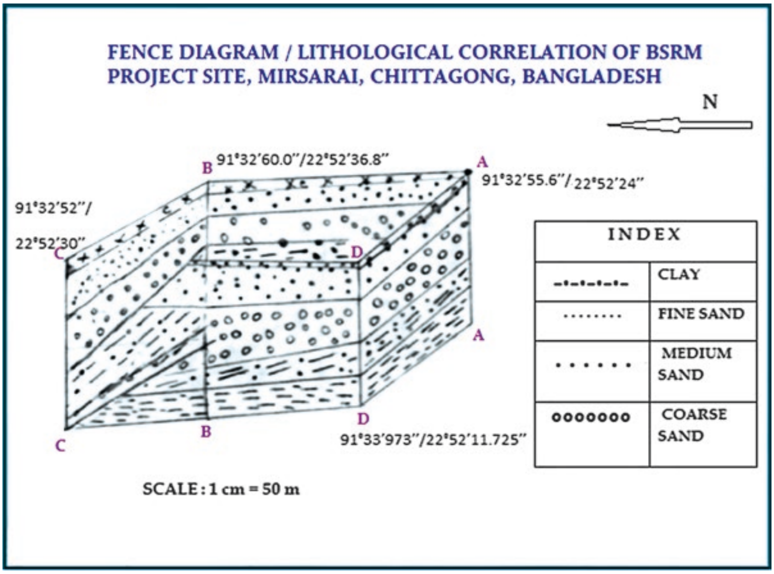


Plate 6 A lithological correlation/fence diagram at Mirsarai area, Chittagong, Bangladesh

Table 1 Stratigraphical sequence for the entire stretch north to south of the study area, Chittagong, Bangladesh

Location	Recent (m)	Dupitila (m)	Tipam (m)
Covering entire study area north to south	0–3	3–6	6–260
	0–3	3–25	25–299
	0–3	3–22	22–296
	0–9	9–39	39–299
	0–3	3–64	64–299
	0–3	3–42	42–293
	0–3	3–6	6–274
	0–3	3–9	9–274
	0–3	3–2	21–305
	0–3	3–36	36–305

numbers of VES results and from electrical logging of test wells and production tube wells.

According to the available literature, the thickness of the soil from 0 to 3 m can be described as of Recent age. From 3 to 25 m (varies from place to place) depth, all the sediments within this zone can be grouped into Dupitila bed/group, and beyond that 25 m depth extending up to 299 m, sediments can be grouped under Tipam group of sediments.

8.2 Subsurface Geology

From the records of several production tube wells as sunk during the total span of investigational programme, several sand, silt and clay and also hard horizons have been depicted. Geologically the area is underlain by formation belonging to Lower Tertiary to Recent in age. There are three to four major sand horizons (aquifers) encountered within a depth of 300 mbgl in the synclinal valley of the area. Mostly, the aquifers occur in Tipam formations. The sediments of Tipam group comprise of medium- to fine-grained, semi-consolidated and friable sandstones which form the major aquifer system of the area (Table 1).

9 Hydrogeology

To have a clear understanding of the depth to water level of the area, more than 100 numbers of inventoried wells have been selected for the entire area of investigation from north to south from which different hydrogeological data including depth to water level data were collected; water samples for chemical quality study were also collected. The reduced level data has also been measured by total station during the field survey. From the water level data, the water level contour map has also been prepared. The overall direction of the groundwater flow is from west to east. The hydrogeological framework.

To have a thorough knowledge about the hydrogeological setup of the study area, a linear tract of about 70 km in north–south direction, both reconnaissance hydrogeological survey including the study of chemical quality of groundwater and geophysical surveys, has been carried out. For convenience, the entire area has been subdivided into three sectors:

(a) Northern sector: Mirsarai Upazilla – covering Mirsarai, Sonpahar and Bansberia areas
(b) Central sector: Sitakunda Upazilla – covering Chota Kumira, Baraulia, Bara Kumira and Fauzdarhat areas
(c) Southern sector: Chattagram municipality – covering Nasirabad and Karnaphuli areas

Depth to water level varies from 1.45 to 9.452 mbgl during the study, and depth of the inventoried wells as reported from the local people varies from 7.00 to 137.00 m, and most of the tube wells are fitted with ordinary handpump.

In the whole of the study area, groundwater occurs under both water table condition in the near-surface aquifers and under confined condition in deeper aquifers. Groundwater occurs at a very shallow depth within recent river-borne sediments and forms prolific aquifer in the floodplains. The groundwater table lies very close to the surface and fluctuates with the annual recharge-discharge condition. Recharge to aquifers is mainly from vertical percolation of rainwater and floodwater. Charras and other standing water bodies provide local recharge to the nearby aquifers. The main component of discharge is the withdrawal of groundwater by different types of tube wells besides discharges through natural flow towards lower gradient. The groundwater level is very close to the surface during monsoon, whereas it deepens during months of April and May. From the lithological data as revealed from the production tube wells, it may be concluded that potential aquifer zones exist at three different depths down to the explored depth of 300 mbgl. But the depth and characters of the potential zones vary to some extent around the central and southern sectors of the study area. In the central and southern sectors, a number of hard stones were encountered during drilling operation, and in the southern sector at places (Nasirabad area), a sticky hard clay formation occurs, and this formation creates a problem during drilling operation.

The discharge of the production tube wells in the northern sector is satisfactory, whereas in the central and southern sectors of the study area, discharge of the production tube well is moderate. The details have been shown in Table 2.

Water level contour map and depth to water level zonation map have also been prepared (Plates 7, 8 and 9). From the above maps, it can be stated that groundwater flow direction from north–east to south–west and five zonations (<1 m, 1–2 m, 2–3 m, 3–4 m and >4.00 m) at an interval of 1.00 m have been shown in the water level zonation map.

Table 2 Details of granular zones, zones tapped, discharge, etc. of PTWs

Locations	Granular zones (mbgl)	Tapping zones (mbgl)	Discharge m^3/h	DWL (mbgl)	Remarks
Northern sector	(1) 114–132				
	(2) 200–218	201.00–215.00			Deeper aquifer highly potential
	(3) 222–274	224.00–254.00	70–162	8.60–13.54	Iron content high
	(1) 114–132				
	(2) 200–218	200.00–218.00			
	(3) 222–260	224.00–254,00			
Central sector	(1) 54.90–106.75	135.00–155.00	15–20	5.60–12.67	Upper aquifers saline infested
	(2) 112.85–121.05				
	(3) 158.60–183.00	264.00–288.00			Discharge low
	(4)196.72–219.60				Iron content high
	(5) 253.15–289.75				
Southern sector	(1) 6–57	150.00–162.00	12–15	10.43–20.32	Discharge low
	(2) 57–108	180.00–215.00			Iron content high
	(3) 150–219				

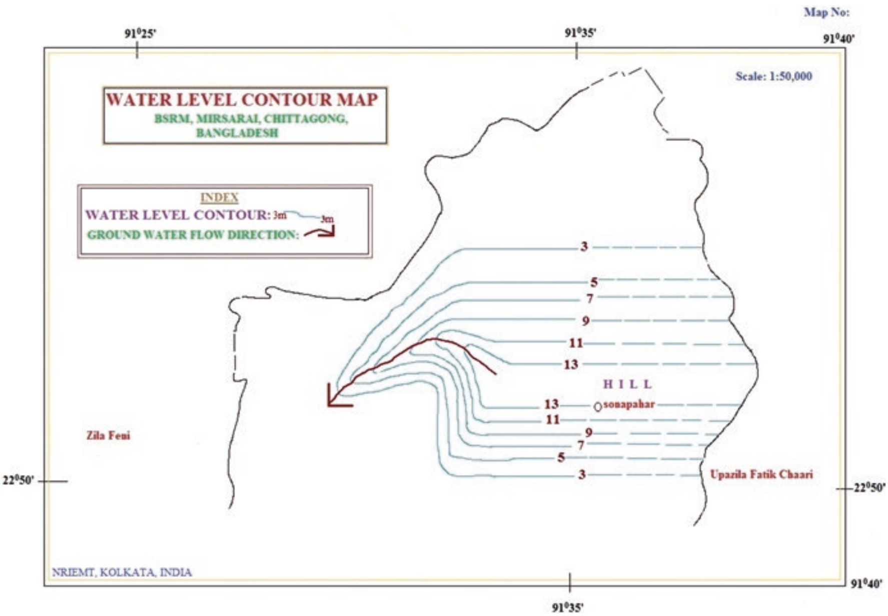


Plate 7 Water level contour map, Mirsarai, Chittagong, Bangladesh

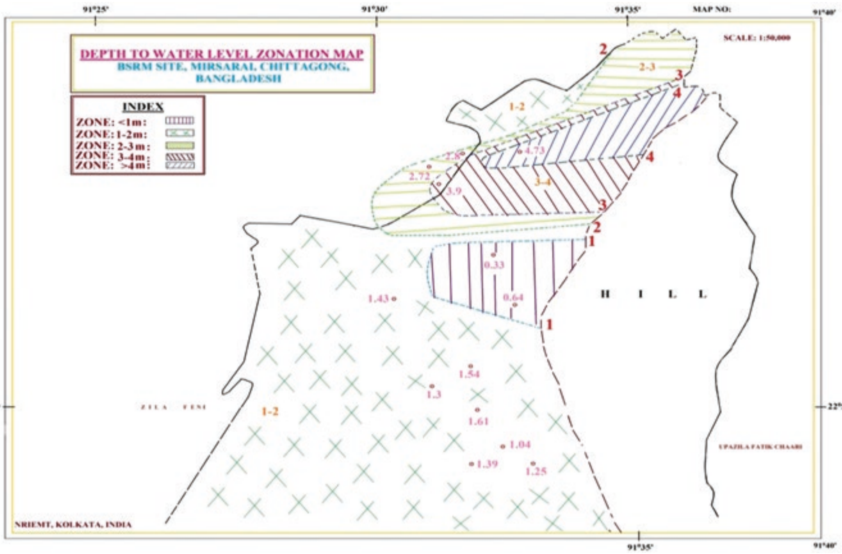


Plate 8 Water level zonation map, Mirsarai, Chittagong, Bangladesh

It has been noticed that groundwater moves from east and has flatter gradient towards the west. The hydraulic gradient being from 5 to 6 m/km. The principal source of groundwater recharge in the area is rainfall, a part of which infiltrates underground, while a major part of it discharges as surface run-off and evapotranspiration.

10 Geophysical Resistivity Survey

Geophysical electrical resistivity has been carried out at 175 locations covering the northern sector and southern sector as shown:

The results of the geophysical electrical resistivity survey conducted in northern, central and southern sectors of the study area show the presence of three sections of layers spread over the entire area under the investigation.

1. Top layer: Top wet soil/sandy clay cover
2. Second layer: Clay with hard formation/clay
3. Third layer: Clay and sand section (alternation of clay and sand)

The thickness of wet soil/sandy clay layer is expected to continue up to a depth of 4–7 m, then beyond this depth starts the second clay layer with the thickness of 30–48 m, finally beyond the depth of 37–58 m strikes a third clay and sand section (alternately clay and sand) that is expected to continue beyond the depth of investigation of 270 m (approx), and this third layer section shows the presence of different

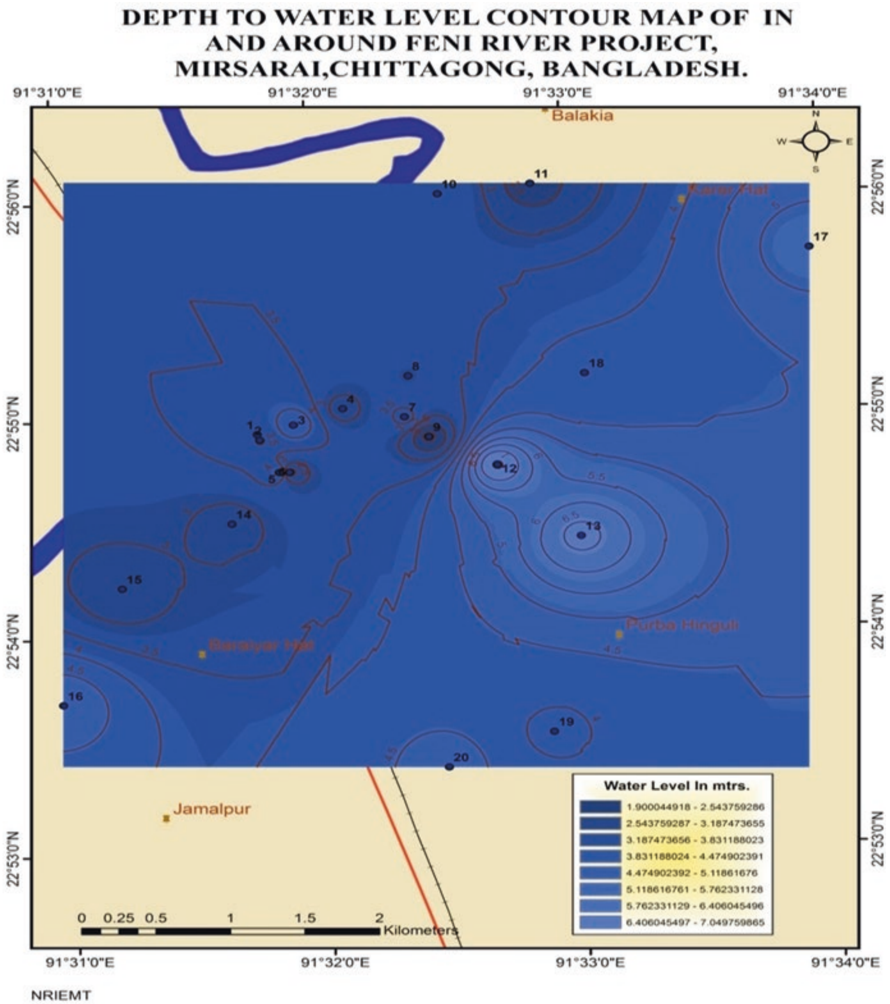


Plate 9 Depth to water level contour map

aquifer zones consisting of medium to fine sand existing at different depths. The deeper sandy zones beyond the depth of 170 m are spreading all over the area under investigation. On the basis of geophysical resistivity survey and hydrogeological survey, 10 nos. of PTWs as shown in the map were taken up for construction (as shown in Map No. 3).

Several diagrams from the VES study and SP and resistivity graphs from electrical logging reports in different sectors have been shown separately (Plates 10 and 11).

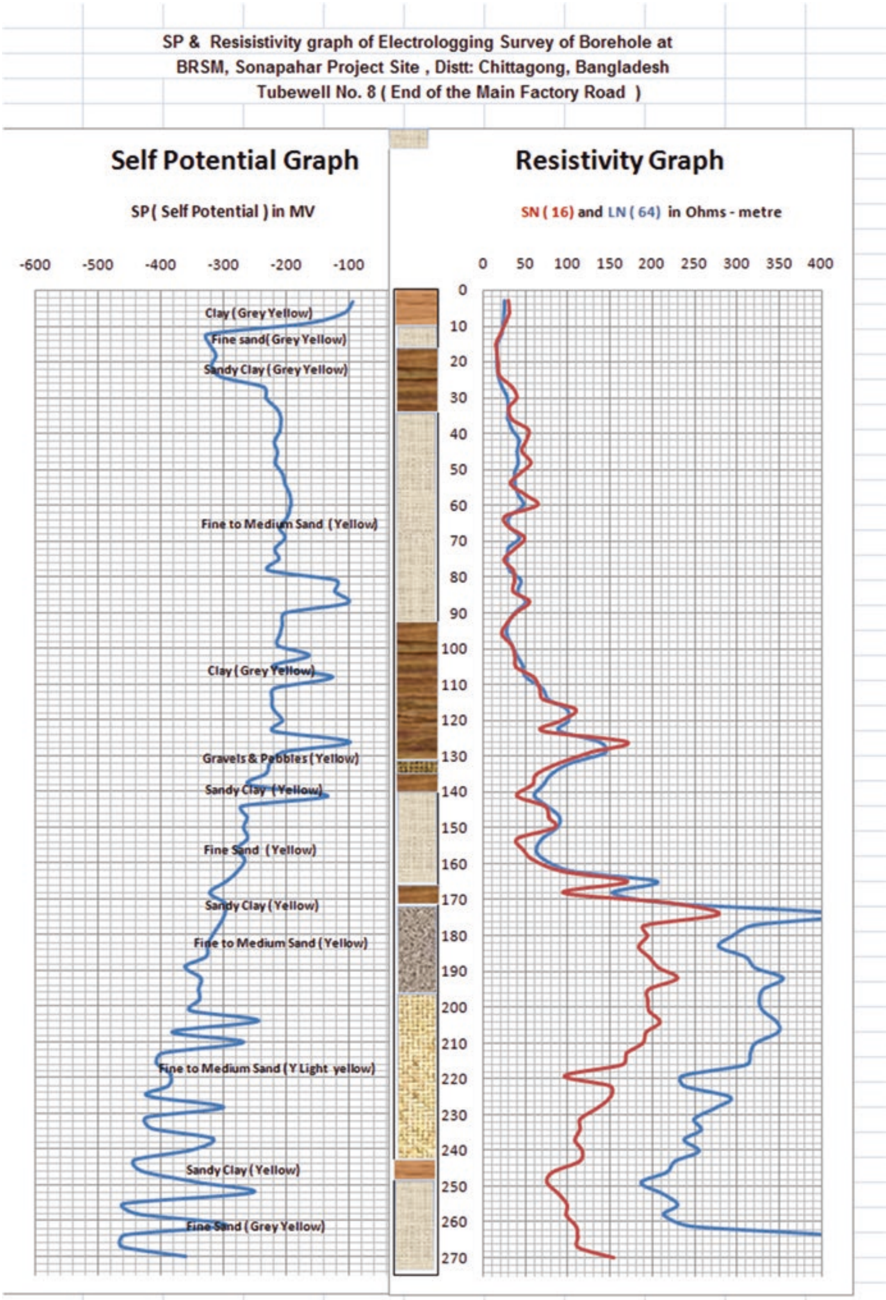


Plate 10 Northern sector

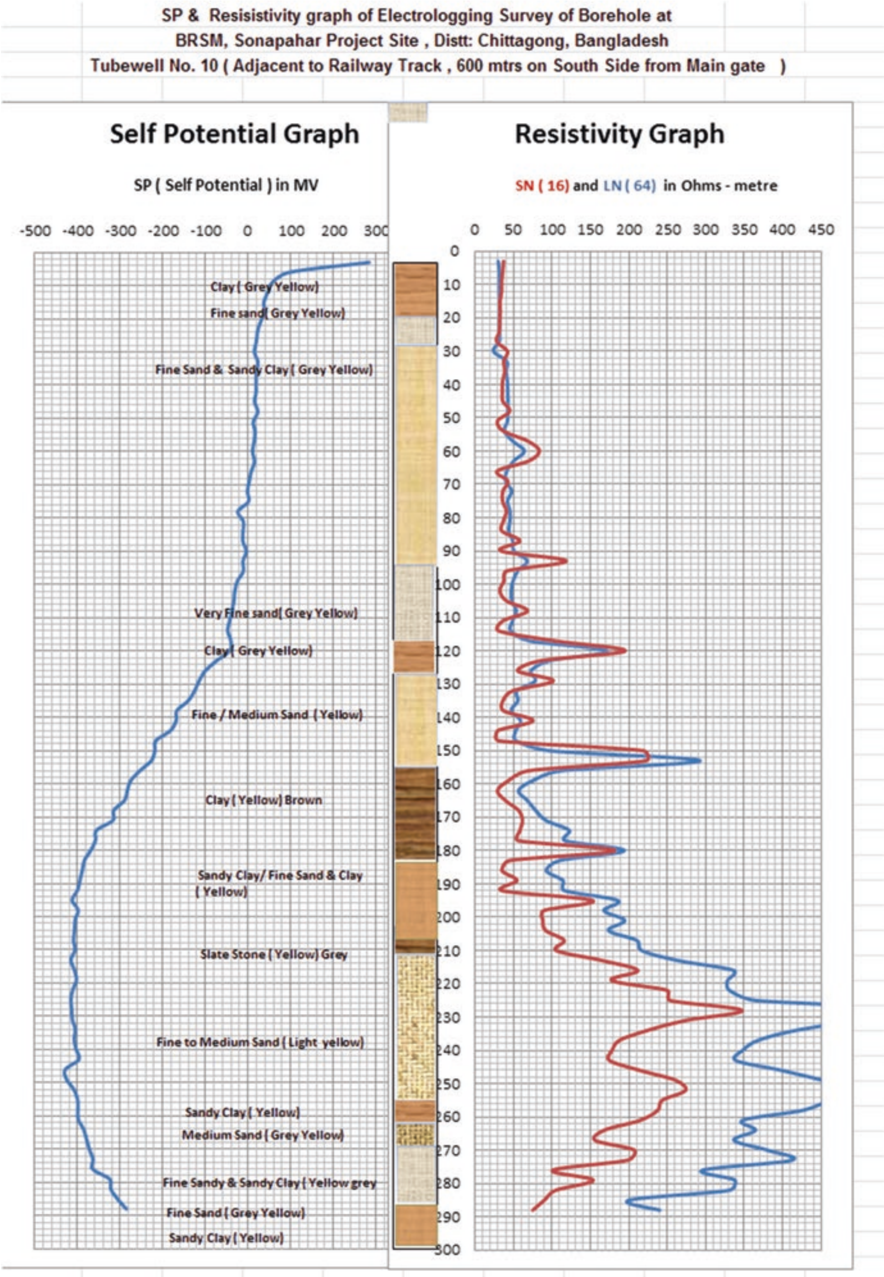
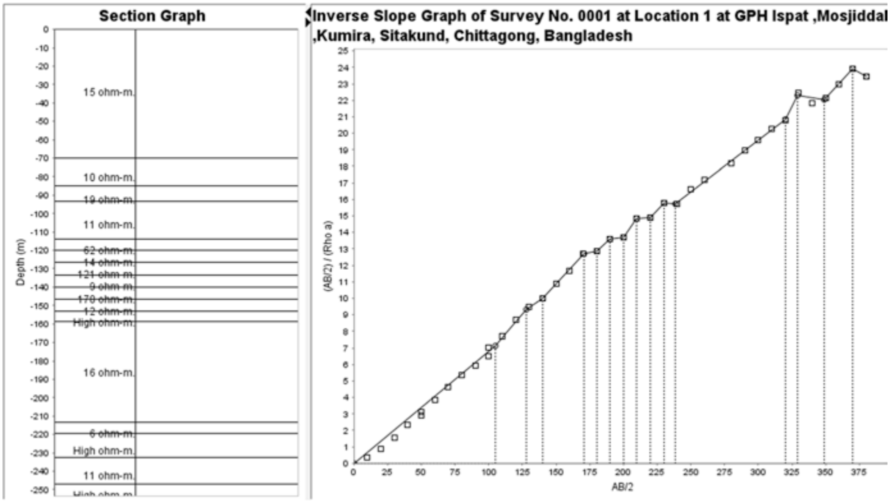
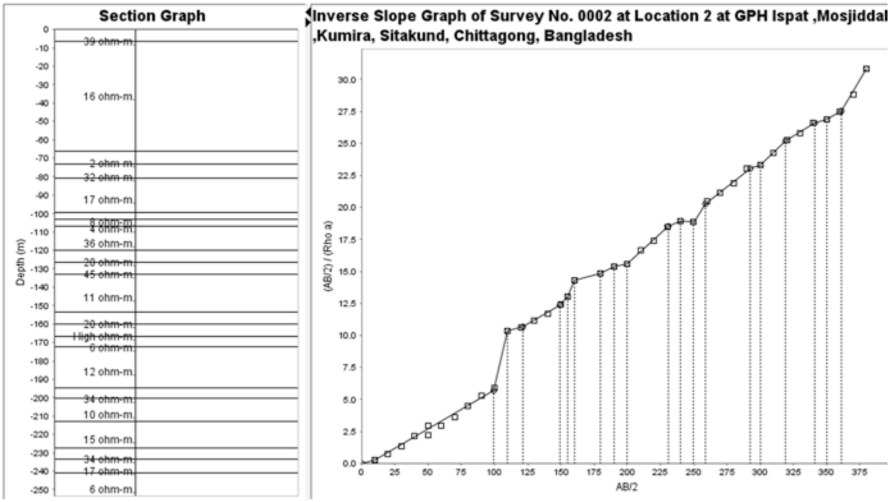


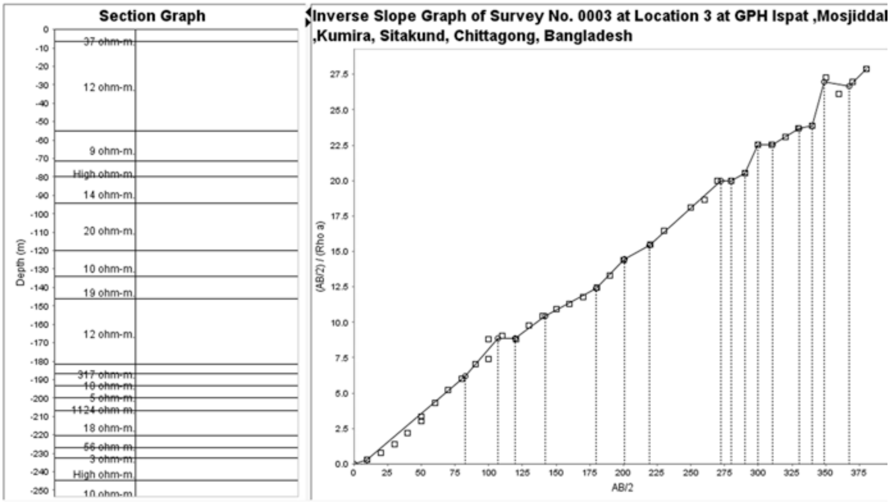
Plate 11 Southern sector

10.1 From VES and Geophysical Test (Central Part)

All the 50 nos. of VES (vertical electrical sounding) tests have given a similar nature of reading and curves. The VES depth examined was 350 m. The resistance values are in the range of 5–20 Ωm. But at higher depths, the resistance increases and rises abruptly. The trend of the resistance is linear. The values have been plotted and analysed with different hydrogeological software (Resist, Inverse slope and IPI2win software are used). The analysis made inferred the zone to be an alluvial tract till 300–350 (with layers of hard formations in the foothill region). Some of the diagrams have been shown below:

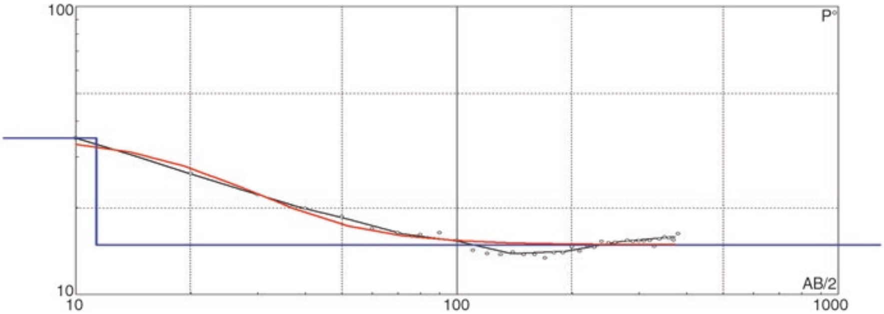




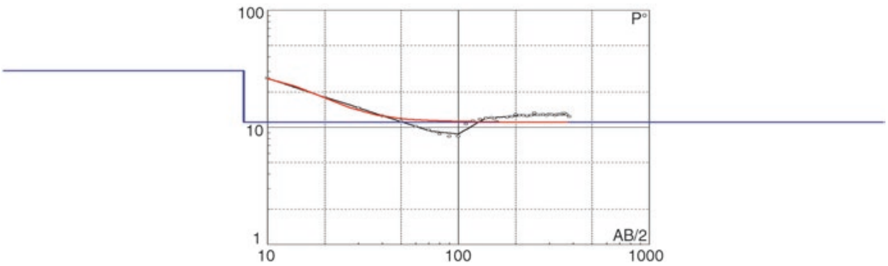


PLOT OF FIELD RESISTIVITY CURVE

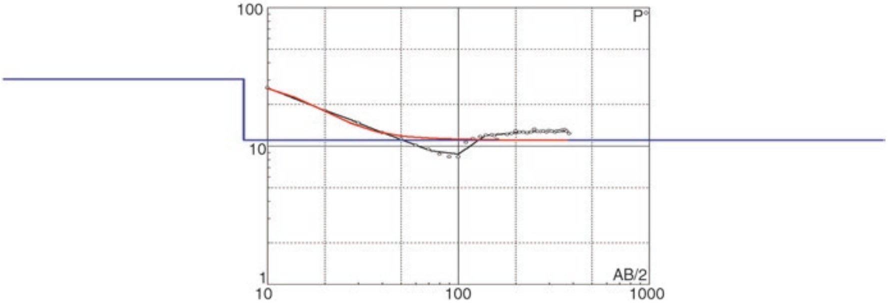
VES – 1 (KUMIRA)



PLOT OF FIELD RESISTIVITY CURVE
VES – 2 (Kumira)



PLOT OF FIELD RESISTIVITY CURVE
VES – 3 (Kumira)



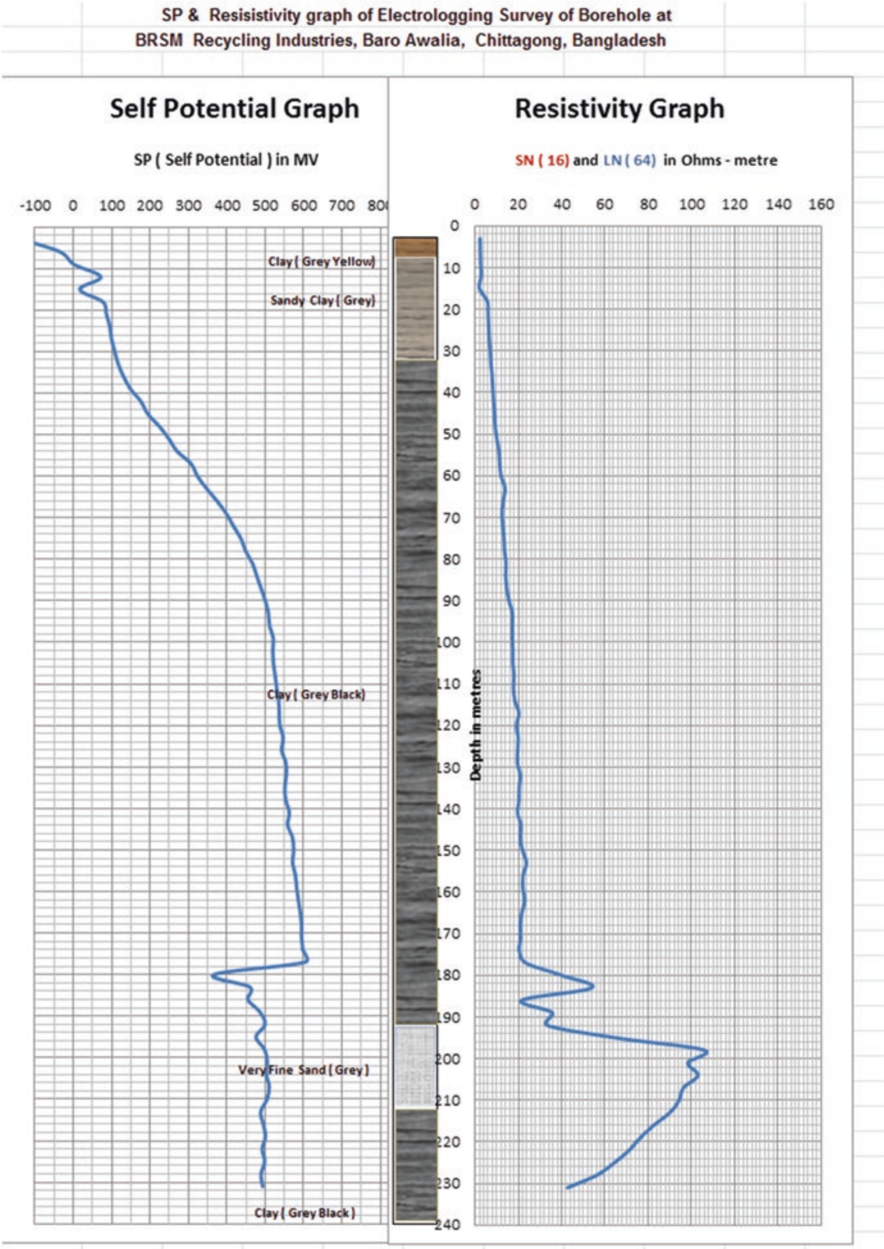


Plate – XII Central sector

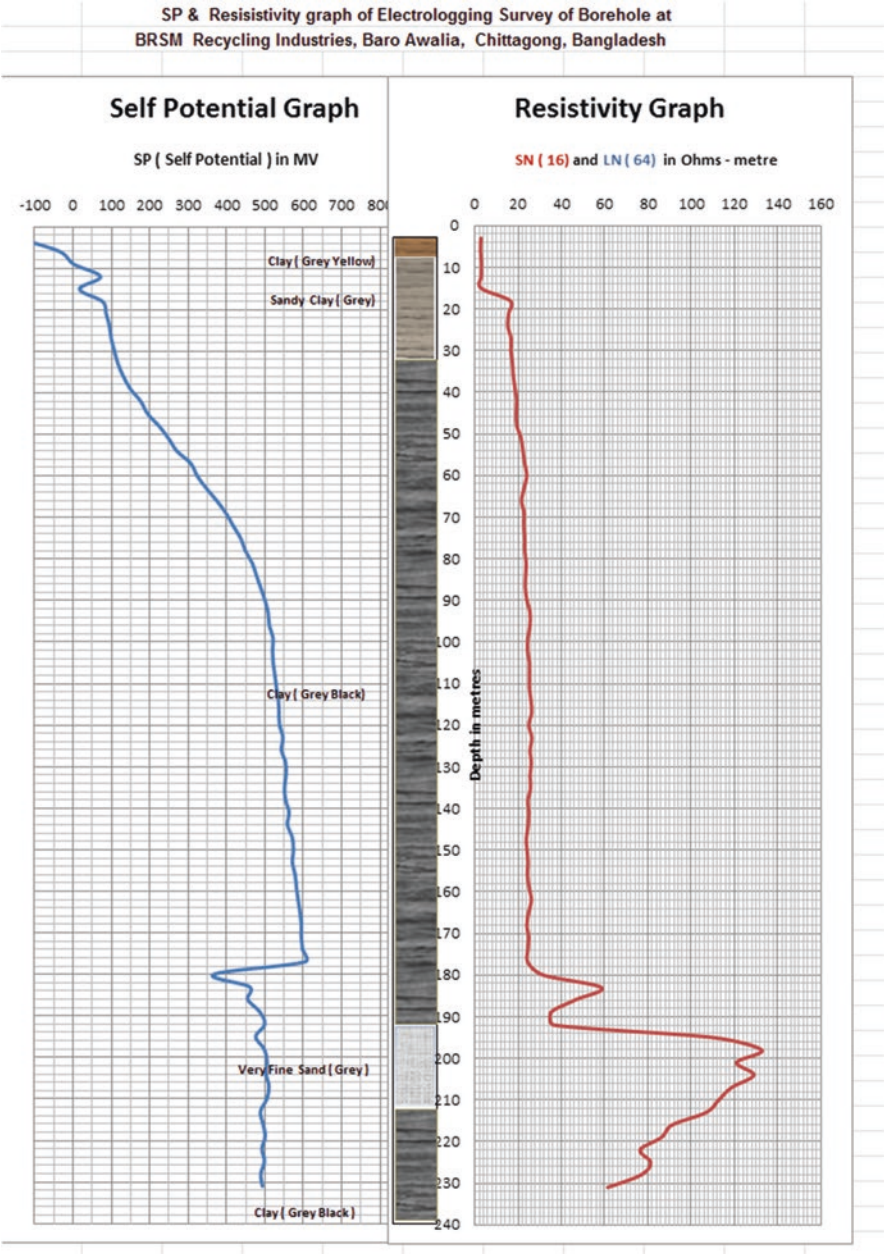

SP & Resisistivity graph of Electrologging Survey of Borehole at
BRSM Recycling Industries, Baro Awalia, Chittagong, Bangladesh
Self Potential Graph
SP (Self Potential) in MV
-100 0 100 200 300 400 500 600 700
Clay (Grey Yellow)
Sandy Clay (Grey)
Clay (Grey Black)
Very Fine Sand (Grey)
Clay (Grey Black)
Resistivity Graph
SN (16) and LN (64) in Ohms - metre
0 20 40 60 80 100 120 140 160
Depth in metres
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220 230 240

Plate – XIII

Table 3 Details of layers encountered

SL no.	Layer	Depth range in (m)	Lithological	Remarks
(a)				
1	1st layer	0.00–20.00	Clay and fine sand	–
2	2nd layer	20.00–50.00	Sandy clay and fine sand	Saline water indication
3	3rd layer	50.00–110.00	Clay, sandstone and slate stone	–
4	4th layer	110–150.00	Sand	Potential aquifer zone
5	5th layer	150.00–230.00	Clay, sandstone and slate stone	–
6	6th layer	230–300.00	Sand	Potential aquifer zone
(b)				
1	1st layer	0.00–10.00	Clay and fine sand	–
2	2nd layer	10.00–20.00	Sandy clay and fine sand deposits	Saline water indication
3	3rd layer	20.00–30.00	Clay and sand	–
4	4th layer	30.00–60.00	Sand	Potential aquifer zone
5	5th layer	60.00–70.00	Clay, sandstone	–
6	6th layer	70.00–100.00	Clay	–
(c)				
1	1st layer	0.00–20.00	Clay and fine sand	–
2	2nd layer	20.00–50.00	Sandy clay and fine sand	Saline water indication
3	3rd layer	50.00–110.00	Clay, sandstone and slate stone	–
4	4th layer	110–150.00	Sand	Potential aquifer zone
5	5th layer	150.00–230.00	Clay, sandstone and slate stone	–
6	6th layer	230.00–300.00	Sand	Potential aquifer zone

Overall six nos. of layers have been encountered during resistivity survey. The details have been shown in the table (Table 3).

11 Type of Aquifers

The aquifer encountered from VES studies may be described as both confined and unconfined in nature, and its aerial extent is large spreading along the course of the floodplain. The aquifer is made up of sand of different grades and sizes ranging from fine sand to very fine sand. The aquifer encountered will be in segments and with intercalation of clay. The sand grading will be from fine to very fine sand zone. The upper aquifer gets replenished by river water and seepage water from the hills; water can be extracted from this kind of aquifer for both agricultural and industrial purpose with proper care during drilling operation (Table 4).

Table 4 Drilling depth, probable aquifer zones and expected yield recommended

SL. no.	Tentative location of drilling point within plant area	Depth of drilling recommended (m)	Expected depth of sand zone (aquifer) (m)	Expected yield (m^3/h)	Remarks
1	The preferred 1st location is in the northern end parallel to the highway	230–300	110–150 230–300	20–30	The recommendation as given is entirely on the basis of hydrogeological as well as geophysical resistivity reports. It is also suggested that proper supervision including preparation of lithological log is necessary during drilling operation
2	The preferred 2nd location is in the southern end parallel to the highway	230–300	110–150 230–300	20–30	
3	The preferred 3rd location is in the northern end of the factory	230–300	110–150 230–300	20–30	
4	The preferred 4th location is at a safe distance from the south of the 1st location along the highway	230–300	110–150 230–300	20–30	
5	The preferred 5th location is at a safe distance from the 4th location along the highway	230–300	110–150 230–300	20.20–30	

12 Conclusions

From the above analytical data, it reveals that the aquifer in and around of the study area is moderately potential. Aquifer zone can be developed for groundwater extraction and supply system.

The terrain is covered by thin alluvial sediments and falls on the western fringe of Sitakunda hills and eastern side of the sea. The overburden is of weathered Tipam sandstone and consists of mainly clay, sandy clay and sand of different grading and colours. The slope of the Sitakunda hill is steep and the river has formed the valley. The valley in the past has been filled by weathered, erosional deposits of clay, sands and gravels, weathered soil and clay in the past. Geomorphologically and topographically, the areas are in a potential zone for groundwater development. In case of necessity, the foothill region may also be able to be considered for the installation of production tube wells, but care should be taken during drilling operation, and proper drilling rigs would have to be deployed.

From the foothill region, there is an indication of existing saline-infested zone in the upper aquifers, and generally, the deeper aquifer consists of potable water. However, after construction of test bores, each and every bore should be electrically logged to have a clear picture of the quality of the aquifer water.

For the northern sector of the study area, the optimum capacity of the production tube well may be fixed up to 50,000 l/h by using submersible pump with capacity of 25–30 HP. Pumping hours should be restricted to maximum 12 h per day with 2–3 h intervals. Whereas in the central and southern sectors of the study area, the optimum capacity should be restricted to a maximum of 20,000 l/h. with pumping hours that should be restricted to a maximum of 12 h per day with 2–3 h intervals.

The systematic scientific approach undertaken for hydrogeological appraisal of the area, coupling geomorphological, geological, geophysical and hydrogeological studies, has established the existence of a moderately large potential of groundwater resources in the Karnaphuli–Feni interfluve area. These precious resources will go a long way in supporting industrialization in this otherwise underdeveloped tract of land which will ultimately usher to a new socio-economic horizon in coming years.

Acknowledgement The author expresses his gratitude to the BSRM, Chittagong, Bangladesh, for giving opportunity to publish their paper.

The author is highly grateful to Dr. S.P. Sinha Ray, Former Member, Central Ground Water Board, for giving his valuable inputs, suggestions, guidance and critical evaluation during the preparation of the paper.

The author would like to express sincere thanks to all the executive directors (hydrogeology) and project scientists of NRIEMT engaged in this project.

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Sustainable Water Resource Management in the Sundarban Biosphere Reserve, India.

Sugata Hazra, Tuhin Bhadra, and S. P. Sinha Ray

Abstract The Sundarban Biosphere Reserve (SBR), India lies in the tide-dominated southern part of deltaic West Bengal and supports 4.43 million strong populations. Freshwater is a scarce resource in the SBR though it is traversed by numerous creeks and rivulets and receives a huge amount of precipitation during the monsoon months. Scarcity of freshwater above and below the ground during the dry season and high salinity of soil and water make it very difficult for the people of the SBR to secure their livelihood. The present paper assesses these sectoral demand and availability of water in 19 administrative blocks of the SBR. Increasing water demand of the ever-increasing population leads to water deficit in most of the blocks during dry season. In this study, the annual demands of drinking and domestic water in the SBR have been estimated at 8.08 million cubic metres (mcm) and 105.1 mcm, respectively. The water demand for agriculture has been calculated as 2782.83 mcm. It is observed that the SBR gets 2000–2500 mcm annual runoff from its upper catchments, and the habitated region of the SBR generates additional 1800–2000 mcm annual runoff within its territory. Blockwise water availability from different sources has also been estimated. The research reveals the growing population pressure on agriculture with an average man-cropland ratio of 14 person/hectare land. The highest cropping and irrigation intensity has been observed in the northern blocks where shallow groundwater is available for agriculture. On the contrary, the lowest values have been observed in the southern blocks nearer to sea, due to existence of saline water in shallow aquifers. Available water from 70,000 freshwater tanks and around 8000 shallow borewells are not sufficient to meet the agricultural water demand during the Rabi (winter) and summer seasons. Unavailability of freshwater restricts food production, which endangers the food security of 87.5% of the people in the SBR. To ensure food security in the present changing climatic condition, expansion of irrigation network and harnessing of new water sources are essential. This study emphasizes that rooftop rainwater harvesting in this region has potential to supply additional 45 mcm water which can be used to meet the domestic water

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S. P. S. Ray (ed.), *Ground Water Development - Issues and Sustainable Solutions*, https://doi.org/10.1007/978-981-13-1771-2_8

demand partially. Large-scale rainwater harvesting, rejuvenation and reconnection of disconnected river channels, artificial recharge within shallow aquifers and desalination of shallow groundwater can be some other major policy options to meet the water demand in the SBR in the future.

Keywords Sundarbans · Water demand · Water availability · Rainwater harvesting

1 Introduction

Water is under stress due to its limited supply and increasing demand all over the world (Rudra 2009). Rivers around the world are highly variable and unpredictable. Groundwater is also vulnerable due to over-exploitation, and the rainwater is most unpredictable over time and space (Bhadra 2013). In this perspective, the present study analyses the water scenario of the critically vulnerable Sundarban Biosphere Reserve (SBR) area of India (Govt. of India 2011a), lying on the south-western tidally active edge of the Ganges-Brahmaputra delta. Freshwater is not available in plenty in the SBR though it is traversed by numerous creeks and rivulets. Sundarbans receives a huge amount of precipitation, but that is not properly utilized to fulfil the water demands of 4.43 million population spread over 19 administrative blocks of the Biosphere Reserve. The present study attempts to assess the freshwater demand vis-á-vis its availability for wise and sustainable water resource management.

The SBR extends from 21°33′32.62″N to 22°38′15.66″N and from 88°2′27.42″E to 89°5′46.06″E, is a part of deltaic West Bengal (Fig. 1). The total area of the SBR is 9630 km^2 comprising the human habitation of 5367 km^2 and reserve forest area of 4263 km^2 (Hazra et al. 2015). The forest area is further subdivided into two parts, a core area and a buffer area. The habitation area is subdivided into 19 community development blocks, in which 13 blocks are in South 24 Parganas and 6 blocks in North 24 Parganas districts of West Bengal. In the present study, the 19 blocks, based on their geographical location, have been divided into three distinctive zones. The northern zone includes Haroa (1), Hasnabad (2), Hingalganj (3), Minakhan (4), Sandeshkhali I (5), Sandeshkhali II (6) and Canning II (7). The central zone includes Canning I (8), Basanti (9), Gosaba (10), Jaynagar I (11), Jaynagar II (12), Kultali (13), Mathurapur I (14) and Mathurapur II (15), whereas the southern zone includes Patharpratima (16), Kakdwip (17), Namkhana (18) and Sagar (19) (Fig. 1).

The people living in the habitation area of the SBR depend on the ecosystem services of the Sundarbans and its rivers which have a dynamic relationship with freshwater availability from upstream flow, rain and groundwater. The prevailing freshwater flow into the Sundarbans depends on the hydrological conditions of its rivers (Hazra et al. 2015; Mirza 2006). Most of the rivers have lost their connections with their parent river because of siltation at offtake points, and their estuarine character is now maintained by the monsoonal runoff alone (Bhadra et al. 2017; Gole and Vaidyaraman 1967; Gopal and Chauhan 2006). The riverwater of the SBR is

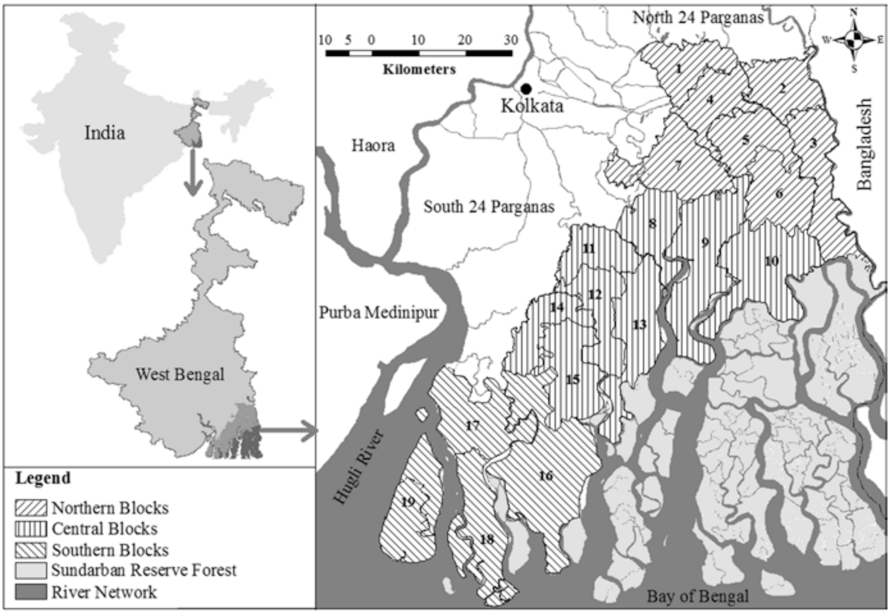

Fig. 1 Location map of the Sundarban Biosphere Reserve, India

mostly saline. The groundwater is also saline except for a few metre thick unconfined aquifer within the first few metres. Fresh groundwater is only available at a depth greater than 250 m (CGWB 2006; Sinha Ray 2010). The saltwater intrusion into groundwater often takes place within the shallow aquifers due to influent discharge of the rivers (Bhadra et al. 2013). This situation may further worsen with current climate change and rising sea level conditions. Salinity of soil and shallow aquifers make agriculture difficult (Haza et al. 2014). Scarcity of surface water or groundwater during dry season, increasing siltation, high soil and water salinity, drainage congestion, etc. make it very difficult for the people of Sundarbans to secure their livelihood (Hazra et al. 2015). In this circumstance, the present study is an attempt to assess the freshwater demand and availability in the SBR to sustain its ecosystem and livelihood in a changing climatic scenario and to suggest appropriate methods to improve the freshwater availability through sustainable water management.

2 Methodology

Sectoral water demand of the SBR is estimated in this study. Blockwise drinking and domestic water demand is estimated based on PHED, Govt. of West Bengal Vision 2020 (Govt. of W. B. 2015), as 70 liters per capita per day and the population census data (Govt. of India 2011b). These 70 liters include the water demand for drinking, cooking, bathing, washing, cleaning pots and household work. In the present study, the domestic water demand excluding the demand for drinking water (5 litres) is considered as that is estimated separately. Blockwise water demand for agriculture in the SBR is estimated by combining the area under different crops (Govt. of W.B. 2010) with the lifecycle water requirement of each crop (Rudra 2009).

To assess the availability of water, a rainfall-runoff analysis is undertaken in the SBR and its upper catchment area using empirical formulas (CGWB 2007). Water availability from different sources is also estimated under the study. Blockwise availability of water from deep and shallow tube wells is estimated using the number of deep and shallow tube wells (Govt. of W.B. 2010), their water yield capacity and time of operation. Water availability from tanks and canals is assessed by subtracting the loss due to evaporation and minimum water requirement for the survival of fish from the water holding capacity of tanks and canals, respectively.

The present agricultural set-up and available irrigation facility in different blocks of Sundarbans is assessed. Blockwise cropping intensity, irrigation intensity and man-cropland ratio are estimated from Agriculture Census data (Govt. of India 2011c) using the following relationships:

$$\text{Cropping Intensity} = \left(\text{Gross Cropped Area} / \text{Net Shown Area}\right) \times 100$$

$$\text{Irrigation Intensity} = \left(\text{Gross Irrigated Area} / \text{Gross Cropped Area}\right) \times 100$$

$$\text{Man cropland ratio} = \text{Population} / \text{Gross Cropped Area}$$

The scope of some relevant water management options to meet the agricultural water demand is also investigated within the study. The rainwater harvesting potential is estimated based on the number of households, their roof types (Govt. of India 2011d), average roof area, precipitation data (IMD) and the runoff coefficient (CGWB 2007).

3 Water Demand

The consumptive water demand of the SBR includes the water demand for drinking, domestic use and agriculture. The annual demand of drinking water in the 19 administrative blocks is 8.08 mcm, whereas the annual water demand for domestic use is 105.1 mcm. In 1951, the drinking water demand and the domestic water demand were 2.12 mcm and 27.52 mcm, respectively. The water requirement for the Rabi and summer crop cultivation is 641.25 mcm, whereas for Kharif crop cultivation, the demand is 2141.58 mcm. The study observes that the water demand for agriculture is highest in July (902 mcm) followed by August (894 mcm) and is

Table 1 Annual sectoral water demand (in mcm) in the Sundarban Biosphere Reserve, India (2010–2011)

Blocks		Population 2011	Drinking	Domestic	Agriculture Rabi+summer	Kharif	Total	Total
Northern	Total	1,369,256	2.49	32.48	234.42	457.09	691.53	726.51
	Average	195,608	0.36	4.64	33.49	65.30	98.79	103.79
Central	Total	2,048,350	3.74	48.59	304.45	1009.69	1314.15	1366.49
	Average	256,044	0.47	6.07	38.06	126.21	164.27	170.81
Southern	Total	1,008,653	1.84	23.93	102.38	674.78	777.15	802.93
	Average	252,163	0.46	5.98	25.60	168.70	194.29	200.73
Sundarbans	Total	4,426,259	8.08	105.01	641.25	2141.58	2782.83	2895.92

lowest in April (1.22 mcm). The water demand in Rabi season is 425 mcm (November to June) which is mainly used for Boro paddy cultivation. The total annual water demand for drinking, domestic use and agriculture in the 19 blocks of the SBR is estimated as 2895.92 mcm.

The blockwise statistics establishes that demands for drinking, domestic and agricultural water are highest in the central blocks. The water demand for Rabi and summer crop cultivation is highest in central blocks, whereas the average demand for Kharif cultivation is the highest in the southern blocks. The average total water demand is also highest in the southern blocks (Table 1).

4 Water Availability

Rainwater is the major freshwater source in the SBR. It receives the rain mainly from south west monsoon which generally starts in the middle of June and withdraws during the second week of October. The average annual rainfall in the SBR is 1625 mm but may increase to 2000 mm in the high rainfall years and drop to 1300 mm in low rainfall years (Dasgupta 2008). To assess the water availability in the Sundarbans, the estimation of runoff is accomplished. According to coefficient method, the SBR gets 2560.67 mcm freshwater as runoff from its upper catchment, it generates 4928.35 mcm runoff within its territory and the 19-block region gets 2176.77 mcm runoff. According to Lacey's formula, the SBR as a whole gets 2118.03 mcm runoff from the upper catchment; it generates 4123.60 mcm runoff within itself, and the 19-block region gets 1821 mcm runoff. The runoff volume has a huge potential to meet the water demand of the Sundarbans blocks.

In the present study, blockwise and sourcewise water availability are estimated. Table 2 shows that the total available water from deep tube well (DTW) in Sundarbans is 8.08 mcm which is used mostly to meet the drinking water demand. Over 70,000 freshwater tanks and around 8000 shallow tube wells (STW) are the major sources of irrigation in the SBR. The STWs have a potential to supply 386.59 mcm water during Rabi and summer cultivation, whereas quantum of available water from tanks and canals are estimated to be around 43.02 mcm and 9.21 mcm, respectively.

Table 2 Annual sectoral water availability (in mcm) in the Sundarban Biosphere Reserve, India (2010–2011) Computed from District Statistical Handbook, N & S 24 Parganas, Govt. of West Bengal and Agricultural Census, 2010-11, Govt. of India

Blocks		DTW drinking	STW irrigation	Total GW	Tank irrigation	Canal irrigation	Total SW	Total
Northern	Total	2.49	305.90	308.39	10.61	1.88	12.49	320.87
	Average	0.36	43.70	44.06	1.52	0.27	1.78	45.84
Central	Total	3.74	71.95	75.69	8.99	4.62	13.62	89.30
	Average	0.47	8.99	9.46	1.12	0.58	1.70	11.16
Southern	Total	1.84	8.73	10.57	23.44	2.70	26.15	36.73
	Average	0.46	2.18	2.64	5.86	0.68	6.54	9.18
Sundarbans	Total	8.08	386.59	394.67	43.02	9.21	52.23	446.90

DTW deep tube well, *STW* shallow tube well, *GW* groundwater, *SW* surface water

Blockwise statistics indicates that the use of tanks in the southern blocks is more prevalent than that in the northern blocks as shallow groundwater is saline in the south. The water availability from STWs is the highest in the northern and lowest in the southern blocks. Total available water is also the highest in the northern and lowest in southern blocks.

5 Agriculture and Water

Agriculture is the backbone of the economy of the SBR, but it remains at the subsistence level only due to small land holdings and inadequate irrigation facilities. In the 2010–2011 census year, the net sown area of the SBR was 285,632 hectares which was 62.44% of the total land. The gross cropped area was 376,150 ha in which 80.53% was unirrigated. The average cropping intensity of the SBR is 129.97% and irrigation intensity is 18.25%. It is observed that the region suffers from water scarcity during *Rabi* season due to lack of irrigation facility. The highest cropping and irrigation intensities have been observed in the northern blocks where shallow groundwater is available for agriculture, while the lowest values have been observed in the blocks closer to the estuary or sea, due to existence of saline shallow groundwater (Table 3). The study shows that the average man-cropland ratio in the SBR is 14 person/hectare of gross cropped area. It illustrates the high population pressure on cultivation in the region. Blockwise statistics reveals that the man-cropland ratio is high in southern blocks, and low in northern and central blocks (Table 3).

Table 3 Blockwise agricultural statistics of the Sundarban Biosphere Reserve, India (2010–2011)

Blocks		Man cropland ratio	Net shown area (hect)	Gross cropped area (hect)	Gross irrigated area (hect)	Cropping intensity	Irrigation intensity
Northern	Total	**	90,627	133,046	42,844	**	**
	Average	13	12,947	19,007	6121	139.81	25.43
Central	Total	**	139,398	181,323	24,056	**	**
	Average	13	17,425	22,665	3007	130.50	13.86
Southern	Total	**	55,607	61,781	7881	**	**
	Average	18	13,902	15,445	1970	111.67	14.49
Sundarbans	Total	14	285,632	376,150	74,781	129.97	18.25

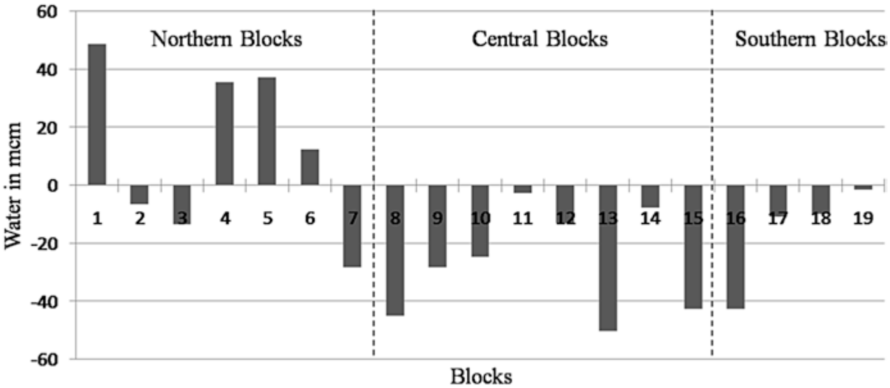

Fig. 2 Blockwise excess/deficit water for Rabi and summer crop cultivation in the Sundarban Biosphere Reserve, India (2010–2011)

6 Water Deficit

The available water from surface and groundwater sources fall far short of the water demand for agriculture during Rabi and summer crop cultivation. The water holding capacity of the existing tanks is also significantly less than the water demand during the *Rabi* cultivation.

Figure 2 shows the water deficit in central and southern blocks during Rabi and summer crop cultivation. The excess water in the northern blocks is mainly used to produce vegetables and other crops. Unavailability of freshwater restricts the food production, which in turn affects the food security. Around 87.5% of the people of Sundarbans face some kind of food shortage during a year.

7 Possible Solutions

The people of the SBR are compelled to depend on groundwater to meet the drinking water demand and on rainwater for agriculture and other needs. Conjunctive use of these water sources may help in sustainable water resource management in this region. The following methods can be suggested to ensure the freshwater availability in the SBR.

7.1 Rainwater Harvesting

The SBR receives sufficient rain in the monsoon months. This rainwater may be conserved to meet the water demand of the people. The harvested rainwater (Gayen and Zaman 2013; Mondal 2014) can be utilized for domestic use as well as drinking purpose after proper treatment. Large-scale rainwater harvesting is one of the major solutions to mitigate the water-related problems in the SBR. Renovation of the existing canals is a primary necessity. This will help to store sufficient quantity of rainwater for cultivation. Roof top Rainwater harvesting also restrains over-exploitation of groundwater resource.

Table 4 demonstrates that about 45 mcm rainwater may be harvested from different types of rooftops in the SBR region. 15.42 mcm rainwater can be harvested in the northern zone, whereas 18.86 mcm and 11.28 mcm rainwater can be harvested in central and southern zones, respectively. This water has a potential to partially meet the domestic water demand in the SBR region.

Table 4 Blockwise rainwater harvesting potential in the Sundarban Biosphere Reserve, India

Blocks		Potential rooftop rainwater resource						Total
		No. of HH concrete Rf.	Water (mcm)	No. of HH asbestos Rf.	Water (mcm)	No. of HH tiles Rf.	Water (mcm)	Water (mcm)
Northern	Total	37,460	3.60	64,484	5.17	104,134	6.67	15.42
	Average	5351	0.51	9212	0.74	14,876	0.95	2.20
Central	Total	37,498	3.60	127,329	10.18	79,464	5.09	18.86
	Average	4687	0.45	15,916	1.27	9933	0.64	2.36
Southern	Total	18,277	1.75	18,933	1.51	125,269	8.02	11.28
	Average	4569	0.44	4733	0.38	31,317	2.01	2.82
Sundarbans	Total	93,235	8.95	2,10,746	16.86	3,08,867	19.77	45.58

HH households, *Rf* roof

7.2 Artificial Groundwater Recharge and Desalination

Excess rainwater can be recharged artificially within shallow aquifer to reduce its salinity. In due course of time, this technique may help to reduce the salinity of shallow aquifer which can subsequently be utilized for agriculture and domestic purposes (Gayen 2009). Sundarban Development Board (SDB) has taken some initiatives to develop water-related infrastructure in Sundarbans. A few solar pumps and RO plants for desalination (Press release GoI 7.5.2015) were installed for providing salt-free water in this region. The RO plants however failed to produce potable water due to high concentration of silt in river water and high salinity (>15 ppt). We suggest that such type of desalination can be tried using silt-free less saline (4–8 ppt) water available at shallow aquifers. Conjunctive use of surface water and groundwater may be helpful for sustainable water resource management in the SBR.

8 Other Methods

Restoration of decayed river channel (Bhadra et al. 2017) is one of the sustainable option to ensure freshwater flow from up stream. Eleven such major disconnections have been identified from field and remote sensing studies (Bhadra et al. 2017) in the feeder river system of Sundarbans. Reconnection of the river Ichamati near its offtake point at Majhdia, restoration of the Bidyadhari-Suti-Noi River system and the Jamuna River system, can greatly benefit the people of the SBR. Rainwater can be harvested by building some large reservoirs in several decayed tidal rivers. A study was done to build a closure dam in the mouth of the Saptamukhi River by the River Research Institute, Government of West Bengal (Delf Hydraulics 1968). One of the essential components of the project was to create a freshwater reservoir which would provide the required freshwater for various consumptive uses. The reservoir was proposed to be constructed on the portion of the Saptamukhi River bounded by the proposed Saptamukhi North and the Saptamukhi South Dams. Though such a reservoir could not be built due to several constraints, such concepts may be reconsidered and implemented to ensure additional freshwater supply in the SBR.

9 Conclusion

The freshwater aquifers of the SBR have been facing threats from arsenic contamination in one hand and saline water ingression in the other. The water policy for the delta therefore needs to be fine-tuned to meet the twin challenges (Bhadra et al. 2013). Judicial use of groundwater and surface water, rainwater harvesting (rooftop/surface water body) and assurance of the environmental flows in the river channel by reconnection and rejuvenations are the major workable options in the water-starved region (Bhadra et al. 2013). Switching to treated surface water rather than extensive deep groundwater exploitation may be a sustainable alternative for drinking water supply in the SBR (Mukherjee 2006). To ensure food security in a changing climatic conditions, expansion of irrigated area and harnessing of new water sources are essential. Large-scale rainwater harvesting to store sufficient rainwater, deepening of existing ponds to increase their water holding capacity, artificial recharge within shallow aquifer to bring down its salinity and desalination of silt free water of shallow brackish aquifer can be some of the major policy options to meet the present and future water demand in the SBR.

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Part IV
Conservation of Ground Water

Conservation of Water: Artificial Recharge to Groundwater

D. K. Chadha

Abstract Rainwater harvesting dates back to many centuries but has recorded history since 300 BC which shows that innovative structures have been constructed all over the world including India. But India has the distinction of inventing two innovative water conservation structures, i.e., Tanka in the fourth century and Baolis (stepwell) in the eleventh century, which entails development of groundwater and conservation of rainwater. The dependence on groundwater resource has increased over the years to provide food security and for meeting drinking water requirements of more than 85% of rural India. The estimation of dynamic resources shows that there are 1071 over-exploited blocks, i.e., 16% of the area, which makes it imperative to use part of the available water resources of about 865 BCM for recharging the depleted aquifers and to create more surface storages. The implementation of pilot projects has showcased the different technologies for water conservation and groundwater recharge. There have been continuous efforts from the central government and from few state governments to promote rainwater harvesting, but the similar efforts are not forthcoming either from the other state governments or the industrial and corporate sectors. There are still many gaps in technology intervention in case of preventing saline ingress in coastal areas and groundwater management in urban and the hilly regions. So there is a need to implement more pilot projects to enhance the technical knowledge to deal with the ensuing problems including the use of treated waste water. Since, it is a compulsion for India to promote rainwater harvesting to make use of the surplus monsoon runoff and to meet the stipulated water requirements, it is important to create a web-based information on rainwater harvesting structures for easy access and to create an exclusive Centre for Excellence for providing training and guidelines on different aspects of rainwater harvesting as well as other sources of water.

Keywords Rainwater harvesting · Runoff · Capacity building and training · Waste water · Web-based information

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1 Introduction

The increasing demand for water is due to many reasons. Water is mainly used for food security and drinking purposes, making it imperative to explore other options to supplement the existing surface water and fresh groundwater resources. It is estimated that the annual groundwater recharge is 432.72 BCM, out of which about 245 BCM have been developed. The stage of groundwater development is 62%, resulting in groundwater over-exploitation in 1071 blocks and critical in 217 blocks, out of the total 6607 blocks, i.e., 19.5% of the area. This development has led to a continuous decline in water levels having a negative impact on water quality, disturbing the saline fresh interface in inland areas and saline ingress in coastal areas (CGWB 2010; Dillon et al. 2011, 2014). The surface water storages estimated to be 220 BCM are providing water mainly for irrigation, and further storages need to be created to mitigate the additional demand for irrigation.

The projected future demand for water resources is estimated at 973 BCM (minimum) in 2050 against the presently available resources of 660 BCM. This makes it imperative to plan for and utilize part of the excess monsoon runoff estimated as 864.7BCM in different river basins and also to utilize saline groundwater in 92 blocks with the help of different technologies.

For the purpose of using the utilizable runoff potential, the Central Ground Water Board (CGWB) brought out the National Ground Water Perspective Plan (CGWB 1996) and the Master Plan for Artificial Recharge to Ground Water (CGWB 2002, 2011a; Chadha 2014a) based on the noncommitted runoff of 36 BCM (Central Water Commission). It is evident that the conservation of water and recharge of the groundwater constitutes one of the best management options to reduce the gaps in demand and supply and to overcome the water scarcity in the coming years.

1.1 Definition: Artificial Recharge

The term "artificial recharge" using monsoon runoff for recharge of groundwater is commonly used in India; however, the origin of the term "artificial recharge" is not documented. To have the frequent use of the term worldwide for water conservation and recharge of groundwater, the subject was debated in the workshop in Adelaide, Australia (2003), and the broad term managed aquifer recharge (MAR) was introduced (Chadha 2014a, b).

In India, no distinction is made, so far, for artificial recharge (AR) and managed aquifer recharge (MAR), artificial recharge being used for rainwater harvesting and MAR understood for using it where treated wastewater is used for recharge. Now the term MAR has a broad connotation and is defined as "The process of adding a water source such as recycled water to aquifers under controlled conditions for withdrawal at a later date, or used as a barrier to prevent saltwater or other contaminants from entering the aquifer." Therefore the term MAR encompasses the other methods used for conservation and recharge of groundwater (Fig. 1).

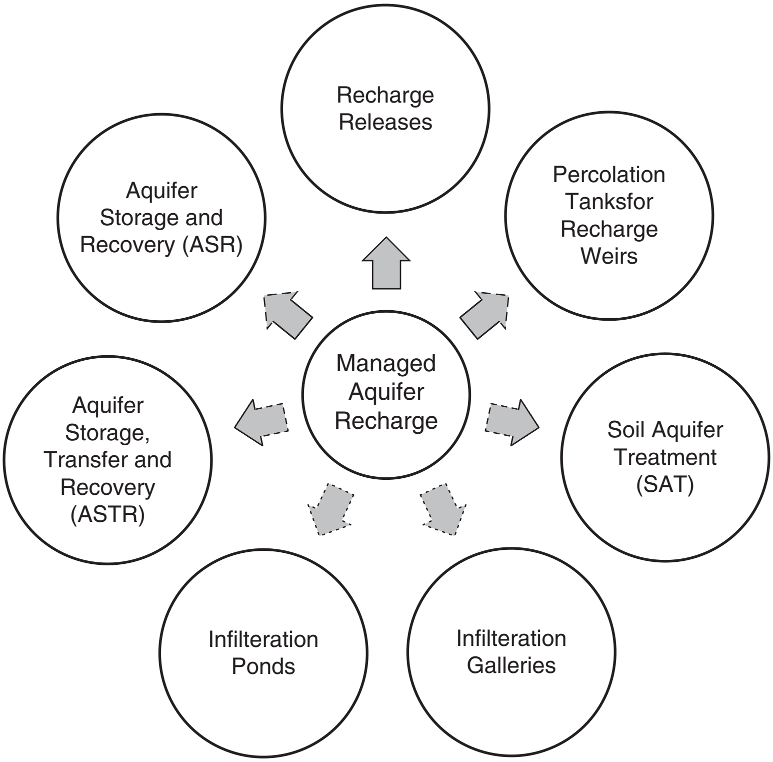

Fig. 1 Components of MAR. (Source: Dillon et al. 2014)

Recently, IGRAC defined the different technologies and subtype under MAR (Table 1).

In India, similar terms are used both for water conservation and recharge to aquifer.

2 Historical Perspective

Historically, all earlier civilizations practiced different methods for water conservation depending upon the geomorphology, rainfall pattern and the local conditions. The technology and methodology, although differed, were innovative to conserve water by using different types of structures in low rainfall areas as briefly described below.

Africa

In Africa, the common practice for water conservation system was "Meskat" – micro-catchment system which consisted of an impluvium called "meskat", of about 500 m^2 in size, and a "manka" or cropping area of about 250 m^2 in low rainfall

Table 1 MAR technologies and subtypes

Methods	Technology	Subtype	
Techniques referring primarily to getting water infiltrated	Spreading methods	Infiltration ponds and basins	
		Flooding	
		Ditch, furrow, drains	
		Irrigation	
	Induced bank infiltration		
	Well, shaft and borehole recharge	Deep well injection	AS(TR)
			ASR
		Shallow well/shaft/pit infiltration	
Techniques referring primarily to intercepting the water	In-channel modifications	Recharge dams	
		Sub surface dams	
		Sand dams	
		Channel spreading	
	Runoff harvesting	Barriers and bunds	
		Trenches	

area having annual precipitation below 50 mm (Fig. 2a). These systems are surrounded by a 20-cm-high bund, equipped with spillways to let runoff flow into the "manka" plots.

North Africa
In North Africa, the annual precipitation is from 150 to 300 mm. For water conservation, "Jessour" system (Fig. 2b) was developed which is a terraced Wadi system with earth dikes ("tabia") which are often reinforced by dry-stone walls ("sirra"). Most "Jessour" have a lateral or central spillway.

Egypt
The rainfall in the region is as low as 170 mm in the east to 100 mm in the west. Water harvesting is done on a small scale, and storage of sheet runoff is done in cisterns or concrete reservoirs (Fig. 2c) which are constructed below the ground at the lowest level of a collection basin or of a small stream to entrap surface or stream runoff.

Iran
The average annual rainfall is 250 mm. The Qanat system (Fig. 2d) consists of horizontal wells created in a sloping manner through the alluvial material and provides water by gravity flow. Vertical shafts are dug closely to provide access to the tunnel.

India
India has the recorded history of practicing rainwater harvesting since 3000 BC, and it has been mentioned in Kautilya's *Arthashastra* giving details of irrigation practices using water harvesting system (NIH 1990). Different technologies and

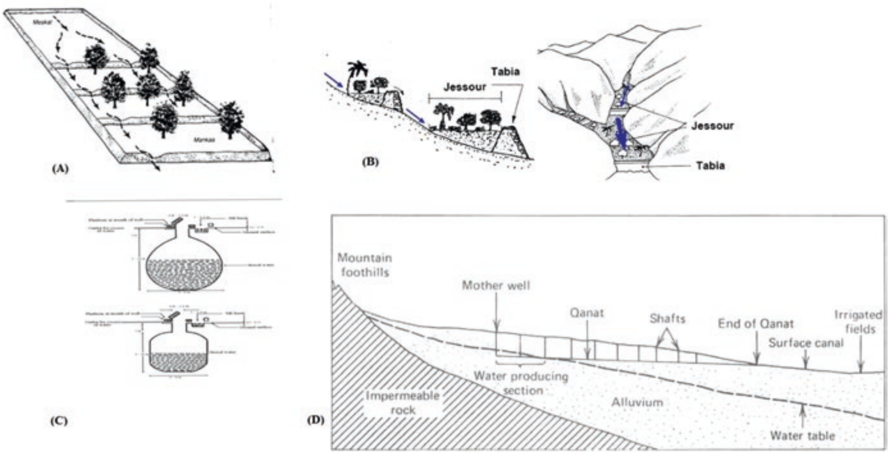

Fig. 2 Ancient water conservation structures (**a**) The Meskat System (**b**) A row of "Jessour" in the South of Tunisia (**c**) Typical Cistern (**d**) Vertical cross-section along a Qanat

practices were used across India for water conservation, and there are a number of publications on this subject. India has the distinction of inventing two innovative structures, i.e., Tanka (Fig. 3a), which has the artificial catchment area, and Baolis, i.e., stepwell (Fig. 3b), for groundwater development and storage of rainwater (Aggarwal and Narain 1997; CGWB 2000, 2011b).

The practice of rainwater harvesting continued until the nineteenth century when the Britishers were ruling the Indian continent demoralized the rainwater harvesting practices and got it discontinued (Aggarwal and Narain 1997). In the post-independence era, the water harvesting structures both surface water conservation and groundwater recharge were initiated between the period of 1972 and 1984, and the following projects were undertaken in association with UNDP:

- Induced recharge at Tatiana village, Kurukshetra district, Haryana, on the left bank of Ghaggar River
- Injection method at Dabkheri, Narwana Branch Canal, Kurukshetra district, Haryana
- Subsurface dyke at State Seed Farm, Ananganadi, Kerala
- Injection well at Kamliwara, Mehsana district, Gujarat
- Spreading channels at Mehsana, Gujarat

To compute the nonutilized runoff potential in different river basins, it requires understanding the feasible groundwater storage out of the available water for recharge; the CGWB has brought out the following two documents for planning and implementation purposes.

Fig. 3 (**a**) Tanka or underground storage of rainwater, (**b**) Baolis or stepwells for groundwater recharge and development

2.1 National Perspective Plan (1996)

This was the first research-based document to estimate the storage potential of recharge in the 3-m-thick unsaturated zone (CGWB 1996). The computation was made for all the 20 river basins identifying the feasible groundwater storage, retrievable groundwater storage, and water availability in each of the river basins to meet the requirement of groundwater storage. It was estimated that available water for recharge is 872 BCM, out of which feasible groundwater storage is 214 BCM, and 160 BCM is retrievable for utilization.

Now since the number of over-exploited blocks has increased and water table has further declined, the possible storage potential has, therefore, increased requiring a revised plan to be prepared for each of the river basins separately.

2.2 Master Plan (2002)

The Perspective Plan was followed by the "Master Plan for Artificial Recharge to Ground Water" (CGWB 2002) which provides information about area-specific artificial recharge techniques to augment the groundwater storages based on the availability of source water and capability of subsurface formations to accommodate it. The total area identified for artificial recharge is 448,760 km^2, the volume of water to be recharged is 36.4 BCM, and the total number of structures proposed is 3.9 million.

A revised master plan is under finalization which would provide the additional potential of noncommitted runoff for surface water and groundwater storages. This will help in checking the decline in the water table and also in reducing the number of over-exploited blocks.

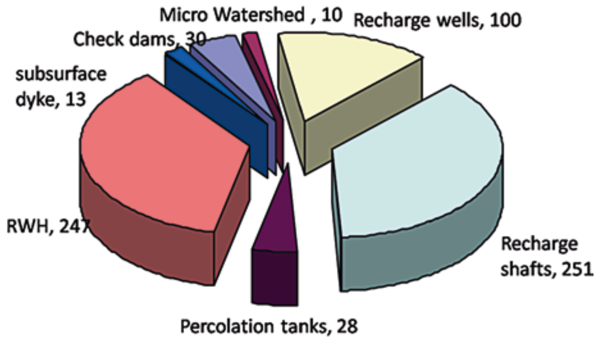

Fig. 4 Types and number of water conservation and groundwater recharge structures

In order to promote the practices of water conservation in groundwater storages using different methods, during the plan period 1992–1997, 24 pilot projects were implemented by constructing 62 recharge structures. The programme was further strengthened during 1997–2002 when 165 pilot projects were implemented by constructing more than 670 structures. The number of the type of structures constructed is presented in Fig. 4.

The pilot projects constructed structures under different hydrogeological conditions to develop a low-cost technology for large storage of rainwater. Of the many structures constructed, the following two are the most important structures to utilize the flood water, a channel through the drain for recharging to the fast-depleting aquifers and the other to check the saline ingress to enhance irrigation potential. These are briefly described below:

2.3 Artificial Recharge: Dhuri Link Drain

Dhuri drain, which is 30.8 km long, is being used for regulating flood water which has been used for recharging groundwater. This envisaged construction of 28 shafts of 3 m diameter in the drain bed, out of which 23 were constructed down to the depth of 6 m and 5 to a depth of 11 m. For a direct recharge, bed was modified by constructing a trench of 250 m length, 5 m wide at the top and 3 m at the bottom and 3 m depth. Sixteen piezometers were installed to study the behaviour of water level due to artificial recharge and three recharge wells to enhance the rate of recharge to unconfined aquifers (Fig. 5). In this pilot project, a combination of methods such as shafts, trenches, and recharge wells were utilized. This study indicates that it is feasible to recharge the unconfined aquifers by utilizing the flood water for supplementing the groundwater storage.

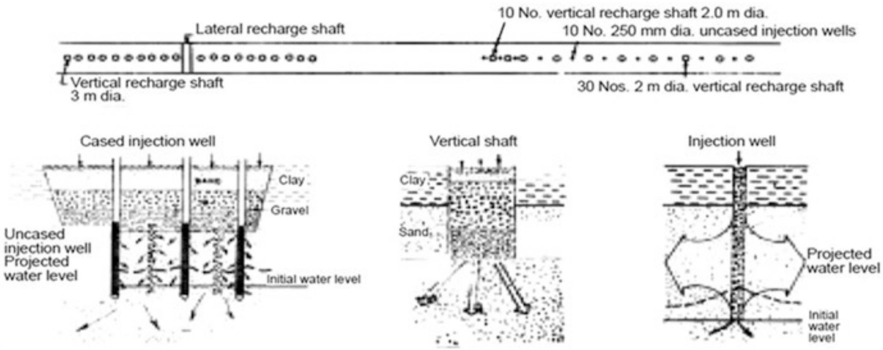

Fig. 5 Artificial recharge in Dhuri Drain, Sangrur District, Punjab

2.4 Preventing Saline Ingress in Coastal Areas: Creeks in Coastal Orissa

The project has conceived the idea of utilizing the minor creeks and nalas or drains for storing freshwater for irrigation and injecting freshwater into the saline water bearing shallow aquifers so that the salinity of the water can be reduced, thus making it useful for irrigation and other purposes. The study pertains to five creeks in the coastal areas of Orissa where (CGWB 2010) the local community is facing problems with irrigation and drinking water due to saline water intrusion. In connection with arresting saline intrusion, the following works were carried out:

- De-silting and renovation of the creeks by excavation
- Remodelling of old sluices and the construction of new ones
- Construction of 15 small bridges and one high-level bridge over the creeks for connectivity

The increased irrigation potential was estimated at 1693 Ham. More such schemes in the coastal areas should be taken up on priority.

3 Technical Gaps

During the implementation of rainwater harvesting, many technical gaps have been identified that need to be looked after before constructing any successful recharge structures. Some of the points requiring attention are enumerated in the following sections.

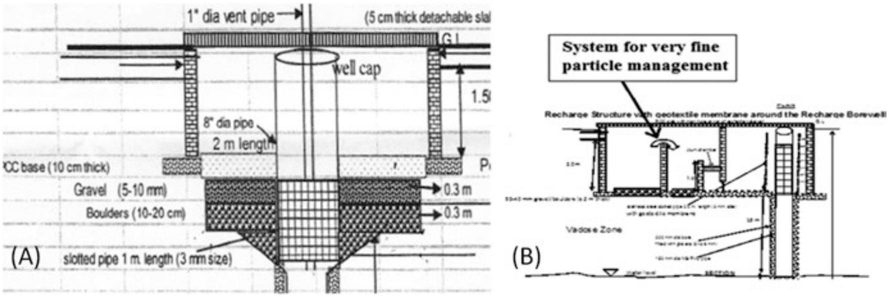

Fig. 6 Recharge structure using (**a**) inverted filter and (**b**) geo-textile

3.1 Research and Development Issues

Many of the recharge structures become defunct for inappropriate design for removal of the suspended load. The structures using inverted filter require continuous maintenance (Olsthoorn and Mosch 2002). Therefore, the design of the structure should be such that it requires minimum maintenance. Global Hydrogeological Solutions carried out initial research on replacing the inverted filter consisting of gravel and different grades of sand with geotextile and other materials to take care of the suspended and colloidal particles (Fig. 6).

3.2 Clogging

Clogging is a normal problem and can occur in the well screen, filter pack or aquifer and can have a physical, chemical and biological origin (Pfeiffer et al. 2002). Minimization of clogging is a primary concern in the designing and operation of MAR structures because clogging can cause a rapid decline in the performance of filter media and recharge wells. Sniegocki (1963) identified the following as causes for clogging in the ASR system:

- ***Physical***
  - Entrapment and filtration of suspended solids
  - Mechanical jamming of the aquifer caused by particle rearrangement when water flow through the aquifer is reserved
  - Gas binding (air entrapment)
- ***Chemical***
  - Chemical reaction between groundwater and injected water causing the precipitation of insoluble products
  - Precipitation of iron in the injected water as a result of aeration

  - Clay swelling
  - Ion exchange reaction that can result in clay dispersion

- ***Biological***
  - Clogging by bacterial growth caused by bacterial contamination of aquifer by injected water or increased growth of indigenous bacteria
  - Biochemical changes in the injected water and groundwater and associated chemical reactions involving iron- and sulphate-reducing organisms

3.3 Quality Checks

This is an important aspect for the recharge structures which are located near to the STP, industrially contaminated sites and solid waste disposal sites as the presence of pathogens is reported in the recharge water.

3.4 Presence of Pathogens

In case the source water is treated wastewater, it is reported that waterborne diseases are associated with high loads of microbial pathogens in the surface water such as *Clostridium* spores, *E. coli*, *Clostridium* perfringens, etc. (Medema and Stuyfzand 2002; Tredoux et al. 2002). Critical situations may arise in the following cases:

(a) Where infiltration intensities are extremely high and travel time is short, like in riverbed filtration (RBF) systems drawing from gravel aquifers during flood events
(b) Where the recollection system may receive inputs through short circuits or imperfections in an air- and water-tight construction, allowing access of animal life or water from above

The other important issues are:

3.5 Ownership of Conserved Water

In case the funding is provided by the government, the conserved/storage water should have the first use for drinking purpose. The community in the area should decide on the utilization of conserved water after its first use for drinking purpose. It is thus important to provide guidelines to the community for the ownership of recharged water and also its use.

3.6 Database Issues

Although a number of water conservation and recharge structures are being constructed across the country, there is no database to know the technologies being used for water conservation and groundwater recharge under different climatic and hydrogeological conditions. Moreover, a database is an important tool to understand the quantum of water which is being conserved and used for groundwater recharge in the overall planning for management of monsoon runoff. It is also important for computing the cost-benefit ratio of all types of recharge structures (Maliva and Missimer 2010).

4 Government Intervention for Rainwater Harvesting

In order to encourage rainwater harvesting, the Government of India has taken many steps by constituting high-level committees and providing technical and financial support.

1. Parliament Forum: The Parliament set up a forum on water conservation and management on 12 August 2005 to identify problems related to water resources and artificial recharge. The Forum can make suggestions/recommendations for considerations and the appropriate actions to be taken by the government/other organizations concerned. It will also encourage the members of the Parliament to augment water resources in their respective constituencies.
2. The Advisory Council on Artificial Recharge to Ground Water: The Ministry of Water Resources constituted the Advisory Council in 2006 with the main objective of popularizing the concept of rainwater harvesting including artificial recharge among stakeholders.

In addition to the above committees, the Ministry of Water Resources (1999) also instituted annual awards, namely, the Ground Water Augmentation Awards (Bhoomi jal Samvardhan Puraskar) and the National Water Award in 2007 for the best structures and also for awareness programmes via school paintings. These awards have motivated stakeholders to take up water conservation and recharge projects in a significant way. To promote rainwater harvesting in urban areas, the subject has been included in urban bye-laws which makes it mandatory to have rainwater harvesting structures in both residential as well as non-residential complexes.

4.1 National Water Policy

In the National Water Policy, 2012, the emphasis has been given on taking up of recharge projects. Although a considerable effort for promoting rainwater harvesting has been made, the issues relating to quality have been totally overlooked. It is therefore important that the major rainwater harvesting structures which are to be used for drinking purpose must be considered seriously for the water quality, the fate of pathogens and organics and health-related issues.

5 Beyond Using Rainwater

The rainfall period averages less than 30 days in a year, and this is a short period for which recharge structure is to be planned and constructed based on different hydrogeological conditions. In contrast to the limited period of rainfall, there are other options such as:

1. Reuse of treated wastewater
2. Storm water excess
3. Surplus water from other areas

The treated waste water in different cities provides large potential which remains mostly unutilized or is used for secondary purposes. In 2013 CPCB estimated that:

1. There are 498 Class I cities (including metropolitan cities) having population more than 1 Lac as per 2001 census.
2. Sewage generated in Class I cities is estimated as 35558.12 MLD.
3. Share of Class I cities is 93% of the total urban sewage generation in the country.
4. Total sewage treatment capacity of Class I cities is 11553.68 MLD, which is 32% of the total sewage generation.

The treated wastewater for recharge can be best utilized in areas, where there is a continuous decline in the water table and there is an ingress of saline groundwater in the freshwater aquifer. There is a need to undertake pilot projects using treated wastewater with quality checks. The guidelines for quality check are still not finalized in India; therefore, Australian guidelines can be used for this purpose.

The other sources of water, other than rainfall and treated wastewater, are the excessive storm water and imported flood water from other areas. The use of excess storm water for recharge has been demonstrated in some of the projects in Punjab. The imported water is the surplus monsoon water which remains unutilized in one country or other areas that should be considered for transporting to another country/state/area for utilization. In case of use of the imported water, CGWB brought out a document on greening Rajasthan by transferring the surplus Sutlej water which used to bring flood in India and Pakistan by transferring water to Rajasthan by recharging the depleted aquifers and thus improving the water quality.

6 A Way Forward

In India, rainwater harvesting is a management compulsion to meet the stipulated future water requirements. Therefore, a number of steps are needed to be taken up to promote rainwater harvesting in all parts of the country. The priority areas are:

1. To create a National Centre for Excellence for MAR (rainwater harvesting and treated wastewater) to provide guidance online on the methodologies and design to be adopted. The Centre so constituted will have GIS database for all the structures being constructed across the country.
2. To create a web-based application for MAR to make the different technologies accessible to all and a ready reckoner for individual stakeholders to undertake rainwater harvesting.
3. Intensive quality checks to be performed on the source water and recharge water, if the recharge water is to be used for drinking purpose.
4. The urban bye-laws in the present context are difficult to be followed by individual houses having carpet area more than 200 m^2; therefore, the urban bye-laws should be relooked and modified.
5. Quality guidelines for using treated waste water should be finalized, and in the absence of it, the quality guidelines following the Australian guidelines should be used. Pilot projects on using the treated waste water should be implemented in different megacities facing water scarcity for domestic use.
6. Community participation along with social mobilization is essential for the success of rainwater harvesting projects. Mass awareness programmes should be introduced on a large scale for popularizing water resources management practices.
7. The government should encourage and support the implementation of the pilot projects in the coastal and mountain areas to showcase the technology to check saline ingress and creating surface storages.
8. To declare some villages/blocks as rainwater harvesting areas, where groundwater quality is bad and water supplies are inadequate.

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Interrelationship Between Surface and Groundwater: The Case of West Bengal

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Abstract The interrelationship between surface and groundwater in West Bengal has not been properly studied. Even the water management planning often suffers from inadequate knowledge at official level. This paper gives an estimate of water resource of West Bengal. The groundwater in West Bengal has been depleting fast. It has been observed that groundwater is depleting at 25.5 cm/year in 296 blocks. This is due to over-exploitation of groundwater to ensure irrigation in bodo(dry variety paddy) season. The situation is further aggravated due to climate change. The farmers are often troubled due to delayed onset of monsoon and decline in monsoon rainfall. We need to formulate a policy to cope with the changing scenario.

Keywords Groundwater · Depletion · Irrigation · Ecology

1 Introduction

Even in West Bengal which receives plenty of rainfall, water is under stress due to its limited supply and increasing demand. The post-independence era witnessed growing demand for irrigation, rapidly expanding urbanization, industrialization, generation of power and rampant pollution of both surface water and groundwater. The problem needs to be addressed with informed interdisciplinary approach. But water-related data available in public domain are inadequate to conduct any research. The initial knowledge base for water management in India was borrowed from British Institutions and that arithmetic hydrology continues to guide our planning. Water management in India during post-independence era was guided by some flawed logics noted below:

- The demand of water for irrigation has been given top priority while damming the rivers, and the importance of the environmental flow was denied.

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S. P. S. Ray (ed.), *Ground Water Development - Issues and Sustainable Solutions*, https://doi.org/10.1007/978-981-13-1771-2_10

- The attempts were made to intercept flowing water and transfer the volume far away. The transmission-distribution loss was not properly addressed.
- The volume of water in groundwater pool was thought to be unlimited and that could satisfy our growing demand.
- The environmental costs of polluting the surface water and groundwater were not paid proper heed.

The utilizable water is popularly defined as the part of the total water resource which can be stored in dams and reservoirs or abstracted from groundwater pool. It is also thought that this water can be put for beneficial use of mankind. The Expert Committee on Irrigation, Government of West Bengal (1987) assessed the surface water of the state as 13.29 million hectare metre (mham) and the groundwater as 1.46 mham. The utilizable water resource was estimated as 6.77 mham only. But the human society survives on many ecosystem services of water. Even the agriculture is not exclusively dependent on stored water or groundwater. The Indian farmers have inherited the culture of utilizing the raindrops falling on the agricultural land. In Bengal, overflow irrigation has been an age old tradition. The farmers learnt the art of sustainable use of water and silt that spilled over the land during the flood. So the phrase "utilizable water" has a wider connotation beyond the engineering understanding. The water resource should not be defined as a stock that can be controlled and regulated but should include every drop available for a particular purpose in a given region and season, having adequate quality for the said purpose.

2 Estimated Water Resource

The Expert Committee on Irrigation (1987) made a comprehensive assessment of both surface and groundwater in 25 river basins of West Bengal, and the database generated in that report has so far been cited by many water managers. But geographical scenario of West Bengal has drastically changed since the expert committee submitted its report, and we need to assess our water resources afresh. It is important to note that the administrative boundary of West Bengal, which is largely the colonial legacy, was drawn without any regard to the holistic eco-hydrology of the area, and as such district-wise assessment of water resources is an important issue. Moreover, the said committee did not take into account the transboundary water which enters the state from upstream region, nor were the aspects of evaporation, evapotranspiration and infiltration estimated. Thus the water resource can be divided into two parts. The rainfall within the territory of West Bengal generates internal water, and the rivers carrying water from upper catchment lying beyond state boundary is called transboundary flow.

The average annual rainfall in West Bengal is estimated as 1766 mm. But it is safe to make the management plan based on 75% assured rainfall which is 1672 mm. The share of each district varies widely. The 76% of annual rainfall is received during 4 monsoon months and 24% of the rainfall during remaining 8 months. Not all these water is directly available for human use. About 21% of water generated by rain infiltrates through the soil and recharges the groundwater, and 49% goes back to atmosphere through evapotranspiration. It is important to note that farmland contributes substantial part of evapotranspiration (Rudra 2009, 2015).

The rain falling within the geographical territory of West Bengal annually generates 101.22 billion cubic metre (bcm) of surface water. But this is unevenly distributed. The 4 monsoon months generate 87.87 bcm, and the remaining 8 months produce 13.46 bcm. The Central Ground Water Board has estimated the utilizable groundwater and that amounts to 30.50 bcm. Thus total water available in West Bengal for beneficial use of mankind is 131.72 bcm. But this does not include the transboundary flow of the rivers which are channelized and cannot be used in a distributed way. This portion of total water resource is accessible only to the people living on river bank. It would have been better to treat this transboundary water as ecological flow and can also be used only for nonconsumptive purposes in addition to ensuring drinking water which does not claim a large volume. However total water resources in West Bengal amounts to 726.79 bcm (Table 1) (Rudra 2009, 2015).

Table 1 Water resource in West Bengal at a glance

District	Area (sq. km)	Internal water resources (billion cubic metre)				Total resources (billion cubic metre)	
		Monsoon season	Lean season	Annual	Annual groundwater	Total internal water	Internal water + transboundary flow
Darjeeling	3149	6.12	0.77	6.89	0.52	7.36	25.19
Jalpaiguri[a]	6227	12.58	1.90	14.48	2.64	16.85	48.61
Koch Bihar	3387	6.73	1.11	7.84	2.34	9.94	55.90
Uttar Dinajpur	3140	4.17	0.63	4.80	1.77	6.42	16.69
Dakshin Dinajpur	2219	2.09	0.32	2.42	1.09	3.40	13.50
Maldah	3733	3.25	0.45	3.70	1.44	5.01	551.48
Murshidabad	5324	3.68	0.30	3.98	2.40	6.16	570.31
Birbhum	4545	3.18	0.41	3.59	1.62	5.06	15.07
Barddhaman	7024	4.63	0.57	5.20	3.37	8.26	88.99
Nadia	3927	2.68	0.17	2.84	2.21	4.83	66.56
N 24 Parganas	4094	3.30	0.84	4.14	1.52	5.51	72.07
Hugli	3149	2.12	0.48	2.60	1.67	4.10	96.61
Bankura	6882	5.07	0.36	5.43	2.16	7.39	31.78
Puruliya	6259	4.62	1.21	5.82	0.83	6.57	24.17
East Medinipur	4795.2	4.70	1.23	5.93	0.80	6.65	16.80
West Medinipur	9285.8	7.01	0.98	7.99	3.75	11.38	22.88
Haora	1467	1.35	0.32	1.67	0.37	2.00	93.30
S 24 Parganas	9960	10.40	1.37	11.78	–	11.78	105.78
Kolkata	185	0.21	0.04	0.14	–	0.25	88.40
West Bengal	**88.752**	**87.87**	**13.46**	**101.22**	**30.50**	**128.92**	**726.79**

[a]The undivided Jalpaiguri includes new born district called Alipurduar

Table 2 Estimated flows in rivers

River	Estimate locations	Average monthly flow (cumec)			
		Feb.	May	Aug	Nov.
Torsa	At border	38.4	571.5	1264	72.2
Jaldhaka	At border	7.2	361.7	808.9	6.3
Teesta	At border	153	549.8	1525.2	327.1
Mahananda	Godagari	43.6	744.7	1622.2	5.8
Bansloi	Jangipur	1.5	27.3	87.3	0.5
Pagla	Jangipur	1.3	15.6	44.8	0.3
Mayurakshi	Kalyanpur	37	204.3	618.2	5
Ajoy	Katwa	16.7	107.5	409.9	4
Jalangi	Mayapur	33	39.3	145.8	2.6
Churni	Chakdah	25.3	17.3	78.8	2.8
Damodar	Uluberia	138.2	360.8	1534.7	7.9
Darakeswar	Arambag	18.1	100.7	235.4	3.4
Silai	Ghatal	7.2	71.9	249.3	2.9
Kansai	Mayna	93.5	247.6	648.7	6.8
Bhagirathi	Nabadwip	1408.2	1937.9	4334.9	1159.6
Hugli	Gangasagar	1541.2	2625	6304.4	1181.2
Padma	Jalangi	4303.1	4833	40,405.5	4295.3

There are two approaches to assess water resources. The first one is district-wise assessment as described above, and the second one is basin-wise assessment as was done by the experts' committee (1987). The discharge data of rivers are generally treated as classified information. In absence of real-time data, an attempt is made to assess the flow in all major rivers of West Bengal, through the mathematical model, and the result is presented in Table 2.

Notably the Irrigation Department earlier identified 25 basins. But here 16 basins have been identified and those that cover a large part of the state. The river basins are shared by districts and thus there are cases of conflicts over transboundary water, especially during lean season. The water contains seed of conflict both at inter- and intrastate levels.

2.1 Depleting Groundwater

The groundwater level in West Bengal has been depleting fast. This is largely due to indiscriminate exploitation of groundwater to ensure irrigation for *bodo* cultivation. State Water Investigation Department in its report (2011) has described the groundwater scenario in 296 blocks of West Bengal. The SWID has monitored fluctuation of groundwater level during the period 2002–2011. It is reported that pre-monsoon (observed in the month of April) has gone down in 259 blocks, and rate of decline observed in the month of April in 136 blocks was found to the tune of more than

20 cm/year. But in all 296 blocks, groundwater level is being lowered at the rate of 25.5 cm/year. Still Central Ground Water Board has identified only 38 blocks of the state where status of the groundwater is described as semicritical. This does not corroborate the reality. Notably if lowering of the groundwater level in a block is more than 20 cm/year and exploitation exceeds 70% of the available water, condition of that block is said to be semicritical. The gap between reality and official report is attributed to the fact that the CGWB (2001, 2006), while estimating the volume of water being abstracted from the groundwater pool, counts only the wells approved by the SWID. But there are many unapproved wells. Even the temporary wells which operate to facilitate *bodo* cultivation are not taken into account. Thus official report leads to an understatement describes stage of groundwater development to the level of 40%. Table 3 describes depleting groundwater scenario in West Bengal.

Rainfall pattern in West Bengal has changed appreciably. It is observed from analysis of the rainfall data during the period 1901–2002 that rainfall in the month of June has been declining and that in September it tends to increase. There is also a tendency of unusually concentrated rainfall which leads to more runoff and less infiltration. The main findings of the analysis are noted below:

- June precipitation has declined from 1901 to 2002 at the rate of about 1 mm per year in North Bengal.
- In south Bengal June rainfall has declined by about 48 mm, and September rainfall has increased about 33 mm.
- Model-based predictions for the future:
  - Delayed onset of monsoon
  - Decline in monsoon rainfall
- Our crop calendar needs to be adjusted.
- Scientists warn that many rivers may go dry by the mid twenty-first century.

Table 3 Pre-monsoon depletion of the groundwater in West Bengal

Districts	Observed blocks	Fall >20 cm/year	Districts	Observed blocks	Fall >20 cm/year
Darjeeling	6	2	Nadia	17	0
Jalpaiguri	13	0	N.24 Parganas	20	5
Cooch Behar	12	0	S.24 Parganas	7	2
N. Dinajpur	9	1	Hugli	18	11
S. Dinajpur	8	2	Bankura	19	10
Malda	12	3	Purulia	20	8
Murshidabad	25	11	E. Medinipur	25	24
Birbhum	19	12	W. Medinipur	22	15
Bardhaman	32	19	Haora	12	8
West Bengal	296	136			

2.2 Water: Stress, Scarcity and Absolute Scarcity

A human being demands 1700 m^3 of water/year to satisfy his/her all kinds of demand. When the annual per capita availability of water is less than 1000 m^3, the area is supposed to be suffering from “water scarcity”. When availability is between 1000 m^3 and 1700 m^3, the area is considered as “water stressed”. In 2011 conditions in 11 districts were found unsafe as per capita water availability was less than 1700 m^3. The four districts were found to suffer from water scarcity. Absolute scarcity was found in two districts where availability was below 500 m^3/year/capita (Table 4). It is important to note that average availability of water in 2011 indicates that it is “water stressed”. The index was computed on the basis of the surface and groundwater available within West Bengal. The transboundary water that comes from the adjoining states is not taken into account.

3 Conclusion

The experts have expressed their anxiety over the future of water management in India. The present system is said to be unsustainable. West Bengal, being located at the tail-end of the Ganga basin, is the hydrologically subsidized state which receives

Table 4 Declining per capita water availability (in cubic metre)

District(s)	1951	1971	1991	2011
Darjeeling	16,529	9414	5662	3996
Jalpaiguri	18,424	9628	6017	4354
Koch Bihar	14,809	7028	4578	3521
Uttar Dinajpur	22,544	5801	3385	2140
Dakshin Dinajpur	7804	4517	2763	2035
Maldah	5339	3104	1898	1252
Murshidabad	3591	2095	1300	867
Birbhum	4744	2850	1980	1445
Barddhaman	3771	2110	1366	1070
Nadia	4220	2166	1254	935
N 24 Parganas	2409	1285	756	546
Hugli	2636	1426	941	742
Bankura	5599	3637	2663	2054
Puruliya	–	4099	2953	2244
Purba Medinipur	4630	2704	1528	1305
Paschim Medinipur	6201	3709	2365	1915
Haora	1240	825	536	413
S 24 Parganas	4820	3214	2061	1444
Kolkata	100	81	58	57
West Bengal	5189	2941	1871	1411

huge volume of transboundary water. But the supply of this water is so skewed that West Bengal bears the brunt of flood during monsoon. In the absence of any regulation regarding equitable sharing of the transboundary water, the withdrawal of water from the rivers by upper riparian states during lean months has been increasing at an uninterrupted pace leaving meagre share for West Bengal. This issue should be addressed afresh at national level. The growth of population and increasing demand of water are intertwined. The increasing population leads to more stress on all natural resources. A plan for revival of our traditional water conservation system would be economically viable and environmentally sustainable. The present agriculture of West Bengal relies on intensive use of water, chemical fertilizer and pesticide. This is leading to loss of biodiversity, decline in land fertility and lowering of groundwater level, associated with arsenic and fluoride contamination. The amount of water required to produce 15 quintals of *bodo* rice can be utilized to produce 36 quintals of wheat and 20 quintals of pulses. The judicious and productive use of scarce irrigation water is important. The National Water Policy (2012) rightly said, "Planning, development and management of water resources need to be governed by common integrated perspective considering local, regional, State and national context, having an environmentally sound basis, keeping in view the human, social and economic needs". A water policy for West Bengal needs to be formulated on top priority.

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Integrated Watershed Management and Groundwater Recharging: Initiatives of Centre for Ground Water Studies – A Public-Private Partnership Endeavour

S. N. Lahiri and S. P. Sinha Ray

Abstract The Government of India has adopted watershed management as a national policy since 2003. The Centre for Ground Water Studies has taken up a number of projects with the mode of public-private partnership. Endeavour has been made to bring together beneficiaries, local Panchayat functionaries and funding agency (M/s Bengal Beverage Pvt Ltd and Coca-Cola India) in Paschim Medinipur District to re-excavate Water Harvesting Structures. In another case, beneficiaries, Panchayat functionaries, IWWA (NGO) and funding agency PHED, WB joined together to construct a model rainwater harvesting hub in Purulia I Block. CGWS has given the necessary input of design, supervised the construction and implemented the project. Groundwater recharging in semiarid areas through re-excavation of ponds below the depth of average water table in driest months is providing water security to the communities in the lean period and also providing limited facilities for irrigation water and pisciculture. The need of the day is to extend such work as a peoples' programme with the funding from industries under their CSR scheme.

Keywords Watershed · Public-private partnership · Beneficiaries · Rainwater harvesting · Groundwater recharging

1 Introduction

The Government of India has adopted watershed management as a national policy since 2003. Various programmes related to watersheds have been in operation in the country at different points of time which have been brought under the single umbrella of Integrated Watershed Management Programme (IWMP) by the National Rainfed Area Authority (NRAA) under the aegis of Planning Commission of India in the year 2008 (which has been revised during 2011) in order to have a unified perspective by all the stakeholders. The scheme is basically for rainfed area.

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S. P. S. Ray (ed.), *Ground Water Development - Issues and Sustainable Solutions*, https://doi.org/10.1007/978-981-13-1771-2_11

Now, the GoI has formulated Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) with a view to ensure effective planning and coordination amongst various departments. The components of PMKSY are the following:

1. AIBP (Accelerated Irrigation Benefit Programme)
2. PMKSY (Har Khet ko Pani)
3. PMKSY (Per Drop More Crop)
4. PMKSY (Watershed Development)

The major objective of PMKSY is to achieve convergence of investments in irrigation at the field level, expand cultivable area under assured irrigation, improve on-farm water use efficiency to reduce wastage of water, enhance the adoption of precision irrigation and other water saving technologies "(More crop per drop)", enhance recharge of aquifers and introduce sustainable water conservation practices by exploring the feasibility of reusing treated municipal waste water for peri-urban agriculture and to attract greater private investment in precision irrigation system. The Centre for Ground Water Studies, a Kolkata-based NGO, is associated with various research and developmental programmes of Central and State Governments and industrial houses in the field of rainwater harvesting at different parts of the country. One such scheme is a pilot project to develop a rainwater harvesting hub in the district of Purulia. During the course of implementation of the said project, the Centre came in touch with the Project Implementing Agency (PIA) of the Durku Watershed Project (IWMP/Purulia/01/2011–2012) and felt the necessity to work in convergence mode with the PMKSY (WD) for National cause. In the effort, the Centre organized to associate (1) M/s Bengal Beverages, Dankuni, and (2) PHED for investment in the schemes.

Three water harvesting schemes have been implemented so far in consultation with the respective PIAs of IWMP by arranging funds with the initiatives of CGWS in the tune of Rs.69.75 lakh from different sources.

2 Pradhan Mantri Krishi Sinchayee Yojana (Watershed Development), [PMKSY (WD)]

2.1 The Challenge

The challenge in rainfed areas is to improve rural livelihoods through participatory watershed development with focus on integrated farming systems for enhancing income, productivity and livelihood security in a sustainable manner. An integrated approach is essential in view of the following:

(a) Grim picture of poverty, water scarcity, rapid depletion of groundwater table and fragile ecosystem.
(b) Land degradation due to soil erosion by water, low rainwater use efficiency, high population pressure, acute fodder shortage, poor livestock productivity, underinvestment in water use efficiency, lack of assured and remunerative marketing opportunities and poor infrastructure.
(c) More than 43% of geographical area is rainfed in the State of West Bengal and is considered to be brought under the PMKSY (WD) in phases.

2.2 Main Objectives of Watershed Development Programme

Amongst others, the main objectives of the programme are:

(a) Conservation, development and sustainable management of natural resources (arable and nonarable lands, water, animals, vegetation and soil) including their use
(b) Enhancement of agricultural productivity and production in a sustainable manner
(c) Restoration of ecological balance in the degraded and fragile rainfed ecosystems
(d) High water use efficiency
(e) Livestock, pisciculture, other household productions/developments
(f) Development/conversion of wasteland
(g) Reduction in regional disparity between irrigated and rainfed areas
(h) Creation of sustained employment opportunities for the rural community including the landless

2.3 Criteria for Selection and Prioritization of Watershed Development Projects

(a) Acuteness of drinking water scarcity.
(b) Extent of overexploitation of groundwater resources.
(c) Preponderance of wastelands/degraded lands.
(d) Contiguity to another watershed that has already been developed/treated.
(e) Willingness of village community to make voluntary contributions, enforce equitable social regulations for sharing of common property resources, make equitable distribution of benefits, create arrangements for operation and maintenance of the assets created.

(f) Proportion of scheduled castes/scheduled tribes.
(g) Area of the project should not be covered under assured irrigation.
(h) Productivity potential of the land.
(i) Incomplete/under-treated/leftover watersheds taken up previously for development under any scheme/programme can be taken up for development on priority basis.

2.4 Project Area

As per the Common Guidelines for Watershed Development Projects, Government of India, geohydrological units of average size of 1000–5000 ha comprising of clusters of micro-watersheds can be considered as single project area. However, the project area can be increased or decreased depending upon the ground situation. While identifying the IWMP watersheds, if a small portion of a GP is lying outside the IWMP watershed boundary, this portion is also to be considered under IWMP watershed. If only a small portion of GP is covered and most of the area is outside of the IWMP watershed project area, the GP is to be ignored. But it is suggested to downsize the number of micro-watersheds limited to four or six by way of clubbing the geohydrological units together to avoid future complication during implementation as well as for successful execution of the project. The DPR shall be prepared accordingly.

3 Initiatives of Centre for Groundwater Studies to Work in Convergence Mode with IWMP

The Government of India always emphasized upon convergence with IWMP wherever the project is under progress. There are some watershed development schemes/works in the project which require fund and also expertise interventions of line departments and NGOs. Moreover such similar works are also being implemented under some approved projects of the state or central government and private companies. Those schemes/works are provided to be completed in convergence mode. Planning of such works is taken up in consultation with the respective PIAs of the IWMP. The CGWS is associated with various research and developmental studies and works in the field of water harvesting both in the government/semi-government undertakings and private sectors. Currently, the Centre is extending consultancy services to Indian Water Works Association and M/s Bengal Beverages Pvt. Ltd., Dankuni, authorized bottler of the Coca-Cola Company. Both organizations had a plan for Rainwater Harvesting Schemes in the district of Purulia and Paschim Medinipur, respectively. The Centre prepared plans of such schemes for the said organizations so that those are taken up in areas where works under IWMP are in progress.

3.1 Rainwater Harvesting Schemes in Convergence with IWMP at Salbani Block, Paschim Medinipur

M/s Bengal Beverages Pvt. Ltd., Dankuni, authorized bottler of the Coca-Cola Company, has a commitment to undertake Rainwater Harvesting Schemes as against its extraction of groundwater for the preparation of soft drinks in the brand name of "Coca-Cola". The CGWS having expertise is engaged as its consultant to locate, plan and design feasible Rainwater Harvesting Schemes in the water-scarce areas in the district of Paschim Medinipur. In the endeavour and having IWMP in mind, the CGWS prepared a plan and design of two Rainwater Harvesting Schemes after the feasibility study in Salbani Block of the district. The schemes are selected within IWMP 20 and 21, respectively. The schemes were approved by the Coca-Cola India, New Delhi, in favour of its authorized bottler, M/s Bengal Beverages Pvt. Ltd., Dankuni.

The re-excavation has been done by outsourcing arranged by the Company. Supervision of works was jointly carried out by the Centre, local Panchayat and the Company. Payment of works was made by the Company. Finish ponds have been handed over to the User Group (UG) as identified by the Watershed Committee (WC) of the IWMP.

Design of Re-excavation

Considerations

1. Good catchment – hills or plains with little cultivation and moderate absorbent soil.
2. Average catchment – flat, partially cultivated stiff gravely/sandy absorbent soil.
3. Bad catchment – flat and cultivated sandy soil.
4. The dependable rainfall is 75% of the average rainfall.
5. Catchment area is good, plains with little cultivation and moderate absorbent soil.
6. Since the catchment is good, 30% of generated run-off can reach the pond (bundh).
7. The pond (bundh) has been measured physically.
8. Only the lowest value of supply side and design side has been taken for recharge estimation.

Re-excavation of Banamalipur Saheb Bandh
Catchment area – 30 ha
Measurements of the pond
Initial volume = 23,750 cum
Finish volume = 56,852 cum
Re-excavated volume = (56852–23,750) cum = 33,102 cum (Table 1)

Re-excavation of Garhmal Tank
Catchment area – 30 ha
Measurements of the pond
Initial volume = 8200 cum
Finish volume = 31494 cum
Re-excavated volume = (31494–8200) cum = 23,294 cum (Table 2)

3.2 Rainwater Harvesting Schemes in Convergence with IWMP at Purulia I Block, Purulia

The Department of Public Health Engineering, Government of West Bengal, is developing a rainwater harvesting hub in Purulia district through Indian Water Works Association, Kolkata. Three schemes under the project were considered, viz., (1) re-excavation of the pond (Figs.1 and 2), (2) rooftop rainwater harvesting and (3) check dam.

Table 1 Re-excavation of Banamalipur Saheb Bandh

Supply side		Design side	
Catchment area (ha)	30	Pond volume (cum)	56,852
Catchment type	Good	Twice filling (hard rocks) (cum)	113,704
Rainfall (RF) (mm)	1539	Usage (20%) (cum)	22,740
Dependable RF (mm)	1154	Evaporation) (20%) (cum)	22,740
Run-off from the catchment (cum)	138,480	Total utilizable pond recharge volume (cum)	68,224

Table 2 Re-excavation of Garhmal Tank

Supply side		Design side	
Catchment area (ha)	30	Pond volume (cum)	31,494
Catchment type	Good	Twice filling (hard rocks) (cum)	62,988
Rainfall (RF) (mm)	1539	Usage (20%) (cum)	12,597
Dependable RF (mm)	1154	Evaporation) (20%) (cum)	12,597
Run-off from the catchment (cum)	138,480	Total utilizable pond recharge volume (cum)	37,794

Fig. 1 Before pond excavation

Fig. 2 After pond excavation

The CGWS is consultant of IWWA for the entire project. The site for the check dam was finalized in consultation with the active co-operation of the PIA, IWMP-1 of Purulia district. The Project Manager, WCDC, Purulia, was also taken into confidence for the construction of the check dam within the project area of IWMP-1.

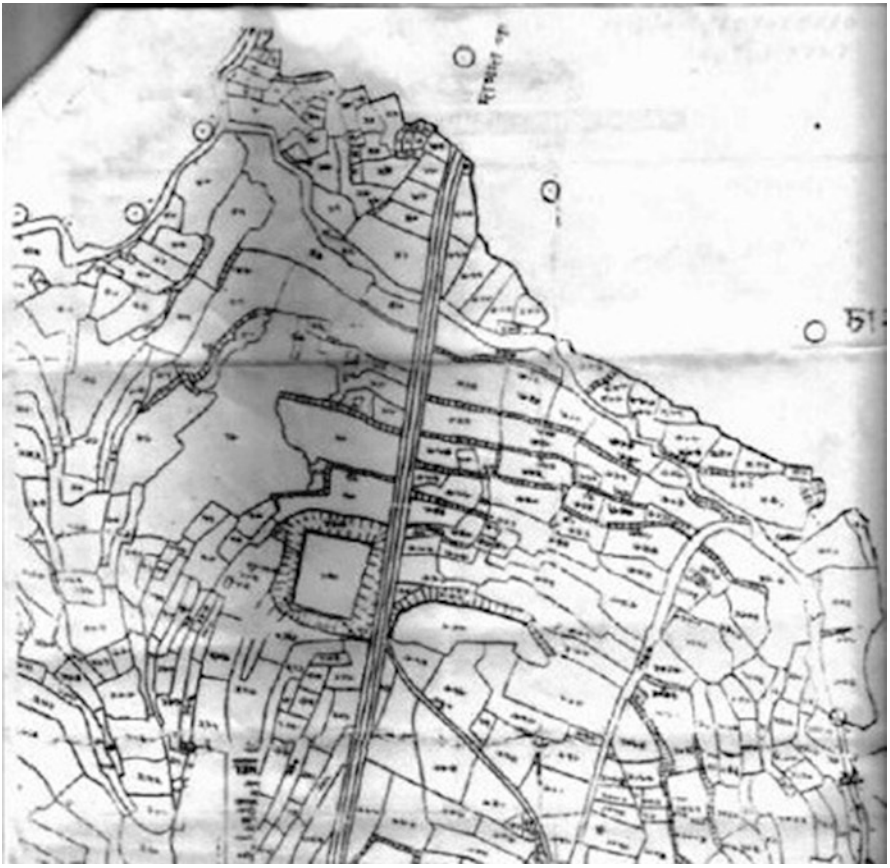

Fig. 3 Mouza map of the study area

A seasonal stream locally known as "Ulta Jore" flows towards North almost along the boundary of Suklara and Chaklator mouza. It was decided to construct the check dam across the said Jore. The plan and design of the check dam has been done followed by feasibility study.

Details of design, drawing and estimates are furnished below in Figs. 3, 4, and 5.

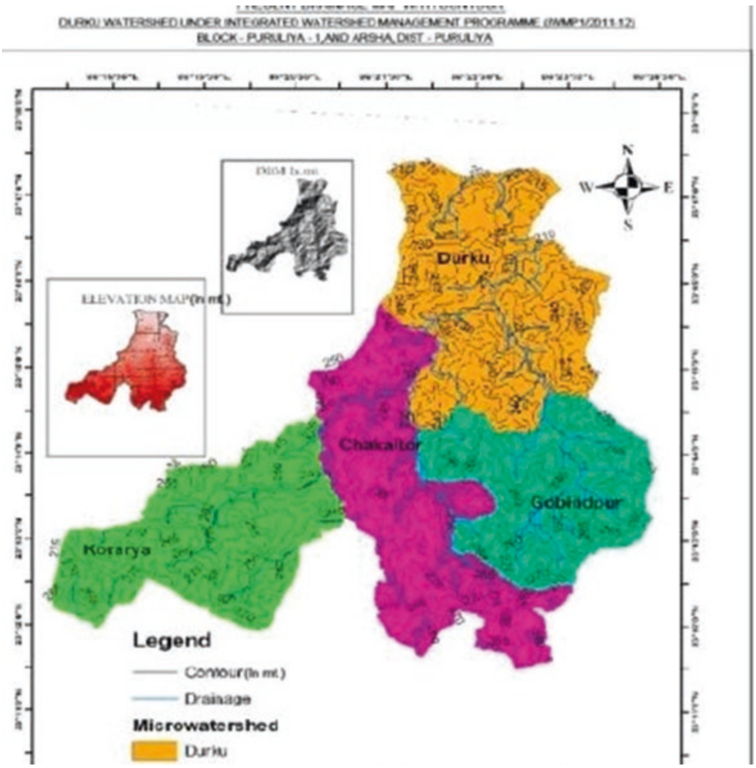

Fig. 4 Present drainage map of the study area

The construction of the dam was completed through outsourcing arranged by the CGWS. Supervision of construction was jointly carried out by the Centre, User Group selected by the WC of IWMP and WDT Engineer of IWMP-1 of Purulia. Measurement of works was noted by the WDT Engineer of IWMP-1 duly checked by the Centre. Payment for the works was arranged by the Centre. The design of the check check dam is shown in Fig. 6. Construction phase and synoptic view of the check dam is given in Figs. 7 and 8 respectively.

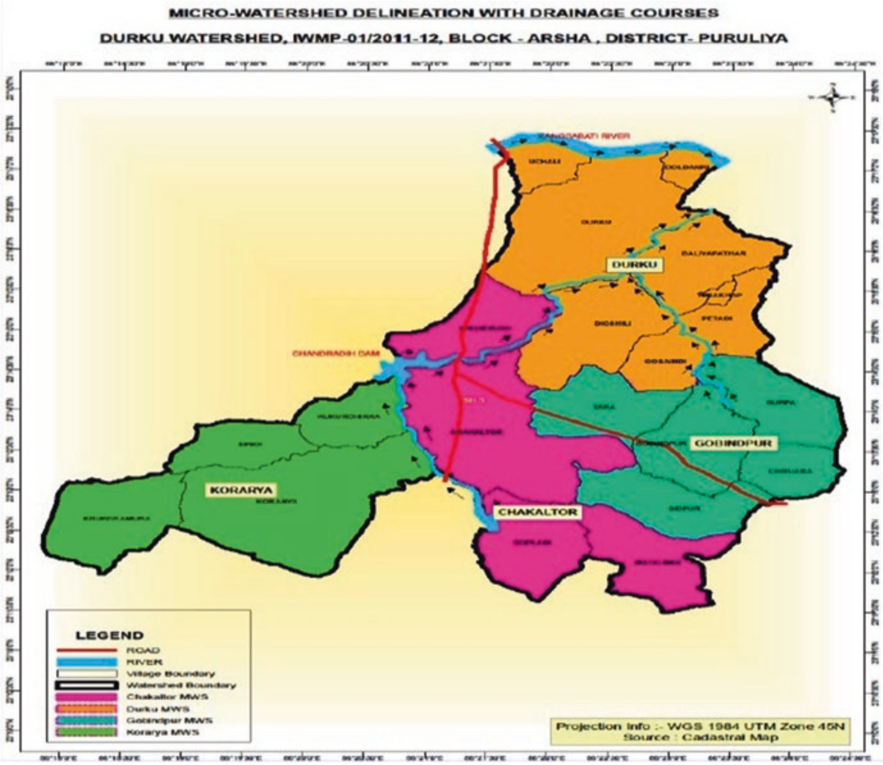

Fig. 5 Micro-watershed delineation with drainage courses of the study area

The check dam thus constructed is handed over to the User Group selected by the Watershed Committee of the IWMP.

4 Conclusions

The development of rural India largely depends upon the successful implementation of micro-watershed development plans involving the development of local resources of land and water and human resources. This will enable us to achieve total sustainable development through prudent management techniques.

Acknowledgements The authors are thankful to the WBSWDA Publication of Operational Guidelines of IWMP; PIA, IWMP-01 of Purulia; PIA, IWMP-20 of Paschim Medinipur; PIA, IWMP-21 of Paschim Medinipur; Project Manager, WCDC, Purulia; PHED, W.B., IWWA-Kolkata Centre; Bengal Beverages (P) Ltd. and Coca-Cola India.

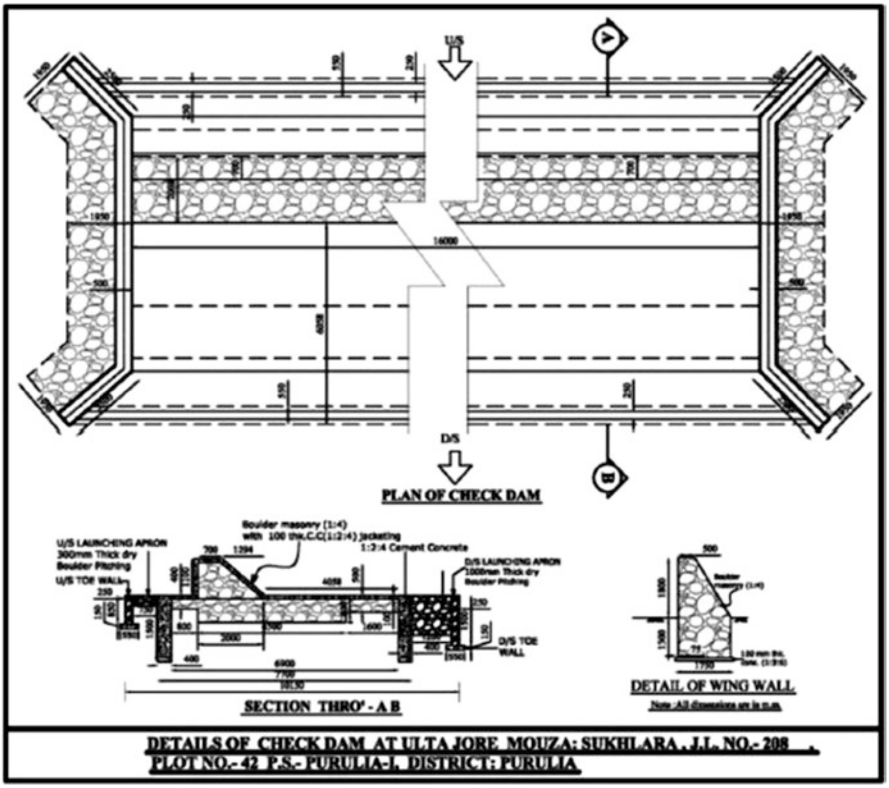

Fig. 6 Detail design of the check dam in the study area

Fig. 7 (**a**, **b**) Construction phase of check dam of the study area

Fig. 8 (**a**–**d**) Synoptic view of check dam

Part V
Advance Research in Ground Water

Application of Modern Geophysical Techniques for Identification of Groundwater Potential Areas

Bimalendu B. Bhattacharya

Abstract One of the scientific approaches for the preparation of an improved geohydrological model is to incorporate systematic geophysical investigations in the program. The electrical and electromagnetic methods are widely used. In large-scale hydrological projects, the geophysical studies are broadly applied mainly in the following ways: (1) airborne electromagnetic survey as groundwater in most of the areas is quite conductive, ranging from 20 to 120 mS/m, for mapping the aquifers in a regional scale and (2) ground electrical and electromagnetic survey. Multifrequency airborne EM surveys are employed as a tool to study aquifer vulnerability. In electrical methods VES and 2D resistivity imaging is extensively used in most of the hydrological problems. The technique of thematic overlays to demarcate the groundwater potential zones in a hard rock terrain in a drought-prone area has been discussed. 2D electrical imaging delineated aquifers in water scarcity hard rock terrain of Deccan trap in Central India, and the yield has been 15,900 l per hour. Self-potential (SP) measurements were made in Armenia where it was required to lower the groundwater level whose higher level was due to the presence of saline water in a major hydroelectric installation area. The SP profile measured is practically a mirror image of the cone of depression showing a better indication of groundwater level than that obtained by the sparse network of piezometers. Mise-a-la-masse method may be used for hydrogeological investigations for finding flow of ground by lowering one of the current electrodes covered by a bag of salt in the aquifer zone. Equipotential contours drawn sometime after charging will show change in shape – from circular to oval, elongated in the direction of flow of groundwater.

Keywords Groundwater · Electromagnetic survey · VES · 2D resistivity imaging · Self-potential · Mise-a-la-masse method

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S. P. S. Ray (ed.), *Ground Water Development - Issues and Sustainable Solutions*, https://doi.org/10.1007/978-981-13-1771-2_12

1 Introduction

Geophysical methods are extensively used for groundwater investigations for the preparation of hydraulic models of the study areas. The validation of the models requires calibration with known hydrogeological parameters and geological information from the borehole data. The models predict the movement of groundwater for a given geological setup. However, such models are not as reliable as desired because of spatially sparse borehole distribution. This, along with inverse hydraulic modeling, produces models with a degree of uncertainty which can be reduced considerably by providing appropriate inputs from the geophysical data. The geophysical investigations may provide information about aquifer geometry and hydraulic properties, vulnerability assessment of aquifers caused by the leakage of pollutants from the adjoining areas, and water quality of the aquifer.

The electrical and electromagnetic geophysical methods are widely used for hydrological investigations. These methods enable to distinguish the formations on the basis of electrical resistivity contrast. Clay due to its distinct low electrical resistivity value enables it to distinguish overwhelmingly between the permeable and impermeable formations – a very important information needed in many hydrological studies. Sorensen et al. (2005) showed that porosity and induced polarization phenomena are directly related. However, the relationship between electrical resistivity, porosity, and hydraulic conductivity is yet to be fully established. In hard rock terrain, in addition, seismic refraction method is also employed (Bhattacharya 2017).

2 Application of Geophysical Methods in Hydrological Studies

In large-scale hydrological projects, the geophysical studies are broadly applied in the following way: (1) airborne electromagnetic (mainly transient electromagnetic (TEM) of different types), along with airborne magnetic surveys (Rottger et al. 2005; Wynn et al. 2005), (2) ground electrical and electromagnetic surveys, (3) additional seismic refraction method in hard rock terrain, and (4) geophysical logging as and when boreholes are made available.

In ground electrical methods, the vertical electrical sounding (VES) and resistivity imaging up to a limited depth of about 200–300 m are in extensive use. In addition self-potential (SP) method has been successfully used to study the pattern of change in the subsurface water level after pumping. Mise-a-la-masse method has also been applied to study the pattern and direction of water flow. In case of electromagnetic methods, various ground versions of TEM are in extensive use. In addition the very low-frequency (VLF), generally in the frequency range of 15–25 kHz, method is used mainly in the hard rock terrain to locate the near-surface fractured, fissure, and fault zones for locating the water-bearing horizons in such geological terrains. In this paper the discussion will be mainly restricted to electromagnetic (airborne and surface) and electrical methods.

2.1 Electromagnetic Methods

Groundwater in most of the areas is quite conductive, ranging from 20 to 120 mS/m – an encouraging feature for incorporating electromagnetic (EM) airborne geophysical study for mapping the groundwater in a regional scale. Airborne magnetic survey is also simultaneously used along with commonly used time domain airborne electromagnetic (TDAEM) survey (Wynn et al. 2005). The resulting data provides valuable information on the aquifer, as well as the disposition of the complex basement below the sediments, to map the important tectonic features crucial to hydrologists trying to model the groundwater contained in the overlying sediments.

2.2 Concepts for Vulnerability Maps

Rottger et al. (2005) explained the vulnerability of an aquifer on the basis of severity of the pollutants. The vulnerability maps play an important role in groundwater management and planning. For the purpose of sustainability, the new groundwater regulations of the European Community Commission stress the need for large-scale aquifer and vulnerability mapping and water quality assessment instead of the general practice of confining the study within localized aquifer region. Vulnerability maps incorporate coupled parameters obtained from the lithological characters of the formations overlying the aquifer. In the Netherlands the vulnerability maps exhibit the variation of groundwater table, clay, and organic contents of soil and cation exchange capacity. The *aquifer vulnerability index* (AVI) indicates the potential of transmission of surface contaminants to the aquifer over a length of time. In Germany, however, AVI is on the basis of classification system which depends on classification number determined according to the character of sediments and their assumed cation exchange capacity.

It is worth noting that the vulnerability maps are reliable at the drilling sites only. The uncertainty of the vulnerability between the drilling locations due to interpolation will be considerably reduced by the judicious use of geophysical maps.

2.3 The Geophysical Approach: Relating Electrical Conductivity to Hydraulic Conductivity

Hydraulic conductivity describes the ease with which a fluid flows through the pore spaces or fractures. For sedimentary formations it varies over a very wide range from 900 to 1230 m/day (coarse gravel) to $4.1 \times 10^{-5} - 4.1 \times 10^{-2}$ m/day (impermeable clay), respectively (Karanth 1995). The hydraulic conductivity of unconsolidated sediments is mainly controlled by its clay contents with an inverse relationship. The reason for high electrical conductivity of clay is due to large porosity, low permeability, and high surface area. Thus, in such cases hydraulic conductivity can be inferred from the estimated electrical conductivity. The reliability of the vulnerability map is reasonably enhanced by using the electrical conductivity data between the boreholes. Thus, the multifrequency airborne EM surveys become useful as a tool to study aquifer vulnerability.

2.4 Vertical Electrical Sounding (VES)

In electrical methods VES is extensively used in most of the hydrological problems. We shall discuss some of the important issues related to VES.

2.4.1 Qualitative Interpretation of VES Curves

Quantitative interpretation gives the parameters of the geoelectric sections: thickness and resistivity of the layers as well as the depth of the layers. It is always desirable to study the VES curves at first qualitatively for obtaining some broad information (Bhattacharya and Shalivahan 2016).

The changes in the coordinates of the minima ($\rho_{\downarrow}$**amin**) of H-type curves ($\rho_1 > \rho_2 < \rho_3$) are related to the changes in the layer parameters. Therefore, studying the nature of minima of H-type curves may provide important information on relative changes of the parameters of the intermediate layer.

The relationship showing the changes in $\rho_{\mathbf{amin}}$ due to changes in the layer parameters for the following five cases is shown in Fig. 1 (Bhattacharya and Shalivahan 2016).

K-Type VES Curves

K-type ($\rho_1 < \rho_2 > \rho_3$) or bell-type curves show maximum value due to the effect of high-resistivity intermediate layer. The nature of maxima like the minima of H-type curves depends on the relationship between the various layer parameters, and it is shown in Fig. 2.

A-Type VES Curves

A-type ($\rho_1 > \rho_2 < \rho_3$) curves show neither minima nor maxima. Relatively small thickness of the intermediate layer or its resistivity not having significant contrast with ρ_3 may not be reflected in VES soundings. In later case the curve appears similar to the ascending type two-layer cases. It is not uncommon that A-type curves are at times difficult to interpret and interpretations may be erroneous.

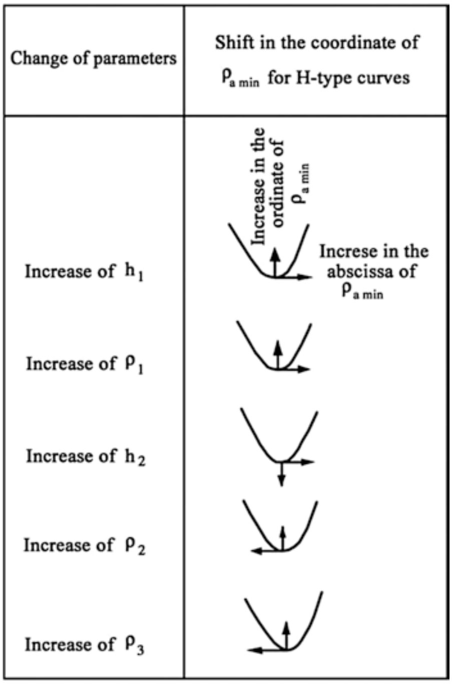

Fig. 1 Relationship between the various layer parameters in H-type VES curves

2.4.2 Field Examples

It is necessary to examine the type of curves obtained over a survey area. This in many cases will provide the characteristics of the area and also the possible reasons for the changes in the nature of curves in the entire region. This may be carried out by plotting the sounding station in the area. The area is then divided on the basis of similarity of curve types. This will help tentatively to transform the geoelectric information to possible geological setup (Bhattacharya and Shalivahan 2016).

In some VES stations, four-layer curves of HK-type ($\rho_1 > \rho_2 < \rho_3 > \rho_4$) may be obtained, whereas in some stations, the VES curves may show three- and two-layer, respectively, as the topmost layer has been eroded at one station and top two layers have been eroded at some of the other stations. Thus, the curve type changes in the area from four-layer to two-layer. The area, on the basis of VES curves, then can be divided into three sectors: one part consisting of four-layer curves of HK-type, another part consisting of three-layer cases of K-type ($\rho_{\downarrow}2 < \rho_{\downarrow}3 > \rho_{\downarrow}(4)$), and the remaining area showing two-layer curves of descending type ($\rho_3 > \rho_4$). It can then be interpreted that the area containing the HK-type curves contains sand as the top layer which has been eroded in an adjoining zone where three-layer VES curves are encountered with clay as top layer. In the subsequent part, the clay layer further gets eroded, and top layer is the limestone formation. The qualitative interpretation does divide the area into three distinct lithological zones.

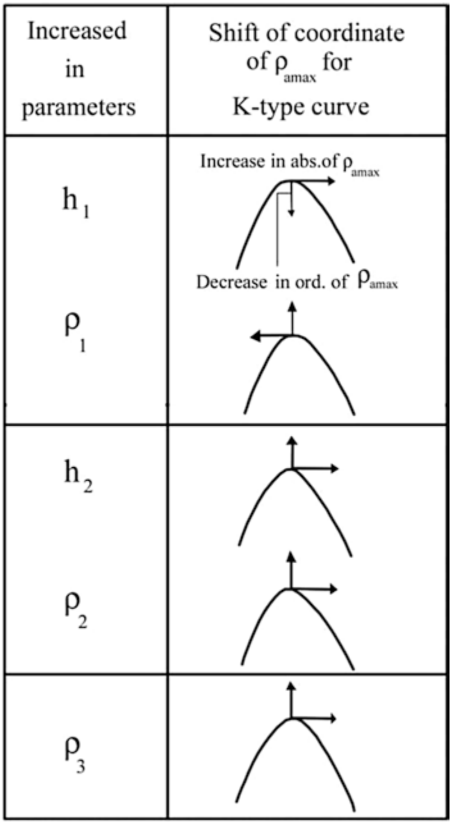

Fig. 2 Relationship between the various layer parameters in K-type VES curves

2.5 Groundwater Exploration in Hard Rock Areas and Drought-Prone Districts of Nawapara and Kalahandi, Odisha, India

Systematic VES was carried out by Central Ground Water Board (CGWB), India, covering part of Nawapara and Kalahandi districts of Odisha, India, with stations separated from each other varying from 1 to 3 km (Adhikari 2001). In this paper the results of one of the areas will be discussed. Lineament density contour map was prepared by dividing the entire area in the pixel of 25 km^2 and lineament density calculated in the unit of km/25 km^2.

VES investigations showed that in general four types of sounding curves, viz., A, AA, H, and HA type, have been observed in this area. VES was also carried out in the vicinity of available boreholes in the area which helped in comparing the geo-electric and geologic sections (Fig. 3). In most of the soundings, a layer of resistivity of 12–140 Ω-m has been detected just below the top soil corresponding to highly weathered and weathered rocks. Below this broad weathered mantle, a series of fracture zones exist within the massive formation at different depths. The effect of

Fig. 3 Fence diagram showing geoelectric layers of Nawapara districts

these fractures within the massive formation provides a resistivity range less than that of the massive rock. The resistivity range in VES measurements near the boreholes just below the weathered mantle varies within 250–390 Ω-m range and includes these fractured zones. The presence of weathering in geologic section below the top soil cover is reflected in the entire geoelectric sections. Fence diagram drawn for the region is presented below (Adhikari 2001; Bhattacharya and Shalivahan 2016).

2.5.1 Groundwater Management Plan of the Hard Rock Area

Results of VES survey along with other relevant features like pre- and post-monsoon depth to water table, short- and long-term water table fluctuation, lineament density, pre- and post-monsoon flow direction and lineament density axes, spatial distribution of total dissolved solids, total hardness, chloride, fluoride, chemical sensitivity maps, etc. have been collated in this area for groundwater management plan. This served, in general, as a broad guideline for groundwater management plan for hard rock areas.

The following steps were taken to enhance the availability of groundwater resources:

- Demarcating groundwater potential zones
- Reducing runoff and thereby increase the storage of water in the aquifer by artificial recharge
- Construction of efficient water-yielding spot sources in different potential zones

2.5.2 Groundwater Potential Zones

The technique of thematic overlays using several sensitivity maps has been used to demarcate the groundwater potential zones (Adhikari 2001; Bhattacharya and Shalivahan 2016).

The major components of this analysis are as follows:

- Depth to massive rock (DMR)
- Aquifer transmissivity (AT)
- Lineament density (LD)
- Chemical quality (CQ)
- Depth to water table (DWT)
- Post-monsoon long-term water table fluctuation (PLWTF)

Each of these components has a number of factors of influence which are visualized in a decision tree (Fig. 4) by breaking up the above components into subcategories to measurable parameter or indicator shown in the decision tree discussed below. The combined effect of various subcategories of each component has been categorized into high-, medium-, and low-potential zones by overlay procedure.

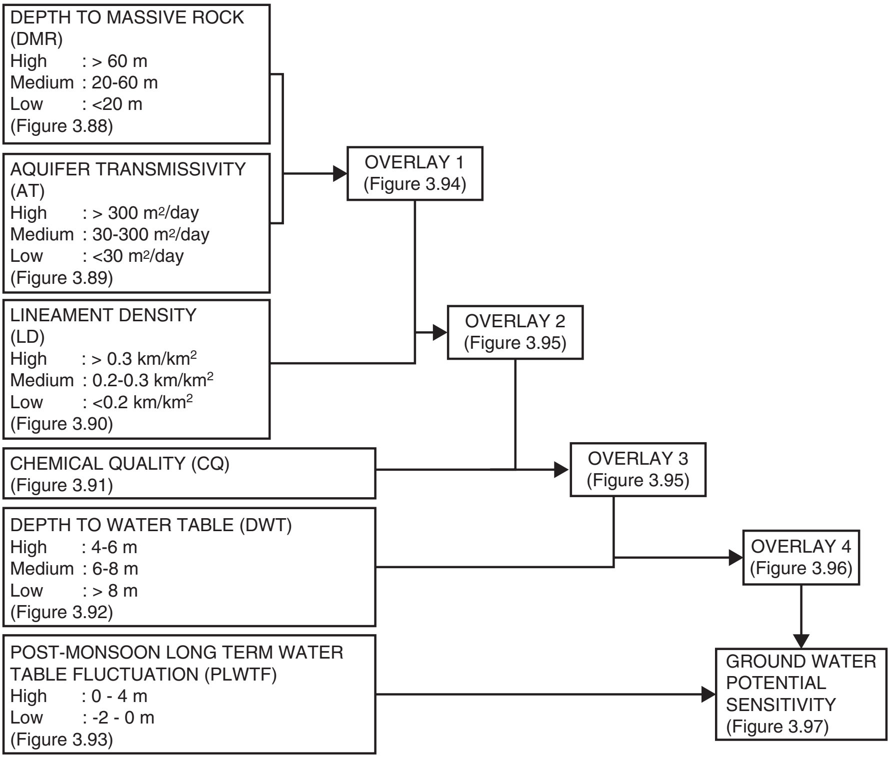

Fig. 4 Decision tree to demarcate groundwater potential sensitivity

Decision tree methodology used for demarcating groundwater potential sensitivity in the hard rock terrain of Kalahandi district, Odisha, India (Fig. 4), is in principle also applicable, in general, for hard rock terrain.

To demarcate the areas where artificial recharge is feasible in the study area, the technique of thematic overlays has again been used. The thematic maps that have been utilized are as follows:

- Depth to water table (DWT) of April, 1997
- Near-surface permeable zone sensitivity (NSPZ)
- Depth of weathered residuum sensitivity (DWR)
- Aquifer transmissivity sensitivity (AT)

Based on the above themes, the areas where groundwater can be artificially recharged have been demarcated. The decision tree for this overlay is shown Fig. 5.

The decision tree concept provided complete groundwater management plan for the area.

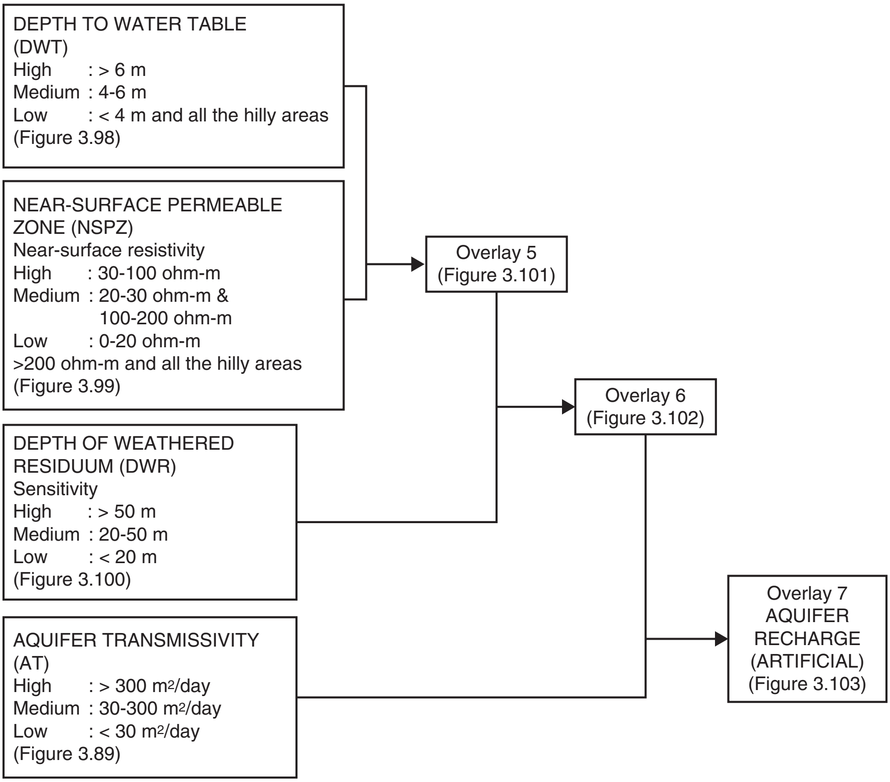

Fig. 5 Decision tree to demarcate artificial recharge area

2.6 2D Resistivity Imaging

The multielectrode resistivity technique uses a multi-core cable connecting large number of electrode, 24 or its multiple (Bhattacharya and Shalivahan 2016) placed on the ground at a fixed spacing, every 5 m, for instance. In this type of measurement, the measuring device, that is, resistivity meter, contains relays which ensure the switching of preselected electrodes according to a sequence of readings predefined and stored in an internal memory of the device. The various combinations of transmitting (*A*, *B*) and receiving (*M*, *N*) pairs of electrodes construct the pseudosection, that is, a combination of profiling and sounding data set, with depth of investigation decided by the total length of the cable. Various types of electrode setups are used, such as Wenner, Schlumberger, Dipole-Dipole, Wenner-Schlumberger, Pole-Pole, Pole-Dipole arrays, etc. The measuring device generally consists of internal microprocessor-controlled circuit and electronic switching system to automatically select the relevant four electrodes of the array decided for the survey.

2.6.1 2D Electrical Imaging for Delineation of Aquifers in Water Scarcity Hard Rock Terrain of Deccan Trap in Central India

Ratnakumari et al. (2012) carried out 2D electrical imaging for delineation of aquifers in water-scarce hard rock terrain of Deccan trap in Central India. In this area, the top layer is generally alluvial soil overlying weathered mantle and varying degree of fractured basalt. Volcanic lava flows lie below the weathered mantle. The inter-trappeans are sandwiched between the lava flows and are sedimentary in nature. The lava flows consist of upper vesicular unit which along with inter-trappean beds are potential aquifer region in many parts of Deccan trap region.

The resistivity surveys in and around this region broadly provide the following range of resistivity values for the main lithological units of the area – alluvial, black cotton soil, 5–15 Ω-m; water-saturated weathered or fractured or vesicular lava, 40–70 Ω-m; massive basalt, >70 Ω-m. Several profiles were measured in this area for 2D resistivity imaging (Ratnakumari et al. 2012; Bhattacharya and Shalivahan 2016).

Two-dimensional resistivity imaging models show the existence of 10–12-m-thick layer of alluvium and weathered formation. Moderately fractured basalt of 40–70 Ω-m underlies the weathered zone. Below the fractured zone lies the massive basalt of more than 70 Ω-m resistivity. A fractured zone at 300 m distance has mapped low resistivity zone of <20 Ω-m at a depth of 35 m which widen at depth. The lithological units obtained from the exploratory borehole at this location agree well with interpreted lithology from the resistivity data. The borehole intercepted the aquifer at a depth of 35 m, and yield has been 15,900 l per hour (lph) or 4200 gallons per hour (gph).

2.7 *Self-Potential Method*

Self-potential (SP) measurements are also made in areas where the need is for a large-scale hydroelectric installation, e.g., in the Arazdayan steppe in Armenia. In this problem the requirement was to lower the groundwater level whose higher level was due to the presence of saline soil. The lowering of groundwater was executed with the help of relatively deeper wells accompanied by series of small piezometers. A positive SP anomaly formed above the cone of depression was observed in the measurement along a profile passing through pumping well. The shape of the variation of water table due to pumping and the corresponding SP profile shows overwhelmingly a mirror image relationship with the cone of depression. The maximum potential is observed directly over the well and corresponds to the maximum depression of the water table due to pumping. The SP profile is more representative of the variation of groundwater table in the neighborhood of the pumping station than at a far distance. It shows the scope of detecting groundwater level using SP method and thereby substantially reducing the number of piezometers.

2.8 Determination of Velocity and Flow of Groundwater Using Mise-A-La-Masse Technique

Mise-a-la-masse method may be used for hydrogeological investigations for finding flow of groundwater (Bhattacharya and Shalivahan 2016). This requires presence of more than one borehole in the area of investigation. In one of the boreholes, the indicator source is inserted and the other serves as observation well. The velocity and direction of flow of groundwater are determined from the observation well.

In the borehole intersecting the aquifer, a porous bag containing easily soluble salt like sodium chloride or ammonium chloride is inserted. The groundwater dissolving the salt will have a flux in the direction of flow of groundwater. The groundwater with salt halo due to the additional mineral content in it will be electrically more conducting, and its distribution in the aquifer zone can be traced by mise-a-la-masse method. One of the current electrodes is inserted in the borehole intersecting the aquifer, and the other is placed on the ground surface far away from the observation zone, i.e., theoretically placed at infinity. Potentials are measured in the neighborhood of the borehole that has been excited by the current electrode. The equipotential contours on the ground surface around the borehole before charging of the borehole would be circular with center as the borehole for the horizontal and homogeneous aquifer which is normally the case. Equipotential contours drawn sometime after charging will show change in shape – from circular to oval elongated in the direction of flow of groundwater for the simple reason that the equipotential surfaces around the salt aureole would be similar to the aureole and equipotential contours on the ground surface give the projection of salt aureole only.

With increasing time the salt aureole increases. The front edge of the aureole moves with the velocity of the groundwater movement, and rear edge of the aureole is closer to the borehole. Correspondingly the position of the centers of the salt aureole and along with it the centers of the equipotential lines changes. Thus, it can be said that the shift of these centers coincides with the direction of flow of groundwater, since the front edge of the aureole moves with the speed of groundwater flow and the rear edge is stationary, then the rate of change of shift in the centers of equipotential lines will be equal to half of the flow velocity, i.e., $v_f = 2\ v_s$, where v_f is the velocity of flow of water and v_s is the rate of change of shift of the centers of the equipotential contours on the surface of the earth. The value of v↓f may be determined from the shift of the equipotential contours drawn on the surface of the earth.

The energizing current electrode in this case is the combination of positive current electrode lowered with the help of a cable and inserted into the porous salt bag charging the borehole with salt. The diameter of the bag is less than the diameter of the borehole at the aquifer region, and it is 0.5–1.0 m long. The lower end of the bag is attached to a weight so that the entire system can be lowered smoothly. The negative current electrode B is placed on the ground surface at a distance 10–15 times the depth to the aquifer.

The receiver consists of two nonpolarizable electrodes M and N connected to the instrument setup. Measurements of potentials are made either for a constant current or normalized for unit current. Generally measurements are made on a set of radial lines with the location of the borehole with indicator source as the center of the radial profiles. The number of radial lines depends on the nature of detail required. Normally it varies between four and eight lines. The stations are at 5–10 m interval. It is preferable to keep the measuring setup near the borehole. The length of the profiles of measurements on either side from the borehole is about 2 and two to three times the depth of the aquifer in case of uncased and cased (with strainer) boreholes, respectively. The measurements should be done in all the profiles in a circular fashion, i.e., at all the stations on the radial profiles with equal distances from the borehole. It is advisable to repeat these circular modes of measurements in quick succession. The greater the time taken for the successive equipotential contours, the slower the flow of groundwater movement. It varies between 1 and 10 h.

3 Conclusions

Applications of geophysical methods in hydrological problems have been well established. The geophysical maps provide the spatial picture of the subsurface. The models provide the subsurface image providing recommendations for a given hydrological problem.

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Role of Remote Sensing and GIS in Integrated Water Resources Management (IWRM)

S. K. Sharma

Abstract Remote sensing and geographic information system have long been recognized as versatile tools, to addressing sustainability issues connected with the development and management of groundwater. Applications of these in targeting groundwater in India have also come of age in as much as it has contributed to production and use of satellite imagery-based groundwater prospect maps. These maps, popularly known as hydro-geomorphological maps, are being used in managing drinking water sources and water supply schemes. This paper outlines the current state of the art of aquifer detection keys of use in setting up drinking water supply bore wells, rainwater harvesting, and groundwater recharging structures toward providing sustainability to drinking water sources. This also reviews the role of remote sensing in the Government of India that sponsored ongoing integrated watershed development programs in various states. The paper also focuses on the general lack of skill on the part of planners and application engineers and scientists in the fruitful application and use of imagery-driven maps in water supply schemes. It may be worthy of its mention that images draped over digital elevation models provide exclusive imagery-driven products of use in groundwater and watershed development programs in various states of India. The land use-land cover, soil, and automated drainage delineations provide instant input to hydrologic models in estimating water and silt yield. The need to develop skill of engineers and planners engaged in the use of satellite imagery data and hydro-geomorphological maps to developing groundwater-based water supplies and integrated water management programs is an inescapable necessity for the successful implementation of water supply- and watershed-related schemes and programs in India. In recognition of this need, some recent training workshops have encouraged the use of satellite-based techniques in locating drinking water sources and strengthening of recharge systems in India.

Keywords Remote sensing · Geography information system · Groundwater · Hydro-geomorphological maps · Integrated water resources management

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S. P. S. Ray (ed.), *Ground Water Development - Issues and Sustainable Solutions*, https://doi.org/10.1007/978-981-13-1771-2_13

Abbreviations

ASTER	Advanced spaceborne thermal emission and reflectance radiometer
CGWB	Central Ground Water Board
CIR	Color infrared imagery
DEM	Digital elevation model
FCC	False color composite
GIS	Geographic information system
GOI	Govt. of India
GSI	Geological survey of India
HGM	Hydro-geomorphological map
IRS	Indian remote sensing satellite
IWF	India Water Foundation
IWRM	Integrated water resources management
LISS	Linear imaging self-scanning system
Lpm	Liters per minute
NRDWS	National rural deportment of water supply
NRSA	National Remote Sensing Agency
PHED	Public Health and Engineering Department
RS	Remote sensing
SRTM	Shuttle Radar Topographic Mission
TIR	Thermal infrared imagery
TM	Thematic mapper

1 Introduction

Groundwater plays a crucial role in national economic development and social upgradation. The holistic development and management of water resources as well as adoption of conservation and protection measures are of paramount importance for sustainability of the resources. This requires application of new techniques of remote sensing, geographic information system (GIS), and development of interactive databases on well inventory to collect, integrate, analyze, and display multilayered information which help in improving the decision-making capacity. Application of remote sensing combined with geomorphic, hydrologic, and hydrogeological inputs provides the best tool for development and management of groundwater resources.

Satellite images of different resolutions are used in targeting sites as potential groundwater areas, identification of waterlogging and soil salinity in canal command areas, identification of water-stressed zones as groundwater overexploited zones, and demarcation of sites for conservation of rainwater and recharge of aquifers.

2 Application of Remote Sensing in Groundwater Exploration

The science of remote sensing depends upon the wavelength of electromagnetic radiation. The groundwater aquifers are not detected directly through aerial photos or satellite imageries. An expert hydrogeologist, however, infers indirectly the subsurface hydrogeological conditions based on various key detection indicators. The technique enables hydrogeologists to view large areas instantly to gain prospective views, which, through ground surveys alone, are not achievable efficiently.

2.1 Feature Identification with Satellite Images

Various remote sensing methods in groundwater investigation are grouped into two categories, viz., (a) regional and (b) local or detailed methods. Regional method utilizes satellite images and aerial mosaic for hydrogeological reconnaissance survey, and local methods utilize large-scale aerial photographs and high-resolution imageries, along with ground truth to verify the validity of the interpretations. Temporal imagery coverage is generally selected for obtaining information on changes in geomorphic features, vegetation and water-stressed vegetation zones, and waterlogged areas. The different types of features identified from satellite data for use in deciphering groundwater occurrence and availability are given in Table 1.

Table. 1 Imagery-based feature identification

Feature detection
Mapping of river morphology, tracing of drainage pattern, types, and textures, surface water bodies, river terraces, alluvial fans, delta plains, soil salinity, etc.
Enhancement of lineaments, dykes, other structural features of hard rock terrains
Mapping of soil moisture and waterlogged areas, locating of artificial recharge sites and recharge structures, etc.
Water-stressed vegetation, groundwater overexploited areas, vegetation anomalies, and aquifer vulnerable area
Artificial recharge sites; mapping of watersheds, landfill sites, urban drainage system; mapping of various land surfaces for capturing of runoff water; calculation of roof areas for rooftop rainwater harvesting; etc.

2.2 Scope of Satellite Images in Integrated Water Resources Management

Multi-temporal satellite data helps in effective monitoring of water resources and locating areas for artificial recharge, conjunctive use, and watershed development. Major applications of satellite images in vogue in India include:

1. Planning of artificial groundwater recharge projects
2. Demarcation of macro- and micro-watersheds and watershed development
3. Planning of rooftop rainwater harvesting in urban cities
4. Site selection for landfill and waste disposal
5. Mapping of groundwater vulnerable/risk zones
6. Identification of permanent and temporary springs in hill regions
7. Monitoring of land use and land cover input to groundwater modeling
8. Monitoring of urban land use
9. Demarcation of economic zone areas and industrial sites
10. Monitoring of soil salinity and waterlogged areas
11. Assessment of groundwater-irrigated areas in different seasons
12. Assessment of the impact on vegetation, soil moisture due to depletion of water levels in groundwater overexploited areas
13. Mapping freshwater discharge to seabeds
14. Mapping of weathering crusts over hard rock areas

3 Characterizing Groundwater with Satellite and Aerial Imagery

3.1 Indices for Analysis and Interpretation

Three broad indices of use in analysis and interpretation of images in integrated management of water resources are described:

3.1.1 Indices of Geomorphology

Alluvial area detection keys include mapping of riverbed forms, alluvial terraces, and alluvial fans, meandering braided-stream belts, and losing and gaining reaches in streams, badland regions, previous river courses, channel fills, and backswamp areas. Indices of geomorphology for detection of aquifers over hard rock regions include mapping of vertical geological barriers and zones of shallow and deep weathering crusts and mapping of pediments, pediment slopes, and buried pediments.

3.1.2 Indices of Geological Structure

Mapping of geology and geological structure of an area has a great bearing on the shape and distribution of aquifers. Mapping of fractured rock aquifers includes orientations, frequency, and density of fractures and lineaments as well as joint planes and orientation of dykes in relation to the country rock. It is pertinent to identify fractures that run parallel to the country rock and those that run transverse to it. The underlying purpose is to differentiate open fractures and close fractures. Fractures enlarged by drainage courses depicting anomalous stream flares could be open fractures transmitting reasonable recharge to subterranean regions.

3.1.3 Geobotanical Indices

Mapping of the vegetation anomalies and types of vegetation along with the study of their affinity to different rock types has great bearing on the occurrence of groundwater. In high rainfall areas, it is always necessary to map vegetation as well as land cover classes for superimposing on morphological maps in making deductions on influences of vegetation on hydrologic processes contributing to groundwater buildup in an area. Mapping density of vegetation stands in forested watersheds offers opportunity for estimating the extent of interception losses of rainfall contribution to groundwater. Vegetation clusters have affinity for the shallow fresh groundwater occurring as springs and seepages in the inland areas and along stream valleys as well as with saline groundwater in coastal regions in India.

3.2 Detection of Aquifers in Alluvial and Hard Rock Environment

Presence and occurrence of groundwater depend upon the factor of porosity in rocks, on the degree of weathering, and on the intensity and nature of fractures and lineaments. The alluvial forms which possess good potential of groundwater are abandoned river channels, meander scrolls, migrating channels, flood plain deposits, sand dunes, and perennial streams.

In hard rock areas, groundwater occurrence and movement are largely controlled by the presence of fractures, joints, and lineaments. Groundwater occurrence in limestone rocks is entirely a function of secondary permeability and solution channels. In basaltic terrains, groundwater occurrence depends upon the presence of open vesicles and weathered zones. Identification of intra-trappean beds, drainage anomaly, and vegetation alignment along certain zones are good indicators of aquifers. The igneous and metamorphic rock terrains present a real challenge for hydrogeologists to search for sites ideal for groundwater development.

3.3 Criteria to Locate Bore Wells with the Use of Satellite Images

Prospecting for groundwater with the use of satellite images has been described by various research workers. Based on the experience of using satellite images in India, several criteria to locate exploratory and production tube wells in different geologic-geomorphic environment are given below:

1. *Geomorphological maps and forms*
   (a) Mapping of pediment, pediment slopes, and buried pediment in hard rock areas
   (b) Mapping of weathering crusts
   (c) Mapping of flood plain, valley fill, intermountain hollows, palaeo-drainage, and coastal plain aquifers
   (d) Mapping of watersheds and drainage network
   (e) Developing digital elevation model (DEM) with the use of SRTM, ASTER, and other types of images and topography contour maps
2. *Lineament fracture and mapping*
   (a) Mapping basement rock fractures
   (b) Mapping dykes as vertical geological barriers
   (c) Demarcation of lineaments and lineament-controlled stream segments
   (d) Identification of open and close fractures in relation to drainage type and pattern
   (e) Mapping of drainage pattern, drainage, density/frequency, and infiltration numbers and classifying the watersheds by permeability classes
   (f) Mapping of lineament and fracture densities
3. *Selective geophysical prospection*
   (a) Selective geophysical surveys with the use of different methods are normally warranted.
4. *Field verification test*
   (a) Test-well drilling and borehole logging
   (b) Well yield tests

3.4 Remote Sensing Criteria to Demarcate Sites for Groundwater Recharge

1. *Mapping of land facets*
   (a) Mapping of weathered zones

(b) Delineation of pediments and buried pediment areas
(c) Buried channel and flood-prone aquifer zones

2. *Compiling drainage network*

(a) Tracing of micro-watersheds and drainage divides
(b) Demarcation of change in course of drainage patterns
(c) Perennial and ephemeral streams
(d) Mapping of surface waterbodies
(e) Mapping changes in water spread areas of water bodies
(f) Evaluating area of various magnitudes of drainage density and drainage frequency
(g) Assigning infiltration numbers to micro-watersheds and classifying watersheds into permeability classes
(h) Mapping of wetlands and lakes
(i) Mapping catchment of lakes and ponds

3. *GIS overlays*

(a) Draping of different geomorphological layers over DEMs
(b) Superimposition of groundwater table contour maps
(c) Superimposition of groundwater flowlines
(d) Identification of runoff-producing areas and recharge zones
(e) Demarcation of sites for percolation tanks and check dams for recharge of groundwater

4. Groundwater recharge prospects
For prospecting of groundwater recharge locations, the techniques include the following:

(a) Borehole yield maps and land use classes
(b) Surface structure feature identification, viz., fractures and faults
(c) Drainage network area assessment
(d) Estimating runoff water for its addition to aquifers
(e) Identification of suitable locations for recharge

3.5 Applicability of Drainage and Lineament Density Factor

Both drainage network and lineament/fractures control the occurrence and availability of groundwater in an area. This procedure is in vogue for the exploration of groundwater in India.

3.6 Drainage Network and Lineament Factor

Drainage density and drainage frequency have bearing on groundwater occurrence. The drainage density in an area signifies presence of relatively impervious areas in drainage catchment. The drainage density is thus directly proportional to runoff and inversely proportional to rock permeability. High-density drainage signifies low-permeability surface areas. The drainage density and frequency together help categorize areas into permeability classes. The numbers of drainage density and frequency when multiplied together generate a number called infiltration number. Infiltration numbers help classify a watershed into permeable and non-permeable watershed areas.

Similarly the lineament density in an area has greater control on occurrence of groundwater. The high-density factor signifies higher infiltration possibilities. Multiple fractures intercepting at a topographic low area are carriers of water to underlying saturated zone.

Both factors have roles in locating water supply bore wells. The drainage density factor helps to locate high runoff-producing areas to be trapped behind check dams. The lineament and fracture density factors represent sites ideal for locating high yielding bore wells.

4 Case Applications of Bore Well Sitting and Water Management

4.1 Borehole Siting

Two case applications founded by ground truth work are described.

4.1.1 Anantpur Area, Andhra Pradesh

The study area of Anantpur in Andhra Pradesh is a crystalline hard rock belt. It is a part of the Chitravati and Madduleru rivers sub-basins of the Pennar river basin. The false color composite image of area is at Fig. 1. The drainage in the area is structurally controlled. Multiband satellite digital data were utilized to trace fractures, drainage, and basic dykes. Areas of structurally controlled drainage were demarcated, and sites were selected on the basis of lineament intersection in valley areas. The sites were controlled by field verifications.

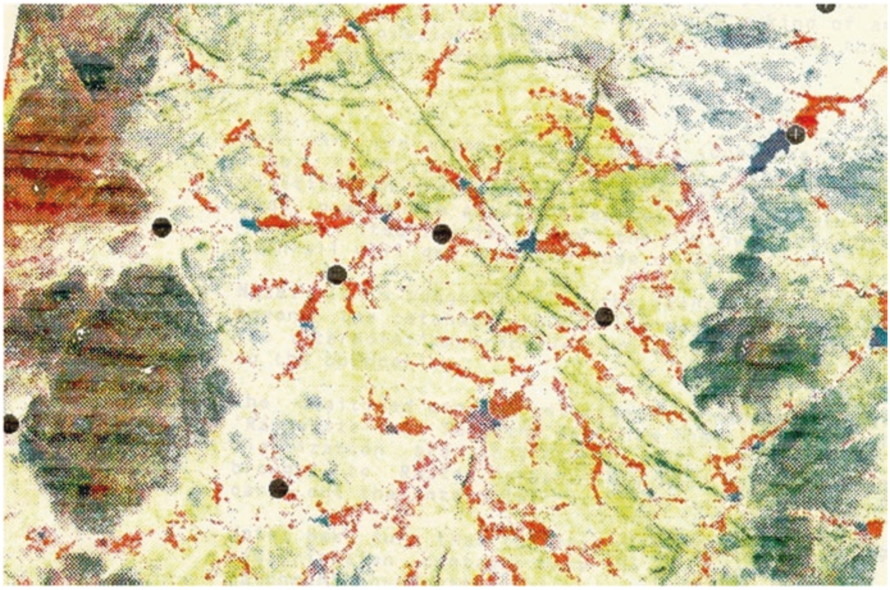

Fig. 1 False color composite of IRS 1A-LISS II image of Anantpur, Andhra Pradesh

4.1.2 Kandaria Catchment, Mayurbhanj, Orissa

Kandaria catchment in Mayurbhanj district of Orissa is also the area occupied by hard rocks. There is practically no irrigation facility in the area. The catchment was selected for detailed study with the twin objectives of (1) understanding the recharge phenomenon in hard rock area and (2) studying the well yield in relation to hydrogeological parameters. The lineament and fracture mapping and land use classification were done by digital image processing using IRS imagery data. High-pass filters were applied that suppressed the low-frequency component and thereby enhanced the edges in the image. The basic dykes identified were having two main trends, viz., NE-SW and E-W. The tube well yield data were utilized to establish relationship between lineament vis-à-vis well yield. Only well yield of those tube wells was considered which were within a distance of less than 1 km from the lineament. The yield range was processed as per lineament trend group. The analysis revealed that the average yield is higher for wells located near lineament trending NE-SW and E-W. About 15% of the total wells analyzed showed yield more than 200–250 litres per minute (lpm). Ten percent of wells had alignment with NE-SW trending lineament. It was thus inferred that fractures aligned in NE-SW are favorable for occurrence of groundwater.

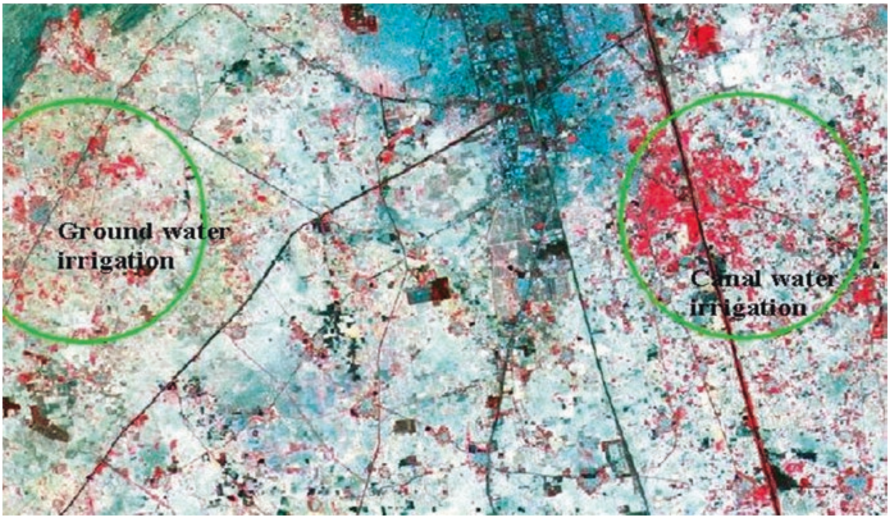

Fig. 2 IRS LISS II false color composite image indicating areas irrigated through groundwater and canal water in Faridabad district, Haryana

4.2 Mapping of Groundwater-Irrigated Cropland in Faridabad District, Haryana

Satellite imagery was processed (Fig. 2), and digital samples of wheat crop irrigated through groundwater, canal water, and industrial drain were picked up from the Faridabad area image. It was found in feature space plotting that wheat plants irrigated through groundwater show higher reflectance in red and infrared bands, whereas wheat plants irrigated with water of industrial effluent water drain had very low reflectance. Separation of these classes was established in multispectral feature space. Wheat crops irrigated through groundwater and canal water showed less separation, whereas waterlogged crops and crops irrigated with drain water showed low reflectance in red and infrared bands. Spectrometer was also utilized to note the reflectance of wheat plants irrigated with different sources of water, and the observation matched with satellite data.

4.3 Detection and Monitoring of Waterlogged Areas of Kosi Canal Command, Bihar

The irrigated lands in canal command areas are subjected to degradation due to waterlogging. Waterlogging conditions arise in areas, where recharge of groundwater regime is more than groundwater discharge. Landsat 5 TM digital data of December 1994 and May 1995 were utilized to map the extent of waterlogging due

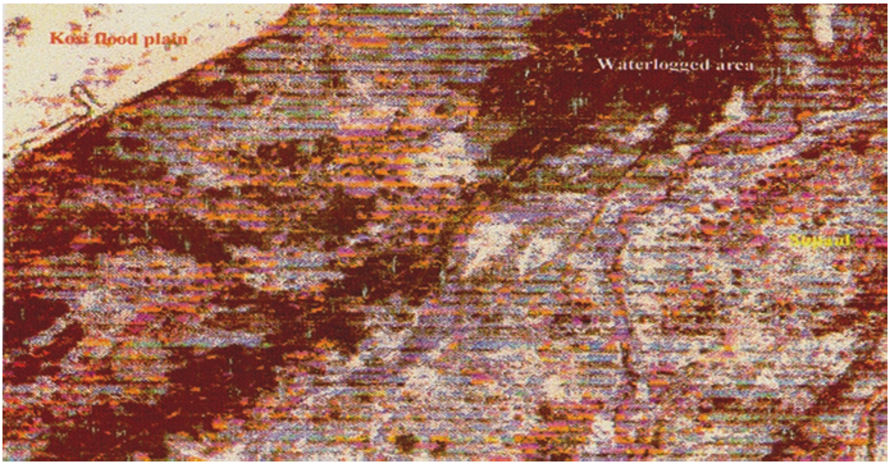

Fig. 3 Landsat TM image showing waterlogged areas along the canal in Supaul district, Bihar

to natural rise in groundwater table in Supaul district, Bihar, falling under Kosi canal command (Fig. 3). Areas of surface water bodies and areas of high moisture were selected for sample values, and an average of 50 samples was plotted for each TM band. The average DN value of high soil moisture area indicating waterlogging was found much higher than surface water bodies in bands 4, 5, and 7. The waterlogged areas were discriminated from the surface water bodies in feature space by plotting of TM band 4 vs 5 and band 5 vs 7, and method of supervised classification using nearest neighborhood method was applied. The comparison of images of the month of May with those of December indicated that waterlogged areas had increased to about double from December 1994 to May 1995 image, due to seepage from the unlined canal distributaries. The surface water bodies had shrunk in summer due to evapotranspiration. The water level data plotted on the classified image confirmed the result. The studies indicated that Landsat TM bands 4, 5, and 7 are useful band information to discriminate groundwater and waterlogged areas from stagnant pools of surface water bodies. The waterlogging in the area is due to shallow groundwater levels which increase in extent during running of unlined distributaries of Kosi canal command.

5 Imagery-Based Hydro-geomorphological Maps

Hydro-geomorphological maps are GIS-based maps of aquifer productivity. In the interpretation of such maps, DEM, recharge, drainage density, lineament density, and geomorphic features of alluvial, coastal, desert, and glacial environment are considered.

NRSA, India, has prepared remote sensing and GIS-based hydro-geomorphological maps (HGMS) of most states of India for use in locating water supply bore wells as well as putting up groundwater sustainability recharging structures. The first-generation country geo-hydrological map was prepared by GSI on 1:2 million scale in 1960s. The second-generation country hydrogeological map on 1:5 million scale was published by the Central Ground Water Board (CGWB) in 1976. The third-generation imagery-based HGMS of the states have been produced by NRSA for use by states. The CGWB 1:2 million scale map published in 2002 is a classic example of relatively large-scale map of immense use. The users in state government departments, responsible for drinking water supply and watershed development and management works, have been making little use of HGMS, largely because of the lack of knowledge and experience to understand and interpret the content and details of such maps for the purpose for which these were constructed. It, therefore, transpires that the state-level Public Health and Engineering Department (PHED)/Panchayat Raj functionaries engaged in water supply and watershed development works be given proper training in the interpretation and use of these maps. Toward this end the Ministry of Drinking Water and Sanitation (GOI) organized a structured program through India Water Foundation (IWF) whereby PHED water supply department personnels engaged in source location and source sustainability was imparted at training in 20 states in the country on the role of HGM in groundwater prospection. The program was well received. The writer of this article had the privilege of being principal trainer on behalf of Indian water foundation to impart training. The feedback of this training was in good measure.

6 CIR Imagery and Water Bodies

In rural areas, village ponds are a source of water supply for nondrinking water purposes. The CIR image of the area of Indian peninsular region (Chittoor, Andhra Pradesh state) is at Fig. 4. The ponds have varied water spread depending upon catchment runoff collected in it. The farmers in its down slope area have done irrigation using pond water. The area downstream of such ponds also gets recharged and leads to improvement in groundwater table in the area. Such ponds when driven with borehole shaft serve as ideal environment to accelerate recharge to underlying aquifer in the area.

7 Lakes and Wetlands

There are large number of wetlands and lakes in various states in India. Lots of imagery-based data have been generated for such water features. There is yet no report on lakes and groundwater interaction studies in India. The students of its interest would surely like to make use of temporal imagery in deciphering lakes and

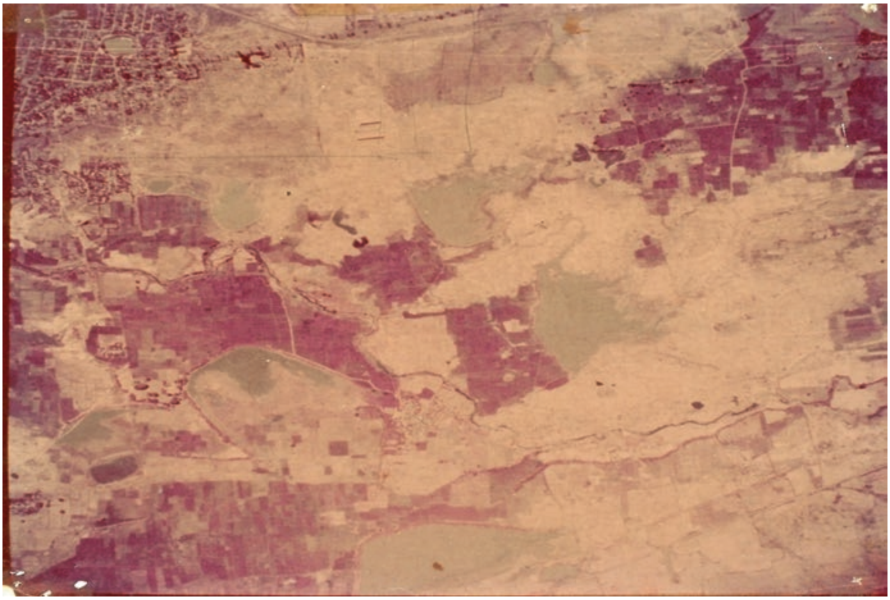

Fig. 4 CIR imagery of Chittoor district, Andhra Pradesh

groundwater interrelationship connected with recharge and discharge of groundwater. Water bodies when draped with groundwater table of the area can enable deductions about conditions of recharge and discharge to help plan local schemes on recharging and developing groundwater-based water supplies.

8 Use of Remote Sensing in Hydrologic Modeling

The application and use of RS and GIS in groundwater studies have been clearly described by Meijrink (1994). Various types of data generated with the use of remote sensing and GIS layers for use in hydrologic modeling in India include the following:

- Stream drainage network
- Canal network
- Recharge zones
- Digital terrain models
- 3-D subsurface aquifer layers
- Land use-land cover layer
- Soil maps

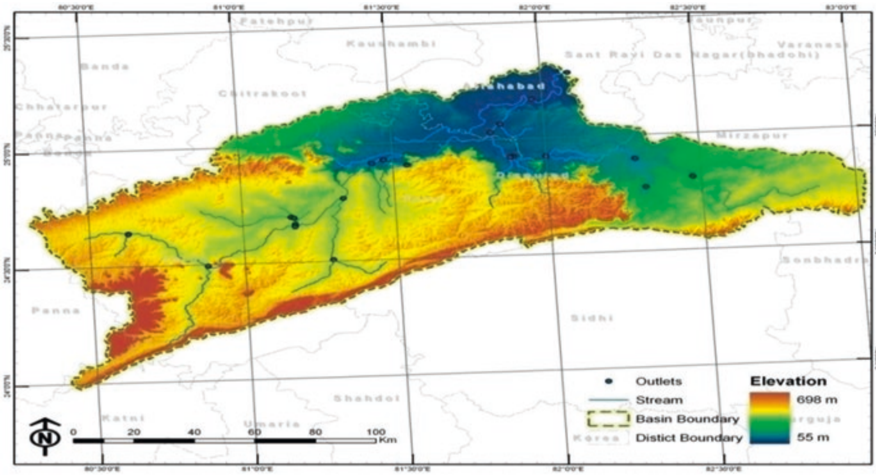

Fig. 5 Digital elevation model of Tons basin

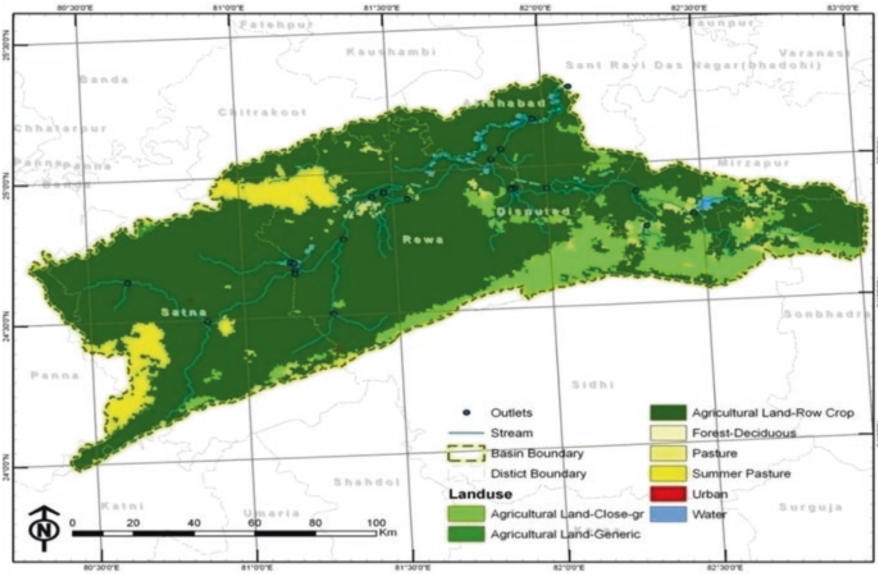

Fig. 6 Land use for Tons basin

GIS layers have proven utility in basin-level hydrologic modeling. GIS-based DEM and land use for Tons river of Madhya Pradesh are shown as example in Figs. 5 and 6.

9 Thermal Imagery in Locating Offshore Freshwater Discharge to Seabeds

It is worth mentioning that in New Mexico, hydrogeologists used thermal infrared (TIR) images and traced water collected in Rocky Mountains all the way to basins in New Mexico about 150 km away. The method used phenomena of temperature contrast in satellite images as anomalous dark spots. Exploring and tapping freshwater discharge to seabed off the coast of Tamil Nadu through Cuddalore sandstone aquifer are worthy of an experiment. The use of airborne remote sensing for groundwater as applied by Chase (1969) together with high-resolution satellite images can be of immense use in such studies.

10 Mapping Trans-boundary Aquifers

A satellite image of the Himalayan area is shown in Fig. 7. Such images provide synoptic view of recharge and discharge areas as well as of streams and rivers draining over the underlying aquifers. The imagery serves as basic maps for identification of surficial aquifer characteristics and overlying surface water regime, contributing to groundwater recharge. Riparian states should work in tandem to understand the utility of such images to take benefits of the actions and impacts of each other's activities on natural groundwater systems. The sharing of information of trans-boundary aquifer system would help increase cooperation.

11 Satellite Images and Derivative Products of Use in Groundwater Prospecting

It is worthwhile listing below the RS-GIS-derived optimal products of utility in groundwater and hydrologic prospection.

- Thermal infrared imagery and FCCs
- Hydro-geomorphological and special purpose morpho-structural maps
- Multi-data classification of land use and land cover
- Drainage network
- SRTM- and ASTER-based digital elevation model (DEMs)
- Drainage density and rock permeability classification map for the spatial distribution and delineation of runoff zones
- Combination of remote sensing and exogenous data

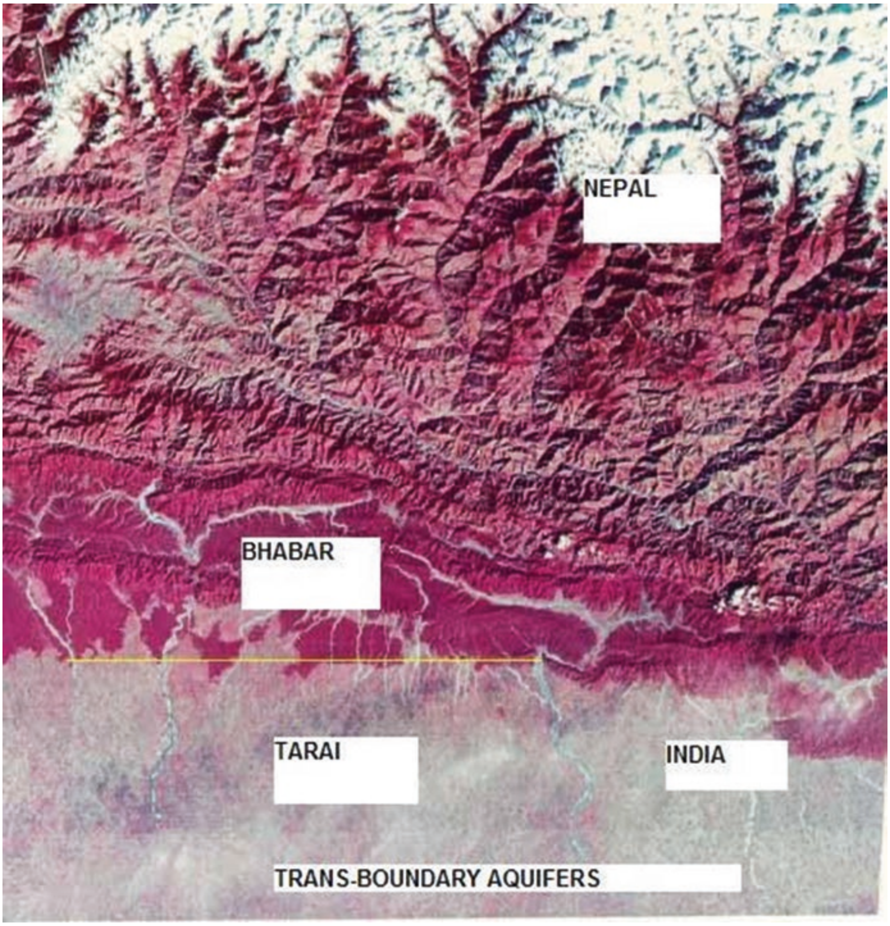

Fig. 7 FCC of trans-boundary aquifer system: the Himalayan foothill region

12 Conclusion

It may logically be concluded that the utility of RS and GIS lies in enabling hydrogeologists to improve their observation and understanding in the scientific exploration and development of groundwater-based water supplies and putting up of source sustainability structures. The use of remote sensing has considerably improved ground investigation work and resultant groundwater exploration capabilities in India. Application of high-resolution satellite data combined with information collected through geophysical and ground surveys has helped in making GIS-based groundwater information system very effective for management of groundwater resource in India.

The FCCs draped with DEMs or exclusive remote sensing products of use in aquifer mapping and aid in planning and executing drinking water supply projects. The imparting of training to water supply planners and engineers engaged in provisioning of drinking water supplies in various states in India in the art of remote sensing imagery interpretations and in the application use of satellite imagery-driven HGMs to locating successful water supply bore wells and sites for sustainable groundwater recharging structures is a recent innovation in India. The academics and resource service organizations need to work in tandem to evolve mechanism to achieve objective use of indigenously acquired satellite imagery data and maps generated from them for their efficient and effective use in water supply-related water management projects.

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Isotope Hydrology

U. K. Sinha, K. Tirumalesh, and Hemant V. Mohokar

Abstract Environmental isotopes were introduced into the study of hydrological cycle during the mid-nineteenth century as complementary tools to existing methods like geology, geochemistry, geophysics, etc. for addressing problems pertaining to movement of water, pathways of streams, residence times of groundwater, etc. However, the applications of environmental isotopes as potential tools to unravel many hidden processes and factors governing water, its source and dynamics in all stages of hydrological cycle have gained momentum after the introduction of advanced instruments for isotope measurement of water. In recent times, the critical information that is being obtained from isotopic tools is precipitation contribution to groundwater, efficacy of recharge structures for augmenting groundwater supplies, source and mechanism of groundwater contamination and its transport, sustainability of deep groundwater, etc. The common isotopes that are widely used include ^{2}H, ^{18}O, ^{13}C, ^{15}N and ^{34}S which are stable in nature and ^{222}Rn, ^{3}H and ^{14}C, which are radioactive in nature. While stable isotopes help in understanding the source and mechanism of groundwater recharge based on their natural distribution over space and time, the radioisotopes help in understanding the groundwater residence times and dynamics of any given water system due to their inherent radioactive decay.

Keywords Environmental isotopes · Oxygen-18 · Deuterium · Tritium · Carbon-14 · Global meteoric water line

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S. P. S. Ray (ed.), *Ground Water Development - Issues and Sustainable Solutions*, https://doi.org/10.1007/978-981-13-1771-2_14

1 Introduction

Isotope hydrology is an emerging discipline with expanding investigation tools for many environmental problems. Naturally occurring elements in water comprise about 1700 stable and unstable (radioactive) isotopes, commonly referred to as environmental isotopes. Globally distributed isotopes produced from anthropogenic sources, such as aboveground nuclear detonation testing and emissions from nuclear reactors, are considered environmental isotopes. The use of artificial isotopes in hydrology has markedly declined because of perceived concerns about injection of foreign substances into water supplies. An important misconception on the use of environmental isotopes for hydrology persists and needs correction before proceeding. There is the perception that one needs to 'manually' inject isotopes into the environment to study their attributes in the subsurface. This is simply untrue, and the entire measurements and interpretations of environmental isotopes are predicated on isotopes occurring naturally in the hydrosphere, originating from cosmogenic nuclide production, or occur as persistent anthropogenic releases into the hydrosphere. Next, while isotopes behave as tracers of hydraulic processes, they also behave as carriers, describing physiochemical changes during fluid, solid, and gas transformations. The limited capability of chemical compounds including dyes, gases, and also particulate tracers, which are still employed (Sanford et al. 1996) as collaborative tools, preceded the advent of environmental isotope applications. Today the terms isotope and tracer are commonly used as synonyms in the scientific community. The progression of isotope techniques in hydrology is rather analogous to the present wide acceptance of numerical modelling in groundwater hydrology following the advancement of microprocessors in portable computers. With further analytical achievements and more publications in practical applications, it is expected that isotope techniques will also become an integrated part of most hydrological investigations.

2 Basic Isotope Concepts

A nuclide is defined in terms of the number of protons and neutrons that make up its nucleus. Isotopes are nuclides with the same atomic number (proton number) but with different numbers of neutrons. About 26 nuclides are stable among the nearly 1700 nuclides (Walker et al.1989), which have been discovered. However, most nuclides are not stable but are radioactive and decay spontaneously until they achieve a stable nuclear configuration.

2.1 Stable Isotopes

There are natural variations in the ratios of the stable isotopes of many elements. Isotope ratio differences in materials containing hydrogen ($^2H/^1H$ usually written as D/H), carbon ($^{13}C/^{12}C$), nitrogen ($^{15}N/^{14}N$), oxygen ($^{18}O/^{16}O$) and sulphur ($^{34}S/^{32}S$) have potential uses in various hydrological studies.

Among the low atomic number or 'light' isotopes, fractionation may occur. Isotope fractionation is the partitioning of isotopes by physical or chemical processes and is proportional to the differences in their masses. Physical isotopic fractionation processes are those in which diffusion rates are mass dependent, such as ultrafiltration or ion and molecular diffusion. Chemical isotopic fractionation processes involve redistribution of isotopes of an element among phases or chemical species. Chemical fractionation effects occur because a chemical bond involving a heavier isotope will have lower vibrational frequency than the equivalent bond with a lighter isotope. Generally, in equilibrium isotopic reactions, heavy isotopes are enriched in the compound with the higher oxidation state. Fractionation may occur during both equilibrium and irreversible chemical reaction. During irreversible chemical reaction, kinetic fractionation processes, the lighter, i.e. lower atomic mass, of two isotopes of an element will form the weaker and more easily broken bond. The lighter isotope is more reactive; therefore it is concentrated in reaction products, enriching reactants in the heavier isotope.

2.1.1 δ Definition

It is difficult to determine accurately the absolute isotope values in every compound through routine analysis. Fortunately for most isotope geochemical studies, it is sufficient to know the relative abundance with respect to standard value. These relative isotope concentrations can be determined easily with great accuracy by a differential isotope ratio measurement using double-collecting mass spectrometers. The relative difference is called δ value and is defined as

$$\delta = \frac{R - R_{\text{std}}}{R_{\text{std}}}$$

where R represents the isotope ratio of a sample ($^2H/^1H$, $^{13}C/^{12}C$, $^{18}O/^{16}O$, etc.) and Rstd represents the corresponding ratio in a standard. The δ value is generally expressed in parts per thousand (per mil, ‰) and written as

$$\delta = \frac{\left(R - R_{\text{std}}\right)}{R_{\text{std}}} \times 10^3$$

2.1.2 Standards

The selection of standards for reporting stable isotope data is very important in environmental isotope geochemical work for comparison of results obtained from different laboratories. The International Atomic Energy Agency is presently coordinating the preparation, calibration and distribution of internationally acceptable standards for use in hydrological investigations.

Standard mean ocean water (SMOW) is used as the standard for measurement of ^{18}O and ^{2}H in waters. It corresponds to hypothetical water having $^{2}H/^{1}H$ and $^{18}O/^{16}O$ isotopic ratio equal to mean isotopic ratio of ocean waters. PDB is the universally accepted ^{13}C standard. PDB refers to calcium carbonate of the rostrum of a cretaceous belemnite from Pee Dee Formation in South Carolina, USA. PDB standard has long been exhausted, and IAEA panel in 1983 (Gonfiantini 1983) adopted NBS-19 new standard, supplied by the US National Bureau of Standard and is now known as the National Institute of Standards Technology (NIST), to define the new VPDB (Vienna PDB) scale as follows:

$$\delta^{13}C_{\text{NBS19/VPDB}} = +1.95\%$$

The accepted reference standard is CDT which is the triolite phase (FeS) from the Canyon Diablo meteorite. It has a ratio of $^{34}S/^{32}S = 22.22$. The IAEA is supplying a secondary sulphur standard called OGS (IAEA 1984). This is a BaSO4 precipitated from ocean water sulphate. OGS has a $\delta^{34}S$ ($SO4^{2-}$) value of about +20‰ with respect to CDT. Atmospheric nitrogen is used as working and reference standard by most of the laboratories. Atmospheric nitrogen (AIR) comes from well-mixed reservoir with a very reproducible mass ratio of 3.677×10^{-3}. IAEA is supplying two samples of ammonium sulphate as secondary standard.

2.2 Radioactive Isotopes

Most isotopes are unstable and become increasingly unstable as the number of neutrons increases or decreases outside the stability zone of nuclides (Walker et al. 1989). Tritium and Carbon-14 (along with a number of other radioactive nuclides) exist in the environment due to continuous production in the atmosphere by cosmic ray-induced reactions and as a consequence of thermonuclear explosions, operations of nuclear plants and other industrial outputs.

2.2.1 Tritium

The radioactive isotope of hydrogen (^{3}H or T) is produced by a nuclear reaction between atmospheric nitrogen and thermal neutrons in the upper atmosphere (Libby 1946):

$$^{14}N + n \rightarrow {}^{12}C + {}^{3}H$$

The ^{3}H thus formed enters the hydrologic cycle after oxidation to $^{1}H^{3}HO$. It finally decays according to

$$^{3}H \rightarrow {}^{3}He + \beta^{-}$$

with Eβmax = 18 keV and a half-life of 12.43 years (Unterweger et al. 1978).

Owing to the low probability of the nuclear reaction and short residence time (Rozanski et al. 1991) of ^{3}H in the atmosphere, the natural ^{3}H concentration in the air is very low. Low-level tritium concentrations are expressed in tritium unit (TU). One TU or TR (tritium ratio) corresponds to one tritium atom per 10^{18} atoms of hydrogen ($^{3}H/^{1}H = 10^{-18}$). A concentration of 1 TU is equivalent to a specific activity of 0.118 Bq/L of water.

Carbon-14

The natural occurrence of the radioactive carbon isotope, ^{14}C or radiocarbon, was first recognized by Libby (1946). It is naturally formed in the transitional region between the stratosphere and troposphere about 12 km above the Earth's surface through the nuclear reaction:

$$^{14}N + n \rightarrow {}^{14}C + p$$

The thermal neutrons required are produced by reactions between very high-energy primary cosmic ray protons. ^{14}C decays according to

$$^{14}C \rightarrow {}^{14}N + \beta^{-}$$

with a maximum $ß^{-}$ energy of 156 keV and a half-life of 5730 ± 40 years (Godwin 1962). Molecules of the atmospheric ^{14}C thus formed very soon oxidize to ^{14}CO and ultimately to $^{14}CO_2$, which mixes with the inactive atmospheric CO_2. $^{14}CO_2$ molecules enter the oceans and living marine organisms. Some are also assimilated by land plants, so that all living organisms, vegetable as well as animal, contain ^{14}C in concentrations about equal to that of atmospheric CO_2. The production and distribution of ^{14}C in nature occur through series of chemical and biological processes, which has become stationary throughout much of geologic time. As a consequence, the concentration of ^{14}C in the atmosphere, oceans and biosphere reached a steady-state value, which has been almost constant during a geologic period, which is long compared to the life span of a ^{14}C nucleus. This natural concentration, $^{14}C/^{12}C$, is of the order of 10^{-12}, which is equivalent to a specific activity of about 0.226 Bq/gC (13.56 disintegrations per minute per gramme of carbon).

It is extremely difficult to make an absolute measurement of a ^{14}C activity. Therefore, the sample activities are compared with the activity of a standard under equal conditions. This results in a ^{14}C activity ratio or ^{14}C concentration ratio:

$$^{14}a = \frac{^{14}A_{\text{sample}}}{^{14}A_{\text{reference}}} = \frac{^{14}A}{^{14}A_R} = \frac{^{14}C_{\text{decay rate in the sample}}}{^{14}C_{\text{decay rate in the reference}}} = \frac{^{14}C_{\text{concentration in the sample}}}{^{14}C_{\text{concentration in the reference}}}$$

The symbol ^{14}A may be used for the ^{14}C content (radioactivity or concentration) of a sample, whether the analytical technique applied is radiometric or mass spectrometric (AMS). Under natural circumstances, the values of ^{14}A are between 0 and 1. In order to avoid the use of decimals, it is a general practice to report these values in %, which is equivalent to the factor 10^{-2}. Thus, ^{14}C activity can be calculated in percent modern carbon (pMC), whereas 100 pMC = 13.56 dpm/g of carbon. Knowing the rate of radioactive decay (λ or $T_{1/2}$), the age (T = time elapsed since death) of a carbonaceous sample, organic or inorganic, can be calculated from the measured activity, ^{14}A, if the ^{14}C activity at the time of death, $^{14}A_{\text{initial}}$, is known using the following equation:

$$t = \left(t_{1/2} / \ln 2\right) \times \left(^{14}A_{\text{initial}} / ^{14}A\right)$$

3 Environmental Isotopes in Hydrological Cycle

The global hydrologic cycle is the vastly, complex dynamic process which transfers all phases of water molecules (gas, liquid and solid) through the atmosphere, land and oceans. Tracers provide a convenient way of obtaining space-time integrals of motion of water molecules over both large and small ranges of space and time. It is now well recognized that several stable (^{2}H, ^{3}He, ^{11}B, ^{13}C, ^{15}N, ^{18}O, ^{34}S ^{37}Cl, ^{87}Sr, etc.) as well as naturally produced radioactive isotopes (^{3}H, ^{14}C, ^{36}Cl, ^{39}Ar, ^{85}Kr and U-disequilibria which includes the large progeny of decay schemes for the parents ^{238}U, ^{235}U and ^{232}Th) can be used to study the hydrological cycle. Stable isotopes (^{2}H, ^{13}C, ^{18}O) and radioactive isotopes ^{3}H and ^{14}C are routinely applied to investigate or identify groundwater or surface water-related problem. Sometimes other isotopes mentioned above are also employed for a specific hydrological solution which cannot be solved by routinely used isotopes.

3.1 Stable Isotopes of Oxygen and Hydrogen

Both hydrogen and oxygen consist of a number of isotopes, whose variations in natural water are the basis for applying the isotope methodology in hydrology. Water is evaporating from the sea. The marine vapour for a large part precipitates over the oceans, as it is transported to higher latitudes and altitudes, where the vapour cools down and condenses. Part of the vapour is brought to the continents where it precipitates and forms different modes of surface water and groundwater. The 'last' marine vapour is precipitated as ice over the Arctic and the Antarctic. Compared to the waters of the ocean, the meteoric waters (i.e. the atmospheric moisture, the precipitation and groundwater and surface water derived from them) are mostly depleted in the heavy isotopic species: ^{18}O, ^{17}O and ^{2}H. The main reason for depleted values of meteoric water is the Rayleigh rainout effect, operating on a limited water (vapour) reservoir in the atmosphere. The average ocean composition is accepted as the reference standard for these isotopes so that δSMOW = 0‰ by definition (Craig 1961b). The δ values of the meteoric waters are thus negative numbers.

Global distribution of isotopes was established by the IAEA in co-operation with WMO in 1961. In this programme, monthly pooled samples of precipitation were collected worldwide and then analysed for their ^{18}O, ^{2}H and ^{3}H content. The degree of depletion is related phenomenologically to geographic parameters such as latitude, altitude and distance from the coast and to the fraction precipitated from a vapour mass content. From δ^{18}O and δ^{2}H values in meteoric waters derived from the data of GNIP (the Global Network of Isotopes in Precipitation), the following observation have been made:

(a) A gradual decrease of the heavy isotopic concentration when going from lower to higher latitude (latitude effect).
(b) A decrease in δ^{18}O and δ^{2}H when going from coast to a continent land (continental effect).
(c) A decrease in δ^{18}O and δ^{2}H content with increasing altitude (altitude effect).
(d) Seasonal variation of δ^{18}O and δ^{2}H is related to seasonal variation in temperature (seasonal effect).

3.1.1 δ^{18}O and δ^{2}H Correlation

The changes of ^{18}O and ^{2}H concentrations in meteoric waters were shown to be fairly well correlated (Friedman 1953; Craig 1961a; Dansgaard 1964; Yurtsever 1975) so that in the (δ^{2}H, δ^{18}O) graph, the isotopic compositions of precipitation are aligned along what is referred to as a meteoric water line (MWL) for which a global average is $\delta^{2}H = 8\ \delta^{18}O + 10‰$ (then called the GMWL).The variations in δ^{18}O and δ^{2}H can be better understood by considering the two main processes in the global water cycle: (i) evaporation of surface ocean water and (ii) the progressive raining out of the vapour masses as they move towards regions with lower temperatures, i.e. higher latitudes and altitudes.

3.1.2 ^{18}O and ^{2}H in Groundwater

Meteoric ^{18}O and ^{2}H signal is transferred to groundwater during recharge. For many groundwaters, their isotopic composition will equal the mean weighted annual composition of precipitation. For others important deviation from precipitation is found. It also sheds light on the mechanism of recharge. Unlike temperate regions, the isotopic composition of groundwater in arid regions can be considerably modified from that of local precipitation. The cause is the strong isotopic enrichment in water during evaporation. However, characteristic trends imparted by evaporation can be useful in understanding the mechanism of recharge, as well as determining recharge rates. Initial stable isotope composition can also be modified by exchange with oxygen-bearing and possibly hydrogen-bearing mineral. This exchange is of importance in geothermal environments. Another process, which may modify the initial stable isotope content of groundwater, is the isotopic exchange with a gas phase, which is not initially in equilibrium with the environmental water. The distinctive and characteristic stable isotopic composition of waters from different geographic origin or of different hydrological nature on one hand and their conservative property on the other hand form the basis for their application in hydrological studies.

3.2 Stable Isotope of Carbon (^{13}C)

The chemical element carbon has two stable isotopes, ^{12}C and ^{13}C. Their abundance is about 98.9% and 1.1%, so that the $^{13}C/^{12}C$ ratio is about 0.011 (Nier 1950). As a result of several fractionation processes, kinetic as well as equilibrium, the isotope ratio shows a natural variation of almost 100‰. The least depleted atmospheric CO_2 had originally $\delta^{13}C$ values near −7‰. Since the nineteenth century, this value has undergone relatively large changes. In general, high values are observed in oceanic air far removed from continental influences and occur in combination with minimal CO_2 concentrations. More negative $\delta^{13}C$ values are found in continental air and are due to an admixture of CO_2 of biospheric and anthropogenic origin ($\delta^{13}C \approx -25‰$), in part from the decay of plant material and in part from the combustion of fossil fuels (Keeling 1958; Mook 1983). Plant carbon has lower ^{13}C content than the atmospheric CO_2 from which it was formed. The fractionation, which occurs during CO_2 uptake and photosynthesis, depends on the type of plant and the climatic and ecological conditions. As complicated biogeochemical processes are involved in the degradation of terrestrial and marine plant material ultimately into coal, oil and natural gas, the range of $\delta^{13}C$ values of these fossil fuels is larger, extending to more negative values, especially of biogenic methane.

3.2.1 ^{13}C Variations in Groundwater

Soil CO2 is important in establishing the dissolved inorganic carbon content of groundwater. After dissolution of this CO2, the infiltrating rainwater is able to dissolve the soil limestone:

$$CO_2 + H_2O + CaCO_3 \rightarrow Ca^{2+} + 2HCO_3^-$$

Because limestone generally is of marine origin ($\delta^{13}C \approx +1‰$), this process results in δ^{13}**C** of the dissolved bicarbonate of about −11 to −12‰ (in temperate climates). In the soil the HCO3⁻ first formed exchanges with the often present excess of gaseous CO_2, ultimately resulting in $\delta^{13}C = -16‰$. In surface waters such as lakes, ^{13}C enrichment of dissolved inorganic carbon can be caused by isotope exchange with atmospheric CO_2 ($\delta^{13}C \approx -7.5‰$) ultimately resulting in values of $\delta^{13}C = +1.5‰$, identical to oceanic values. Consequently, freshwater carbonate minerals may have 'marine' δ^{13}C values. In these cases the marine character of the carbonate is to be determined by δ^{18}O. In addition to $HCO3^-$, natural waters contain variable concentrations of CO_2 which leads to lowering in δ^{13}C value of DIC than that of the bicarbonate fraction alone. Hence, δ^{13}C(DIC) in groundwater (Vogel and Ehhalt 1963) and in stream and river waters derived from groundwater are generally in the range of −12 to −15‰.

3.3 Radioisotope of Hydrogen (^3H)

The natural production by cosmic rays results in a steady-state inventory on the Earth's surface of about 3.5–4.5 kg of tritium (Lal and Peters 1967; O'Brien et al. 1992) most of which is present as part of water molecule (H_2O). As part of water molecules, tritium follows the pathway through the hydrologic cycle almost exactly, with only small perturbation due to fractionation effects during phase changes (Bigeleisen 1962). These fractionations are very small and can be ignored relative to measurement uncertainties and larger change resulting from radioactive decay.

Pre-bomb tritium concentrations are not well known, though some estimates available suggest they were of the order of 2–8 tritium units across US continent (Thatcher 1962). Tritium concentrations in precipitation rose rapidly following the atmospheric bomb test and were found to have a strong dependence on location and season. Tritium concentration in precipitation peaked in the northern hemisphere during 1963 (Fig. 1), rising to a few thousand units in most mid-continental location (IAEA 1981, 1992), whereas ^{3}H levels in atmospheric waters in the southern hemisphere (Fig. 2) were lower than at comparable north latitude stations. This is a reflection of the predominant northern location of weapon testing sites and the slow inter-hemispheric transport of tracers.

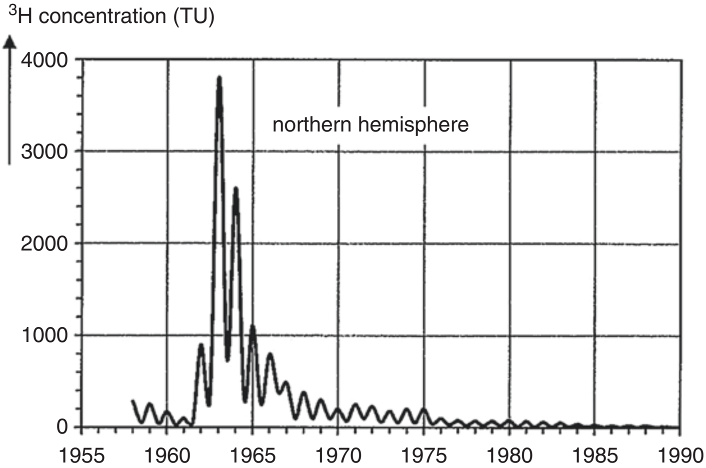


Fig. 1 Smoothed curve representing the average ^3H content of precipitation over the continental surface of the northern hemisphere

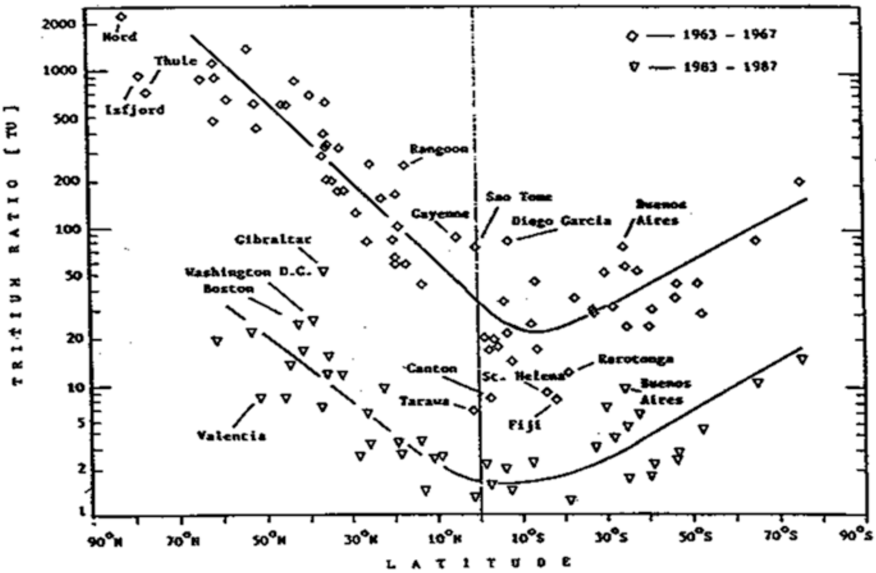


Fig. 2 Latitudinal distribution of tritium content in monthly precipitation for oceanic (inland and coastal) stations of the IAEA/WMO global network

3.3.1 Tritium in the Groundwater

The most important use of tritium as a hydrologic tool is in the study of residence times of surface water and groundwater. Groundwaters and surface expressions of groundwaters such as small springs and seeps have the widest range of tritium concentration of any type of water.

They are also the systems to which tritium has been applied most extensively. At the simplest level, the presence of tritium in groundwater implies that at least a fraction of water in the aquifer has been recharged since the beginning of the bomb era. Approximate age ranges can be given for groundwater samples if one assumes that the highest concentrations represent the tritium peak (Fontes et al. 1980). During recent years, the atmospheric reservoir has been practically exhausted of the ^{3}H introduced by the nuclear tests so that the atmospheric ^{3}H levels have almost returned to the pre-1952 levels, except for some local anthropogenic releases of ^{3}H from the nuclear industry and other uses of tritiated materials. To obtain more information from the tritium data, it is desirable to have a time series of tritium data over decadal time scales. Over the years a series of model and approaches have been developed to work with these sets of data.

3.4 Radioisotope of Carbon (^{14}C)

The production of ^{14}C obeys the same laws as tritium as far as latitude is concerned, but because of its oxidation to gaseous form of CO_2 and long residence time in the troposphere, ^{14}C is much more efficiently mixed in the troposphere. $^{14}CO_2$ of the troposphere dissolves in the ocean or is consumed by vegetation during photosynthesis. Decay of vegetation and root respiration return much of the ^{14}C to the atmosphere. The largest storehouse of ^{14}C is by far oceans, in the form of $HCO3^{-}$ (Berner and Lasaga 1989). Accumulation in the troposphere and the hydrosphere/biosphere is balanced by radioactive decay and burial. This balance or secular equilibrium is relatively robust over the short periods (decades to 100s years) and amounts to an atmospheric concentration of $^{14}CO_2$ on the order of 10^{-2} of the total concentration of CO_2. This ^{14}C activity is defined as modern ^{14}C and is the basis of the radiocarbon standard. This secular equilibrium can be altered by natural processes and man-made activities.

While the industrial age has been pumping dead carbon into the atmosphere and diluting atmospheric ^{14}C, the nuclear age has been creating it. Since the 1950s, atmospheric weapon testing and nuclear power plants have been realizing additional radiocarbon to the atmosphere and biosphere. The strong increase in the atmospheric ^{14}C level due to the nuclear test explosions is of more relevance to the hydrologist. During the bomb explosions, ^{14}C (and ^{3}H) is being produced by the same nuclear reactions that are responsible for the natural production. In the northern hemisphere, the peak concentration occurred during the spring of 1963, when it

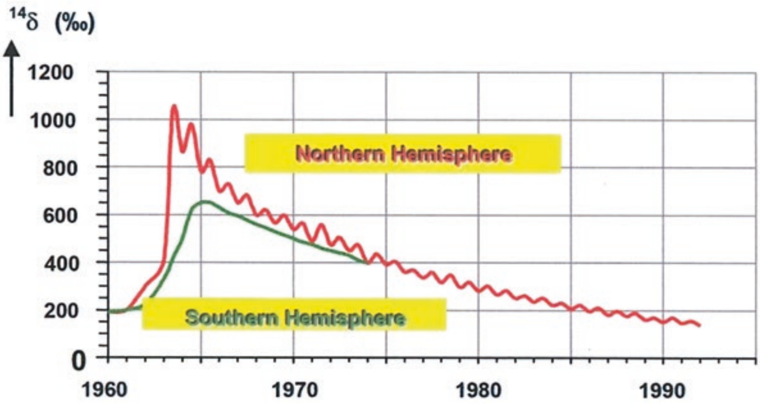


Fig. 3 Curve representing the natural ^{14}C content of atmospheric CO2 during test explosions of nuclear weapons

was about double the natural concentration (Fig. 3). In the southern hemisphere, a more gradual increase has taken place.

3.4.1 ^{14}C in Groundwater

From the atmospheric reservoir, neglecting the direct dissolution of CO2 in rainwater, which will not lead to more than a few ppm of total dissolved carbon, CO2 enters into the water cycle by two main processes:

1. Chemical process: It is the process of dissolution buffered by solid carbonate saturation. The following chain of reactions takes place in free waters:

$$\begin{array}{lcl} CO_2\,(\text{gas}) & \Leftrightarrow & CO_2\,(\text{aqueous}) \\ CO_2\,(\text{aqueous}) & \Leftrightarrow & H_2CO_3 \\ H_2CO_3 & \Leftrightarrow & HCO_3^- + H^+ \\ HCO_3^- & \Leftrightarrow & CO2_3^{2-} + H^+ \\ CO_3^{2-} + Me^{2+} & \Leftrightarrow & MeCO_3 \end{array}$$

where Me^{2+} is generally Ca^{2+} but can include Mg^{2+}, Fe^{2+} and sometimes $2Na^+$ in highly saline continental brine.

2. Biochemical production: The assimilation of atmospheric CO_2 by plants through photosynthesis is accompanied by the release of CO_2 in the soil zone. This occurs by fermentation and decay of organic matter (fulvic, flavic, and humic acids) but mainly by respiration in soil root zone. It is the soil zone that gives the recharging groundwater its radiocarbon signal. Commonly the CO_2 partial pressure in soil

exceeds a value of 10^{-2} atm. This biogenic CO_2 then gives total dissolved inorganic carbon according to several processes depending upon local geological conditions.All of these processes which produce large amount of $HCO3^-$ or $CO3^{2-}$ can be divided into:

1. Those in which all dissolved carbon is of inorganic origin.
2. Those in which the dissolved carbon comes from both biogenic CO_2 and solid carbonate. For the former, the ^{14}C activity of TDIC will exclusively reflect that of CO_2 source; for the latter the ^{14}C activity of biogenic CO_2 will be diluted by the carbon coming from the leaching of solid carbonate since it is generally very old and thus inactive. The chemical dilution of ^{14}C in the TDIC may be observed even in non-carbonate situations (Fritz et al. 1978). The consequence is that age estimation of TDIC cannot simply be done using the modern activity (100 pMC).

4 Case Studies

4.1 Application of Environmental Isotopes to Identify Landfill Leachate Contamination: Gazipur Landfill, New Delhi, India

4.1.1 Introduction

The world urban population was about 1.52 billion in 1975, increased to 2.84 billion in 2000, and is projected to 4.91 billion by 2030 (United Nation 2006). In the past, municipal garbage dumps (sanitary landfills are only a recent technology) were unlined and sited with little regard to local hydrogeology. Groundwater contamination is one of the major problems associated with improper waste disposal. Leaching of hazardous elements in the groundwater in surrounding areas of landfill sites is reported from different sanitary landfill sites all over the world (Harris and Parry 1982; Harris and Lowe 1984). One of the most significant impacts of a landfill has been consistently identified as arising from leachate (Farquhar 1989; CAE 1992; Mulvey 1997). Environmental isotopes are being extensively used for investigating landfill sites and tracing pollution plumes. Leachate with high dissolved organic carbon (DOC) will generate large quantities of these gases. The isotopic fractionations associated with these bacterially mediated reactions are huge. Values of $\delta^{13}C$ and δ^2 H in the reaction products fall outside of the range associated with natural water. Most landfills where strong methane production occurs have co-existing CO_2 or dissolved inorganic carbon (DIC) that is enriched in ^{13}C (Lansdown et al. 1992). Hackley et al. (1996) provided evidence that methanogenesis occurring in the landfills leads to unique ^{13}C isotopic signature identifiable in leachate samples. Tritium activity present in landfill leachate provides useful tracer in the study of landfill site. Luminescent paint that contains tritiated hydrocarbons is considered as the most probable source of tritium in landfill leachates.

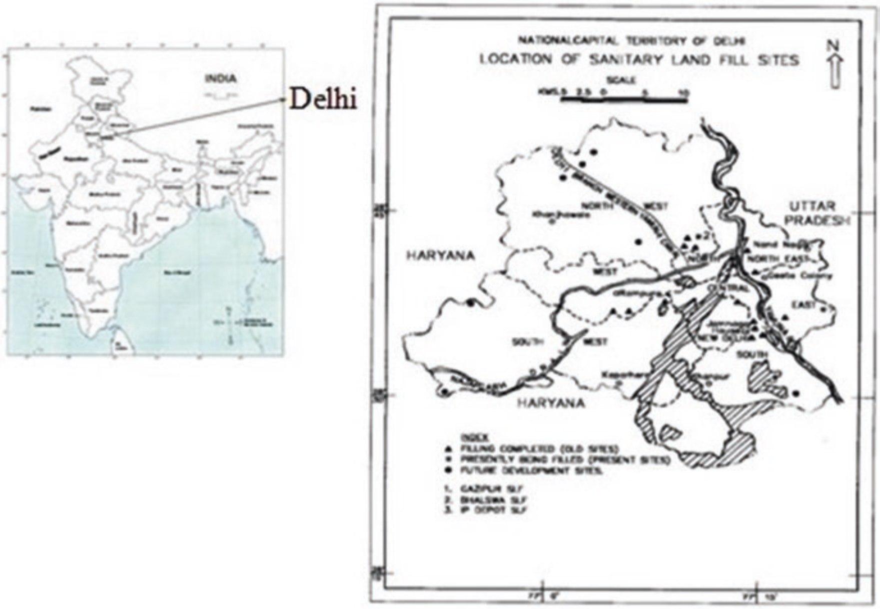


Fig. 4 Map of India showing Delhi and landfill sites in the National Capital Territory of Delhi

4.1.2 Gazipur Sanitary Landfill (SLF) Site, New Delhi

The quantity of municipal solid wastes generated in Delhi has been consistently rising over the years. This can be attributed to the rapid population growth, mass migration of population from rural to urban areas, increase in economic activities in general in the city and the change in lifestyle of the people. The continuous generation of solid waste has developed several landfill areas (Fig. 4), and the land is retrieved for various purposes. There are two major categories of landfills in Delhi:

1. Landfills completed and retrieved land is used for various purposes.
2. Active landfills where present filling is taking place.

Gazipur is an active landfill site and the total area of the site is 70 acres. Filling in this landfill site commenced in 1993, and the service zones for this landfill site are East Delhi, New Delhi and Central Delhi. This site was selected for the present study and environmental stable isotopes ^{18}O, ^{2}H and ^{13}C, and radioactive isotope ^{3}H has been used to find out the contamination of groundwater by landfill leachate and direction of the flow of the leachate as well as extent to which the leachate has moved.

Leachate sample from Gazipur landfill site was collected for isotopic (δ^{18}O, δD, δ^{13}C and ^{3}H) and chemical analysis in the post-monsoon (November 2003) period. Groundwater samples in the vicinity of landfill site were collected for environmental isotopes as well as chemical analysis during post-monsoon (November 2003) and pre-monsoon (June 2004) period. Sampling points have been represented as circle in the site plan map (Fig. 5).

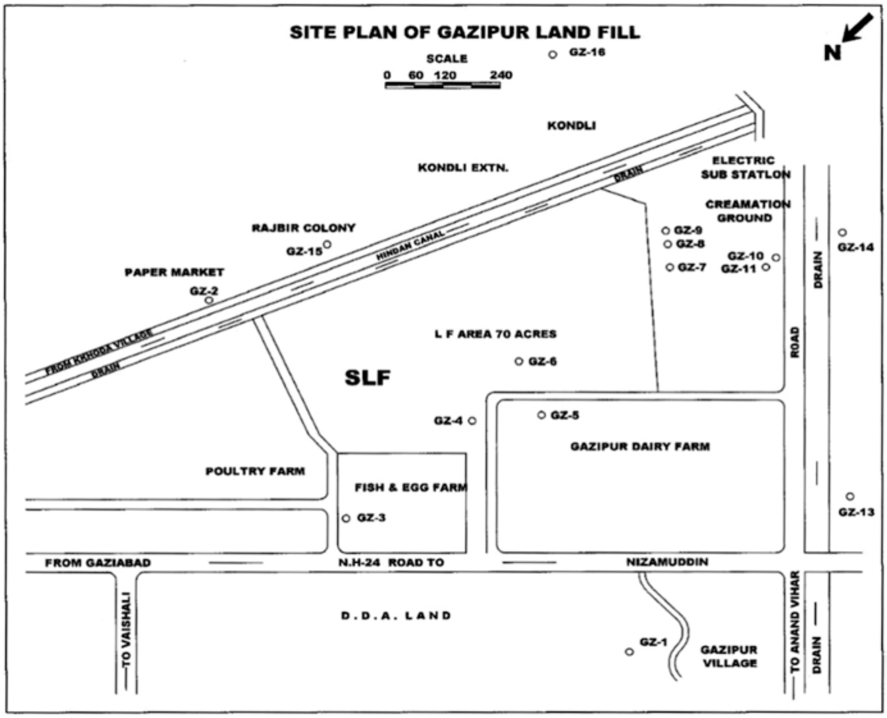


Fig. 5 Site plan map of Gazipur landfill site showing locations of sampling points

The landfill site is situated 8 km east of river Yamuna and about 0.5 km north of Hindon canal. About 10 m thick landfill materials had been dumped in this site till study period. The area is underlain by quaternary alluvium of about 134 m thick below which weathered and fractured quartzite is present. The area is underlain by fine to medium sand mixed with coarse hard kankar up to a depth of 50 m. Thus, on macro-level it can be inferred as a single aquifer system of depth 50 m only. Lenses of minor clayey silt horizons are also present within this sand horizon at a few places. Sediments below this depth are predominantly clayey in nature.

4.1.3 Results and Discussion

Electrical conductivity of almost all the samples is less than 2000 μS/cm that is below the permissible level (Bureau of Indian Standards) except GZ-7, GZ-3 and GZ-1. Since GZ-1 is situated opposite to the direction of the flow from landfill site, quality of groundwater at this location may be in situ groundwater quality at 30 m depth. High concentration of iron has been found in GZ-3, GZ-10 and GZ-11 samples. High concentration of Fe in GZ-3, GZ-10 and generally low nitrate concentrations in all groundwater near landfill site could be due to percolation of landfill leachate. Usually leachate generation is favoured by reducing condition. Therefore,

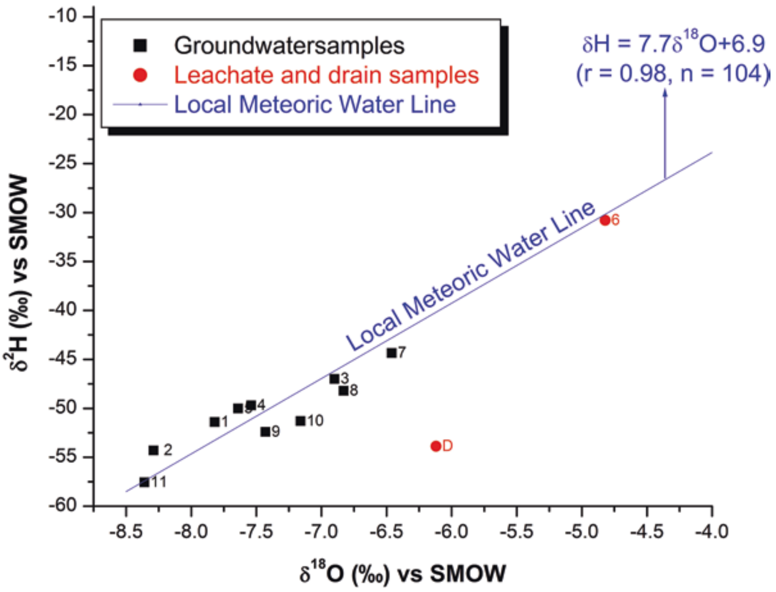


Fig. 6 δ^{18} O vs. δ^{2} H plot of post-monsoon samples

leachate contaminating groundwater may show low nitrate content as it may undergo anaerobic reduction at various redox zones. Heavy metals Cr, Ni, Zn and Cd concentrations in the leachate are relatively low as compared to the amount of refuse. It could due to natural attenuation of heavy metals in landfill leachate. Negligible concentrations of heavy metals in groundwater in the vicinity of landfill do not give any indication of leachate contribution to the groundwater.

The leachate sample GZ-6 is highly enriched in ^{18}O and ^{2}H isotopes compared to nearby groundwater samples (Figs. 6 and 7). Fritz et al. (1991) have shown similar results in their study. Most of the groundwater samples fall along the meteoric water line. GZ-7, GZ-8, GZ-9 and GZ-10 samples located at the southeast side of the landfill are slightly enriched in stable isotope ^{18}O and ^{2}H than other groundwater samples. It could be due to movement of pollution plume from landfill leachate towards southeast of landfill site. In general post-monsoon samples are slightly depleted than pre-monsoon samples. It could be due to high rainfall during monsoon period in Gazipur area.

The tritium content of rainwater of Delhi during monsoon period of the study was found to be about 8 TU. High tritium content of about 102 TU has been found in Gazipur landfill leachate sample. Liu et al. (1992) have also found the unique tritium relative to the surrounding groundwater in their study. Plots of δ^{18}O vs. tritium (Figs. 8 and 9) show that GZ-2, GZ-3, GZ-4, GZ-7 and GZ-11 are above 10 TU in post-monsoon samples indicating contribution from leachate in all these samples. GZ-1 showing less than 2 TU seems to be unaffected from landfill leachate contamination. GZ-3, GZ-4 and GZ-7, which are close to landfill site, show significantly

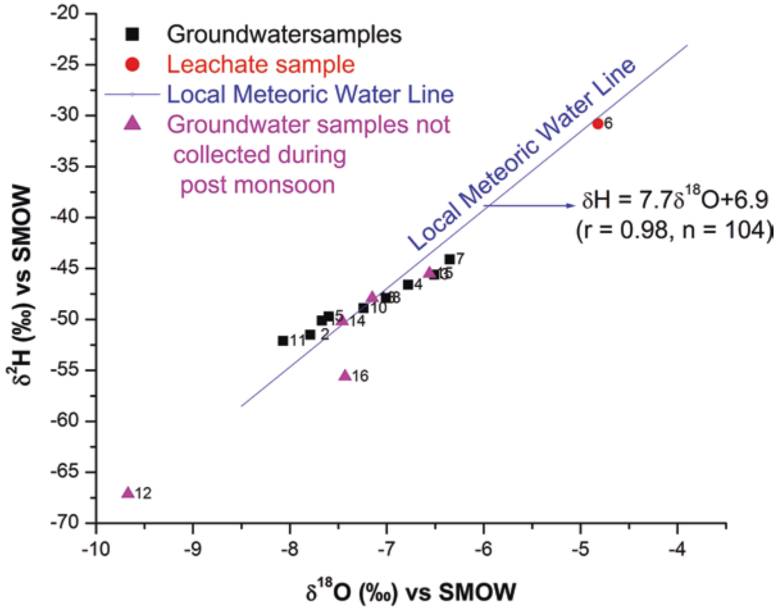


Fig. 7 δ^{18} O vs. δ^{2} of H plot of pre-monsoon sample

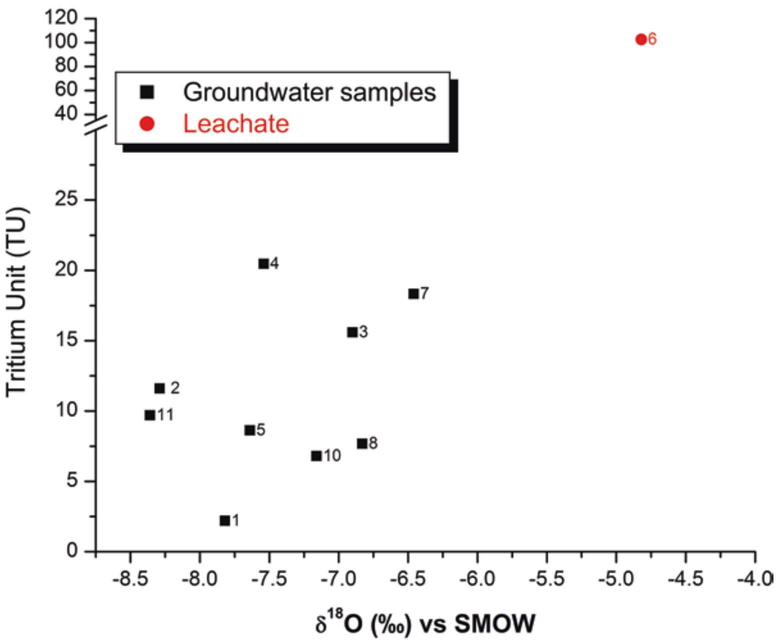


Fig. 8 δ^{18} O vs. ^{3}H plot of post-monsoon sample

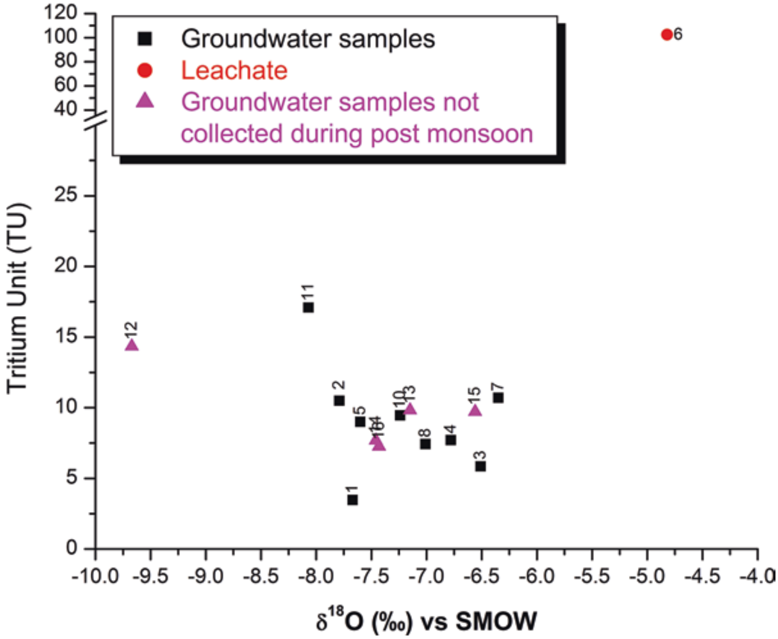


Fig. 9 δ^{18} O vs. ^{3}H plot of pre-monsoon sample

lower concentration of tritium in pre-monsoon period than post-monsoon period. It could be due to high rainfall during monsoon, which caused rapid leachate movement to these wells during and immediately after the monsoon season. Canal water collected in post-monsoon period showed 14 TU. The shallow wells GZ-15 (12 m deep) and GZ-13 (10 m deep) show tritium concentration of about 10 TU. High tritium content of GZ- 15 could be due to leachate contribution. GZ-13 located at northeast of landfill site may be getting high tritium concentration from drain water because stable isotope values do not support contamination from leachate. Similarly, high tritium content of GZ-11 may be due to adjacent drain in pre-monsoon time.

δ^{13}C values of DIC of groundwater and leachate have been shown in Figs. 10 and 11. ^{13}C of leachate sample is highly enriched. Lansdown et al. (1992) and Hackley et al. (1996) have explained about enrichment in δ^{13}C of leachate. GZ-1 shows about −12‰ which could be the natural groundwater value unaffected by leachate. Thus, carbon-13 result further supports the tritium and stable isotope result. Enriched value of GZ-7 and GZ-15 indicates that these wells are being contaminated from landfill leachate. GZ-3 and GZ-4 samples are isotopically enriched in post-monsoon than pre-monsoon. It is once again an indication of rapid movement of leachate into GZ-3 and GZ-4 wells due to heavy rainfall during monsoon period. Enriched value of GZ-15 indicates that leachate has contributed to this well too. Depleted value of δ^{13}C of GZ-13 tells about the absence of leachate contribution towards the east side of the drain.

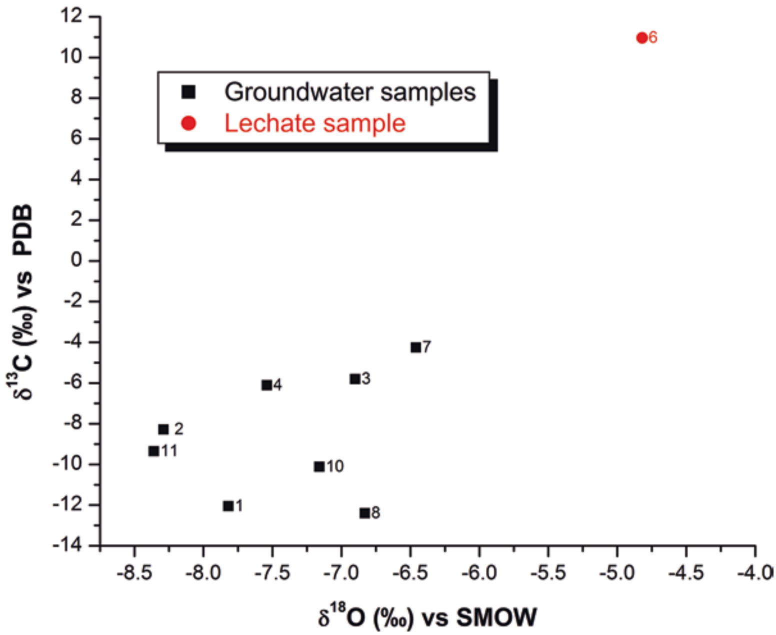


Fig. 10 δ18 O vs. δ^{13}C plot of post-monsoon sample

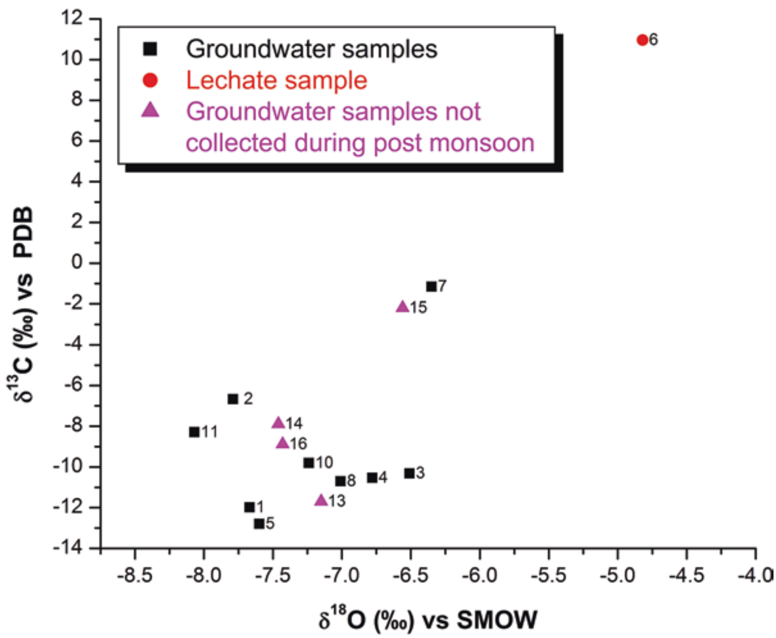


Fig. 11 δ18 O vs. δ^{13}C plot of pre-monsoon sample

4.1.4 Conclusion

Thus, on the basis of tritium, stable isotopes ^{18}O, ^{2}H and carbon-13 data supported by chemical and hydrological data, it can be concluded that leachate plume is moving in southeast direction as well as in south direction from landfill site. The pollution plume is moving beneath and across the canal, but it has not reached to Kondli village (GZ-16).

4.2 Investigation of Recharge Areas to the Springs Using Isotope Techniques as Well as Hydrogeology and Geomorphology in the Mountainous Region of Himalaya, Uttarakhand

4.2.1 Introduction

A spring is the result of an aquifer being filled to the point that the water overflows onto the land surface. They range in size from intermittent seeps, which flow only after much rain, to huge pools flowing hundreds of millions of gallons daily. The amount of water that flows from springs depends on many factors, including the size of the caverns within the rocks, the water pressure in the aquifer, the size of the catchment, and the amount of rainfall. Human activities also can influence the volume of water that discharges from a spring. Many of the current classification systems borrow heavily from the works of Bryan (1919) and Meinzer (1923) and incorporate parts of these systems and refine or expand portions based on modern quantification and knowledge of springs. Meinzer, in 1923, proposed a classification of springs based on the discharge of the spring. Mountainous region of Uttarakhand (Fig. 12) has a large number of perennial as well as ephemeral springs. These springs are mainly non-artesian springs. Majority of them are sixth and seventh magnitude springs and have seepage type outlet. Owing to anthropogenic activities, most of the springs in the mountainous region of Uttarakhand show reduced or negligible discharge during summer season. The present study aims to identify the recharge zones for the springs, to study various hydrological processes in this region and to evaluate the feasibility of artificial recharge to increase discharges of springs in dry period.

4.2.2 Study Areas

Four sites, one each from Dehradun (Pipaya) and Uttarkashi (Brahmkhal) and two in Rudraprayag (Isala and Kakodakhal) districts of Uttarakhand (Fig. 12), were selected for the investigation. Pipaya site is located about 80 km away from Dehradun towards north direction. There are 11 springs in this site located in 2 main valleys and 1 spring in each of 3 sub-valleys with elevations ranging from 1350 to

Fig. 12 Districts map of Uttarakhand and location of the selected sites

1650 m above mean sea level (amsl), and discharges of these springs vary from 0.1 to 22 l/min. Brahmkhal area belongs to Uttar Kashi district located about 40 Km southwest of Uttar Kashi city. There are eight springs present in two valleys, and the elevation of these springs ranges from 1200 to 1760 m amsl. The minimum and maximum discharges of the springs are 0.5 and 30 l/min. Isala area is located in Rudraprayag district of Uttarakhand state, and there are four springs situated in one valley between elevation 1250 and 1450 m amsl. Kakodakhal site is also located in Rudraprayag district of Uttarakhand state and falls north of river Alaknanda. There are five springs located in one valley, and the elevation of these springs ranges from 720 to 920 m amsl.

Geology of Pipaya project site is characterized by mostly slates interbedded with siltstones and phyllites with minor quartz, and this area has an average rainfall of 2100 mm per year from 2004 to 2009. In Brahmkhal, the entire area is covered by hard rock, and the main rock types are quartzites, phyllites, slates, and gneisses of varying degrees of metamorphism along with granite intrusive and metabasics. The rocks have undergone intensive metamorphism and recrystallization. This area has an average rainfall of 1690 mm per year from 2004 to 2009. In the case of Isala and Kakodakhal, the lithological sequence belongs to Rudraprayag Formation of Garhwal Group (late Precambrian to Cambrian age) and is characterized by argillo-arenaceous facies. The average rainfall is found to be 930 mm per year from 2004 to 2009. However, all the project sites have received very high rainfall during 2010, and the increase in rainfall varies from 50% to more than 200%.

4.2.3 Results and Discussion

Four sets of spring water samples were collected from the above-mentioned sites during February, June, September and November of the year 2009 for physico-chemical, chemical and isotope measurements. In addition to spring water, rainwater samples were also collected during 2009 and 2010 at each site from different altitudes.

Spring water quality was found to be fresh with electrical conductivity less than 350 μS/cm and neutral to slightly alkaline at all the project sites. Based on Piper's classification, the spring waters are of Ca-Na-HCO3 and Ca-Mg-HCO3 types, and there is a change in water types in different seasons. The change was most significant in the case of Isala and Kakodakhal sites. The variation in chemical type can be attributed to the diverse lithology of the formation as well as increased leaching of the minerals due to relatively long residence times of the spring waters.

δ^2H versus $\delta^{18}O$ was plotted for rainwater samples from all the four project sites, and local meteoric water lines (LMWLs) were drawn for all the four sites. Most of the spring water samples fall slightly below the local meteoric water line in the case of δ^2H versus $\delta^{18}O$ plots, indicating that major component of spring water is local precipitation. It is observed that $\delta^{18}O$ stable isotope composition of spring waters collected during February 2009 is most depleted among the four sets, suggesting the contribution of winter precipitation. However, all the samples collected during February 2009 from all the four sites fall above the LMWL due to enriched values of δ^2H. It seems there may be measurement error of δ^2H values for February 2009 samples.

The variation of rainwater isotopic composition of Pipaya samples with respect to altitude is shown in Fig. 13. An altitude effect is found, and it is estimated to be 0.37‰ $\delta^{18}O$ per 100 m elevation. In the plot altitude versus $\delta^{18}O$ (Fig. 14a), there is no correlation found in springs waters of valley 1. Most of these springs fall within a narrow altitude range of ~100 m (i.e. from 1350 to 1460 m amsl); therefore, altitude effect in isotope composition has not been observed. In valley 2 of this site, there is no correlation found between altitude and $\delta^{18}O$ as shown in Fig. 14b except the depleted values of February 2009 which show altitude effect.

From the $\delta^{18}O$ variation of rainwater of Brahmkhal with respect to altitude, it has been found that $\delta^{18}O$ are more and more depleted with increase in altitude, and from the slope of the best fit line, altitude effect is calculated to be 0.4‰ $\delta^{18}O$ per 100 m elevation (Fig. 15).The spring water samples of valley 1 collected during February

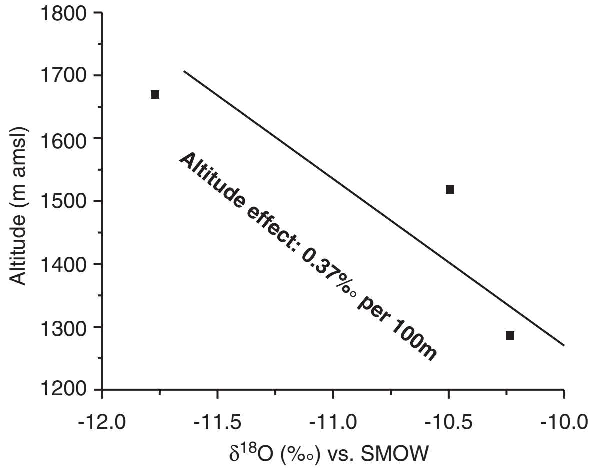


Fig. 13 Altitude versus $\delta^{18}O$ composition of rainwater samples collected during monsoon

and June 2009 show altitude effect of −0.2‰ $\delta^{18}O$ per 100 m which is within the values reported in the literature (Zuppi et al. 1974; Shivanna et al. 2008; Navada 1988). The altitude effect is not seen in the case of September and November 2009 samples (Fig. 16a) which could be due to the contribution of rainwater from different altitudes. In valley 2, altitude effect is seen in all sets of samples shown in Fig. 16b. In this case, the altitude effect is different for different months, and it is found to vary from −0.15‰ to −0.28‰ per 100 m elevation.

Variation of $\delta^{18}O$ values of rainwater of Isala collected during 2010 with altitude shows no correlation, as shown in Fig. 17. In fact the highest and lowest altitude rainwater samples show similar isotopic values. A similar trend has been found in spring water of all seasons of 2009 (Fig. 18).

The variation of $\delta^{18}O$ of Kakodakhal rainwater sample collected in 2010 with altitude shows depletion in $\delta^{18}O$ value with increase in altitude (Fig. 19). The altitude effect is calculated to be −0.54‰ per 100 m elevation. In the case of spring waters collected during February and November 2009, there is no correlation between altitude and $\delta^{18}O$, whereas June and September spring water samples show altitude effect with different slopes of −0.2‰ and −0.5‰, respectively, shown in Fig. 20. High rainfall in the month of August/September causes high spring discharges without undergoing appreciable evaporation, whereas evaporation effect causes low altitude effect in the month of June.

Environmental tritium content of the rain water samples show about 8 TU. In general the spring samples of four sites have tritium in the range of 6.5–8.5 TU. It clearly indicates that all the spring waters are freshly recharged precipitation water.

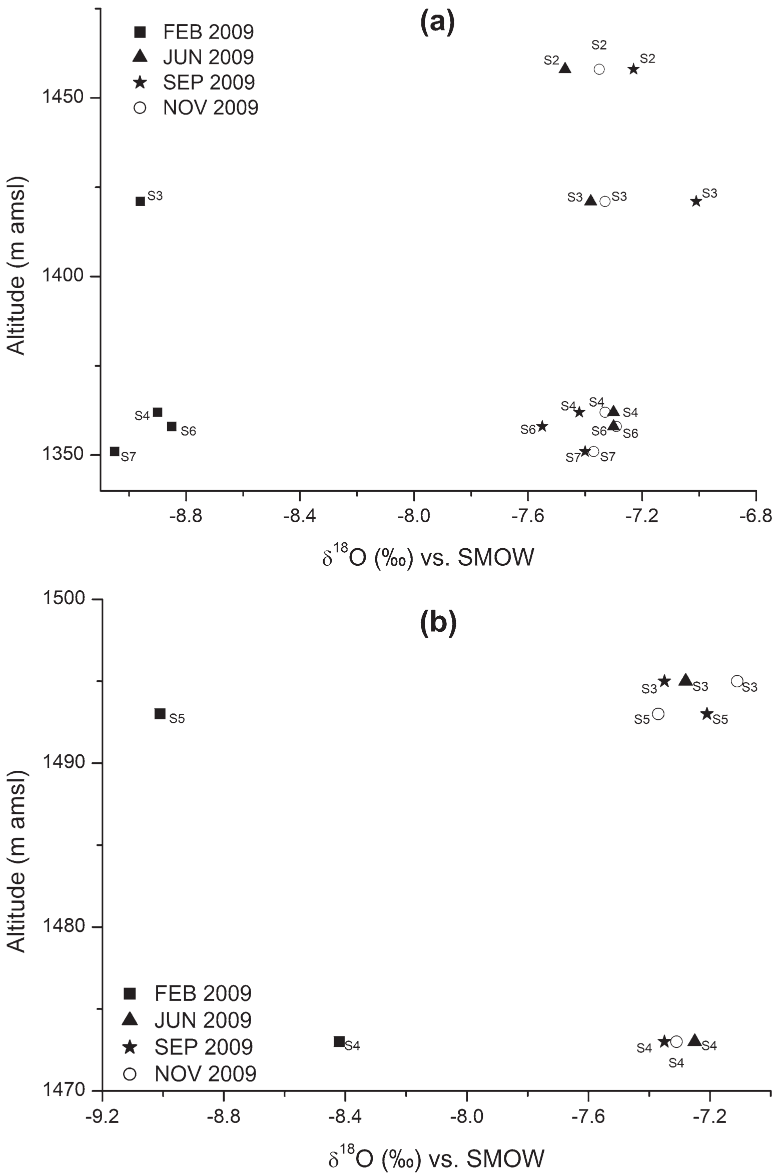


Fig. 14 (**a**, **b**) Altitude versus δ^{18}O composition of spring water samples collected in different valleys; (**a**) valley 1 and (**b**) valley 2

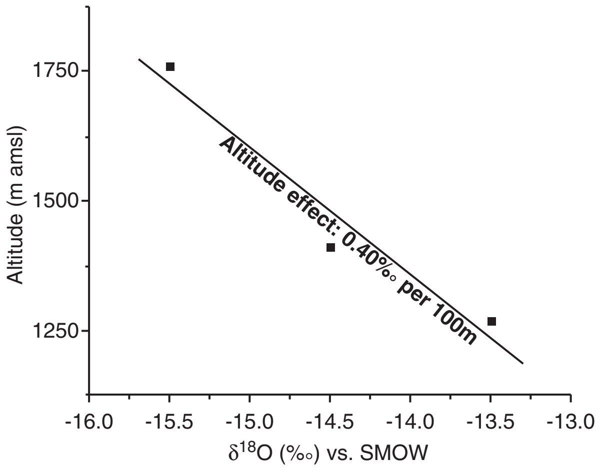


Fig. 15 Altitude versus $\delta^{18}O$ composition of rain water samples collected during 2010

4.2.4 Conclusion

Based on the isotope hydrogeochemical investigations, the following conclusions can be drawn:

- All the spring waters are freshly recharged precipitation water.
- Contribution of winter monsoon is observed in February spring discharges at all sites.
- During the peak monsoon periods (August/September), various subsurface channels contribute to the spring discharges leading to high discharges and wide variation in isotopic content.
- In Pipaya, no altitude effect in isotope content of spring waters is observed, so exact altitude of recharge zones of the springs could not be established using environmental isotopes; however, using local geology and geomorphology, it can be inferred that the recharge altitude is about 1700 m amsl for V3S1 and V4S1, whereas for the rest of the springs, it may vary from 1400 to 1600 m amsl.
- In Brahmkhal, altitude effect was found. Based on altitude effect and geomorphology, it can be inferred that the recharge zone for high altitude springs of both valleys is 1900 m amsl and for low altitude springs, it is 1500 m amsl.
- In Isala, the variation of spring altitudes is about 200 m so no altitude effect was observed. It can be inferred from isotope and hydrochemistry that the springs are recharged by local precipitation and based on geomorphology, recharge altitude was found to be 1600 m amsl.
- In Kakodakhal, based on altitude effect and geomorphology, the recharge area was found to be 1100 m amsl for the springs except one whose recharge areas were found to be 800 m amsl.

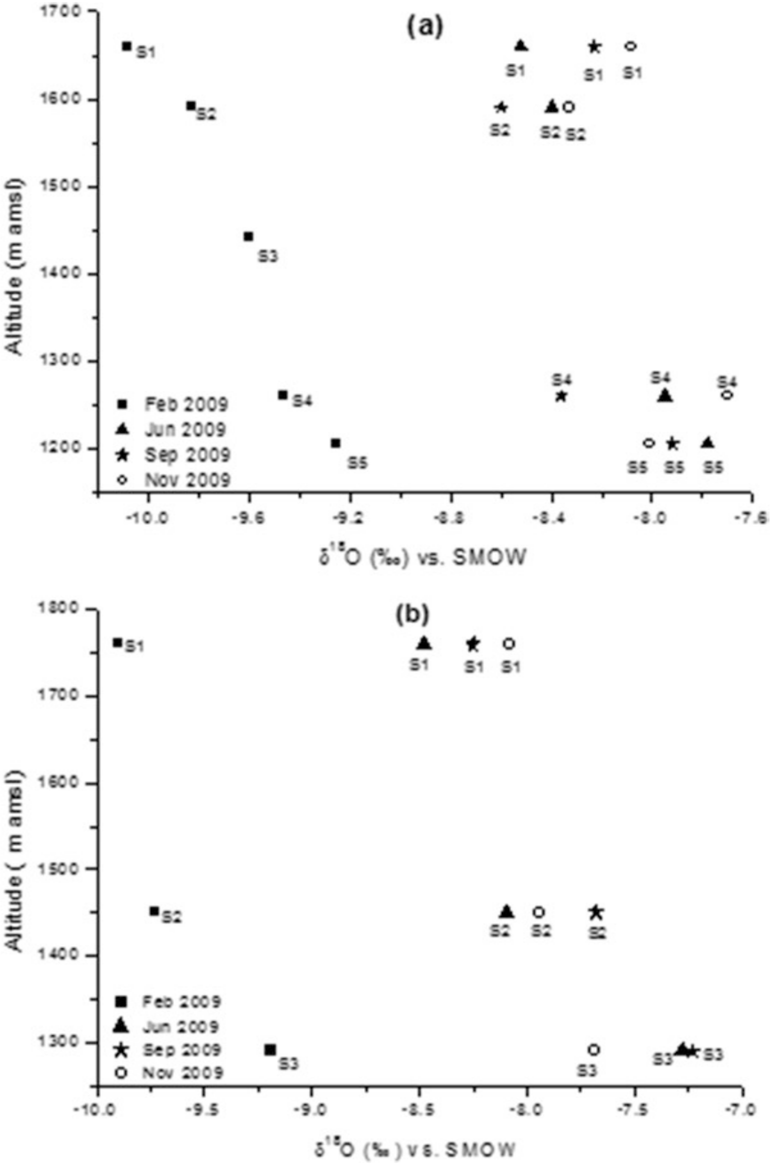
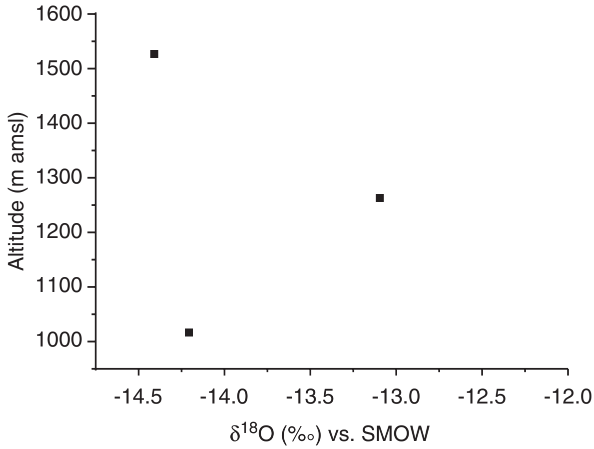


Fig. 16 Altitude versus $\delta^{18}O$ composition of spring water samples collected in different months; (**a**) valley 1 and (**b**) valley 2

Fig. 17 Altitude versus $\delta^{18}O$ composition of rain water samples collected from Isala site



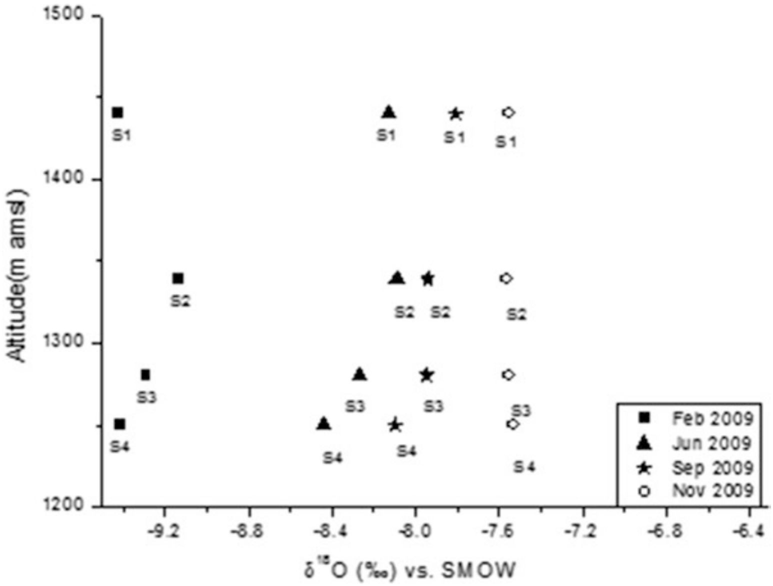


Fig. 18 Altitude versus $\delta^{18}O$ composition of spring water samples collected in different valleys

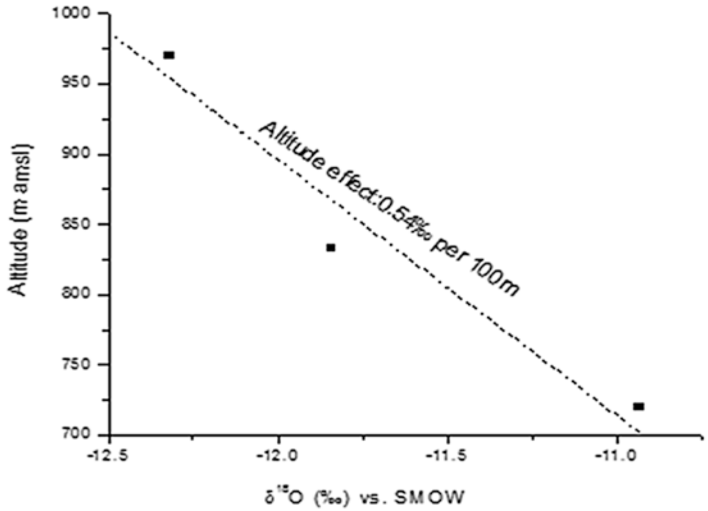


Fig. 19 Altitude versus δ^{18}O composition of rain water samples collected from Kakodakhal site during September 2010 monsoon

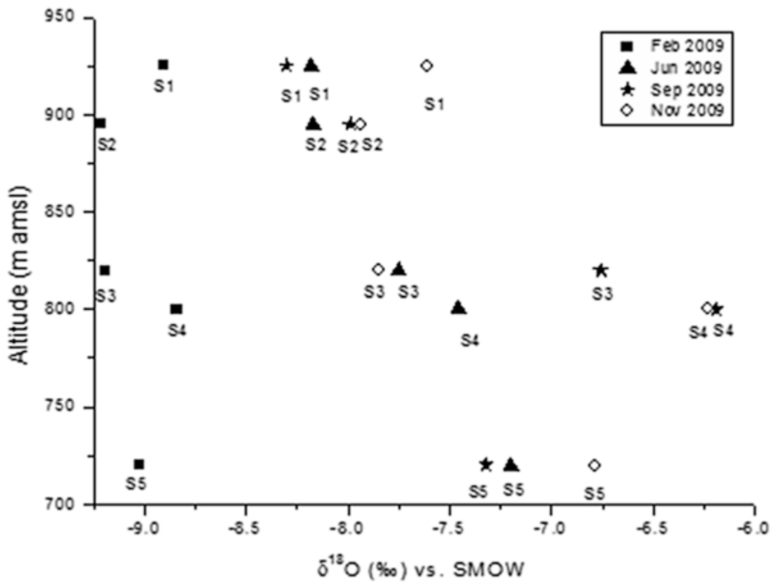


Fig. 20 Altitude versus δ^{18}O composition of spring water samples collected in different months from Kakodakhal site

4.3 Application of Environmental Isotopes in Identifying Source of Seepage Water in the Basement in Some Parts of Jodhpur City, India

4.3.1 Introduction

Seepage water accumulation in the basement of a number of buildings and rise in the static water level (SWL) has been reported in March 1998 in some parts of Jodhpur city. With the availability of water from Rajiv Gandhi Lift Canal located about 209 km from the city, feeding of Kaylana Lake by canal water started in 1998. Jodhpur gets a water supply of about 200 million litres daily. The main source of water supply to the city is from Rajiv Gandhi Lift Canal. Hence, the use of water impounding structures and groundwater has been reduced significantly. Bacteriological analysis has revealed the presence of coliform above permissible limit in all the water samples irrespective of seepage water and groundwater. However, faecal coliform (*E. coli*) is absent in all the samples including basement samples. An isotopic study was carried out to find out the source of seepage in March 2000. Difference in isotopic characteristics of water from different sources helped to understand the source of seepage.

4.3.2 Study Area

Jodhpur is an important city located in the state of Rajasthan of India. It is located at the edge of the Thar Desert and situated at 26°17′N latitude and 73°02′E longitude. It has an average elevation of 232 m. The climate of Jodhpur is generally hot and arid. The amount of rainfall increased tremendously in Jodhpur city and was primarily designed to arrest rainwater in impounding structures to provide sustained water supply to the populace. The city consists of a number of water impounding structures called baories. Seepage from these structures was exploited through a number of wells and step wells. Before 1998 groundwater was the main source of water supply through impounding structures or bore wells. Kaylana Lake in the Jodhpur city was also used for drinking water supply. A rise in the static water level (SWL) ranging from 0.01 to 3 m was noticed in different parts of the Jodhpur city mainly in the old city area. Rise in SWL caused seepage of water in the basement of a number of buildings in some parts of Jodhpur city (Kunj Bihari Ka Mandir and Sojati Gate areas). Kaylana Lake is situated at the higher elevation than the seepage area. Hence, it is believed that there may be direct hydraulic continuity of Kaylana Lake with the seepage area. Increase in the level of Kaylana Lake, due to feeding from the lift canal to meet the demand of the rising urban population, may be responsible for increase in SWL and hence seepage in the basement.

Jodhpur city area that includes areas affected by seepage consists of mainly alluvium and rhyolite, whereas Kaylana Lake area, situated about 10 km on the western side of the city (Fig. 21), consists of fractured rhyolite. A massive rhyolite ridge is

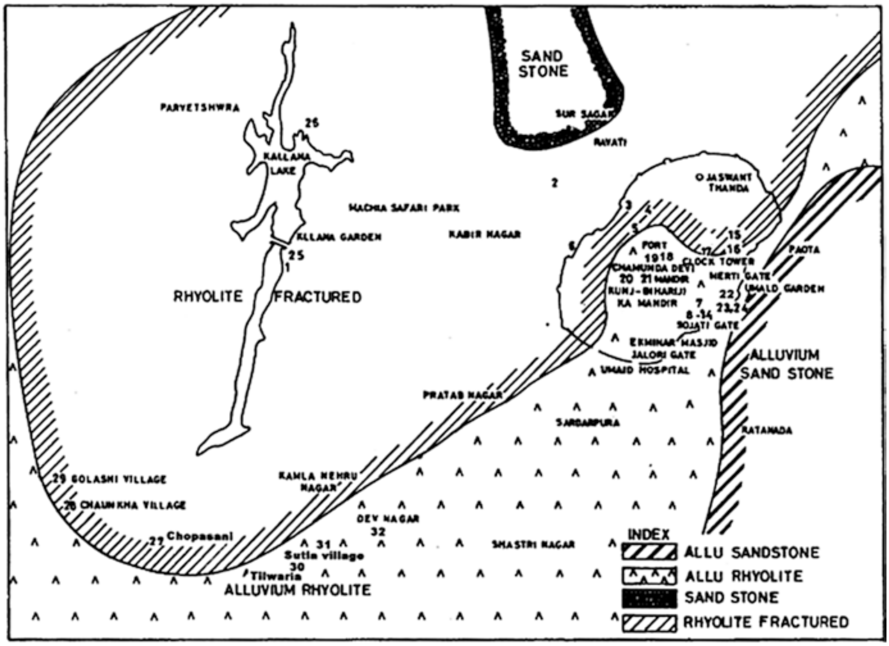


Fig. 21 Location and geological map of Jodhpur city and surrounding areas

running from northeast to southwest between Kaylana Lake and city area. Northern and eastern peripheries of the Jodhpur city consist of alluvium and sandstone. Water samples from wells fitted with hand pumps, basement, lake, filter houses, baories and ponds were collected for environmental isotopes (oxygen-18, deuterium, tritium) as well as chemical analysis in March 2000.

Figure 22 shows reduced levels of different parts of the city. Reduced level of Kaylana Lake is 280 m amsl, whereas reduced level of seepage locations is about 250 m amsl. The affected area is sloping from north to east and southeast. The hills on which the fort is located have higher elevation, and the relief is fairly steep. A number of surface water impounding structures were constructed in the immediate foothill zone and also at suitable location within the city to receive monsoon flows.

4.3.3 Results and Discussion

Chemical quality of water accumulated in the basement does not completely resemble that of the groundwater in wells in the immediate vicinity. EC of lake water from Kaylana Lake and filter houses is around 100 μS/cm since origin of this water is from lift canal. EC of the basement seepage water is less than the bore well and dug well water (groundwater) in the immediate vicinity. Similarly, EC of basement seepage water is less than the groundwater in the immediate vicinity. Therefore, it seems that the seepage water is a mixture of groundwater and lake water.

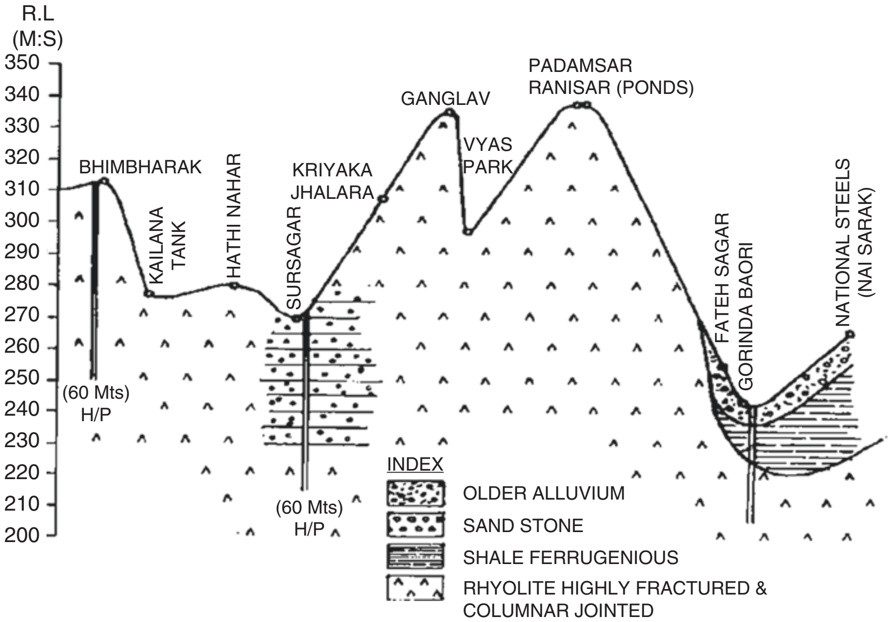


Fig. 22 Reduced level of seepage locations and Kaylana Lake, etc

Bore wells located at south of Kaylana Lake have lower EC than the groundwater near the seepage point. The same trend has been observed for major ion species. Bacteriological analysis (Report GWD 1998) has revealed the presence of coliform bacteria above permissible limit in all the water samples irrespective of seepage water and groundwater. However, faecal coliform (*E. coli*) is absent in all the samples including basement samples. Therefore, water from sewer line is not contributing to the seepage water. Thus, it is very difficult to infer the source of seepage water on the basis of chemical quality. Lake water is fed by the Rajiv Gandhi Lift Canal, and the source of canal water is a Himalayan river (River Satluj) originating from higher altitude and hence is highly depleted in $\delta^{18}O$ and $\delta^{2}H$ (Lambs 2000; Singh and Quick 1993; Singh and Kumar 1996; Singh et al. 1997). Plot of $\delta^{18}O$ vs. $\delta^{2}H$ (Fig. 23) shows that the water samples from lake and filter houses (which has been supplied by lake) are depleted in stable isotopes $\delta^{18}O$ and $\delta^{2}H$ compared to other surface water bodies like baori water and pond water due to Himalayan origin of the water feeding the lake. Pond water is highly enriched in stable isotopes $\delta^{18}O$ and $\delta^{2}H$ due to evaporation effect in desert conditions (Craig et al. 1956). Baories are water impounding structure, which supplies water to nearby wells. Water from baories is slightly enriched than groundwater. $\delta^{18}O$ and $\delta^{2}H$ values of both baori water and groundwater fall near the global meteoric water line indicating that source of baori water and groundwater is recent precipitation. $\delta^{18}O$ and $\delta^{2}H$ value groundwater suggest that groundwater is recharged by modern precipitation without showing evaporation effect (Allison 1982) of desert condition. This can be due to the frac-

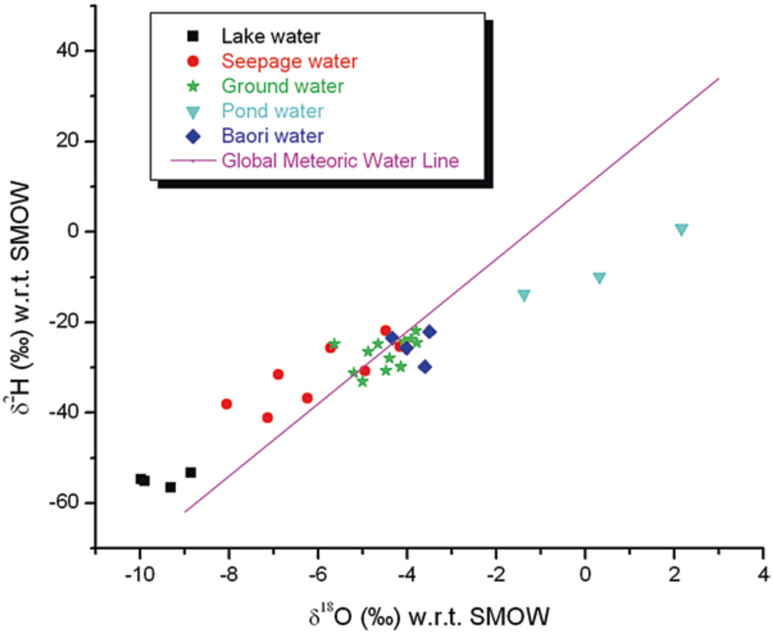


Fig. 23 Stable isotope composition of Jodhpur sample

tured rhyolite geological formation of the Jodhpur city area. Isotopic composition of basement samples fall between lake water and groundwater, which suggests that basement water is a mixture of lake water and groundwater. One spring sample (6) at Byas Park shows significantly depleted values of $\delta_{18}O$ and δ_2H indicating lake water as a major component of spring water, but its elevation (310 m) is greater than Kaylana lake which rules out the possibility of direct hydraulic continuity between lake and spring.

Tritium content of lake water and filter house water varies from 9 to 12 TU, whereas basement samples show tritium content of 6.5–10 TU (Fig. 24). Tritium content of bore well waters is in the range of 2.5–7 TU. Tritium values of groundwater suggest that groundwater contains major component of modern recharge. Groundwater sample, which is south of Kaylana Lake, shows tritium contents of 9.2 TU indicating that it may be getting some contribution from the lake. One groundwater sample from a hospital premise, which is far away from the old city (seepage location), shows very high value of about 15 TU. It seems that the tritium of groundwater is from hospital wastewater disposed off in open. Tritium concentration of spring water (~10 TU) at Byas Park suggests its similarity with lake water. Tritium content of basement samples (seepage water) varies from 7 to 9 TU. Tritium results also suggest that basement samples are mixture of lake water and groundwater. Tritium contents of baori water vary between 7 and 8 TU. Except two groundwater samples, all other groundwater, lake water baori water and spring water show tritium contents of more than 6 TU. Therefore, most of the water is recent water.

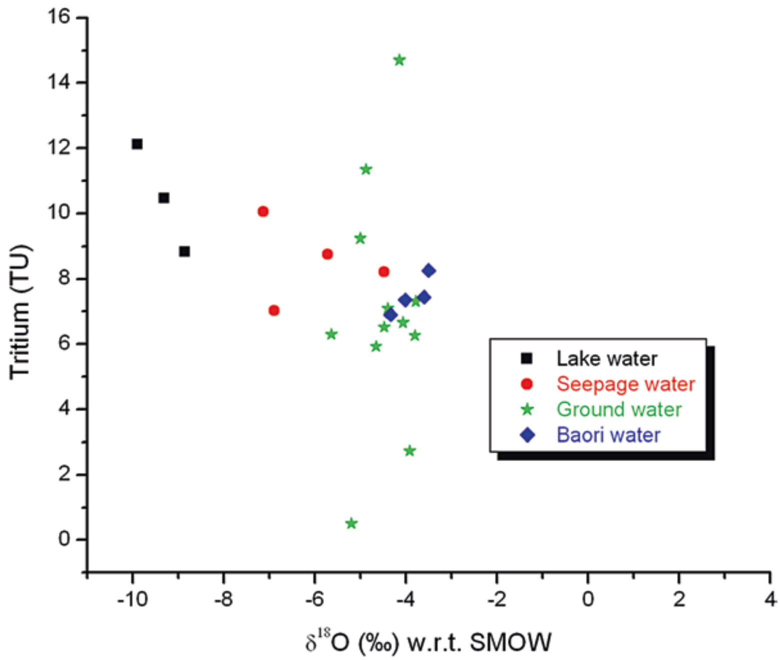


Fig. 24 Tritium contents of Jodhpur sample

4.3.4 Conclusion

On the basis of isotopic, chemical analysis and hydrogeological data, it can concluded that the lake water, which is supplied to the city, is contributing to the seepage water in the basement. The lake water contribution to the seepage could be either due to direct seepage from Kaylana Lake (due to the fractured nature of rhyolite) or seepage from pipelines (carrying lake water) and used water (waste water) percolating to the subsurface. Isotopic content of one spring sample is very close to lake water and the spring is situated at higher elevation than Kailana lake which is about 10 Km from the seepage locations and the spring. Therefore, direct hydraulic continuity of lake water to the seepage water is remote. The absence of *E. coli* in the entire basement samples rules out the possibility of seepage from sewer lines. Engineers from the drinking water supply department could not find any breakage in the water-carrying pipelines in Jodhpur city particularly in the seepage locations. Therefore, lake water contribution through this mechanism is also remote. Old Jodhpur city (seepage location) does not have very planned sewage system. Used water (waste water) supplied from Kaylana lake percolating to the subsurface seems to be the most probable mechanism of lake water contribution to the groundwater. Open dumping of wastewater and low permeability aquifer in the area particularly the old city area of Jodhpur caused the rise in the static water level (SWL) and hence seepage in the basement of building. After availability of water from the lift canal, which is fed to Kaylana Lake, consumption of lake water increased, and groundwater consumption decreased. Therefore, increased consumption of lake water and discontinuation of groundwater withdrawal have further aggravated the seepage situation in the area.

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Part VI
Contaminated Ground Water & Its Mitigation

Arsenic and Fluoride Contamination in Groundwater: Mitigation Strategies

K. J. Nath

Abstract Presence of arsenic and fluoride in groundwater has been reported in many parts of the world. The anthropogenic causes of such contamination are understood, but the mechanism for release of arsenic and fluoride in the aquifer water is yet to be explained. Millions of people depending on groundwater sources are at risk with adverse health impacts due to arsenic or fluoride poisoning. To meet the challenges, mitigation strategies are suggested adjusting the most critical issues.

Keywords Keratosis · Mottled enamel · Defluoridation · Adsorption · Co-precipitation

1 Introduction

Groundwater sources like deep tube wells have generally been taken as safe, without any bacteriological contamination. However, in post-independence India, particularly during the 1960s and 1970s, contamination of groundwater sources with elevated levels of arsenic, fluoride and other geogenic and anthropogenic contaminants has emerged as a major public health concern. The current crisis in the country is primarily due to geogenic reasons. Fluorosis is endemic in 19 states of India; 65 million people including 6 million children are affected. Arsenic contamination of groundwater is most serious in West Bengal where 16 million rural and 12 million urban populations are at risk. The problem is assuming serious proportion in a number of other states in the Ganga-Brahmaputra plains. In this paper, the mitigation strategies against arsenic and fluoride contamination of groundwater are discussed.

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S. P. S. Ray (ed.), *Ground Water Development - Issues and Sustainable Solutions*, https://doi.org/10.1007/978-981-13-1771-2_15

2 Arsenic Contamination: Extent and Magnitude

The most affected countries include India, Bangladesh, Myanmar, Laos, Cambodia, Thailand, Vietnam, etc. There is no report of arsenic contamination of groundwater from Sri Lanka, Maldives and Bhutan. An exact evaluation of the extent and magnitude of contamination of groundwater sources and its impact on community health is difficult in the absence of effective and regular water quality surveillance in the rural areas of these countries. Data on epidemiological assessment is also scanty. On a rough estimate, 100–150 million people might be living in the potentially and hydrogeologically risk zone.

In India, the most affected state is West Bengal, where 83 blocks out of 172 in 8 districts in the Gangetic Delta are affected (more than 0.05 mg/l). With the downwards revision of the national standard from 0.05 to 0.01 ppm, the number of affected blocks in the state now stands at 111. Reports of arsenic in groundwater have been received from six other Indian states like Bihar, Jharkhand, Uttar Pradesh, Assam, Chhattisgarh and Madhya Pradesh. The extent of the problem in these states is not yet fully known in the absence of data regarding water quality in the potentially risk areas and epidemiological information.

2.1 The Cause of Arsenic in Soil and the Mechanism of Its Dissolution in the Groundwater

The arsenic contamination of groundwater in West Bengal and Bangladesh and many other South East Asian countries is basically geogenic in character. A few cases of anthropogenic contamination have also taken place in recent past. During the late 1980s, a number of tube wells in South Kolkata of West Bengal were contaminated with arsenic by the effluence from pesticide waste dump. There are also reports of anthropogenic contamination of groundwater with arsenic from coal ashes, mining activities, fertilizers, etc. However, in most of the cases, contamination is geogenic.

The concentration of arsenic in soils (sand and clay) in Gangetic belt could be anywhere between 3 and 6.5 mg/kg (reports from Bangladesh) much higher concentrations have also been reported from other countries. However, the concentration of arsenic in groundwater is not always proportional to that in soil. That is largely determined by the geochemical and environmental condition prevailing underground.

2.2 Health Impact

Preliminary symptoms of chronic arsenic poisoning, when one drinks water containing arsenic above the permissible limit for a significantly long period, include hyperpigmentation, dyspigmentation and keratosis. Continuing the same could

Table 1 Estimated incidence of excess lifetime skin cancer in Bangladesh

Drinking water supply in Bangladesh	Estimated incidences of excess skin cancer (% of present population)
At present arsenic contamination level	375,000 (0.290%)
Satisfying the Bangladesh standard of 50 ppb	55,000 (0.043%)
Satisfying the WHO guideline value of 10 ppb	15,000 (0.012%)

Source: Prof. F. Ahmed, BUET, Dacca

cause skin cancer and internal cancer like bladder cancer or lung cancer. An epidemiological study with adequate sample size is yet to be undertaken to assess the health impact of groundwater contamination with arsenic in our country. According to the mathematical model developed by EPA to estimate lifetime risk of skin cancer, WHO guideline value of 10 ppb arsenic in drinking water is associated with a lifetime skin cancer risk 6 per 10,000 people. As per that model, the predicted lifetime skin cancer is given below (Table 1).

Limited information are available regarding the disease burden due to arsenicosis in West Bengal. In an epidemiological survey carried out by Dr. Guha Majumdar et al. (1998)$_{xii}$, in 1 of the affected districts of West Bengal (South 24 Parganas), where 7683 people were examined in 57 arsenic-affected villages, the prevalence of arsenical skin lesion was found to be 4.6%. Further, Saha (2003)$_{xvii}$ reported the incidence of arsenic-related cancer to be 5.1% among 4865 cases of arsenicosis examination during the period of 1983–2000. However, the data of the former study represented information in a highly exposed region of the state, while the later data were compiled from cases examined in a tertiary referral centre, and some scattered survey carried out in the affected districts of the state. Increasing malignancy due to arsenic contamination in West Bengal during the 1980s and 1990s were reported by Dr. K C Saha (Fig. 1).

Drinking arsenic-rich water over a long period is unsafe, as arsenic is a documented carcinogen. The commonly reported symptoms of chronic arsenic poisoning include hyperpigmentation, dyspigmentation and keratosis. Skin cancer and internal cancer can also occur which is shown in Fig. 1. A scientific epidemiological assessment of the extent and magnitude of the problem has not yet been made. High concentrations of arsenic in community water sources do not always correlate with high levels of arsenicosis symptoms in the community. According to a multistage model applied by EPA to estimate lifetime risk of skin cancer (based on an epidemiological study in Taiwan), WHO guideline value of 10 ppb arsenic in drinking water is associated with a lifetime excess skin cancer risk of 6 per 10,000 people. The same for the national standards 50 ppb, followed in India, Bangladesh and many other Asian countries, is 29 per 10,000 people (0.29%).

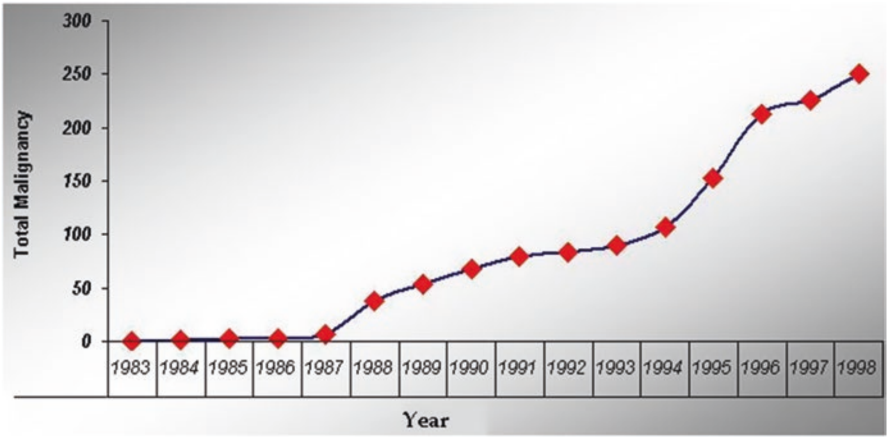

Fig. 1 Increasing malignancy due to arsenic contamination in West Bengal. (Source: Dr. K.C. Saha, Ex-Prof. of Dermatology, School of Tropical Medicine, Calcutta)

2.3 Mitigation Strategies: Critical Concerns

The basic objective and principal agenda of a mitigation strategy should include identification of unsafe sources and affected population and to arrange adequate supply of safe water to the affected people. It is often seen that in affected areas, all the tube wells are not contaminated with arsenic/fluoride in a village. If we could take up effective awareness campaign and mark the contaminated sources, most people could stop drinking water from unsafe sources. The government's capacity to supply safe drinking water in the arsenic- and fluoride-affected areas should be augmented significantly to redress the grievance of the people. Creation of a scientific GIS database and formulation of a long-term master plan for mitigation of the problem is suggested. Health Dept. should take adequate medical care of the seriously sick people. But we must understand that there is no medical cure to arsenicosis/fluorosis if the person continues to drink arsenic/fluoride contaminated water. The emerging danger of arsenic contamination of soil and crops should be studied urgently for a long-term change in agriculture and irrigation practice and restricting the use of groundwater (Fig. 2).

2.4 Setting National Standard

WHO guideline value for arsenic in drinking water is 0.01 mg/l. India has very recently adapted the same as its national standard. However, many countries are still adhering to the standard of 0.05 mg/l. Table 2 depicts the standards for arsenic in groundwater in various countries.

Fig. 2 Arsenic affected patients

Table 2 Standard for arsenic in groundwater in various countries

Countries	Standard (mg/L)	Countries	Standard (mg/L)
Australia	0.007	Bolivia (1997)	0.05
European Union (1998)	0.01	China	0.05
Japan (1993)	0.01	Egypt (1995)	0.05
Jordan (1991)	0.01	India	0.05
Laos (1999)	0.01	Indonesia (1990)	0.05
Mongolia (1998)	0.01	Oman	0.05
Namibia	0.01	Mexico	0.05
Syria (1994)	0.01	Philippines (1978)	0.05
USA (2001)	0.01	Saudi Arabia	0.05
Canada	0.025	Sri Lanka (1983)	0.05
Bahrain	0.05	Vietnam (1998)	0.05
Bangladesh (1997)	0.05	Zimbabwe	0.05

2.5 Technology Options

Appropriate technology options are the most important and critical precondition for successfully addressing the problem of arsenic contamination in groundwater. Initially in many countries, it was attempted to sink tube wells in the deeper aquifer more than 150 m depths, which is more or less arsenic-free. However, this option has a risk of leaking of arsenic-contaminated water from the upper carboniferous aquifer to the deeper aquifer.

Another option is to supply arsenic-free water from alternate arsenic-free water sources like rivers, lakes, etc. However, this option requires that the water from surface sources should be appropriately treated for removal of pathogenic microbes. Often, as in case of West Bengal, large treatment plants are constructed for the water treatment, and the same is carried by trunk water main for distribution to distant villages. However, this approach is capital intensive and often faces chronic O&M problems. A more decentralized and cost-effective alternative could be to use the water of local ponds, canals, dug wells, etc. for supply to the people. This approach requires capacity building in the villages for installation and operation of low cost and user-friendly for quality upgradation of pond water. This will be ideal solution if rain water harvesting is combined with the same to make the pond sustainable.

Another alternative is to remove arsenic from the groundwater and distribute the same to the nearby villages by designing mini-piped water scheme. For removal of arsenic from groundwater, various technologies have been used like adsorption, co-precipitation (oxidation, coagulation, filtration) and ion exchange. For adsorption, various kinds of media are being used like activated alumina, iron oxide, laterite and nanomaterials. Among various emerging technologies, the application of various kinds of nanomaterials for arsenic removal appears to be most promising (Figs. 3 and 4).

Fig. 3 Arsenic Treatment Units with hand pump operated tubewells

Fig. 4 Large surface water-based plants – PHED, Govt. of West Bengal

3 Fluoride in Groundwater: Extent and Magnitude

The contamination of groundwater with excessive fluoride has become a huge health problem in many states of India.

- Fluorosis is endemic in 22 states (200+ districts and 1 lakh+ villages) of India. Sixty-five million people, including 6 million children, are affected.
- Fluoride levels in India's groundwater vary from 1 to 48 mg/l (The WHO guideline for maximum permissible level of fluoride in drinking water is 1.5 mg/l).
- A 1999 study by New Delhi-based Fluorosis Research and Rural Development Foundation has identified 59,111 problem villages with fluoride levels above 1.5 mg/l.
- 1997 study by the Rajasthan Voluntary Health Association shows that almost 35,000 people in the state are consuming water having more than 10 mg/l of fluoride.

3.1 Health Impact

People drinking fluoride for a long time are likely to suffer from dental fluorosis (drinking water having fluoride marginally above 1 mg/l). When fluoride level in drinking water exceeds 3 mg/l, the crippling skeletal fluorosis might result. Skeletal fluorosis creates pain in the joints finally crippling the patients. There have been reports that drinking water with fluoride level above 3 mg/l might also cause gastro-intestinal problems, allergies and urinary tract problems. WHO guideline suggests the maximum level of fluoride in drinking water at 1.5 mg/l.

3.2 Fluoride Control Options

(a) In fluoride-affected area, firstly one should attend to use drinking water from alternate sources which do not fluoride above permissible limit.
(b) Transporting water from a distance source.
(c) Use of dual water sources
(d) Rain water harvesting
(e) Use of defluoridation technologies for removal of fluoride from water.

3.3 Defluoridation Technologies

Defluoridation technologies can be broadly classified into three categories according to the main removal mechanism:

- Chemical additive methods
- Contact precipitation
- Adsorption/ion exchange methods

3.4 Reverse Osmosis Technology

In recent years, reverse osmosis (RO) technology which uses membrane with fine pores for removing dissolved substances from the water is being used widely for water purification purposes. This process is not specific for particular substance. Along with undesirable elements like fluoride/arsenic, these would also remove all other dissolved substances and bacteria from water, including some beneficial minerals. One of the critical operational problems faced by RO units is clogging of fine pores. The process involves significant wastage of water with elevated concentration of dissolved impurities.

4 A Decentralized Low-Cost Approach Based on Traditional Rural Surface Sources (Ponds, Rivers, etc.) in Arsenic/Fluoride Endemic Areas

International Academy of Environmental of Sanitation and Public Health (a subsidiary of Sulabh International Social Service Organization) has successfully demonstrated that the water from the rural surface sources like ponds, rivers, etc. could be treated in a simple treatment plant as depicted in Fig. 5 and the same could be

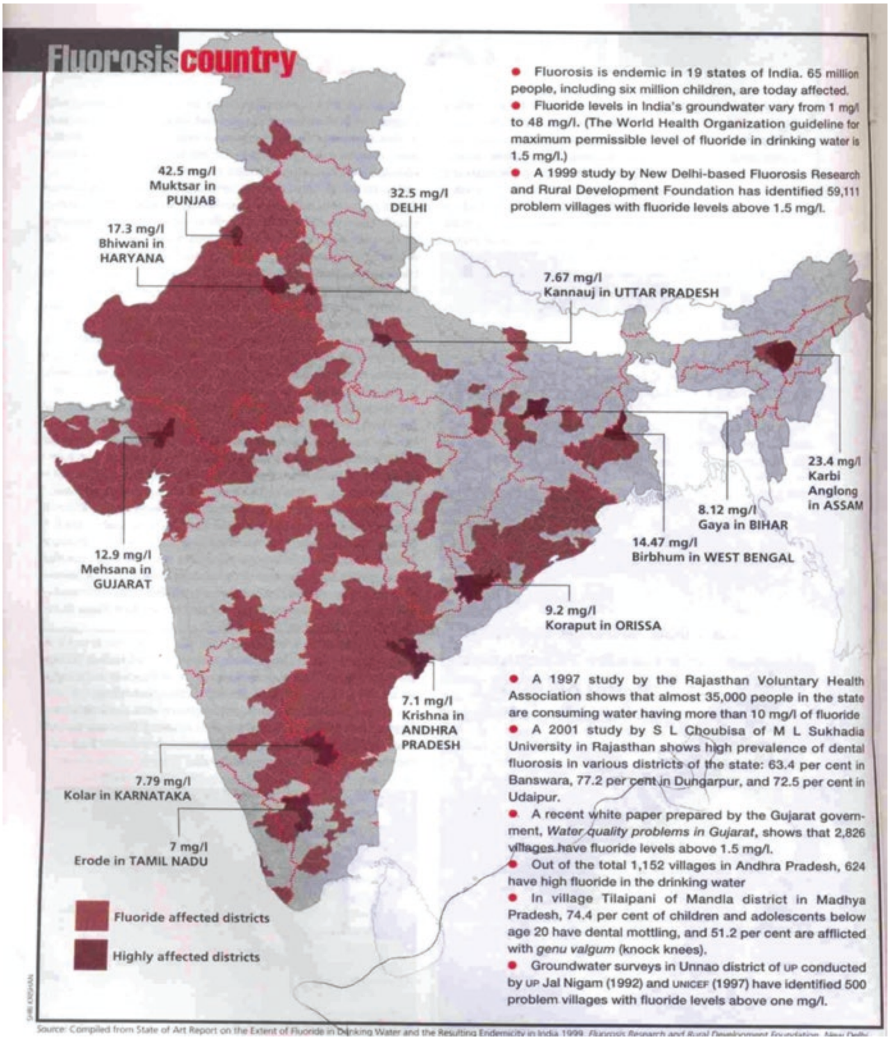

Fig. 5 Fluoride-affected states of India

Fig. 6 Fluorosis-affected patients

operated, maintained and managed at the village level. This could be a cost-effective and people-friendly approach for safe drinking water supply in the arsenic/fluoride endemic areas. Salient features of the treatment plant including the operation, maintenance and capital cost is given below. The example of capacity building (Fig. 6) at the grass root level and empowering the rural people would be an ideal solution in many of the arsenic and fluoride-affected villages.

In West Bengal and other states in the planes of river Ganga in eastern India, the annual rainfall is quite satisfactory, and there are many perennial and sustainable water sources like pond and canals in the rural area. Unfortunately, these are often abused by human behaviours and as a result get heavily contaminated, resulting in epidemics of diarrheal diseases and endemicity of the same in the community. A low-cost and community-friendly treatment process which could be successfully operated and maintained by trained rural workers would provide the rural community absolutely safe and free from arsenic/fluoride (Figs. 7 and 8).

5 Conclusion

Given the experience in the developing countries of Asia, where arsenic in groundwater is posing a great challenge to the health of a large number of people, the following could be mentioned as the major factors impeding the progress of the projects to address the problem:

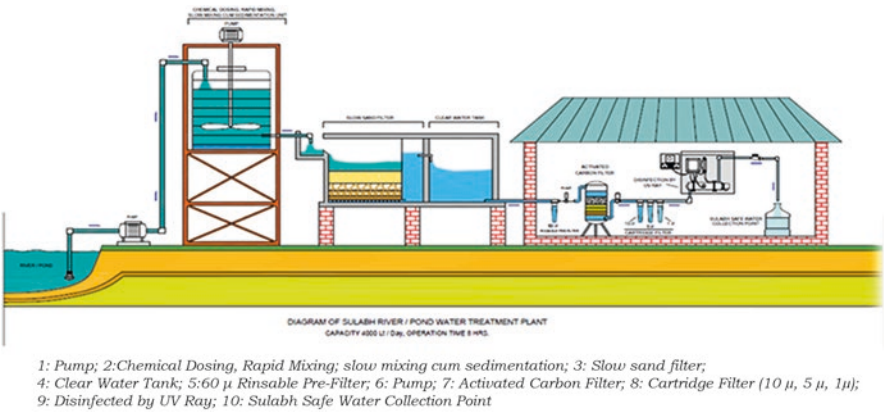

Fig. 7 Flow sheet of Low-cost rural water supply from ponds/rivers

Fig. 8 Capacity building at the grass root level and empowering the people

- Gap between the perceived need of the people and approach of the implementing agencies.
- Long period of completion for large capital-intensive government project/lack of interim relief.
- In general, rural populations are largely unaware of the technologies developed by various institutions and organizations due to poor promotional activities.
- Lack of knowledge among the people regarding the health impact of the arsenic problem.
- Lack of facilities at the grass root level for water quality monitoring.

Central and state governments have invested significant amount of resources for the mitigation of arsenic and fluoride programme, but implementation of the same is facing a number of constraints. Lack of people’s participation in the programme is a critical concern. There is an acute need for generating awareness among the beneficiaries regarding the arsenic/fluoride contamination of groundwater and its health impact. We need to be objective and realistic in making technical and economic decisions in relation to the current problem of arsenic and fluoride contamination of groundwater.

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Community-Based Defluoridation of Groundwater by Electrocoagulation Followed by Activated Alumina Adsorption

Arindam Haldar, Banhita Pal, and Anirban Gupta

Abstract Water is essential to human life, yet over billion people across the world have no access to safe drinking water. It is evident in the report of WHO that there is an excess fluoride concentration in groundwater of more than 25 countries including developed and developing countries across the world. Widespread fluorosis cases related to the presence of fluoride in groundwater supplies are major public health problems. Electrocoagulation is an emerging technology for fluoride removal. Activated alumina is a common adsorbent for fluoride removal. In this study, electrocoagulation along with sand filtration was tried as a pretreatment followed by activated alumina adsorption. This technology has been installed in Chhoto Irga village of Purulia district of West Bengal. The results show that electrocoagulation can remove fluoride to a significant extent. Provision of activated alumina bed helps to take care of fluoride removal in case of the electrocoagulation setup malfunctions. Electrocoagulation removes a significant amount of fluoride, and therefore, the challenge to the subsequent alumina bed is reduced helping to prolong the life of alumina bed before exhaustion. In this design, the alumina bed is split into two columns – lead and lag. It helps to utilize more adsorption capacity of alumina and also allows for a time before regeneration of an exhausted alumina column can be actually performed without jeopardizing the safety of the treated water. The aluminum concentration was found to be below permissible limit in the drinking water. The community-based and self-sustained defluoridation unit is functioning till date.

Keywords Fluoride · Electrocoagulation · Activated alumina · Defluoridation · Aluminum

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S. P. S. Ray (ed.), *Ground Water Development - Issues and Sustainable Solutions*, https://doi.org/10.1007/978-981-13-1771-2_16

1 Introduction

Widespread fluorosis cases related with the presence of fluoride in groundwater supplies are major public health problems. Many countries of the world and most of the states in India are affected by fluoride contamination. Sporadic incidences of high fluoride content in groundwater have been reported from Asian, African, European, and North and South American countries. Geographically, the affected areas include the countries like India, China, Sri Lanka, West Indies, Spain, Holland, Italy, Mexico, and North and South American countries. India and China, the two most populous countries of the world, are the worst affected. Fluoride level above permissible limit of 1.5 mg/L occurs in 19 Indian states, namely, Andhra Pradesh, Assam, Bihar, Chhattisgarh, Delhi, Gujarat, Haryana, Jammu & Kashmir, Jharkhand, Karnataka, Kerala, Maharashtra, Madhya Pradesh, Orissa, Punjab, Rajasthan, Tamil Nadu, Uttar Pradesh and West Bengal affecting, according to PHED, India (http://www.wbphed.gov.in/main/index.php/component/content/article/95; water – quality/134-fluoride). The significant fact is that fluoride has beneficial effects on teeth at low concentrations in drinking water, but, on the other hand, excessive exposure to fluoride in drinking water or in combination with exposure to fluoride from other sources can give rise to a wide range of adverse effects like mild dental fluorosis (McKee and Johnston 1934) to crippling skeletal fluorosis (Bhu-Jal News 2009). The latter, skeletal fluorosis, is more hazardous and carries a significant cause of morbidity in different regions of the world.

There are several conventional and nonconventional processes for fluoride removal like chemical coagulation, activated alumina adsorption, ion exchange, reverse osmosis, etc. Electrocoagulation is one of the emerging technologies that can be applied for fluoride removal. The most common technique that is used in India is coagulation-sedimentation (CPHEEO 1999) by addition of alum and lime (Nalgonda technique). However, increased TDS and generation of high quantity of sludge and high aluminum in effluent water are found to be problematic for this technique. Larger amount of alum and pH control is another problematic issue. On the other hand, the electrocoagulation system was chosen for fluoride removal because its capacity is high, almost 95–98%. It requires simple equipment and less maintenance and is easy to operate. EC produces effluent with less TDS. Moreover, the operating cost is lower for this technique.

1.1 Electrocoagulation

Electrocoagulation is an electrochemical process to remove fluoride from aqueous solution. In this process, electro-dissolution of the sacrificial anode to the water leads to the formation of hydrolysis products (hydroxo-metal species) that are effective in the destabilization of pollutants and/or in the formation of particles (flocs) with low solubility that entrap the pollutants. Subsequent removal of flocs by settling or filtration will also remove significant extent of fluoride. The main cathodic and anodic reactions for fluoride removal using aluminum electrodes are as follows:

$$\mathrm{Al} \rightarrow \mathrm{Al}^{+3} + 3\mathrm{e}\left(\text{At the anode}\right) \quad (1)$$

$$2\mathrm{H}_2\mathrm{O} + 2\mathrm{e} \rightarrow \mathrm{H}_2 + 2\mathrm{OH}\ \left(\text{At the cathode}\right) \quad (2)$$

Some researchers (Mameri et al. 1998; Emamjomeh and Sivakumar 2006; Mameri et al. 2001; Hu et al. 2003) have demonstrated that EC using aluminum electrodes is effective in fluoride removal. It was found that electrocoagulation by using aluminum electrode is better than using iron electrode (Zhu et al. 2007) in case of fluoride removal. Moreover, the influence of parameters such as inter-electrode distance, fluoride concentration, temperature, and pH of the solution was investigated and optimized with synthetic water in batch mode. Aluminum ions (Al^{3+}) produced by electrolytic dissolution of the anode (Eq. 1) immediately undergo spontaneous hydrolysis reactions (Behbahani et al. 2011) which generate various monomeric species. From thermodynamic calculation, it was determined that the aluminum fluoride complexes are generally the dominant inorganic aluminum species (Emamjomeh et al. 2011). The complexes of Al are not precipitated until the solution pH is reached to 6. Mameri et al. (1998) proposed that the dissolution of aluminum anode produces Al^{3+} ions which at appropriate pH are transformed to aluminum hydroxide Al(OH)3 and finally polymerized to Aln(OH)3n. The polymerized compound has strong affinity to fix fluoride ions. It was also found that the fluoride removal process is more efficient for a pH ranging from 5 to 7.6 and the removal is higher for lower temperature. The removal of fluoride was found to be better for higher current density (Taştaban et al. 2013). Bipolar connection was better than the monopolar connection for fluoride removal (Ghosh et al. 2008). Zhu et al. (2006) found that at low pH 5.5, the removal of fluoride by flocs was 35% and 45% by electrode, whereas at pH 7.0 the removal of fluoride by flocs was 10% and 50% by electrode. For higher charge loading, the fluoride removal by electrode is increased up to 85% at 4.13 faraday/m^3. For higher current density, the removal by electrode is decreased 40–20% (current density 4.63–92.59 A/m^2).

1.2 Activated Alumina

Activated alumina (AA), which is Al2O3 nH2O, is prepared by the dehydration of aluminum hydroxide in the temperature range of 300–600 °C. Activated alumina is a granular, highly porous material consisting essentially of aluminum trihydrate. It is extensively used for the removal of fluoride and arsenic from drinking water (Kubli 1947; Ghorai and Pant 2005). The fluoride uptake capacity of activated alumina depends upon the specific grade of AA and its particle size as well as the characteristics of the source water being treated.

According to WHO (1984, 1993) the fluoride removal capacity of alumina is between 4 and 15 mg/g. Experience from the field, however, shows that the removal capacity is often about 1 mg/g (Fawell et al. 2003). One of the explanations may be due to variation in pH. The capacity of alumina is highly dependent on pH, the optimum being about pH 5. Activated alumina has absorbance property. It can adsorb fluoride from water. It was also found that fluoride removal can be done from drinking water by magnesia-amended activated alumina granules (Maliyekkal et al. 2008).

2 Laboratory Investigations

Several tests were conducted at the laboratory to design an electrocoagulation system for fluoride removal in field applications. Fluoride content was determined by an ion-selective electrode (ORION model no. 290A+ made by Thermo Electron Corporation, APHA 1995) using TISAB-III. The aluminum content was determined by DR-2800 spectrophotometer made by HACH using aluminum reagent.

The electrocoagulation tests in batch mode were carried out with IIEST groundwater spiked with fluoride (NaF) as well as water from Chhoto Irga village, Para block of Purulia district which was naturally contaminated with fluoride. The water characteristics are shown in Table 1.

A study was carried out to find the effect of electro-charge loading (ECL) on fluoride removal. It is expected that larger amount of aluminum will be released at the anode for higher ECL, and as a result, higher concentration of aluminum hydroxide in the water will help in enhanced removal of fluoride. One ampere of current was passed through aluminum electrodes in 1 L fluoride-spiked water (5.05 mg/L of fluoride) for 150 s, 250 s, and 350 s to generate different ECL. After passage of current, the water is passed through a sand filter (0.6 m long, 0.038 m diameter, flow rate 25–30 l/min.m^2). The effluent was monitored for fluoride, and the results are tabulated in Fig. 1. The removal was increased significantly while the ECL was increased. Even 90% removal of fluoride occurred when ECL of 350 coulombs/L were applied.

In practical application of electrocoagulation, it may be possible to detain the floc suspension period if that helps in enhanced adsorption of fluoride. To observe the effect of detention time on fluoride removal, an experiment was conducted with IIEST groundwater (spiked with fluoride 5.76 mg/L). One ampere of current was passed in 1 L water for 150 secs (ECL 150 coulombs/L), and thereafter flash mixing

Table 1 Characteristics of various water samples

Types of sample	pH	Alkalinity (mg/L as $CaCO_3$)	Conductivity (micro Siemens/cm)	Total hardness (mg/L as $CaCO_3$)
IIEST groundwater	7.6	395	2500	855
Chhoto Irga groundwater	6.9	290	645	210

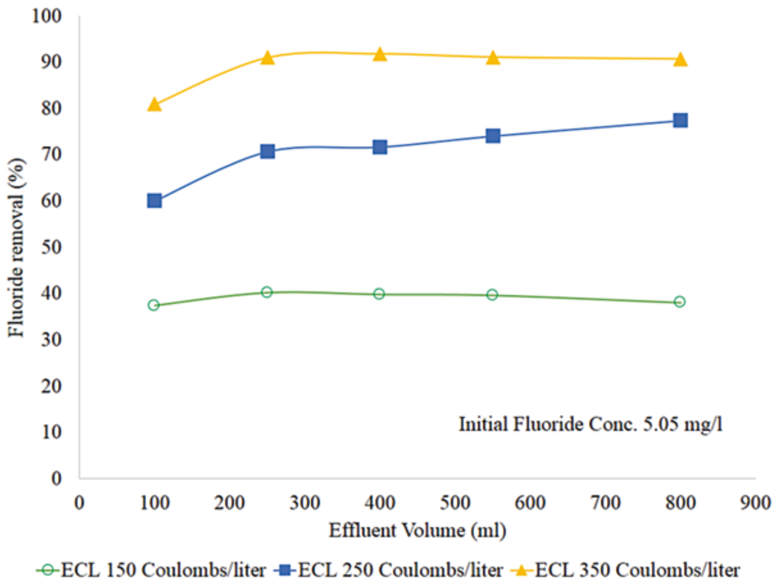

Fig. 1 Effect of ECL on fluoride removal

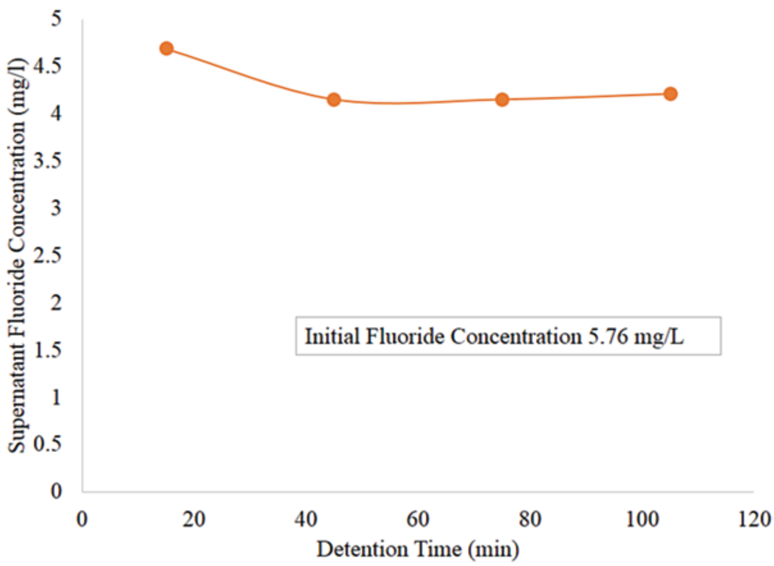

Fig. 2 Effect of detention time on fluoride removal

was provided for 1 min. Samples of supernatant were withdrawn after allowing settling for different time periods from 15 min up to 105 min and analyzed for fluoride. The results (Fig. 2) indicate no significant change of fluoride removal with higher detention time.

3 Field Trial of Electrocoagulation

After getting positive indications regarding applicability of electrocoagulation for fluoride removal, such system has been piloted in Chhoto Irga village of Purulia district of West Bengal, where the groundwater source was having fluoride level about 4.0 mg/L. The defluoridation unit was installed in the premises of the Chhoto Irga Primary School to serve the schoolchildren and also the local community. The electrocoagulation unit was installed in the overhead tank where the groundwater is pumped. The water passed through the electrocoagulation unit whereby dissolved aluminum ions are mixed from the sacrificial aluminum anodes. Thereafter, filtration through sand bed was helpful to get rid of the aluminum hydroxide flocs along with adsorbed fluoride. No additional detention was provided in the overhead tank after electrocoagulation and prior to filtration as it was observed in laboratory study that detention does not improve the fluoride removal. In this unit, an activated alumina bed for posttreatment follows the electrocoagulation setup. Electrocoagulation is influenced by seasonal variation of water composition and gradual passivation of electrodes, and therefore, a downstream treatment with activated alumina bed will make the treatment chain more robust and reliable to bring down the fluoride level below the desirable limit. Moreover, the alumina bed is split in two columns in series which helps to utilize greater adsorption capacity of activated alumina in lead-lag combination and reversal of flow (Figs. 3 and 4). Moreover, regeneration of only the lead column will be needed when it is exhausted. This provides reasonable reaction time for the maintenance personnel to arrange for regeneration/replacement of the lead column as the lag column will still be able to remove fluoride to provide safe water during that period.

Initially the charge density of about 50 coulombs/L was applied, and as a result, about 20% fluoride removal was achieved by electrocoagulation. Passivation was initially a problem, and aluminum plates had to be cleaned periodically by acid. After a few months, a higher wattage power supply was used, and around 120–140 coulombs/L of charge density could be applied for electrocoagulation, resulting in higher fluoride removal of 40–50% (Fig. 5), which is in concurrence with predicted removal from the laboratory studies. A suitable electrode configuration was also developed which reduced the maintenance problems of the electrodes due to passivation.

The fluoride concentration in final water (after activated alumina adsorption) was always below the acceptable limit (1.0 mg/L as per IS10500-2012). Due to high concentration of fluoride, one activated alumina column (lead column) was exhausted within the 3 months of the installation. However, due to the presence of the second activated alumina column (lag column), the final water was fluoride-safe, and the villagers got the time for regeneration of replacement of activated alumina. There was a concern about soluble aluminum (which is suspected to be

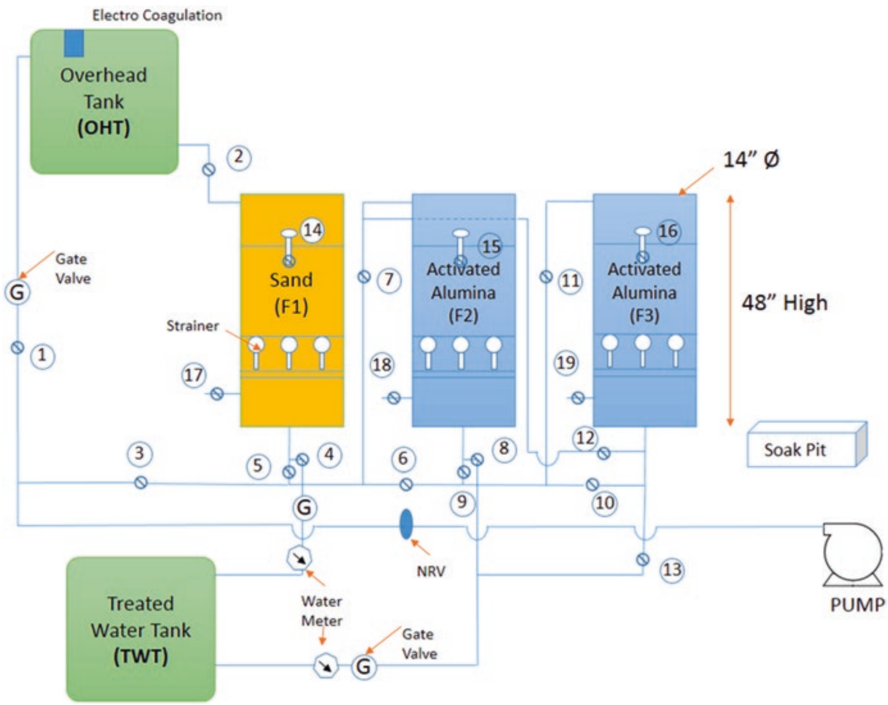

Fig. 3 Scheme of defluoridation unit diagram for electrocoagulation

Fig. 4 Defluoridation unit at Chhoto Irga, Purulia, West Bengal

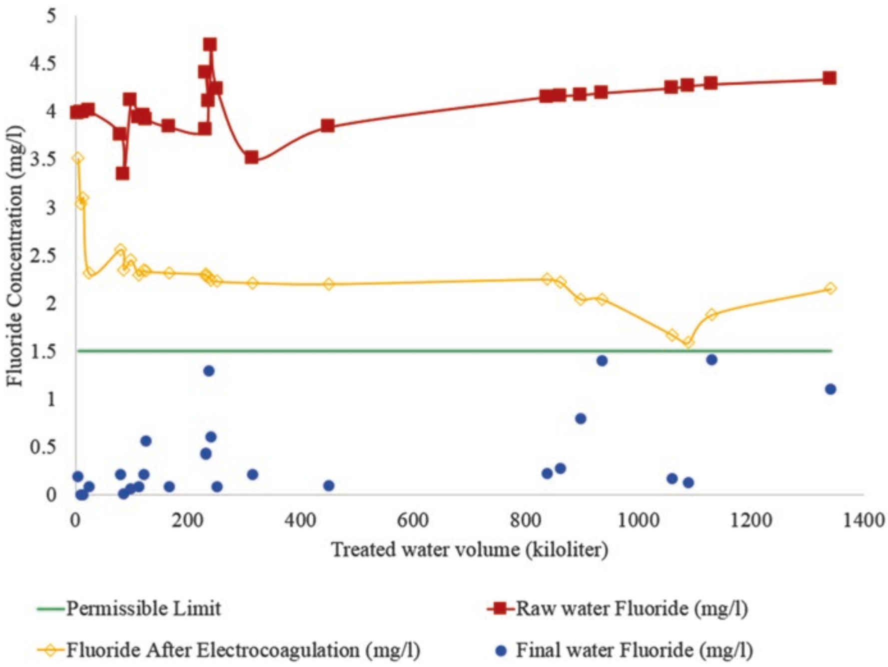

Fig. 5 Performance of defluoridation unit at Chhoto Irga, Purulia, West Bengal

Table 2 Aluminum concentration in treated water

Water filtered (kilo liter)	Aluminum concentration in treated water (mg/L)
1	0.00
9	0.11
14	0.13
24	0.00

neurotoxic) in product water as an effect of solubilization of aluminum from electrodes during electrocoagulation. Filtrates of the sand filter were tested, and aluminum concentration (Table 2) was always below permissible limit (0.2 mg/L as per IS10500-2012).

4 Community-Based Management of the Defluoridation Unit

Sustainability of a community-level water treatment device is helped when operation and maintenance are decentralized and the responsibility of O&M is borne by the beneficiaries. Keeping that in mind, a water committee was formed at that location with 11 members, all of whom are local beneficiaries and 5 of the members are women. The water committee decided to collect monthly water tariff at Rs.30 per family for the purpose of O&M. The water committee appointed a local young person as caretaker for the operation of the defluoridation unit, tariff collection, filter backwash, etc., and the caretaker is paid an honorarium. The village is economically very backward, and the local government (Panchayat) is also helping the community to compensate for any shortfall of money for incurring significant expenditure like regeneration of activated alumina. Ownership feeling of the local people for the defluoridation unit has emerged; strong participation of community people is ensured. The fluoride removal unit (FRU) is serving safe water for the last 4 years with active community O&M in place. Health improvement of the local beneficiaries was also observed within a short time.

5 Conclusion

Electrocoagulation is an emerging technology for fluoride removal. Activated alumina is a common adsorbent for fluoride removal. In this study, electrocoagulation along with sand filtration was tried as a pretreatment followed by activated alumna adsorption. The results of the pilot FRU at a fluoride-affected village show that electrocoagulation can remove fluoride to a significant extent. Provision of activated alumina bed helps to take care of fluoride removal in case the electrocoagulation setup malfunctions. Electrocoagulation removes significant amount of fluoride, and therefore, the challenge to the subsequent alumina bed is reduced helping to prolong the life of alumina bed before exhaustion. In this design, the alumina bed is split in two columns – lead and lag – which were found to be convenient for practical operation. It helps to utilize more adsorption capacity of alumina and also allows for a time before regeneration of an exhausted alumina column can be actually performed without jeopardizing the safety of the treated water. The risk of aluminum coming with the treated water is also checked, and aluminum level was found to be at a low level, below the permissible limit in drinking water. The community-based and self-sustained defluoridation unit is functioning till date. The villagers are using the water enthusiastically. Significant health improvement was also found through a systematic survey for the fluoride patients and schoolchildren.

Acknowledgments We acknowledge our gratefulness to UNICEF for funding the project. We like to thank all the members of SATHEE for helping the field implementation of the pilot project. We also wish to thank Chhoto Irga Primary School and members of the Chhoto Irga water committee.

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Variation of Arsenic Accumulation in Paddy Plant with Special Reference to Rice Grain and Its Additional Entry During Post-harvesting Technology

Nilanjana Roy Chowdhury, Madhurima Joardar, Soma Ghosh, Subhojit Bhowmick, and Tarit Roychowdhury

Abstract Groundwater arsenic contamination is a crucial drinking water quality issue leading to various health hazards in rural people globally. Moreover, irrigation of agricultural fields with arsenic-contaminated groundwater has led to increase of arsenic in soil, with consecutive elevation of arsenic in crops grown up on these soils, particularly in Bengal Delta. The present study attempts to measure arsenic uptake level from these contaminated soils and groundwater logging by paddy plants at various stages of its cultivation. Distribution of arsenic from root to grain has been further studied. Finally, variation of arsenic concentration in the grain for both sunned and parboiled rice was investigated. The observations provided deeper insight into the arsenic accumulation, distribution, and role of parboiling in additional entry of arsenic. Arsenic concentrations were found to be considerably high in all the parts of paddy plant in final stage of cultivation with hundred folds higher accumulation in roots and minimum in grain. Role of post-harvesting procedures in additional entry of arsenic during parboiling was statistically confirmed by observing higher concentrations in parboiled rice grain and its by-products. This study, therefore, suggests use of arsenic-free water for both irrigational and parboiling processes to minimize arsenic exposure through food chain.

Keywords Groundwater · Arsenic · Accumulation · Paddy plant · Rice grain · Post harvesting

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S. P. S. Ray (ed.), *Ground Water Development - Issues and Sustainable Solutions*, https://doi.org/10.1007/978-981-13-1771-2_17

1 Introduction

One of the world's gravest natural disaster is arsenic contamination, which is established in the Ganga–Meghna-Brahmaputra plain, mainly covering West Bengal. Apart from Bengal delta, this staggering issue spatially encompasses Bangladesh, China, Taiwan, Vietnam, United States of America, Argentina, Chile, Mexico, etc. (Rahman et al. 2008). In rural areas, not only the arsenic-contaminated drinking water is the elevated source of arsenic exposure but the arsenic-contaminated groundwater which is mainly used for irrigation is also responsible for food chain contamination. In West Bengal, 88,750 km^2 has been detected as arsenic-contaminated area among which 38,861 km^2 has been recognized to be highly affected areas, which include Nadia, North 24 Parganas, South 24 Parganas, Murshidabad and Malda districts (Santra et al. 2013) where rice cultivation is a regular practice. Rice being a kharif crop, requires heavy rainfall for its cultivation. But, in the dry season, the paddy cultivation practice is solely dependent on groundwater in rural Bengal, as the sources of surface water regime becomes dry during that period (Rahman et al. 2007).

The groundwater majorly used for irrigation is contaminated with arsenic due to its natural release from aquifer sediments. Arsenic is the most critical global environmental toxicant, which poses harmful influence on the ecosystem. Arsenic from soil can be absorbed by the plants through their roots via vascular system (Juen et al. 2014). Prolonged use of contaminated groundwater for irrigation practice in a specific land, results a huge amount of arsenic accumulation in soil and eventually in the entire paddy via its root system. Some surveys have already reciprocated that the paddy soil of this exposed area show a higher arsenic concentration as the shallow tube wells have been in operation for longer period of time and contaminated water constantly used for irrigation practice (Meharg and Rahman 2003).

Carbonell-Barrachina et al. (2009) proposed that among the global arsenic hotspots, India is categorized as the third most arsenic exposed country where arsenic intake is mostly contributed by consumption of rice. A comparative analysis of drinking water, raw rice and cooked rice as arsenic exposure routes showed a positive impact on arsenic in cooked rice (Roychowdhury 2008). Rice which is marketed either as raw or sunned rice is directly prepared by hulling, or parboiled rice which is prepared by light boiling of the paddy followed by mechanical hulling to obtain the parboiled rice. The parboiling process includes two different steps which include an initial boiling for 30 min, followed by final boiling for about 15 min of the whole grain, followed by sun drying. The volume of water used for parboiling procedure is thrice the mass of the whole grain.

This chapter presents and discusses the arsenic changing pattern throughout the irrigation period and quantify the arsenic load in each part of paddy plant according to their age variation. Samples for the above said analysis were obtained from arsenic-contaminated paddy fields of Deganga block of North 24 Parganas district, West Bengal, which has been previously reported to be among one of the most arsenic-affected areas in West Bengal (Mandal 1998).

Distribution of arsenic in different parts of paddy plants at its early growing stage (1 month old) during boro cultivation and different fragments of soils (surface soil, root soil and soil collected depth wise below ground level) have been investigated in our earlier studies from Nadia district, another arsenic-affected districts in West Bengal (Roychowdhury et al. 2008). This chapter illustrates a highly structured study on arsenic concentration of paddy plants at varying stages along with their part-wise distribution and contribution of post-harvesting treatments using arsenic-contaminated water in additional increase of arsenic in parboiled rice. These studies particularly shed light on the levels of arsenic exposure from agricultural land to human body via food chain in the rural areas of West Bengal which definitely has vital health implications and risk assessment.

2 Materials and Method

2.1 Study Area

North 24 Parganas district in West Bengal is part of the Gangetic delta, lying east of the river Hooghly. The present study area is Deganga, which is a community block of North 24 Parganas located 20 km from Barasat Sadar subdivision. This area has been reported as the tremendous arsenic-contaminated site in West Bengal (Mandal et al. 1996; Chakraborti et al. 2001).

2.2 Sample Collection, Preparation, and Preservation

An elaborate study on the distribution of arsenic in agricultural field soil and groundwater and the accumulation of arsenic in various parts of the paddy plant, whole grains of both sunned and parboiled rice collected from the farmers and those obtained from Deganga market and available rice by-products, was performed. Accumulation in various parts of the plant was analyzed by individually estimating the arsenic concentrations in grain, pedicle, leaf, stem, and root of the collected paddy plants at various stages of paddy cultivation, i.e., initial (20 days), intermediate (45 days), and final (85 days) stages. Paddy plant was collected at each stage of cultivation followed by segregation of each part (grain, pedicle, leaf, stem, and root) of the plant manually. Following this, both root soil and surface soil were collected, ground to fine particles using mortar and pestle. All the samples were preserved in polyethylene zip lock packets for further analysis. Arsenic concentrations in paddy whole grain of raw rice and at several stages of parboiling (i.e., half boiled and full boiled stage) were estimated. Besides, concentration of arsenic in the groundwater being used for parboiling process at raw (unboiled), half boiled, and full boiled stages were also analyzed. Finally, arsenic concentrations in sunned and parboiled rice grain and that in rice by-products such as puffed rice, parched rice, beaten rice, and rice flours (from sunned/parboiled) obtained from Deganga market were analyzed.

The solid grain and individual plant part samples obtained from the farmers were washed using deionized water, sonicated to remove the dirt present from its external surface, and were dried at 50 °C for overnight. These samples were then subjected to digestion for arsenic estimation. The water samples were likely collected in sterile polyethylene bottles and filtered through Whatman 42 to remove the colloidal particles followed by preservation with addition of 0.1% concentrated HNO_3 (v/v) and storage at 4 °C for analysis (Roychowdhury 2008a). Rice by-product samples and grains obtained from local markets of Deganga were collected in polyethylene ziplock packets and subjected to analysis.

2.3 Chemicals and Reagents

All the chemicals used in this study were of analytical grade. Arsenate standard solutions traceable to Standard Reference Materials (SRM) from the National Institute of Standards and Technology (Gaithersburg, MD, USA) of 10, 20, 30, and 50 μg/L were prepared from a stock solution of 1000 mg/L through serial dilution in 0.5 M HNO_3. A solution of 1.25% sodium borohydride (Merck, Mumbai, India) in 0.5% sodium hydroxide and 6.5 (N) HCl (Merck, Mumbai, India) were used for flow injection hydride generation atomic absorption spectrometry (FI-HG-AAS) method. Concentrated HNO_3 (Merck) and H_2O_2 (30% v/v) (Merck) were used for sample digestion procedure.

2.4 Digestion Protocol

The different parts of the paddy plants were digested using Teflon bomb. The paddy whole grain, leaf, stem, root, root soil, surface soil, and different stages of rice grain samples were individually placed in Teflon followed by an addition of concentrated HNO_3 and H_2O_2 (30% v/v) in a 2:1 ratio. The Teflons were then placed into their respective bombs and kept in hot air oven at 120 °C for 6 h to digest the samples under maintained high temperature and pressure. After cooling, volume of the digested samples was reduced by evaporating on hot plate at about 90 °C for 1 h. The evaporated samples were finally adjusted to their respective volume with deionized water and filtered using a suction filter (Millipore 0.45 μm). The digested samples were preserved at 4 °C for analysis of arsenic concentration. In case of water samples, no digestion protocol was followed for analysis of arsenic concentration.

2.5 Analysis

Determination of total arsenic concentration in all the samples collected from Deganga, North 24 Parganas were performed through hydride generation atomic absorption spectroscopy (HG-AAS) (Varian AA140) following the protocol mentioned in Roychowdhury (2008a). Absorbances obtained from the digested samples were used to calculate the final concentration of arsenic in the samples.

2.6 Statistical Analysis

A chi-square test was performed to validate the role of parboiling in significant increase of arsenic concentrations in parboiled rice grains than that of sunned rice grains obtained both from field (expected) and market (observed). Arsenic concentrations of two random samples both from field and market were considered for this analysis.

2.7 Quality Control and Quality Assurance

Arsenic concentrations in the samples were rechecked by digesting 30% of the solid samples on hot plate at 90 °C to compare with that digested samples by Teflon bomb process. Arsenic concentrations of the SRM (Standard Reference Materials) samples were estimated through Teflon bomb digestion process to validate the accuracy of the procedure.

The SRM samples used in this study were rice flour 1568a (National Bureau of Standards, Gaithersburg, MD, USA), river sediment 1645 (National Bureau of Standards, Washington, DC 20234), and tomato leaf 1573a (National Institute of Standards and Technology, Gaithersburg, MD, USA). The certified values of arsenic concentrations in the SRM samples were 0.29 μg/g, 66 μg/g, and 0.112 μg/g, respectively. Digestion of all the SRMs in Teflon bomb and subsequent analysis of arsenic showed 94%, 104%, and 103% recovery, respectively, whereas hot plate digestion of the same SRM sample showed 82%, 89%, and 87% recovery, respectively. These results confirmed that the arsenic leach out percentage (%) is high in Teflon bomb digestion than hot plate digestion due to high temperature and pressure maintained during the digestion in Teflon. This endorses the quality assurance of the mentioned protocol. The quality control was also performed by duplicate analysis and spiking recovery of the digested samples.

3 Result and Discussion

3.1 Arsenic Accumulation in Rice Grain of Studied Area

The study area Deganga is reported as the severely arsenic-affected area since the 1990s (Chakraborti et al. 2009). The total area of Deganga block is 201.05 km^2, and the population strength is 319,213 according to 2011 census report (Fig. 1).

Appx. 6.4 tons of arsenic was withdrawn per annum from all the large diameter shallow tube wells used for agricultural irrigation and deposited on soil throughout the year in Deganga block (Chakraborti et al. 2001). In this block, about 96% of the shallow tube wells used for agricultural irrigation have been reported to contain arsenic higher than the limit prescribed by the World Health Organization (WHO), i.e., 0.01 mg/l (Mandal 1998). The presence of considerable amount of arsenic has been reported in the rice grain cultivated in these regions by using arsenic-contaminated groundwater (Chowdhury et al. 2001). The groundwater serves as the primary source of arsenic accumulation in agricultural crops and vegetables

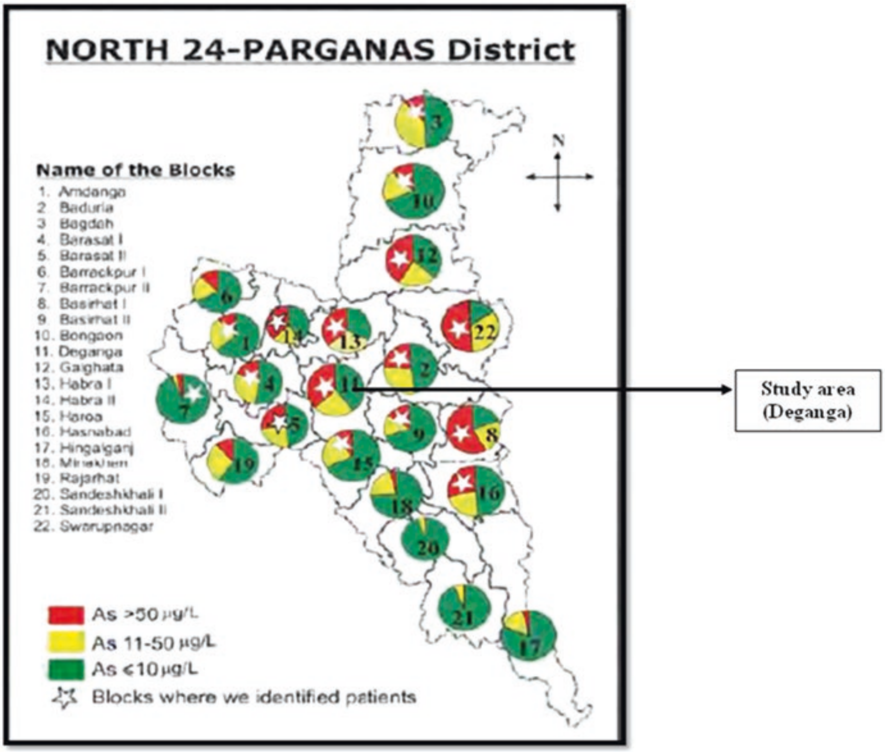


Fig. 1 Physical map showing individual blocks of North 24 Parganas with various levels of arsenic contamination in their groundwater (Sengupta et al. 2009)

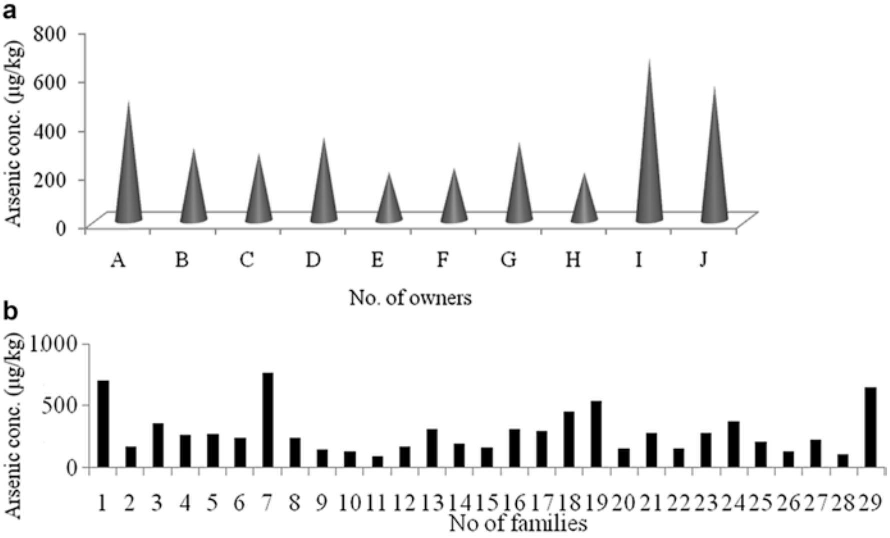


Fig. 2 (**a**) Arsenic concentration in different paddy samples collected from ten owners of exposed area. (**b**) Arsenic concentration in different rice grain samples collected from 29 families of exposed area

cultivated in different districts of West Bengal (Roychowdhury et al. 2002, 2008). Some investigators proposed that 0.082–0.202 mg arsenic kg^{-1} to be the standard limit of arsenic present in rice grain which is well lower the secure limit suggested by WHO (1 mg/kg) (Bhattacharya et al. 2010). As rice is the staple diet for the population of Bengal basin, importance is given to focus on the accumulation of arsenic in paddy plants throughout its cultivation period and additional accumulation of arsenic, if any, during post-harvesting process. The work was carried on the arsenic-exposed whole and rice grain provided by the local population of Deganga. The exposed whole (n = 10) and rice grain (n = 29) showed arsenic concentration in the range of 198–668 µg/kg and 91–765 µg/kg with an average concentration of 357 µg/kg and 290 µg/kg, respectively. A visible difference in the arsenic concentrations of whole grain and rice grain of both types (sunned and parboiled) indicates that there is a considerable accumulation in the husk, which needs further study (Fig. 2a).

After observing, the higher level of arsenic accumulation in rice grains obtained from various families, an effort was made to determine arsenic accumulation in sunned (raw) and parboiled rice grain available in local market. The sunned rice grains (n = 8) and parboiled rice grains (n = 8) thus obtained showed an average arsenic concentration of 42 µg/kg and 191 µg/kg, respectively.

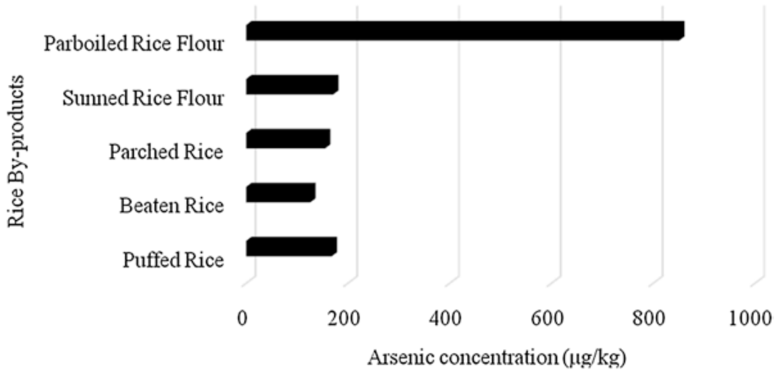


Fig. 3 Average arsenic concentration in various rice by-products collected from exposed area

3.2 Arsenic Status in Rice by-products from Studied Area

Subsequently, analyzing the arsenic concentration in sunned and parboiled rice grain, some consumable rice by-products, namely, puffed rice (muri), beaten rice (chire), parched rice (khoi), rice flour (sunned), and rice flour (parboiled) were also estimated. Puffed rice ($n = 5$), beaten rice ($n = 4$), parched rice ($n = 2$), sunned rice flour ($n = 3$), and parboiled rice flour (n = 2) showed an average concentration of 168, 126, 155, 171, and 851 µg/kg, respectively. Not much research attention has been given to the rice by-products as a potential exposure route of arsenic, yet, a study by Sun et al. (2009) with such rice products available in the UK market showed arsenic concentrations in the same range as determined in this study (e.g., arsenic concentration in puffed rice = 0.24 mg/kg). Considering the recommended value of arsenic in rice grain for human consumption is 100 µg/kg (WHO 2006), arsenic concentration that is found in rice by-products in this survey was not within the safe limit of consumption. Among all, arsenic concentration of rice flour obtained from parboiled rice was found to be the highest. This conformed our previous observation in Sect. 3.1 that accumulation of arsenic is far greater in parboiled rice than that in sunned rice and indicated a contributing role of parboiling process in additional entry of arsenic in rice (Fig. 3).

Therefore, this study provided an overview of the current situation of arsenic concentrations in paddy (whole grain), rice grain, and their by-products which were all found at a commendable and risky state. So, there is a need to survey the arsenic status of agricultural land throughout the paddy cultivation period.

3.3 Arsenic Concentration in Various Aged Paddy Along with their Part Wise Distribution

Each single paddy plant was collected from three different positions ($n = 3$) from the same field. Arsenic concentration of the shallow water used during irrigation process in the field was 290 µg/L. The arsenic concentration at different stages of paddy

Table 1 Variation of arsenic concentration in each part of paddy plant throughout the cultivation period

Stage	Leaf (μg/kg)	Stem (μg/kg)	Root (μg/kg)	Root soil (μg/kg)	Surface soil (μg/kg)
1st stage	8310	15,444	4,020,027	50,233	32,872
2nd stage	3109	5544	44,539	22,144	26,909
% of decrease from 1st stage to 2nd stage	62.58	64.1	98.89	55.91	18.14
3rd stage	4366	8561	348,874	23,192	30,324
% of increase from 2nd stage to 3rd stage	40.43	54.41	>100	4.73	12.69

(boro) reveals that arsenic concentration of each part of the plant is higher in the initial stage (22 days) than the intermediate (45 days) and final stages (85 days). For all the parts of the plant, there was an abrupt fall of arsenic concentration in the intermediate stage as compared to the initial stage and finally a considerable increase in the final stage could be noted (Table 1).

With the same trend being followed, root showed excessive amount of arsenic accumulation compared to other parts of the plant. However, grain and pedicle appear only in the final stage; therefore, no comparison is possible for these two parts of the paddy plant.

At the initial stage, leaf of paddy plant showed least amount of arsenic accumulation compared to the soil arsenic, whereas with due course of time, the arsenic concentration of paddy leaves showed a decrease of 63% in the intermediate stage and an abrupt increase of 41% in the final stage. This observation was followed in all other parts of the paddy plant, except the root which showed the highest accumulation of arsenic (348,874 μg/kg at the final stage) (Table 1). This huge buildup of arsenic concentrations in the roots may be due to the prolonged arsenic-contaminated waterlogged condition during the irrigational procedures. The root showed a decrease of 99% arsenic concentration in intermediate stage from initial stage and an unexpected increase of >100% arsenic in the root of the final stage from intermediate stage. Soil quality is the most important factor of irrigation, specifically the two layers: surface soil and root soil which forms the major nutritional base for the plant. Arsenic concentrations found in these layers provide the arsenic available for plant uptake. Analysis of both the soils showed that their arsenic concentrations do not vary diversely from each other. Mainly, the changing pattern of arsenic is high in root soil compared to surface soil, but in both layers, the trend of the three stages was the same like other parts of the plant (Fig. 4).

Considerable amounts of arsenic were found in all the parts of paddy plant. However, arsenic concentrations in grain (edible part) and pedicle were found to be 1277 and 2178 μg/kg, respectively, which were way lower than those found in lower parts of the plant. Considering, the hypothesis of translocation factor (Liu et al. 1985; Abedin et al. 2002; Roychowdhury et al. 2005, 2008) that propagates the theory of decreasing trend of metal accumulation from root to leaf, our observations are concurrent with the theory as we find decreasing arsenic concentrations from root>stem>leaf>pedicle>grain (Fig. 5).

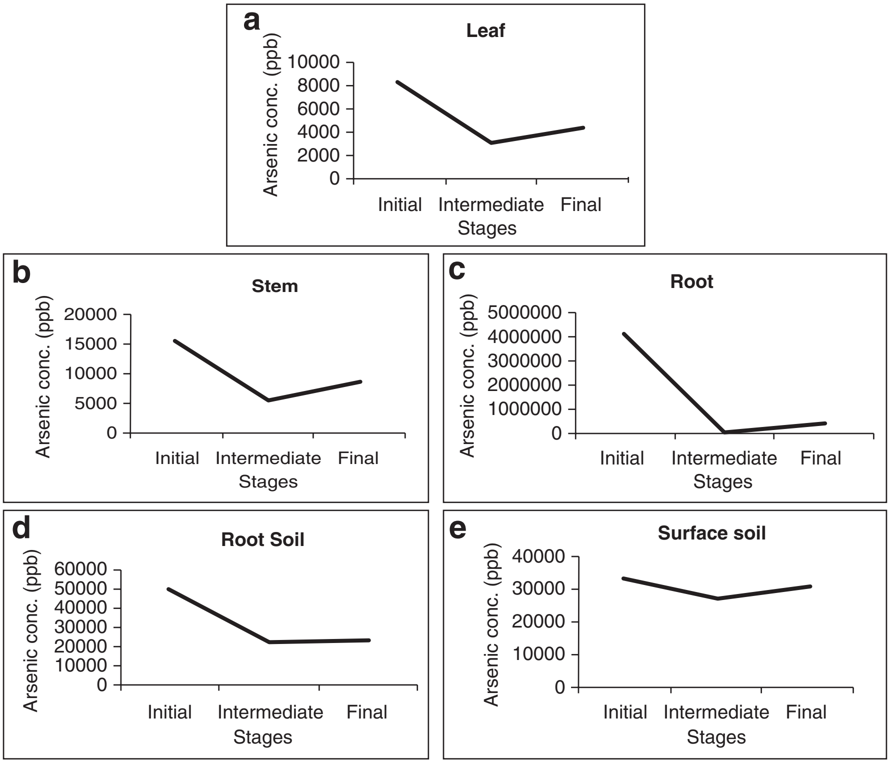


Fig. 4 Arsenic changing pattern in each part (leaf (**a**), stem (**b**), root (**c**), root soil (**d**) and surface soil (**e**)) of paddy plant throughout the cultivation period

Arsenic concentration is always found to be high in root of the paddy plant, due to the formation of iron oxide around the root. These iron plaques bind the arsenic of the root and reduce its translocation to the upper parts of the plant (Liu et al. 2004).

3.4 Arsenic Accumulation in Various Stages of Rice Grain During Post-harvesting Procedure

Post-harvesting or parboiling procedure is a multistepped process in which the paddy whole grain undergoes four stages, i.e., sunned, half boiled, full boiled, and parboiled whole grain. During the process, use of arsenic-contaminated groundwater is expected to contribute in the observed increase of the arsenic concentration in the parboiled grain as found in our previous observations (Sect. 3.1) (Fig. 6).

The half boiled whole grain shows an increase of 43% of arsenic concentration from that of raw whole grain, and a final increase of 61% was observed in the full boiled whole grain (Table 2).

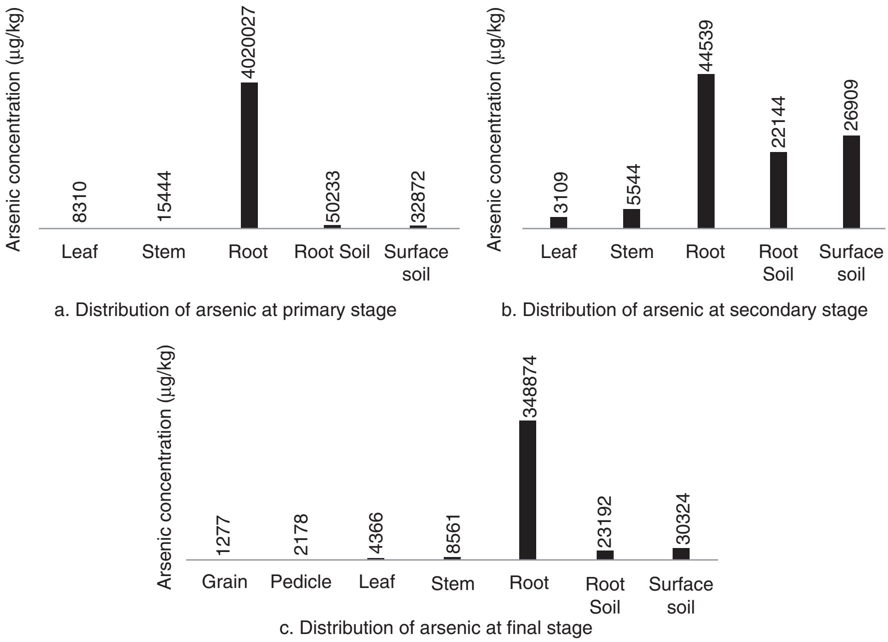
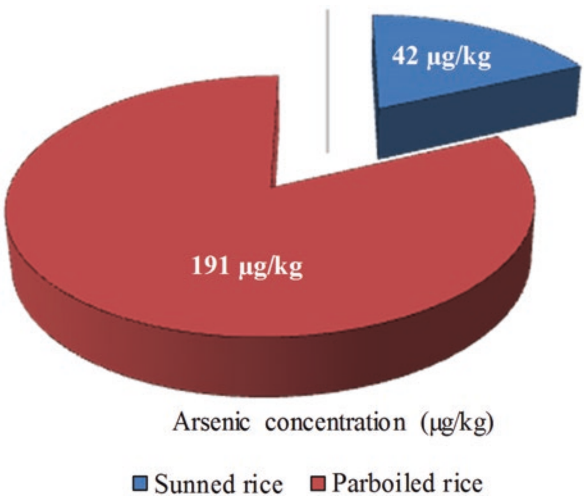


Fig. 5 Accumulation of arsenic at three stages (**a**–**c**) of the paddy cultivation

Fig. 6 Average arsenic concentration in sunned rice and parboiled rice



A simultaneous increase of arsenic concentrations in the water samples at half boiled and full boiled stages were also noted. Increases of 1.2% and 7.56% of arsenic concentrations were found in half boiled and full boiled water samples (Fig. 7).

This notable increase of arsenic concentration in the water samples after parboiling can be attributed to the ultimate decrease of final volume of water due to obvious

Table 2 Distribution of arsenic concentration at various stages of post-harvesting process

Different parts	Raw grain (µg/kg)	Half boiled grain (µg/kg)	% of increase from raw grain	Full boiled grain (µg/kg)	% of increase from half boiled grain	% of increase from raw grain
	342	489	43	550	12.4	61
Different parts	Raw water (µg/L)	Half boiled water (µg/L)	% of increase from raw water	Full boiled water (µg/L)	% of increase from half boiled water	% of increase from raw water
	251	254	1.2	270	6.29	7.56

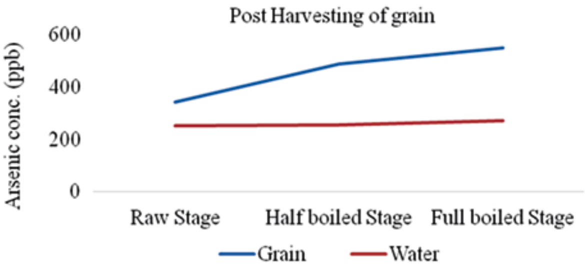


Fig. 7 Trend of arsenic changing pattern throughout the post-harvesting technology

evaporation phenomenon and starch gelatinization during parboiling procedure. Such increase in arsenic concentrations in water samples after cooking of rice samples has been reported by Ohno et al. (2009) and Mondal et al. (2010).

3.5 Statistical Validation of the Difference in Arsenic Concentration in Rice Due to Parboiling

A chi-square test was performed with randomly collected sunned and parboiled rice samples from Deganga market ($n = 2$) and those obtained from agricultural fields before and after post-harvesting procedures ($n = 2$). Chi-square test is a test of significance which indicates whether the random samples show significant differences from the expected value (null hypothesis). Difference in arsenic concentrations of parboiled and sunned rice were collected from market (observed value), and those from agricultural fields (expected value) were calculated (Table 3).

A chi-square value of 4 at degrees of freedom (df) 1 and level of significance 0.05 (critical value) being >3.84 rejected the null hypothesis and established that the variation between the differences of arsenic concentrations of parboiled and sunned rice obtained from Deganga market and agricultural fields is nonsignificant. This

Table 3 Chi-square analysis

Expected as concentrations (µg/kg)			Observed as concentrations (µg/kg)		
Sunned	Parboiled	Parboiled – sunned	Sunned	Parboiled	Parboiled – sunned
338	362	24	95	125	30
268	328	60	102	149	47
Null hypothesis: the difference of as concentrations in parboiled and sunned rice obtained from market and agricultural fields is significant					
Alternative hypothesis: the difference of as concentrations in parboiled, and sunned rice obtained from market and agricultural fields is nonsignificant					
Chi-square analysis					
Observed (O)	Expected (E)	O-E	$(O\text{-}E)^2$	$\chi^2 = \varepsilon(O\text{-}E)^2/E$	Decision
30	24	30–24 = 6	36	1.2	Therefore, null hypothesis rejected
47	60	47–60 = (−)13	169	2.8	
				$\chi^2 = 4.0$	
Degrees of freedom (df) = 2–1 = 1	Critical value = 0.05, $\chi^2 = 3.84$				Alternative hypothesis accepted

observation definitely inferred the role of post-harvesting procedure with arsenic-contaminated water in the additional entry of arsenic in parboiled rice.

3.6 Validation of Quality Assurance

The SRM samples used in this study were rice flour 1568a, river sediment 1645, and tomato leaf 1573a whose arsenic concentrations were 0.29 µg/g, 66 µg/g, and, 0.112 µg/g, respectively. Digestion of all the SRMs in Teflon bomb and subsequent analysis of arsenic showed 94%, 104%, and 103% recovery, respectively, whereas hot plate digestion of the same SRM sample showed 82%, 89%, and 87% recovery, respectively. These results confirmed that the arsenic leach out % is high in Teflon bomb digestion than hot plate digestion due to high temperature and pressure maintained during the digestion in Teflon. This endorses the quality assurance of the mentioned protocol.

4 Conclusion

The study overviewed that the current situation of arsenic concentration in paddy plants grown in the exposed area (Deganga) including the whole grain and rice grain of both sunned and parboiled rice and by-products of rice grain are at a commendable state. Therefore, this study fulfilled the need for a detailed survey on the arsenic status of agricultural land throughout the paddy cultivation period. The results led to the conclusion that there occurs a considerably high accumulation of arsenic in all the parts of the plant in the final stage of cultivation, i.e., prior to harvesting which leads to an ultimate dissemination of arsenic in the food chain. Among all the parts of the paddy plant, the roots showed the maximum accumulation, whereas the grains revealed minimum buildup of arsenic in them which justifies the renowned translocation theory. Although comparatively least amounts of arsenic accumulated in the grains, prolonged exposure to such levels through daily intake of such arsenic-contaminated rice grains may pose serious health risks. Therefore, this study finally aimed to analyze the arsenic distribution in sunned and parboiled rice where a role of arsenic-contaminated water being used during parboiling is found in additional entry of arsenic in parboiled rice grain. These observations are further substantiated by the higher arsenic concentrations found in rice by-products formed from parboiled rice grain than those from sunned.

Therefore, the study suggests the imperative use of arsenic-free water during irrigational procedure which would reduce its accumulation in the root. This would directly result in even lower arsenic translocation to the grains reducing human exposure to arsenic through rice intake. Moreover, use of such arsenic-contaminated groundwater must be avoided during post-harvesting procedures to stop additional entry of arsenic in parboiled rice grain.

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Arsenic Menace in West Bengal (India) and Its Mitigation Through Toolbox Intervention: An Experience to Share

Tanay Kumar Das

Abstract Arsenic contamination in ground water in West Bengal was first detected in 1978, and subsequent epidemiological study in the 1990s revealed that the arsenic contamination in ground water was being spread over almost the entire meander belt of the river Ganga in West Bengal and Padma in Bangladesh and around 16.66 million population (2001) in 8 districts in West Bengal was at risk. Contamination range was more than permissible limit of 0.05 mg/l and even as high as 0.21 mg/l. The menace was vast, and both provincial Government of West Bengal and union Government of India jointly with UNICEF, WHO, universities, institutions and commerce houses mitigated the problem through administrative–medical–engineering toolbox intervention. A number of technologies had been developed for arsenic removal from ground water, and most sustainable was indigenous, as well as most promising was nano-media. More than 25 years fighting the menace, milestone experiences have been gathered for sharing with all water and wastewater professionals.

Keywords Menace · Toolbox · Indigenous

1 Background

Presence of arsenic in ground water in West Bengal was first reported by CGWB – Eastern Regional Office, Kolkata, in 1978. Chronical dermatosis was first diagnosed in patients in July 1983 by School of Tropical Medicine, Kolkata. Subsequently, within 6 months' time, reports of chronical dermatosis in around 1214 patients from 36 villages in the Districts of Malda, Murshidabad, Nadia, North 24 Parganas, South 24 Parganas and Burdwan were received through health centres and hospitals. Assessing the severity and impact of the problem, the Government of West Bengal in 1983 constituted a working group comprising experts from different fields, i.e. universities, institutes, UNICEF, WHO and government departments, to

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S. P. S. Ray (ed.), *Ground Water Development - Issues and Sustainable Solutions*, https://doi.org/10.1007/978-981-13-1771-2_18

epidemiologically study and investigate the source and presence of arsenic in ground water. The working group in two teams carried out extensive epidemiological survey and studied the source of arsenic in ground water, as well as other sources.

The findings of expert team was that the ground water below 20–80 m depth is contaminated with arsenic beyond permissible limit of 0.05 mg/l and even as high as 0.21 mg/l at some places. The water from pond, lake and rivers are free from arsenic. Water from deeper aquifer was found arsenic-free or below the permissible limit. The team also studied all other possible source of arsenic, i.e. from tube well pipe material, industry, fertilizer, ancient or recent human activities, etc. From above-mentioned studies, the working group concluded that the arsenic poisoning is due to contaminated ground water.

2 Occurrence of Arsenic

The working group along with international organizations like UNICEF and WHO exchanged information on occurrence of arsenic and came to know that ground water in a large number of Districts in Bangladesh is also contaminated with arsenic. Similar occurrences were also reported from many countries all over the globe like China, Vietnam, the USA, Argentina, Chilli, Nicaragua and many others.

In India and Bangladesh, arsenic was found in ground water in the Ganges–Meghna–Brahmaputra basin and occurrence is geogenic. Arsenic-rich pyrite (FeS_2) and arsenopyrite (FeAsS) in the meander belt of Ganges–Meghna–Brahmaputra basin are the sources of arsenic. Oxidation–reduction, pH and aqueous chemistry in favourable geophysico-chemical environment drive for leaching out of arsenic to the ground water. Though there is no clear and conclusive evidence for leaching out of arsenic due to depletion of ground water table for large-scale use of ground water in irrigating boro crops, a group of experts believe that this was the main reason for arsenic contamination in ground water in the meander belt (alluvial sand and silt). It is the geophysico-chemical condition that triggers arsenic contamination in ground water, which is the main source of drinking and cooking water for a large number of population habitating in the region. Table 1 below shows some rocks or sediments and content of arsenic.

Table 1 Rock or Sediment and Arsenic content

Rock or sediment type	Arsenic content (mg/kg)	
	Average	Range
Sandstone	4.10	0.60–120
Limestone	2.60	0.40–20
Granite	1.30	0.20–15
Basalt	2.30	0.20–113
Alluvial sand (Bengal)	2.90	1.00–6.20
Alluvial silt (Bengal)	6.50	2.70–18

Table 2 Predominant processes trigger release of Arsenic in Ground Water

Process	Characteristic geochemical conditions	Generalized geological environment	Countries	Remarks
Reductive dissolution	Anoxic ground water; low levels of dissolved oxygen, nitrate (NO_3) and sulphate (SO_4), high iron (Fe), high manganese (Mn), ammonia (NH_4), bicarbonate (HCO_3) and pH -7	Holocene sediments deposited in floodplain areas of rivers draining geologically from recent mountain chains	India, Bangladesh, Vietnam, China, Cambodia, Hungary	May affect large areas 64% of known occurrences of arsenic in ground water due to this process

Source – Arsenic Primer by UNICEF

Experts emphasized that four main geophysico-chemical processes (Table 2) trigger the natural release of arsenic from aquifer materials into ground water, and these processes can occur in a wide range of geological environments. But most serious occurrence, in terms of numbers of people affected, is located predominantly in young alluvial basins adjacent to active mountain belts, as in the case of Ganges–Meghna–Brahmaputra basin.

Apart from above, other processes as reported by experts are **alkali desorption, sulphide oxidation and geothermal.**

3 Extent of Arsenic Contamination in West Bengal

To assess the extent of arsenic menace, PHED of West Bengal carried out extensive water quality testing programme and found initially that ground water in 79 blocks of 8 districts located on the meander belt of River Ganges–Padma is contaminated with arsenic. Around 17.95 million (2001 census) are affected (Fig. 1 and Table 3).

4 Health Effects for Arsenic Contaminated Ground Water

Arsenic is a systemic poison and prolonged consumption can lead to a wide range of health problems which are collectively called arsenicosis or chronic arsenic poisoning. The effects include skin lesions; cancer of skin, lung and bladder; and gastrointestinal and pulmonary conditions. Chronic arsenic poisoning has also been found to have slowed children's cognitive development.

Besides skin lesions and cancers, arsenic has been linked to a wide range of health problems like peripheral neuritis or tingling sensation in the fingers and toes. The stigma of arsenicosis symptoms created significant impact on the lives of

Fig. 1 (**a**–**c**) Arsenic contamination in West Bengal

Table 3 Extent of Arsenic contamination in different districts

Sl. No.	District	Total blocks	Affected blocks	Population at risk (2001)
1.	Malda	15	07	1.626
2.	Murshidabad	26	21	3.975
3.	Nadia	17	17	3.853
4.	North 24-Prgs	22	21	3.876
5.	South 24-Prgs	29	08	1.981
6.	Burdwan	31	05	0.796
7.	Howrah	14	02	0.333
8.	Hooghly	18	02	0.215
Total:		172	83	16.66 mn

affected people, especially women in some parts of West Bengal. Arsenicosis sufferers have been shunned by spouses and community members; even selecting bride or grooms from arsenic-affected villages has been suffering.

5 Mitigation

The Government of West Bengal reviewed the report of working group formed in 1983 and decided to mitigate the problem by (1) treatment and medical care of affected people and (2) provision of arsenic-free safe water to affected area.

In 1988 the Government of West Bengal under Public Health Engineering Department constituted a steering committee comprising leading experts from institutes, universities, government departments, UNICEF and individuals to study further and recommend appropriate mitigation and remedial measures. The steering committee observed, studied and analysed the situation in West Bengal and neighbouring Bangladesh and all possible aspects for mitigation of arsenic menace. In 1992 the Steering Committee submitted its report with the following recommendations:

- Arsenic contamination is geogenic.
- Intermediate aquifer (20–80 m bgl) is affected and dipper aquifer is almost arsenic-free.
- Setting up of laboratories for ground water quality monitoring and surveillance on regular basis.
- Development of arsenic treatment plant for handpump tube wells and PWSS.
- Trained doctors, nurses and paramedical workers opened special clinics at PHCs and hospitals and treated people with arsenicosis.
- Awareness generation among affected people with the support of PRIs, UNICEF, NGOs, etc.

The Government of West Bengal further formed state-level Arsenic Task Force Committee with more number of experts and institutions for advising & planning mitigation activities, its implementation and monitoring.

5.1 Mitigation Measures Undertaken by PHED

As suggested by Arsenic Task Force, PHED undertook the following mitigation measures:

- New handpump fitted tube wells tapping deeper aquifer.
- Ring wells at upper aquifer.
- Arsenic treatment units (ATU) with existing handpump fitted tube wells contaminated with arsenic.
- New large bore tube wells tapping deeper aquifer for existing PWSS based on ground water.
- Arsenic removal plants (ARP) for existing ground water-contaminated PWSS.
- New ground water-based PWSS with ARP for affected people/area.
- Surface water-based (mainly river source) PWSS.
- PWSS using pond water where possible.

As long-term mitigation measure, in 1996 PHED took up planning and implementation of three surface water-based piped water supply schemes sourcing water for the river Ganga for severely affected three districts.

5.2 Arsenic Master Plan for Long Term Mitigation

During 2002–2003, PHED taken up rapid ground water quality testing survey in West Bengal including in 79 arsenic-affected blocks with the support of UNICEF office for West Bengal as Joint Plan of Action (JPOA). As an outcome of the water quality testing survey, arsenic-affected habitations in villages were identified in all the 79 blocks. On the basis of water quality testing results and with the guidance of ATF as well as UNICEF office for West Bengal, a Master Plan to tackle arsenic contamination in ground water in West Bengal was prepared in 2006. The Government of West Bengal adopted the Master Plan in consultation with the Government of India. Recommendations of the Master Plan were as follows:

- All arsenic-affected mouzas to be covered by PWSS.
- Replacement/provision for ATU fitted handpumps sunk as short and midterm measures.
- Most of the affected areas should be covered by surface water based PWSS.
- Ground water-based PWSS tapping deeper aquifer where surface water is not available and with the provision of ARP.
- All existing arsenic-affected PWSS to be provided with ARP.
- All newly sunk ground tube wells should be separated by sealing from contaminated upper aquifer.

5.3 *Mitigation Plan Implementation and Status*

PHED took up Mitigation Plan through dual approach, i.e.:

1. GIS-based mapping for each gram panchayat showing all public water sources including handpump tube wells, demarcating arsenic-contaminated source in three categories **– (a) <=0.01 mg/l as green, (b) 0.01–0.05 mg/l as yellow and (c) >0.05 mg/l as red.** Awareness generation programme was carried out for using safe water from category (a) and (b) type of sources for cooking and drinking, and (c) type unsafe sources were marked red and sensitized for using for other purposes.
2. In Arsenic Master Plan, it was recommended to implement eight number surface water-based piped water supply schemes apart from already implemented or ongoing four numbers of such schemes. The Arsenic Master Plan also recommended for implementation of 338 number new ground water-based piped water supply schemes tapping deeper aquifer and with the provision of arsenic removal plant (ARP) and166 number existing arsenic-affected water supply schemes for providing arsenic removal plant (ARP).

Since 1995 onwards PHED had been implementing all possible mitigation measures by engineering intervention and up till now status of achievement is shown in Table 4 below.

Table 4 Status of implementation of Arsenic Master Plan

Measures	Planned (nos.)	Implemented (nos.)	Population covered (mn/2001 census)
A. *Short term*			
1. New handpump tube well tapping deeper aquifer	8037	8037	2.009
2. Ring well	166	166	0.041
B. *Medium term*			
1. ATU with existing hand tube well	2396	2396	0.599
2. ARP for existing PWSS	12	12	0.190
3. New large bore tube wells tapping deeper aquifer	08	08	0.120
4. New ground water-based PWSS	361	259	4.094
C. *Long term*			
1. Surface water-based PWSS	19	15	8.665
Total fund available (approx)	**Rs. 30.0 Bn or USD 0.50 Bn**		**15.718 mn**

6 Arsenic Removal from Contaminated Ground Water

As arsenic contamination in ground water was a major threat to human health in a large part of West Bengal in India and Bangladesh, R&D works, and development and scaling up of ARP took place globally. Arsenic in ground water is present in the form of trivalent As^{3+} and pentavalent As^{5+}. Presence of Iron is also very common in arsenic contaminated ground water. Removal of arsenic from contaminated ground water, so far developed are categorised in three techniques; i.e.

1. Co-precipitation
2. Adsorption
3. Ion exchange

Different treatment flow charts based on above three techniques are:

Flow chart 1: Raw water → oxidation by chlorination → co-precipitation through coagulation, flocculation, clarification and filtration → polishing through activated alumina → treated safe water

Most suitable for all levels of concentration and large PWSS, sustainable removal efficiency as high as 99–100% and ease of operation and maintenance

Flow chart 2: Raw water → normal aeration or oxidation by chlorination → pre-filtration or treatment unit → **adsorption media**[1] for arsenic removal → polishing through activated alumina (optional) → treated safe water

Flow chart 3: Raw water → electrocoagulation → arsenic removal through sand and activated alumina filter → treated safe water

Flow chart 4: Raw water → aeration with compressor → iron filtration unit → **nano-media**[2]-based arsenic removal unit → treated safe water

Many types of adsorption media have been developed, patented and used. Activated aluminium and iron-based compounds, either naturally occurred or developed and improved, are found more suitable.

6.1 Discussion

Among different techniques as mentioned above, indigenously developed **co-precipitation** using alum or ferric chloride is found most suitable, highly efficient for all levels of concentration of arsenic as well as iron, sustainable and easy to operate and maintain. The R&D model was first developed by PHED and installed at Sujapur and Shadipur in Malda District in 1996 and subsequently improved and modified. Standard sizes ranging from 10 to 180 m^3/h have been developed and implemented in good numbers and functioning efficiently.

In adsorption method use of activated alumina or iron compositions/compounds as adsorption media was found suitable as developed by different institutes and agencies and implemented by PHED. Adsorption method works efficiently with the provision of pretreatment unit to reduce iron, manganese, organic matters, odour and other impurities.

All above-mentioned technologies have its own advantages and disadvantages, especially in terms of monitoring of performances and quality of treated water. Trained and skilled manpower is necessary for day to operation and monitoring. Timely regeneration or replacement of adsorption media is extremely important in adsorption technique. Sludge containing and disposal is also a very crucial aspect in all the techniques.

Recent development of **nano-media** by IIT-Madras and other agencies for removal of arsenic added new dimension to arsenic removal technology. Nanomedia is composed of nanoscale iron oxyhydroxide, prepared with particle size less than 3 mm. Nanomedia can remove both form of arsenic As^{3+} and As^{5+} equally with high efficiency. Advantages of nanotechnology are very small in size (five to six times less in size than other adsorption media), thereby requiring very less land area, easy back wash, longer media life, low sludge production and simple disposal of exhausted media and overall low capital and O&M cost. Removal efficiency is around 99–100%.

6.2 Sludge Disposal

As all arsenic removal technologies produce sludge with high concentration of arsenic, disposal of sludge appeared as a serious concern and major issue among the experts, scientists, engineers and other stakeholders. Lot of research and development works took place in India and abroad, and there are literatures and publications. However best engineering solution of sludge disposal was developed indigenously by AIIH&PH jointly with PHED-WB. In this method produced sludge from ARP is drained and contained in a concrete tank and may thicken due to evaporation. Sludge is then facilitated to dispose to mix with concrete for construction work. It is studied that arsenic-rich sludge mixed with concrete does not leach out.

Another safe and suitable option developed indigenously was to mix sludge with clay, pugging it properly and burnt to mud ball, which could be disposed as filling material or making brick and using the same in construction work is also practiced safely.

7 Conclusion

Arsenic menace due to contamination of ground water in 79 blocks in West Bengal was of high magnitude. Since identifying the menace, slowly but steadily PHED of West Bengal tackled the problem with the support of the Government of India, UNICEF and other organizations through administrative, medical engineering and social interventions. Though the full benefit has not yet reached to all affected people, it is expected that within a short period of time, the entire affected population shall be covered with safe water supply. As West Bengal is endowed with the River Ganges and all the arsenic-affected districts are located either on right bank or left bank of the said river, most appropriate long-term mitigation measure would be implementation of surface water-based piped water supply schemes sourcing water from the River Ganges, and PHED is gradually moving towards that option. Ground water-based piped water supply schemes with ARP may give some relief, but not sustainable due to many reasons. The opportunity still remains, as with time the ground water-based piped water supply schemes with ARP shall be converted/connected to surface water-based piped water supply schemes by exclusion of ARP units.

Today any solution for water supply to the communities requires a *tool box* comprising (1) human resources, politicians, policy-makers, professionals, NGOs, FBOs and community; (2) technological resources, both developed and indigenous; and (3) natural resources i.e all types of water resources. Working together in holistic manner is the only option for ameliorative management and sustainability for safe water supply. The most crucial role lies with the community. Safe water supply to the community is a movement, and for its success community has to come forwards to take major responsibility; otherwise we are to pay huge cost, both directly and indirectly for a glass of safe water.

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Part VII
Community Involvement & Participatory Management

Participatory Groundwater Management in the Flood Plains of North Bihar: Preliminary Results of Arsenic Distribution

Siddharth Patil, Eklavya Prasad, Himanshu Kulkarni, and Sarang Kulkarni

Abstract The alluvial flood plains of north Bihar are considered to be safe from a groundwater perspective given the abundance of water, both surface water and groundwater. These aquifers, however, are showing the presence of various contaminants including arsenic, iron, and microbial pathogens. Drinking water problems are compounded by regular floods and absence of or poor sanitation facilities. Given the shared nature of regional alluvial aquifers, the interventions in such settings should consider groundwater as a common pool resource requiring a participatory approach for developing contextual solutions. The participatory groundwater management (PGWM) program in north Bihar has shown that there is considerable variability at local scales in alluvial aquifers, thus requiring a sound understanding of local hydrogeology for proposing solutions. The PGWM program in north Bihar is focused on drinking water security in the alluvial flood plains, and as a part of the program, arsenic is one of the major issues being researched. Arsenic is a major health concern when it occurs in drinking water and has been reported from the regions near the Ganga and Kosi rivers in north Bihar. Ongoing action research in five districts has shown the presence of arsenic in districts that have not been reported to have shown the presence of arsenic contamination. This paper discusses certain trends in arsenic contamination in the selected locations.

Keywords Aquifers · Arsenic in groundwater · Participatory groundwater management (PGWM) · North Bihar · Groundwater · Alluvial flood plains · Drinking water

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1 Introduction

About 76% of Bihar's population is "flood-affected," while 73% of the area of the state is "flood prone," making Bihar the most flood-affected state in India (Water Resources Department, Bihar). In the backdrop of such floods, the focus naturally remains on providing relief during floods, improving livelihoods and health. The problem of excess during floods leads to difficulties in access to established drinking water sources in a habitation (Kulkarni et al. 2009a, b). Figure 1 shows the dependence of drinking water on different sources for all the districts in the state of Bihar based on the data from the household survey of Census 2011. It is clear that groundwater forms the major source for drinking water across all districts in Bihar. In the flood-prone regions, groundwater is commonly the only source of perennial domestic water, especially for meeting drinking water needs of scattered habitations that are part of such flat landscapes. In summer, problems of access to drinking water are uncommon, but issues pertaining to quality are surfacing in the region, with evidence suggesting a strong nexus between groundwater quality and related health problems (Kulkarni et al. 2010).

Figure 2 is an indicative map of the districts where groundwater contamination has been reported. Only three major contaminants have been selected including arsenic, fluoride, and iron. The scale of the groundwater problem in Bihar is clear from the map. Figures 1 and 2 together show the widespread and complete dependence of drinking water on groundwater and the intensity of groundwater contamination in Bihar. Figure 3 is a map of hydrogeological formations developed

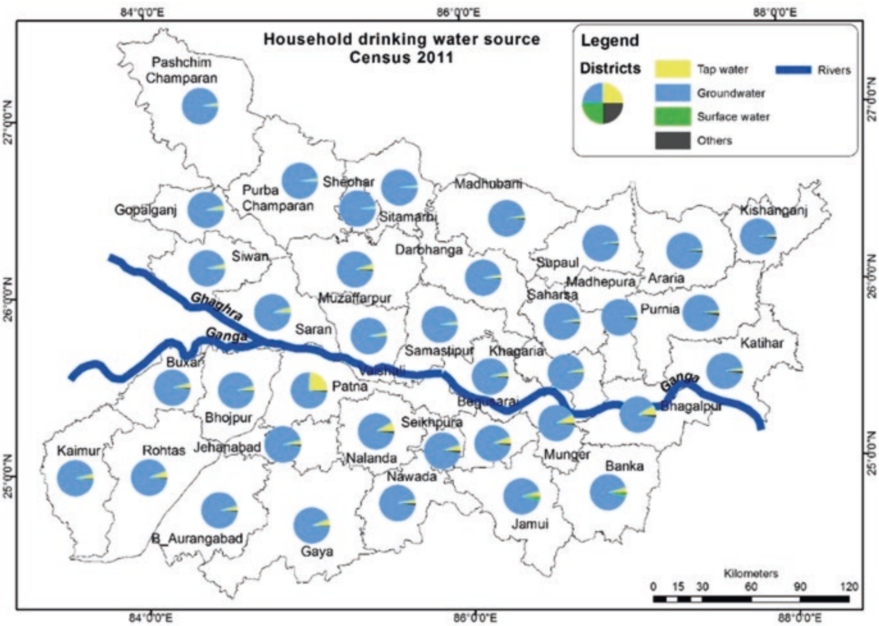

Fig. 1 Dependence of drinking water on different sources in Bihar (Data sourced from NRDWP)

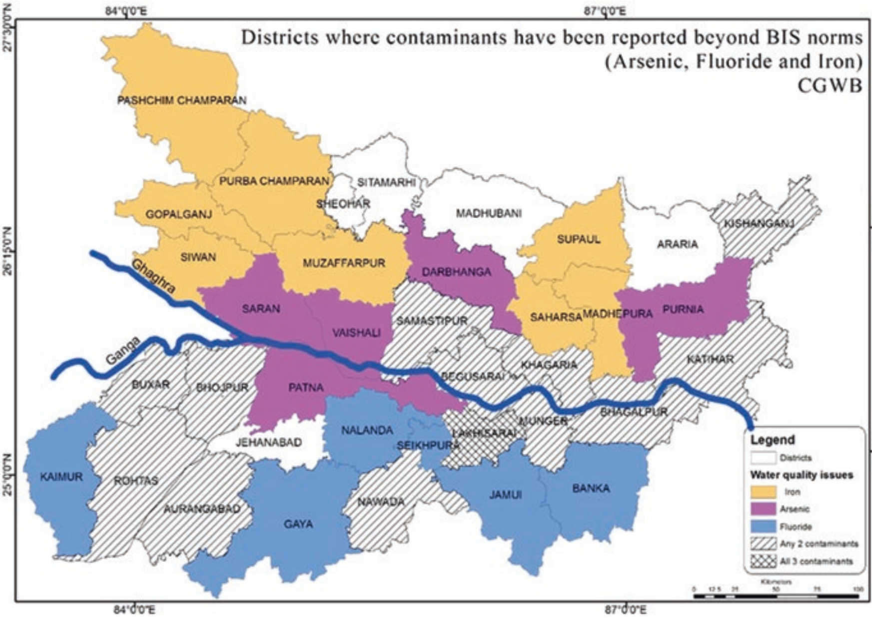

Fig. 2 Districts where groundwater contamination (for only arsenic, fluoride, and iron) has been reported by the CGWB (CGWB 2010, and contaminated areas, CGWB http://www.cgwb.gov.in/Documents/Contaminated%20Areas.pdf)

Fig. 3 Hydrogeological formations in Bihar (After Kulkarni et al. 2009a)

by ACWADAM which are representative of broadly typical groundwater conditions (Kulkarni et al. 2009a). ACWADAM developed six broad hydrogeological formations for India based on the Geological Survey of India's map (Geological Survey of India 1993), other sources (Comman 2005), and also ACWADAM's own work in different parts of India. Rocks and geology form the primary basis for deriving groundwater typologies as rocks form the framework through which groundwater accumulates and moves (Kulkarni et al. 2015). Figures 2 and 3 together show that the distribution of the contaminants matches with the underlying geology. While the southern parts of Bihar show the presence of crystalline basement rocks, north Bihar is dominantly alluvial. The alluvial flood plains of north Bihar are prone to iron and arsenic contamination, while the south is more fluoride affected.

The strategies of drinking water quality mitigation revolve around providing technologies such as reverse osmosis and other such filters which are aimed at three main contaminants in north Bihar – microbial pathogens, arsenic, and iron. It goes without saying that slip backs are very common under this scenario of dependence and contamination, when it comes to public domestic water supplies. The committee on estimates setup to evaluate rural drinking water programs states that on an average 1.4 lakh habitations at an India level slip back every year during the 7 years prior to 2014 owing to water quality problems. The Ministry of Drinking Water and Sanitation, in the same report, mentions that the reasons for slip backs are dominantly related to drying up of sources because of overpumping (Ministry of Drinking Water and Sanitation 2015).

It is clear therefore that the slip backs are related to a lack of information of the resource (aquifers) as the emphasis on providing drinking water solutions revolves around technologies such as tube wells, hand pumps, and reverse osmosis plants and other water quality mitigation measures. Such slip backs are common in north Bihar where schemes implemented for providing safe quality of drinking water are not being used owing to various technology-related issues. In light of the slip backs, the technologies in itself are not questionable; however, the applicability of the technologies to the flood plains of north Bihar and other similar "typologies" requires rethinking.

The need to shift the focus from sources (hand pumps, piped water supply, dug wells, deep borings, etc.) to the resource (aquifers in the case of groundwater-based sources) is felt in all parts of India but more so in north Bihar. Almost complete dependence on groundwater, high risk of groundwater contamination, and a clear linkage between the geology and groundwater quality call for developing a deeper understanding of the hydrogeological settings of the region. An aquifer-based focus will add value to any research and the consequent set of interventions. Alluvial aquifers are generally regional in spread and consist of a vertically layered system of multiple aquifers. These aquifers are largely a result of various permutations and combinations of layers of clay, silt, sand, and gravel. The classical approach to understanding alluvial aquifers considers these as very large spatial units exhibiting a great deal of homogeneity as compared to hard rock aquifers. However, as is evident from even the preliminary research that was pursued as part of the program from which this paper is derived, aquifer heterogeneity is significant when one looks at their specific character in different locations.

2 Typologizing Alluvial Aquifers

The approach of types – typology, a combined classification of a particular hydrogeological setting which includes the hydrogeological as well as the socioeconomic setting – can be used to understand the diversity which influences the patterns of utilization at local scales. A typology classifies the local physical and anthropogenic characteristics of groundwater which can enable developing better strategies for its management. The key lies in capturing local diversity which is important with regard to two basic requirements in groundwater understanding – identifying the right unit in understanding aquifers and creating the understanding at the appropriate scale as groundwater issues are most strongly felt at the microlevel (Kulkarni et al. 2009b).

2.1 Participatory Groundwater Management (PGWM) in North Bihar

The large spatial extents of alluvial aquifers directly result in the sharing of the resource by multiple villages. The resultant aquifer properties, including availability and quality, are common across a large area affecting a substantial number of people. Similarly, the effects of human interactions have a combined effect on the common aquifers, which may manifest as falling water levels and deterioration of groundwater quality even over a very large area. This characteristic of large, shared systems of aquifers requires an approach that considers groundwater and aquifers as a common pool resource (Patil et al. 2011). The participatory groundwater management program is an attempt to study groundwater in north Bihar as a common pool resource, understand the aquifers at local scales, and develop participatory processes to evolve solutions to groundwater issues.

Understanding alluvial aquifers, based on the aquifer-as-a-unit approach, is an enormous task given the regional nature of these aquifer systems. “Typologizing” the north Bihar alluvial aquifer setting, based on different physical features, was the first step in moving forward with practical objectives. The flood plains of north Bihar are characterized by regular annual floods, embankments, groundwater quality issues, high population density, and poverty. Five typologies for groundwater management were observed based on action research conducted in an earlier program. These are:

- Waterlogged regions
- Flood-affected regions inside the embankments
- Flood-affected regions in the absence of embankments
- Flash flood-affected regions
- Transboundary aquifers along the Nepal – Bihar (India) border

Central to the above typologies is the issue of drinking water security – access to drinking water during floods and access to safe drinking water throughout the year, with a focus on arsenic, iron, and microbial contamination. Developing alternatives to the current design and practices of sanitation is also an integral element in the program, given its close linkages with drinking water security, especially in high water table conditions. The five typologies mentioned in this paper are not absolute and are an attempt to dive deeper into the nuances of the alluvial aquifer setting, based on ACWADAM's and MPA's previous research.

2.2 The Locations for PGWM Action Research

The selected locations according to the above typologies are given in Table 1. Figure 4 shows the Google Earth locations of the selected study locations. Although the PGWM action research program deals with various facets of drinking water security and sanitation issues in alluvial settings of north Bihar's flood-affected regions, this paper describes the initial results regarding arsenic in the selected locations for highlighting the issue in regions where it has not been widely reported and to present the scientific basis for PGWM for one aspect of the action research.

The process of scientific understanding of the aquifers in the selected villages included:

- Setting up of a monitoring network for regular water level measurements
- Seasonal water quality monitoring of 14 parameters including arsenic, iron, and microbial contamination
- Developing hydrogeological cross sections of the villages displaying the geology and aquifers, based on a participatory inventory of logging subsurface information through tube-well owner interviews
- Drilling and logging of observation tube wells
- Analysis and inferences from the data obtained from the above steps

Table 1 Locations and typologies of selected regions under the PGWM action research program

Tola (hamlet)	Revenue village	Block	District	River	Typology
Phulkaha	Sohagpur	Kishinpur	Supaul	Kosi	Waterlogged regions (outside the eastern Kosi embankment)
Hardiya Basa	Ara	Mahishi	Saharsa	Kosi	Flood-affected regions inside the embankments (inside the eastern Kosi embankment)
Paswan and Das	Chaidha	Mansi	Khagaria	Burhi Gandak	Flood-affected regions without embankments
Godiyari	Suriyahi	Phulparas	Madhubani	Bhootahi Balan	Flash flood-affected regions
Kairi	Kairi	Gaunaha	Pashchim Champaran	Pandai	Transboundary aquifers along the Nepal – Bihar (India) border

Fig. 4 (**a**) Phulkaha tola in Supaul district, (**b**) Hardiya Basa tola in Saharsa district, (**c**) Chaidha village in Khagaria district, (**d**) Godiyari tola in Madhubani district, (**e**) Kairi village in Pashchim Champaran district

2.2.1 Results

The hydrogeological cross sections of the five typologies are shown in Fig. 5. These cross sections have been developed using villagers' narratives regarding the different layers tapped during drilling of their individual hand pumps. Although there can be marginal errors in terms of the thicknesses of the layers narrated by the villagers, this magnitude of errors is minor as compared to the scale of the data that can be obtained when compared to more accurate data from drilling a few observation tube wells spread over a large area – a constraint faced in research projects in India. The developed cross sections can be verified in the field using vertical electrical surveys (VES) along with drilling of observation tube wells (Patil et al. 2014).

The sections have been verified with the strata from the drilled observation tube wells. The variability in alluvial aquifers in the selected study locations is clear from the hydrogeological sections in Fig. 5. The occurrence of groundwater in confined and leaky aquifers at shallow depths of less than 10 m is notable, as it forms an important link in understanding the processes of groundwater occurrence and movement in north Bihar's alluvial systems.

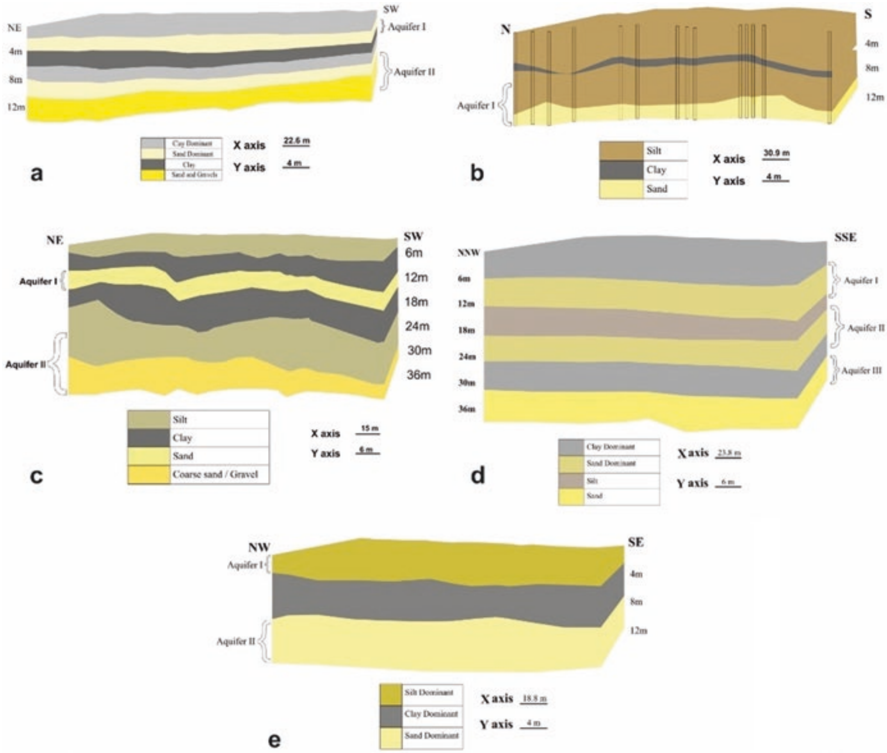

Fig. 5 (**a**) Phulkaha tola in Supaul district, (**b**) Hardiya Basa tola in Saharsa district, (**c**) Chaidha village in Khagaria district, (**d**) Godiyari tola in Madhubani district, (**e**) Kairi village in Pashchim Champaran district

An important finding of this research is that the dug wells which generally tap shallow unconfined systems may be tapping shallow confined aquifers due to the predominance of clay at shallow levels. In many cases, the dug wells and hand pumps (that form the most common source of groundwater abstraction in north Bihar) are observed to be tapping the same aquifer systems.

2.3 Arsenic: Evidence of Contamination in Districts Not Marked as Arsenic Affected

Arsenic testing in the research locations was conducted using field test kits that were being used since 2010 for conducting tests in other programmatic locations in the same districts. These kits have been tried and tested in the field and the results verified through testing of a smaller number of samples from certified laboratories. According to the Indian drinking water standard (second revision of IS 10500, 2012), the acceptable limit for arsenic in drinking water is 10 μg/L, while permissible limit in the absence of alternate sources is set at 50 μg/L. Khagaria, Supaul, and Saharsa districts have been reported by the Central Ground Water Board (CGWB 2010) as affected by arsenic contamination, but Madhubani and Pashchim Champaran have not been reported. The research location in Pashchim Champaran shows arsenic contamination well beyond the permissible limit of 50 μg/L with concentrations in the range of 100–200 μg/L reported in field tests conducted in December 2013 and June 2015. The village in Madhubani district shows the presence of arsenic above the acceptable limit. However, given the local scale of the current research, it will not be surprising that arsenic at higher concentrations is observed in other locations of Madhubani district. In light of these findings, the commonly accepted theory that arsenic in Bihar occurs only in close proximity of the Ganga and Kosi rivers is questionable, also raising larger questions on the distribution patterns of arsenic on one hand and the various degrees of arsenic vulnerability on the other.

2.4 Arsenic: Temporal and Spatial Distribution

Figure 6 shows plots of arsenic concentration in groundwater for the five typologies. The plots are for two seasons – December 2013 and June 2015 – where the sources have been plotted according to the depth from which groundwater is being tapped. The preliminary observations that can be made on the basis of these plots are as follows:

- Almost all the sources are tapping a single aquifer in Phulkaha (Supaul, waterlogged typology), Hardiya Basa (Saharsa, floods inside embankment typology), and Chaidha (Khagaria, floods in the absence of embankments typology).
- Across all five typologies and all aquifers within the typologies, it is clear that there is significant variation in arsenic concentrations within respective aquifers.

The sources being monitored currently are all in the "shallow aquifer system" of less than 50 m depth. These are being focused on, as the villagers are sourcing their drinking water from these shallow aquifers. The plots show that despite being from the shallow system, arsenic concentration in groundwater does not show a constant temporal trend – there is no common trend of recharge leading to dilution or mobilization of arsenic. Some locations show dilution, while some are showing an increase in arsenic concentrations with change in season. This strengthens the argument for understanding alluvial aquifers at a far more disaggregated scale than under the current practice. The spatial distribution of arsenic for December 2013 and June 2015 (Figs. 7 and 8) confirms that there is no common trend in the seasonal change of arsenic concentration despite all sources in all locations being from the "shallow aquifer system" of less than 50 m. These plots also show that arsenic, unlike fluoride, cannot be interpolated to assess its spatial trends, and its occurrence seems to be random in nature.

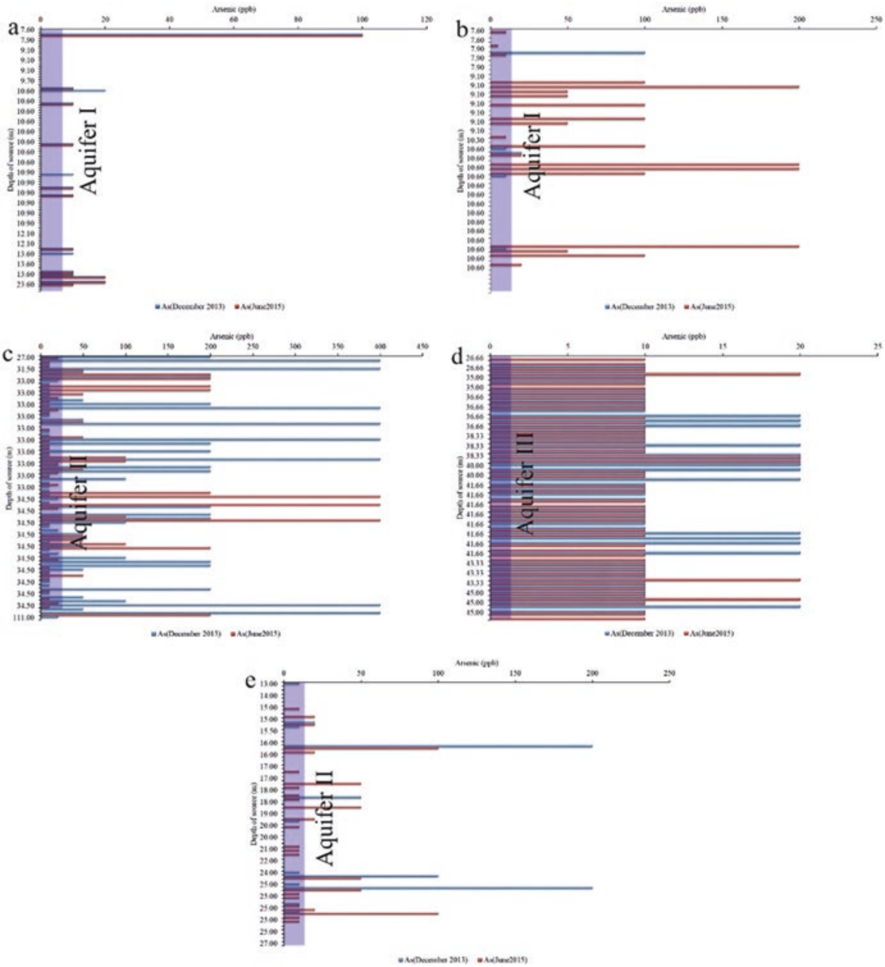

Fig. 6 Depth-wise arsenic concentrations in hand pumps (**a**) Phulkaha tola in Supaul district, (**b**) Hardiya Basa tola in Saharsa district, (**c**) Chaidha village in Khagaria district, (**d**) Godiyari tola in Madhubani district, (**e**) Kairi village in Pashchim Champaran district

3 Conclusion

The preliminary results from the arsenic aspect of the PGWM effort in five locations of north Bihar have yielded some interesting and surprising results. First, the presumed aquifer homogeneity for alluvial systems is not necessarily true. The five locations represent various typologies of aquifer and other socio-ecological situations. Perhaps, the differing situations accord the heterogeneity to the otherwise seemingly homogeneous systems. Understanding the subsurface is a function of both, a conventional approach of using geophysics and drilling as well as enabling a socio-informative process through interviews and narratives on drilling that help build a picture of the subsurface, which in turn helps develop a conceptual

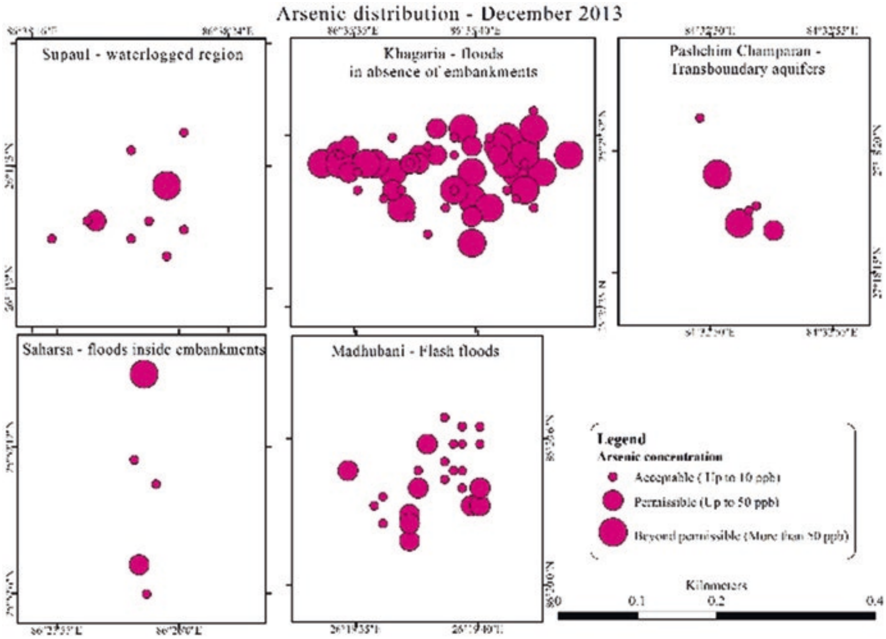

Fig. 7 Spatial distribution of arsenic in the five typologies in December 2013

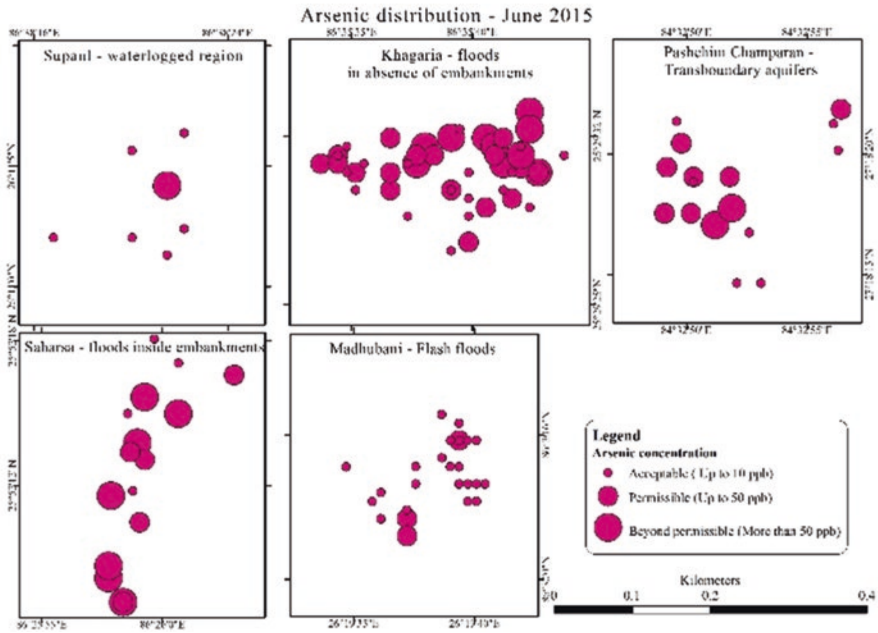

Fig. 8 Spatial distribution of arsenic in the five typologies in June 2015

illustration of the aquifer system. The latter, in fact, forms an effective alternative when one deals with limitations of resources. Seasonal trends of arsenic are different in the five different typologies, although some similarities do exist. Finally, what is even more interesting is the pattern of arsenic distribution, especially when one uses the three categories of limits – "acceptable," "permissible," and "beyond permissible" – to chart such patterns for understanding the source-wise arsenic content even in a small habitation. Patterns are quite unique to the habitation under each typology, and these need further studies, especially in developing participatory responses to arsenic proof drinking water security in these habitations.

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Spring Protection and Management: Some Case Histories from Across India's Mountainous Regions

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Abstract Communities across mountain regions of India, from Nilgiris to Himalayan areas, get drinking water supply from approximately five million springs. These springs formed due to intersection of groundwater level with the land surface not only supply safe drinking water round the year but also feed rivers and maintain the ecosystems. However, environmental degradation, spirally increasing water demand and climate change phenomenon may pose sufficient stress to these vital resources. Effective steps are required to control dwindling spring discharge and deteriorating water quality, so that water scarcity, biodiversity and ecosystem can be protected. The combined efforts of NGOs, the state governments and communities to protect springsheds wherein studies of hydrogeological set up in identifying, protecting and augmenting groundwater recharge may be a better approach in the management of springs. However, such interventions are likely to vary in different valleys giving due considerations of the communities therein. It has been found that such interventions may result into fivefold increase of spring discharge and reduction of faecal coliform bacteria in drinking water through social fencing. Because of revival of traditional knowledge and decentralization of science, such approach is becoming successful. Collective and participatory actions by the

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S. P. S. Ray (ed.), *Ground Water Development - Issues and Sustainable Solutions*, https://doi.org/10.1007/978-981-13-1771-2_20

communities and the local institutions are even taking up hydrogeological mapping which are being encouraged with public investment in several locations. This paper focuses on some of these encouraging results and experiences.

Keywords Hydrogeology · Springshed · Water security

1 Introduction

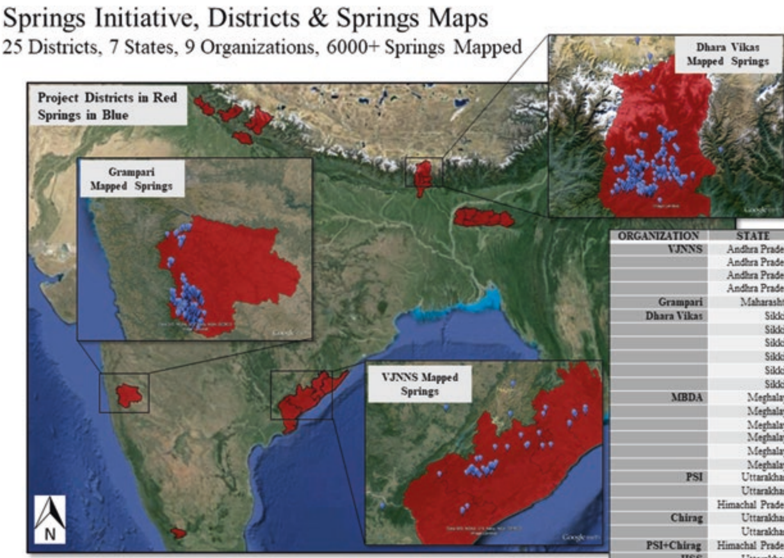
Water from more than five million springs across India has been used by people for drinking, cultural, irrigation and livestock purposes (Kulkarni 2015, *personal communication*). In Uttarakhand, 90% of drinking water supply comes from springs, and in Meghalaya all villages generally use spring water for drinking and irrigation purposes (Shabong and Swer 2015). Vital components of biodiversity and ecosystems are dependent on the numbers of springs of a region. The river Krishna, Godavari and Cauvery as also most of the rivers in central and south India are spring-fed (Molur et al. 2011). However, these springs are declining gradually due to increased groundwater pumping, changing land use patterns, increased demand of water and ecological degradation and climatic change. Although the entire state of Sikkim is largely dependent on springs for drinking water, a survey indicates that the spring discharge has shown almost 50% decline which is quite alarming (Tambe and Arrawatia 2012).

Again, in the Western Ghats, perennial springs have been reduced to seasonal causing enormous hardships to the communities to meet their water demand. Such perennial springs due to continuous competition for drinking water and irrigation water are getting dry (Buono et al. 2016). Further, the quality of such spring water also is showing deterioration under changing land use and sanitation. As a result, such springs located near the contaminated latrines are no longer in use for drinking purposes.

It is needless to mention that reduction in water supply and water quality has considerable impact on regional livelihood, health, biodiversity, agriculture, tourism, power general and industry.

In response to the deterioration of springs, actors across the country are giving spring protection a renewed focus. The Government of Sikkim and Meghalaya have initiated state-wide programmes to inventory, monitor, protect and rejuvenate springs. NGOs in all major mountain chains have also developed successful spring programmes, many of which are now being emulated by local government at block and district levels. The Central Himalayan Research and Action Group (CHIRAG) and People Science Institute (PSI) have well-established spring protection programmes in Uttarakhand and Himachal Pradesh. In other parts of the country over the last few years, similar initiatives were independently developed, for example, in the Eastern and Western Ghats (Fig. 1).

These initiatives have all moved beyond supply-side improvements realizing that to manage springs sustainably it is necessary to map and protect the recharge areas. So organizations with specialized knowledge in hydrogeology, such as the Advanced



ORGANIZATION	STATE	DISTRICT
VJNNS	Andhra Pradesh	East Godavari
	Andhra Pradesh	Vishakhapatnam
	Andhra Pradesh	Viziangaram
	Andhra Pradesh	Srikakulam
Grampari	Maharashtra	Satara
Dhara Vikas	Sikkim	North Sikkim
	Sikkim	West Sikkim
	Sikkim	West Sikkim
	Sikkim	South Sikkim
	Sikkim	East
	Sikkim	Darjiling
MBDA	Meghalaya	Jainti Hills
	Meghalaya	East Khasi Hills
	Meghalaya	East Garo Hills
	Meghalaya	S. Garo Hills
	Meghalaya	West Garo Hills
	Meghalaya	W. Khasi Hills
PSI	Uttarakhand	Rudra Prayag
	Uttarakhand	Bageswar
	Himachal Pradesh	Solan
Chirag	Uttarakhand	Nainital
	Uttarakhand	Pithoragar
PSI+Chirag	Himachal Pradesh	Sirmaur
HSS	Uttarakhand	Tehri Garhwal
Himmotthan	Uttarakhand	Tehri Garhwal
Keystone	Tamil Nadu	Niligris

Fig. 1 Map of known spring protection programmes by district and organization. The 25 districts with active programmes are highlighted in red. Inset maps show three examples of ongoing spring surveys with spring locations denoted by blue pins. Activities span 9 states and include over 6000 springs. Organizations implementing the springshed approach include Central Himalayan Rural Action Group (CHIRAG), Dhara Vikas (Government of Sikkim), Grampari, Himalaya Seva Sangh (HSS), Himmotthan, Keystone Foundation, Meghalaya Basin Development Authority (MBDA), People Science Institute (PSI) and Visakha Jilla Nava Nirmana Samithi (VJNNS)

Centre for Water Resources Development and Management (ACWADAM), began providing technical and capacity-building support. Recognizing the potential for cross-learning, Arghyam, a funding agency supporting several of these efforts, gathered these groups together in 2014. What emerged was a commonality in approach despite the differences in geography.

Springs are now beginning to be recognized within policy and public institutions at the national level. For example, aquifer mapping activities are now recognized as a sanctioned activity under National Rural Employment Guarantee Act, 2005, and as part of the mandate and training for Central Ground Water Board aquifer mapping activities.

This paper highlights some of these recent efforts to manage springs in mountain regions, including the general programmatic approach and scientific methods to maintain or augment spring discharge and water quality. Examples from around the country are provided including impacts on discharge and water quality and efforts to scale. Recommendations are made for future activities.

2 Methods

The methodologies include:

1. Hydrogeology is used to map springsheds.
2. Vulnerable areas are taken up for restoration, protection and augmentation of spring recharge.
3. To have proper understanding of science based on hydrogeological perception, traditional local knowledge and community participation are emphasized.
4. Local institutions are entrusted with monitoring and management of springs.

Community participation and hydrogeology are keys to this process. Unlike traditional watershed approaches, springs require a "valley-to-valley" approach. In other words, a spring in one village can be recharged in another village on the opposite side of a mountain in a different watershed – thus typical "ridge-to-valley" methods are often inadequate (Fig. 2). Therefore, the process in generally starts with a field survey of the spring and the surrounding area. Rock type and structures are mapped, including strike and dip of geologic formations and features, and a geologic cross section is developed. Infrastructure, socioeconomic and other

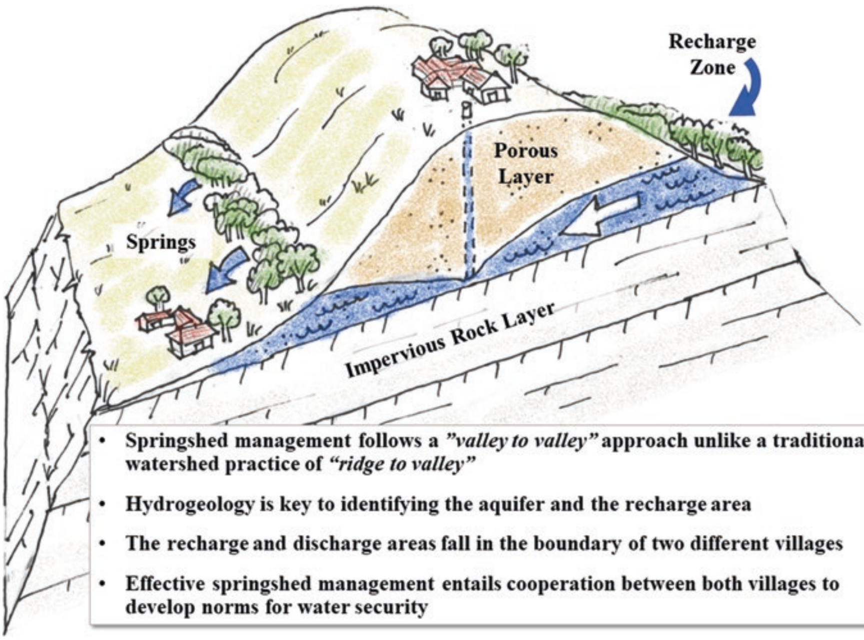


Fig. 2 Simplified hydrogeological model of a springshed showing a typical setting where the recharge area falls in a different watershed in a different village. Traditional "ridge-to-valley" approaches may not be effective in protecting the springs so a "valley-to-valley" approach is needed. This allows for targeted restoration and protection of the recharge area, as well as an avenue for cooperation between villages sharing the common resource

environmental data are collected. Hydrological monitoring of discharge and water quality are initiated. Google Earth satellite imagery, topographic maps or other sources are used to delineate the local watersheds, and the field survey information is placed on the map. The above steps are often sufficient to delineate the springshed when employed by a trained and experienced field team.

Once the springshed has been delineated, the human impact is assessed, and goals are established. Then a plan is developed with the community. Action plans may include restoration and protection of the springshed or even augmentation of groundwater recharge. For example, if the community is facing dry-season water shortages, the goal would be increased discharge. If the springshed was found to be affected by intense grazing, tree cutting and annual burning, then the plan would be to reduce the human pressures on the springshed. Secondarily, restoration-based practices may be used to restore ecological function, that is, plantation of native species to increase soil cover. In addition, structures such as *chaals*, ponds or staggered trenches may be used to increase natural rates of infiltration.

Local stakeholders are a part of each of these steps. Gram panchayat (GP) members, self-help groups (SHGs) and individual community members help to locate springs that were traditionally used by the villagers. They are encouraged to map the geology of the area and to monitor hydrology. The survey and discovery process is open to all and the hydrogeology is shared. This "demystification" of the science provides a powerful tool for stakeholder engagement. This, along with community-based monitoring of discharge and water quality, is used to transfer long-term ownership of the project to the community. Communities are trained in measuring discharge, rainfall and sometimes even water quality parameters such as faecal coliform (using H2S field testers or similar).

3 Results and Discussion

3.1 Impact on Discharge and Water Quality

Evidence suggests that it is possible to restore and even augment spring discharge. In Sikkim, the government took up 50 pilot springs starting in 2008 under its Dhara Vikas programme. Communities developed "village water security plans" that focused on protection and restoration of springsheds. This often involved restoration or placement of traditional *chaals* (rainwater ponds) in the upper springshed to increase infiltration and recharge. The results were positive with some springs yielding increased discharge of up to fivefold (Norbu 2015). While many springs are likely to be of limited potential, due to natural characteristics of their catchment sizes and aquifers, the results in Sikkim were strong enough to take this to the state level.

In Uttarakhand and Himachal Pradesh, NGOs such as CHIRAG and PSI have well-established spring protection programmes that partner with GPs to demystify the hydrogeology through field mapping. Targeted restoration of springsheds has resulted in improved water quality and quantity.

Figure 3 illustrates the impact on spring discharge from a CHIRAG project implemented in 2010. After installing infiltration basins in the springshed, discharge increased for all three seasons of post-intervention monitoring. Even more compelling is that discharge remained relatively high despite significantly lower rainfall in 2012 as compared to 2010 (Bisht and Mahamuni 2015). This suggests that climate adaptation or climate proofing may be possible on some springs.

Figure 4 illustrates similar results on project undertaken by PSI in 2012. Discharge appears to be trending up across the 3 years of monitoring. Both monsoon and lean season discharges are greater (Sharma and Kumar 2015).

Spring management also improves water quality, for example, by reducing faecal coliform contamination. Figure 5 shows data from work done by PSI in Himachal Pradesh. In this case, water quality was determined to be an issue for the drinking water in several springs. The solution was social fencing to reduce open defecation in the springshed to reduce microbial load – social fencing is the practice of enforcing behaviour change in a geographically sensitive area; in this instance it was used to prevent defecation in the recharge area. The result was that for 2-year post-intervention, faecal coliform continued to decline in the spring-based drinking water supply (Sharma and Kumar 2015).

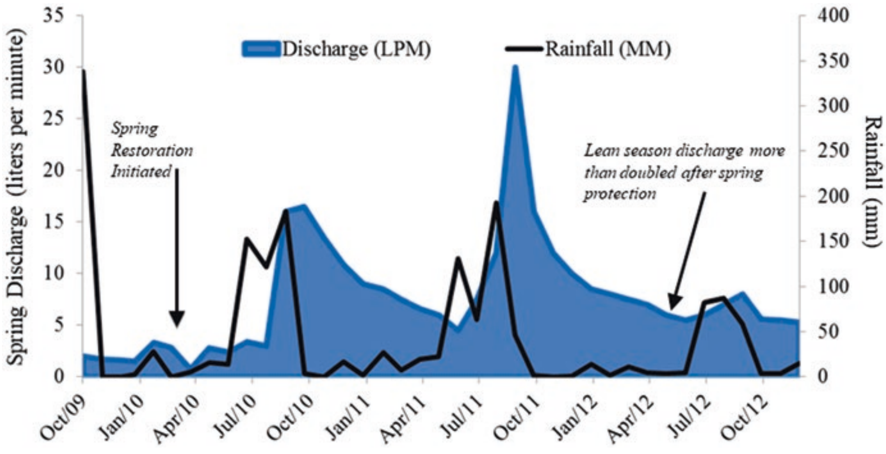


Fig. 3 Spring discharge and rainfall over three seasons on Navli Spring, Uttarakhand. After the springshed was identified, best management practices were implemented to protect biodiversity, increase infiltration and build healthy soil. The result was increased discharge per unit rainfall in both peak and low seasons

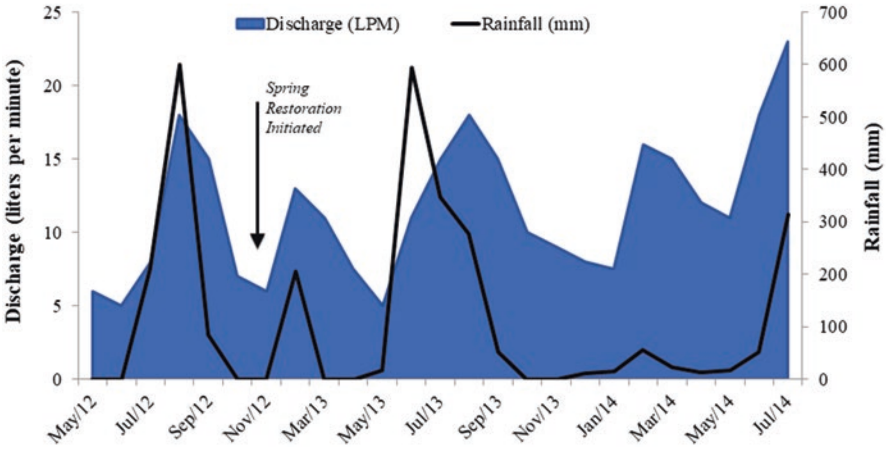


Fig. 4 Spring discharge and rainfall, Dhalyi Spring, Uttarakhand, showing an upwards trend in water discharge despite decreased rainfall. This suggests a possible climate proofing of drinking water supply on some springs

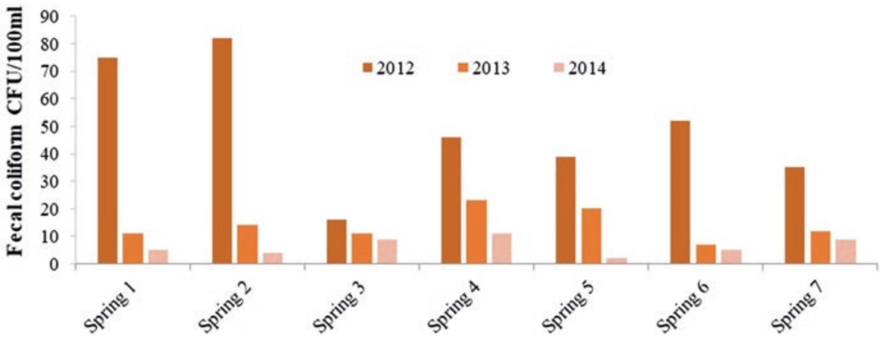


Fig. 5 Reduction in faecal coliform pre- (2012) and post- (2013–2014) spring protection and introduction of social fencing to eliminate open defecation in the springshed

3.2 Efforts at Scale

The Sikkim government began a state-wide springshed management programme in 2008. After piloting 50 springs with significant results, they scaled up and have since mapped over 1000 springs. They also have initiated village water security plans. Over the last 5 years, it is estimated that over 900 million litres of water have been recharged annually at a cost of 1 paisa per litre (Norbu 2015). A key element in this success was the partnership that the government built between its own departments and with other stakeholders such as NGOs, academic institutions and donors. Collaboration included knowledge transfer and training in hydrogeology.

More recently, other state governments are showing interests in this approach. Meghalaya has trained hundreds of government field staff and volunteers. Thousands of springs have been inventoried, and there are plans to protect springs in nearly all the villages in the state – the first such activity at this scale anywhere in the nation (Shabong and Swer 2015).

In the Eastern Ghats, Visakha Jilla Nava Nirmana Samithi (Siva Kumar 2015) has demonstrated that gravity-fed spring water supply and village-maintained filtration systems can provide safe and sustainable drinking water – a programme now being replicated in hundreds of villages by the Andhra Pradesh government (Siva Kumar 2015).

3.3 Challenges

There have also been other challenges too. Springs used by one village are often recharged in another village or on Forest Department land – complicating restoration measures. There is also a lack of knowledge on groundwater, in general, and springs, in particular, across all stakeholders. There are not enough trainers to meet the current demand for spring-related planning and capacity building. More capacity-building efforts are needed such as those currently conducted by ACWADAM (a 2-week training on groundwater) and PSI (a 2-week training on Participatory Groundwater Management). The Springs Initiative is currently developing a pan-India spring management curriculum.

4 Conclusions

While the results above are encouraging, springs remain off-radar for the vast majority of stakeholders, from regulatory agencies to engineers, research institutions, gram panchayats and last mile workers. Greater awareness and understanding of springs will improve management of aquifers and groundwater in general. Springs also represent an opportunity – they are the nexus between groundwater and surface water, a growing area of research. They also improve monitoring due to ease of access. And in many places, infrastructure such as tanks and pipes is already in place due to historic use – something that facilitates monitoring. Finally, springs are the proverbial canary in the coal mine for the mountain aquifers that feed rivers and support hundreds of millions of people downstream.

Springs should therefore be a national priority in terms of research, policy and implementation. What is the density and distribution of springs and how much do they contribute to river base flow? What ecosystem services suffer if springs die and what does it mean for people and the economy? How can we best manage springs? These are some of the questions that need to be addressed to ensure water security under increasing demand, changing land use and climate variability.

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Part VIII
Ground Water Development Issues & Sustainable Solutions

Ground Water Development and Sustainable Solutions

S. P. Sinha Ray

Abstract Ground Water development in South Asia, when viewed critically, exhibits a number of identical issues. As many as twelve number of such critical issues have been listed. Each issue has been viewed with adequate emphasis. The Author also suggests ways and means to address such issues and suggests a number of measures towards solution of protecting such vital resources. Ground water governance based on the sound understanding of such ground water development problems, including participatory management may bring encouraging results.

Keywords: Development issues · Groundwater governance · Participatory management · Sustainable solutions

1 Introduction

An overview of the ground water development in South Asia has brought out a number of identical issues being faced by this part of Asia in planning and executing different ground water development schemes. The long-term sustainability of such programs would depend upon framing effective policies for ground water protection keeping in view of the institutional and cultural environment in the country, the interrelationship of quantity and quality of ground water, and the financial viability and acceptability of the measures by the society.

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S. P. S. Ray (ed.), *Ground Water Development - Issues and Sustainable Solutions*, https://doi.org/10.1007/978-981-13-1771-2_21

2 Development Issues

Based on the experiences gained in the ground water development practices and findings of the in-depth research by various organizations, a number of key issues have been emerged:

1. Reliability and adequacy of resource information
2. Degradation of fresh ground water resources
3. Resource depletion and equity
4. Overexploitation of ground water
5. Saline water intrusion in freshwater aquifers
6. Ground water quality deterioration and contamination of ground water
7. Efficiency of ground water development schemes
8. Lack of community participation
9. Community awareness
10. Management of poor quality aquifer
11. Institutional convergence
12. Policy issues and establishment of legal framework

2.1 Reliability and Adequacy of Resource Information

Hydrological and hydrological aspects of ground water resources to be developed need to be reasonably reliable and based on the scientific information utilizing current advance techniques in the field of study. Ground water quality information is sporadic and not adequate. Extensive geo-referenced information about ground water quality and quantity is not available. Spatial analysis of water quality is limited.

2.2 Degradation of Fresh Ground Water Resources

The indiscriminate use of ground water and installation of tube well structures without any regard to safe distance between the tube wells have caused degradation of otherwise fresh ground water both in the terms of quality and quantity.

2.3 Resource Depletion and Equity

Large-scale ground water withdrawal has created a situation like "ground water mining," especially in the urban and peri-urban agglomerates. The overdraft of ground water has already caused considerable impact on the water supply to the poorer section of the society, since shallow ground water zone is getting depleted by such heavy duty ground water pumping.

2.4 Overexploitation of Ground Water

The availability of inexpensive drilling technologies, free to almost negligible electricity charges, the absence of surface water-based irrigation, and initiative from the government to boost up agricultural production have largely encouraged unregulated and unplanned ground water withdrawal throughout South Asian region. This has resulted in lowering of water table and enhanced the unsaturated zone in the aquifer system. Such overexploitation has already endangered ecological balance, and a situation like land subsidence has been created in some places. Overexploitation of ground water in near proximity to the seafront has caused salt water intrusion into the freshwater aquifer. The trend of continuous decline of ground water has to be reversed.

2.5 Ground Water Quality Deterioration and Contamination of Ground Water

The high concentration of arsenic in ground water has emerged as a big problem in South Asian countries. Similarly, excess fluoride in ground water is increasing in time and space. Other geogenic ground water contaminations include higher levels of iron, manganese, chromium, selenium, etc. In addition, shallow ground water is getting contaminated from anthropogenic sources, like industrial discharges, urban activities, application of fertilizers and pesticides in agriculture field, and disposal of sewage wastes. Release of chemical effluents from dye industries, pharmaceutical industries, nuclear wastes, etc., which migrate in the ground water system through leaching, is making the ground water unpotable, and ingestion of such water has already created critical health menaces.

2.6 Saline Water Intrusion into Freshwater Aquifers

A major section of the population in South Asia lives in the coastal areas. Pumping of ground water without any regard to its safe yield creates lowering of water table which changes the hydraulic gradient of seaward ground water flow. This reversal of hydraulic gradient induces saline water intrusion from the sea water. The salt-affected soils associated with the use of poor quality ground water further deteriorate ground water quality. Excessive pumping of ground water is also causing the upconing of underlying saline aquifer, and overlying freshwater aquifer is getting contaminated.

2.7 Efficiency of Ground Water Development Schemes

There is a need to rationalize the electric tariff for conservation of water and energy. Cheap electricity charges encourage farmers to run the tube wells for 24 h. Again efficiency of some of pumping devices being less than 60% results in higher pumping cost. In planning and execution of some of the ground water development schemes, proper care is not taken for operation and maintenances by unskilled operators. In the absence of suitable training, the development schemes often loose its efficiency and smooth running for longer period.

2.8 Lack of Community Participation

As the development process seldom involves the community in the appraisal and planning phases of ground water development, operation and maintenances of the schemes are not managed with responsibility by the community. Financial constraints due to non-provision of adequate fund for operations and maintenances also discourage the community for active participation. An atmosphere needs to be created so that the community feels attachment to the development schemes of being its own.

2.9 Community Awareness

Community should be continuously empowered with knowledge about ground water availability, its quality aspects, and positive and adverse impact of ground water development schemes in which they are the important stakeholders. The various IEC materials prepared to cater enhancement of their knowledge base about such vital resources will bring the desired impact.

2.10 Management of Poor Quality Water

In one hand, fresh ground water resources are dwindling due to lack of proper management; on the other, large brackish ground water sources, occurring in coastal and inland pockets, remain unutilized. Resources, on the improvement of such poor quality ground water and its effective use, may increase alternate water supply scenario in South Asia.

2.11 Institutional Convergence

In the existing setup, a number of government and nongovernment agencies are associated with the development of ground water resources. Often, the various agencies do not coordinate with each other. As a result, chances of overdevelopment take place, and for any adverse impact in the environmental scenario, agencies try to blame others. To avoid such situation, a real and effective convergence by various institutions responsible for ground water development would be imperative.

2.12 Policy Issues and Establishment of Legal Framework

Integration of ground water and agriculture development is a must, as ground water basin is gaining large momentum day by day. The institutional constraints also restrict farmers "and other stakeholders" participation. A single institution dealing with all aspects of ground water is absent. Linkages with other institutions dealing with ground water are also weak. Well-conceived legal framework controlling ground water development is either absent or not really effective.

3 Suggested Solutions

3.1 Creation of Scientific Database

In order to adopt a sound policy of ground water development, each country should develop scientific database based on a well-conceived monitoring network to decipher various quantity and quality aspects, modeling of aquifer using recent available technology, together with a data sharing mechanism with the user agencies. Still there lies a huge gap in proper assessment of ground water resources, and ground water continues to remain as unseen source. The data available from comprehensive ground water monitoring system should be utilized for preparation of hydrogeological maps, atlases, and bulletins with a view to disseminate those data electronically to user agencies.

3.2 Improving Water Productivity

Ground water being a precious resource, its optimum utilization is essential for any developed economy. The tendency to over-irrigate has to be curbed; water pricing structure may lead to savings. Rationalizing cropping pattern may provide better water productivity. Highly water-intensive crops may be replaced by low water demanding and high-market value crops. Introduction of high-value crops like pulses, sunflower, and high-yielding vegetables, requiring much less water for irrigation, may make the water more productive.

3.3 Management of Poor Quality Aquifers

Large brackish water sources available in the shallow aquifers need to be assessed and converted to resources. Salt-tolerant crops can be introduced in those areas. Its application in pisciculture process may be profitable. While efforts should be made not to create a situation in which freshwater resources do not get contaminated with saline and other metallic/nonmetallic elements like As, F, iron, manganese, chromium, uranium, etc., effective user-friendly, economically viable techniques should be adopted to make the water useable.

3.4 Springshed Development

In the hilly and hydrogeologically favorable regions throughout South Asia, springs may provide important source of water. Keeping in view of the changing land use and climate variability, springshed development can cope up with increasing water demand of the society. Complete mapping of such springs involving the community, building their capacities backed by facilities of physiochemical and bacteriological analyses of water samples, can provide formidable alternative water supply system.

3.5 Water Conservation and Managed Ground Water Recharge

Traditional water conservation practices and enhancement of ground water resources through desilting of ponds would provide water securities in the time of extreme moisture stress. Rejuvenation of village tanks and ponds on a massive scale, for which communities are already aware, can really bring a sea-change in the water availability and ground water recharge domain.

Promoting rainwater harvesting based on traditional and modern know-how can help in a big way of making surface water storage and managed ground water recharge. Various techniques for such recharge are already available. Although many fragmented efforts have been made in various parts of South Asia, rainwater harvesting and ground water recharging should be taken up in most comprehensive way in a missionary mode. Artificial recharging to ground water can establish a balance between discharge and natural recharge. Investments to develop small-scale surface structures, subsurface recharging is necessary to improve the availabilityof ground water at local level.

3.6 Conjunctive Use of Surface and Ground Water

Planned conjunctive use of surface (canal) water and ground water should be encouraged which ensures an optimum utilization of both the water in an irrigation command area whereby upstream farmers make better use of surface water supplies in the canals and ground water-based irrigation can be made wise use by the tail-end farmers. Canal flows need to be regulated to match the requirements. In this process, water logging due to canal seepage can also be addressed making best use of ground water in the lean period.

3.7 Networking of Institutions

There is a need to establish central agency dealing with different aspects of ground water and its management. In each country of South Asia, a number of institutions are dealing with ground water for different purposes. Specially, drinking water, rural development, and agricultural sectors are the major users of ground water. Since health sector is also involved with remediation of health hazards associated with using contaminated ground water, it has also become an important stakeholder. Networking all such institutions to have effective partnership for exchange of information, planning, design, and management of ground water resources is a necessity.

3.8 Research and Development Inputs

With the advancement of various scientific techniques and innovative research, ground water development and associated issues need to be examined, and generated information should be shared for sustainability of ground water-based development schemes. Continuous research on site-specific development can make a fine-tuning of the project. Research and technological development for preventing saline water contamination and conversion of contaminated water to safe freshwater should be economically viable and technically sound and user-friendly.

3.9 Institutional Policy and Legal Framework

It is essential to have a sound ground water protection (both for quantity and quality) policy for each country. A lead agency to coordinate the activities of different institutions involved in ground water development. This lead agency should evolve suitable strategy for ground water development, protection, and effective management.

Keeping in view of the country's human, social, and economic needs suitable legislative framework has to be created. Although, in general, every country has its limited control, it is imperative to adopt suitable legislation which is implementable. Mere legislation may not really serve the purpose. An environment needs to be created in which people shall have respect and desire to abide by legislative measures to be taken.

3.10 Ground Water Pollution and Chemical Quality Management

The primary step is to aim at generating reliable and accurate information about the ground water quality. The data collected by different agencies are to be collated, and data banks may be established. Tools for ground water quality protection should include suitable protection plans, vulnerability assessment, codes of practice, economic instrument, land use planning, water management, community education, awareness, and involvement.

3.11 Community Awareness and Participation

Transparency of information dissemination, development of mutual trust of the communities and the institution responsible for ground water development, and understanding the need of the communities are prerequisite to ensure ongoing participation with the sense of ownership of the communities. IEC materials suitably tailored to create awareness among the rural and urban stakeholders regarding health hazards associated with ground water pollution will produce effective results.

Capacity building of the stakeholders at the grassroot level to handle ground water development schemes will be extremely beneficial.

3.12 Social Convergence

Social convergence of governmental and nongovernmental agencies together with stakeholders at user level holds the key for the success. Decentralization of testing of water samples with a view to develop an easy access of the communities to the test results will be very helpful. Nongovernmental organizations can facilitate effective communication between the government and the user stakeholder.

4 Conclusions

Ground water has acquired a pivotal role in the agricultural economy of South Asian countries. Major drinking water supply to the rural population comes from ground water. However, a serious problem is steadily growing up regarding deterioration of ground water quality and depletion of ground water resources which may get worse in coming years, if not prevented right now. The potential solutions suggested to contain such situation needs careful consideration while effecting ground water governance for sustainable development of economically important such precious resources.