Water Science and Technology Library

Vijay P. Singh
Shalini Yadav
Ram Narayan Yadava *Editors*

# Groundwater

## Select Proceedings of ICWEES-2016

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# Water Science and Technology Library

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# Preface

Fundamental to sustainable economic development, functioning of healthy ecosystems, reliable agricultural productivity, dependable power generation, maintenance of desirable environmental quality, continuing industrial growth, enjoyment of quality lifestyle, and renewal of land and air resources is water. With growing population, demands for water for agriculture and industry are skyrocketing. On the other hand, freshwater resources per capita are decreasing. There is therefore a need for effective water resources management strategies. These strategies must also consider the nexus between water, energy, environment, food, and society. With these considerations in mind, the International Conference on Water, Environment, Energy and Society (WEES-2016) was organized at AISECT University in Bhopal, M.P., India, from 15 to 18 March 2016. The conference was fifth in the series and had several objectives.

The first objective was to provide a forum to not only engineers, scientists, and researchers, but also practitioners, planners, managers, administrators, and policy makers from around the world for discussion of problems pertaining to water, environment, and energy that are vital for the sustenance and development of society.

Second, the Government of India has embarked upon two large projects one on cleaning of River Ganga and the other on cleaning River Yamuna. Further, it is allocating large funds for irrigation projects with the aim to bring sufficient good quality water to all farmers. These are huge ambitious projects and require consideration of all aspects of water, environment, and energy as well as society, including economics, culture, religion, politics, administration, law.

Third, when water resources projects are developed, it is important to ensure that these projects achieve their intended objectives without causing deleterious environmental consequences, such as water logging, salinization, loss of wetlands, sedimentation of reservoirs, loss of biodiversity.

Fourth, the combination of rising demand for water and increasing concern for environmental quality compels that water resources projects are planned, designed, executed, and managed, keeping changing conditions in mind, especially climate change and social and economic changes.

Fifth, water resources projects are investment intensive and it is therefore important to take a stock of how the built projects have fared and the lessons that can be learnt so that future projects are even better. This requires an open and frank discussion amongst all sectors and stakeholders.

Sixth, we wanted to reinforce that water, environment, energy, and society constitute a continuum and water is central to this continuum. Water resources projects are therefore inherently interdisciplinary and must be so dealt with.

Seventh, a conference like this offers an opportunity to renew old friendships and make new ones, exchange ideas and experiences, develop collaborations, and enrich ourselves both socially and intellectually. We have much to learn from each other.

Now the question may be: Why India and why Bhopal? India has had a long tradition of excellence spanning several millennia in the construction of water resources projects. Because of her vast size, high climatic variability encompassing six seasons, extreme landscape variability from flat plains to the highest mountains in the world, and large river systems, India offers a rich natural laboratory for water resources investigations.

India is a vast country, full of contrasts. She is diverse yet harmonious, mysterious yet charming, old yet beautiful, ancient yet modern. Nowhere can we find as high mountains as snow-capped Himalayas in the north, the confluence of three seas and large temples in the south, long and fine sand beaches in the east as well as architectural gems in the west. The entire country is dotted with unsurpassable monuments, temples, mosques, palaces, and forts and fortresses that offer a glimpse of India's past and present.

Bhopal is located in almost the centre of India and is situated between Narmada River and Betwa River. It is a capital of Madhya Pradesh and has a rich, several century-long history. It is a fascinating amalgam of scenic beauty, old historic city, and modern urban planning. All things considered, the venue of the conference could not have been better.

We received an overwhelming response to our call for papers. The number of abstracts received exceeded 450. Each abstract was reviewed and about two-thirds of them, deemed appropriate to the theme of the conference, were selected. This led to the submission of about 300 full-length papers. The subject matter of the papers was divided into more than 40 topics, encompassing virtually all major aspects of water and environment as well energy. Each topic comprised a number of contributed papers and in some cases state-of-the-art papers. These papers provided a natural blend to reflect a coherent body of knowledge on that topic.

The papers contained in this volume, "Groundwater", represent one part of the conference proceedings. The other parts are embodied in six companion volumes entitled, "Hydrologic Modelling", "Energy and Environment", "Environmental Pollution", "Water Quality Management", "Climate Change Impacts", and "Water Resources Management". Arrangement of contributions in these seven books was a natural consequence of the diversity of papers presented at the conference and the topics covered. These books can be treated almost independently, although significant interconnectedness exists amongst them.

This volume contains three parts. Part I deals with some aspects of groundwater focusing on delineation of groundwater zones, spatio-temporal variability of groundwater, and aquifer vulnerability. Part II is on some aspects of groundwater recharge, dealing with recharge sources, management of recharge, and recharge technology. The concluding Part III covers groundwater quality, encompassing cause and sources of pollution, leachate migration, river bank filtration, variability of quality, and management of quality.

The book will be of interest to researchers and practitioners in the field of water resources, hydrology, environmental resources, agricultural engineering, watershed management, earth sciences, as well as those engaged in natural resources planning and management. Graduate students and those wishing to conduct further research in water and environment and their development and management may find the book to be of value.

WEES-16 attracted a large number of nationally and internationally well-known people who have long been at the forefront of environmental and water resources education, research, teaching, planning, development, management, and practice. It is hoped that long and productive personal associations and friendships will be developed as a result of this conference.

College Station, USA — Vijay P. Singh
Bhopal, India — Shalini Yadav
Hazaribag, Bhopal, India — Ram Narayan Yadava

# Acknowledgements

We express our sincere gratitude to Shri Santosh Choubey, Chancellor, and Dr. V.K. Verma, Vice Chancellor, Board of Governing Body, and Board of Management of the AISECT University, Bhopal, India, for providing their continuous guidance and full organizational support in successfully organizing this international conference on Water, Environment, Energy and Society on the AISECT University campus in Bhopal, India.

We are also grateful to the Department of Biological and Agricultural Engineering, and Zachry Department of Civil Engineering, Texas A&M University, College Station, Texas, USA, and International Centre of Excellence in Water Management (ICE WaRM), Australia, for their institutional cooperation and support in organizing the ICWEES-2016.

We wish to take this opportunity to express our sincere appreciation to all the members of the Local Organization Committee for helping with transportation, lodging, food, and a whole host of other logistics. We must express our appreciation to the Members of Advisory Committee, Members of the National and International Technical Committees for sharing their pearls of wisdom with us during the course of the Conference.

Numerous other people contributed to the conference in one way or another, and lack of space does not allow us to list all of them here. We are also immensely grateful to all the invited Keynote Speakers, and Directors/Heads of Institutions for supporting and permitting research scholars, scientists, and faculty members from their organizations for delivering keynote lectures and participating in the conference, submitting and presenting technical papers. The success of the conference is the direct result of their collective efforts. The session chairmen and co-chairmen administered the sessions in a positive, constructive, and professional manner. We owe our deep gratitude to all of these individuals and their organizations.

We are thankful to Shri Amitabh Saxena, Pro-Vice Chancellor, Dr. Vijay Singh, Registrar, and Dr. Basant Singh, School of Engineering and Technology, AISECT University, who provided expertise that greatly helped with the conference organization. We are also thankful to all the Heads of other Schools, Faculty Members and Staff of the AISECT University for the highly appreciable assistance in different organizing committees of the conference. We also express our sincere thanks to all the reviewers at national and international levels who reviewed and moderated the papers submitted to the conference. Their constructive evaluation and suggestions improved the manuscripts significantly.

# Sponsors and Co-Sponsors

The International Conference on Water, Environment, Energy and Society was Jointly organized by the AISECT University, Bhopal (M.P.), India, and Texas A&M University, Texas, USA, in association with ICE WaRM, Adelaide, Australia. It was partially supported by the International Atomic Energy Agency (IAEA), Vienna, Austria; AISECT University, Bhopal; M.P. Council of Science and Technology (MPCOST); Environmental Planning and Coordination Organization (EPCO), Government of Madhya Pradesh; National Bank for Agriculture and Rural Development (NABARD), Mumbai; Maulana Azad National Institute of Technology (MANIT), Bhopal; and National Thermal Power Corporation (NTPC), Noida, India. We are grateful to all these sponsors for their cooperation and providing partial financial support that led to the grand success to the ICWEES-2016.

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# About the Editors

**Prof. Vijay P. Singh** is a University Distinguished Professor, a Regents Professor, and the inaugural holder of the Caroline and William N. Lehrer Distinguished Chair in Water Engineering in the Department of Biological and Agricultural Engineering and Zachry Department of Civil Engineering at Texas A&M University. He received his B.S., M.S., Ph.D., and D.Sc. degrees in engineering. He is a registered professional engineer, a registered professional hydrologist, and an Honorary Diplomate of American Academy of Water Resources Engineers.

Professor Singh has extensively published the results of an extraordinary range of his scientific pursuits. He has published more than 900 journal articles; 25 textbooks; 60 edited reference books, including the massive *Encyclopedia of Snow, Ice and Glaciers and Handbook of Applied Hydrology*; 104 book chapters; 314 conference papers; and 72 technical reports in the areas of hydrology, ground water, hydraulics, irrigation engineering, environmental engineering, and water resources.

For his scientific contributions to the development and management of water resources and promoting the cause of their conservation and sustainable use, he has received more than 90 national and international awards and numerous honours, including the Arid Lands Hydraulic Engineering Award, Ven Te Chow Award, Richard R. Torrens Award, Norman Medal, and EWRI Lifetime Achievement Award, all given by American Society of Civil Engineers; Ray K. Linsley Award and Founder's Award, given by American Institute of Hydrology; Crystal Drop Award, given by International Water Resources Association; and Outstanding Distinguished Scientist Award given by Sigma Xi, amongst others. He has received three honorary doctorates. He is a Distinguished Member of ASCE, and a fellow of EWRI, AWRA, IWRS, ISAE, IASWC, and IE and holds membership in 16 additional professional associations. He is a fellow/member of 10 international science/engineering academies. He has served as President and Senior Vice President of the American Institute of Hydrology (AIH). Currently, he is editor-in-chief of two book series and three journals and serves on editorial boards of 20 other journals.

Professor Singh has visited and delivered invited lectures in all most all parts of the world but just a sample: Switzerland, the Czech Republic, Hungary, Austria, India, Italy, France, England, China, Singapore, Brazil, and Australia.

**Prof. Shalini Yadav** is a Professor and Head of the Department of Civil Engineering, AISECT University, Bhopal, India. Her research interests include Solid and Hazardous Waste Management, Construction Management, Environmental Quality, and Water Resources. She has executed a variety of research projects/consultancy in Environmental and Water Science and Technology and has got rich experience in planning, formulating, organizing, executing, and management of R&D Programs, Seminars, and Conferences at national and international level. She has got to her credit guiding an appreciable number of M.Tech and Ph.D. students. She has published more than 10 journal articles and 30 technical reports. Dr. Shalini has also visited and delivered invited lectures at different institutes/universities in India and abroad, such as Australia, South Korea, Kenya.

Professor Shalini Yadav graduated with a B.Sc. in Science from the Bhopal University. She earned her M.Sc. in Applied Chemistry with specialization in Environmental Science from Bhopal University and M.Tech in Civil Engineering with specialization in Environmental Engineering from Malaviya National Institute of Technology, Jaipur, India, in 2000. Then, she pursued the degree of Ph.D. in Civil Engineering from Rajiv Gandhi Technical University, Bhopal, India, in 2011. Also, she is a recipient of national fellowships and awards. She is a reviewer in many International journals. She has been recognized for one and half decades of leadership in research, teaching, and service to the Environmental Engineering Profession.

**Dr. Ram Narayan Yadava** holds position of Vice Chancellor of the AISECT University, Hazaribag, Jharkhand. His research interests include Solid Mechanics, Environmental Quality and Water Resources, Hydrologic Modelling, Environmental Sciences, and R&D Planning and Management. Yadava has executed a variety of research/consultancy projects in the area of Water Resources Planning and Management, Environment, Remote Sensing, Mathematical Modelling, Technology Forecasting, etc.

He has got adequate experience in establishing institutes/organizations, planning, formulating, organizing, executing and management of R&D Programs, Seminars, Symposia, Conferences at national and international level. He has got to his credit guiding a number of M.Tech. and Ph.D. students in the area of Mathematical Sciences and Earth Sciences. Dr. Yadava has visited and delivered invited lectures at different institutes/universities in India and abroad, such as the USA, Canada, UK, Thailand, Germany, South Korea, Malaysia, Singapore, South Africa, Costa Rica, and Australia.

He earned an M.Sc. in Mathematics with specialization in Special Functions and Relativity from Banaras Hindu University, India, in 1970 and a Ph.D. in Mathematics with specialization in Fracture Mechanics from Indian Institute of Technology, Bombay, India, in 1975. Also, he is recipient of Raman Research Fellowship and other awards. Dr. Yadava has been recognized for three and half decades of leadership in research and service to the hydrologic and water resources profession. Dr. Yadava's contribution to the state of the art has been significant in many different specialty areas, including water resources management, environmental sciences, irrigation science, soil and water conservation engineering, and mathematical modelling. He has published more than 90 journal articles; four textbooks; and seven edited reference books.

# Part I
# Groundwater

# Delineation of Groundwater Potential Zones in Jaisamand Basin of Udaipur District

**P. K. Singh, Praveen Dahiphale, K. K. Yadav and Manjeet Singh**

**Abstract** The groundwater potential zones in the Jaisamand Basin with a catchment area of 1813 $km^2$ have been delineated using various thematic layers including geomorphology, drainage, soil, land use, slope, topographic elevation, and net recharge. As the topography is highly undulating with rolling uplands and in-filled valleys, the velocity of runoff is high whenever the rainfall occurs during the monsoon months. Suitable relative weights have been assigned to the thematic layers on a scale of 1–5 based on their influence on the occurrence of groundwater potential, and thereafter integrated using ILWIS GIS software. The analysis indicated a net recharge of 2–5 cm per year takes place in about 62% of the study area. The study area has been divided into four groundwater potential zones, viz. 'good,' 'moderate,' 'poor,' and 'very poor,' which covers 12.82, 49.65, 33.21, and 4.32% of the study area. Since 37.53% of the study area has poor-to-very poor groundwater potential, immediate measures are required for ensuring sustainable groundwater management in the basin through supply–demand management as well as artificial groundwater recharge of potential aquifers. About 15% percent of the study area is suitable for artificial recharge in the southern part of the basin.

## Introduction

Water is a prime natural resource and a precious national asset. It is a major constituent of all living beings. Water is available in two basic forms, i.e., surface water and groundwater. Water is used for various purposes ranging from domestic, agricultural, industrial, and allied purposes. Water is probably the only natural resource to touch all aspects of human civilization from agricultural and industrial development to cultural and religious values embedded in society. Earth is also

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called as ‘blue planet’ because 70% area of it has been covered by water. The total amount of water on the earth is about 1.35 billion cubic kilometers. About 97.1% has been locked into oceans as saltwater and ice sheets, whereas glaciers contain 2.1%. Only the 0.2% freshwater present on the earth can be used by human beings for variety of purposes, whereas the remaining 0.6% occurs underground aquifers (Anonymous 2007).

The first groundwater potential estimates in Rajasthan were made during 1983–84. Despite an increase in the area of groundwater potential due to more exploratory studies, there has been a total decline of 39.89% in the groundwater potential from 1984 to 2001. As a result, ‘safe’ water zones (i.e., those safe for exploitation) declined from 86% in 1984 to 10.6% in 2004. Also in the year 2001, 70.3% of total groundwater potential zones were classified as ‘dark’ and ‘gray’ (Rathore 2005). Therefore, there is an urgent need to manage the available groundwater resources of Rajasthan to meet the future demands.

For delineating the groundwater potential/prospective zones, GIS has been found to be an effective tool. Several conventional methods such as geological, hydrogeological, geophysical, and photogeological techniques were employed to delineate groundwater potential zones. The Jaisamand lake catchment is located in the Udaipur district which falls under semiarid region of Rajasthan. Drought is normal phenomena of Rajasthan. In the southern region context, its intensity is once in three years, though this is valid only when long-term rainfall data are considered. There is urgent need for augmentation of water table through identification of potential recharge zones and managing aquifer recharge system. Looking to the magnitude of the problem of declining trend of water table and water scarcity in the Jaisamand catchment, an effort have made to conduct groundwater resources study of the basin which will provide a guide line to mitigate the drought and also to enhance the crop yield of the area through sustainable interventions of groundwater management.

## Materials and Methods

### *Description of Study Area*

The Jaisamand lake catchment is located in the Udaipur district which falls in semiarid region of Rajasthan bounded by 73° 45′–74° 25′E longitude and 24° 10′–24° 35′N latitude. The lake is also a prime source supply drinking water for the city of Udaipur located at a distance of about 52 km from the lake. The Jaisamand lake, with a gross capacity of 414.6 $mm^3$ and live storage of 296.14 $mm^3$, is Asia’s second largest artificial water storage reservoir built across the Gomati River. In Jaisamand catchment, Gomati, Thavaria, Siroli, Kheradi, Jhamri, Sukhali, Godi, Makradi, and Bhangar are the major rivers. The location of the study area shown in Fig. 1.

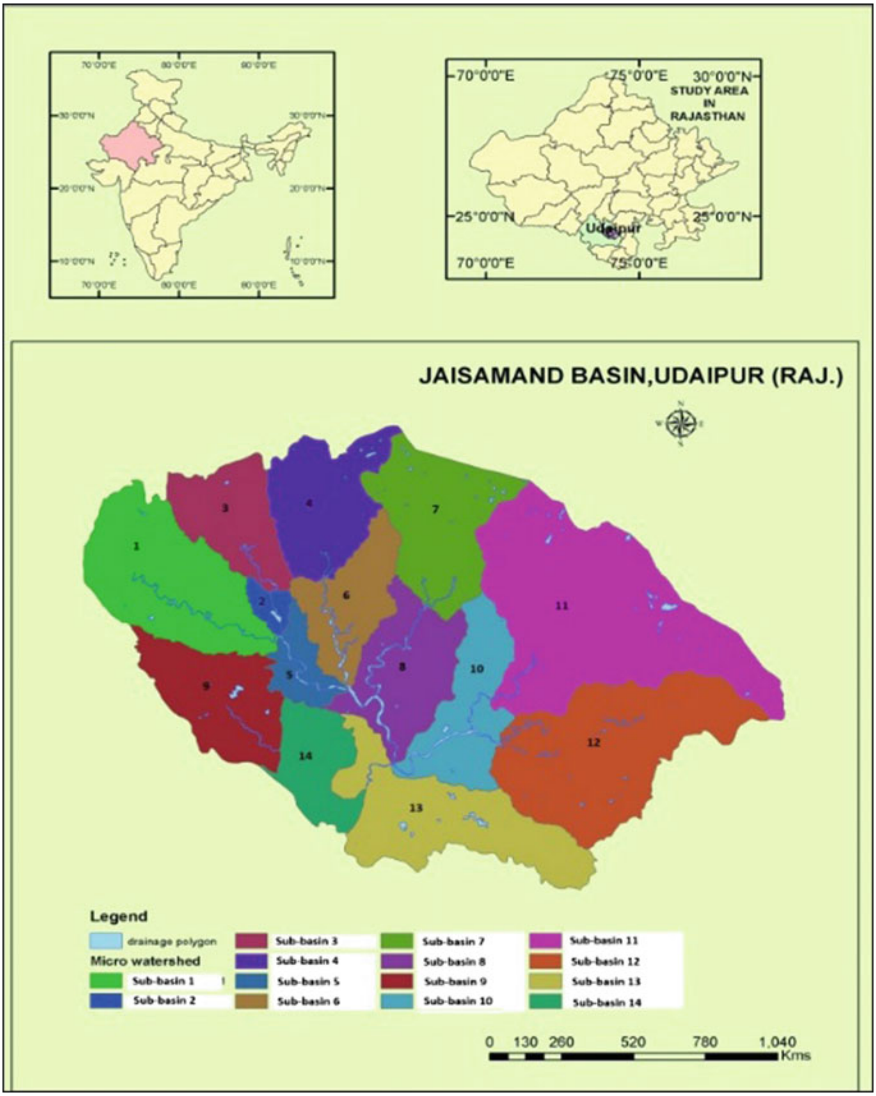



**Fig. 1** Location map of study area

## *Data acquisition*

(a) Extent of Jaisamand catchment and geomorphologic features was extracted from Geodetic Toposheets at 1:50,000 scale, which were procured from Survey of India (SOI), Dehradun.

(b) Soil information and soil map of the study area at 1:250,000 scales were gathered from the Regional Centre of National Bureau of Soil Survey and Land Use Planning (NBSS and LUP), Udaipur, Rajasthan.
(c) Digital elevation model (DEM) for the study area was downloaded from the ASTER database.
(d) Pre- and post-monsoon groundwater depths in meter below ground surface (m bgs) in year 2013 were monitored in 109 selected open dug wells of the Jaisamand catchment.
(e) Aquifer characteristics (i.e., transmissivity and specific yield) were determined by conducting 12 pumping tests in selected wells of Jaisamand catchment.

## *Software Used*

Present study deals with use of GIS for preparation, handling, and processing of different thematic layers. All the GIS-related works were carried out by using ArcGIS 10 software. ArcGIS software is a PC-based GIS and remote sensing software, developed by the ESRI. ArcGIS desktop software products allow users to analyze, map, manage, share, and publish geographic information. At all levels of licensing, ArcMap, ArcCatalog, and ArcToolbox are the names of the applications comprising the desktop package. ArcGIS Explorer, ArcReader, and ArcExplorer are basic freeware applications for viewing GIS data.

## *Determination of Aquifer Parameters by Pumping Test*

Evaluation of aquifer characteristics is the prime task for harnessing an aquifer for optimum results yielding information about how much groundwater is available for development and what will be the consequences of withdrawing a certain quantity of groundwater.

Aquifer parameters, i.e., transmissivity ($T$) and specific yield ($S_y$), are often determined by means of pumping test. Scientifically planned pumping tests provide information for solution of many regional, as well as local, groundwater flow problems. It also provide information about the yield and drawdown of the well, which in turn is essential for selecting the type of pump, estimating cost of pumping, well efficiency, etc. Minimum spacing requirement between two wells to avoid mutual interference can also be determined with these parameters.

In a pumping test or an aquifer test, a well is pumped at constant/variable rate for a certain period. The effect of pumping on the water level is measured in the pumped well and in one or more observation wells, penetrating the aquifer in the vicinity of the pumped well with the help of stage gauge recorder or a measuring tape. Type of an aquifer is identified by plotting time-drawdown curve on double-logarithmic scale and comparing with standard drawdown curve on double-logarithmic scale. Aquifer parameters ($T$ and $S_y$) are then found with the help of the measured drawdown, discharge and the well function by use of a graphical technique called ‘curve matching.’

In present study, a total 12 pumping tests were performed in different geological formations of selected wells (Fig. 2) in the Jaisamand catchment. Wells selected for pumping tests were large diameter shallow open dug wells, which while pumped extract groundwater from the unconfined aquifer. The pumping test of selected well and measurement of water level using acoustic water level indicator is shown in Fig. 3.

## *Analyzing Pumping Test Data by Curve-matching Technique*

Plentiful techniques are available for analyzing pumping test data depending upon the type of aquifer (e.g., confined, semi-confined, unconfined), type of pumping well (e.g., infinitesimal or large diameter), well penetration (full or partial), and

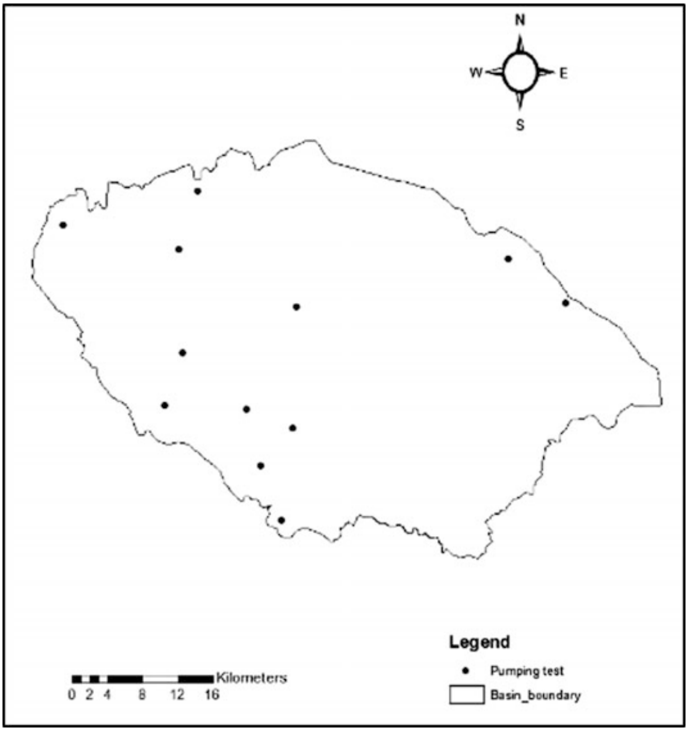



**Fig. 2** Location map of pumping test sites

**Fig. 3** Measurement of water level by using acoustic water level indicator

discharge rate (constant or variable). In this study, pumping tests were performed in large diameter open dug wells in shallow unconfined aquifer situated in hard-rock area of Jaisamand catchment. Moench method is available for analyzing the pumping test data of large diameter wells in unconfined aquifer. However, solution of Moench method is very complex for practical application. Some of the past studies conducted in Udaipur by Jat (1990) and Verma (2005) reported that Papadopulos and Cooper (1967) method can successfully be used for analyzing pumping test data of large diameter wells in unconfined aquifers after converting unconfined aquifer drawdown into equivalent confined aquifer's drawdown. Therefore, Papadopulos and Cooper (1967) curve-matching technique was adopted for determining aquifer properties in this study. The Papadopulos and Cooper solution accounts for well bore storage effects in a large diameter (finite diameter) pumping well. Papadopulos and Cooper method is described below.

## *Groundwater Potential Assessment by Using Remote Sensing and GIS*

The remote sensing (RS) technique provides synoptic coverage and accurate spatial information, which enable economical utilization over conventional methods of hydrogeological surveys. Rapid advances in the development of geographic information system (GIS), which provides spatial data integration and tools for natural resources management, have enabled integrating the data in an environment which has been proved to be an efficient and successful tool for groundwater studies.

This study utilized RS and GIS techniques for generating thematic layers of different factors influencing groundwater occurrence. The multi-criteria decision-making technique coupled with GIS has been used to identify groundwater potential zones in the study area. The procedures adopted to identify and delineate groundwater potential zones using RS, GIS, and MCDM techniques are illustrated in Fig. 4.

## *Selection of Thematic Layers*

In past groundwater studies concerning combined use of RS and GIS techniques, various thematic maps for delineating groundwater favorability zones were selected believing that all the thematic parameters have some influence on the occurrence of groundwater. The number of thematic layers used depends on the availability of data in an area.

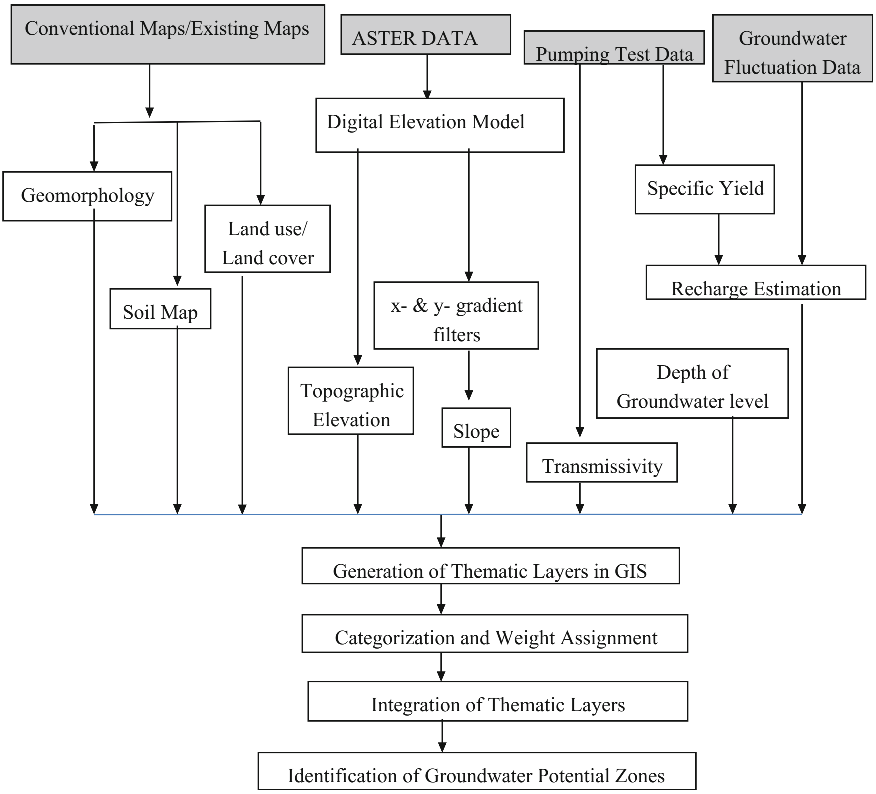



**Fig. 4** Flowchart for groundwater potential zoning using GIS

### Generation of Thematic Layers

In order to assess groundwater potential in the study area, eight thematic maps were generated using remote sensing and conventional data. Out of these thematic maps, topographic elevation and slope maps were generated from ASTER data, whereas the remaining maps were generated using conventional data. These thematic maps were developed using ArcGIS software.

### Groundwater Recharge Map

Recharge is broadly defined as water that reaches an aquifer from any direction. It can be classified as direct, localized, and indirect. The term direct recharge refers to the recharge derived from precipitation or irrigation that occurs fairly uniformly over large areas, whereas the term localized recharge refers to the concentrated recharge from depressions in surface topography such as streams and lakes. Point estimates of the net recharge at 109 sites for the study area were estimated using Water Table Fluctuation method. Using this point recharge values, a recharge map of the study area was prepared.

### Transmissivity Map

Aquifer transmissivity is very important factor as it governs groundwater movement and recharge process. The higher value of transmissivity increases the suitability of an area for artificial recharge. In this study, transmissivity values obtained in pumping test were used to prepare a thematic layer on transmissivity using ArcGIS software. Different transmissivity classes in the study area were identified and then assigned weights according to their transmissivity values using the Saaty's analytical hierarchy approach.

### Delineation of Groundwater Potential Zones

The thematic layers on geomorphology, soil, slope, topographic elevation, land use/land cover, post-monsoon groundwater depth, recharge, and transmissivity were used for the delineation of groundwater potential zones in the study area. To demarcate the potential zones, all these thematic layers were assigned weights and then were integrated using ArcGIS software. The weights of thematic map and their individual features were decided based on the experts' opinions and local field experience (Machiwal et al. 2011).

The weights of the different themes were assigned on a scale of 1–5 based on their influence on the groundwater potential. Different features of each theme were assigned weights on a scale of 1–9 according to their relative influence on groundwater potential. Based on this scale, the qualitative evaluation of different features of a given theme was performed as poor, moderate, good, very good, and excellent. The relative influence of the individual themes and features on groundwater potential was decided based on the experts' opinion, information, and local knowledge. Thereafter, a pair-wise comparison matrix was constructed using the Saaty's analytical hierarchy process to calculate normalized weights for individual themes and their features. To demarcate groundwater potential zones, all the eight thematic layers after assigning weights were added (overlaid) using ArcGIS software. The total weights of different polygons in the integrated layer were derived from the following equation to obtain groundwater potential index:

$$\begin{aligned}\mathrm{GWPI} = (&\mathrm{GM}_w\mathrm{GM}_{wi} + \mathrm{SO}_w\mathrm{SO}_{wi} + \mathrm{SL}_w\mathrm{SL}_{wi} + \mathrm{TE}_w\mathrm{TE}_{wi}\\ &+ \mathrm{LU}_w\mathrm{LU}_{wi} + \mathrm{WD}_w\mathrm{WD}_{wi} + \mathrm{RE}_w\mathrm{RE}_{wi} + \mathrm{TR}_w\mathrm{TR}_{wi})\end{aligned}$$

where

GWPI = groundwater potential index, GM = geomorphology, SO = soil type, SL = slope, TE = topographic elevation, LU = land use/land cover, WD = post-monsoon groundwater depth, RE = groundwater recharge, TR = transmissivity, $w$ = normalized weight of a theme, and $wi$ = normalized weight of the individual features of a theme.

GWPI is a dimensionless quantity that helps in indexing probable groundwater potential zones in the area. The range of GWPI values was divided into four equal classes (called zones), and the GWPI of different polygons falling under different range was grouped into one class. Thus, the entire study area was qualitatively divided into four groundwater potential zones, and a map showing these zones was prepared using ArcGIS software. The entire process of groundwater potential zoning is shown in Fig. 4.

## *Suitable Strategies for Sustainable Groundwater Resources Management*

For the management of groundwater resources, artificial recharge is a very important factor. Artificial recharge is the process of augmenting the natural movement of surface water into underground formations by some artificial means. This is accomplished by constructing infiltration facilities or by inducing recharge from surface water bodies. In hard-rock areas, the underlying lithological units do not have sufficient porosity and permeability. In these areas, groundwater recharge falls short of the water that is being taken out of the aquifers. Hence, groundwater cannot suffice the requirement for agriculture or drinking water. Thus, additional recharge by artificial methods becomes necessary to meet the water deficit. The performance of artificial recharge efforts can be immensely increased if they are performed through proper scientific planning. A remote sensing and GIS-based method is found to be very useful in suitability analysis for artificial recharge sites in the hard-rock terrain. For such analysis, the first task is to identify the factors facilitating recharge to take place. In this study, the thematic layers used for determining recharge zones are (a) transmissivity, (b) recharge, (c) groundwater level (post-monsoon), (d) topographic elevation, (e) soil, and (f) slope. All the six thematic layers were combined using Boolean Logic Analysis to delineate to zones of suitability for artificial recharge structures. The prime task in this method is to identify the criterion and to formulate the set of logical conditions to extract the suitable zones. With this criterion, the output has only two classes: suitable or unsuitable. The criteria considered in this study for demarcating suitable zones for artificial recharge are mentioned in Table 1. A flowchart showing steps for delineating artificial recharge zones is presented in Fig. 5.

**Table 1** Criteria for demarcating suitable artificial recharge zones

| Thematic layer | Suitability criteria |
|---|---|
| Slope | <5% |
| Groundwater level (post-monsoon) | >4 m below ground surface |
| Transmissivity | 200–300 $m^2$/day |
| Recharge | 2–4 cm/year |
| Topographic elevation | <600 m |
| Soil | Coarse loamy and rock outcrop to loamy skeleton |

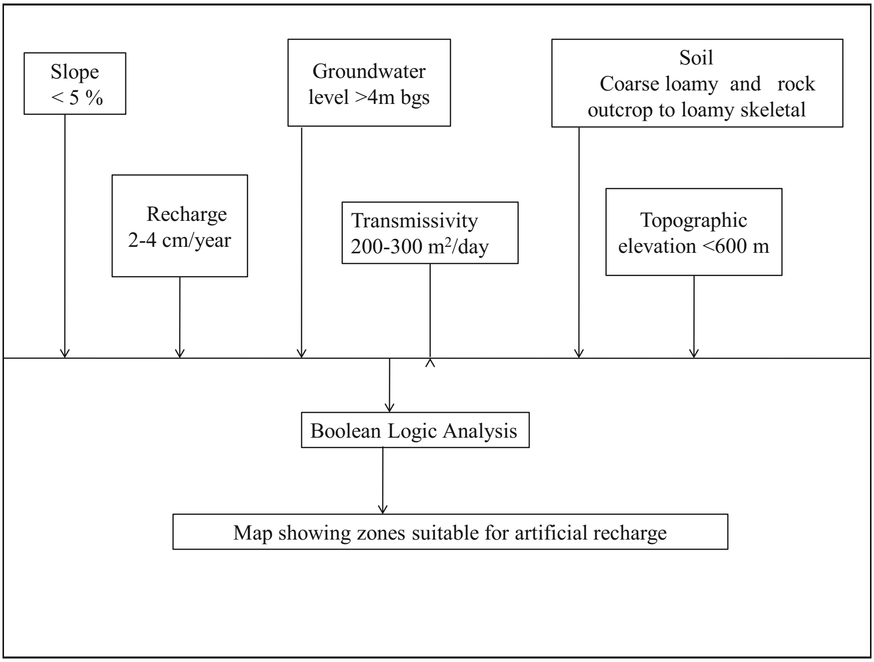



**Fig. 5** Flowchart showing steps for delineating artificial recharge zones

# Results and Discussion

## *Aquifer Parameters*

Evaluation of aquifer parameters, i.e., transmissivity and specific yield, is an important task in groundwater assessment leading to an optimal development. Pumping test is the main field test for determining these parameters. Special significance of these tests is enhanced particularly in dealing with replenishable natural resources for optimum utilization, location of recharge/barrier boundaries, prediction of drawdown and well yields for efficient use of groundwater. The tests are analyzed, especially, in view of hard-rock formations, and large diameter wells existing at the sites were tested during the course of investigations.

## *Estimation of Aquifer Parameters*

Pumping test data of 12 sites over the different geological formation of the study area of Jaisamand catchment were analyzed by Papadopulos and Cooper type curve-matching technique. Matching of the observed time-drawdown curve with the type curves of the Papadopulos and Cooper for one test site is illustrated in Fig. 6 as an example. Results of the pumping test data analysis along with the details of pumping tests are summarized in Table 2. The aquifer transmissivity varies from 123.82 to 386.94 $m^2$/day, and the specific yield ranges from 0.000160 to 0.03047. The transmissivity and specific yield are highly site-specific and vary significantly over small distances (Table 2). This wide variation in hydraulic parameters of the aquifer suggests strong heterogeneity, which is most likely in fractured subsurface formations of the study area. From these point estimates of transmissivity, a raster map is prepared which is used as one of the thematic layer for delineating groundwater potential zones for the Jaisamand catchment.

### *Groundwater Recharge*

Groundwater recharge for 109 sites was estimated by using Water Table Fluctuation method explained earlier in methodology. The average value of specific yield estimated at various locations is taken for different geological formations in computation of groundwater recharge. The minimum computed recharge is 0.18 cm/year, and the maximum value is 14.58 cm/year. Average value of groundwater recharge for the study area is found to be 2.87 cm.

### *Features of Different Thematic Maps*

The eight thematic layers, i.e., geomorphology, soil, slope, topographic elevation, land use/land cover, post-monsoon groundwater depth, recharge, and transmissivity were generated for the Jaisamand catchment (Fig. 7).

### *Groundwater Potential Zoning*

The eight thematic maps, namely geomorphology, soil, slope, topographic elevation, land use/land cover, post-monsoon groundwater depth, recharge, and transmissivity described in the previous section were considered for identifying groundwater potential zones in the study area. The assignment of weights to the themes and their features and the integration of different themes in a GIS environment are discussed in the following sections.

**Table 2** Transmissivity and specific yield in selected wells of Jaisamand catchment

| Geological formation | Grid no. | Latitude | Longitude | Well diameter (m) | Depth of well (m) | Test duration (min) | Transmissivity ($m^2$/day) | Specific yield |
|---|---|---|---|---|---|---|---|---|
| Migmatite, gneiss, feldspar, schist | 18 | 24° 23.921′N | 73° 55.432′E | 3.2 | 14.35 | 372 | 260.02 | 0.000483 |
| | 29 | 24° 27.529′N | 73° 59.735′E | 5.40 | 15.50 | 390 | 386.94 | 0.00884 |
| | 37 | 24° 31.334′N | 73° 56.829′E | 3.48 | 15.50 | 418 | 174.66 | 0.000160 |
| | 46 | 24° 32.705′N | 73° 55.306′E | 3.38 | 10.30 | 376 | 183.43 | 0.01529 |
| Granite, granodiorite, tonalitic gneiss | 4 | 24° 18.037′N | 74° 01.352′E | 5.60 | 17.10 | 388 | 200.43 | 0.00949 |
| | 11 | 24° 21.016′N | 73° 59.828′E | 3.9 | 12.60 | 333 | 321.37 | 0.002582 |
| | 12 | 24° 19.646′N | 74° 04.702′E | 2.98 | 14.80 | 372 | 366.63 | 0.002385 |
| Phyllite and mica schist | 1 | 24° 32.240′N | 74° 10.229′E | 5.30 | 8.00 | 369 | 385.22 | 0.03047 |
| | 44 | 24° 33.677′N | 73° 50.360′E | 3.18 | 16.80 | 365 | 123.82 | 0.00136 |
| Conglomerate | 10 | 24° 19.542′N | 73° 53.217′E | 4.00 | 16.20 | 370 | 375.07 | 0.0286 |
| Quartzite | 43 | 24° 32.735′N | 74° 13.935′E | 3.80 | 21.35 | 362 | 275.15 | 0.004234 |
| | 34 | 24° 26.506′N | 74° 17.465′E | 4.20 | 14.00 | 374 | 278.59 | 0.007019 |

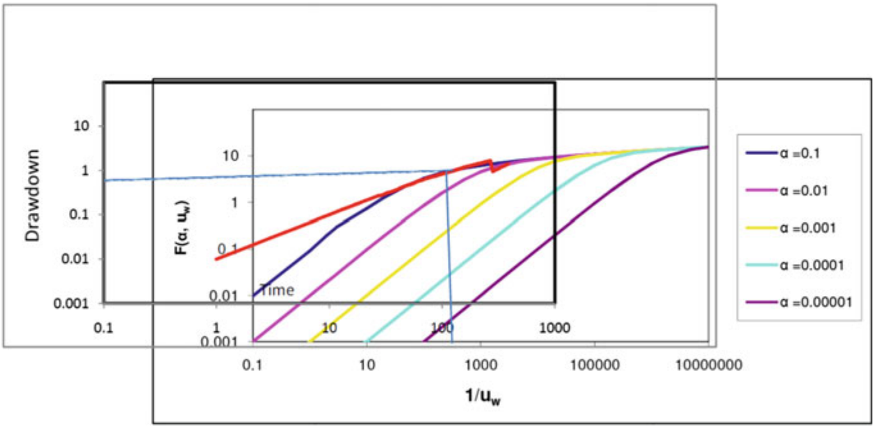



**Fig. 6** Matching of observed time-drawdown curve with standard Papadopulos–Cooper type curve

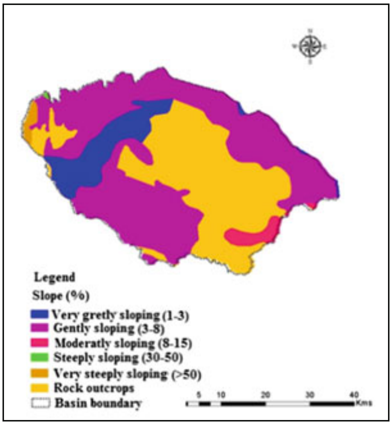
## *Weights for thematic maps*

After understanding the behavior of different thematic features with respect to groundwater control in the study area, the different themes and their individual features of these themes were assigned suitable weights (Machiwal et al. 2011). The weights assigned to all the thematic layers are presented in Table 3.

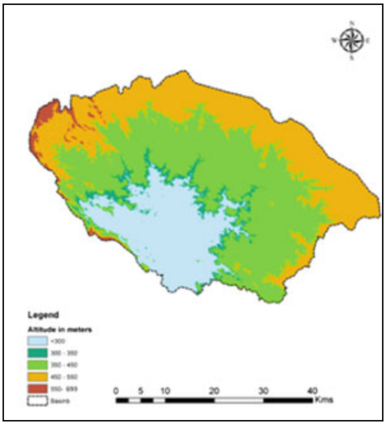
The assigned weights of different features of individual themes were normalized by AHP and eigenvalue technique and are presented in Tables 4 and 5.

## *Groundwater Potential Zones*

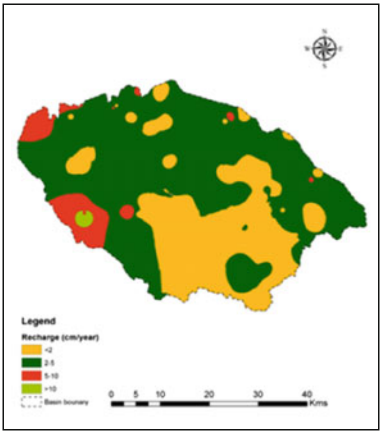
The groundwater potential map of the study area (Fig. 8a) reveals four distinct zones representing 'good,' 'moderate,' 'poor,' and 'very poor' groundwater potential in the area. The 'good' groundwater potential zone mainly encompasses valley fill and buried pediment areas around the lake. It demarcates the areas where the terrain is most suitable for groundwater storage and also indicates the availability of water below the ground. The area covered by 'good' groundwater potential zone is about 12.82% and contributed Kheroda, Neemri, Mansing Pura, Lakarwas, Adinda, Runeeja, Edana, Gingla, Wali, Bed, etc. villages. The maximum area has moderate groundwater potential, and it covers 49.65% area. This zone includes Deopura, Karawali, Kharka, Ratanpura, Morpura, Talab, Jamboora, Buthel, Mamadeo, Karget, Pindoliya, Loda, Basa, Bemla, Rayala, Phoosariya



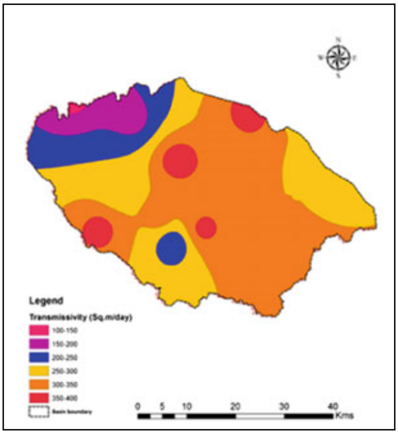

Thematic layer of Slope




Thematic layer of Topographic Elevation




Thematic layer of Recharge




Thematic layer of Transmissivity

**Fig. 7** Thematic layer of geomorphology

**Table 3** Weights of eight themes for groundwater potential zoning

| S. No. | Themes | Weight |
|---|---|---|
| 1 | Geomorphology | 5 |
| 2 | Land use/land cover | 4 |
| 3 | Soil | 3.5 |
| 4 | Slope | 3.5 |
| 5 | Topographic elevation | 3 |
| 6 | Recharge | 4.5 |
| 7 | Post-monsoon groundwater depth | 4 |
| 8 | Transmissivity | 1 |

**Table 4** Normalized weights of the geomorphology classes for groundwater potential zoning

| Geomorphology classes | Groundwater prospect | Weight assigned | Normalized weight |
|---|---|---|---|
| Water body | Very good | 8 | 0.381 |
| Valley fill | Good | 7 | 0.333 |
| Phyllite and schist | Moderate | 3 | 0.143 |
| Granite and gneiss | Poor | 2 | 0.095 |
| Structural hill | Very poor | 1 | 0.048 |

**Table 5** Normalized weights for the recharge classes for groundwater potential zoning

| Recharge classes (cm/year) | Groundwater prospect | Weight assigned | Normalized weight |
|---|---|---|---|
| <2 | Very poor | 2 | 0.105 |
| 2–5 | Poor | 3 | 0.158 |
| 5–10 | Moderate | 6 | 0.316 |
| >10 | Good | 8 | 0.421 |

villages. The 33.21% area shows poor groundwater potential zone, and in this zone, Agar, Deoliya, Ajani, Ramina, Kund, Kelwa, Kaccher, Bhekra, etc., villages are fall. In study area, 4.32% area shows very poor groundwater potential which includes villages of Dhawari, Patiya, Bobri, Arniya, Tekan, Kasotiya, etc. The various classes of groundwater potential zones along with corresponding area are shown in Table 6.

## *Groundwater Resources Management*

The favorable artificial groundwater recharge zone for the study area is delineated using RS and GIS techniques. In this map, green color indicates the favorable zone for artificial recharge. It was found in the southern part of the basin which includes villages of Karawali, Deopura, Talab, Kharka, Payari, Basa, Pheela, Okhariya, Loda, Gingla, Buthel, Edana, etc., and some other scatter portion of catchment. For artificial recharge, suitable recharge structures such as percolation ponds, check dams, and earthen dams are recommended for construction. The area which is favorable for artificial recharge is 279 km$^2$, which contributes only 15.02% of the total study area. Similar study was also carried out for the Ahar River basin of Udaipur district revealed that the favorable artificial recharge zone for the study area was found to be 44.6 km$^2$, which was 12.7% of the total study area. Map of the suitable zones for artificial recharge in the study area is shown in Fig. 8b.

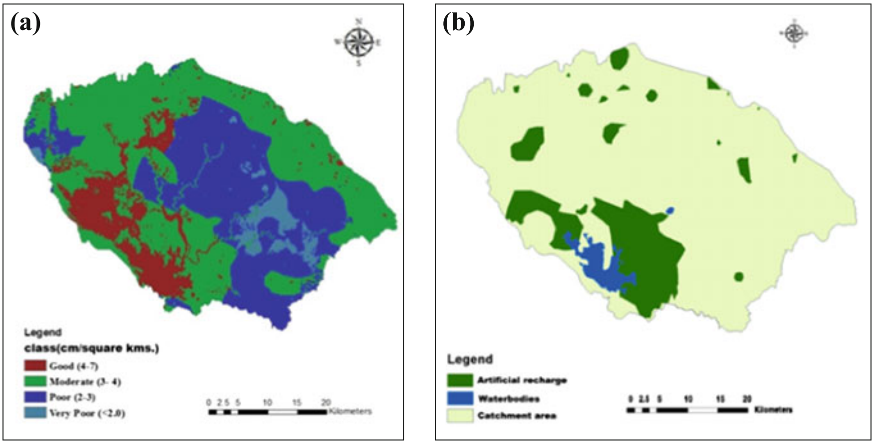



**Fig. 8** **a** Groundwater potential zone of Jaisamand catchment. **b** Favorable artificial groundwater recharge zones of Jaisamand catchment

**Table 6** Groundwater potential zone classes and area

| Class | Area ($km^2$) | % Area |
|---|---|---|
| Good | 238.10 | 12.82 |
| Moderate | 922.38 | 49.65 |
| Poor | 617.07 | 33.21 |
| Very poor | 80.33 | 4.32 |

# Conclusions

The groundwater potential index map of the study area was prepared by considering eight thematic maps, viz. geomorphology, soil, slope, topographic elevation, land use/land cover, recharge, post-monsoon groundwater depth, and transmissivity. These maps were prepared using conventional and remote sensing data with the help of ArcGIS software.

The maximum area has moderate groundwater potential and covers 49.65% area, and this zone includes Deopura, Karawali, Kharka, Ratanpura, Morpura, Talab, Jamboora, Buthel, Mamadeo, Karget, Pindoliya, Loda, Basa, Bemla, Rayala, Phoosariya villages. The 12.82% area has good groundwater potential, and it covers Kheroda, Neemri, Mansing Pura, Lakarwas, Adinda, Runeeja, Edana, Gingla, Wali, Bed, etc., villages. The area which is favorable for artificial recharge is 279 $km^2$, which contributes only 15.02% of the total study area.

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# Spatial and Temporal Variations of Groundwater Level: A Case Study of Wainganga Sub-basin, Nagpur, India

**Chandan Kumar Singh and Yashwant B. Katpatal**

**Abstract** Groundwater is one of the most important natural resource used for drinking, industrial, agriculture, etc. Understanding spatial and temporal variations of groundwater level throughout the basin is essential for sustainable development of groundwater resources. The objective of the present study is to analyze the spatial and temporal variations of groundwater levels in the Wainganga sub-basin. Mann–Kendall and ordinary kriging methods were used to analyze the groundwater levels with space and time. Pre- and post-monsoon groundwater levels from 1991 to 2012 were used for analysis. For the last 22 years, from the spatial variation maps, small fluctuations were observed in groundwater levels and it is found to be deeper, particularly in industrial areas. Also, temporal variation of groundwater level shows the decreasing trends.

**Keywords** Groundwater · Kriging · Mann–Kendall · GIS

## Introduction

Groundwater is the important natural resources played very useful role for the development of agriculture in India (Sharma 2009). Large-scale development and utilization of groundwater in various parts of India have resulted in the depletion of fresh groundwater resources and increase of gray and dark areas in the country (CGWB 2012). Tabari et al. (2012) investigated the temporal trends in annual, seasonal, and monthly groundwater-level fluctuations for the period 1985–2007 in the north of Iran using the Mann–Kendall test and the Sen's slope estimator. They demonstrated that nonparametric approaches can be used for analysis of the trend of

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groundwater level. Spatiotemporal analysis of regional trends and shift changes of autocorrelated temperature series in Urmia lake basin using Mann–Kendall and change point tests (Malekian and Kazemzadeh 2016). Kousari et al. (2011) studied trend of mean, minimum, and maximum air temperature, precipitation, and relative humidity based on the Kendal test in Iran and suggested an increasing trend for air temperature while a decreasing one for precipitation and relative humidity at the majority of the studied stations. The temporal and spatial changes in the groundwater level were studied by several researchers. Ahmadi and Sedghamiz (2007) and Mini et al. (2014) used geostatistics approach for mapping of groundwater level to identify the trends. Antonellini et al. (2008) created salinity and water table maps using kriging for the coastal aquifer of the southern Po Plain, Italy, to identify the causes and extent of seawater intrusion. Taany et al. (2009) applied kriging technique to study the spatial and temporal variation of groundwater-level fluctuation in Amman–Zarqa Basin. The objective of present study is to analyze the spatial and temporal trend for WGK4 watershed within the Wainganga sub-basin in Nagpur district. The Mann–Kendall test and Sen's slope estimator were used to detect the trends in the groundwater levels from 1991 to 2012 using 5 observation wells. Spatial variation of groundwater level was analyzed using ordinary kriging interpolation method. It was observed that the groundwater level shows decreasing and increasing trends with time in some parts of the area under study.

## Methodology

### *Study Area*

Wainganga sub-basin is selected as study area which is in Nagpur district of Maharashtra, India. It lies between north latitudes 20° 35′ and 21° 44′ and east longitudes 78° 15′ and 79° 40′ and falls in Survey of India toposheets 55 K, O and P, with an elevation about 310 m above mean sea level. Kanhan and Pench are the main rivers flowing through the district. Major crops in entire district are jowar, cotton, wheat, and pulses, and the normal annual rainfall is around 1000–1200 mm. Wainganga sub-basin has 40 watersheds (Singh and Katpatal 2015) within Nagpur district out of which WGK4 watershed is selected for study (Fig. 1), and its total geographical area is approximately equal to 490.98 km$^2$. Observation well data for WGK4 watershed was obtained from Central Ground Water Board (CGWB) and Groundwater Surveys and Development Agency (GSDA). There are 5 observation wells, dug wells used for agriculture are 1978, 239 for domestic purpose, and bore wells with hand pump is 300 (CGWB and GSDA 2014).

The Mann–Kendall test and Sen's slope estimator were used for trend analysis and to find slope of the trend line. To analyze the spatial trend of groundwater-level fluctuation, groundwater-level data of pre- and post-monsoon season were used because there is negligible discharge from the agricultural wells for irrigation. The

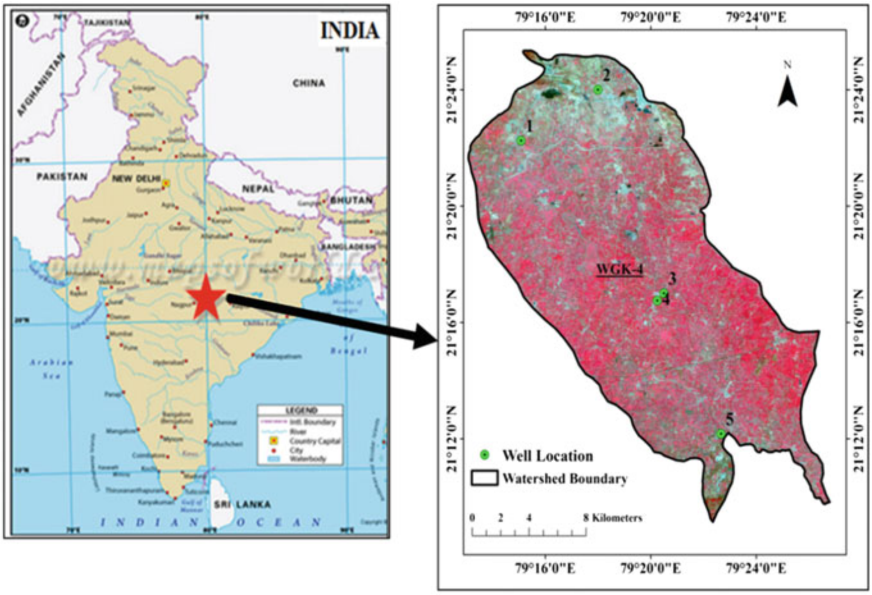


**Fig. 1** Location map of the study area

data were obtained from Groundwater Survey and Development Agency (GSDA) and Central Ground Water Board (CGWB), and these are government agencies working under the Maharashtra state and Central Government of India. These agencies are monitoring groundwater-level data from several decades in different parts of Nagpur district, state of Maharashtra. Pre-monsoon and post-monsoon groundwater-level data for the period of 1991–2012 were used for the analysis.

## *Mann–Kendall Test*

Mann–Kendall test is one of the nonparametric tests and commonly used method for trend analysis of time series data (Kendall 1975). The advantage of this test is that it does not rely on data belonging to any particular distribution, i.e., no assumption of normality is required; as such, it is required for parametric method. This test can be mostly stated to observe trend of the variable parameters with time, i.e., increase or decrease (monotonic trend). The Mann–Kendall Statistic is calculated using the formula:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}\left(x_j - x_i\right) \tag{1}$$

where $S$ is Mann–Kendall test statistic, $n$ is the size of the sample, and sgn is the signum function. The application of trend test is done to a time series $x_i$, which is ranked from $i = 1, 2, \ldots, n-1$, and $x_j$, which is ranked from $j = i + 1, 2, \ldots, n$:

$$\mathrm{sgn}(x_j - x_i) = \left\{ \begin{array}{ll} 1 & \text{if } (x_j - x_i) > 0 \\ 0 & \text{if } (x_j - x_i) = 0 \\ -1 & \text{if } (x_j - x_i) < 0 \end{array} \right\} \tag{2}$$

If $n < 10$, the value of $S$ is compared directly to the theoretical distribution of $S$ derived by Mann–Kendall (Gilbert 1987). For $n \geq 10$, the statistic $S$ is approximately normally distributed with means and variance as follows:

$$\mathrm{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(i)(i-1)(2i+5)}{18} \tag{3}$$

$$\begin{cases} \frac{s-1}{\sqrt{\mathrm{Var}(S)}} & \text{if } S > 0 \\ Z = 0 & \text{if } S = 0 \\ \frac{s-1}{\sqrt{\mathrm{Var}\,(S)}} & \text{if } S < 0 \end{cases} \tag{4}$$

## *Sen's Slope Estimator Test*

Sen's slope estimator test is a nonparametric alternative to the parametric ordinary least-squares regression line (Sen 1968). Sen's slope is used to calculate true slope in time series data (change per unit time), and magnitude of trend is predicted by Sen's slope estimator ($Q_i$):

$$(Q_i) = \frac{x_j - x_k}{j - k} \quad \text{for} \;\; i = 1, 2, 3 \ldots N \tag{5}$$

where $x_j$ and $x_k$ are data values at times $j$ and $k$ ($j > k$), respectively.

## *Ordinary Kriging*

Geostatistics can be defined as the branch of statistical sciences that studies spatial/temporal phenomena and capitalizes on spatial relationships to model possible values of variables at unobserved, unsampled locations (Caers 2005). Geostatistical methods (ordinary kriging) that are based on statistical models include autocorrelation, i.e., statistical relationships among the measured points. Not only do these techniques have the capability of producing a prediction surface, but they can also provide some measures of the certainty or accuracy of the predictions. The general equation of kriging estimator is:

$$Z^*\left(x_p\right) = \sum_{i=1}^{n} \lambda_i Z(x_i) \tag{6}$$

In order to achieve unbiased estimations in kriging, the following set of equations should be solved simultaneously:

$$\begin{cases} \sum_{i=1}^{n} \lambda_i \gamma\left(x_i, x_j\right) - \mu = \gamma(x_i, x) \\ \sum_{i=1}^{n} \lambda_i = 1 \end{cases} \tag{7}$$

where $Z^*\left(x_p\right)$ is the kriged value at location $\left(x_p\right), Z(x_i)$ is the known value at location $x_i$, $\lambda_i$ is the weight associated with the data, $\mu$ is the Lagrange multiplier, and $\gamma$ $(x_i, x_j)$ is the value of variogram corresponding to a vector with origin in $x_i$ and extremity in $x_j$.

## Results and Discussion

### *Temporal Analysis*

To estimate the groundwater potential, continuous record of pre- and post-monsoon groundwater level is necessary. The difference between post- and pre-monsoon groundwater level indicates the amount of recharge and draft in the region. The results obtained from the Mann–Kendall test and Sen's Slope were used to establish the trends in time series of pre-monsoon and post-monsoon groundwater level. Mann–Kendall's standard test statistics are represented in Table 1 for pre- and post-monsoon groundwater level. A positive value of $Z$ indicates an increasing trend, and negative value indicates decreasing trend. Sen's slope estimator was used to find out the slope of trend line in m/year (Fig. 2). Positive and negative values of slope show the declining trend and increasing trend of groundwater level during the period 1991–2011. The depth of water level with respect to ground surface is increasing for positive trend, and vice versa; it is decreasing for negative trend. It was observed from the Sen's slope that well Nos. 1, 3, and 4 show the negative trend, i.e., depth-to-water level with respect to ground surface is decreasing (Fig. 2a, c, d); for well No. 5, trend is positive and no trend was observed for well No. 2 (Fig. 2b, e). Rainfall in the watershed (WGK4) is approximately constant, but

**Table 1** Mann–Kendall standard test statistics for pre- and post-monsoon groundwater level

| Well No. | Test $Z$ post-monsoon | Trend post-monsoon | Test $Z$ pre-monsoon | Trend pre-monsoon |
|---|---|---|---|---|
| 1 | 0.59 | Increasing | 2.19 | Increasing |
| 2 | 1.24 | Increasing | 1.95 | Increasing |
| 3 | 2.37 | Increasing | 1.13 | Increasing |
| 4 | −0.57 | Decreasing | 0.96 | Increasing |
| 5 | −3.69 | Decreasing | −0.7 | Decreasing |

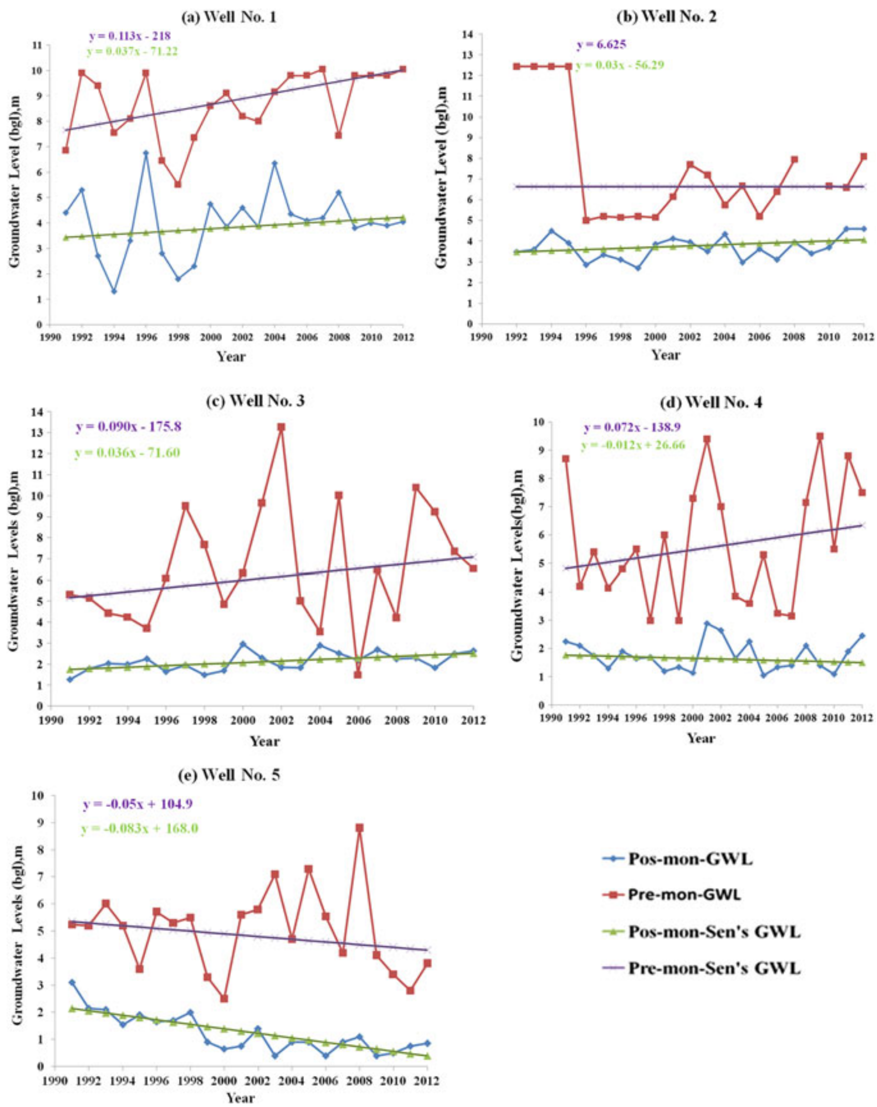


**Fig. 2** **a–e** Sen's slope trend for pre- and post-monsoon groundwater levels

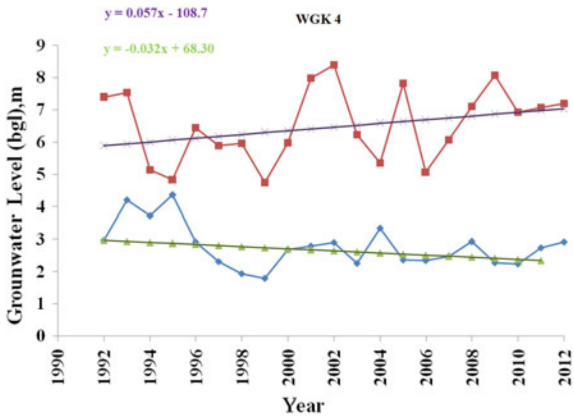


**Fig. 3** Average Sen's slope trend for pre- and post-monsoon groundwater levels of watershed WGK4

the trends are changing which indicates that the groundwater pumping within the watershed is increasing. An average trend throughout the watershed is negative (0.03 m/year) (Fig. 3) which shows that the groundwater level is declining in last 22 years.

## *Spatial Analysis*

The spatial variability map of groundwater levels for both pre- and post-monsoon seasons of 1991–2011 were created using ordinary kriging method and are shown in Figs. 4 and 5, respectively. Maps of pre-monsoon groundwater level show the decrease in groundwater level for northwest part of the area. Central part of the area shows the decrease in groundwater level from (3 m–5 m bgl) to (7 m–8 m bgl) during 2006–2011 (Fig. 4d, e). Southeast part of the area shows increase in the groundwater level from (5 m–7 m bgl) to (3 m–5 m bgl). Maps of post-monsoon groundwater level show the considerable improvement in groundwater depth in north and central parts from 1991 to 2012, while from central region to south region, groundwater level is improved and shows approximately constant trend from 1996 to 2012.

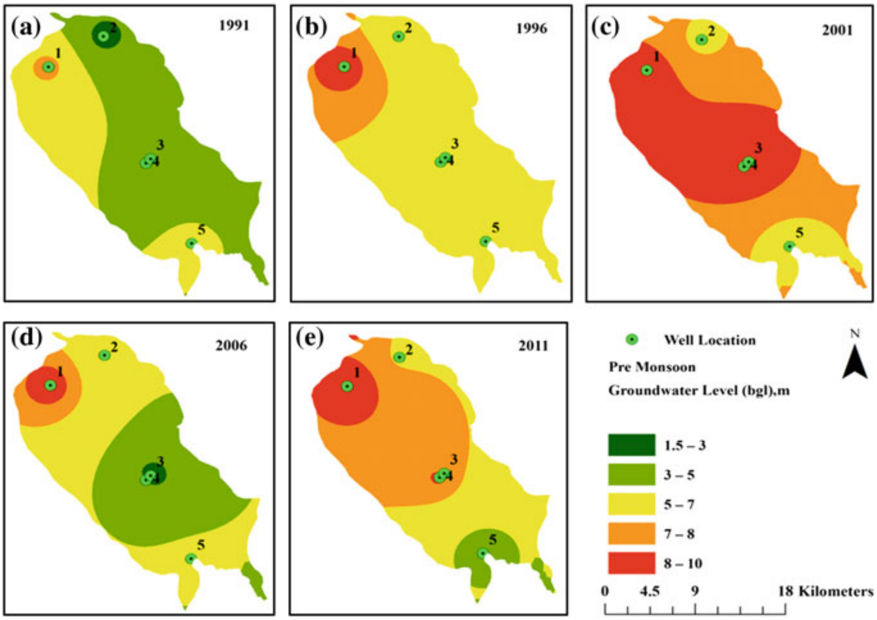


**Fig. 4 a–e** Spatial variability maps of pre-monsoon groundwater level from 1991 to 2011 at an interval of 5 years

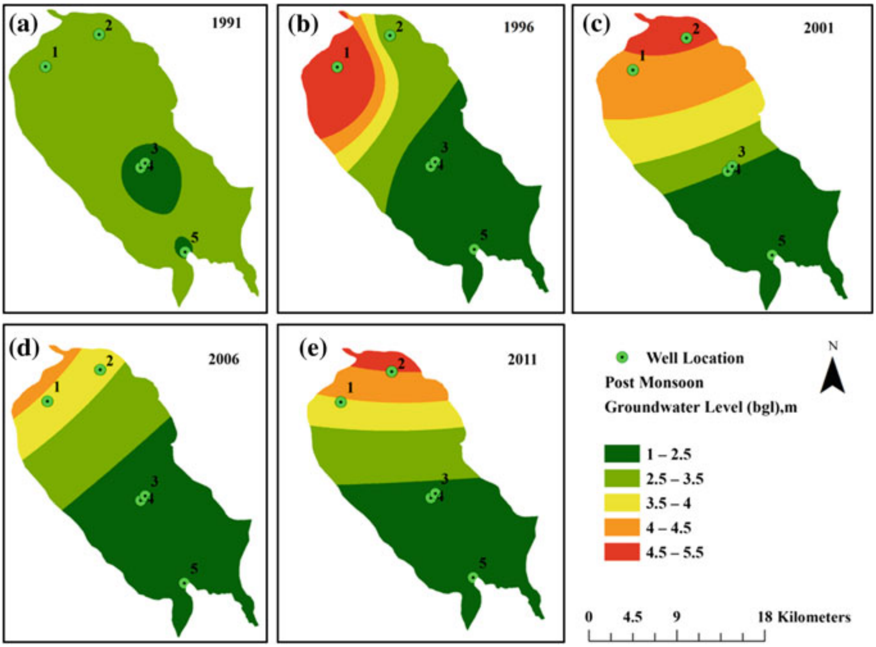


**Fig. 5 a–e** Spatial variability maps of post-monsoon groundwater level from 1991 to 2011 at an interval of 5 years

## Conclusion

Mann–Kendall test and Sen's slope estimator were performed on time series data of pre- and post-monsoon groundwater levels in WGK4 watershed. Five observation wells were used for analysis, and it was found that the well Nos. 1, 3, and 4 show the decrease in depth-to-water level. Well No. 5 shows marginal increase in the depth-to-water level, and well No. 2 had no trend. It was observed that in last 22 years average groundwater level of the entire area shows declining trend of 0.03 (m/year). This decline in groundwater level is due to excessive pumping of groundwater for irrigation. Spatial variations of pre-monsoon show decline in groundwater level for NW part of the area, and groundwater-level decreases significantly from 1996 to 2012 in central part of the area. For post-monsoon season, groundwater-level changes are approximately constant throughout the study area from past 16 years. These fluctuations in groundwater level for pre- and post-monsoon season are due to the anthropogenic activities and excessive pumping of groundwater for irrigation. From the present study, it is suggested the outcome of the spatial and temporal analysis can be useful for the decision makers and practitioners to effectively manage the groundwater resources at large and small scales.

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# Spatio-Temporal Variation and Trend Analysis of Groundwater Level in Raipur City, Chhattisgarh

**Sumant Kumar, Surjeet Singh, R. V. Kale, N. C. Ghosh, Mahesh M. Sonkusare and S. K. Chandniha**

**Abstract** Assessment of spatio-temporal variation provides a principal source of information regarding groundwater recharge, storage and discharge. Spatio-temporal variation of groundwater level (GWL) in Raipur city has been studied using statistical and graphical methods. Monthly trend of GWL has been investigated using Mann–Kendall test and Sen's slope estimator. The monthly GWL data of thirty observation wells (dug well) of Raipur city for the period 2010–2014 have been used for the study. The minimum and maximum GWL has been found out to be 0.84 m below ground level (bgl) which is 267.98 m above mean sea level (amsl) and 16.61 m bgl (271.53 m amsl). Contour map shows that average GWL varies between 1.74 and 13.80 m bgl (i.e. 280.34 m to 287.12 amsl) during pre-monsoon and 1.64 m to 6.75 m bgl (i.e. 279.92 m to 282.54 m amsl) during post-monsoon. GWL is shallower in central part of the city, whereas deeper GWL has been observed in western and northern part of the city. The groundwater contour maps depict that the groundwater flow direction is towards north and west. The results of trend analysis reveal that no significant trend is detected at 5% significance level except few locations.

**Keywords** Raipur · Groundwater level · Trend · Well · Mann–Kendall test

## Introduction

Groundwater is preferred source for drinking and irrigation purposes in rural as well as urban areas in India. Increasing population and their dependence on groundwater cause heavy stress on groundwater resources, leading to decline of groundwater levels (Chopra and Krishan 2014; MacDonald et al. 2013; Rodell et al. 2009). To

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prepare a sustainable management strategy for groundwater development, it is important to understand the fluctuation of groundwater levels (GWL) with reference to natural or artificial recharge and abstraction of groundwater in space and time domain. The spatial and temporal variations in the GWL were investigated by many researchers. Finke et al. (2004) and Ahmadi and Sedghamiz (2007) used kriging for mapping of groundwater level to identify critical area.

Geostatistical methods are good tools for water resource management and can be effectively used to derive the long-term trends of the groundwater (Raghunath et al. 2005). Statistical methods for trend analysis vary from simple linear regression to more advanced parametric and nonparametric methods (Helsel and Hirsch 2002). Many researchers (Arora et al. 2005; Dash et al. 2007) investigated rainfall and temperature trend analysis, but few studies have been done for GWL trend analysis. Few researchers (Shamsudduha et al. 2009; Hossein and Shifteh 2011) attempted to study trend analysis using statistical methods for analysing groundwater levels. Hossein and Shifteh (2011) investigated the temporal trends in annual, seasonal and monthly groundwater levels using Mann–Kendall test and the Sen's slope estimator. Shamsudduha et al. (2009) studied recent trends in groundwater levels in highly seasonal hydrological system of Ganges–Brahmaputra–Meghna Delta of Bangladesh using nonparametric techniques. In the present study, spatio-temporal variations of groundwater level in Raipur city, Chhattisgarh, have been analysed. The monthly trend analyses using Mann–Kendall (MK) and Sen's slope test have also been ascertained. The study will provide useful input to the engineers and water resource planners for development and management of groundwater resources.

## Study Area

The study area (Fig. 1) comprised of Raipur city, the capital city of Chhattisgarh, along with its outgrowths lies between 21° 10′ and 21° 21′N latitudes and 81° 32′ to 81° 44′E longitudes and falls under Survey of India toposheets number 64G/11 and 64G/12. The present population of Raipur city is about 1,200,000. Water supply requirement of the city is mainly met from Kharun River—a tributary of Mahanadi River. Approximately 65% of the city's drinking water supply is met from Kharun River, and the rest is supplied from groundwater resources developed through hand pumps and tube wells. In general, Raipur area features semi-arid tropical climate having hot long summer from March to mid-June followed by rainy season of about four months from mid-June to September. The winter season commences from December and continues till end of February. The annual rainfall varies from 831 to 1719 mm with average rainfall of 1207 mm (Saph 2013).

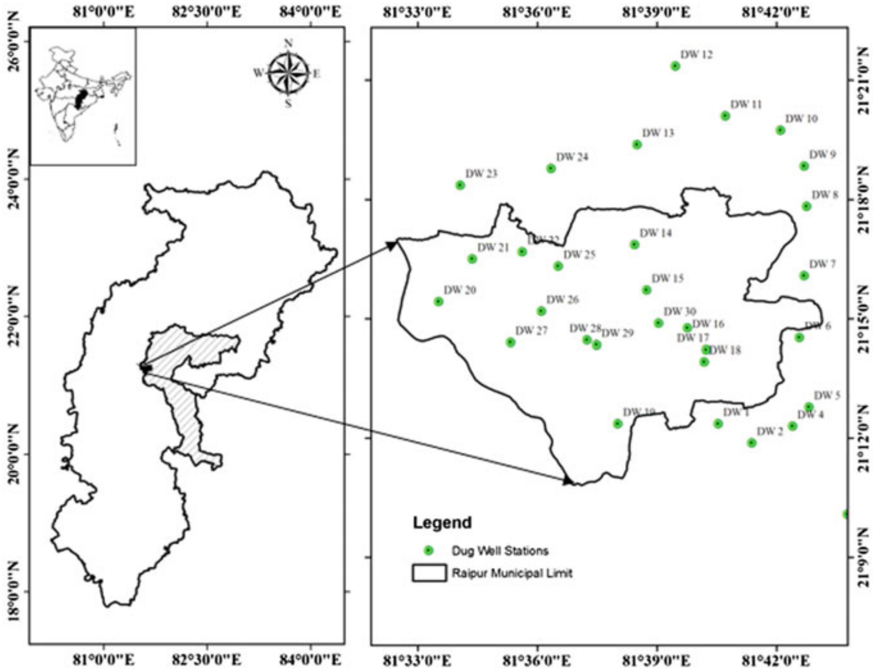


**Fig. 1** Study area (Raipur city) with observation wells in and around the city

## Data and Methodology

Monthly GWL of 30 observation wells (dug well) during the period of five years (2010–2014) of Raipur urban area collected from CGWB, Raipur, has been used for the analyses. Spatial and temporal variations have been analysed for observation wells to predict groundwater flow direction and fluctuations in the respective wells. The groundwater levels are available at the depth below ground surface; therefore, by collecting the RL of the respective well locations, these data were converted to groundwater level above msl and then georeferenced with respect to their latitude and longitude. Trend analysis, using MK test and Sen's slope, has been performed for each wells based on monthly data. The MK test is one of the most commonly used nonparametric method, most of the literature significantly contains this approach for trend analysis. Magnitude of trend has been quantified by Theil–Sen's estimator, and positive and negative values of magnitude showed increasing and decreasing trend, respectively. The minimum and maximum GWL observed in dug wells during five years period has been presented in Table 1. Dug wells are shallow-depth wells, and groundwater levels indicate the level of phreatic aquifer.

**Table 1** Dug well identification and coordinates with minimum and maximum GWL

| Dug well ID | Location name | Latitude | Longitude | Minimum GWL m bgl | Maximum GWL m bgl |
|---|---|---|---|---|---|
| DW 1 | Deopuri | 21.206 | 81.676 | 1.61 | 14.20 |
| DW 2 | Dumartarai | 21.198 | 81.690 | 1.02 | 9.97 |
| DW 3 | Mana Basti | 21.168 | 81.730 | 1.47 | 10.74 |
| DW 4 | Temri | 21.205 | 81.707 | 0.95 | 5.32 |
| DW 5 | Dharampura | 21.213 | 81.714 | 0.91 | 6.70 |
| DW 6 | Jora | 21.242 | 81.710 | 0.95 | 7.66 |
| DW 7 | Kachna | 21.268 | 81.712 | 1.07 | 8.70 |
| DW 8 | Baronda | 21.297 | 81.713 | 0.97 | 7.00 |
| DW 9 | Bhurkoni | 21.314 | 81.712 | 1.04 | 8.50 |
| DW 10 | Tekari | 21.329 | 81.702 | 0.86 | 7.80 |
| DW 11 | Giroud | 21.335 | 81.679 | 0.98 | 6.60 |
| DW 12 | Sankra | 21.356 | 81.658 | 1.10 | 12.86 |
| DW 13 | Rawabhata | 21.323 | 81.642 | 0.87 | 6.17 |
| DW 14 | MVH Colony | 21.281 | 81.641 | 0.97 | 3.77 |
| DW 15 | Shastri Nagar | 21.262 | 81.646 | 0.93 | 7.30 |
| DW 16 | Shankar Nagar | 21.246 | 81.663 | 1.31 | 2.67 |
| DW 17 | Telibandha | 21.237 | 81.671 | 1.13 | 3.65 |
| DW 18 | New Purena | 21.232 | 81.670 | 0.98 | 8.87 |
| DW 19 | Math Purena | 21.206 | 81.634 | 1.31 | 3.15 |
| DW 20 | Tatibandh | 21.257 | 81.559 | 1.80 | 16.61 |
| DW 21 | Jarwai | 21.275 | 81.573 | 0.91 | 12.28 |
| DW 22 | Sondongri | 21.278 | 81.594 | 1.12 | 4.37 |
| DW 23 | Guma | 21.306 | 81.568 | 0.95 | 8.67 |
| DW 24 | Urla | 21.313 | 81.606 | 1.28 | 13.37 |
| DW 25 | Gogaon | 21.272 | 81.609 | 1.26 | 10.92 |
| DW 26 | Kota | 21.253 | 81.602 | 0.84 | 7.25 |
| DW 27 | RSU | 21.240 | 81.589 | 2.32 | 9.12 |
| DW 28 | Ashram | 21.241 | 81.621 | 1.24 | 5.66 |
| DW 29 | Amapara | 21.239 | 81.625 | 1.52 | 4.62 |
| DW 30 | Raja Talab | 21.248 | 81.651 | 0.98 | 5.70 |

## Results and Discussion

The minimum depth to water (0.84 m bgl) has been observed in July 2010 at Kota, whereas maximum value (16.61 m bgl) observed in May 2012 at Tatibandh, based on five years GWL monthly data. The pre- and post-monsoon groundwater contours maps (Fig. 2a, b) depict the spatial variation of average groundwater level. The average groundwater level in pre-monsoon (month—May) varies from 1.74 to 13.80 m bgl (i.e. 279.92 m to 282.54 m amsl), whereas during post-monsoon

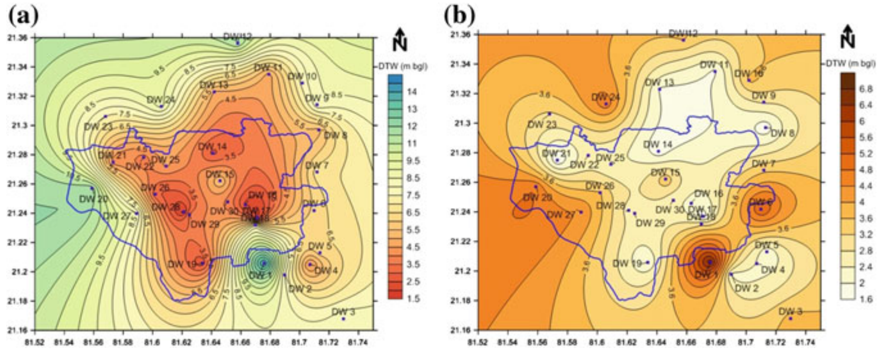


Fig. 2 DTW contour map for **a** pre-monsoon **b** post-monsoon

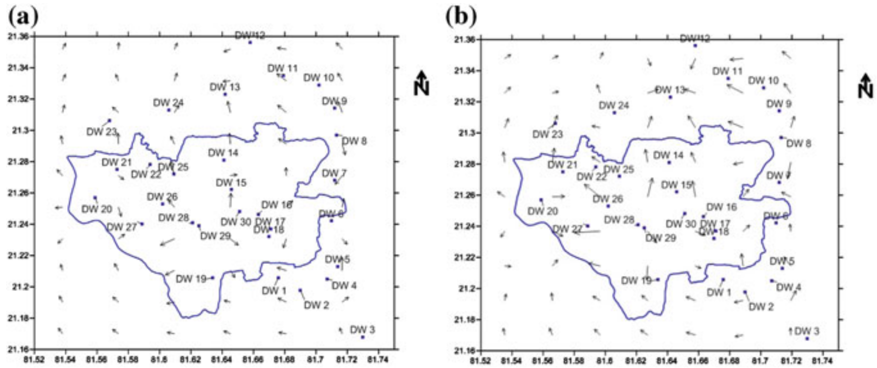


Fig. 3 GW flow direction during **a** pre-monsoon **b** post-monsoon

(month-November) groundwater level varies from 1.05 to 6.75 m bgl. GWL is shallower in central part of the city, whereas deeper GWL can be observed in western and northern part of the city. Groundwater flow direction in the area helps us decide the location of abstraction wells and pollutant transport path. The directions of the groundwater flow are found similar for the pre- and post-monsoon periods (Fig. 3). The direction of groundwater flow is towards north and west.

Trend analysis was performed using Mann–Kendall test (at 5% significant level) and Sen's slope estimator method for monthly groundwater level. The summarised results of trend analysis have been presented in Table 2. The negative *S*-statistics indicate a falling trend and vice versa. The computed *Z*-statistics less than the *z*-value corresponding to 5% significance level (1.96) indicate no significant trend. It can be observed from Table 2 that groundwater level is showing falling and rising trend, which are not significant except few locations. There are few locations viz. Telibandha, Shankar Nagar, Gogaon, where groundwater level shows significant rising trend, whereas Math Purena showing significant falling trend.

**Table 2** Summarised results of trend analyses for each observation wells

| Station | DW 1 | DW 2 | DW 3 | DW 4 | DW 5 | DW 6 |
|---|---|---|---|---|---|---|
| Location | Deopuri | Dumartarai | Mana Basti | Temri | Dharampura | Jora |
| *S*-statistics | −140 | −234 | −133 | −19 | −139 | 58 |
| *Z*-statistics | −1.164 | −1.949 | −1.104 | −0.151 | −1.155 | 0.477 |
| Trend | Falling | Falling | Falling | Falling | Falling | Rising |
| Significant (5%) | Not significant | Not significant | Not significant | Not significant | Not significant | Not significant |
| Sen slope | −0.044 | −0.041 | −0.024 | −0.002 | −0.019 | 0.004 |
| Intercept | −6.373 | −1.894 | −3.641 | −2.387 | −2.263 | −5.872 |
| Station | DW 7 | DW 8 | DW 9 | DW 10 | DW 11 | DW 12 |
| Location | Kachna | Baronda | Bhurkoni | Tekari | Giroud | Sankra |
| *S*-statistics | −95 | −207 | −150 | 0 | −124 | −216 |
| *Z*-statistics | −0.786 | −1.723 | −1.247 | −0.008 | −1.029 | −1.799 |
| Trend | Falling | Falling | Falling | No Trend | Falling | Falling |
| Significant (5%) | Not significant | Not significant | Not significant | Not significant | Not significant | Not significant |
| Sen slope | −0.015 | −0.022 | −0.022 | 0 | −0.011 | −0.042 |
| Intercept | −4.211 | −1.744 | −3.918 | −4.58 | −1.967 | −3.482 |
| Station | DW 13 | DW 14 | DW 15 | DW 16 | DW 17 | DW 18 |
| Location | Rawabhata | MVH Colony | Shastri Nagar | Shankar Nagar | Telibandha | New Purena |
| *S*-statistics | 38 | −101 | 18 | 371 | 548 | −171 |
| *Z*-statistics | 0.31 | −0.837 | 0.142 | 3.098 | 4.577 | −1.422 |
| Trend | Rising | Falling | Rising | **Rising** | **Rising** | Falling |
| Significant (5%) | Not significant | Not significant | Not significant | **Significant** | **Significant** | Not significant |
| Sen slope | 0.004 | −0.006 | 0.001 | 0.007 | 0.011 | −0.027 |
| Intercept | −2.325 | −1.915 | −2.339 | −2.382 | −1.868 | −3.952 |
| Station | DW 19 | DW 20 | DW 21 | DW 22 | DW 23 | DW 24 |
| Location | Math Purena | Tatibandh | Jarwai | Sondongri | Guma | Urla |
| *S*-statistics | −319 | 206 | 198 | 113 | 105 | 55 |
| *Z*-statistics | −2.661 | 1.715 | 1.648 | 0.937 | 0.87 | 0.452 |
| Trend | **Falling** | Rising | Rising | Rising | Rising | Rising |
| Significant (5%) | **Significant** | Not significant | Not significant | Not significant | Not significant | Not significant |
| Sen slope | −0.008 | 0.043 | 0.01 | 0.009 | 0.018 | 0.013 |
| Intercept | −1.913 | −7.509 | −2.236 | −3.265 | −4.734 | −4.627 |
| Station | DW 25 | DW 26 | DW 27 | DW 28 | DW 29 | DW 30 |
| Location | Gogaon | Kota | RSU | Ashram | Amapara | Raja Talab |
| *S*-statistics | 247 | 50 | −168 | −102 | 16 | 179 |

(continued)

**Table 2** (continued)

| Station | DW 19 | DW 20 | DW 21 | DW 22 | DW 23 | DW 24 |
|---|---|---|---|---|---|---|
| *Z*-statistics | 2.058 | 0.41 | −1.397 | −0.846 | 0.126 | 1.489 |
| Trend | **Rising** | Rising | Falling | Falling | Rising | Rising |
| Significant | **Significant** | Not significant | Not significant | Not significant | Not significant | Not significant |
| Sen slope | 0.016 | 0.003 | −0.032 | −0.002 | 0 | 0.01 |
| Intercept | −2.882 | −2.345 | −5.224 | −1.592 | −3.062 | −2.61 |

Magnitudes of above trends are calculated using Sen's slope estimator method and have been presented in Table 2. A positive slope gives rising trend and vice versa. It is noticed that the trend pattern is same as detected using Mann–Kendall analysis.

The time series plot of GWL with linear trend for the locations showing significant rising or falling trend has been shown in Fig. 4. The rising trend of some wells maybe due to recharge from water bodies and less or no abstraction of groundwater from phreatic aquifer.

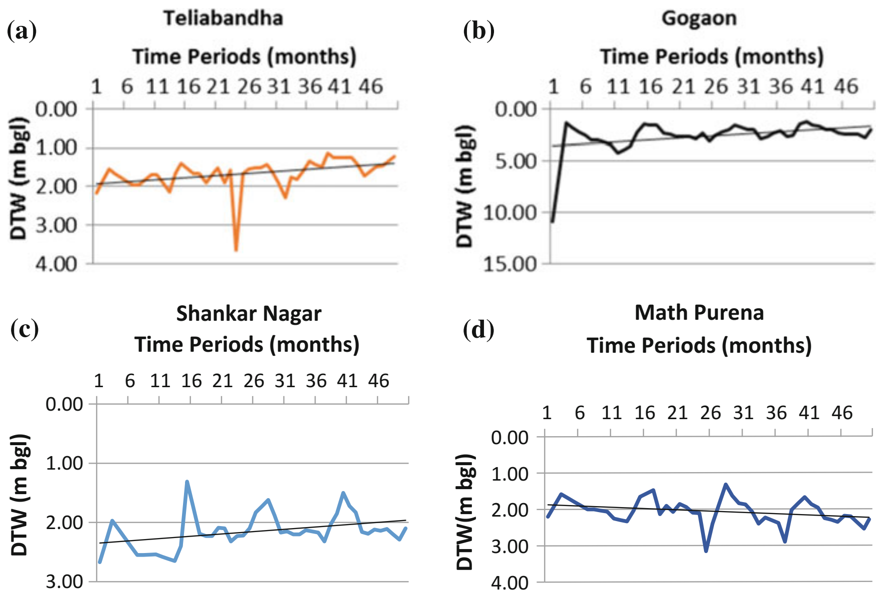


**Fig. 4** Time series plot for depth to water for **a** Telibandha area showing rising trend **b** Gogaon area showing rising trend **c** Shankar Nagar showing rising trend **d** Math Purena showing falling trend

## Conclusions

The present study has been carried out to study the spatio-temporal variation and trend analysis of groundwater level in the Raipur city, Chhattisgarh. For the study, monthly groundwater level of 30 observation wells (dug well) for the period of five years (2010–2014) have been used. The minimum depth to water (0.84 m bgl) has been observed in July 2010 at Kota, whereas maximum value (16.61 m bgl) observed in May 2012 at Tatibandh. The average groundwater level in pre-monsoon varies from 1.74 to 13.80 m bgl, whereas during post-monsoon it varies from 1.05 to 6.75 m bgl. The shallower GWL has been observed in central part of the city. The direction of groundwater flow is towards north and west. The trend analysis is carried out using the Mann–Kendall analysis and Sen's slope estimator method. It may be concluded that no significant trend is detected at 5% significance level except four locations. Locations showing significant rising trend are Telibandha, Shankar Nagar, Gogaon, whereas Math Purena shows significant falling trend.

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# Spatiotemporal Relationship Linking Land Use/Land Cover with Groundwater Level

**Vishwanatha Bhat, M. Prajwal, Amba Shetty, Abhishek Srivastava and Rahul Bhosale**

**Abstract** Land use and land cover changes have been undergoing at a rapid rate universally. Anthropogenic activities where human intervention is involved is been considered as a major driver for land use changes. This type of advancement in land activity has caused depletion of natural resources more so groundwater table. There is a great need for assessment of groundwater profile at local level. Groundwater is maximally harnessed for many water use purposes in Dakshina Kannada district, Karnataka. This study aims to analyze and quantify the effect of land use/land cover (LU/LC) transformations along a time scale with the fluctuating groundwater levels. Groundwater level information of the year 2003 and 2013 from observation wells and satellite imagery from Landsat with ETM 7 and OLI sensors were used. Kriging, a geostatistical method of interpolation, used well data as points taken at different locations (29 wells) all over the district and created a continuous surface using interpolation with the estimate of error. LULC map of 2003 and 2013 was derived from classification of TM images using supervised, parametric maximum likelihood classifier. Area is broadly categorized into four classes, namely vegetation, urban areas, water, and other category. Accuracy assessment of this classification yielded kappa statistics of greater than 0.8 for both the images and overall accuracy greater than 90%. Further, relationship between LULC and groundwater level is inferred with the help of 1 by 1 km grid. Rainfall and stream network were used in ascertaining the sensitive areas in terms of groundwater that hold a hydrogeological importance. It was inferred from the study that the groundwater depletion to the extent of 2 m has been evident in the urban areas with an increase in built-up greater than

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25 acres per 250 acres. These fluctuations are evident in the northwest and south regions of the district compared to the other areas. Moreover, these hydrogeologically sensitive areas for recharge need protection from further development activities.

**Keywords** LULC · Landsat · Accuracy assessment · Kriging
Groundwater level · Gaussian maximum likelihood classifier

## Introduction

India is a land of varying climate. It observes extreme variations in terms of weather phenomena and one among them is precipitation. Most of the precipitation that occurs is carried away as runoff and remaining contributes to the recharge of groundwater table. Groundwater is one of the major sources of available water in India that accounts for more than 400 $km^3$ of the annual utilizable resources. Due to variable climate across India, groundwater has become a major alternative for domestic and irrigational uses (Groundwater Resources, NIH 2016). Judicious management of groundwater resource is crucial in order to meet the rapidly increasing demands of water for domestic, agricultural, and industrial uses. In this regard, Central Groundwater Board (CGWB) has taken an initiative of developing microlevel and macrolevel management studies. This has been supported by other studies such as monitoring groundwater level through a network of observation wells (both open well and piezometer) and implementation of schemes for artificial recharge.

The Conference Speaker is Mr. Rahul Bhosale.

To implement these management measures, temporal and spatial behaviors of groundwater should be known. Spatial and temporal behaviors can be addressed by the use of remote sensing and geographic information systems (GIS). Initially, GIS concentrated on deriving thematic maps and their overlay operations. But, in the recent past, statistical packages have linked to GIS for statistical analysis and hypothesis testing. Moreover, GIS provides a platform to operate statistical analysis on georegistered data with effective data display and visualization (Burrough 2001). Groundwater level is usually monitored at locations where wells are available or sometimes at test wells dug specifically for this purpose. Data obtained are point data, and to use them at the surface level, they need to be interpolated over an area.

Kriging has been used in variety of data analysis, including mapping spatial patterns of pollutants (Goovaerts et al. 2008; Saito et al. 2005; Saito and Goovaerts 2000), spatial variation of soil properties (Goovaerts and Journel 1995; Goovaerts 1999), groundwater levels (Barabas and Goovaerts 2004; Kumar 2007; Srivastava et al. 2012), and health data (Goovaerts 2008). A major advantage of kriging over other interpolating methods is that the requirement of sparsely sampled observations and an estimate of error as a measure of accuracy.

Increased anthropogenic activities exert changes on the hydrological cycle through rapid transformation in land use/land cover (LU/LC). The demand for water continues to increase as the development takes place. This in turn compels the researchers to understand the linkage between groundwater source and the overlaying

LU/LC (Foster and Cherlet 2014). Groundwater research had been mainly focused on the linkages relating its quality aspect (Langroodi et al. 2015). But, region under study does not have quantity as an issue still the paper focuses on the quantity issue.

Recent studies (Scanlon et al. 2005; Zhang and Schilling 2006; Dams et al. 2008; Ross and Martinez 2010; Mukherjee et al. 2012) have shown the mutual relationship between LULC and groundwater resources. Further, to some extent, the linkage has been coined as dynamic (Li et al. 2011). Rapid urbanization and concerned hike in imperviousness have a major impact on groundwater (Mishra et al. 2014). These influences both from groundwater exploitation and land use degradation have a direct effect on the species habitat including human (Waco and Taylor 2010). Hence, this linkage is important as land use changes are everlasting and may impart irreversible impacts on aquifers.Temporal availability of remotely sensed images has stimulated LU/LC-related studies. In this respect, coupling of geospatial and geostatistical approaches can be thought of in understanding the linkage.

Present study focuses on understanding spatiotemporal relationship among LU/LC and groundwater levels by coupling geospatial analysis and geostatistical analysis over an administrative section. Remaining part of this paper focuses on the study area Dakshina Kannada district and methodology adopted. This is followed by the discussions and conclusion.

## Study Area

Study area is Dakshina Kannada, a southern coastal district, located at Karnataka state of India (Fig. 1). The district has an area of 4859 km$^2$. It extends from 74° 45′ E to 75° 30′ 30″E and 12° 30′N to 13° 15′N. Population of the district is 21 lakhs.

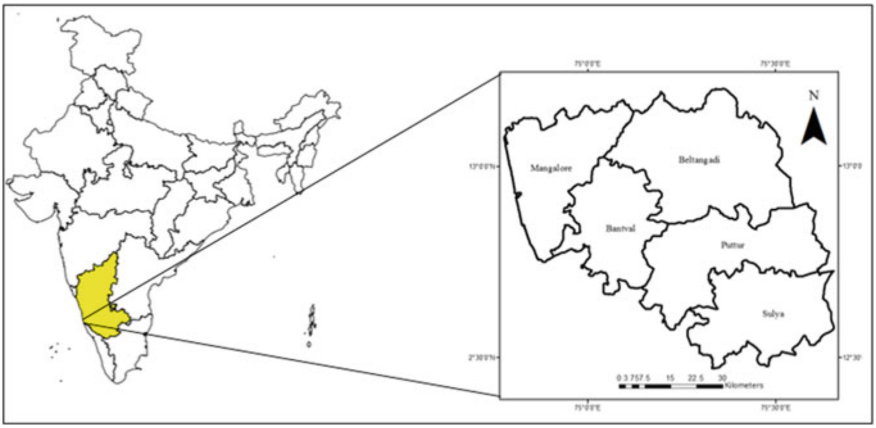


**Fig. 1** Dakshina Kannada district with taluks

Present study area falls under Western Ghats river basins, where the approximate groundwater potential available for use is 11.18 $km^3$/year out of total replenishable groundwater source of 17.69 $km^3$/year (Central Ground Water Board 2015; Groundwater Resources, NIH 2016). In the region, as there is no major dam across the stream, people mainly depend on groundwater resources. The underlining formations are mainly laterite where the porosity is very high. The water table almost reaches the ground surface during monsoon season. Observation wells target shallow unconfined aquifer.

## Data

Groundwater level data collected from district groundwater department were used for kriging. Landsat satellite images downloaded from public domain of United States Geological Survey Web portal. Table 1 lists various data, source of data, and purpose adopted in this study.

## Methodology

Methodology of this study has been divided into four steps, namely base map creation, geostatistical analysis, land use/land cover classification, and grid generation. A detailed methodology has been presented in Fig. 2. Each of these has explained below.

## Base Map Creation

The district boundary is digitized using district census book, and base layer is matched with survey of India toposheets. It is georeferenced and projected to UTM 43 N coordinate system. The *X*, *Y* coordinates of each of the well, as obtained from

**Table 1** Data used for the study

| Data | Source | Purpose |
|---|---|---|
| Groundwater level | District groundwater department | Geostatistical analysis |
| District boundary | Toposheet, district census hand book | Ascertaining study area |
| Digital elevation model | ASTER web portal | Elevation profile and stream network |
| Satellite images | Landsat look viewer | LULC map |

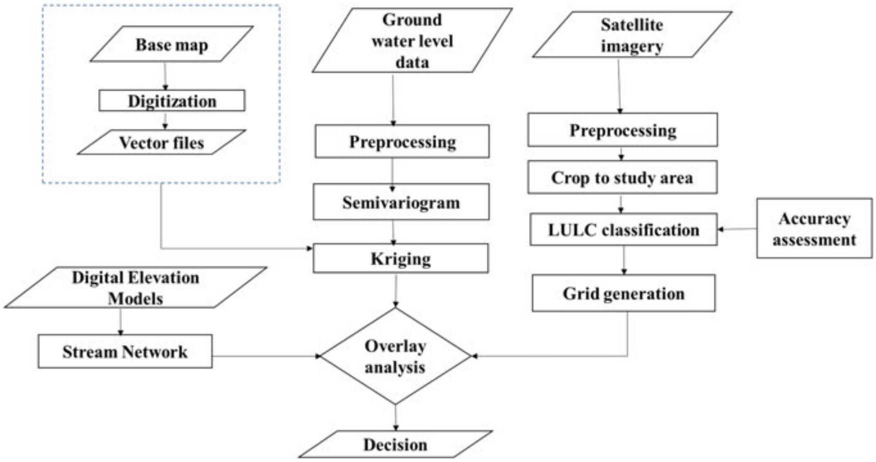


**Fig. 2** Methodology

metadata, is marked in point shapefile and is also projected to the same coordinate system.

Digital elevation models (DEM) are downloaded and mosaicked, and study area is extracted using district boundary shapefile. Further, DEM is utilized to delineate stream network of the region

## Groundwater Level Kriging

Groundwater level data, monitored monthly, were categorized into three seasons, namely pre-monsoon for February, March, April, and May; monsoon for June, July, August, and September; and post-monsoon for October, November, December, and January. These sampled groundwater data shows near-normal distribution. Groundwater level data of all the months of 2003 and 2013 is tagged as attributes to respective wells in the well location point shapefile. Kriging analysis in general involves constructing semivariogram for given data set, finding a mathematical model for continuous data in semivariogram, and obtaining optimal weights for the selected samples from kriging. Spatial variation of an attribute in kriging comprises of three terms: a trend or drift, a spatially correlated component, and random error term, as represented by Eq. (1).

$$z(x) = \mu + \epsilon'' + \epsilon(s) \tag{1}$$

where $z(x)$ a spatial variable, $\mu$ is the trend or drift, $\epsilon''$ is the spatially correlated component, and $\epsilon(s)$ is random error.

Semivariogram is used as a measure to quantify the spatial autocorrelation. Further, to extract information from semivariogram cloud, a process called binning is applied. Binning averages semivariogram cloud by distance '$h$' and direction. Semivariance and average semivariance are calculated based on Eqs. (2) and (3).

$$\gamma(h) = \frac{1}{2}\left[z(x_i) - z(x_j)\right]^2 \tag{2}$$

where $\gamma(h)$ is the semivariance between the sample points $x_i$ and $x_j$

$$\gamma(h) = \frac{1}{2n}\sum_{i=1}^{n}\left[z(x_i) - z(x_j + h)\right]^2 \tag{3}$$

where $\gamma(h)$ is the average semivariance between the sample points $x_i$ and $x_j + h$ separated by lag $h$.

Average semivariogram is fitted with an exponential model as the spatial dependence of groundwater levels exponentially decreases with increasing distance and finally vanishes at infinite distance. Absence of certain trend in the data set dictates to adopt ordinary kriging and concentrates only on the spatially correlated component. Equation for estimating an unknown value $Z$ from sample points $Z_x$ with weight $w_x$ is given by Eq. (4).

$$z_0 = \sum_{i=1}^{x} z_x w_x \tag{4}$$

where $w_x$ is the weight calculated from kriging.

Weights calculated from nearby samples should ensure the error to approach zero and minimization of error variance. Here, the primary goal is to calculate weights $w_x$. Equations (5) and (6) are given to show the matrix form of ordinary kriging system.

$$\gamma . w = g \tag{5}$$

$$\begin{bmatrix} \gamma_{11} & . & . & \gamma_{1N} & 1 \\ . & . & . & . & . \\ . & . & . & . & . \\ \gamma_{N1} & . & . & \gamma_{MN} & 1 \\ 1 & . & . & 1 & 0 \end{bmatrix} * \begin{bmatrix} w_1 \\ . \\ . \\ w_n \\ m \end{bmatrix} = \begin{bmatrix} \gamma_{10} \\ . \\ . \\ \gamma_{N0} \\ 1 \end{bmatrix} \tag{6}$$

where $\gamma(h_{ij})$ is the semivariance between known points $i$ and $j$; $\gamma(h_{i0})$ is the semivariance between known point $i$ and unknown point $o$, and $m$ is the Lagrange multiplier.

With the help of calculated weights, unknown value $Z$ can be written as the linear combination of weights along with the samples (Eq. 7).

$$z_0 = z_1 w_1 + z_2 w_2 + z_3 w_3 \quad (7)$$

where $w_1$, $w_2$, $w_3$ are weights calculated from Eq. (6).

Kriging is considered as the best geostatistical method as it provides the error of estimates. Further, classification approach is employed to build the relation between groundwater level and LULC of the region.

## Land Use/Land Cover (LU/LC) Classification

Landsat data of the year 2003 and 2013 using the bands NIR, Red, and Green was stacked on top of each other to create a FCC image. A supervised, maximum likelihood classification technique was used for land use/land cover classification. Training polygons from different classes have considered and fed into the algorithm. Images were classified into 4 classes: built-up (urban and all paved areas), vegetation (grass, plantation, and forest), water, and others (open spaces, barren land, waste land, etc.). Accuracy assessment for both the images was carried out by ascertaining overall accuracy and kappa statistics.

## Grid Generation

Grid generation helps to understand LU/LC changes within a grid of 1 km $\times$ 1 km. Built-up areas from each of the classified image have extracted to these grids. The area occupied by urban class in each grid was computed for 2003 and 2013, respectively, and the increase in area was computed.

## Overlay Analysis

Results of kriging, grid generated from LU/LC, and stream network delineated using digital elevation model are employed in making decision of the region using overlay analysis. A visual overlay analysis was performed. Factors involved here are decadal increase in built-up area, ground water level, total annual rainfall, and catchment details. Decadal increase in built-up area in the respective taluks is indicated in terms of areal rise. Increase or decrease in groundwater levels are quantified with the directions as well. Further, total annual rainfall along with the catchment details have also used. Based on the actual values of above factors against the taluks, critical areas are identified.

## Results

### *Geostatistical Analysis of Groundwater Level*

Kriging is done for three categories of the season, namely pre-monsoon, monsoon, and post-monsoon periods, respectively. Filled contour maps of the groundwater levels were generated for both 2003 and 2013.

Results of the analysis indicate that groundwater level varies from 1 to 16 m depth below ground surface. Validation of kriging has yielded a standard root-mean-square error of 0.8 m. Resulting variation is denoted by a spectrum of color—blue to red. The groundwater depleted areas are denoted in red color (Fig. 3).

## LU/LC Classification

LU/LC classified maps (Fig. 4a) for the study area bear overall accuracy of greater than 90% and kappa value of 0.8. This shows a good agreement with the reference data. LU/LC statistics for the region are represented in Fig. 4b. Within a decade, there is an increase of built-up area by three folds. LU/LC classified maps for 2003 and 2013 were gridded. Increase in urban area in each segment was noted. The locations with major increase in built-up area were marked and tabulated against difference in groundwater level between 2003 and 2013 as evident from Fig. 4c.

Also the total annual rainfalls in these locations were obtained from district rainfall records. Fig. 4d denotes well locations, places with significant increase in urban area, and the stream network of the major catchments of the district.

## Discussion

LU/LC maps offer an insight of land transformations over a decade. There has been a significant increase in built-up area along with decrease in vegetation which is evident from the Fig. 4b. This may be attributed with the arrival and extension of industrial sectors and improved transportation facilities within the suburban patches. At present, Baikampady, Karnad, Puttur, Tannirbhavi, Ganjimutt, Bajpe, etc., are some of the locations that house the industries in Dakshina Kannada district. In addition to this, land use changes are also driven by various economic, political, and social drivers at local level. A crucial linkage between LU/LC changes and groundwater level fluctuations is shown in Table 2. Five taluk headquarters: Bantwal, Puttur, Sullia, Belthangadi, and Moodabidri have been chosen for further analysis. Table 2 compares groundwater depletion with the total annual rainfall for 2003 and 2013. Decadal change in built-up area among these taluk headquarters

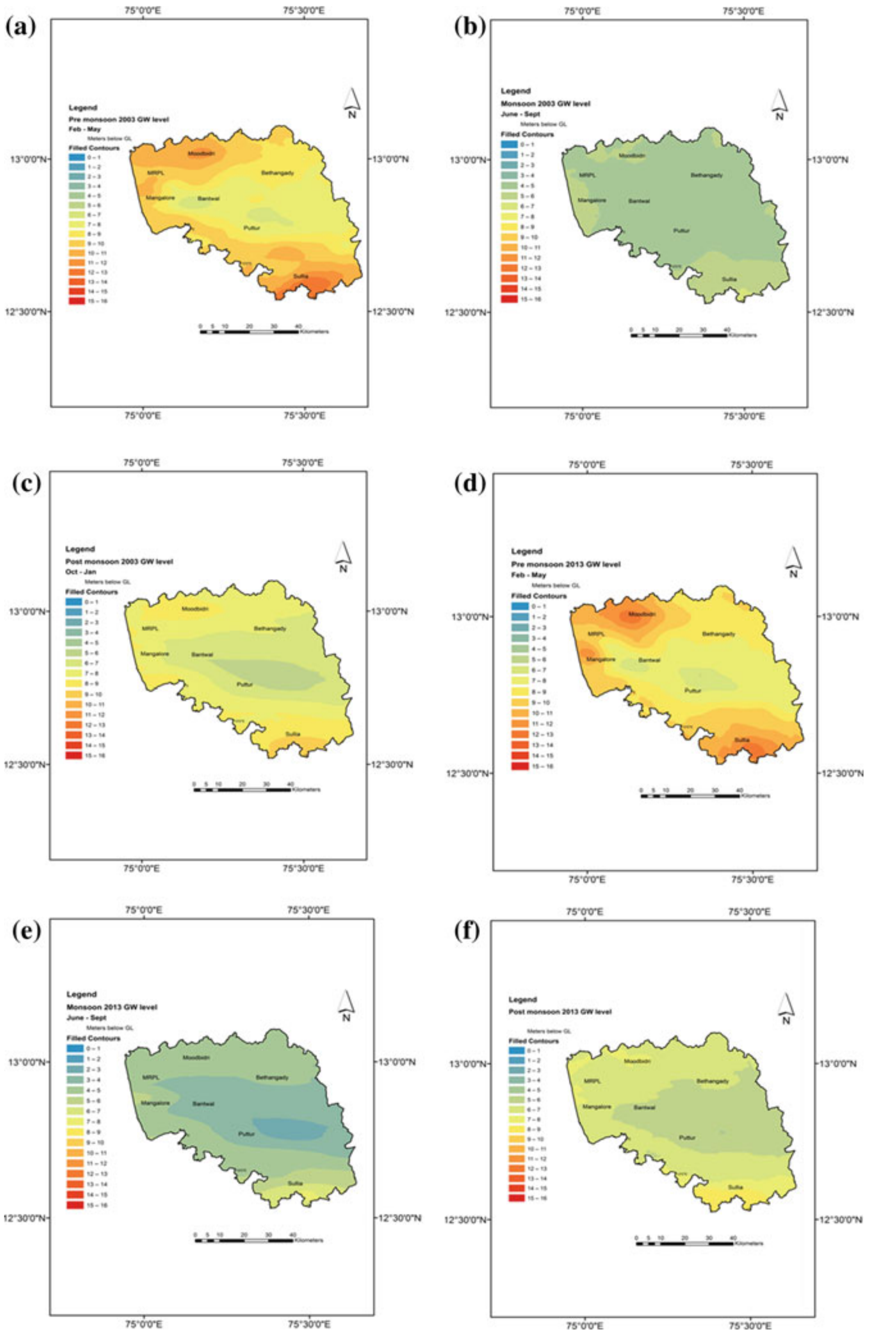


**Fig. 3** Groundwater level ordinary kriging for the season **a** pre-monsoon of 2003, **b** monsoon of 2003, **c** post-monsoon of 2003, **d** pre-monsoon of 2013, **e** monsoon of 2013, and **f** post-monsoon of 2013

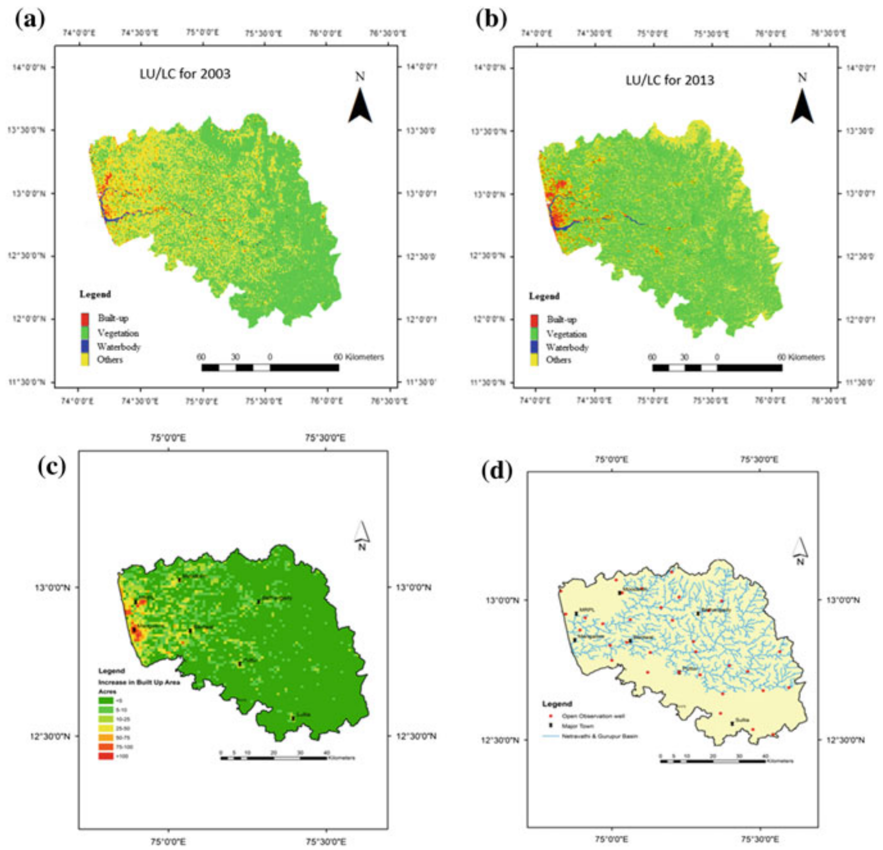


**Fig. 4** **a** Classified LU/LC map, **b** land use/land cover profile of Dakshina Kannada, **c** decadal changes in built-up area, and **d** well locations with stream network

ranges from 25 acres to 100 acres. Elevation also plays a major role in the availability of groundwater. Mangaluru, Bantwal, and MRPL (Industrial sector) are present in 30 to 60 m elevation range, whereas Puttur, Sullia, Belthangadi, and Moodabidri are located at a relatively higher altitude between 90 and 120 m. So, it may be the elevation difference that has caused the lowering of groundwater level. Though Puttur and Moodabidri have the same decadal increase in built-up area which is about 50 acres, groundwater level during pre-monsoon was lowered in Moodabidri, whereas it was constant in Puttur. It has been observed in the study region that industries mostly rely on surface sources of water to meet their demands. Over 70% of the area irrigated in the district is dependent on groundwater sources such as dugwells and borewells. Although, rainfall being constant over the decade, except some high altitudes, groundwater fluctuations are substantial over the decade. In this case, the groundwater extraction also has a role apart from LU/LC changes. Positive levels in Table 2 represent decrease in groundwater, whereas negative levels indicate the hike. Built-up change was also examined in the district headquarter, Mangaluru, and in an industrial sector. The highest increase of around 100 acres per sq. km was observed in Mangaluru, which is the district headquarters. Rest of the places noted had an increase of about 50 acres per sq. km, i.e., 50 acres increase per 250 acres.

Groundwater level in monsoon season is static near the groundwater level reason being the abundant rainfall during monsoon. Post-monsoon for the months: October, November, December, and January over the district have seen increase in groundwater level due to rainfall-fed recharge, whereas pre-monsoon (also summer season) shows a decrease in groundwater level. But, the changes in groundwater level over the decades as shown in Table 2 have a stabilizing effect for pre-monsoon months. Rainfall is the principal source for groundwater recharge. Increase in paved areas has led to a decrease in natural groundwater recharge. Location of these wells within the catchment also governs the groundwater level. Moodabidri lies high up in the head water region of the Mulki River system which leads to less available catchment area for yield compared to Bantwal, Sullia, and Belthangadi which have a greater catchment area due to their lower elevations. A critical observation can be drawn on the post-monsoon phase which has a depletion of groundwater level of 1 m in contrary to the increase of about 0.5 m in annual rainfall.

Unlike surface water, groundwater is locally available at the household level and provides greater economic benefits per unit volume. This can also be attributed by the increase in groundwater harness for domestic and industrial uses over the district. It is evident that the groundwater fluctuations are inconsistent throughout the area under study. This can be addressed by the differential hydrogeological aspects of the region. By analyzing the selected urban patches including the industrial sector of the district (Table 2), hydrogeologically sensitive areas can be identified. These regions can be prioritized and protected instead of treating all the lands equally. To summarize, the areas of Moodabidri, Mangaluru, and MRPL region which are affected by the problem should be brought under a suitable groundwater management program.

## Conclusion

This study aims to inquire the relationship of land use/land cover change on groundwater level profile over a decade in Dakshina Kannada district. The conclusion drawn here is: Decadal total rainfall over the district is more or less static, but associated groundwater fluctuations are substantial. In recent years, the district has seen lowering of groundwater levels to the extent of 2 m in pre-monsoon

**Table 2** Locationwise fluctuation of groundwater level

| Location | Decadal increase in built-up area (approximately in acres) | Groundwater level depletion (meters below ground level) | | | Total annual rainfall (cm) | | Catchment details |
|---|---|---|---|---|---|---|---|
| | | Pre-monsoon | Monsoon | Post-monsoon | 2003 | 2013 | |
| Mangaluru | 100 | 2 | 0 | −1 | 326 | 357 | Lowland of Netravathi–Gurpura basin |
| Bantwal | 50 | 0 | −1 | 0 | 319 | 412 | Midland of Netravathi basin |
| Puttur | 50 | 0 | −1 | 0 | 338 | 364 | Upland of Netravathi basin |
| Sullia | 25 | 0 | 1 | 0 | 358 | 387 | Payasvini basin |
| Belthangady | 25 | 0 | 0 | 0 | 330 | 587 | Midland of Netravathi basin |
| Moodabidri | 50 | 1 | 0 | −1 | 368 | 491 | Mulki basin |
| MRPL (industrial sector) | 75 | 1 | 0 | −1 | 246 | 396 | Pavanje basin |

season, i.e., summer season. Linkage between LU/LC and groundwater levels has been assessed, and grids are claimed as vulnerable if the decadal increase of built-up area exceeds 25 acres per grid. These depletions are prominent on the northwest and south regions of the district. Since the decrease is non-uniform over the area, sensitive areas for recharge need to be identified and protected.

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# Groundwater System Modelling and Sensitivity of Groundwater Level Prediction in Indo-Gangetic Alluvial Plains

**Prabhakar Shukla and Raj Mohan Singh**

**Abstract** The aquifer systems in the Indo-Gangetic alluvial river systems are recharged by rains and also by seepage from the irrigation canal commands. Groundwater resource is threatened due to rising water demand for advancement in the agricultural sector together with rapid industrialization. Utilization of groundwater at a rate greater than annual recharge constitutes unsustainable groundwater development. The problems of excessive groundwater extraction in the tail reaches of canal commands are common. In such areas, there is considerable potential for sustainable groundwater management through groundwater system modelling. Present work simulates the groundwater system in Sai–Gomti interfluve region which is a part of Indo-Gangetic alluvial plain in Uttar Pradesh, India. Groundwater simulation was carried out using Visual MODFLOW. The study area comprises mainly of agricultural land and is part of Sharda Sahayak Canal System in Uttar Pradesh. Visual MODFLOW was calibrated and validated for water level data available for 9 years (2005–2013). The effect of change in recharge rate and withdrawal rate is also investigated to predict the corresponding changes in water levels. Groundwater level was predicted beyond five years for future. Deterministic as well as fuzzy sensitivity analysis is performed to characterize uncertainty in predicted groundwater levels due to possible uncertainty in hydraulic conductivity and porosity.

**Keywords** Groundwater simulation · Visual MODFLOW
Sai–Gomti interfluve region · Sensitivity analysis · Fuzzy variable

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## Introduction

Major urban settlements worldwide face depletion of water resources due to increasing water demands of fast-growing population and rising industrial water needs (Munoz et al. 2003; Lorenzen et al. 2010; Liu et al. 2008; Romano and Preziosi 2010). The Sai–Gomti interfluvial region in India is an example of such a case, imposing obligations of integrated water resource management (Livingston 2009; Foster and Choudhary 2009; CGWB 2009). The inefficient water distribution network and growing urban population further accentuate the water demand in the Sai–Gomti interfluvial region. This has resulted in installation of a number of licensed and unlicensed groundwater extraction wells, resulting in reduced groundwater level. Groundwater depletion threatens many riparian ecosystems in arid and semi-arid regions of the world. Groundwater irrigation demand has been growing steadily over the past decades, for many reasons including the unreliability of the traditional large canal schemes and the increasing need of farmers to manage their own irrigation applications. Therefore, proper groundwater system modelling and management is imperative. Chakravorty et al. (2014) investigated the effect of conjunctive water use on waterlogging in lower Gandak basin of Bihar. Groundwater flow modelling of Hindon–Yamuna interfluve region, western Uttar Pradesh, was conducted by Alam and Umar (2013). Gosh and Kashyap (2012) utilized optimization technique in precalibrated simulation model of groundwater flow. Optimized sustainable groundwater extraction management of Lucknow city was carried out by Singh et al. (2013). Ahmed and Umar (2008) investigated water balance studies in parts of Krishna–Yamuna interstream area in western Uttar Pradesh. Local scale groundwater flow model was developed by Ebraheem et al. (2004); Palma and Bentley (2007) for groundwater resource management. Groundwater system modelling of Azraq basin, Jordan, was performed by Abdulla et al. (2000).

In the present study, groundwater system modelling in Sai–Gomti interfluvial region of Uttar Pradesh in India has been performed. The effect of change in recharge rate and withdrawal rate has been investigated to predict the corresponding changes in water levels up to five years of the future period. Also, deterministic as well as fuzzy uncertainty analysis is performed to characterize uncertainty in predicted groundwater levels due to hydraulic conductivity and porosity.

## Groundwater System Simulation

The equation describing steady, 2D areal flow of groundwater through a non-homogeneous, anisotropic and saturated aquifer can be written in Cartesian tensor notation (Pinder and Bredeoeft 1968; Srivastava and Singh 2014) as:

$$\frac{\partial}{\partial xi} = \left( T_{ij} \frac{\partial h}{\partial xj} \right) = W; \quad i,j = 1,2 \tag{1}$$

where $T_{ij}$ = transmissivity tensor; $h$ = hydraulic head; $W$ = volume flux per unit area (+sign = outflow and −sign = inflow); and $xi$, $xj$ = Cartesian coordinates.

In the present study, Visual MODFLOW groundwater model has been used for the simulation of groundwater flow processes. It solves numerically the 3-D groundwater flow equation (Eq. 2) for porous media by finite-difference method. Equation (1) can be further expanded as (McDonald and Harbaugh 1988):

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial x}\left(K_{zz}\frac{\partial h}{\partial z}\right) - W = S_s\frac{\partial h}{\partial t} \tag{2}$$

where $x$, $y$, $z$ are Cartesian coordinate axes, $h$ = potentiometric head [$L$], $K_{xx}$, $K_{yy}$, $K_{zz}$ = hydraulic conductivities along $x$, $y$, and $z$ axes [$LT^{-1}$], $W$ = volumetric flux/unit volume and represents sources and/or sinks of water [$T^{-1}$], $S_S$ = specific storage of the porous material [$L^{-1}$] and $t$ = time.

## Study Area

The location map of study area is shown in Fig. 1. The study area comprises the districts of Barabanki, Raebareli, Sultanpur, Pratapgarh and Jaunpur, in Uttar Pradesh, India. It lies between latitude 26° 45′ 36″ and 25° 41′ 60″N, and longitude 81° 6′ 36″ and 82° 49′ 12″E and is estimated to be 8287 km$^2$. The study area is bounded by River Gomti in north direction and Sai River in south direction. The confluence of Sai–Gomti River in Jaunpur district forms an eastern extremity of the area. The area is representative of the whole of the Sharda Sahayak Canal command. It is expected that the methodology adopted and conclusions arrived at would be applicable elsewhere in the canal command area.

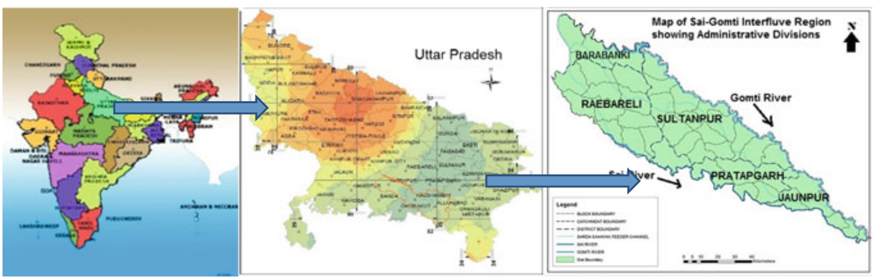


**Fig. 1** Location map study area: **a** India. **b** Uttar Pradesh. **c** Sai–Gomti interfluve region

## Geology of Study Area

The Sai–Gomti interfluvial plain forms a part of central Ganga Plain. It is underlain by soft/unconsolidated sediments of enormous thickness which varies from place to place. The observations of deep drilling study conducted by CGWB (2009) indicated that it is 487 m thick at Janauli in Raebareli district where granite basement was encountered; 399 m at Kandhai in Pratapgarh district (Vindhyan sandstone as basement) and 745 m at Leduka in Jaunpur district. The alluvium comprises alternation of sand–silt–clay sequence, which sometimes gets admixed with concentrations of calcium carbonate or Kankar as called in local language.

## MODFLOW Model Design and Software

A number of groundwater simulation models (GMS, FEFLOW and Visual MODFLOW) have been used for accessing the response of groundwater system. The performance of all three models is comparable, and any of these can be used for the simulation of groundwater system. In the present study, finite-difference groundwater model Visual MODFLOW has been used for groundwater system modelling. The Visual MODFLOW is a strong numerical code for groundwater flow regime representation and related physical processes. Visual MODFLOW is a three-dimensional groundwater flow modelling environment for practical applications and contaminant transport simulations. It solves a system of equations describing the major flow and related processes in the hydrological system using finite-difference methods. It is being extensively used worldwide to carry out research in the field of groundwater resource management (Ahmed and Umar 2008, Ghosh and Kashyap 2012, Singh et al. 2013 and Chakravorty et al. 2014). A full description of the capabilities of MODFLOW can be found in McDonald and Harbaugh (1988). The steps include design of grid, selecting time steps, setting boundary and initial conditions, preliminary selection of values for aquifer parameters and hydrologic stresses (Anderson and Woessner 1992). The following steps are considered in the model design of Sai–Gomti interfluve region:

1. **Design of Grid**: The Sai–Gomti interfluve region is bounded by rivers Sai and Gomti on the southern and northern sides, respectively. The area of 8287.50 $km^2$ has been divided into equal sizes of grid network of 30 columns and 86 rows. Thus, the area has been divided into 2580 square cells based on the available data sets for groundwater system modelling.
2. **Layer**: Single-layer groundwater flow model has been developed based on the available information related to aquifer characteristics, rainfall and other data sets of study area.

3. **Hydraulic Parameters**: Due to inadequacy of the data on aquifer parameters, the figures for hydraulic conductivity and specific yield were adopted from similar contiguous areas. The input value of hydraulic conductivity (*K*) was taken as 7.0 m/day and specific storage value of 0.001/m with coefficient of storage (*S*) as 0.15. These values were modified during the process of calibration of the model. After the parameter estimation (PEST) run, these values were modified as hydraulic conductivity (*K*) = 6.005 m/day and specific storage value of 0.900/m with coefficient of storage (*S*) as 0.16.
4. **Stress Period**: Simulation time has been divided into stress periods. The stress period is defined as that period of time in which all the stresses (recharge, boundary conditions, pumping rate, etc.) on the system do not change. A stress period of 8 years (2005–2013) has been considered.
5. **Specification of Boundary Condition and Recharge Estimation**: River Sai and River Gomti have been assigned river boundary condition. Cluster of few grid cells in western part of the area is simulated as general head boundaries, as these grid cells are not bounded by either of the rivers. Heads were assigned to general head boundaries with the help of water level data. The areal recharge due to rainfall has been taken as 20% of rainfall as per Groundwater Estimation Committee (GEC 1997) recommendations. The estimated values were applied to the respective grid in the model using recharge boundaries.

## *Model Calibration and Validation*

The purpose of model calibration is that the model can replicate field-measured heads and flows. Calibration can be carried out by trial-and-error adjustment of parameters or by using an automated parameter estimation (PEST). In the present study, automated parameter estimation (PEST) technique has been used.

## *Steady-State Calibration*

The aquifer system was taken to be in steady state during November 2005. It was chosen to run and calibrate the model under steady state for this period using 36 observation wells in the study area. The groundwater head in the aquifer model was computed by using Visual MODFLOW. Waterloo Hydrogeologic Software (WHS) solver package of MODFLOW has been used for groundwater flow computation. The computed water level accuracy was judged by comparing the mean error with mean absolute and root mean square (RMS) error (Anderson and Woessner 1992). Mean error is 0.005 m, and RMS error in the present simulation is 0.08 m. The correlation coefficient is observed as 0.94. The absolute residual mean is 0.056 m.

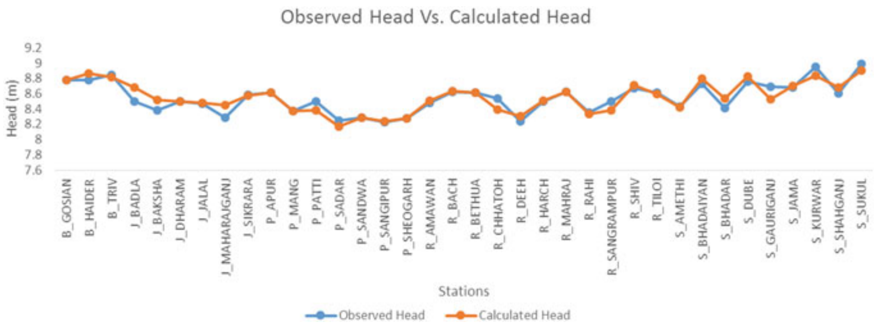


**Fig. 2** Observed head versus calculated head for the year 2013

## *Transient State Calibration*

The model was calibrated in transient state from 2005 to 2012 (7 years). Visual MODFLOW uses boundary conditions imposed by the user to determine the length of each stress period. After a number of trial runs, computed water levels were matched reasonably well to observed values. The RMS error for the transient state model is 0.442 m. The calibrated model provided hydraulic conductive ($K$) value as 6.005 m/d and coefficient of storage ($S$) as 0.23.

## *Model Validation*

The calibrated model was validated with the available data of year 2013, and acceptable difference between observed and calculated values was observed. Figure 2 shows a comparison between observed and calculated head values for the year 2013. The correlation coefficient value was observed as 0.98.

# Results and Discussion

## *Groundwater Level Prediction*

Calibrated and validated groundwater simulation model is further employed to predict groundwater scenarios. Groundwater level for the Sai–Gomti interfluve region has been predicted during the period of 2014–2018. Two different scenarios were considered to predict the groundwater level.

**Scenario 1: Constant recharge and increase in abstraction rate**
In this scenario, the ongoing abstraction rate was increased by 20% during the period of 2014–2018. It was observed during prediction run that the areas near

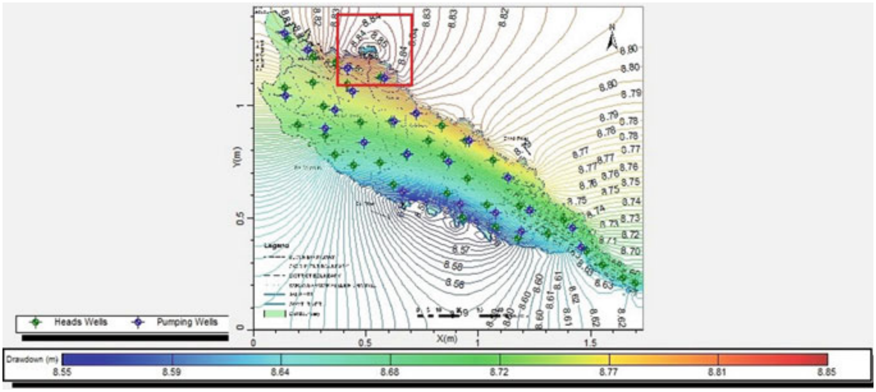


**Fig. 3** Groundwater level in scenario 1

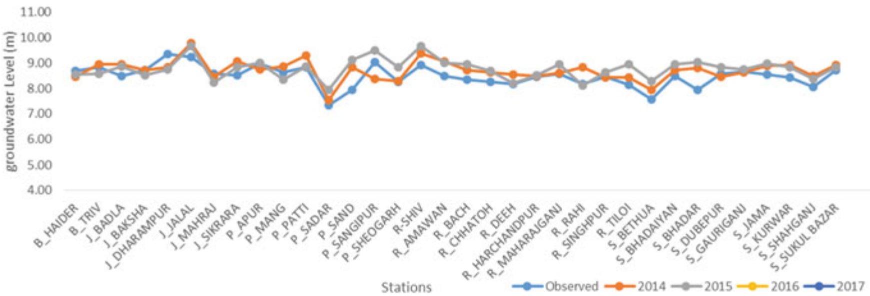


**Fig. 4** Predicted groundwater level trend in study area under scenario 1

River Gomti are significantly affected as shown in Fig. 3. The blocks, Goasainganj, Trivediganj, Haidergarh, Jagdishpur, Sukul bazar, have higher groundwater level ranging between 8.76 and 8.85 m as shown in Fig. 4.

**Scenario 2: Reduced recharge and increase in abstraction rate**
In this scenario, combined effect of reducing recharge by 20% and increasing abstraction rate by 20% was examined. It was observed that the maximum groundwater level increased as compared to scenario 1. The maximum groundwater level of 8.90 m in Haidergarh block of Barabanki followed by Trivediganj Musafirkhana, Kurwar blocks of Sultanpur and Shivgarh, Singhpur block of Raebareli district (Fig. 5).

Predicted groundwater level from 2014 to 2018 is also plotted for different well locations (Fig. 6). In general, there is declining trend of groundwater level in study area, as shown in Fig. 6. A sector of economy such as agriculture is most affected due to decline of groundwater level. Consequently, food production, manpower and employment are affected which also affect the society in general.

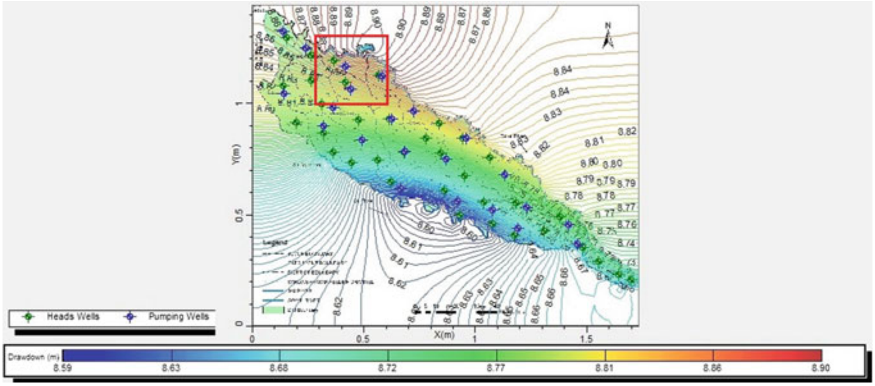


**Fig. 5** Groundwater level in scenario 2

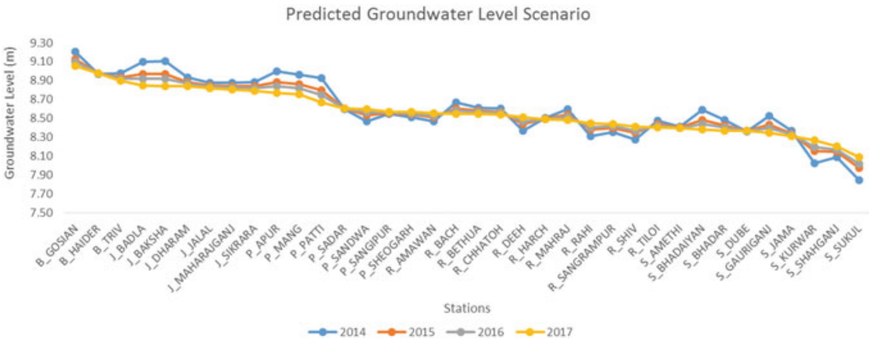


**Fig. 6** Predicted groundwater level trend in study area under scenario 2

## *Uncertainty Analysis*

Groundwater systems are composed of soil, water and many non-deterministic components. A systematic uncertainty analysis provides perception of the level of confidence in model estimates. Fuzzy numbers are used as alternative tool to address the parametric uncertainty when the model input parameters are limited or imprecise (Singh 2011). In the present study, fuzzy α-cut technique is utilized for uncertainty in hydraulic conductivity and porosity of groundwater flow model Visual MODFLOW. This technique uses fuzzy set theory to represent uncertainty in the parameters. Figure 7 shows a parameter $P$ represented as a triangular fuzzy number with support of $A_0$. The wider the support of the membership function, the higher the uncertainty. The fuzzy set that contains all elements with a membership of $\alpha$ ε [0, 1] and above is called the α-cut of the membership function. At a resolution level of $a$, it will have support of $A\alpha$. The higher the value of $a$, the higher the confidence in the parameter (Li and Vincent 1995).

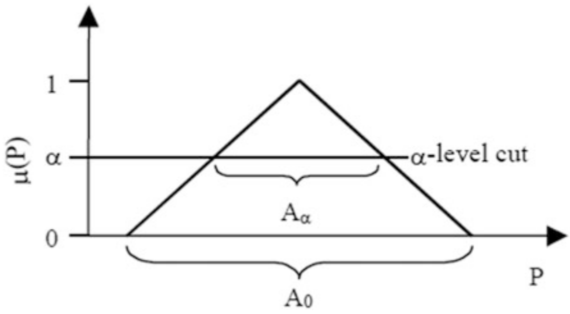


**Fig. 7** Fuzzy number, its support and α-cut

Fuzzy alpha-cut technique is based on the extension principle, which implies that functional relationships can be extended to involve fuzzy arguments and can be used to map the dependent variable as a fuzzy set. An alpha-cut is the degree of sensitivity of the system to the behaviour under observation. At some point, as the information value diminishes, one no longer wants to be "bothered" by the data. In many systems, due to the inherent limitations of the mechanisms of observation, the information becomes suspect below a certain level of reliability (Abebe et al. 2000). Membership functions define the degree of participation of an observable element in the set, not the desirability or value of the information. The membership function is cut horizontally at a finite number of α-levels between 0 and 1 (Fig. 7). For each α-level of the parameter, the model is run to determine the minimum and maximum possible values of the output. This information is then directly used to construct the corresponding fuzziness (membership function) of the output which is used as a measure of uncertainty.

In the present study, uncertainty analysis is performed to access the uncertainty associated with hydraulic conductivity and porosity of groundwater flow model Visual MODFLOW. Two different uncertainty scenarios, i.e. ±10 and ±15%, have been assumed for the assessment of uncertainty associated with above parameters. In case of hydraulic conductivity, the resulting uncertainty in both the uncertainty scenarios is found below 1%, which suggests that the head value is least sensitive to hydraulic conductivity up to ±15% uncertainty, while, in case of porosity, resulting uncertainty is observed to be zero.

## *Sensitivity Analysis*

The purpose of a sensitivity analysis is to quantify the uncertainty in a calibrated model caused by uncertainty in the estimates of aquifer parameters, stresses and boundary conditions (Kumar and Elango 2004). Sensitivity analysis is typically performed by changing one parameter value at a time (Anderson and Woessner 1992). In the present study, the sensitivity of model with respect to hydraulic conductivity was examined. The model was run with changes in hydraulic

**Table 1** Sensitivity analysis of hydraulic conductivity

| S. No. | Variation in $K$ | $K$ (m/d) | RMSE (m) |
|---|---|---|---|
| 0 | No change | 6.005 | 0.94 |
| 1 | Increased by 5% | 6.31 | 0.94 |
| 2 | Increased by 10% | 6.60 | 0.95 |
| 3 | Increased by 15% | 6.90 | 0.95 |
| 4 | Decreased by 5% | 5.71 | 0.92 |
| 5 | Decreased by 10% | 5.40 | 0.92 |
| 6 | Decreased by 15% | 5.11 | 0.91 |

conductivity, and RMSE value was calculated comparing the observed head value and model-simulated head values. The results are obtained from sensitivity analysis (Table 1) with changes in hydraulic conductivity values up to ±15%. Results revealed that the model is sensitive to decrease in hydraulic conductivity ($K$) value up to 15% compared to similar percentage of increase in $K$ values. Lower values of RMSE are obtained for decrease in $K$ values.

## Conclusions

In this study, a groundwater system model has been developed for Sai–Gomti interfluve region, Uttar Pradesh, India. Groundwater system modelling has been performed using groundwater flow model Visual MODFLOW. The groundwater system has been simulated in both steady state and transient state for 8-year stress period. Further, this calibrated and validated model has been utilized to predict the groundwater levels from year 2014 to 2018 considering the effect of varying pumping and recharge rates. The observations from the different scenarios showed declining water level trend in study area. The maximum groundwater level of 8.90 m was observed during scenario 2 in Haidergarh block of Barabanki followed by Trivediganj Musafirkhana, Kurwar blocks of Sultanpur and Shivgarh, Singhpur blocks of Raebareli district. Also, sensitivity and parametric uncertainty analyses were performed using deterministic as well as fuzzy $\alpha$-cut techniques. The analysis results revealed that the model is more sensitive to negative changes (decreased values) in hydraulic conductivity compared to positive changes (increased values) up to 15%. The simulation results show that the groundwater level is declining in Sai–Gomti interfluve region. This may be possible due to excess withdrawal of groundwater mainly for agricultural activities.

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# Assessing Aquifer Vulnerability Using GIS-Based DRASTIC Model Coupling with Hydrochemical Parameters in Hard Rock Area from Southern India

**N. C. Mondal, S. Adike, P. Anand Raj, V. S. Singh, S. Ahmed and K. V. Jayakumar**

**Abstract** In this article, aquifer vulnerability has been assessed by incorporating the major geological and hydrogeological factors that affect and control the groundwater contamination using GIS-based DRASTIC model. This work demonstrates the potential of GIS to derive a vulnerability map by overlying various spatially referenced digital data layers (i.e., depth to water, net recharge, aquifer media, soil media, topography, impact of vadose zone, and hydraulic conductivity) that portray cumulative aquifer sensitivity ratings across a tannery belt affected by the untreated 80 functional tannery effluents and located in a hard rock area (granitic terrain) in Southern India. It provides a relative indication of aquifer vulnerability to contamination. It has been also cross-verified with the association of selective hydrochemical parameters such as total dissolved solids (TDS), $Cl^-$, $HCO_3^-$, $SO_4^{2-}$, and $Cl^-/HCO_3^-$ molar ratios. The results have recognized four aquifer vulnerability zones based on DRASTIC vulnerability index (DVI), which ranged from 39 to 132. It has been deduced that approximately 18, 25, 34, and 23% of the area lies in negligible, low, medium, and high vulnerability zones, respectively. It shows that about 43% of the study area is under negligible and low vulnerable area where TDS varies from 650 to 1,796 mg/l and $Cl^-$ varies from 106 to 148 mg/l. It occupies in the southern and northern most parts, whereas about 57% area in central part is moderately and highly contaminated due to the disposal of tannery industries and is more prone to aquifer vulnerability, where the high ranges of TDS (2,304–39,100 mg/l), $Na^+$ (239–6046 mg/l), and $Cl^-$ (532–13,652 mg/l) values are well correlated with the observed high vulnerable zones. The $Cl^-/HCO_3^-$ molar ratios (=1.4–106.8) of the high vulnerable zone obviously

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indicate deterioration of the aquifer contamination due to the tannery effluents. It is realized that GIS is an effective platform for aquifer vulnerability mapping with reliable accuracy, and hence, the study is more useful for environmental planning and predictive groundwater management in granitic terrain.

**Keywords** Aquifers · Vulnerability assessment · DRASTIC model
Hydrochemistry · Granitic area · Southern India

## Introduction

The term vulnerability is being used in hydrogeology from the 1970s in France (Albinet and Margat 1970) and more widely in 1980s DRASTIC model (Aller et al. 1987). The word 'DRASTIC' is an acronym abbreviated for seven parameters like Depth of water table (*D*), net Recharge (*R*), Aquifer media (*A*), Soil media (*S*), Topography (*T*), Impact of vadose zone (*I*), and hydraulic Conductivity (*C*). It is the measure of possibility of pollution or contamination at the ground level to reach an aquifer. Numerous schemes have been developed for assessing vulnerability, and DRASTIC technique is one among them grouped under index and overlay analysis. The DRASTIC modeling is preferred among many other techniques as it has the capacity to show all hydrogeological properties in the final map. Also it can be feasibly inferred for the results by plotting groundwater contaminations like nitrate, chloride, TDS (Prasad et al. 2011; Kaliraj et al. 2015).

Aller et al. (1987) is the first to introduce the DRASTIC modeling under US Environmental Protection Agency (USEPA). The complete methodology to evaluate the pollution potential, systematically, of any hydrogeological setting has been described. Later, this typical DRASTIC technique has been applied in various places to assess the groundwater vulnerability (Moulton 1992; Kim and Hamm 1999; Al-Rawabedh 2013). They have divided the entire study area into different zones like low, medium, moderate, and high. Prasad et al. (2008), Javadi (2011), Prasad and Shukla (2014), and Kaliraj et al. (2015) have made an improvement over the technique by comparing the results with the groundwater pollutant samples, which were collected on different zones for nitrates, chlorides, and bicarbonates contamination. Wolters et al. (2014) compared the DRASTIC method and SINTACS method to narrow the highly polluted zone in an area. An analytical hierarchy process applied in DRASTIC model to fix the weights and ratings of DRASTIC parameters (Bai et al. 2012; Tirkey et al. 2013). An advanced technique, namely map removal sensitivity and single parameter model, is used by applying sensitivity analysis to delineate the sensitive parameter among seven DRASTIC parameters (Insaf et al. 2005; Mamadou and Zhonghua 2010; Salwa et al. 2011; Akhtar and Tang 2014).

Nowadays, severe contamination of surface and groundwater affects the health of rural farming community and nearby livelihood (Mondal and Singh 2010, 2011).

Especially in the present study scenario which is being affected by uncontrolled discharge of untreated effluents by 80 tanneries (Fig. 1), they turned the fertile land into unfertile. Local masses suffered from occupational diseases such as asthma, chromium ulcers, and skin diseases (Mondal et al. 2005; Mondal and Singh 2005). This situation is aggravated by the contaminated water supply. The place is heading toward freshwater crisis, varying in scale and intensity depending on the time of the year, mainly due to improper management of local water bodies and environmental degradation which has lead to a lack of access to safe water supply to the regional people. Apart from the natural factors, the situation is the result of human actions. During the past few decades, the water level in several parts has been contaminated due to an increase in the industrialization (Mondal and Singh 2011). Due to heavy industrialization, atmospheric air is also getting polluted. For example, when the air is polluted, rainfall will settle many pollutants on the ground, which can then seep into and contaminate the groundwater resources. In addition, industrial waste and the municipal solid wastes have also polluted surface and groundwater (Mondal and Singh 2010). Hence, it is important to realize that groundwater is not a resource that could be utilized unmindfully simply because it is available in abundant quantities. Problems and issues such as water logging (Gupta and Kamra 2006; Karma and Keledhonker 2007), salinity (Datta and Jong 2002), agricultural toxins (Uppal and Mangat 1981), and industrial effluents (Jutter et al. 2000; Anjaneyulu et al. 2005) all need to be properly scrutinized and explored especially the dangerous industrial effluents. These effluents, if not properly treated and disposed, get seeped into the ground and infect the underground water.

Processing the leather requires a large amount of freshwater including various chemicals like lime, sodium carbonate, sodium bicarbonate, common salt (NaCl), fat liquors, chrome sulfate, dyes, and vegetable oils. In fact, every 10 kg of raw skin requires about 350 l of freshwater till it completes the process (Mondal and Singh 2010). Since the water sources are very low in the area, they have been overexploited for the very low water table depth (range: 2.3–25.9 m, below ground level, bgl). Also the chemicals contaminate the agricultural lands nearby. The wastewater discharged for 100 kg of skin varies from 3000 to 3200 l (Mondal et al. 2005). Tannery waste is primarily characterized by bulk amount of salt, strong color, high pH, BOD, and dissolved solids. The effluents when discharged into the ground affect the groundwater table. Also the effluents which are stuck in the soil pores are pushed forward during rainfall, thereby affecting the groundwater recharge. Not only the chemicals but also the dischargeable wastewater from the tanneries seeps into the ground to affect the net recharge. Since recharge is getting affected, the contamination spreads to other properties associated with the recharge like transmissivity, vadose zone, conductivity. Thus, considering all these parameters, the objectives of this study are twofold to: (1) assess the vulnerability extent using DRASTIC model in a granitic area, Southern India, and (2) cross-verify using the selective hydrochemical parameters.

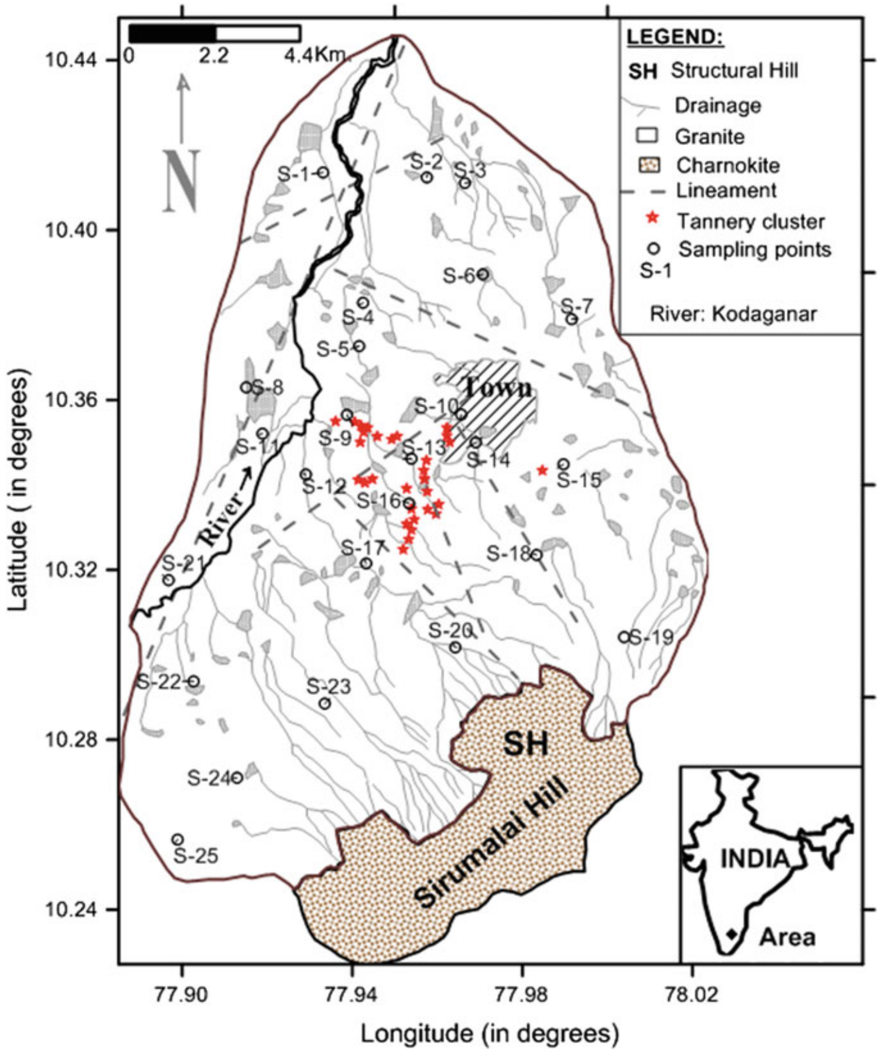


**Fig. 1** Location of the study area

# Materials and Methods

## *Data Collection*

Seven DRASTIC parameters like groundwater table, recharge, aquifer discharge, soil types, surface elevation, vadose zone thickness, and aquifer properties were collected from the field condition and also existing collateral data. The depths to groundwater table were measured using water-level indicator at 46 open wells.

Elevation was estimated at 600 locations in grid pattern (200 × 200 m) and incorporated in GIS format to produce the topography map. Vadose zone thickness was calculated using the groundwater-level data (PWD 2000). Aquifer properties like hydraulic conductivity (*K*), transmissivity (*T*), and storativity (*S*) were estimated through large diameter pumping (Singh et al. 2003). The collateral data like groundwater recharge was estimated at PWD wells by entropy method (Mondal et al. 2012). It was utilized to prepare recharge map for the DRASTIC model. The aquifer yields of the study area had been estimated during the pumping test in the field condition (Singh et al. 2003). The soil map data had been collected from Public Works Departments (PWD 2000). The collected 25 groundwater samples from the represented dug wells and dug-cum-bore wells distributed throughout the area were utilized, which were under use at 0.5 m below the water table, and pumped more than 5 min. Methods of collection and analysis of groundwater samples for major cations and anions followed were essentially the same as given by Browen et al. (1974) and APHA (1985). These data were used to verify the vulnerability zones.

## DRASTIC Model

In this study, aquifer vulnerability evaluation was initiated by DRASTIC modeling. Through this model, the vulnerable zones were demarcated and divided. The methodology used in this process was similar to the DRASTIC modeling process. It was proposed by EPA for scoping the potential magnitude of hydrogeological parameters which are sensitive to transfer the contaminant materials into aquifers (Aller et al. 1987). The word DRASTIC is an acronym abbreviated for seven parameters like **D**epth of water table (*D*), net **R**echarge (*R*), **A**quifer media (*A*), **S**oil media (*S*), **T**opography (*T*), **I**mpact of vadose zone (*I*), and hydraulic **C**onductivity (*C*) (see Table 1). Since these are the functioning parameters in defining the groundwater contamination, mapping and overlapping of these parameters help in evaluating the degree of susceptibility for groundwater pollution. The parameters in the DRASTIC model were initially divided into ranges for corresponding hydrogeological settings, and these individual ranges should be assigned with a definite rating factor on a scale of 1–10 where symbolizing 1: for least vulnerable region and 10: for high vulnerable region. This was succeeded by assigning weights value for the individual parameter, on a scale of 1–5, in relative to their importance in contributing to the vulnerability. In this study, Delphi approach was adopted in fixing the range, rating, and weights. Finally, the DRASTIC Vulnerability Index was calculated by the formula given below.

**Table 1** The relative assigned weight (s) of DRASTIC model parameters and its description

| Factor(s) | Description | Relative weight (after Aller et al. 1987) | Assigned relative weight |
|---|---|---|---|
| Depth to water | It is the depth from ground surface to the top of groundwater table, deeper the water level is lesser chance of contamination | 5 | 5 |
| Net recharge | It is an amount of water which recharges the aquifer, high amount of recharge carries more contaminant | 4 | 4 |
| Aquifer media | It represents the property which defines the aquifer matrix like discharge, high discharge constitutes to high contamination | 3 | 3 |
| Soil media | It is the controlling parameter of infiltration, which represents the soil type, cohesive soils retain the contaminants than non-cohesive soils | 2 | 2 |
| Topography | It represents the slope of land surface, gentle undulations sustain the water in a place forcing water to percolate into the ground | 1 | 1 |
| Impact of vadose zone | It is the unsaturated part of earth between ground surface and top of the phreatic zone, lesser the soil thickness is higher chance of contaminant interaction with the water table | 5 | 5 |
| Hydraulic conductivity | It is the ability of aquifer to transmit water, high transmissivity injects more contaminants into the aquifer | 3 | 3 |

$$\text{DRASTIC.Index} = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w \tag{1}$$

where, capital letters indicate corresponding parameter, and suffixes ($r$ and $w$) indicate the assigned rates and weights, respectively.

The above-described system was processed under GIS environment, as it is an immense platform for thematic layer preparation and mathematical calculations. The choice of this particular software is because of its varied features of storage, retrieval, mapping, and analysis of geographic data; spatial features can be stored in a coordinate system (latitude/longitude, state plane, UTM, etc.), which reference a particular place on the earth. Also its specialty in associating spatial features with descriptive attributes in tabular form and these in the same coordinate system can then be layered together for mapping and analysis helps in decreasing the tedious job. The 'Spatial Analyst Tools' from the extension tools of Arc catalog were used. After digitizing the map, seven vectors layers were constructed for each parameter. They were then converted into raster form and reclassified by assigning suitable ratings based on their nature. Each of the seven layers was overlapped by weighted sum tool; in this section, respective weights were allocated to each of the layers. The DRASTIC index calculation was performed by default, and the final score of

DRASTIC index was displayed. This index was divided into four zones according to their scoring value. The high DRASTIC index zone was most vulnerable than lower score zone.

## Results and Discussion

### *DRASTIC Model Parameters*

Equation (1) discussed was fitted in ArcGIS 10.1 software after preparing the DRASTIC maps. Specified ratings in Table 2 were given for different ranges. It shows the weights portioned for seven parameters of DRASTIC model and ratings for individual range.

## Depth to Groundwater Table

Depth to groundwater table is a significant factor in DRASTIC modeling as it affects the vertical travel time of contaminant from surface poundage (Stigter et al. 2006). It varied from 2.30 to 25.90 m with an average of 11.97 m. High rating

**Table 2** GIS-based DRASTIC model parameter rating(s) for the vulnerability study

| Parameter | Rating | Parameter | Rating |
|---|---|---|---|
| *Depth to water table* (*m*, *bgl*) | 10 | *Topography* (*m*, *amsl*) | 10 |
| 2.30–9.52 | 8 | 230.01–258.43 | 7 |
| 9.53–12.20 | 6 | 258.44–283.58 | 5 |
| 12.21–15.07 | 4 | 283.59–308.17 | 3 |
| 15.08–18.40 | 2 | 308.18–334.96 | 1 |
| 18.41–25.90 | | 334.97–369.39 | |
| *Net recharge* (*mm*/*year*) | 2 | *Impact of vadose zone* (*m*) | 10 |
| 22.42–31.91 | 4 | 0.52–1.41 | 8 |
| 31.92–38.12 | 6 | 1.42–1.90 | 6 |
| 38.13–42.50 | 8 | 1.91–2.51 | 4 |
| 42.51–51.27 | 10 | 2.52–3.59 | 2 |
| 51.28–64.96 | | 3.60–5.35 | |
| *Aquifer media* ($m^3$/*day*) | 2 | *Transmissivity* ($m^2$/*day*) | 2 |
| 95.07–179.94 | 4 | 15.00–51.27 | 3 |
| 179.95–254.21 | 6 | 51.28–81.02 | 5 |
| 254.22–326.70 | 8 | 81.03–115.83 | 7 |
| 326.71–423.95 | 10 | 115.84–156.73 | 9 |
| 423.96–545.96 | | 156.74–199.96 | |
| *Soil media* | 5 | | |
| Red sandy soil | 1 | | |
| Black cotton soil | | | |

(10) was assigned to low water table locations (range: 2.30–9.52 m, in Table 2) as it is inversely related to the groundwater contamination. If depth to water level is less from ground surface, then the time of travel for pollutant to reach the water table is less. Hence, it was assigned with high rating (10). Since there are high hills located in southeast region, there was comparatively deeper water table and runoff from the hills spreads over the hills foot area. The depth gradually decreases till toward central part where the tannery clusters are located (Fig. 1).

## Recharge

Recharge basically represents the amount of water that infiltrates into the ground. High recharge indicates high infiltration, and when this infiltration contains pollutants, the rate of contamination increases. Hence a proportional rating had been assigned for the recharge values as a high recharge implies in high contamination infiltrated into the ground. Since the DRASTIC model has been developed for moderate climate with uniform rainfall distribution and natural land surfaces, it is not straightway applicable for the city Dindigul, where very low degree of precipitation and moderate undulations exit (Mondal and Singh 2012a). Thus, the monsoon data had been considered, and the recharge had been estimated by entropy method (Mondal et al. 2012a). It varied from 22.42 to 68.98 mm/year. The recharge is high in northeast corner and gradually decreases at the middle of northeastern part due to the presence of black cotton soil. Then, it increases toward southwest part. The recharge mainly deviates due to topography variation and hydrogeological setting in the area (Mondal and Singh 2004).

## Aquifer Yields

The aquifer yield map of the study area had been prepared by estimating the discharge in the field condition (Singh et al. 2003). Discharge value varies from 95.07 to 545.96 $m^3$/day. High permeability allows more water, and accordingly more contaminants enter into the aquifer. Therefore, a high permeability (range: 423.96–545.96 $m^3$/day) will yield a high vulnerability rating. The aquifer yield was high in the middle-eastern part and decreased spatially on either direction.

## Soil Media

Soil media refers to the uppermost portion of vadose zone characterized by significant biological activity (Aller et al. 1987). It has a significant impact on the amount of recharge which can infiltrate into the ground and hence on the ability of a contaminant to move vertically into the vadose zone. Moreover, where the soil zone is fairly thick, the attenuation process of filtration may be quite significant. The soil characteristic of the study area is shown in Fig. 2. Since black cotton soils are cohesive and aquicludes in nature, low rating (1) had been assigned when compared to red sandy soils (rating: 5) where yielding and transmission of water was better when compared to black cotton soils. Black cotton soils occupy in central part of the area leaving the northernmost and southernmost sites with the red sandy soils.

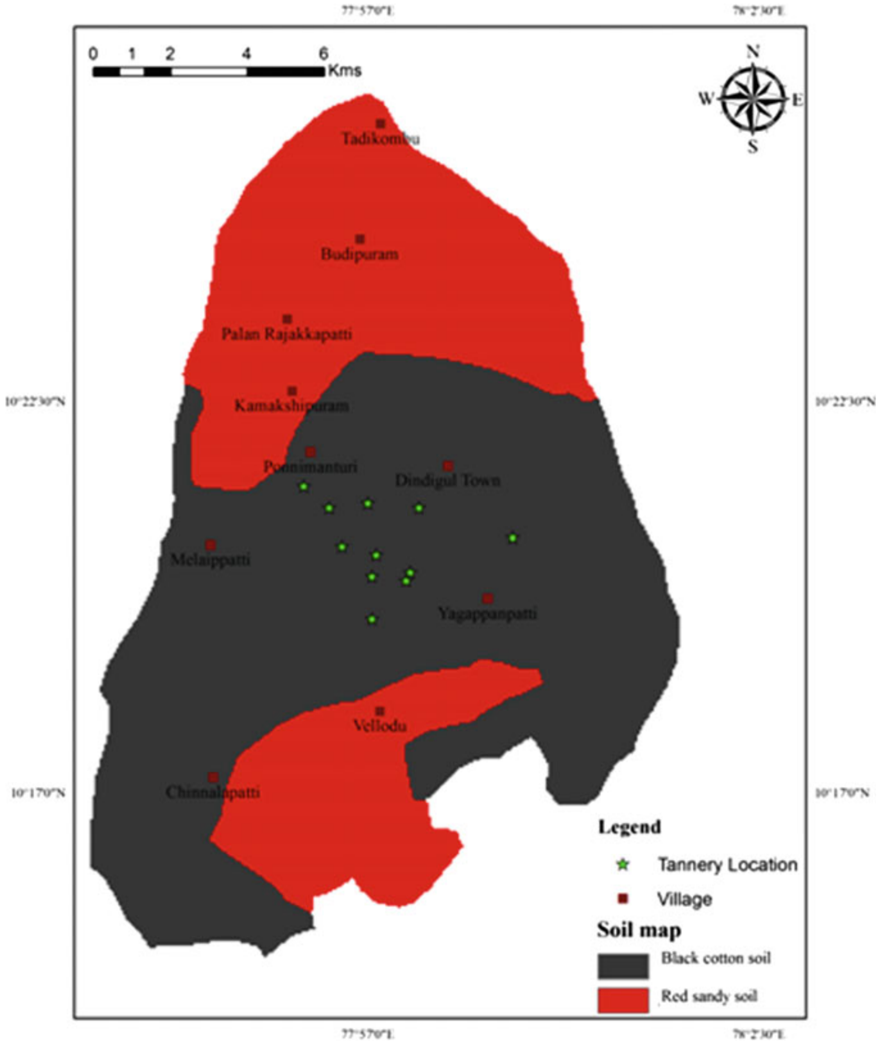


Fig. 2 Soil distribution of the study area

## Topography

Topography refers to the slope and variability of land surface. It helps to control the likelihood that a pollutant will run off or remain on the surface in one area long enough to infiltrate. In the present study, DEM map was used to define the topography. The ratings were used for the analysis as shown in Fig. 3. Since there are hills located in southeast part, the slope is high and gradually decreasing toward north.

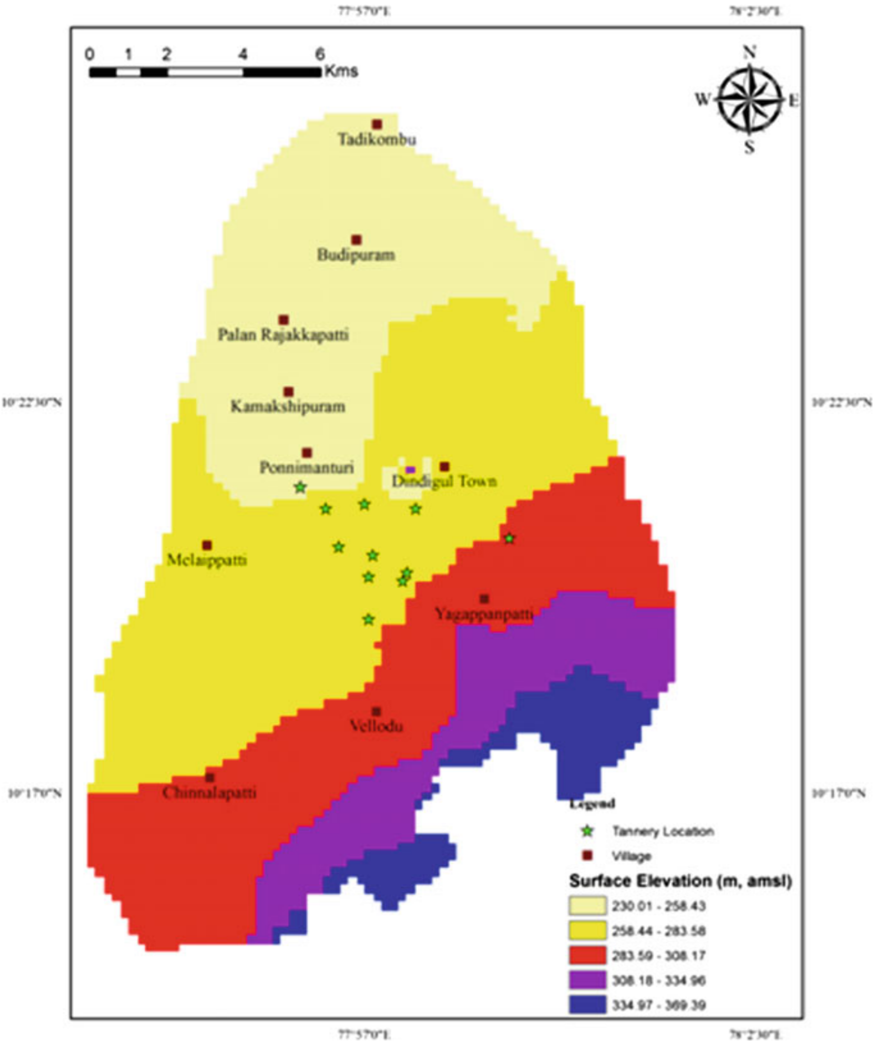


**Fig. 3** Topography pattern in the study area

## Impact of Vadose Zone

The vadose zone is a typical soil horizon and partially weathered zone above the water table, which is unsaturated or discontinuously saturated. It ranges between 0.52 and 5.35 m, bgl, with an average of 1.59 m. This media controls the path length and routing when the water is flowing into the aquifer. Thicker the zone longer is the path length and thus affecting the travel time in routing. Hence, an inverse proportional relation had been given to the vadose zone map, i.e., low rating (=2) was given to thicker vadose area (range: 3.60–5.35 m). Low-to-medium thickness ranges were assigned all over the area except in few spatial points where the thickness range was deeper.

## Conductivity

Conductivity is the rate of groundwater flow under a unit hydraulic gradient through a unit cross-sectional area. High groundwater flow rate represents high contaminant advection; hence, a high rating was assigned to high conductivity zone. Since hydraulic conductivity is directly proportional to transmissivity, the pumping test results yielded transmissivity in horizontal plane, those values were considered to get the transmissivity map. The values range from 15.00 to 199.96 $m^2$/day, while 84.31 $m^2$/day was an average of the data set in the study area. A low transmissivity zone (range: 15.00–51.27 $m^2$/day) existed at foot of the hills at which the rating was assigned as ‘2’. It increased spatially to a high value in northeastern part and accordingly assigned the ratings (Table 2).

## Vulnerable Map Using the DRASTIC Model

The attribute layers for 7 DRASTIC parameters were assembled within a GIS format, and commercially available ArcGIS 10.1 software was used to execute the necessary computations in raster format. Using the created 7 maps and based on the rating system, a final DRASTIC map was divided into different classes. In the created 7 thematic layers, each pixel was reclassified to a rating value with some reference or by Delphi method. The reclassification tool in spatial analyst tool box was used to reclassify each pixel. These reclassified maps were overlaid by the weighted sum tool in the spatial analyst tool box. The process of multiplying reclassified rating of each pixel with the weight given to definite parameter was done in this step. Finally, the vulnerability index or DRASTIC index was calculated. Total DRASTIC index varied from 39 to 132 for the vulnerability. The resulted index was divided into 4 equal groups (Aller et al. 1987). Small numbers indicated low vulnerability potential, and large numbers were related to those areas that had high pollution potential. These are represented on a DRASTIC map (Fig. 4), and the corresponding values for each point were also extracted. This vulnerable map shows that about 103.2 km$^2$ (43%) of the area lies between low and negligible risk of pollution zone but the remaining 136.8 km$^2$ (57%) is occupied by moderate risk to high risk of pollution zone. The high-risk zones are presented in middle part of the study area (red color zone). The low-risk-to-negligible-risk zones are presented on lower half part of the region.

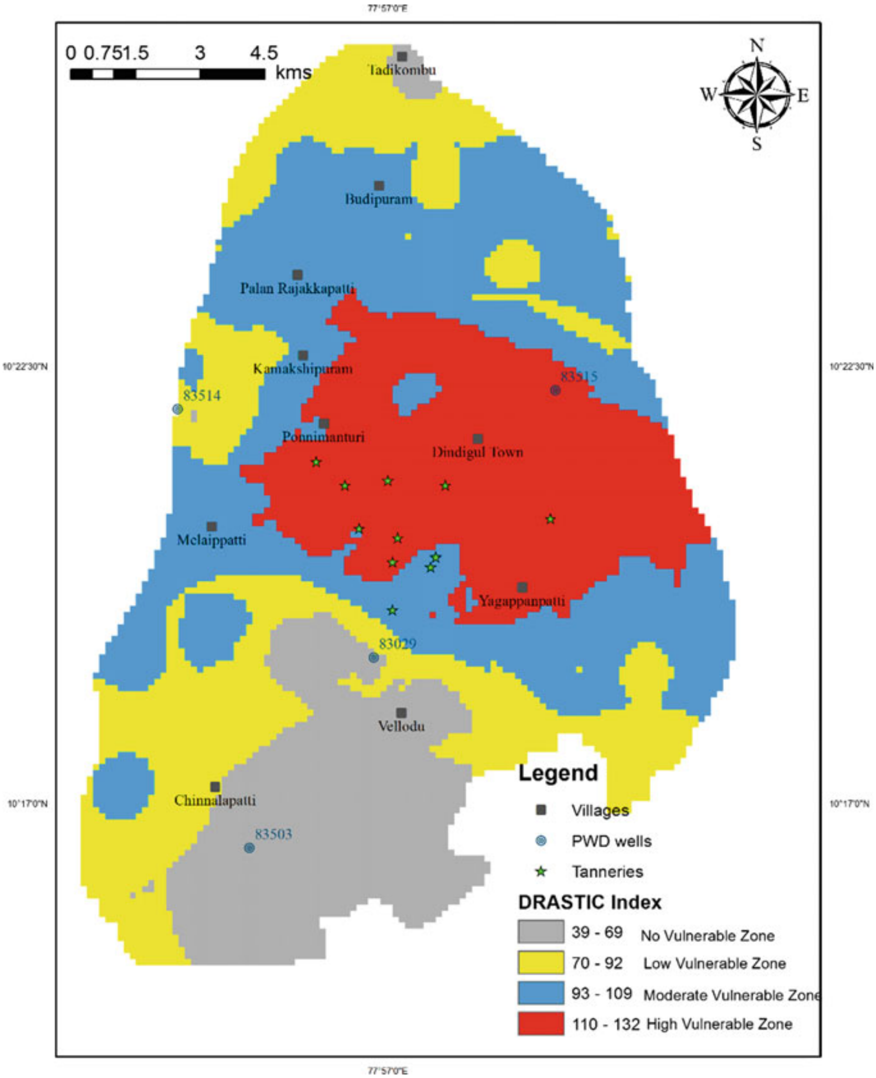


**Fig. 4** DRASTIC model for vulnerability assessment in the study area

## Validation Aquifer Vulnerability

Hydrochemical parameters represent the hydrodynamic processes involved within an aquifer. The spatial variation of these parameters such as TDS and all major cations and anions were investigated to explore the relationship between the aquifer vulnerability and hydrochemical variations. In total, 3, 7, 6, and 9 groundwater samples were collected from negligible, low, moderate, and highly vulnerability zones, respectively, for assessing hydrochemical composition. Statistical parameters, including minimum, maximum, mean, and standard deviation, of different chemical constituents of the analyzed groundwater samples ($N = 25$) from the study area were computed. Comparison of hydrochemical data with the World Health Organization (WHO 1984) drinking water standards showed about 96% ($N = 24$), 80% ($N = 20$), 60% ($N = 15$), 56% ($N = 14$), and 8% ($N = 2$) of the samples exceeded the guideline values for total dissolved solids (TDS: 500 mg/l), sodium ($Na^+$: 200 mg/l), chloride ($Cl^-$: 200 mg/l), sulfate ($SO_4^{2-}$: 200 mg/l), and nitrate ($NO_3^-$: 45 mg/l), respectively. This indicated that groundwater quality has deteriorated significantly in the study area.

In general, the TDS and chloride ion ($Cl^-$) are high in the contaminated water and relatively less in fresh groundwater (Saxena et al. 2003; Sarwade et al. 2007; Mondal and Singh 2011; Mondal et al. 2011). However, bicarbonate ($HCO_3^-$) is dominant in the fresh groundwater than that of saline water. The molar ratio of $Cl^-/HCO_3^-$ is referred to as the Revelle coefficient (Revelle 1941) and could be appraised the intensity of salinity into the aquifer. Hence, these hydrochemical parameters had been used to verify the site-specific vulnerability toward aquifer contamination.

The result showed that the samples were fallen within the negligible vulnerable zones having low concentration of TDS (650–1, 389 mg/l), $Na^+$ (47–161 mg/l), $Cl^-$(106–298 mg/l), $HCO_3^-$ (340–500 mg/l), and the molar ratios $Cl^-/HCO_3^-$ ranged from 0.54 to 1.03. These were relatively lower in the southern and northern parts than other parts of the study area. In this area, the aquifers were found with lower vulnerability conditions due to the subsequent replenishment of freshwater by infiltration from the Sirumalai Hill. But the samples fallen within the high vulnerable zones in and around the tannery clusters were recorded with high concentration of TDS (2, 304–39, 100 mg/l), $Na^+$ (239–6, 046 mg/l), $Cl^-$(532–13, 652 mg/l), and the molar ratios $Cl^-/HCO_3^-$ ranges from 1.43 to 106.81. This area is highly susceptible to the advection of contaminants in the form of pollutants into the aquifers (Mondal and Singh 2012b). The moderate vulnerability conditions were observed around the highly vulnerable zones having a moderate hydrochemical concentrations of TDS (1, 204–3, 976 mg/l), $Na^+$ (182–654 mg/l), $Cl^-$ (213–1, 596 mg/l), and the molar ratios $Cl^-/HCO_3^-$ ranges from 0.77 to 8.28. The $SO_4^{2-}$ concentration ranges from 110 to 263 mg/l, and the $NO_3^-$ concentration ranged between 5 and 15 mg/l, which indicated comparatively fair groundwater quality. The movement of groundwater is slower in the black cotton soil surface due to poor porosity and impermeability. It controls the rate of groundwater flow and reduces groundwater contamination (Mondal and Singh 2012b). The comparatively lower values of TDS (499–1, 796 mg/l) and $Cl^-$ (57–418 mg/l) were noticed in the northern and southern parts of the study area which was underlain by the low vulnerable zones.

## Conclusions

In this article, an attempt is made to assess the aquifer vulnerability through DRASTIC Vulnerability Index in a granitic terrain of Southern India, which is being affected by the tannery pollution. The results are that about 43% of the area is healthy with little vulnerability, but remaining 57% of the area is highly polluted. This is mainly because of the tannery industries which release untreated dangerous chemicals into the ground. This effect has also reached to the surrounding agricultural farms hence polluting the land as well as the production coming from the land.

To verify the efficiency of the vulnerability index in natural hydrogeological system, vulnerable zone-wise hydrochemical parameters such as TDS, $Cl^-$, $HCO_3^-$, $SO_4^{2-}$, and $Cl^-/HCO_3^-$ molar ratios have been analyzed. The samples fallen within the high vulnerable zone have been recorded with high concentration of TDS (2, 304–39, 100 mg/l), $Na^+$ (239–6, 046 mg/l), $Cl^-$ (532–13, 652 mg/l), and the molar ratios $Cl^-/HCO_3^-$ ranges from 1.43 to 106.81, whereas the low concentrations of TDS (650–1, 389 mg/l), $Na^+$ (47–161 mg/l), $Cl^-$ (106–298 mg/l), $HCO_3^-$ (340–500 mg/l), and the molar ratios $Cl^-/HCO_3^-$ (0.54–1.03) were observed within the negligible vulnerable zone(s).

The hydrochemical results well correlated with the DRASTIC model in the study area. Hence, the vulnerability assessment through the DRASTIC model in any hydrogeological system along with hydrochemical study is important in future which will help in the protection and designing of remedial measures in a micro-scale for sustainable groundwater management.

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# Part II
# Groundwater Recharge

# Development of Groundwater Recharge Plan for Bemetara District of Chhattisgarh Using GIS

**M. P. Tripathi, D. Khalkho, P. Katre, Jyotsana Khakha and Priti Tiwari**

**Abstract** Proper groundwater recharging may drastically change the scenario of groundwater availability of the area. It needs appropriate groundwater recharge locations, which can be prepared by using satellite data and GIS. Eight blocks of five districts including Bemetara in Chhattisgarh are reported to be semi-critical. Average groundwater development of Bemetara district is reported to be 63.24%. Looking to the need of groundwater recharge plan for Bemetara district a study on groundwater recharge planning was carried out in the Department of Soil and Water Engineering, Faculty of Agricultural Engineering, IGKV, Raipur. Accordingly, thematic maps were superimposed to identify the appropriate locations for artificial groundwater recharge structures. Various thematic maps including district and block boundaries, drainage, slope, soil texture, lineaments, geology and water level depth were generated in the environment of GIS. A satellite image, IRS P6 LISS IV, was classified using supervised classification method to generated land use map of the area. Different structures and their sizes were decided on the basis of topography and drainage pattern. The upper, middle and lower reaches of drainage lines were considered for different sizes of check dam. The site for percolation tank was identified for groundwater recharge. The field survey of study areas was also carried out to find out the suitability of proposed artificial groundwater recharge structures. It is concluded that suitable sites for artificial recharge structures in these districts were found to be 68%. Finally, 130 locations for check dam and 59 locations for percolation tank in Bemetara district were identified. The subsurface storage space was estimated on the basis of thickness of available vadose zone. The vadose zone of 285 $Mm^3$ is available for artificial recharge in the Bemetara district. The volume of water required for artificial recharge was found to be 379 $Mm^3$ for this district. It was found that sufficient volume of water required for artificial recharge is available. Availability of source water to recharge the subsurface

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reservoir were found to be 1099 $Mm^3$ in the form of non-committed surplus run-off out of which 30% (329.67 $Mm^3$) is considered as surplus monsoon run-off which is available for artificial recharge.

## Introduction

Artificial groundwater recharge is the planned, human activity of augmenting the amount of groundwater available through works designed to increase the natural replenishment or percolation of surface water into the groundwater aquifers. Presently, many states do not have plan for groundwater recharging. The groundwater recharge structure that can be constructed are percolation tanks, check dams, cement plugs and nala bunds, Gabian structures, village tanks, recharge shaft, subsurface dykes or groundwater dams, dried up or disused dug wells, injection wells in alluvial aquifers and rooftop water harvesting structures.

The intensive groundwater development in many parts of the country has resulted in depletion of groundwater levels and availability of the water resource. Artificial recharge can be an appropriate option to optimize total water resource management. Artificial recharge is feeding water to a permeable formation with the purpose of enhancing groundwater table. An appropriate groundwater recharge plan can help to enhance the sustainable yield in areas where over development has depleted the aquifers (Shah 2008). It supports conservation and storage of excess surface water for future requirements which often changes within a season or a period and also improves the quality of existing groundwater through dilution.

The countries average annual rainfall is 1194 mm, which when considered over a geographical area of 328 Mha amounts to a total volume of about 400 Mha. Out of this, the utilizable potential is only 67 Mha m of surface water and 26.5 Mha m of groundwater. So, there is an urgent need for augmentation of the limited groundwater resources by taking appropriate measures including suitable management interventions.

The average annual rainfall of Chhattisgarh state is 1240 mm. About 87% area of the state is covered by hard rocks. Groundwater availability is largely influenced in these rocks by the topography and rainfall. Because of varied topography and hydrogeological condition in the state, the groundwater potential is not uniform, and it changes from one area to another. Out of 146 blocks in the state, 21 have been categorized as semi-critical from groundwater development point of view as the stage of groundwater development in these areas is more than 70% but less than or equal to 90%. Out of these 21 blocks, two blocks falls in Bemetara district (CGWB 2014).

Several research workers have been developed recharge plan of an area using different methods. Previous studies revealed that the run-off stored in the pond traverses through the geological material and improves the water table in the wells. About 70–80% of water stored in the pond percolated into the deeper layers and improved the yield of wells in the zone of influence. Kumar et al. (2011) suggested comprehensive and proper ground water recharge plan for the identified land forms to maintain the groundwater at a safe and desired level in Ganga–Ramganga inter-basin.

A simple technology had been developed, which consists of collection of run-off from rooftop through PVC pipe, passed through a filter and finally the filtered water was put into an aquifer/sandy formation above water table through a recharge well (Taneja and Aggarwal 2005). Thematic maps such as hydrogeomorphology, slope and drainage density can be integrated with the help of GIS by assigning the weights to various attributes controlling the occurrence of groundwater. These thematic maps can be used to generate the groundwater potential map of an area (Israil et al. 2006).

In water scarce regions of India, run-off harvesting does not offer any potential for groundwater recharge or improves water supplies at the basin scale. Even at the local level, physical efficiency of water harvesting is likely to be poor, mainly due to groundwater surface water interactions and the poor storage capacity of hard-rock aquifers underlying most of the water scarce regions (Kumar et al. 2008).

The groundwater could be developed through dug wells and bore wells. The optimum development of balance groundwater resources can supply assured irrigation, and there was huge scope which exists for artificial recharge (Nivasarkar and Verma 2009). The potential impact on groundwater recharge of arable land is an important issue for spatial environmental assessments (Busch 2009).

The artificial groundwater recharge is a process by which the groundwater reservoir is augmented at a rate exceeding the augmentation rate under natural conditions of replenishment (Bhattacharya 2010). In some parts of India, due to over exploitation of groundwater, decline in groundwater levels resulting in shortage supply of water, and intrusion of saline water in coastal areas have been observed. In such areas, there is need for artificial recharge of groundwater by augmenting the natural infiltration of precipitation or surface water into underground formations by methods such as water spreading, recharge through pits, shafts, wells, etc. (Bhattacharya 2010).

Integration of remotely sensed data and field survey data on a GIS platform provides convergent analysis of diverse data sets for decision-making in groundwater management (Gautam et al. 2010). The over exploitation of local groundwater resources can be prevented by inducing groundwater mounding through artificial recharge using rainwater stored in specially constructed basins (Patel and Desai 2010).

The intersection zones of lineaments provide potential for groundwater accumulation and groundwater recharge (Sharma and Kujur 2012). Occurrence of groundwater in sedimentary rocks is essentially confined to fractured and weathered zones. Basic information for site selection of rainwater harvesting/artificial recharge structures to the aquifer systems has been established by preparing various thematic maps (Sharma and Kujur 2012).

During the last decade, groundwater recharge plans were developed using remote sensing data and GIS by many research workers for different groundwater basins having various management regimes in India and abroad (Anbazhagan et al.

2005; Nouri et al. 2005; Tweed et al. 2006; Tripathi et al. 2006; Hamilton 2009; Chowdhury et al. 2010; Jenifa et al. 2010; Deka et al. 2011; Suryawanshi 2011; Nirmala et al. 2011).

Groundwater recharge assessment has been done by previous researchers using different techniques including water balance, groundwater fluctuation and other recommended techniques, which were found suitable for the different areas (Bekesi and McConchie 1999; Scalon et al. 2002; Kumar 2002; Naik and Awasthi 2003; Mamifarananahary et al. 2007; Dages et al. 2009; Kumar 2009; Unde et al. 2009; Tripathi and Katre 2010; Meshram et al. 2010).

Looking to the status of groundwater development and alarming situation of water table in Chhattisgarh state there is urgent need of groundwater recharging. Since, there is no perfect and appropriate recharge plan available for different districts of the state, especially which comes under semi-critical category, there is need of appropriate plan for groundwater recharge. Therefore, the present study was undertaken to prepare the thematic maps of the study area for identifying the locations of groundwater recharge structures and to prepare the plan of artificial recharge of groundwater for Bemetara district.

## Materials and Methods

The Bemetara is located between 81° 56′ 56″ to 82° 24′ 49″E longitude and 21° 20′ 37″ to 22° 15′ 05″N latitude and covers an area of 2872 $km^2$. The altitude of the Bemetara district is 317 m above mean sea level (MSL). It falls in topographic map nos. 64G (1:2,50,000 scale). The district receives an average annual rainfall of 968.50 mm. Satellite image of these districts was procured from the National Remote Sensing Agency, Hyderabad, which was provided by Department of Soil and Water Engineering (SWE), Faculty of Agricultural Engineering (FAE), Indira Gandhi Krishi Vishwavidyalaya (IGKV), Raipur. Meteorological and hydrological parameters are being monitored under AICRP on “Ground Water Utilization” (GWU), IGKV, Raipur, centre were used in this study. Some hydrogeological data were collected from the Central Ground Water Board (CGWB), NCCR, Raipur. Some of the maps like depth to water level (pre and post-monsoon) and well location map were prepared under the supervision of scientist working in the Central Ground Water Board, NCCR, Raipur. Drainage and water bodies map were prepared with the help of topographic map and GIS (MapInfo Professional 8.5). Watershed map and lineament map collected from the State Water Resource Department, Government of Chhattisgarh, Raipur, were used, which have been modified as per required file format with the help of GIS. Several hardware including computer, scanner, printer, digital camera and GPS and software including MS-Office, GIS (MapInfo Professional 8.5) and other statistical packages were used in this study.

The delineated watersheds in the Bemetara district, namely 4G3AB, 4G3B5, 4G3B7, 4G3C1, 4G3C2, 4G3C3, 4G3C4, 4G3C5, 4G3C6 and 4G3C7, having

11021 ha, 31442 ha, 24822 ha, 74307 ha, 14548 ha, 7910 ha, 50867 ha, 38539 ha, 33618 ha and 188 ha, area in the watershed.

Bemetara district is mainly drained by Sheonath, Kharun and Hamp River and their tributaries. Sheonath River flows through the eastern periphery to central and western part of the district along with its tributaries. Kharun River flows through the eastern periphery from south east to south and eventually join the Sheonath River in the eastern part of the district. The Hamp River along with its tributaries flows through the northern part of the district and also joins Sheonath River in north-eastern part of the district. Drainage density is more or less same in most of the parts of the district. All these river systems come under Mahanadi River basin. Low-drainage density is reflective of somewhat low run-off and higher infiltration. This entire drainage network is governed by the master slope of the districts. Drainage map of the Bemetara district used in this study is shown in Fig. 1.

There were a total of 575 streamlets found in the entire Bemetara district out of which 452 streamlets are of first order, 95 are of second order, 18 are of third order, 7 are of fourth order and 3 are of fifth order. The total length of the streams was found to be 1528 km. Drainage density of the area was found to be 0.532 km/km$^2$. Stream frequency of the Bemetara district was found to be 0.20 which is also low showing more or less plain topography of the area and lack of structural control. Bemetara district comprises of Chandi formation, Tarenga formation, Hirri formation and Maniyari formation. The groundwater recharge was suitable in all formation except in Biladila, Tarnga, Hirri, Nandgaon and Gunderdehi formations.

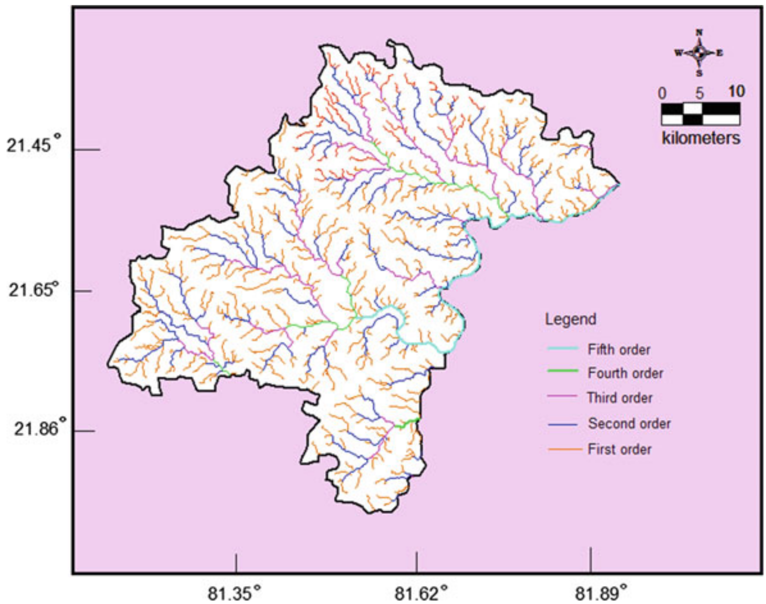


**Fig. 1** Drainage map of Bemetara district

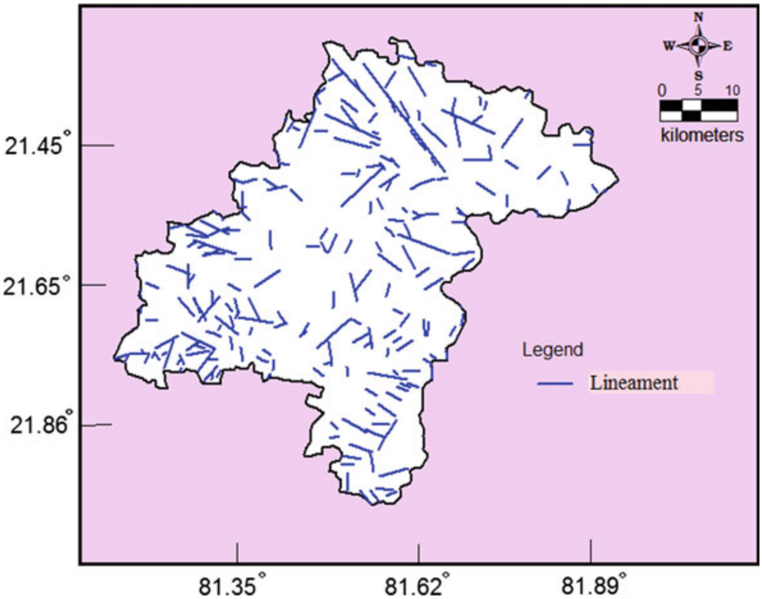


**Fig. 2** Lineament map of Bemetara district

**Table 1** Lineament map of the Bemetara district

| S. No. | Block | Length (km) |
|---|---|---|
| 1 | Bemetara | 116.1 |
| 2 | Berla | 224.6 |
| 3 | Saja | 178.4 |
| 4 | Nawagarh | 138.2 |
| Total | | 658.3 |

Figure 2 shows the lineaments present in the Bemetara district, and the information about the length of lineaments present in this district is given in Table 1.

In Bemetara district nearly 92.26% (i.e. 2650 km$^2$) of the total area is covered by arable land and 7.74% area is covered by Shrubs and grass land. Soil texture map of Bemetara district indicated that the deep black soil occupied 15.9% area whereas medium black soil occupied 82.49% area and red loamy soil covers only 1.6% area in the district. The digital elevation model (DEM) of Bemetara district was generated using contour map having 10 m interval and is shown in Fig. 3. Overall, the topography in the Bemetara district varies between 238 and 324 m above MSL. The area has general slope along east direction with average elevation of 281 m above MSL. The highest elevation recorded in the district is 324 m above MSL, and the lowest point is 238 m above MSL. In Bemetara district, depth to water level measured during the pre-monsoon (May) and post-monsoon (November). It may be seen that in pre-monsoon period, the lowest water level was recorded as 3 mbgl and the deepest water level was recorded more than 15 mbgl.

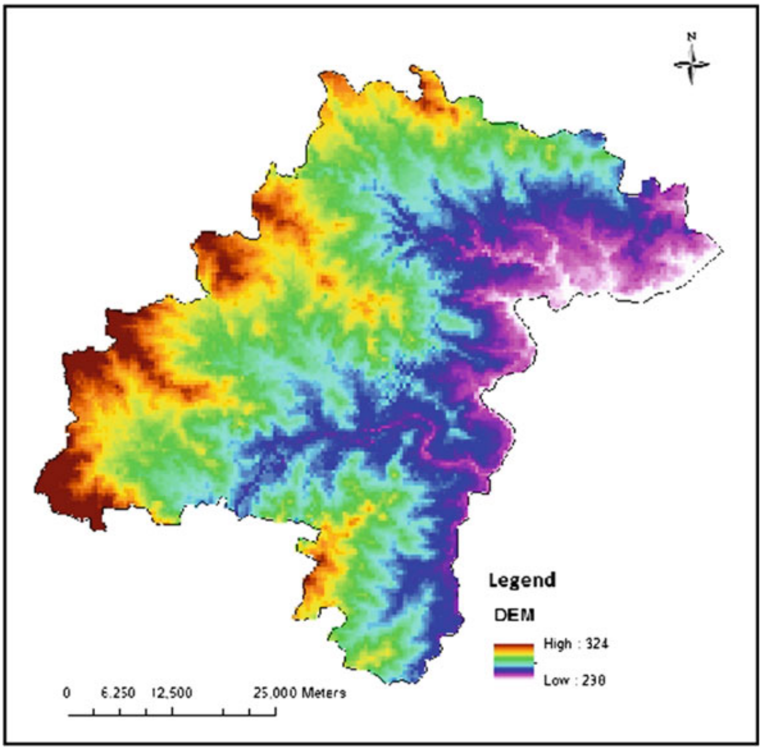


**Fig. 3** Digital elevation model (DEM) of Bemetara district

Depth to the water level in the district during pre-monsoon period is less than 10 m in almost 45% of the total area. It may be seen that in post-monsoon period, the depth to water level was less than 3 m (minimum value) and the maximum depth to the water level was around 15 m. The water levels increase and decrease in post-monsoon and pre-monsoon period.

## Results and Discussion

Various thematic layers including drainage, land use/cover, soils, lineaments, slope and geology were generated which have been integrated with each other in the environment of GIS. Other collateral data were also integrated with GIS for developing the recharge plan for Bemetara district. The site for percolation tank has been identified on the basis of depression point (sink), and for check dam intersection point of lineament and drainage was considered.

The Bemetara districts have four blocks and each was found with two types of structure, i.e. check dam and percolation tank of different size (small, medium and

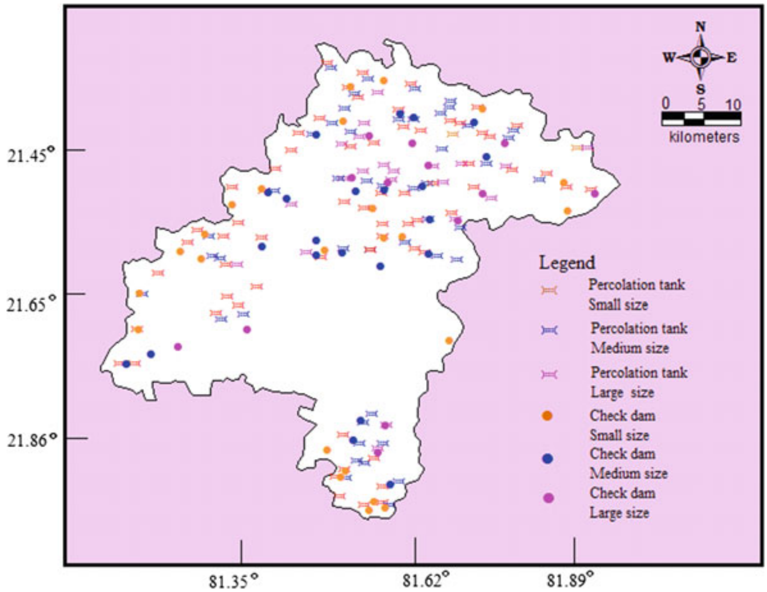


**Fig. 4** Proposed groundwater recharge plan for Bemetara district

**Table 2** Block wise number of groundwater recharge structures along for Bemetara

| Size | Bemetara | | Berla | | Saja | | Nawagarh | | Total |
|---|---|---|---|---|---|---|---|---|---|
| | CD | PT | CD | PT | CD | PT | CD | PT | |
| Small | 23 | 7 | 7 | 7 | 19 | 7 | 15 | 3 | 88 |
| Medium | 22 | 12 | 9 | 3 | 7 | 5 | 8 | 2 | 68 |
| Large | 11 | 5 | 2 | 2 | 1 | 2 | 6 | 4 | 33 |
| Total | 56 | 24 | 18 | 12 | 27 | 14 | 29 | 9 | 189 |

large). In Bemetara block, check dam and percolation tank were found to be 23 and 7, 22 and 12, 11 and 5 numbers of small, medium and large size, respectively. In Berla block, check dam and percolation tank were found to be 7 and 7, 9 and 3, 2 and 2 numbers of small, medium and large size, respectively. In Saja block, check dam and percolation tank were found to be 19 and 7, 7 and 5, 1 and 2 numbers of small, medium and large size, respectively. In Nawagarh block, check dam and percolation tank were found to be 15 and 3, 8 and 2, 6 and 4 numbers of small, medium and large size, respectively (Fig. 4 and Table 2).

The field survey of study area was also carried out to find out the suitability of proposed artificial groundwater recharge structures. It is concluded that suitable sites for artificial recharge structures in the Bemetara district were found to be 68% and finally 130 and 59 locations for check dam and percolation tank, respectively, in Bemetara district were identified. The subsurface storage space was estimated based on the thickness of available unsaturated zone (below 3 mbgl) in post-monsoon and the specific yield of phreatic aquifer. The limit to saturate the vadose zone below 3 m is kept with a view to avoid water logging and soil salinity. So, the vadose zone of 284.89 $Mm^3$ is available for artificial recharge in the Bemetara district.

After assessing the actual volume of water required for saturating the vadose zone, the net amount of source water available has been calculated by taking 75% efficiency of the artificial recharge structure. The value obtained was multiplied by 1.33 (a reciprocal of 75% efficiency). The quantum of water required for artificial recharge in Bemetara district was 379 $Mm^3$. Availability of source water to recharge the subsurface reservoir in these districts has been assessed in the form of non-committed surplus run-off. The run-off is estimated by using Stranger's table for the normal monsoon rainfall of the area. The normal monsoon rainfall of the Bemetara district is 983.75 mm. The total yield of run-off generated from Bemetara district having 2872.29 $km^2$ area workouts to be 1099 $Mm^3$ and 30% of the total run-off i.e. 329.67 $Mm^3$ is considered as surplus monsoon run-off available for artificial recharge.

## Conclusions

This study revealed that percolation tanks and check dams will be suitable for the study area for recharging the groundwater. These structures were suggested after overlaying various thematic layers. Study clearly indicated that the groundwater recharge planning for Bemetara district will be adequate for sustainable agriculture development. This study concludes that 130 locations are suitable for check dam and 59 locations for percolation tank are suitable in the Bemetara district.

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# Paleochannel Recharge Sources in the Central Godavari Delta, A.P., India

**Y. R. Satyaji Rao and S. V. Vijaya Kumar**

**Abstract** The quality of groundwater in shallow alluvial aquifers exhibits wide range of variations, due to deltaic nature of the deposits, paleochannel and drainage conditions. In alluvial aquifers, the deeper aquifers are invariably saline. Demand for freshwater for drinking purposes in deltas is increasing day by day. Keeping in view such conditions, paleochannels contain and yield freshwater in significant quantities if they have hydraulic connection from the original river course from where they get recharged. One such major paleochannel of central Godavari delta has been identified by Andhra Pradesh State Ground Water Department during their investigations. The present paper deals with characterization of hydrochemistry in and around identified paleochannel spatially and temporally. The chemical analysis indicated that the electrical conductivity (EC) of paleochannel water is less than groundwater. Detailed hydrochemistry of canal water, drain water and river water is presented in the paper. The hydrochemistry of paleochannel water indicated that there is no significant seasonal change in paleochannel water, and most of the samples belong to Ca-$HCO_3$ type. The recharge to the paleochannel is studied by analysing stable isotopes ($\delta^{18}O$ and $\delta D$) in groundwater, rainwater, canal water and river water. It is found that recharge to the paleochannel is mainly from river water and canal water than from rainwater. Optimum utilization planning of this limited freshwater resources in identified paleochannel is of immense importance, and it is also necessary to protect its quality from anthropogenic activities.

**Keywords** Paleochannel · Godavari · Delta · Hydrochemistry
Isotopes

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## Introduction

The ever-growing demand for freshwater for human consumption has become a worldwide cause for concern. Nowadays, groundwater reserves are exposed to intensive exploitation, which may create serious problems in coastal area where some hydraulic connection exists between the water reservoirs and sea water. Intensive withdrawal of freshwater in this type of aquifer can favour salt water intrusion, which is extreme situation can strongly affect the pumping wells. Increase in the sea level along the coast of India as a result of climate change might become a serious problem with dramatic consequences projected for the next century, such as the retreat of shorelines, loss of wetlands and intrusion of salt water into aquifers and estuaries. The effect of higher mean sea level on the hydrology of coastal areas, apart from the effects of increased flooding, is also important in coastal areas. Along coastal areas and deltas, the sea water intrusion phenomena can be better understood by going through the time series of some typical parameters of chemistry of groundwater and supported by stable isotopic characteristics. Sea water encroachment inland is the most common observation that causes increase in salinity. Several other sources that can affect groundwater quality along coasts are fossil sea water in un-flushed parts of the aquifer following invasion of sea water during relatively high sea levels; displacement of old saline groundwater from underlying or adjacent aquifers or aquitards; pollution from various sources including sewage effluents, marine water etc. Paleochannels contain and yield freshwater in significant quantities if they have hydraulic connection from the original river course, where they get recharged. One such major paleochannel course in central Godavari delta of East Godavari district, A.P., India, has been identified by AP State Ground Water Department (APSGWD) from areal photographs, remote sensing methods and ground truth surveys.

The effective technique for identification of source of paleochannel water is stable isotopes. The differences in stable isotopic species in water play an important role in the variation that is observed in the atmospheric water cycle by promoting fractionation effects during vapour/liquid and vapour/solid phase changes. Thus, isotope fractionation occurs at each phase change except sublimation and melting of compact ice. Stable isotopes are the atoms of an element, which are satisfied with the current arrangement of proton, neutron and electron. According to Clark and Fritz (1997), stable isotopes such as $\delta D$ and $\delta^{18}O$ can be used as conservative groundwater tracers since their values remain constant as long as there is no phase change or fractionation along flow path. Dansgaard (1964) described in detail the process of formation of stable isotopes in precipitation. Munnich (1968) has studied the moisture movement and recharge using isotope techniques and prepared guidelines for IAEA. Bhandari et al. (1986) conducted hydrogeological investigations in Sabarmati and Mahi basins and coastal Saurashtra using radioisotope and chemical tracers. The objective of the paper is to characterize paleochannel water in central Godavari delta and identification of source of paleochannel water using isotopic characterization.

## Study Area

The Godavari delta is located on the east coast of India and lies between Bay of Bengal and the +12 m contour. Godavari is the largest river, draining Peninsular India that has made an extensive delta on the east coast of India protruding 35 km from adjoining coast into the Bay of Bengal. The present day delta is the third largest delta of India after those of Ganges and Mahanadi. Significant discharges from Godavari commence from June and reach a maximum in August. August and September are the months of peak discharge. The region exhibits a hot tropical climate characterized by a range of low daily temperatures in summer, high humidity and a moderate annual rainfall. The temperature continuously increases from the end of February to the hottest month (May) between 35 °C and over 40 °C in the interior. In the coldest month (January), 22 °C is recorded in the coastal region and 19–20 °C in the interior. The normal annual rainfall of the district is 1075 mm. The Godavari delta irrigation is one of the oldest and most important irrigation systems in the state of Andhra Pradesh playing a vital role in the rice economy of India over a century. From agricultural point of view, the alluvial soils are considered to be the most fertile lands and paddy being the major crop of the Godavari delta system; it is known as rice bowl of A.P. A large number of coconut trees also grow in the study area. There is no forest area in the delta system. The Kharif season commences from 01 June when irrigation water is released through the canal system, which extends up to November. The Rabi season is from December to April of the succeeding year. The location of East Godavari district with demarcated delta is shown in Fig. 1.

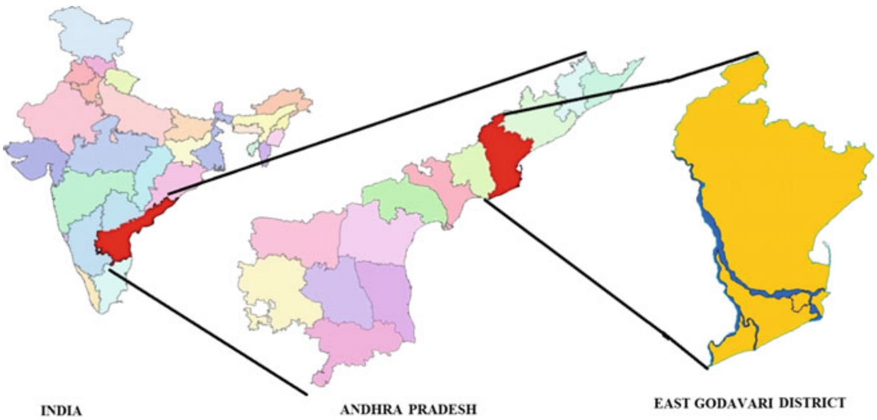



**Fig. 1** Location of East Godavari district and Godavari delta

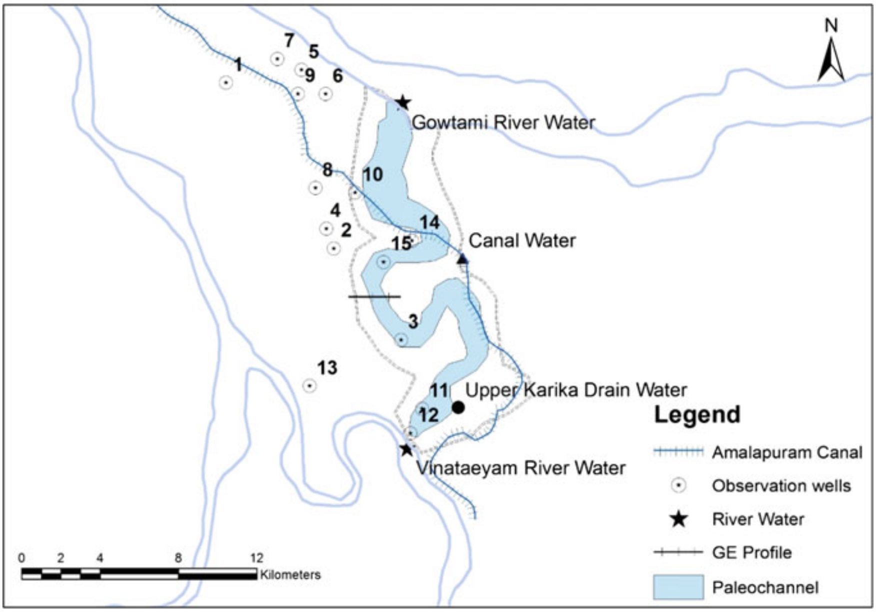



**Fig. 2** Map showing canal network and identified paleochannel

## Irrigation Canal Network

The irrigation system of the Godavari Central Delta comprises of central delta main canal taking off from the SAC barrage at Dowlaiswaram. The central delta is served by number of major, medium and minor drains to remove the surplus water from the fields that gets accumulated especially during southwest monsoon when the area is subjected to incidence of heavy and widespread rainfall. Three branch canals namely Gannavram canal, Amalapuram canal and Bank canal, all taking off at Ryalli at main River. The paleochannel under study is along the main canal from Mandapalli and the Ambajipeta channel that takes off from Palivela lock. The canal system remains operational for nearly 11 months with a closure period of one month during April and May in summer. The map showing the major canal and identified paleochannel is shown in Fig. 2.

## Hydrogeology

The coastal alluvium in Godavari delta consists of clayey soils with sands. Silts and gravel beds are mixed with clay in varying proportions. The thickness of alluvium varies from a few metres to more than 300 m, and it overlies Rajahmundry sand stones. The thickness of granular zones in the alluvium ranges from 18 to 258 m within the explored depths. Groundwater in the deltaic alluvium occurs under both water table and confined conditions. In the alluvium of East Godavari district, dug wells range in depth from 2 to 11 m below ground level (bgl) and tap groundwater mostly for domestic purposes. The depth of the water table ranges from 0.2 to 8.5 m bgl, generally is within 2 m bgl tap confined aquifers and yield as much as 4000 $m^3$/day. The wells yield between 700 and 22,000 $m^3$/day. The pumping water levels in these wells are generally with 14 m bgl. The freshwater is limited to shallow depths locally. This freshwater pockets are developed by dug wells and filter point well. At favourable places, the filter point wells yield up to 11,000 $m^3$/day. In the major portion of the alluvial area, the entire alluvium explored down to 300 m depth contains saline water. The quality of groundwater in the alluvium varies widely both horizontally and vertically. The quality is generally good near the positive hydrological boundary to the Godavari down to depth of 300 m but the freshwater zone tapers gradually towards the coast, the freshwater saline interface sloping inland (CGWB 2003).

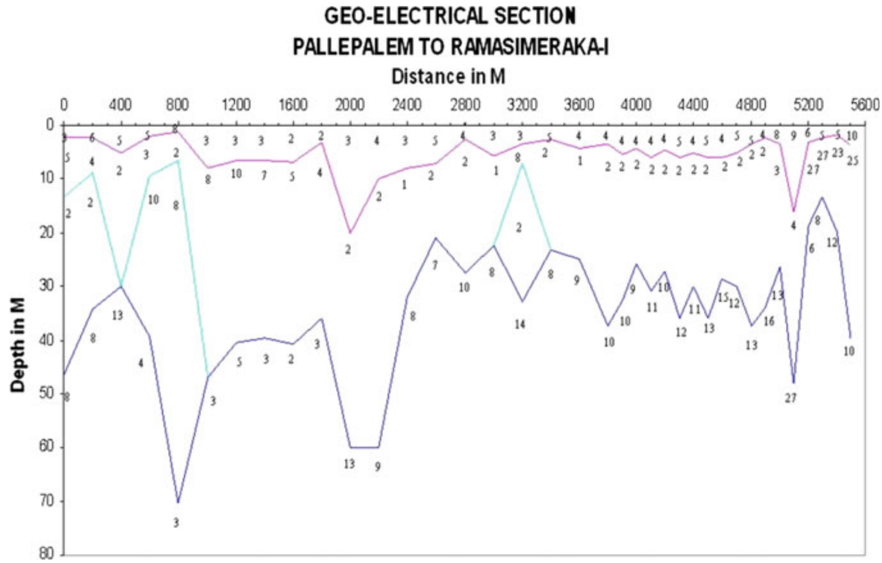
## Identified Paleochannel

The geographical distribution of the paleochannel is about 100 $km^2$ comprising of an unconfined single aquifer. The paleochannel emerges in the North, just above Mandapalli village on the right bank of Gowtami Godavari and disappears in the South near Tondavaram on the left bank of Vynateyam river branch of Vasista Godavari River of the Godavari river delta system. The delineated map of paleochannel is shown in Fig. 2, and location details of water samplings are given in Table 1. Geophysical traverses have been conducted by APSGWD across the paleochannel and shown in Fig. 3. Groundwater utilization is by means of filter point wells down to 10–15 m. It is found that in the southern part of the paleochannel, where it merges into the Vynateyam River, groundwater extraction is considerably high and the quality is also poor. The paleochannel under investigation is sloping towards the Vynateyam branch with the head located near Mandapalli near Gowtami branch of the Godavari River. The delta is crossed by many paleochannels which are common in such deltaic morphological conditions, especially in highly fluvial dominant river deltas like the Godavari. Moreover, almost the entire paleochannel is geographically distributed in the area under Ambajipeta channel of Amalapuram Canal System.

**Table 1** Average chemical parameters of shallow wells (May, June and September), canal, river and drain waters during the year 2006

| S. No. | Name of the location | EC | pH | TDS | Ca | Mg | Na | K | Cl | $HCO_3$ | $SO_4$ | $NO_3$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Shallow wells* | | | | | | | | | | | | |
| 1 | Devarapalli (N) | 683 | 7.21 | 437 | 50 | 27 | 54 | 3 | 39 | 320 | 44 | 10 |
| 2 | Chirutapudi (D) | 766 | 7.11 | 490 | 38 | 26 | 36 | 1 | 45 | 265 | 35 | 2 |
| 3 | Machavaram (P) | 851 | 7.16 | 544 | 44 | 35 | 40 | 4 | 49 | 349 | 44 | 0 |
| 4 | Pappula vari palem (D) | 710 | 7.13 | 454 | 67 | 21 | 31 | 2 | 47 | 308 | 26 | 0 |
| 5 | Penkulapati garuvu (N) | 635 | 7.15 | 406 | 68 | 13 | 18 | 1 | 44 | 288 | 20 | 59 |
| 6 | Vadapalem (N) | 727 | 7.31 | 465 | 49 | 18 | 18 | 2 | 57 | 257 | 17 | 13 |
| 7 | Mandapalli (N) | 679 | 7.15 | 435 | 65 | 17 | 22 | 1 | 48 | 287 | 21 | 80 |
| 8 | Avidi (N) | 855 | 7.0 | 547 | 10 | 8 | 208 | 3 | 75 | 349 | 68 | 8 |
| 9 | Kothapeta (N) | 647 | 7.0 | 414 | 35 | 19 | 28 | 2 | 52 | 260 | 20 | 7 |
| 10 | Rakurthi palem (D) | 954 | 7.0 | 611 | 57 | 39 | 49 | 1 | 52 | 344 | 75 | 11 |
| 11 | Nandampudi (P) | 1510 | 7.3 | 966 | 45 | 47 | 109 | 6 | 127 | 447 | 89 | 1 |
| 12 | Tondavaram (P) | 3007 | 7.2 | 1924 | 98 | 83 | 398 | 4 | 628 | 368 | 88 | 6 |
| 13 | Karupalli padu (D) | 930 | 7.1 | 595 | 37 | 34 | 82 | 12 | 52 | 404 | 53 | 0 |
| 14 | Mukkamala (D) | 1016 | 7.3 | 650 | 50 | 44 | 69 | 4 | 72 | 407 | 84 | 5 |
| 15 | Vyagreswaram (P) | 944 | 7.2 | 604 | 31 | 33 | 58 | 5 | 72 | 341 | 46 | 0 |
| Canal water | | 184 | 8.1 | 118 | 14 | 9 | 17 | 2 | 26 | 84 | 13 | 1 |
| Gowtami river water | | 723 | 7.5 | 463 | 27 | 37 | 78 | 5 | 68 | 312 | 65 | 20 |
| Vynateyam river water | | 30,200 | 6.8 | 19,328 | 802 | 462 | 4500 | 250 | 12,100 | 184 | 910 | 3 |
| Drain water | | 607 | 8.1 | 388 | 26 | 19 | 45 | 3 | 6 | 304 | 41 | 2 |

All units are in ppm, *EC* electrical conductivity: µmho/cm and *TDS* total dissolved solids




Source:APSGWD

**Fig. 3** Geo-electrical section across the paleochannel

## Sampling and Analysis

Network of fifteen observation wells has been established in around paleochannel in central Godavari delta. Water sampling surveys were collected in the months of 06 March, 06 June and 06 September and collected water samples from shallow wells/ filter points, canal water, river water and drain water in and around major paleochannel in the central Godavari delta. In order to characterize water quality and its seasonal variations, March 2006, June 2006 and September 2006 samplings were considered as representative seasons of pre-monsoon, monsoon and post-monsoon, respectively, in the study area. All the samples collected were analysed at water quality laboratory of Deltaic Regional Centre of NIH, Kakinada, for physical and chemical parameters by following the standard procedures (APHA 1998). The computed ion balance error is within $\pm 10\%$. The Piper's tri-linear classification of shallow wells collected in the paleochannel, north side of paleochannel and downward of paleochannel in the months of March 2006, June 2006 and September 2006, is shown in Figs. 4, 5 and 6, respectively. Further, shallow wells, river water, canal water and drain water hydrochemistry are plotted on Piper's tri-linear diagram and shown in Fig. 7. The average chemical concentrations of each sample collected from shallow wells, canal water, drain water and river water are shown in Table 1. Results indicate that there is no major contaminant type in the shallow groundwater of the study area except Tondavaram area (nearby Vynateyam River). This salinity is mainly due to backwater effect in the river. The chemical analysis indicated that the EC of groundwater in the paleochannel is clearly distinct from the groundwater

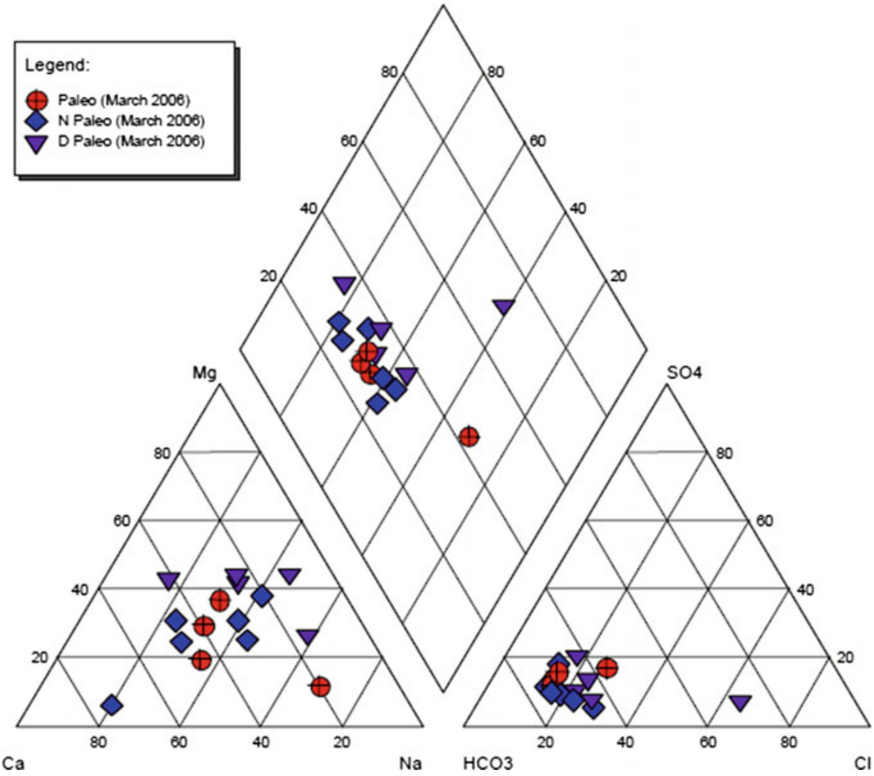



**Fig. 4** Piper's tri-linear classification plots of shallow wells (within paleochannel (P), north side paleochannel (N) and downward paleochannel (D)) during March 2006

in the neighbourhood and towards the Vynateyam river end, and the average EC is going up to 3007 μs/cm (back water effect).

## Stable Isotope Characterization

The procedures of sampling water for deuterium and oxygen-18 analyses are very simple. A very small amount of sample is enough. But to be on safer side and for repeated measurements, a minimum of 20 ml sample is collected in a HDPE bottle. While collecting samples, groundwater from shallow well was pumped for sufficient time so that the sample represents groundwater of the aquifer understudy. The sample bottles were sealed with wax and transported to laboratory for isotopic analysis. The physical properties of water were measured in situ. These samples were analysed for $\delta D$ and $\delta^{18}O$ stable isotopes using continuous flow isotope ratio

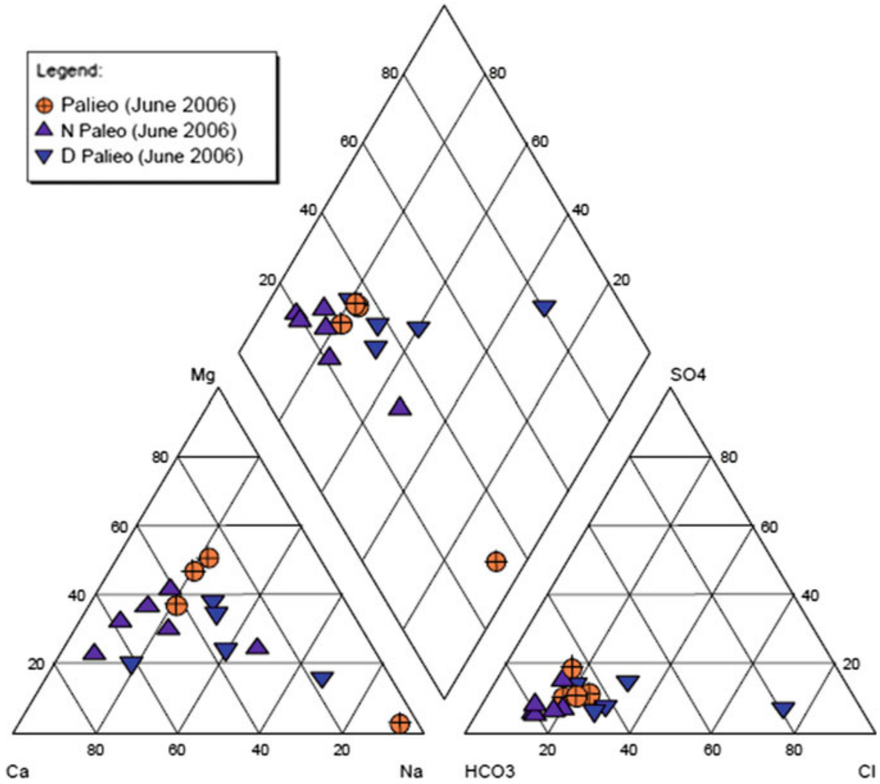



**Fig. 5** Piper's tri-linear classification plots of shallow wells (within paleochannel (P), north side paleochannel (N) and downward paleochannel (D)) during June 2006

mass spectrometer and dual inlet isotope ratio mass spectrometer available at NIH, Roorkee. The measured error in estimates is ±0.1‰ in $\delta^{18}O$ and is ±1.0‰ in δD. The rainfall is collected at Kakinada, which is about 50 km from the study area. The same is considered as representative of local precipitation of the study area. The δD and $\delta^{18}O$ relationship help in understanding the contribution of different recharge sources and also to pinpoint the most important recharge source. From the Fig. 8 it is observed that the stable $\delta^{18}O_{16}$ and δD, i.e. deuterium isotopes, have strong correlation in the groundwater samples of paleochannel. $\delta^{18}O_{16}$ ratio is around 2.5–3.5 per mil and is a strong characteristic in paleochannel groundwater compared to groundwater of surrounding formations. It is observed that $\delta^{18}O_{16}$ ratio is as an index to identify paleochannel groundwater. The recharge to the paleochannel is mainly due to recharge from Amalapuram Canal System (Fig. 8).

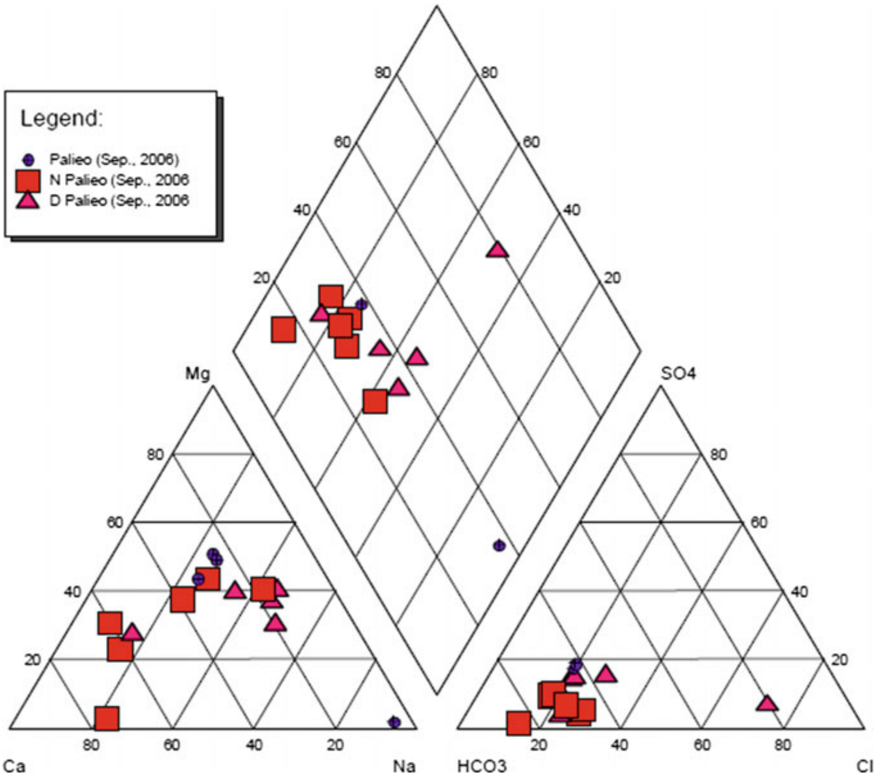



**Fig. 6** Piper's tri-linear classification plots of shallow wells (within paleochannel (P), north side paleochannel (N) and downward paleochannel (D)) during September 2006

## Conclusions

The chemical analysis data indicated that there is no significant seasonal change in water quality in paleochannel, and most of the samples belong to calcium-bicarbonate type. In the upstream side of paleochannel, groundwater quality is similar at most of the places (nearby Gowtami river). This scenario is mainly due to the influent characteristics of river branches at the head of the delta and due to the three major canals of the delta system. However, the groundwater quality towards the downstream is deteriorating from the aspect of major cations and anions (Vynateyam River). The stable isotope plots for $\delta^{18}O$ and $\delta D$ indicated that the recharge into paleochannel is not much from rainfall, and most of the recharge is from river and canal waters.

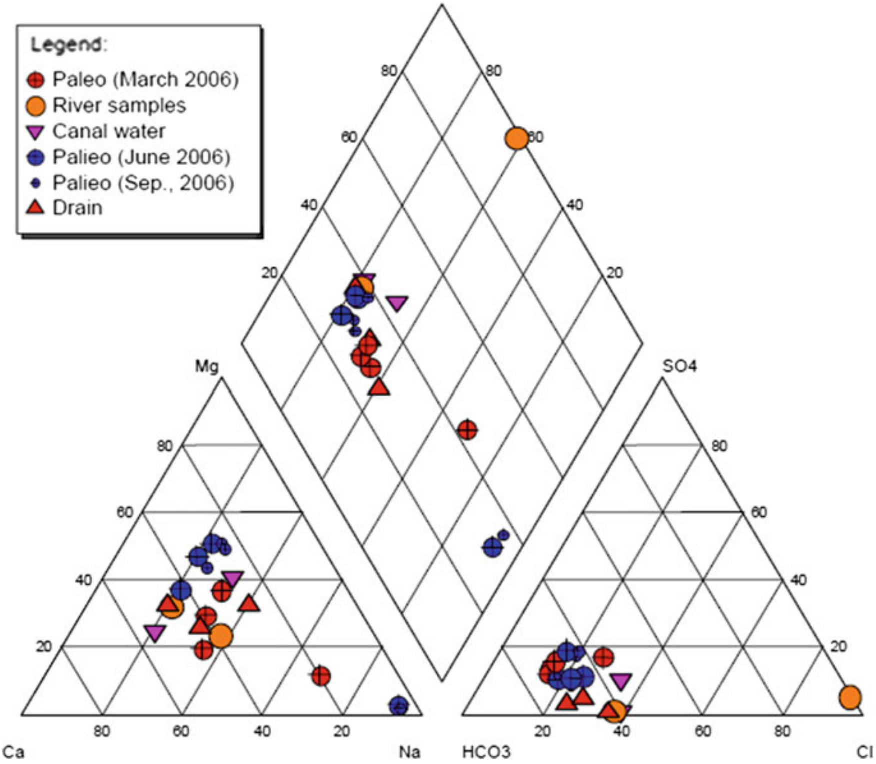



**Fig. 7** Piper's tri-linear classification plots of shallow wells (within paleochannel (P)), river samples, canal water and drain water in the year 2006

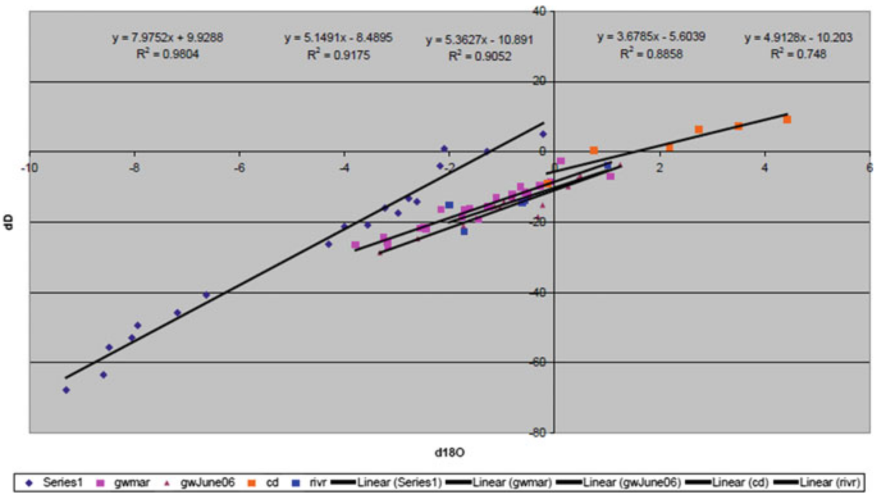



**Fig. 8** δD versus $\delta^{18}$O of precipitation, groundwater, canal, river and drain waters in the study area

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# Change of Land Use/Land Cover on Groundwater Recharge in Malaprabha Catchment, Belagavi, Karnataka, India

**B. K. Purandara, B. Venkatesh, M. K. Jose and T. Chandramohan**

**Abstract** In recent years, large-scale reduction in the forest cover is observed all over the country due to various reasons, particularly in the humid tropics. However, there are concerted efforts by government departments and NGO's to bring back the degraded forests to original position through plantation and related agro-forestry activities. Reforestation/afforestation is often recommended as a means of reducing the increased surface water losses associated with soil degradation, returning water to the roots through the soil profile, thereby ultimately restoring base flow. Most of the rehabilitation programs often adopt fast-growing exotic species such as, *Eucalyptus* spp., *Acacia auriculiformis*. Many researchers raised concerns over the increased afforestation with exotic forest species on water availability. However, such studies are quite sparse, particularly in humid tropical climates. The Western Ghats in south India, is a treasure house for number of rivers which feeds locally and plays a significant role in socio-economic growth of this part of the country. It is reported that, there is a tremendous change in land use/land cover mainly because of deforestation and also due to afforestation with exotic species such as *A. auriculiformis*. In spite of such wider change in the land use/land cover, studies on its impact on groundwater resources are lacking. Therefore, the present study has been carried out to understand the influence of land use/land cover changes on groundwater in parts of Malaprabha catchment, a tributary of River Krishna accentuating hydrological and hydrogeological investigations. Rainfall and groundwater level data have been collected from State and Central organizations. Groundwater recharge was estimated using empirical and Groundwater Estimation Committee methods. A numerical model, soil water infiltration movement model (SWIM), was applied to estimate the groundwater recharge under different land covers. It was observed that the groundwater recharge is mainly dependent on the rainfall pattern and land use/land cover changes. The forested areas have shown relatively higher recharge as compared to degraded and agriculture lands.

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**Keywords** Land use/land cover · Groundwater recharge · Reforestation/afforestation · SWIM

## Introduction

In the last few decades, one of the major causes for environmental hazard including climate change is due to dramatic changes in land use (LU) and land cover (LC). The challenge is still worst in humid tropics which have resulted in rapid rates of deforestation and urbanization. In response, Giambellucca (2002) remarked that hydrologists have traditionally focused on the hydrological impacts of forest conversion to cleared, actively used land, that is, at the respective extremes of this LC taxonomy (Bruijnzeel 2004). The LC of the tropics is now becoming more fragmented and highly complex, and secondary forest is now emerging as the dominant forest type interspersed with remnants of old-growth forest and other intermediate LCs (Holscher et al. 2004; Cuo et al. 2008). The storm run-off hydrology of these intermediate LCs from multi-decades of human occupancy, and 'forestation' (afforestation–reforestation) of land in various states of degradation, has been much less studied across a range of soils and scales (Van Dijk et al. 2001; Malmer et al. 2010). The need for such attention is emphasized when one considers that globally an increasing proportion of the population in the humid tropics is becoming dependent on these intermediate LCs for their livelihoods and ecosystem services because of decreasing availability and access to less disturbed (or old-growth) tropical forest (Chazdon 2008). For example, within South and Southeast Asia, it was estimated that about 45% of the total land area has been affected by human-induced soil degradation (Eswaran et al. 2001).

Land cover/land use change is a matter of serious concern as it influences the water availability both in terms of quality and quantity. This is particularly true in the humid tropics of South and Southeast Asia where there is a significant impact due to population explosion and human interference. In India, the Western Ghats is one of the worst affected parts of the country which lost considerable part of the forest covers resulting in large-scale deforestation and biodiversity. Therefore, in the recent years, efforts have been made to conserve the forest resources through appropriate afforestation and reforestation strategies. However, there is a lack of scientific research to adopt suitable methods for taking policy decisions with regard to afforestation and reforestation. Purandara et al. (2006) carried out detailed hydrological investigations in parts of Western Ghats, North Kanara district of Karnataka and observed an improvement of soil hydraulic properties (particularly, field saturated hydraulic conductivity) in areas afforested with acacia auriculiformis. The enhanced occurrence of infiltration-excess overland flow (IOF) was inferred (and thus reduced vertical percolation and groundwater recharge) when comparing selected rainfall intensity–duration–frequency with field saturated hydraulic conductivity across both land covers and soil types. Later work using experimental catchments also showed how land cover change from native forest to heavily used forest and its subsequent reforestation have major effects on the rainfall-run-off process in the wet-season (Bonell et al. 2010; Jagdish et al. 2013). Therefore, in the present study an attempt is made to understand the impact of land use/land cover change on groundwater recharge.

## Study Area

The Malaprabha River is a right bank tributary of River Krishna. The Malaprabha catchment lies in the extreme western part of the Krishna basin. It extends between 74° 15′ and 74° 35′E longitudes and 15° 30′ and 15° 45′N latitude in Belagavi district of Karnataka (Fig. 1). Catchment area of the river up to Khanapur gauging site is 520 km$^2$ (Chandramohan et al. 2015). The Malaprabha originates from the Chorla Ghats, a section of the Western Ghats at an elevation of about 792 m about 35 km south-west of Belagavi in Karnataka.

The terrain is flat to gently undulating except for a few hillocks and valleys. The northern boundary is the common ridge between the Malaprabha and the Ghataprabha rivers. The eastern boundary is the common ridge between the Malaprabha, Krishna and Tungabhadra rivers. The ridges in the southern and

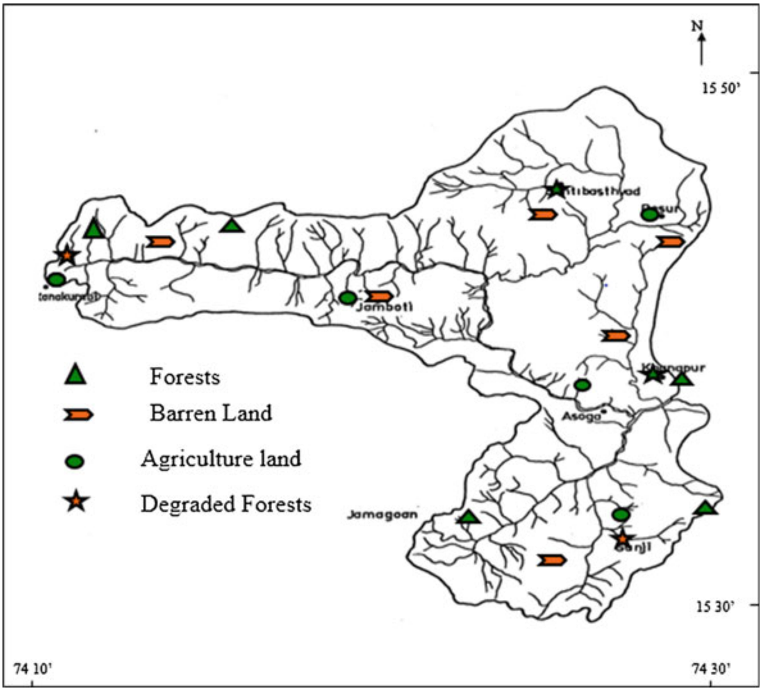


**Fig. 1** Malaprabha catchment with locations of experimental sites

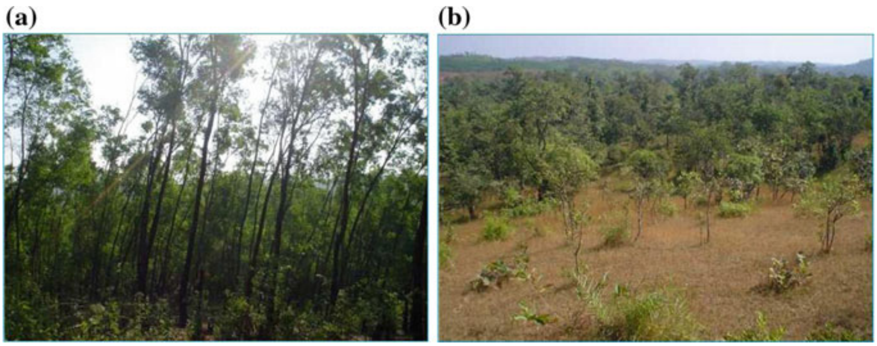


**Fig. 2** Catchment overview **a** afforested area, **b** degraded forest in Malaprabha catchment

western boundaries are common between the Malaprabha and the west-flowing rivers. The important rock formations in the sub-basin are (i) sedimentary rock formations (Kaladgi Group) comprising limestone, shale and quartzite (ii) schistose rock formations (Dharwad Supergroup) comprising granite, gneiss and crystalline rocks (Choubey and Purandara 1992).

Data pertaining to rainfall, temperature, sunshine hours have been collected from various State and Central organizations. The average annual rainfall of the upper catchment (up to Khanapur) is around 2500 mm. The annual average maximum temperature is 32 °C, and minimum is 18 °C. The sunshine percentage in the catchment varies from 21 to 96. An overview of the Malaprabha catchment is shown in Fig. 2a (afforestation) and b (typical degraded area).

Soils are very deep, dark brown to dark red, sandy loam to clay loam on the surface and loam to clay loam and at places gravelly sandy clay in the sub-surface horizon, with distinct argillic (clay-rich) horizon. They are neutral to weakly acidic in reaction, low in cation exchange capacity and medium to high in water holding capacity. The clay complex is dominated by kaolinitic and hydrous oxides of iron and alumina minerals. The soils are well drained with moderate permeability.

## Methodology

Twenty sites were selected for the experimental determination of infiltration and saturated hydraulic conductivity in selected locations of Malaprabha catchment based on land covers (such as forests, different kinds of plantations, shrubs, agriculture and barren land). Disc permeameter (Perroux and White 1988) and Guelph permeameter (Reynold and Elrick 1987) were used for the determination of infiltration and saturated hydraulic conductivity, respectively. When the disc permeameter is operated with $h \leq 0$, flow into the soil profile is unconfined, and infiltration is in three dimensions. The final steady state infiltration from the disc permeameter was estimated by using the expression given by White and Sully

(1987) found that the final, steady-state infiltration rate from the disc permeameter can be expressed as:

$$K_0 = \frac{q}{\pi r_0} - \frac{4bS_0^2}{\pi r_0(\theta_0 - \theta_n)} \tag{1}$$

where '$r$' is the radius of disc permeameter ring (cm), $\theta_n$ is the initial moisture content and $\theta_0$ is saturated moisture content. When a disc permeameter test is run, data are collected to obtain cumulative infiltration ($I$) at various times after the start of the test. The slope of early time plot of $I$ versus $t^{1/2}$, and the slope of the late time plot of $I$ versus $t$ were used to calculate the values of sorptivity and cumulative rate of infiltration.

Laboratory investigations were carried out to determine the saturated moisture content, and soil moisture retention characteristics using the pressure plate apparatus.

**Ground Recharge Estimation using Krishna Rao Method**: Krishna Rao gave the following empirical relationship in 1970 to determine the groundwater recharge in limited climatological homogeneous areas:

$$\mathrm{Rr} = K(P - X) \tag{2}$$

The following relation is stated to hold good for different parts of Karnataka:

Rr = 0.20 ($P$ − 400) for areas with annual normal rainfall ($P$) between 400 and 600 mm
Rr = 0.25 ($P$ − 400) for areas with $P$ between 600 and 1000 mm
Rr = 0.35 ($P$ − 600) for areas with $P$ above 2000 mm

where Rr and $P$ are expressed in millimetres.

Groundwater availability was estimated using GEC norms (1997). This is based on groundwater level fluctuation method. However, in areas, where groundwater level monitoring is not being done regularly, or where adequate data about groundwater level fluctuation are not available, ad hoc norms of rainfall infiltration factor was considered.

## Results and Discussion

### *Rainfall Analysis*

In order to analyse the spatial distribution of rainfall over the study area, the data for 22 years were considered. Monthly average rainfall and annual average rainfall were computed for the basin. There are seven rain gauge stations well spread over the catchment. Long-term averages were calculated for each individual station. The highest rainfall exceeds 5000 mm in the western part of the catchment. This region is fully covered with the forest. The lowest rainfall is 1232 mm in the eastern part of the basin. The mean annual rainfall derived from these long-term data for the shallow catchment is 2260 mm.

The monthly average rainfall and the coefficient of variation for all individual stations are shown in Table 1. Out of the total rainfall, 90.46% occurs during the monsoon season, i.e. from June to September. July and August months are heavy rainfall months which contribute about 60.92% of the total rainfall. The coefficient of variation of the rainfall over the basin as a whole is 23.9%, whereas the coefficient of variation of the individual stations for their long-term data varies from 82.7 to 168.4%. This clearly indicates that the variations in rainfall over the basins are very much less than that of the point rainfall. Gauging records are available for the first gauging station on the river. Also a probability analysis of rainfall was carried out using the Gumbel and Pearson Type III to estimate the dependable rainfall. The analysis shows that the value of rainfall at 75% dependability is 1983 mm by the method of plotting position, and 1650 mm by probability distribution. The value obtained by probability distribution is used to estimate the groundwater recharge over the catchment.

**Table 1** Rainfall characteristics of Malaprabha catchment (Kankumbi to Khanapur)

| Stations | Kankumbi | Jamboti | Asoga | Khanapur | Gunji | Desur | S. Bastwad |
|---|---|---|---|---|---|---|---|
| Longitude | 74° 13′ | 74° 22′ | 74° 29′ | 74° 30′ | 74° 29′ | 74° 13′ | 74° 25′ |
| Latitude | 15° 42′ | 15° 04′ | 15° 36′ | 15° 38′ | 15° 32′ | 15° 44′ | 15° 46′ |
| Elevation | 868 | 762 | 670 | 680 | 686 | 762 | 670 |
| Months | Rainfall (mm) | | | | | | |
| January | 0 | 0 | 0 | 1.80 | 0 | 0 | 0.62 |
| February | 0 | 0 | 0 | 0.89 | 0.17 | 0 | 0.062 |
| March | 2.85 | 7.11 | 1.23 | 4.81 | 0 | 0.64 | 5.43 |
| April | 19.12 | 16.70 | 12.99 | 26.51 | 2.06 | 14.47 | 28.61 |
| May | 46.48 | 67.02 | 49.12 | 74.33 | 8.62 | 22.88 | 50.96 |
| June | 1237.31 | 408.43 | 371.96 | 431.73 | 264.59 | 245.50 | 273.46 |
| July | 1691.16 | 836.83 | 593.90 | 672.24 | 474.73 | 291.10 | 400.01 |
| August | 1511.40 | 516.05 | 379.43 | 415.21 | 424.73 | 291.10 | 330.08 |
| September | 352.22 | 149.64 | 115.79 | 131.75 | 138.11 | 149.90 | 139.43 |
| October | 187.45 | 77.62 | 53.81 | 91.82 | 70.94 | 100.10 | 84.46 |
| November | 34.93 | 28.10 | 11.97 | 44.01 | 7.75 | 23.72 | 15.01 |
| December | 0 | 4.72 | 1.62 | 3.10 | 0.38 | 0.24 | 1.50 |
| Annual avg. | 5353.92 | 2039.22 | 1591.33 | 1898.34 | 1439.38 | 1232.20 | 1330.15 |
| CV | 0.837 | 1.01 | 1.14 | 1.25 | 1.684 | 1.545 | 1.357 |

## Infiltration and Saturated Hydraulic Conductivity

Table 2 shows the rate of infiltration and saturated hydraulic conductivity (Kfs) in the Malaprabha catchment.

The average rate of infiltration in the forests and acacia plantation of Malaprabha catchment varies between 30 and 50 mm/h. Saturated hydraulic conductivity was relatively higher in the acacia plantation as compared to forested watersheds. This variation in the saturated hydraulic conductivity is attributed to change in textural characteristics of the soil. In the scrubs/degraded lands, the rate of infiltration varied from 20 to 30 mm/h. However, the saturated hydraulic conductivity was between 10 and 20 mm/h. In the agriculture and barren land, both infiltration rate and saturated hydraulic conductivity are much lower (10 to 30 mm/h) than other land use types. In the barren land, variation in infiltration is between 20 and 30 mm/h. It is also noticed that the rate of infiltration and saturated hydraulic conductivity are quite comparable with that of barren land (20–30 mm/h), which is much higher than the scrubs and agriculture land. Earlier studies reported a drastic reduction in recharge particularly in eucalyptus plantation, whereas the present study does not substantiate the above concept. However, in the present study experiments were conducted only in a single soil type (red gravelly soil). Therefore, to conclude, further experiments are required in different types of soil. In the teak plantation, the infiltration rate varied between 20 and 30 mm/h. The saturated hydraulic conductivity was minimum (10 mm/h). This typical nature of teak plantation could be attributed to infiltration-excess overland flow (Hortonian flow). The hydraulic conductivity depends mainly on soil properties and type of land covers. Various studies carried out in Malaprabha representative basin by Rawat and Purandara (1992), Purandara et al. (1999, 2010) revealed the fact that the groundwater recharge may be considered as a factor of soil and land use types.

**Table 2** Infiltration and saturated hydraulic conductivity under different land covers

| S. No. | Land use | Type of soil | Soil texture | Saturated hyd. cond. (mm/h) | Infiltration rate (mm/h) |
|---|---|---|---|---|---|
| 1 | Forest | Black and grey | Light loam to heavy loam | 30–40 | 30–50 |
| 2 | Scrubs | Black, grey and red | Medium to heavy loam | 10–20 | 20–30 |
| 3 | Agriculture | Black, grey and red | Medium to heavy loam | 10–20 | 10–30 |
| 4 | Barren | Black, grey and red | Light loam to clay loam | 20–30 | 20–30 |
| 5 | Acacia | Red and black | Medium to heavy | 40–50 | 30–50 |
| 6 | Eucalyptus | Red | Light loam | 20–30 | 20–30 |
| 7 | Teak | Grey | Medium loam | 10–20 | 20–30 |

## Estimation of Groundwater Recharge Using Empirical Methods

Groundwater recharge was estimated based on Krishna Rao method as suggested by Kumar (2009). Table 3 shows the variation in rainfall and recharge over the years. It is noticed that the groundwater recharge is directly proportional to rainfall, i.e. the increase in rainfall showed an increase in the groundwater recharge. The highest rainfall observed is of the order of 3526 mm in the year 1995–96 against which a recharge of 1024 mm is observed. The minimum recharge was observed in the year 1989. Therefore, the method suggested by Kumar (2009) does not include

**Table 3** Groundwater recharge estimated by using the Krishna Rao method

| S. No. | Years | Rainfall (mm) | Groundwater recharge (mm) | % recharge |
|---|---|---|---|---|
| 1 | 1976 | 2789.29 | 766.25 | 27.60 |
| 2 | 1977 | 3176.83 | 901.88 | 28.30 |
| 3 | 1978 | 2238.11 | 573.33 | 25.60 |
| 4 | 1979 | 2806.44 | 772.05 | 27.40 |
| 5 | 1980 | 1942.30 | 469.80 | 24.10 |
| 6 | 1981 | 3200.50 | 910.18 | 28.40 |
| 7 | 1982 | 2713.67 | 739.83 | 27.26 |
| 8 | 1983 | 2834.64 | 782.12 | 27.60 |
| 9 | 1984 | 2795.76 | 768.51 | 27.40 |
| 10 | 1986 | 2465.63 | 652.68 | 25.40 |
| 11 | 1987 | 2206.38 | 562.23 | 25.40 |
| 12 | 1988 | 1760.35 | 406.12 | 23.07 |
| 13 | 1989 | 1531.16 | 325.90 | 21.20 |
| 14 | 1990 | 2696.04 | 733.61 | 27.20 |
| 15 | 1991 | 1997.93 | 489.27 | 24.40 |
| 16 | 1992 | 2335.86 | 607.54 | 26.00 |
| 17 | 1993 | 2225.99 | 569.09 | 25.50 |
| 18 | 1994 | 2526.76 | 674.36 | 26.60 |
| 19 | 1995 | 2690.34 | 731.50 | 27.19 |
| 20 | 1996 | 3526.93 | 1024.42 | 29.00 |
| 21 | 1997 | 1894.23 | 452.98 | 23.90 |
| 22 | 1998 | 2036.59 | 502.80 | 24.60 |
| 23 | 1999 | 1733.63 | 396.77 | 22.80 |
| 24 | 2000 | 2060.47 | 511.00 | 24.80 |
| 25 | 2001 | 2530.66 | 675.72 | 26.60 |
| 26 | 2002 | 2021.53 | 497.53 | 24.60 |
| 27 | 2003 | 1974.19 | 480.96 | 24.40 |
| 28 | 2004 | 1766.53 | 408.28 | 23.10 |
| 29 | 2005 | 2449.26 | 647.23 | 26.40 |

any other hydrological parameter such as soil moisture percentage, infiltration factor, evaporation and evapotranspiration due to which the recharge percentage does not reflect the change in land use/land cover changes.

## Modelling

Daily rainfall and evaporation data from 1975 to 2005 were used for the study. Water balance components like run-off, evapotranspiration and drainage (recharge to groundwater) were determined by using Soil Water Infiltration Movement model (Ross 1990). The model is based on a numerical solution of the Richard's equation and the advection-dispersion equation. It can be used to simulate run-off, infiltration, redistribution, solute transport and redistribution of solutes, plant uptake and transpiration, soil evaporation, deep drainage and leaching. Precipitation, evaporation, initial conditions, soil hydraulic properties are the basic input parameters of the model. The governing partial differential equation (Richard's equation) applicable for one-dimensional flow in the unsaturated zone is presented below.

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} K \left[ \frac{\partial \psi}{\partial x} + \frac{\mathrm{d}z}{\mathrm{d}x} \right] + S \tag{3}$$

$\theta$ volumetric water content ($cm^3/cm^3$)
$t$ time (h)
$x$ distance into the soil (cm soil)
$K$ hydraulic conductivity ($cm^2$ water/cm soil/h)
$\psi$ matric potential (cm water)
$z$ gravitational potential (cm)
$S$ sink strength ($cm^3$ water/$cm^3$ soil/h)

For the purpose of modelling, it is considered that the soil is vertically inhomogeneous and laterally uniform in nature. In the present study, point values of soil hydraulic properties were determined in the field and laboratory for two soil layers and the data were used as an input. There is only one hydraulic conductivity function for each layer, so that any macropore or bypass flow can only accounted in a limited way. Based on the field measured and laboratory determined parameters, water balance components were estimated (Table 4) for each land use/land covers, viz., forest, degraded lands, agriculture, acacia, eucalyptus, teak and barren land. Vapour conductivity is not taken into consideration nor is the effect of osmotic potential. There are two hydraulic property sets (upper and lower horizons) that are applied to 30 nodes of the 300 cm deep soil profile. Hysteresis is not taken into account. Initially, there is no water is ponded on the surface. Run-off is governed by a simple power law function and a surface conductance function. No bypass flow was included. Matric potential gradient of 0, i.e. 'unit gradient', has been applied as bottom boundary condition throughout the simulation. Cumulative rainfall and

**Table 4** Estimated run-off, ET and ground recharge under different land covers

| S. No. | Land use | Estimated run-off (%) | Estimated ET (%) | Groundwater recharge (%) |
|---|---|---|---|---|
| 1 | Forest | 25.69 | 34.76 | 39.55 |
| 2 | Scrubs | 36.55 | 33.27 | 30.18 |
| 3 | Agriculture | 49.50 | 24.25 | 29.25 |
| 4 | Barren | 46.25 | 27.90 | 25.85 |
| 5 | Acacia | 33.35 | 29.65 | 37.00 |
| 6 | Eucalyptus | 31.58 | 37.19 | 31.23 |
| 7 | Teak | 35.09 | 34.75 | 30.16 |

evaporation records (daily) for the period 1975–2005 were given as the input for determination of water balance components (run-off, evapotranspiration and groundwater recharge). Table 4 shows the various water balance components estimated using SWIM model.

The above estimate clearly indicates that, the groundwater recharge is maximum (39.55%) in the forested region, followed by acacia plantation (37%). Groundwater recharge was minimum in the areas with no land covers. Very high evapotranspiration was observed in the forested region and eucalyptus plantation. Similar observations were made by Lalitha et al. (2015), Purandara et al. (2010).

## Summary

The results of the field and laboratory investigations showed the extent of variations in soil hydraulic properties such as infiltration and saturated hydraulic conductivity. It indicated that both rate of infiltration and saturated hydraulic conductivity are relatively higher in the forested watersheds and also in the areas afforested with acacia auriculiformis as compared to degraded forests and plantations (teak and eucalyptus) including agriculture lands. The barren lands showed the least recharge characteristics (25.85%). This clearly substantiated the fact that, irrespective of higher ET as reported in the literature for the forested catchments, the recharge is significantly high (39.55%) in forests and is least in degraded lands and teak plantation. It is also interesting to notice that the recharge characteristics in the acacia plantation (37%) showed a considerable increase in comparison with degraded and barren lands. In the case of eucalyptus (31%) and teak (30%), the recharge values are higher than agriculture and barren lands. The variations in recharge values of different plantations (acacia, eucalyptus and teak) could be attributed to higher ET values of eucalyptus (37.19%) and teak (30.16%). It is also observed that groundwater contribution to stream flow depends on stream morphology, soil type and land use pattern. It is also noticed that the saturated hydraulic conductivity of the soil exerts a far greater influence on the run-off generating system than does the properties of the rainfall event or the slope of the soil surface.

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# Part III
# Groundwater Quality

# Causes and Sources of Groundwater Pollution: A Case Study of Nagpur City, India

**Sahajpreet Kaur Garewal and Avinash D. Vasudeo**

**Abstract** Assessment of groundwater quality is equally important as its quantity. Dependency on groundwater increases with population, hence it is necessary to quantify the causes and sources of groundwater pollution. The possible contaminants in groundwater are practically unlimited; a wide range of contaminants are found in groundwater. The main sources and causes of groundwater pollution are municipal, industrial and agricultural. The objective of the present study is to enumerate on the sources and causes of groundwater pollution in relation with municipal usage within the Nagpur city. Finally, relation between Land use/Land cover and groundwater pollution has been established using geographical information system (GIS).

**Keywords** Groundwater · Source · Cause · GIS · Land use · Land cover

## Introduction

Groundwater is the water located beneath the earth's surface in soil pore spaces and in the fractures of rock formations. It is stored in and moves slowly through geologic formations of soil, sand and rocks called aquifers. Introduction of certain pollutants into the groundwater which reduces the quality of groundwater making its use very limited or in some cases impossible is known as Groundwater pollution. Contaminants found in groundwater cover a broad range of physical, inorganic, organic chemical, bacteriological and radioactive parameters. Groundwater is considered as the predominant source of domestic water supply, irrigation and industrialization, hence potential exposure to contaminants is of serious concern.

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Numerous studies have explained associations between specific type of land use and chemical constituents in groundwater (Harbor 1994; Scanlon et al. 2005). The type and severity of water contamination often is directly related to human activity (such as agriculture, industrial, municipal waste), which can be quantified in terms of the intensity and type of land use in the source areas of water.

Various sources of groundwater pollution are listed in Table 1. The groundwater is contaminated either by uncontaminated recharge that passed through a contaminated area before reaching the well, or it may be primarily related to the geology of the parent material from which the soil was formed or by the contaminants detected in groundwater present within the well's (such as buried septic systems and leaking underground fuel tanks) contributing area and were transported by groundwater flow to the well.

The vast majority of environmental studies related to water quality have been conducted in agricultural, mining, urban and industrial regions to detect their contribution in groundwater pollution (Jalali 2009). The intensive farming by using fertilizers and pesticide may deteriorate soil health, leading to poor productivity and adverse environmental effects (Wells et al. 2000). Moreover, groundwater contamination is an imperceptible and irreversible process, and prohibitive costs and time requirements may limit efforts to improve the groundwater condition (Yu et al. 2010). The behaviour is determined by the properties of the contaminants, which mainly include toxicity, mobility and degradation (Javadi et al. 2011). Khan et al. 2010 studied the influence of changing land use patterns on the groundwater quality of the hard rock aquifer system in the Maheshwaram watershed, near Hyderabad, India. Dimitriou and Moussoulis (2011) identify the impacts from specific land use change scenarios in the protected area of Loutraki catchment by a physically based, distributed hydrologic model.

**Table 1** Sources of groundwater contamination

| Place of origin | Potential groundwater contamination source | | | |
|---|---|---|---|---|
| | Municipal | Industrial | Agricultural | Individual |
| At or near the land surface | Municipal waste land spreading | Chemicals: storage and spills | Chemical spills | Fertilizers |
| | Salt for de-icing streets | Fuels: storage and spills | Fertilizers<br>Pesticides | Homes<br>Motor oil paints |
| | Streets and parking lots | Mine tailing piles | Livestock waste storage facilities and land spreading | Cleaners<br>Detergents |
| Below the land surface | Landfills | Pipelines | Underground storage tanks | Septic systems |
| | Leaky sewer lines | Underground storage tanks | Wells: poorly constructed or abandoned | Wells: poorly constructed or abandoned |

The objective of the present study is to enumerate on the sources and causes of groundwater pollution within the study area. In Nagpur city, groundwater is vulnerable to various types of land uses. The analysis of patterns of land use/land cover, topography and population provides a tool in the investigation of sites with known contamination and in the prediction and prevention of future contamination of groundwater. The extent of groundwater contamination is analysed based upon the previous years groundwater quality data of Central Ground Water Board (CGWB) within Nagpur Municipal Corporation (NMC) limits. It was observed that all the studied parameters such as F, Ca, TDS, pH, EC, TH and Cl were within permissible limit except some isolated pockets but concentration of nitrate was above permissible limit and its presence mostly found in east zone of the city.

## Study Area

Nagpur is situated at 21° 06′N latitude and 79° 03′E longitude and a mean altitude of 310 m above sea level and is located at practically the geographical centre of India (Fig. 1). The total area within the Municipal Corporation limits is 217.56 km$^2$. Nagpur city is divided into two main parts, i.e. west of Nagpur occupied by the Deccan trap formation and the east part is occupied by the

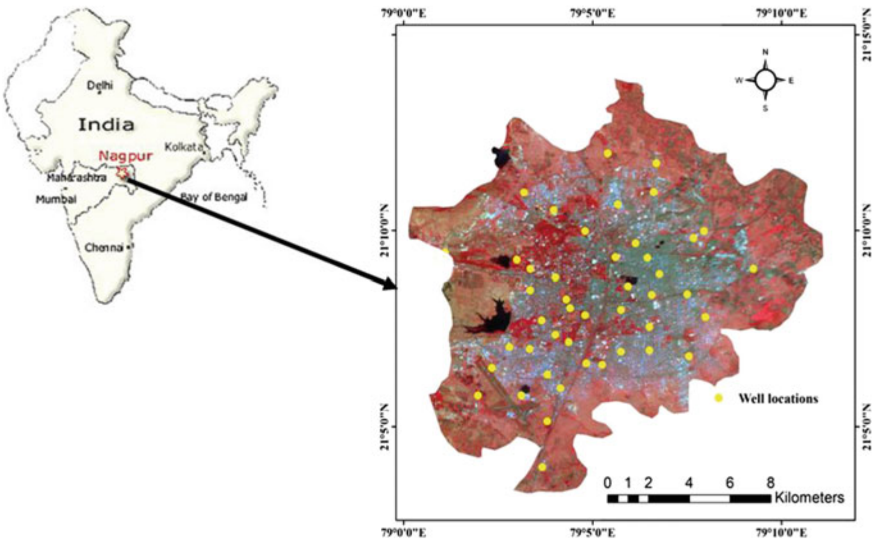


**Fig. 1** Location map of study area

metamorphic and the crystalline series. The city has topography with a natural gradient in one direction, i.e. from west to east. There are two major rivers flowing within the city. The Nag River starts from the Ambazari Lake's overflow weir at the western end of the city and runs through the middle of the city towards the east. Nagpur city is named after the Nag River. The second Pili River also having a length of 17 km starts from the weir of Gorewada lake at the north-west end of the city and runs through the north to the eastern end of the city where it meets the Nag river. All these rivers finally drain into the Kanhan River which is the tributary of Godavari River. The climate of Nagpur city is characterized by extremely hot summer and a cold winter. The city experiences tropical climate and records the rise of temperature up to 48 °C in summer season (March to May). The cold season is from December to February, and the mercury drops down to as low as 6–8 °C. It receives an annual rainfall of 1,205 mm (47.44 inches) from monsoon rains during June to September.

## Methodology

A study was taken up to evaluate the contaminants concentration in groundwater from pollution in Nagpur city area of Maharashtra, India. For finding the causes and sources of contaminations in Nagpur city, land use/land cover map has been used and to justify the extent of pollution in city, parameter such as topography is used. The effects of land use on groundwater quality can be studied by comparing the predominant land use within a given area to the concentration of selected contaminant in water drawn from aquifers within that area. For assessment of groundwater quality and the chemical aspects of groundwater in the study area, 45 monitoring wells have been selected for investigation. Quantity and quality data of these monitoring wells are maintained and analysed by Central Ground Water Board (CGWB) in perspective of standards proposed by the Bureau of Indian Standards (BIS) for drinking water (IS-10500-91, revised 2003) to decide the suitability of groundwater. The data collected from CGWB have been used to examine the groundwater quality within study area by observing the variations in concentration of the different chemical components in different types of land use areas, to observe the pattern of various pollutants in space and time due to topography of the area and to account the observed pattern with respect to land use/ land cover within study area. Geographic information system (GIS) is used to create maps such as location of different wells, DEM, depth to water level and spatial variation of various contaminants concentration within study area. The data from 10 different zones of Nagpur Municipal Corporation (NMC) are also being used to observe the effect of solid waste material to groundwater.

## Result and Discussion

The spatial variation of different contaminants concentration such as F, Ca, TDS, pH, EC, TH and Cl within the city limit is shown in Fig. 2, all are well within the permissible limit except few isolated pockets. The groundwater of the city is found to be affected by the higher concentration of nitrate (Fig. 3) which is mainly in the east zone of the city and concentration on the other parts of city are mostly within permissible limit. Out of 45 monitoring wells of CGWB, 17 wells are affected by the nitrate contaminant. The land use map of the city is (Fig. 4) prepared using tool of GIS. In land use map, the built up area covers 54% and wastelands, agriculture, water bodies, forest covers 20, 19, 2 and 1%, respectively, of the total city area. Increase in built up area due to urbanization increases the use of chemical in daily life such as detergents, oil, paints, etc. Due to increasing population density the uses of pesticides for killing unwanted pests, such as termites, ants, and rodents around

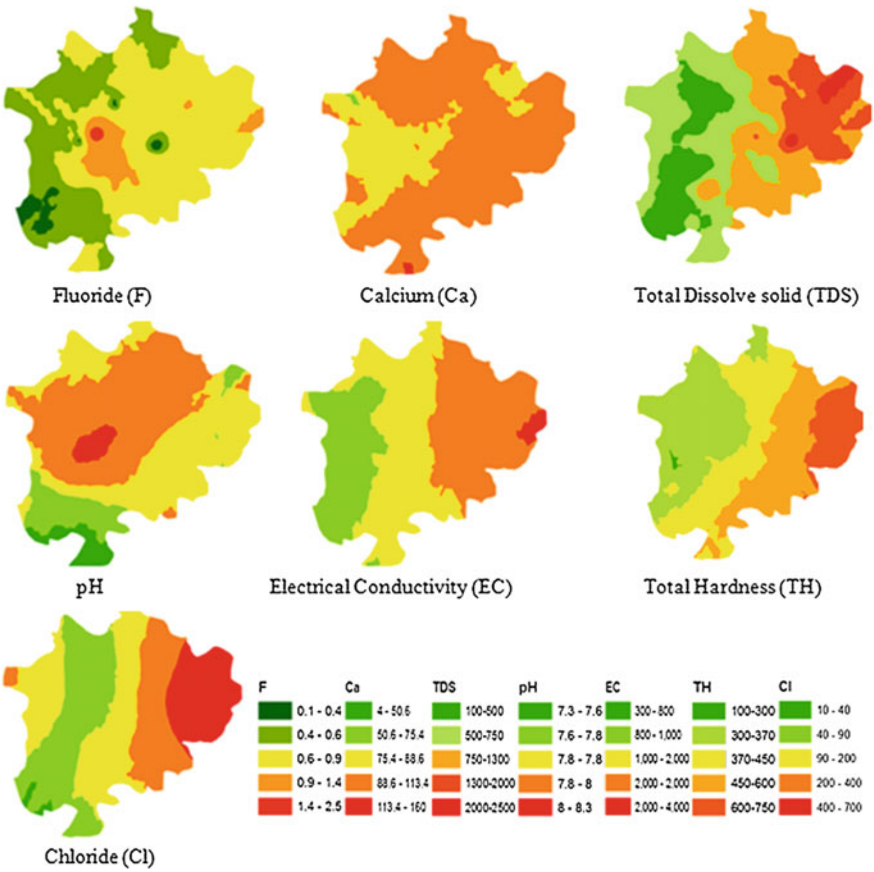


**Fig. 2** Spatial variation of different contaminants concentration in Nagpur city

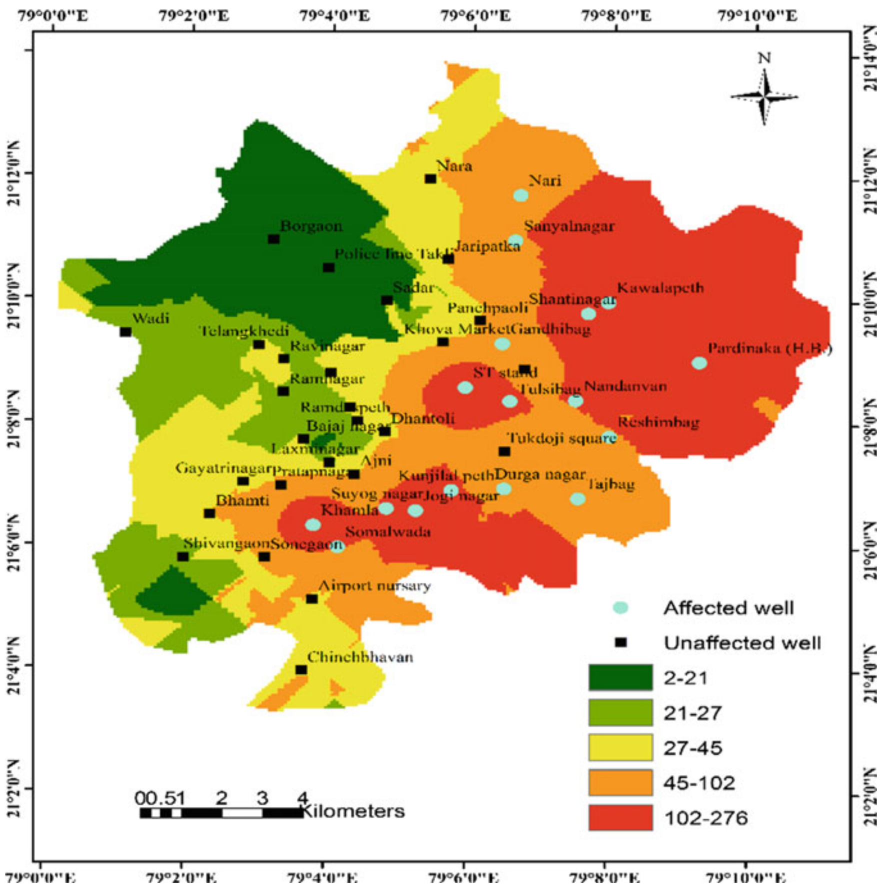


**Fig. 3** Spatial variation of nitrate concentration in Nagpur city

homes affects the properties of groundwater and soil. Similarly, use of herbicides to kill undesirable weeds and grasses in lawn contaminants the groundwater. The presence of septic tanks, pit latrines, poultry washouts and cattle sheds contributes to the nitrate contamination in groundwater to great extent because all these sources are especially rich in nitrate. The main source of nitrate pollution in the groundwater results from agriculture. More use of nitrogen-based fertilizer to increase the crop productive results in more of the nitrate contaminant in groundwater. Presence of agriculture in east of the city is one of the reason for higher concentration of nitrate in east zone.

The main stream of the city is Nag River (Fig. 5) which has become a sewage disposing drain. It traverses through the city from west to east. The untreated city sewage is disposed off in this river through pipes and drain. The results of the chemical analysis revealed that there is a big patch of high nitrate content of the groundwater in the adjoining areas of Nag River in eastern part of the city in

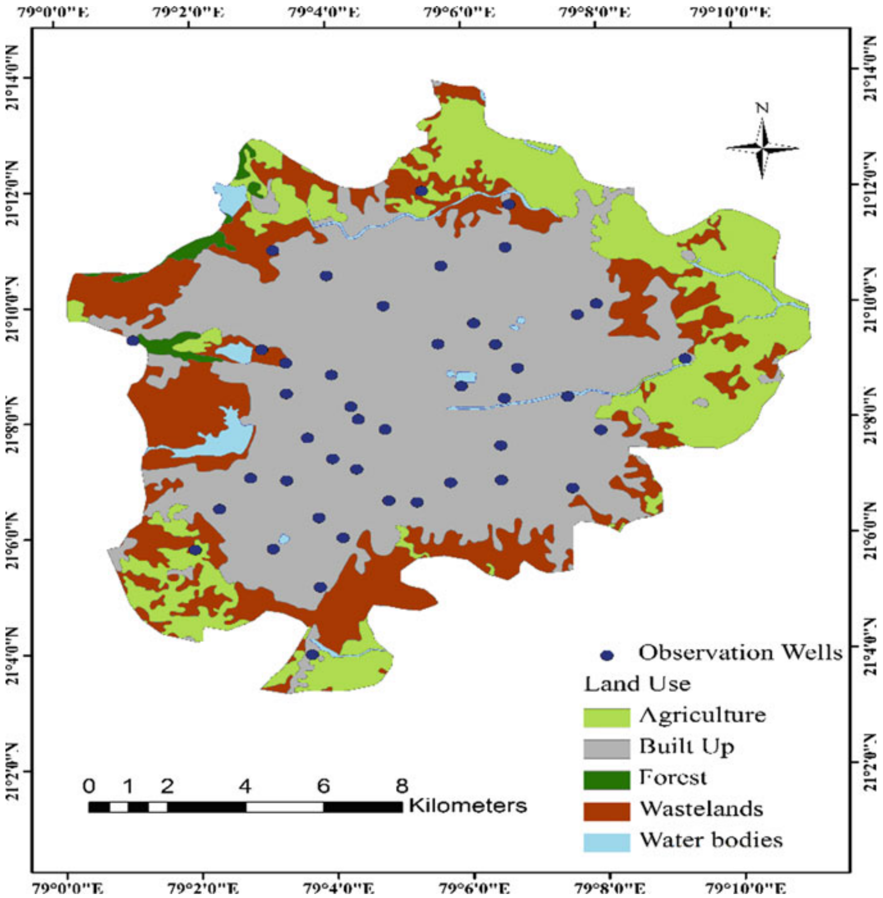


**Fig. 4** Land use/land cover map of Nagpur city

Bhandewadi, where the population density is very high because of presence of many slums. The adjoining area at the start of the Nag River in the west of the city shows very less concentration of below 45 mg/L nitrate in groundwater, which probably indicates increasing concentration from west to east attributing to amount of sewage going into the river as per the population density. Higher concentration of nitrate is found to be more in the adjoining slums of the current disposal site of Nagpur city in Bhandewadi. The study reveals different types of land uses such as water bodies, disposal sites, slums and localized factors are the major source of nitrate pollution of groundwater in Nagpur city.

Lower concentration of nitrate in the samples from remaining wells of the area is likely to be due to dilution from precipitation and topography of the area. Digital elevation model (DEM) is used to extract the slope of the study area (Fig. 6); the degree of the slope will govern whether the extent of the contaminants released will

**Fig. 5** Nag river of Nagpur city

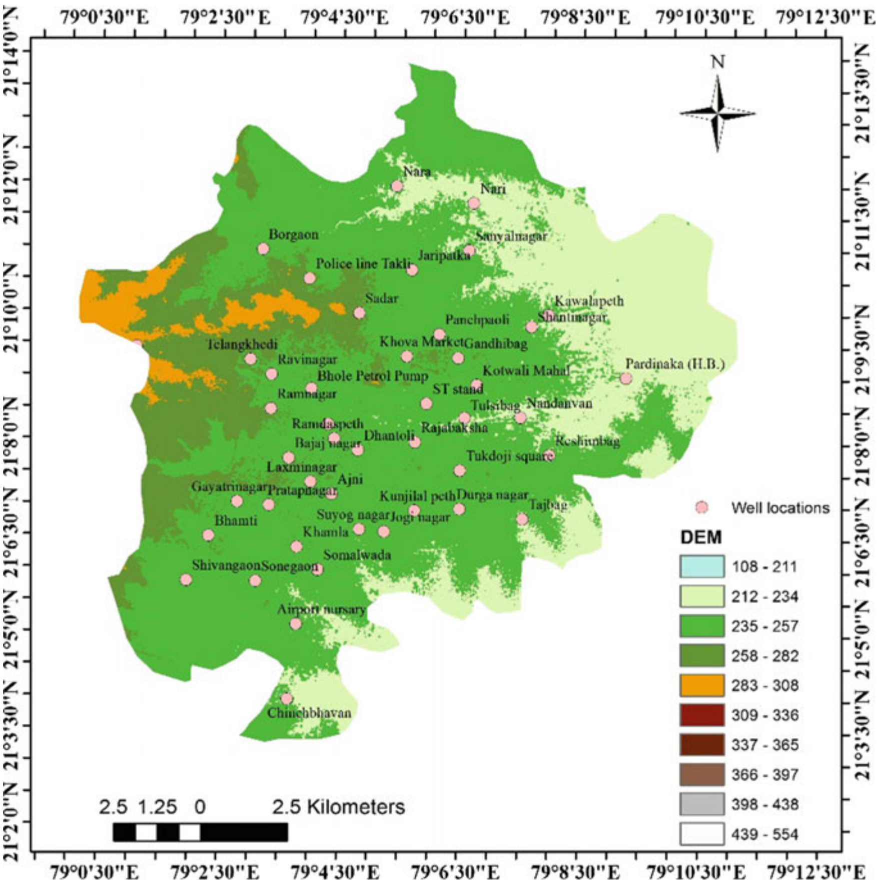


**Fig. 6** Digital elevation map of Nagpur city

become run-off or infiltrate the aquifer. As the city has topography with a natural gradient in one direction, i.e. from west to east, degree of slope in the east were milder and steeper in the south-west direction, it is justified that the extent of the various contaminants flow follows the general topography of the area and affects the low-lying areas of east zone.

NMC boundary is divided into ten different zones; the waste of the city is collected from 10 different zones and dumped on Bhandewadi (dumping site). Table 2 shows the statistical values for the physical characteristics of municipal solid wastes (MSW) samples and chemical characteristics of all the ten zones within the city, and it directly gives the comparison of various parameters in different zones and helps in finding the source of contaminations in different zones (Modak and Nangare 2011). Dumping sites contaminate groundwater when rain water leaks into aquifers below the site. The percolating water leaches toxic chemicals from batteries, broken fluorescent bulbs, electronic equipment, discarded household chemicals, paints and solvents.

Out of 10 different zones, only in few zones namely Laxmi nagar, Dharmpeth and Mangalwari all the contaminants are under permissible limits. In Hanuman nagar, Dhantoli, Nehru nagar, Gandhi bagh, Satranji para and Ashi nagar except nitrate all the other contaminants are within permissible limits. Lakadganj is found to be highly affected zone as nitrate, TDS and TH are beyond permissible limits. Laxmi nagar, Dharmpeth, Hanuman nagar, Dhantoli and Mangalwari are sited at higher elevation ranges from 234 to 397 m above mean sea level and the remaining zones ranges between 211 and 257 m above mean sea level. The dumping site of the city is located in the eastward having a low elevation range 211–237 m.

From the analysis of data shown in Table 2, it was observed that Mangalwari zone of the city shows the higher waste generation rate still these area is free from the contaminants, because this zone is located at higher elevation, which allows the natural movement of contaminants flow through gravity which ultimately moves towards low-lying areas. Dumping site of the city is located at Bhandewadi in east zone lower elevation area and highest waste generation rate of the Nehru nagar zone and Lakadganj zone can be the major source of the nitrate content in these areas and it’s mainly due to leaching.

## Conclusion

Impact of land use/land cover and digital elevation map (DEM) on groundwater are studied to analyse the groundwater quality in Nagpur city. Groundwater quality data of 45 monitoring wells and municipal solid waste data of 10 different zones of NMC are used to find the reason of spatial variation of contaminants in the city. Out of all the contaminants such as pH, TDS, TH, Ca, K, F, Cl, the groundwater is mainly affected by the nitrate concentration. GIS is used to prepare the entire map like spatial variation of contaminants in different locations, DEM and land use. On the basis of the land use map and DEM, it is concluded that the concentration of

**Table 2** The comparison of values for different parameters in different zone within Nagpur city (Modak and Nangare 2011)

| Zone | Location | Chemical characteristics | | | | | | | | Physical characteristics | Observation |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | F | Ca | TDS | EC | pH | TH | Cl | $NO_3^-$ | [a]MSW (kg/day) | |
| 1 | Laxmi nagar | 0.1–0.7 | 75–112 | 100–600 | 800–2000 | 7.3–7.6 | 300–450 | 10–90 | 15–42 | 109.87–57.85 | All contaminants are within permissible limit |
| 2 | Dharmpeth | 0.4–1.4 | 75–88 | 100–750 | 800–2000 | 7.8–8 | 300–370 | 40–200 | 2.3–27 | 105.95–62.30 | All contaminants are within permissible limit |
| 3 | Hanuman nagar | 0.6–1.4 | 88–113 | 500–1300 | 1000–2000 | 7.6–7.8 | 370–600 | 90–200 | 45–270 | 106.82–66.37 | All contaminants are within permissible limit except $NO_3^-$ |
| 4 | Dhantoli | 0.9–1.4 | 75–113 | 500–1300 | 1000–2000 | 7.8–8.2 | 300–600 | 40–200 | 20–100 | 111.84–66.03 | All contaminants are within permissible limit except $NO_3^-$ |
| 5 | Nehru nagar | 0.6–0.9 | 86–113 | 650–1300 | 1000–2000 | 7.5–7.8 | 450–600 | 90–400 | 45–100 | 133.62–67.35 | All contaminants are within permissible limit except $NO_3^-$ |
| 6 | Gandhi bagh | 0.4–1.0 | 75–113 | 500–1300 | 1000–2000 | 7.8–8.2 | 300–600 | 40–200 | 25–270 | 111.12–68.14 | All contaminants are within permissible limit except $NO_3^-$ |
| 7 | Satranji para | 0.6–0.9 | 80–113 | 750–2000 | 500–2000 | 7.8–8 | 370–600 | 40–400 | 45–276 | 104.86–66.9 | All contaminants are within permissible limit except $NO_3^-$ |
| 8 | Lakadganj | 0.6–0.9 | 86–113 | 1300–2500 | 2000–4000 | 7.5–7.8 | 450–750 | 300–700 | 100–276 | 112.12–60.70 | $No_3$, TH, TDS are beyond permissible limit |
| 9 | Ashi nagar | 0.4–0.9 | 86–113 | 750–2000 | 1000–2000 | 7.6–7.8 | 370–600 | 90–400 | 26–100 | 110.00–66.08 | All contaminants are within permissible limit except $NO_3^-$ |
| 10 | Mangalwari | 0.1–0.5 | 75–113 | 100–750 | 800–2000 | 7.8–8 | 300–370 | 40–200 | 2.3–26.7 | 112.88–82.35 | All contaminants are within permissible limit |

[a]MSW (municipal solid waste) = paper + plastic + metal + glass + rubber/leather + ash/fine earth + total compostable matter. F, Ca, TDS, TH, Cl values are in mg/L except pH and EC. Unit of EC is µS/cm

nitrate is more in the city specially affecting east zone is due to the presence of sources which are rich in nitrate and the topography of the area which follows the natural gradient from west to east. These assessments could help to screen out potentially harmful sources and areas threatened by groundwater contamination, which could be an important basis for decision-making, such as land planning and groundwater monitoring. Septic tank and cesspools management in homes must also be considered seriously. Large quantity of city wastewater is discharged to the rivers, such as Nag River, its tributaries, open drains, as well surface water bodies. It is suggested that along with lateral lining; bottom lining can also be constructed to the channels to stop the seepage. To prevent the nitrate concentration in Nagpur city, sanitary protection around the wells can be done. Disposal sites of the city should be selected at a place away from the habitation, considering the topography and hydro geological settings of the area.

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# Modeling Leachate Migration

**S. K. Pramada and T. R. Anjana**

**Abstract** This paper presents the development of a one-dimensional numerical model that can be used for quantifying groundwater contamination due to discharge from a landfill. The model can be used for the simulation of contaminant transport in aquifers. The present goal is to assess leachate migration from a landfill in order to control its environmental impacts on groundwater. Leachate is one of the main causes of surface and ground water contamination. A poorly designed landfill can create contamination of groundwater. As water percolates through the landfill, contaminants are leached from the solid waste. A finite difference model is developed and compared with analytical model to study the leachate migration for a one-year period for a case study. A column study is also conducted to determine the aquifer parameters. Due to the uncertainty in the input parameters, the result obtained from the numerical modeling may not give the exact behavior. A code was developed in Matlab to link numerical model with Monte Carlo Simulation and the uncertainty in the concentration was obtained.

## Introduction

A poorly designed landfill can create contamination of groundwater, soil, and air. The most commonly reported danger to the human health from these landfills is the use of groundwater that has been contaminated by leachate. As water percolates through the landfill, contaminants are leached from the solid waste. Contamination of groundwater due to the landfill leachate depends upon the recharge in the locality. Leachate may contain dissolved material associated with wastes disposed off in the landfill, as well as many by-products of chemical and biological reactions. To reliably predict the fate of contaminant transport in groundwater, an accurate numerical modeling is required. There are many numerical investigations of

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advection dispersion equation (transport equation). Among the numerical methods, finite difference method (FDM) and finite volume method (FVM) seem to be more popular for the ease of implementation and their relative simplicity (Ataie et al. 1999; Moldrup et al. 1996; Sheu et al. 2000). The modeling process requires knowledge of the fundamental properties of the media. In most applications, the amount of data that is available or can be collected to address a given issue will be limited, and clearly will not be adequate to resolve the detailed temporal and spatial variability that actually exists in nature. To obtain reliable results from modeling, accurate data should form the input to the model. It is difficult to obtain reliable information regarding hydrogeological properties. Because of this uncertainty about the actual subsurface situation, the model results are uncertain and the validity of the modeling may be questioned. A very few studies have been devoted to uncertainty analysis.

## Methodology

In the present study, an experimental study was carried out to analyze the leachate characteristics and aquifer parameters. A code was developed to solve the numerical model using finite difference technique and compared with analytical model and also developed a code in Matlab to link numerical model with Monte Carlo simulation, and the uncertainty in the concentration was obtained.

## Experimental Study

In order to study the characteristics and parameters required for modeling of leachate, a column study was conducted. To test the parameters for modeling, a soil column experimental study was carried out, and for leachate characteristics another column study was conducted. The experiments were carried out in the Geotechnical and Environmental Engineering laboratory of National Institute of Technology (NITC). The soil sample from the open dumping site was collected. The top soil was removed from the identified location, and the undisturbed soil samples were collected from 1 m depth in polythene bags and brought to the laboratory. For the leachate quality characteristics, solid waste was collected and brought to the laboratory.

## Leachate Quality Analysis

The dumping site in the campus is not an engineered landfill. Proper leachate collection pipes were not provided in the site. Since it is difficult to collect the leachate, leachate was allowed to generate in the laboratory. The wastes from

**Table 1** Leachate characteristics

| Parameter | Value |
|---|---|
| pH | 8 |
| Alkalinity | 180 mg/l |
| Chloride | 320 mg/l |
| Sulfate | 281 mg/l |
| Parameter | Value |
| Iron | 0.3 mg/l |
| TDS | 8859 mg/l |

dumping site were collected. The solid waste was filled in a column. Distilled water was allowed to pass through the waste for a certain period of time. Leachate effluent was collected at the bottom of the column using a pipe. Leachate obtained is analyzed for water quality parameters as per IS 3025. The leachate was analyzed for pH, Alkalinity, total dissolved solids (TDS), chloride, sulfate, and iron. The results obtained are shown in Table 1.

## Soil Column Test to Determine the Parameters

The experimental set up of the soil column ensemble is shown Fig. 1. For the column study, a glass column of diameter 1 cm and length 10 cm were used. The column is filled with the soil collected from the site. On the top of the column, an arrangement is fixed with a control valve to allow constant velocity of flow and for passing the leachate generated in the laboratory. At first, the soil was saturated with distilled water. It took one day for the saturation of the soil. Then, leachate was allowed to flow through the column by opening the valve. The velocity of the flow was also noted. The effluent coming out of the column was collected at a definite time interval. The concentration of TDS in the effluent samples was analyzed. Figure 2 shows the breakthrough curve (BTC) obtained from the experimental study.

From the BTC obtained from the test, the dispersivity of the soil is calculated using equation given by Ogata and Banks (Eq. 1).

$$C = \frac{C_0}{2}\left[\operatorname{erfc}\left(\frac{L - V_x t}{2\sqrt{D_L t}}\right) + \exp\left(\frac{V_x L}{D_L}\right) * \operatorname{erfc}\left(\frac{L + V_x t}{2\sqrt{D_L t}}\right)\right] \tag{1}$$

$$D_L = \alpha * V_x, \tag{2}$$

where

$C_0$ is the initial concentration of the effluent in mg/l
$C$ is the Concentration of the effluent in mg/l
$L$ is the length in cm

**Fig. 1** Experimental set up

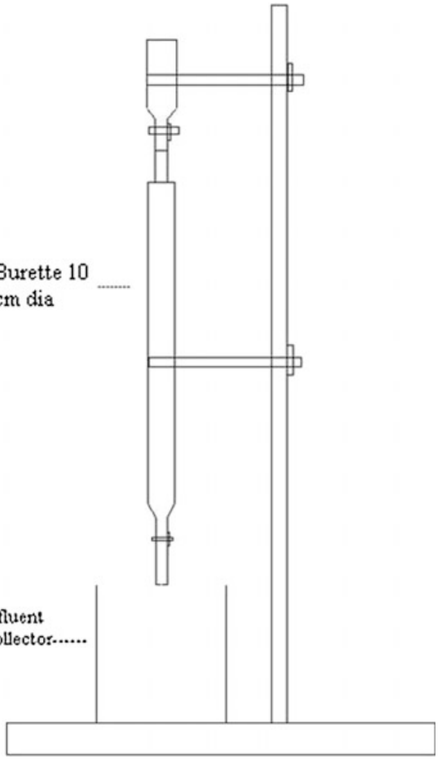
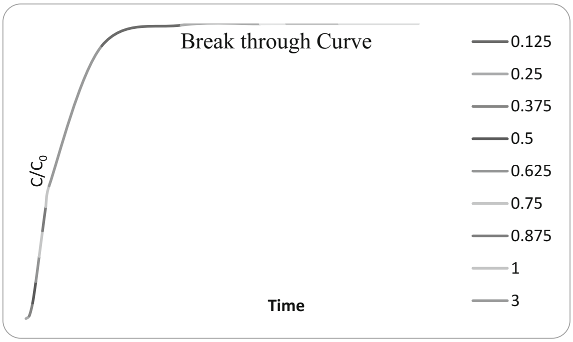



**Fig. 2** BTC of column test




$V_x$ is the actual velocity of flow in cm/s
$t$ is the time period in s
$D_L$ is the Dispersion coefficient in $cm^2/s$
$\alpha$ is the dispersivity in cm

From Eq. (1) the value of $D_L$ is calculated. Using Eq. (2), the dispersivity was calculated. The value obtained was 2.9 cm. Permeability of the soil was determined by conducting variable head permeability tests (IS 2720 [part X VII]—1966) in the geotechnical laboratory. The collected soil sample from 1 m depth was used to get the permeability. The value obtained was $2.11 \times 10^{-4}$ cm/s.

## Analytical Model

The governing equation for the mass transport equations in one dimension is

$$\frac{\partial C}{\partial t} = D_x \frac{\partial^2 C}{\partial x^2} - V_x \frac{\partial C}{\partial x}. \tag{3}$$

## Assumptions

- The flow and dispersion through the soil under consideration is one-dimensional
- The source is continuous with the same concentration of $C_0$
- The depth of porous medium is finite
- The porous medium is in saturated condition

## Initial Conditions

Initial conditions are used to define the contaminant concentration in porous media just prior to beginning of contaminant transport. So the initial condition applied to equation is, at $t = 0$.

$$C\,(x, 0) = 0 \quad 0 < x < \infty.$$

## Boundary Conditions

Boundary conditions specify the interaction between the area under investigation and its external environment. There are three types of boundary condition for mass transport. The following types of boundary conditions are used:

- Dirichlet boundary condition: It specifies the value of concentrations along a section of flow system boundary.
- Neumann boundary condition: It specifies the gradient in contaminant concentration across a section of the boundary.

- Cauchy boundary condition: It is applied where the flux of contaminant across the boundary is depending on the difference between a specified concentration value on one side of the boundary and contaminant concentration on the opposite side of the boundary.

Boundary conditions applied for the system are

$$C(0,\, t) = C_0 \quad \text{for} \;\; t > 0$$
$$C(\infty, t) = 0 \quad \text{for} \;\; t \geq 0.$$

The solution to the above equation is given by Ogata and Banks (1961) and given in Eq. (3).

$$C = \frac{C_0}{2}\left[\operatorname{erfc}\left(\frac{L - V_x t}{2\sqrt{D_L t}}\right) + \exp\left(\frac{V_x L}{D_L}\right) * \operatorname{erfc}\left(\frac{L + V_x t}{2\sqrt{D_L t}}\right)\right]. \tag{4}$$

Using Eq. (3), concentration of TDS effluent at different depth is calculated.

## Numerical Model

The partial differential equation of groundwater flow in one dimension is

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) = S_s \frac{\partial h}{\partial t} - W. \tag{5}$$

$K_x$ is hydraulic conductivity in $x$ direction $LT^{-1}$
$S_s$ is the Specific storage, $L^{-1}$
$W$ is the fluid sink/source term, $L^3T^{-1}$

The governing equation for the mass transport equations in one dimension (Eq. 3) with the initial condition

$$C(x, 0) = 0 \quad 0 < x < \infty,$$

and the Boundary conditions

$$C(0, t) = C_0 \quad \text{for} \;\; t > 0$$
$$C(\infty, t) = 0 \quad \text{for} \;\; t \geq 0.$$

A finite difference code was developed using Matlab for the one-dimensional groundwater flow and transport equation. The TDS was taken as the indicator of leachate migration. The general position of the migration for a one-year period was determined by solving the flow and contaminant transport equation. Dirichlet

**Table 2** Initial and finally adopted parameter values

| Parameter | Initial value | Final calibrated value |
|---|---|---|
| Hydraulic conductivity (K cm/s) | $2.11 \times 10^{-4}$ | $2.11 \times 10^{-3}$ |
| Specific yield | 0.15 | 0.15 |
| Effective porosity ($\theta$) | 0.2 | 0.2 |
| Longitudinal dispersion ($\alpha_L$ in m) | 2.9 | 10 |

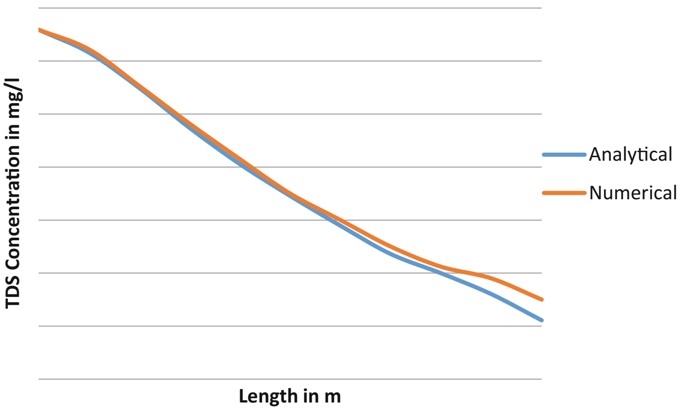



**Fig. 3** Comparison of numerical and analytical solution

boundary condition was adopted for the top boundary with a constant TDS concentration of 8859 mg/l.

The aquifer parameters obtained from the experimental study were used in the numerical model. Table 2 shows the initially and finally adopted parameters.

The model was calibrated by comparing the analytical solution with numerical solution by adjusting the hydraulic conductivity and dispersivity. Figure 3 demonstrates the comparison between analytical and numerical modeling. Although the two solutions are same at the initial portion, slight variation comes at the greater length. The calibrated longitudinal dispersivity was found to be 10 m. From the figure, it is clear that after one year of continuous dumping at a depth of 10 m from the ground the concentration of TDS is around 8350 mg/l.

## Uncertainty Analysis

All simulations in groundwater transport modeling are subjected to uncertainty. The precise values of the model parameters are never known, especially the hydraulic conductivity. Stochastic methods that consider uncertain and heterogeneous hydrogeologic parameters in groundwater and transport models have been developed by several research groups (Dagan 1984). Stochastic approaches can be generally sorted into two different approaches, namely, Monte Carlo (MC) simulations and the moment equation approach. Monte Carlo (MC) simulation has been the most widely used method for calculating uncertainty. This method employs classical statistics to calculate the variance of model output from a set of input parameters that are randomly generated. Each time the process is repeated, and a new realization of uncertain parameters is generated and used in the model (Woldt et al. 1992; Copty et al. 2000). In the moment equation (ME) approach, random parameters are included as coefficients in the partial differential equations that describe the system. Then the stochastic differential equations are solved, using the perturbed forms of equations (classical perturbation) (Morales-Casique et al. 2006).

Recent research papers have been directed at reducing the number of realization in Monte Carlo simulation by Latin hypercube sampling or stratified sampling and reducing the computational time in classical perturbation method (Yang and Huang 2010; Liodakis et al. 2015).

The basic idea here is to characterize quantitatively, the uncertainty in the concentration due to heterogeneity of the aquifer. The linked model with Monte Carlo and finite difference model was used to quantify the uncertainty on the concentration. This is achieved through the probability distribution function of hydraulic conductivity value. Hydraulic conductivity is normally assumed to be log-normally distributed (Gelhar 1994), which shows that the hydraulic conductivity varies over many orders of magnitude. The mean and standard deviation of the hydraulic conductivity were arrived at based on the calibration results. Hydraulic conductivity field is randomly generated and assigned to each cell, and each iteration results in new realization of hydraulic conductivity. The hydraulic conductivity field is generated based on Eq. 6.

$$f(x') = \frac{1}{\sigma_{x'}\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{x' - \mu_{x'}}{\sigma_{x'}}\right)^2\right], \tag{6}$$

where $x'$ is the random variable, $f(x')$ is probability density function of $x'$, $\sigma_x{}'$, and $\mu_x{}'$ are standard deviation and mean, respectively.

New realizations of the head and concentration values for each realization of the hydraulic conductivity are obtained by running the numerical model for the same boundary and initial conditions. The number of required realizations depends mainly on the model, the assumed input parameter distribution, and the desired accuracy of output, and variance in output. It is necessary to ensure that Monte Carlo simulation is slowly getting converged.

This is done by carrying out different set of simulations with increased number of realizations. The statistical parameters can be compared with those of the previous set, and if significant difference in the result occurs then it is an indication that the Monte Carlo simulation has not converged. The procedure can be repeated with increased realizations until convergence of the Monte Carlo is confirmed. For this

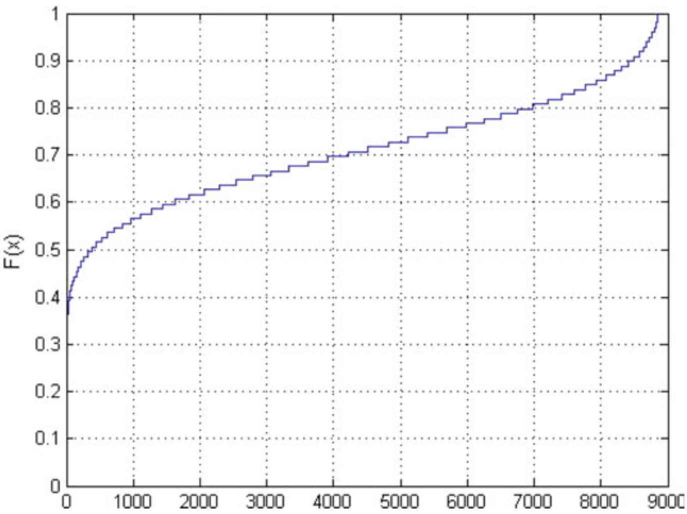



**Fig. 4** CDF plot of concentration

particular problem, the Monte Carlo simulation is converged for a realization of 20. The number of required realizations depends mainly on the model, the assumed input parameter distribution, and the desired accuracy of output, and variance in output. The uncertainty in the concentration was obtained by plotting the CDF and found to be 201 mg/l. The derived cumulative distribution function (CDF) for the concentration is shown in Fig. 4. The probability that the TDS concentration assumes taking a value less than or equal to 8900 mg/l is 1. Flow chart for linking Monte Carlo simulation with numerical model is given in Fig. 5.

## Conclusions

In order to prevent/control the leachate migration into groundwater and reduce its environmental impact, better and efficient solid waste management is necessary. The leachate models can be used to evolve efficient management strategies. Due to uncertainties in model input parameters, model predictions may not represent the exact behavior. In order to study the effect of hydraulic conductivity on leachate migration, an interface is developed to link Monte Carlo simulation with the numerical model by treating hydraulic conductivity as an uncertain random variable. The uncertainty on the concentration was examined by conducting several realizations. Uncertainty in the concentration was found to be 201 mg/l.

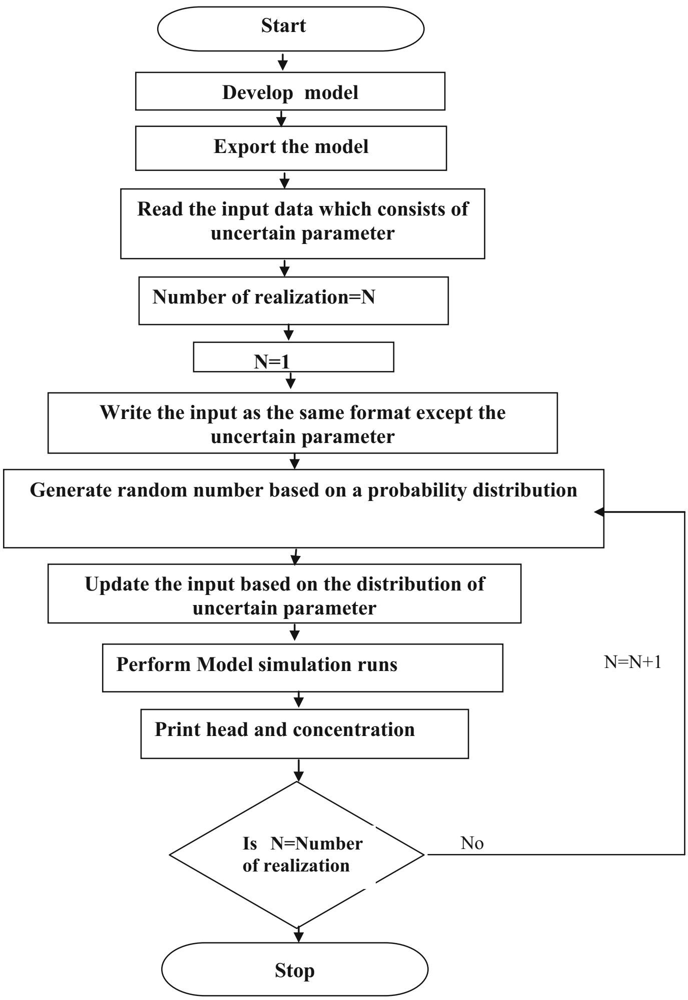



**Fig. 5** Flow chart linking Monte Carlo with numerical mode

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# Assessment of Groundwater Quality and Identification of Hydrogeochemical Process in Hard Rock Terrain

**K. Rama Mohan and A. Keshav Krishna**

**Abstract** Environmental geochemical studies are carried out to assess the groundwater quality and identification of hydrogeochemical process in hard rock terrain of Bhongir watershed nearer to the Greater Hyderabad. A total of thirty-eight groundwater samples were collected and analysed for important physicochemical parameters, anions and cations. The analytical data of alkalis ($Na^+$ and $K^+$) and alkaline earths ($Ca^{2+}$ and $Mg^{2+}$), reveal that high concentration of $Na^+$ than others (Na > Ca > Mg > K) is probability due to the loss of $Ca^{2+}$ and $Mg^{2+}$ and gain of $Na^+$ by the cation exchange process. Among the anions, bicarbonate is identified in majority of the samples in the following order $HCO_3 > Cl > SO_4$ which confirms that all carbonate minerals might have been dissolved and leached to the groundwater system. Most of the samples (81%) are exceeding the WHO allowable limits of electrical conductivity for drinking. The data sets further suggest that the water chemistry in the study area is not homogeneous and influenced by complex contamination sources and geochemical processes. Besides, highest concentration of nitrate (565.7 mg/L), sulphate (414 mg/L) and chloride (1444 mg/L) firmly suggests the impact of agricultural activities such as irrigation return flow, fertilizer application on water chemistry. The elevated concentrations of fluoride (i.e. maximum 4.1 mg/L) in most of the water samples (66%) reveal the origin and geochemical mechanisms, i.e. rock–water interaction is driving its enrichment. As majority of the parameters are above the permissible limit, the groundwater is not potable for drinking.

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## Introduction

Groundwater is the major sources of drinking water both in urban and in rural areas of India. It is also an important source of agriculture and industrial sector. The demand of water has increased over the year, and this had led to water scarcity in many parts of the world. Generally, the variation of major elements in the groundwater can be controlled by cation exchanges, dissolution and precipitation of minerals, evaporation and oxidation–reduction reactions. These complicated hydrogeochemical processes help to get an insight into the contributions of rock–water interaction (geochemical study) that influences groundwater quality. These geochemical processes are responsible for the seasonal and spatial variations in groundwater chemistry (Matthess 1982; Kumar et al. 2006). Groundwater chemically evolves by interacting with aquifer minerals or internal mixing among different groundwater along flow paths in the subsurface (Domenico 1972; Wallick and Toth 1976; Toth 1984; Schuh et al. 1997). This indicated that the increase in solute concentrations in the groundwater is caused by spatially variable recharge, governed by geochemical evolution controls. Further, the weathering of primary and secondary minerals is also contributing cations and silica in the system (Jacks 1973; Freeze and Cherry 1979; Bartarya 1993). Many discussed analyses, such as leaching and dissolution, mixing, cation exchange, oxidation–reduction, precipitation, hydrolysis, control the water quality during its movement from the recharge to discharge areas. As far as the quality of groundwater concern, many states in India have been identified as endemic to fluorosis due to abundance in naturally occurring fluoride-bearing minerals. One such example is at Bhongir Watershed of Nalgonda district, Telangana state, as the groundwater is major source of drinking and agricultural purposes.

The aim of this work is to find out the hydrogeochemical processes controlling groundwater quality in granite aquifer based on major ion chemistry and groundwater quality assessment in the proposed watershed. The hydrochemical processes and geochemical evolution are studied and investigated through the evaluation of 38 water points tapping granite aquifer.

## Description of the Study Area

The study area has chosen on watershed scale in order to understand the hydrogeochemical behaviour of groundwater. Bhongir is a major town in the selected watershed, which is 48 km from the state capital Hyderabad. The watershed falls in the district of Nalgonda, Telangana, India. The study area covers 390 km$^2$. The watershed experiences semi-arid-to-arid climate with temperature ranging from 28 to 44 °C. The average annual rainfall is 650 mm, of which 70% of rainfall contributes due to south-west monsoon (June to September). The location map of the study area (i.e. Bhongir Watershed) is shown in Fig. 1.

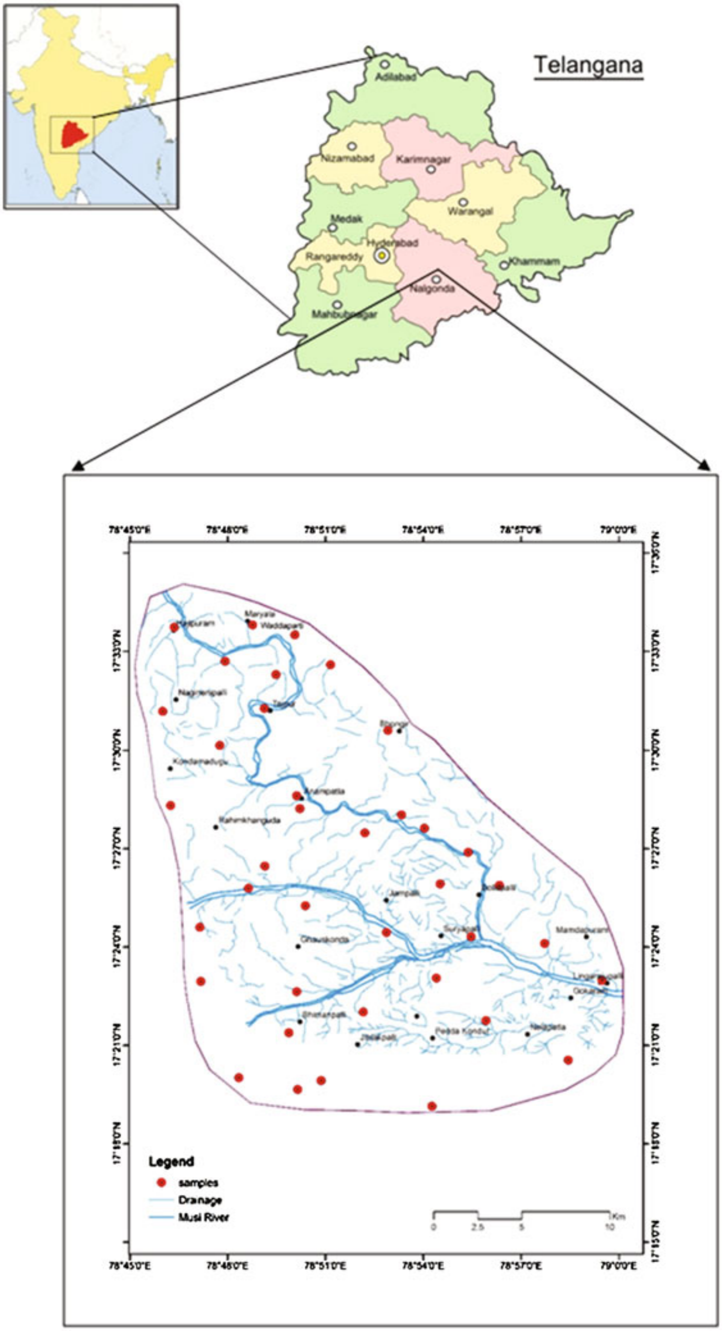



**Fig. 1** Location map of the Bhongir Watershed of Nalgonda District, Telangana

## Geology of the Study Area

The study areas consist of major rock formation of medium- to coarse-grained granite. The granite can be divided into two major varieties based on colour: grey granite and pink granite. Both varieties occupied large part of the area, and it is not possible to draw a line of demarcation between two types, as they intermingle with no sharp point of contact. These granites are presumed to be the part of peninsular gneissic complex and to content basic enclaves of aplites, pegmatite, epidote and quartz vein. Dolerite dyke is frequently traversing the granite as well (GSI 1995).

The Srisailam formation: the youngest member of Cuddapa supergroup directly overlies the basement granite with a distinct unconformity. The meta-sediments of Srisailam formation include pebbly-gritty quartzite, shale, dolomite limestone, intercalated sequence of shale–quartzite and massive quartzite. The litho-units of this formation are dipping at angle ranging from 3° to 5° towards SE. The generalized stratigraphic sequence of the study area is shown in Table 1 (Natranjan and Murthy 1974).

## Sample Collection

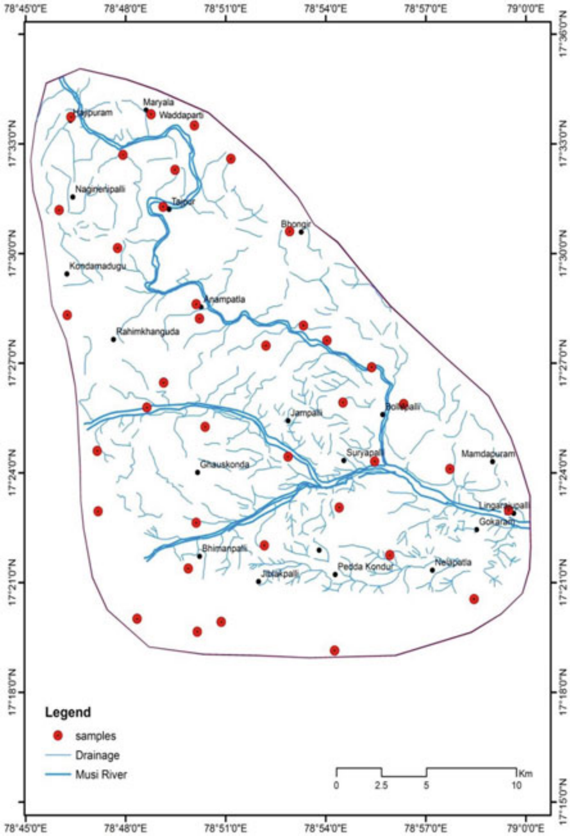
In order to study the hydrogeochemistry and quality of groundwater from the Bhongir Watershed, samples are collected during the month of June 2012 (pre-monsoon) only. Usually, this area is expected the monsoon in the month of June, but it delayed. The samples were collected according to the grid pattern (1.6 × 1.6 km) to spread the entire study area. Sample locations were recorded using GPS. Groundwater samples are collected from thirty-eight (38) bore wells in Bhongir Watershed of Nalgonda district in Telangana.

The water samples are collected in one-litre polypropylene (PP) bottles. Prior to the collection of samples, the bottles are rinse two times with water and completely filled to avoid air bubbling. The groundwater samples are transported to the laboratory on each day of the sample collection. Physicochemical parameters such as pH, EC and TDS values of groundwater are measured in situ in the field using

**Table 1** Generalized stratigraphic sequence of the area

| Cuddapa supergroup | Massive quartzite, upper shale |
|---|---|
| Srisailam formation<br>Intercalation lower shale with limestone<br>intercalation pebbly and gritty quartzite/arenite | Quartzite with shale |
| *Eparchaean unconformity* | |
| Late archaean/lower proterozoic | Granite/granitic gneiss intrusion of dolerite dykes and quartz vein |

portable metres.




## Analytical Methods

The groundwater samples were analysed for various parameters according to the standard methods (APHA 2005). The pH, EC and TDS of water samples were measured using portable metres (Eutech Instruments, model: pHTester10, ECTester11$^{+}$ and TDSTester11$^{+}$, respectively). Bicarbonate and carbonate were analysed by classical volumetric method. Major cations, such as calcium, magnesium, sodium, potassium and anions, such as chloride, nitrate, sulphate, fluoride, were analysed by ion chromatography.

## Results and Discussion

### *Hydrogeochemical Process*

The groundwater hydrogeochemistry is primarily controlled by water–rock interactions as well as anthropogenic pollution. Thus, the following indices were evaluated to identify the hydrogeochemical process in hard rock terrain of the proposed watershed.

#### Physicochemical Parameters

Summary of analytical results of different parameters of groundwater samples is presented in Table 2. These include physicochemical parameters such pH, EC, TDS, total hardness as well as major anion and cation concentrations. The analytical results show that the pH value of the groundwater is in the range of 6.9–7.6, indicating that groundwater in the study area is in alkaline nature. However, its higher range accelerates the scale formations in water heating apparatus either in industrial or in domestic purposes. The EC values are varied in between 786 and 4840 µs/cm, while TDS values are in between 480 and 3040 mg/L, indicating that most of the samples are not suitable for drinking as these are above the desirable levels prescribed by WHO guideline values.

**Table 2** Summary of statistical of analytical data of groundwater samples

| Water quality parameters | Concentration | Statistical data | | | |
|---|---|---|---|---|---|
| | | Min | Max | Average | SD |
| *Physicochemical parameters* | | | | | |
| pH | – | 6.9 | 7.6 | 7.12 | 0.19 |
| EC | (µS/cm) | 786 | 4840 | 2420.95 | 0.48 |
| TDS | mg/L | 480 | 3040 | 1622.29 | 2.06 |
| Total hardness | mg/L | 100 | 1235 | 586.32 | 8.68 |
| *Cations* | | | | | |
| Sodium | mg/L | 51.30 | 677.66 | 229.07 | 2.79 |
| Potassium | mg/L | 0.50 | 115.69 | 11.39 | 3.59 |
| Calcium | mg/L | 54.64 | 294.08 | 142.92 | 1.09 |
| Magnesium | mg/L | 11.55 | 131.34 | 58.31 | 0.37 |
| *Anions* | | | | | |
| Bicarbonate | mg/L | 286 | 1183 | 590.92 | 2.91 |
| Fluoride | mg/L | 0.87 | 4.114 | 1.91 | 0.84 |
| Chloride | mg/L | 54.08 | 1444.27 | 501.56 | 4.47 |
| Nitrate | mg/L | b.d.l. | 565.70 | 110.63 | 6.72 |
| Sulphate | mg/L | 20.89 | 414.01 | 153.53 | 6.69 |

### Major Ion Chemistry

The data of alkalis ($Na^+$ and $K^+$) and alkaline earths ($Ca^{2+}$ and $Mg^{2+}$) reveal high concentration of $Na^+$ than others with the following order Na > Ca > Mg > K. In contrast, the increased $Na^+$ concentration and decreased $Ca^{2+}$ and $Mg^{2+}$ concentration values can be explained by the probability of the loss of $Ca^{2+}$ and $Mg^{2+}$ and gain of $Na^+$ by the cation exchange process (Shanmugam and Ambujam 2012).

Among the various anions (Table 2) determined in groundwater samples, $HCO_3^-$, $Cl^-$, $SO_4^{2-}$ are the major anions identified in the groundwater and their presence is in the following order $HCO_3$ > Cl > $SO_4$. This could be due to available carbonates in the rocks that might have been dissolved and added to the groundwater system during irrigation and rainfall infiltration, and groundwater movement increases the bicarbonate (Sunne et al. 2005). Further, an increased chloride concentration may be due to the process of the removal of other ions from the system, either by precipitation or by adsorption. The high content of chloride in water causes salinity-related problems.

## *Water Quality Assessment*

The analytical results of groundwater samples (Table 3) were compared with the standard guideline values recommended by the World Health Organization (WHO 1993) for the drinking purpose. It included the most desirable limits and maximum allowable limits of various parameters. The following key parameters are considered and discussed in detail in order to assess the suitability of the groundwater in the study area for drinking purposes.

### Physicochemical Parameters

The prescribed limit of pH value for drinking purpose is given by Bureau of Indian Standards (BIS 2012) and is in the range of 6.5–8.5. In the study area, most of the groundwater has pH value within the prescribed limits (Table 3) indicating its suitability for drinking.

Classifications of electrical conductivity of groundwater in study area are given in Table 4. It is found that 18% of the samples are within the permissible limits and 55% of samples fall in not permissible limit, but they are marginally poor in quality and only 26% of the sample locations are classified as hazardous. However, according to the WHO standards, 81% of the samples are exceeding the allowable limits for drinking (Table 3).

**Table 3** Groundwater sample of the study area exceeding the permissible limit prescribed by World Health Organization

| Water quality parameters | Concentration | WHO (1993) | | Pre-monsoon | |
|---|---|---|---|---|---|
| | | Most desirable | Max. allowable limit | No. of sample exceeding allowable limit | % of sample exceeding allowable limit |
| *Physicochemical parameters* | | | | | |
| pH | – | 6.5–8.5 | 9.2 | Nil | Nil |
| EC | (μS/cm) | – | 1500 | 31 | 81.58 |
| TDS | mg/L | 500 | 1500 | 19 | 50 |
| Total hardness | mg/L | 100 | 500 | 28 | 73.68 |
| *Cations* | | | | | |
| Sodium | mg/L | – | 200 | 12 | 31.58 |
| Potassium | mg/L | – | 12 | 4 | 10.53 |
| Calcium | mg/L | 75 | 200 | 4 | 10.53 |
| Magnesium | mg/L | 50 | 150 | Nil | Nil |
| *Anions* | | | | | |
| Bicarbonate | mg/L | – | 300 | 37 | 97.39 |
| Fluoride | mg/L | – | 1.5 | 25 | 65.79 |
| Chloride | mg/L | 200 | 600 | 13 | 34.21 |
| Nitrate | mg/L | 45 | – | 20 | 52.63 |
| Sulphate | mg/L | 200 | 400 | 2 | 5.26 |

**Table 4** Groundwater classification based on electrical conductivity

| EC μS/cm | Classification | Pre-monsoon | | |
|---|---|---|---|---|
| | | Sample No. | No. of samples | % of samples |
| <1500 | Permissible | 3, 8, 9, 10, 13, 18, 21 | 7 | 18.42 |
| 1500–3000 | Not permissible | 1, 4, 5, 7, 12, 14, 15, 16, 17, 22, 24, 25, 28, 29, 30, 31, 34, 35, 36, 37, 38 | 21 | 55.26 |
| >3000 | Hazardous | 2, 6, 11, 19, 20, 23, 26, 32,33 | 10 | 26.32 |
| Total | | | 38 | 100 |

It is essential to classify the groundwater depending upon their TDS values obtained in the study area as reported in the literature (Davis and Dewiest 1966; Freeze and Cherry 1979) to understand their suitability for drinking purposes. The data are classified according to Davis and DeWiest (1966) and Freeze and Cherry (1979) and presented in Tables 5 and 6, respectively. Further, the contour map of TDS in groundwater is shown in Fig. 2. The data represent that only 2% of the samples is below 500 mg/L of TDS (Davis and DeWiest 1966) which can be used for drinking without any risk (Table 5). On the other hand, results demonstrated

**Table 5** Groundwater classification based on TDS (Davis and DeWiest 1966)

| TDS (mg/L) | Classification | Jun-12 | | |
|---|---|---|---|---|
| | | Sample No. | No. of sample | % of sample |
| <500 | Desirable for drinking | 3 | 1 | 2.63 |
| 500–1000 | Permissible for drinking | 8, 9, 10, 13, 21 | 5 | 13.16 |
| 1000–3000 | Useful for irrigation | 1, 2, 4, 5, 6, 7, 11, 12, 14,15, 16, 17 18, 19, 22, 23, 24, 25, 26, 27, 28, 29 30, 31, 32, 33, 34, 35, 36, 37, 38 | 31 | 81.58 |
| >3000 | Unfit for drinking and irrigation | 20 | 1 | 2.63 |
| Total | | | 38 | 100 |

**Table 6** Groundwater classification based on TDS (Freeze and Cherry 1979)

| TDS (mg/L) | Classification | Pre-monsoon | | |
|---|---|---|---|---|
| | | Sample No. | No. of samples | % of sample |
| <1000 | Fresh water type | 3, 8, 9, 10, 13, 21 | 6 | 15.79 |
| 1000–10,000 | Brackish water type | 1, 2, 4, 5, 6, 7, 11, 12, 14, 15, 16, 17, 18, 19, 20, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38 | 32 | 84.21 |
| 10,000–100,000 | Saline water type | Nil | Nil | Nil |
| >100,000 | Brine water type | Nil | Nil | Nil |
| Total | | | 38 | 100 |

that the groundwater of the area 16% is only the freshwater type and remaining (84%) samples represent brackish water in accordance with Freeze and Cherry classification (Table 6). The spatial distribution of TDS in the watershed is shown in Fig. 2 exhibiting in the range of 480–3039 mg/L.

Total hardness of groundwater samples in the present study exhibited minimum content of 100 mg/L to a maximum of 1235 mg/L with the average of 586 mg/L. Please note that the maximum allowable limit of TH for drinking purpose is 500 mg/L and the most desirable limit is 100 mg/L as per the WHO standard (Table 3).

The spatial distribution of hardness (Fig. 3) shows that higher concentrations were observed in the south-western part of the study area. According to the Sawyer and McMacartly classification (Sawyer and McCarty 1967), 95% of the groundwater samples in the study area fall in the very hard category (Table 7) and rest of

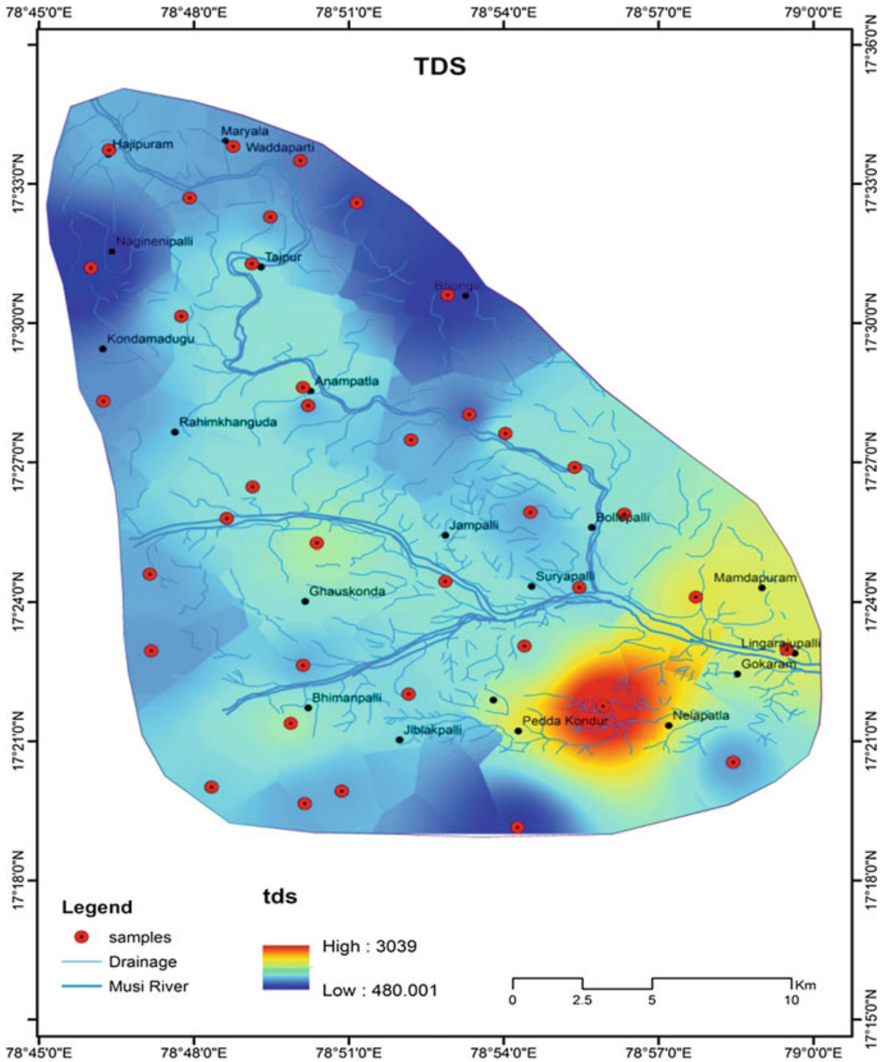



**Fig. 2** Spatial distribution of TDS (mg/L) in groundwater

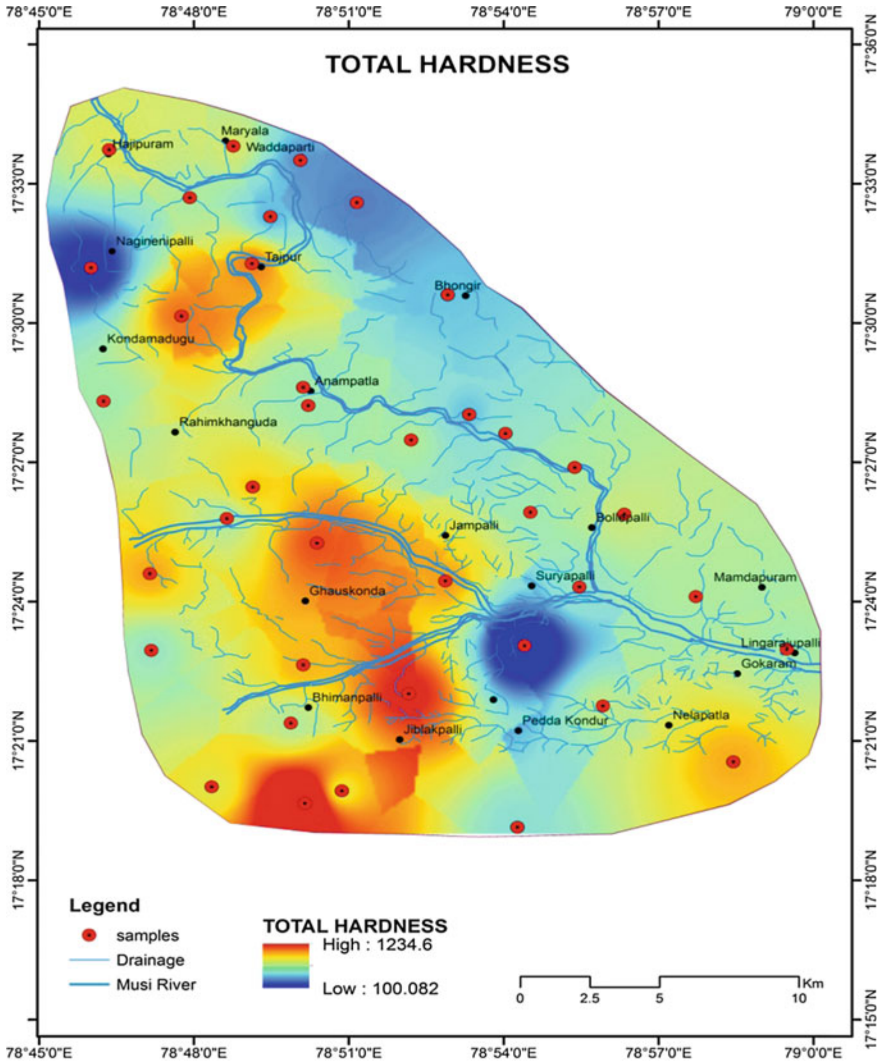



**Fig. 3** Spatial distribution of total hardness (mg/L) in groundwater

**Table 7** Groundwater classification based on hardness (Sawyer and McCarty 1967)

| TH as $COCO_3$ (mg/L) | Classification | Pre-monsoon | | |
|---|---|---|---|---|
| | | Sample No. | No. of samples | % of Samples |
| <75 | Soft | Nil | Nil | Nil |
| 75–150 | Moderately hard | 33 | 1 | 2.63 |
| 150–300 | Hard | 3 | 1 | 2.63 |
| >300 | Very hard | 1, 2, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 34, 35, 36, 37, 38 | 36 | 94.74 |
| Total | | | 38 | 100 |

5% of the samples are in moderately hard to hard category. Therefore, the groundwater in the study area is not suitable for drinking.

## Cations

The analytical data on cations demonstrated that 32% of samples with $Na^+$ and each of $K^+$ and $Ca^{2+}$ concentration (11% each) are exceeding the WHO limit, whereas $Mg^{2+}$ concentrations are within permissible limits. This may be due to the ion exchange process occurring in the aquifer. The spatial distribution of sodium, potassium, calcium and magnesium in groundwater samples of the study area is shown in Figs. 4, 5, 6 and 7.

## Anions

Anions such as bicarbonate 97% and nitrate 52% of the sample locations exceed the standards. The spatial distribution of bicarbonate in groundwater is shown in Fig. 8. The permissible limit for bicarbonate (i.e. 300 mg/L) exceeded in majority of the samples which confirm that all carbonate minerals are dissolved in the groundwater. This is further evident that no carbonate is detected in all the groundwater samples investigated.

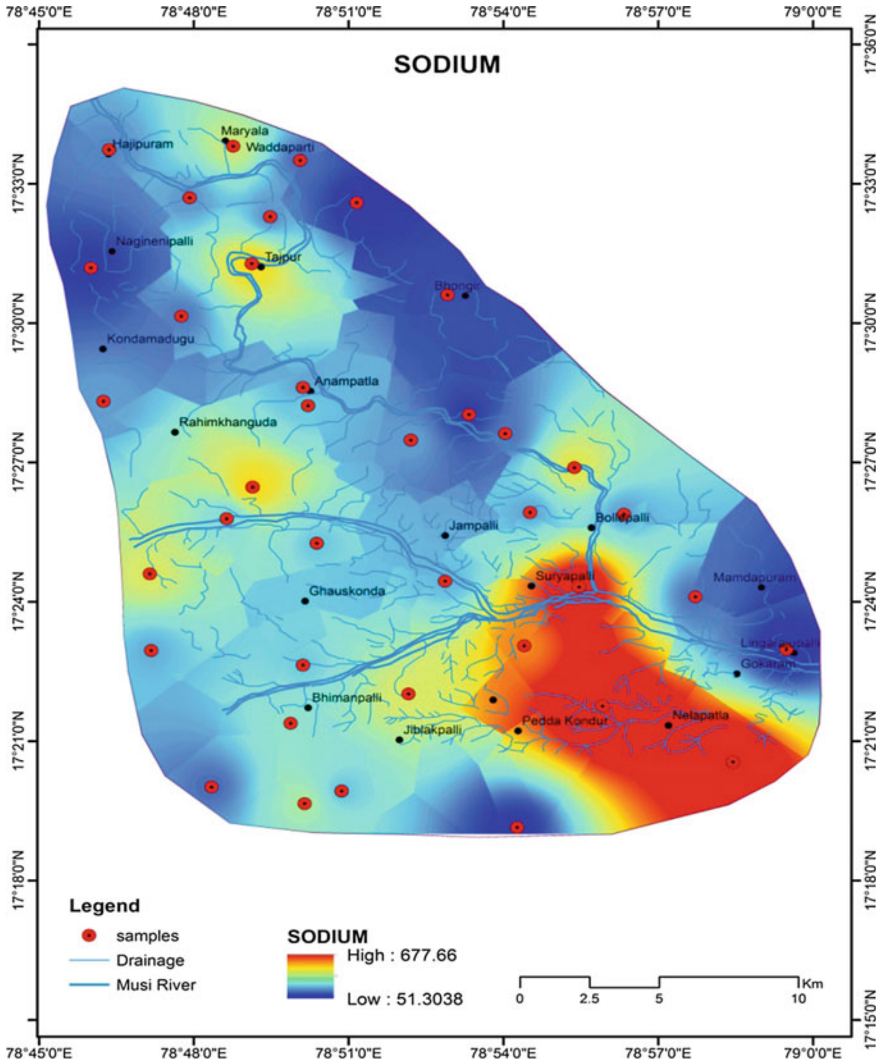



**Fig. 4** Spatial distribution of sodium (mg/L) in groundwater

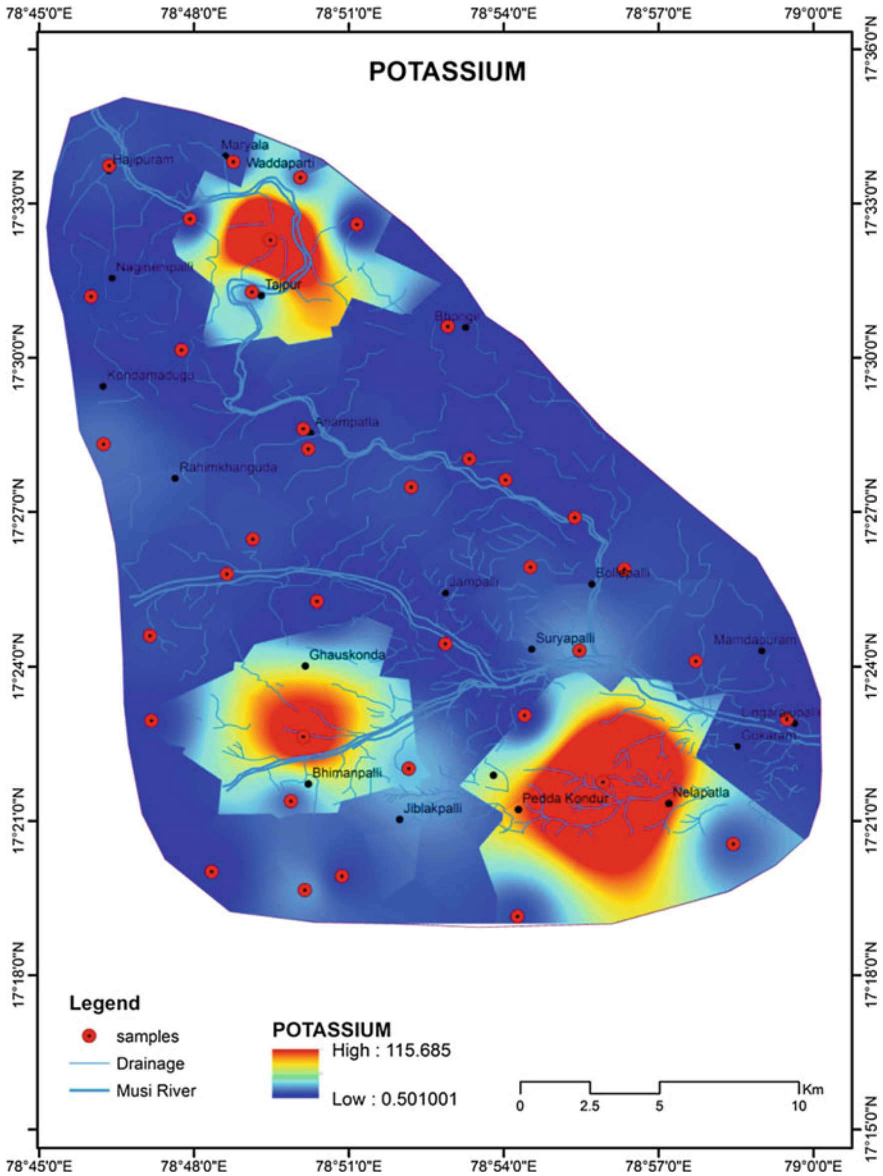



**Fig. 5** Spatial distribution of potassium (mg/L) in groundwater

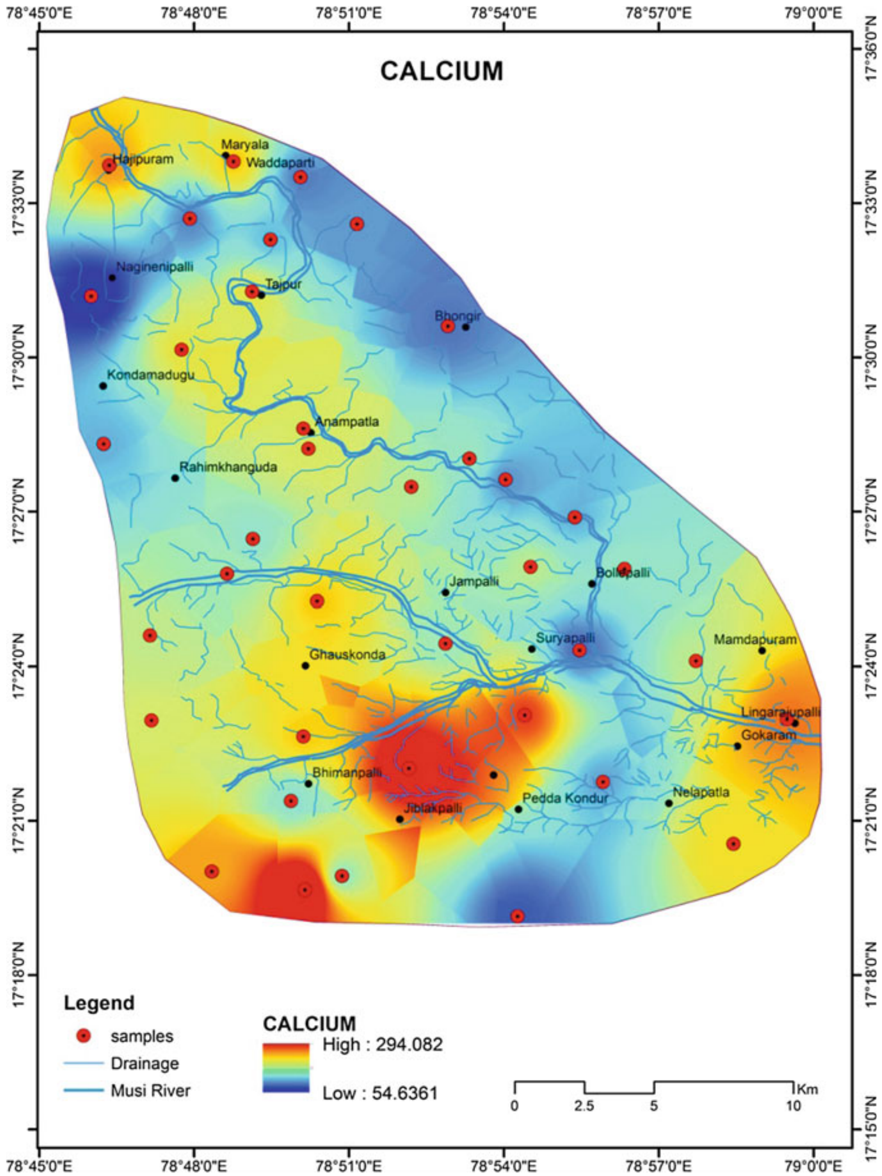



**Fig. 6** Spatial distribution of calcium (mg/L) in groundwater

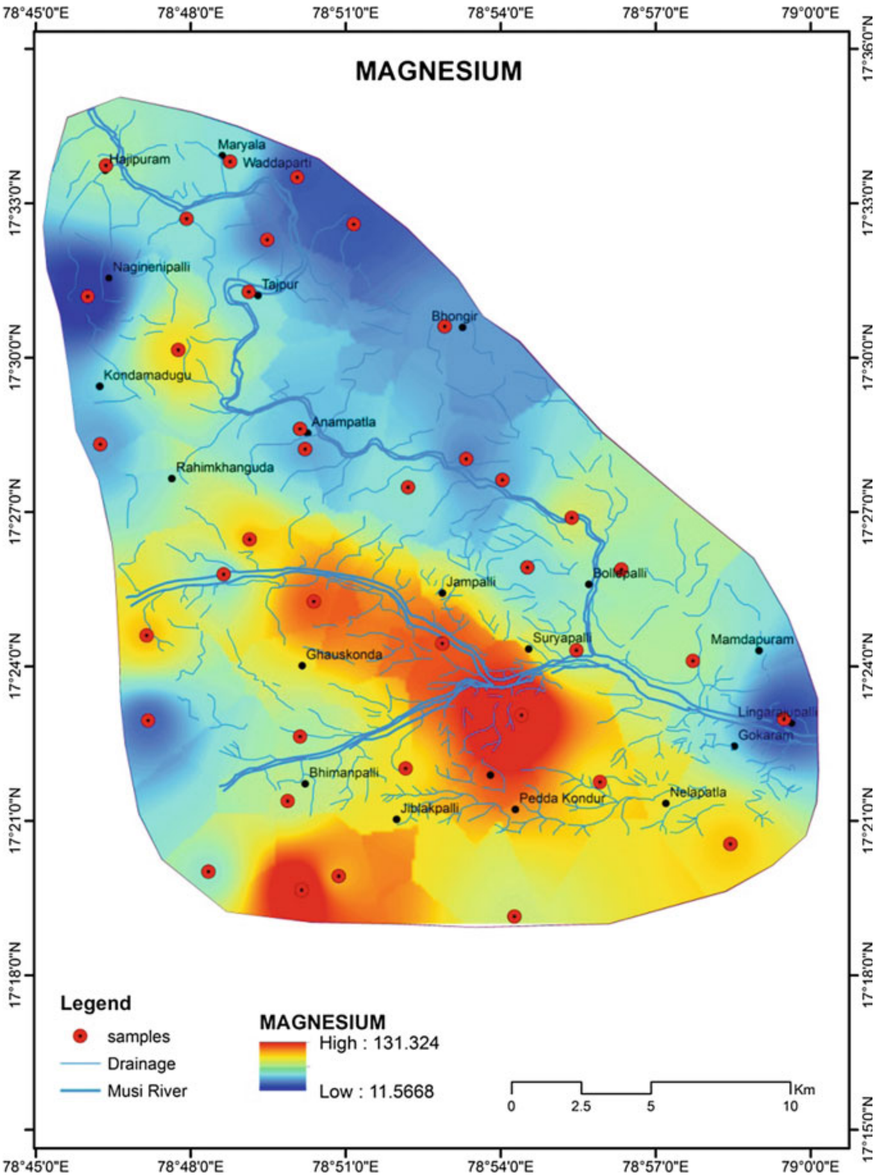



**Fig. 7** Spatial distribution of magnesium (mg/L) in groundwater

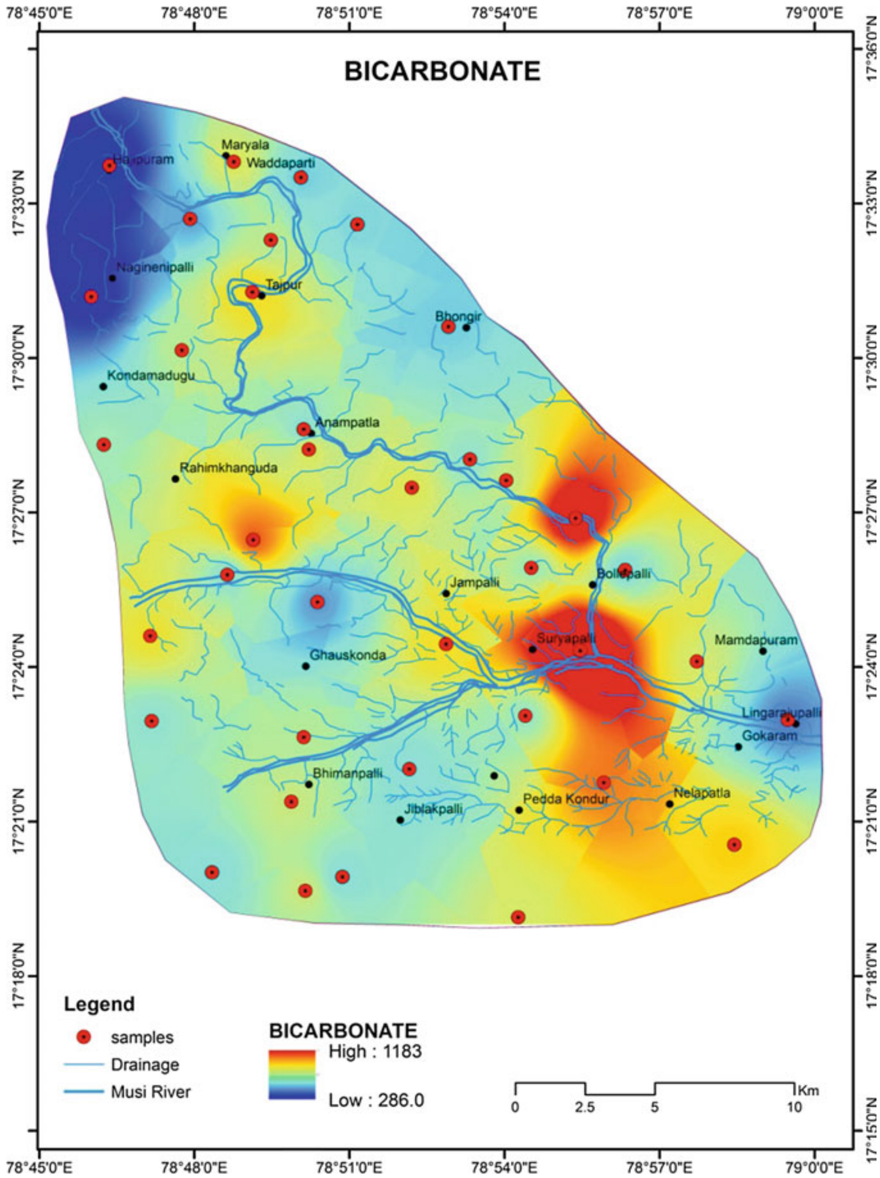



Fig. 8 Spatial distribution of bicarbonate (mg/L) in groundwater

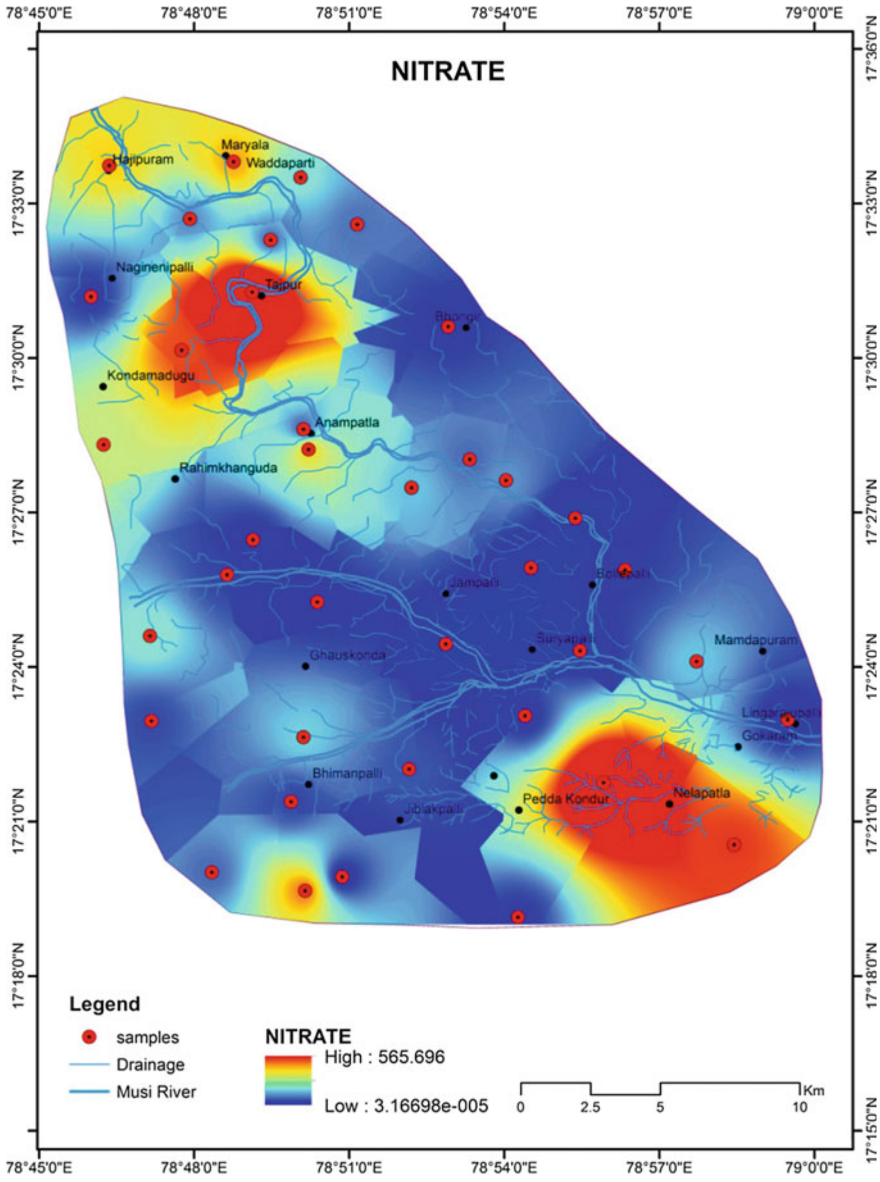



**Fig. 9** Spatial distribution of nitrate (mg/L) in groundwater

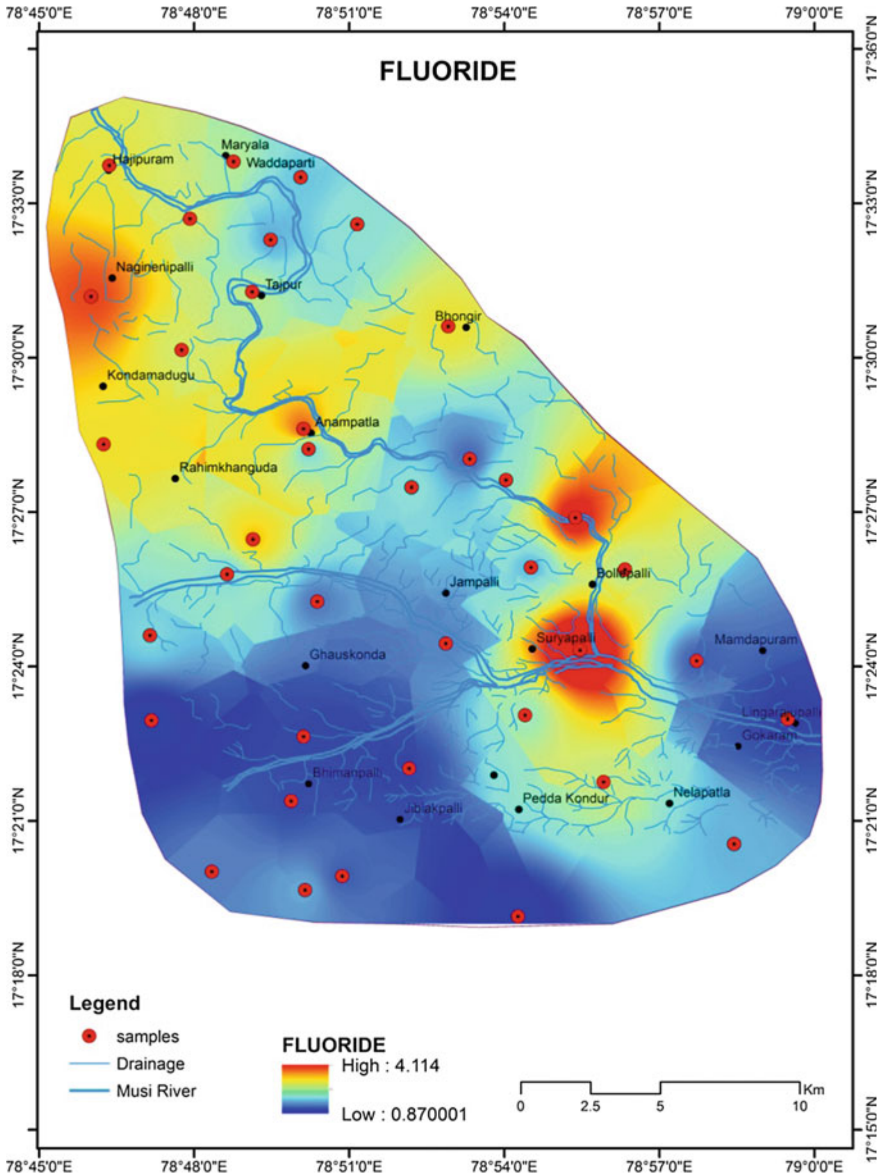



**Fig. 10** Spatial distribution of fluoride (mg/L) in groundwater

**Fig. 11** Dental fluorosis affected in the people of the study area

Further, distribution of nitrate in groundwater samples of the study area is shown in Fig. 9. The groundwater samples exceed the WHO permissible limit of 45 mg/L nitrate, and it varies between below detection limit to 565.69 mg/L with an average of 110.63 mg/L. Nitrate content in groundwater is because of the excess use of fertilizer on to the agricultural land. Further, this may be evident from the reported literature (Jalali 2005).

Fluoride concentration varies between 0.87 and 4.12 mg/L with average 1.91 mg/L. The spatial distribution of the fluoride in the study area is shown in Fig. 10. On the other hand, high concentration of fluoride in the study area is observed in 66% of the sampling locations. The average concentration observed (1.91 mg/L) in the study area is also above the WHO permissible limit of 1.5 mg/L which further indicates that the people in the area are severely affected with dental fluorosis (Fig. 11).

Natural waters contain chloride and sulphate ions, and their concentrations vary considerably according to the mineral content of the earth in any given area. Low-to-moderate concentrations of both chloride and sulphate ions add palatability to water. In fact, they are desirable for this reason. Chlorides give salty taste to water. Excessive concentrations of either, of course, can make water unpleasant to drink. The high concentration of sulphate in drinking water is toxic and cause laxative effective on human beings.

The present investigations showed that chloride content varying between 54.08 and 1444 mg/L (average = 501.56 mg/L) with 30% of the total samples exceeded the permissible limit. Sulphate is found to be within the permissible limit of 400 mg/L as per WHO standards except 5% of the samples. The spatial distribution of chloride and sulphate is shown in Figs. 12 and 13.

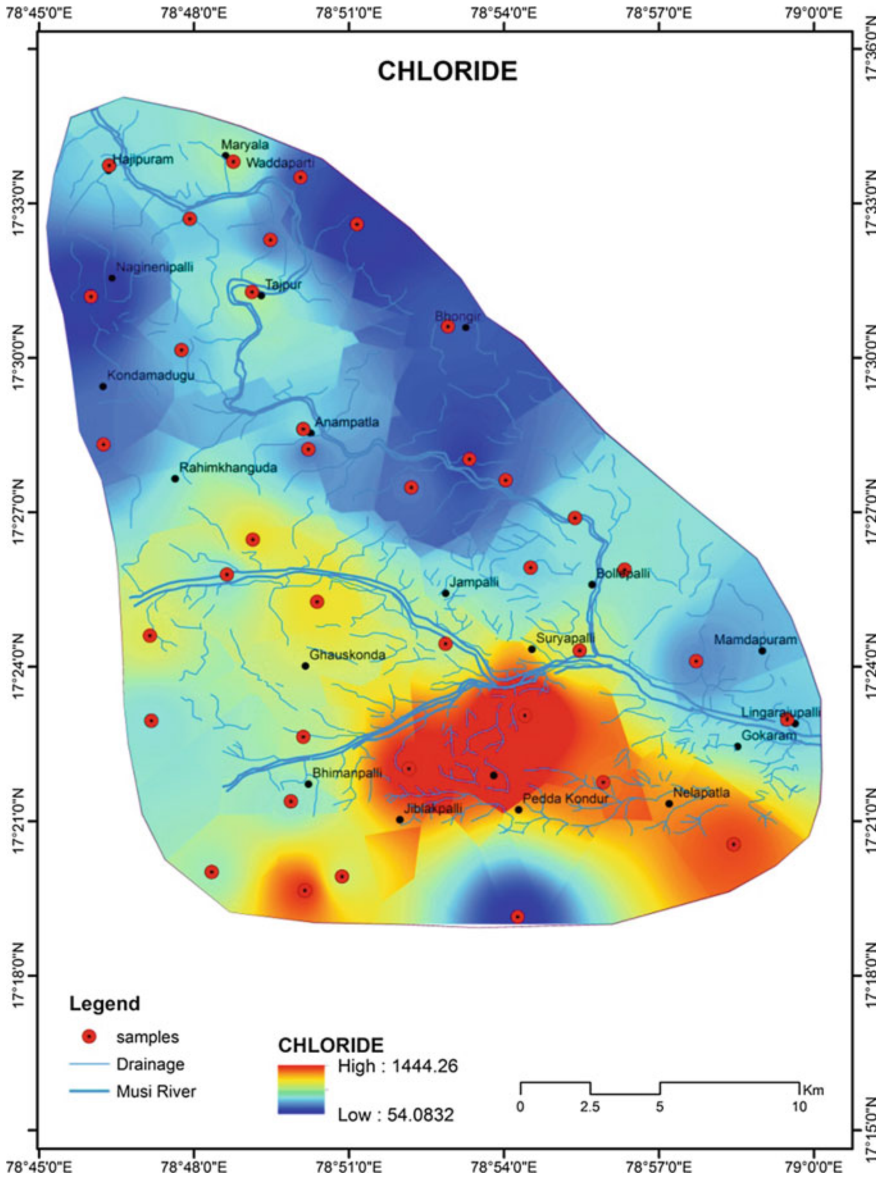



**Fig. 12** Spatial distribution of chloride (mg/L) in groundwater

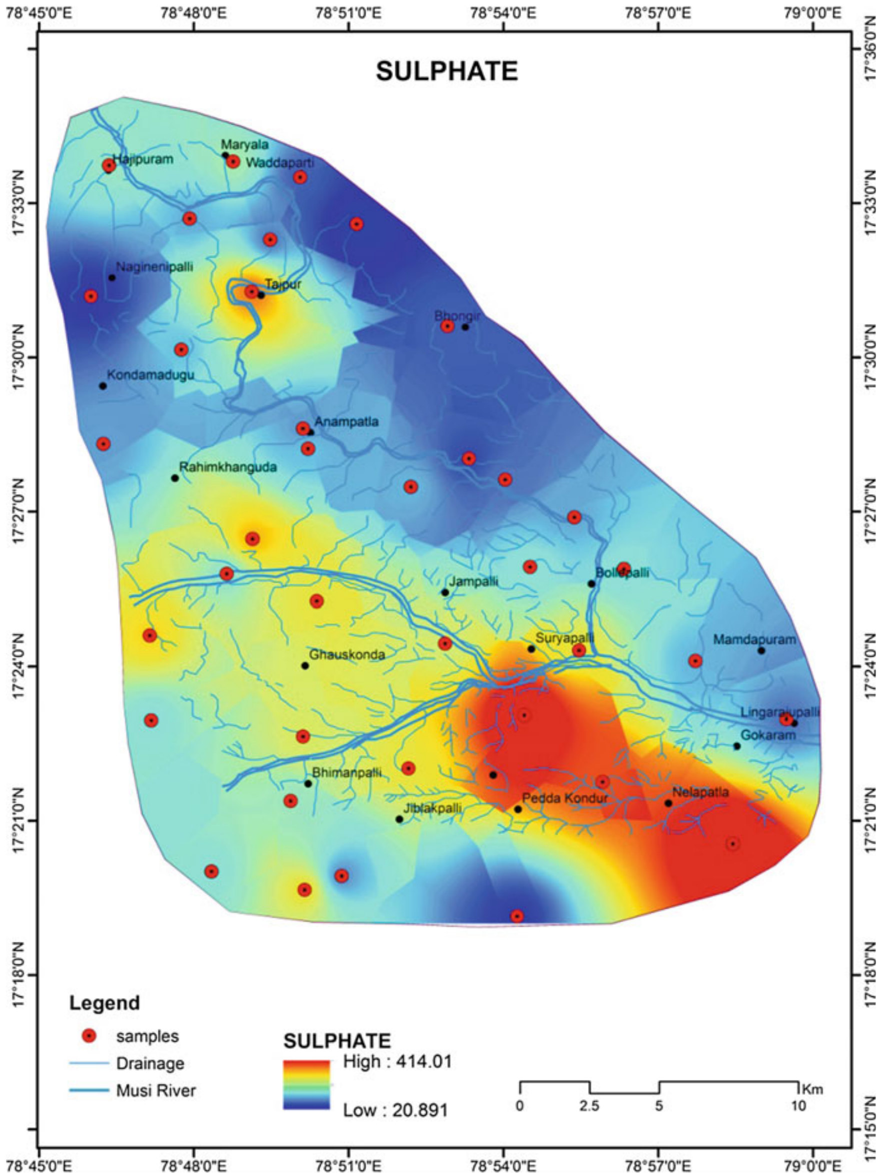



**Fig. 13** Spatial distribution of sulphate (mg/L) in groundwater

## Conclusions

The study of major ion concentration of the groundwater of the Bhongir watershed showed high concentration of $Na^+$ than the others cations (Na>Ca>Mg> K) is probably due to the loss of $Ca^{2+}$ and $Mg^{2+}$ and gain of $Na^+$ by the cation exchange process. Among the anions, bicarbonate is identified in majority of the samples in the following order $HCO_3$ > Cl > $SO_4$ which confirms that all carbonate minerals might have been dissolved and added to the groundwater system. Nitrate and fluoride levels are higher than the permissible levels in most of the samples around 53 and 66% of samples, respectively. This indicates that the nitrate may be due to anthropogenic influence, whereas fluoride is due to geogenic sources.

It is evident from the higher values of physicochemical results, especially hardness, alkalinity and bicarbonates, that most of the water samples analysed in this study are contaminated due to geogenic as well as anthropogenic activities. The groundwater quality is poor in the study area due to various contaminants at higher concentration than permissible; thus, it is unfit for drinking purposes. The present investigations recommended stringent monitoring and control/mitigation measures in the regions where low groundwater quality is essential to ensure sustainable safe use of the resource.

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# Spatial and Temporal Nitrate Transport in Deep Heterogeneous Vadose Zone of India's Alluvial Plain

**Jahangeer, Pankaj Kumar Gupta and Brijesh Kumar Yadav**

**Abstract** Nitrate percolates through deep vadose zone before entering groundwater. In the previous few years, researchers have only focused on the movement of nitrate up to the root zone depth of the crops. Few studies have been done on movement of nitrate in unsaturated region beyond root zone depth. In the present paper, spatial and temporal nitrate transportation in deep vadose zone has been studied. A case study, considering the hydrogeological features of alluvial plain, has been done for nitrate transportation in deep vadose zone. Heterogeneity in the subsurface layers of vadose zone has also been incorporated in this study. The fate of nitrate plume for varying concentration has been studied. The results in this study mainly quantify nitrate flux along with water flux, pressure head, and water content in various heterogeneous layers before entering groundwater table. Simulation results suggest that heterogeneity with dual permeability has a profound impact on nitrate transport in vadose zone.

**Keywords** Nitrate transport · Vadose zone · Alluvial soil · Heterogeneity Groundwater

## Introduction

Protection of soil-groundwater resources from surface pollutants needs greater attention as groundwater, once polluted, is very difficult to remediate. Solute transport and groundwater pollution risk assessment is an effective way of identifying areal extent of aquifers which are more vulnerable to contamination. Changing land use patterns like expansion in urban areas, industrial setups, excessive use of fertilizers, and pesticides in agricultural sector pose serious threat to the quality of groundwater (Soutter and Pannatier 1996). The groundwater is not readily contaminated, but once it has been contaminated, it is expensive, time

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consuming, and extremely difficult to restore the lost integrity of this precious resource (Vrba and Zaporožec 1994; Yadav et al. 2012). The groundwater contamination occurs in the areas where the surface pollutant load generated from industries, agricultural land, dairy farms, urban area, and mining activities (Al-Adamat et al. 2003; Kumar et. al. 2015). Groundwater contamination concern relates primarily to the so-called unconfined aquifers, particularly the areas where vadose zone is highly pervious and water table is shallow (Gupta et al. 2013; Jahangeer et al. 2017). Sufficient contaminant menace may also be present in areas where underlying aquifers are semi-confined and the confining aquitards are significantly thin. Hence, in-depth study of subsurface water resources and associated pollution risk and allied vulnerabilities is required for taking preventive measures in advance. Therefore, the management of groundwater quality is receiving a widespread attention all around the world.

Heterogeneity is ubiquitously present in the entire vadose zone (Vogel et al. 2010). Because of this heterogeneity, nonuniform flow of water takes place leading to the nonequilibrium conditions in the vadose zone. Water flows from these macro-pores bypassing the rest of the soil matrix resulting in nonuniform wetting of the soil as flowing water has very less time to equilibrate with the soil matrix. These nonequilibrium conditions were termed to be most frustrating processes in terms of hampering accurate predictions of contaminant transport in soils and fractured rocks by Simunek et al. (2003). Preferential flow and transport hasten the movement of agricultural contaminants like fertilizers, pesticides, pathogens, trace elements to the groundwater through vadose zone (Gärdenäs et al. 2006; Wang et al. 2007). Due to intensive use of Nitrate as chemical fertilizers or manure to increase the agricultural productivity of the soil, which is necessary to cater the demand of growing population and its high mobility in the vadose zone is emerging as potential groundwater contaminant (USEPA 1990). Onsoy et al. (2005) and Botros et al. (2009) studied the process of movement of water and nitrate in the deep and heterogeneous vadose zone using the soil core samples to the vadose zone and found that non-equilibrium movement of water and nitrate in the vadose zone resulting in faster leaching of the nitrate to the groundwater and hence higher number of non-detects in the soil sample.

Computer modeling is also a useful tool for simulating nitrate distribution under laboratory and also in field conditions. Many numerical models have been tested so far such as NCSWAP (Molina and Richards 1984), LEACHM (Hutson and Wagenet 1992), RZWQM (RZWQM Team 1995), CHAIN-2D (Simunek and van Genuchten 1994), CHAIN_IR (Zhang 1997), and HYDRUS-2D (Simunek et al. 1999). HYDRUS programme numerically solves Richards' equation for variably saturated water flow, and advection–dispersion equations for both heat and solute transport. In addition to this, the model also allows specification for root water uptake, which tends to affect the spatial distribution of water and nitrate between different nitrate applications. Therefore, the objective of this study is to investigate spatial and temporal transport of nitrate in deep heterogeneous considering the hydrogeological features of alluvial plain.

## Methodology

The numerical simulation was performed using HYDRUS 2/3D to solve the governing equation of transport of nitrate in unsaturated zones. Modeling flow and transport processes in porous media rely on the continuum approach which averages flux over a local volume of a porous medium, referred to as the representative elementary volume (REV) (Bear 1972). This REV-averaged flux is then assigned to the center of the REV that serves as the mathematical definition of the spatial location of the flux.

## Governing Equations for Flow

Based on the continuum concept and the REV approach, water flow in variably saturated media at the laboratory scale is governed by the classical Richards' equation stated as below for one-dimensional flow:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z} + 1\right)\right] - S_{\mathrm{W}} \quad (1)$$

where $\theta$ is volumetric water content [−], $t$ is the time [$T$], $h$ is the soil water matric head [$L$], $z$ is vertical coordinate taken positive upward [$L$], and $S_{\mathrm{W}}$ is a sink term which represents the volume of water removed per unit time from a unit volume of soil [$T^{-1}$]. $K(h)$ is the unsaturated hydraulic conductivity [L $\mathrm{T}^{-1}$].

A number of closed-form formulas have been proposed to empirically describe the dependence of hydraulic functions $K(h)$ and $\theta$(h) on pressure head (Brooks and Corey 1966; Gardner 1958; Haverkamp et al. 1977; van Genuchten 1980; Russo 1988). Among these relationships Mualem (1976) and van Genuchten (1980) are widely used in modeling of unsaturated flow and are therefore used in this paper. They can be summarized as follows:

$$K(h) = K_{\mathrm{s}} S_{\mathrm{e}}^{l}\left[1 - \left(1 - S_{\mathrm{e}}^{1/m}\right)^{m}\right]^{2} \quad (2a)$$

$$S_{\mathrm{e}} = \frac{\theta(h) - \theta_{\mathrm{r}}}{\theta_{\mathrm{s}} - \theta_{\mathrm{r}}} = \left[1 + |\alpha h|^{n}\right]^{-m} \quad (2b)$$

where $K_{\mathrm{s}}$ denotes saturated hydraulic conductivity ($\mathrm{LT}^{-1}$), $S_{\mathrm{e}}$ (−) is called effective water saturation ($0 \leq S_{\mathrm{e}} \leq 1$), $\theta_{\mathrm{s}}$, and $\theta_{\mathrm{r}}$ (−) are the saturated and residual water content, respectively, and $\alpha$ ($\mathrm{L}^{-1}$), $m$ (−), and $n$ (−) are empirical parameters dependent on soil type where $m = 1 - 1/n$ and $l$ denotes tortuosity/connectivity coefficient (−) which is found to have a value of 0.5 from the analysis of a variety of soils (Mualem 1976).

## Governing Equations for Solute Transport

The classic advection-dispersion equation for transport has been adopted to account for mixing and spreading of an inert solute during transient simulations. Advection-dispersion equation for a conservative trace is written as:

$$\frac{\partial \theta C}{\partial t} = \frac{\partial}{\partial x_i}\left(\theta D_{ij}\frac{\partial C}{\partial x_j}\right) - \frac{\partial v_i C}{\partial x_i} - S_c \tag{3}$$

where $C$ is the local concentration in the soil solution [$M\ L^{-3}$], $v_i$ is the $i$th component of water velocity [$L\ T^{-1}$], $D_{ij}$ is the hydrodynamic dispersion coefficient tensor [$L^2\ T^{-1}$] ($i, j$ = 1, 2, 3), and $S_c$ ($M\ L^{-3}\ T^{-1}$) represents a sink term for solutes. Knowledge on water content and water velocity, $v$, is obtained from solutions of the Richards' and Darcy's equations. The second term on the right-hand side of Eq. (3), $\partial v_i C/\partial x_i$, is referred to as the advection term that describes the transport of solute traveling at the same velocity as water. The hydrodynamic dispersion coefficient $D_{ij}$ tensor, which describes the combined effect of mechanical dispersion and molecular diffusion, is given by (Scheidegger 1960)

$$D_{ij} = (\alpha_L - \alpha_T)\frac{v_i v_j}{v} + \alpha_T v \delta_{ij} + D_o \tag{4}$$

where $\alpha_L$ and $\alpha_T$ are longitudinal and transverse dispersivities, respectively, $v$ is the magnitude of pore water velocity, $\delta_{ij}$ is the Kronecker delta ($\delta_{ij} = 1$ if $i = j$, and $\delta_{ij} = 0$ otherwise), and $D_o$ is molecular diffusion.

## Model Domain and Boundary Conditions

In 2D models, the model domain is extended in the lateral horizontal direction and domain dimensions are assumed to be 1 m [$x$] × 0.2 m [$z$]. In the simulation domain, the left and right boundary conditions are "No flux" for water and solute transport. The top water boundary condition for the simulation domains is applied as the rainfall depth (cm/day), and bottom water boundary conditions are specified as seepage face (Fig. 1).

## Results and Discussion

Figure 2 shows that the nitrate content is varying in vadose zone with respect to simulation time due to transient flux boundary taken at top surface. The observed BTCs for the study domain are shown in Fig. 2 using the dot points of black colors

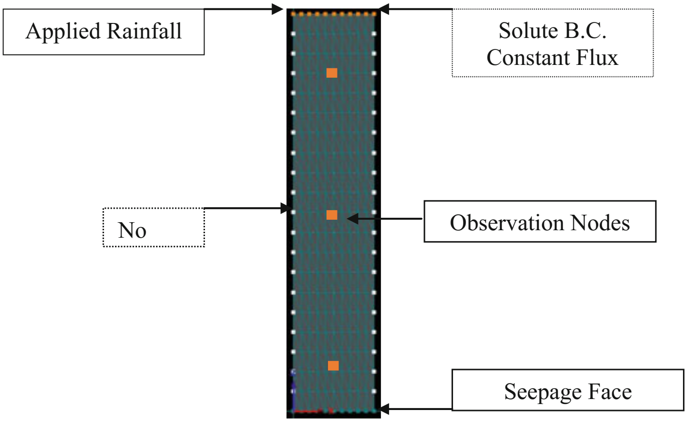
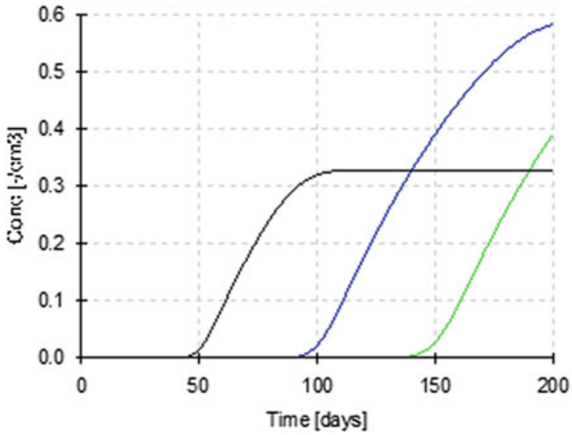



**Fig. 1** Study domain for simulation of nitrate in 2D

**Fig. 2** Simulated BTCs for nitrate transport in study domain




denoted the upper observation point, blue line denoted the middle observation point, and green line denoted the lower most observation point.

The simulated domain concentration profile for time, $t$ = 00 days, $t$ = 50 days, $t$ = 100 days, $t$ = 200 days, and $t$ = 365 days, is plotted in Fig. 3. It shows that the nitrate movement is dominated by water velocity and reached to water table. In Fig. 3, the concentration at time $t$ = 365 days, the high concentration is at mid of the profile, which indicates the equilibrium concentration in mid-region and attenuating concentration in upper region. The concentration profile more clearly shows in contour map presented in Fig. 4.

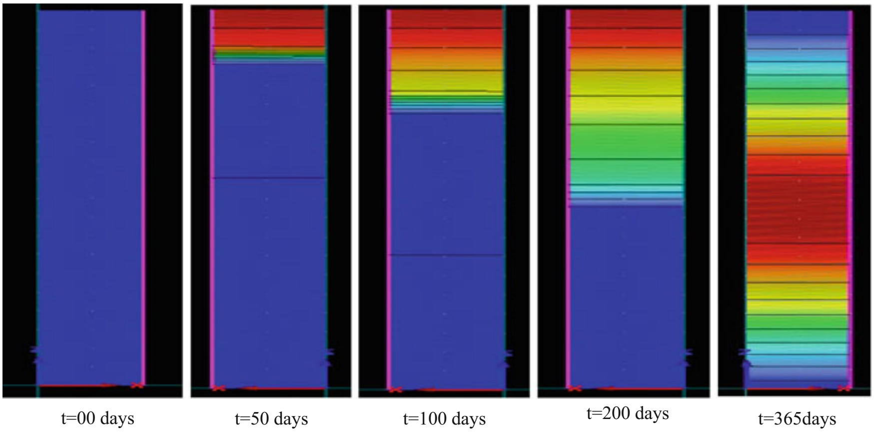



**Fig. 3** Simulated concentration profile of the domain at time $t$ = 00 days, $t$ = 50 days, $t$ = 100 days, $t$ = 200 days, and $t$ = 365 days

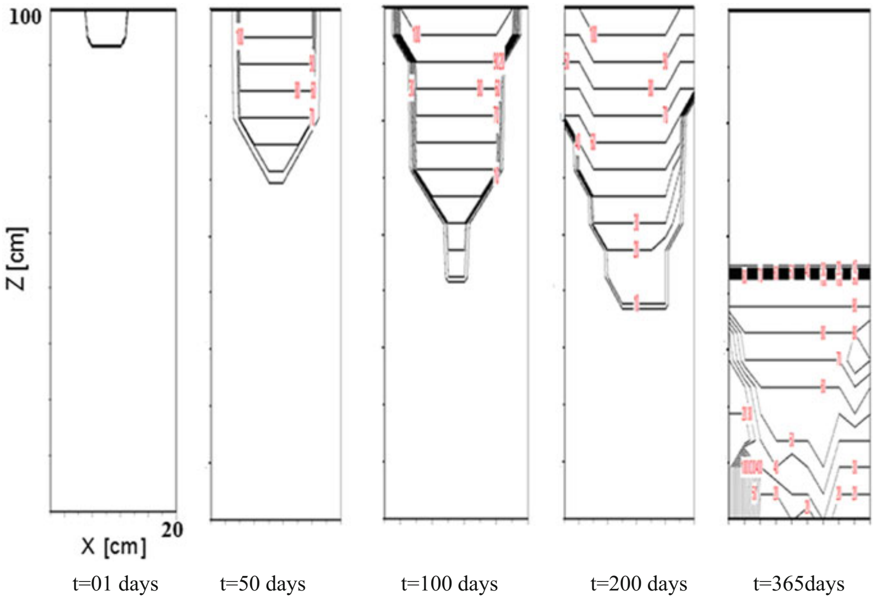



**Fig. 4** Observed concentration profile of the domain at time $t$ = 00 days, $t$ = 50 days, $t$ = 100 days, $t$ = 200 days, and $t$ = 365 days

## Conclusions

This study provides a detailed long-term, multiyear transient simulation of nitrate transport in a deep vadose zone. It is based on the site conditions, which offers a rich database for detailed geologic, hydraulic, and chemical characterization of the deep vadose zone stratigraphy that is typical for alluvial sediments. The site database provides a foundation for the development and validation of alternative modeling tools to assess the potential for nitrate leaching to groundwater in the presence of a deep, heterogeneous vadose zone at the site. In conclusion,

(i) Simulation results suggest that heterogeneity with dual permeability has a profound impact on nitrate transport in vadose zone.
(ii) Low irrigation efficiencies (on the order of 45–65%) contribute not only to significant leaching of fertilizer, but also to rapid transport of nitrate to groundwater.

Other conceptual elements that require more field data prior to further model development include spatially variable denitrification, e.g., high denitrification rates in stagnant zones of water flow but not in preferential flow paths, nitrogen losses due to volatilization at the land surface.

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# Riverbank Filtration as a Sustainable Solution for Drinking Water Quality and Quantity Problems in Haridwar, Uttarakhand

**Shashi Poonam Indwar and N. C. Ghosh**

**Abstract** River bank filtration is a sustainable solution for drinking water quality and quantity problems in Haridwar, Uttarakhand. Riverbank filtration (RBF) is an efficient and low-cost natural alternative technology for water supply application, in which surface water contaminants are removed or degraded as the infiltrating water moves from the river/lake to the pumping wells. The removal or degradation of contaminants is a combination of physicochemical and biological processes. This paper presents an investigation to the full set-up of 22 RBF large diameter (10 m) caisson wells located along the bank of River Ganga in order to supply portable drinking water for Haridwar (112,617 persons residing permanently in the main city). These 22 RBF large diameter (10 m) caisson wells were constructed along the bank of River Ganga at Haridwar, each 7–10 m deep, and are located 50–450 m from the Ganga River or the Upper Ganga Canal. Water samples from River Ganga as induced surface water, from Upper Ganga Canal (UGC), groundwater (open well) and from RBF wells were collected and analysed for pre-monsoon and post-monsoon period. Quality measurements of physical, chemical and microbiological characteristics were obtained. Comparison of water supplied from RBF wells with surface, UGC and background natural groundwater for the investigated Haridwar site has proven the effectiveness of RBF technique for potable water supply in Haridwar district of Uttarakhand. Physicochemical and microbiological characteristics of the produced water are better than the allowable standards (IS 10500) for drinking purposes or recommended WHO limits. The results prove effectiveness of RBF method for sustainable drinking water supply in feasible locations.

**Keywords** Riverbank filtration · Portable water supply · Quality

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## Introduction

As the world's growing population puts greater demands on the available supply of high-quality drinking water, several advanced treatment technologies have been developed and applied by water utilities to treat waters of degraded quality. These technologies include adsorption, ion exchange, membrane filtration, soil aquifer treatment and advanced oxidation. Notwithstanding the effectiveness of these technologies, there are challenges for their widespread applications in developing countries. This is primarily attributed to cost (especially for treating large quantities). In this context, an old method called riverbank filtration (RBF) is returning and evolving as an inexpensive and a sustainable approach to improving the quality of surface waters (Shamrukh and Abdel-Wahab 2008). Riverbank filtration is natural pre-treatment technology, where the water is extracted from wells instead of direct surface water abstraction from the river. The underground passage has several advantages, which are useful for drinking water treatment. The underground passage removes particles, bacteria, viruses, parasites, biodegradable compounds, etc. It is well known that river water is characterized by extreme varying concentrations, depending on the water flow, seasonal effects, emissions by municipal and industrial sewage, run-off, etc. However, concentration peaks are compensated and blended during an underground passage. This is due to different retention times, required for the water particles to flow from the river bottom through the underground to a well or to the different porosity of the soil. Therefore, the underground passage acts as a barrier against shock loads, caused from emergency situations such as defects in industrial wastewater plants. The compensation of temperature peaks will improve the water quality, too. This treatment technique is currently being used in Europe along the Rhine, Danube, Elbe and Seine rivers (Kühn and Müller 2000; Doussan et al. 1997). Along the Rhine, there is one of the first RBF plants in Dusseldorf, Germany, to supply drinking water to a population of about 600,000 (Ray et al. 2002a). In India, RBF technology is being implemented in Haridwar, Satpuli, Agastmuni, Srinagar, Karanprayag, Nainital and Delhi (Ghosh et al. 2015).

Riverbank filtration is typically conducted in alluvial valley aquifers, which are complex hydrologic systems that exhibit both physical and geochemical heterogeneity. During RBF, which is similar to slow sand filtration, the impurities of river water are attenuated through combination treatment processes. The performance of RBF systems depends upon well type and pumping rate, travel time of surface water to wells, site hydrogeologic conditions, source water quality, biogeochemical reactions in sediments and aquifer, and quality of background groundwater (Schijven et al. 2000; Ray 2001). River bank filtration (RBF) is considered as an efficient treatment (or pre-treatment) for removing various physical, chemical and biological contaminants that may be present in surface water (Ray et al. 2002b; Berger 2002; Shankar et al. 2009).

## Study Area Description

The bottom-entry caisson wells (RBF) are 7–10 m deep and are located 50–450 m from the Ganga River or the Upper Ganga Canal. As of April 2011, at least 12 wells operated continuously (24 h), with the remaining wells operating for 9–19 h per day. Each well usually has 2–3 fixed-speed vertical line shaft pumps, with each pump having a rated discharge of 600–2820 litres per minute (LPM), with a mean rated discharge of 1620 for all pumps. However, the pumps operate on a rotational basis for a fixed number of hours each day, which is necessary for the other pump(s) to cool and avoid malfunctions. Usually during the summer (pre-monsoon) and during religious festivals, the wells operate continuously as the demand for drinking water peaks. At other times, only some wells operate continuously. The abstracted water is chlorinated at the wells and then supplied directly into the distribution network. The shortest travel time of bank filtrate to the RBF wells located on Pantdweep Island <15 m from the bank of the surface water body is 2 days to >100 days for wells located further away.

Haridwar is one of the very important Hindu pilgrimage sites of the world. The city, situated along the right bank of the River Ganga, has population of approximately 225,235 (Census of India 2011). More than 50% (>64,000 $m^3$/day) of drinking water requirement of the city is supplied by 22 RBF wells. Each RBF well is equipped with a pump set above the ground surface and extracts water by a suction pipe of 15 cm diameter. Some have been constructed as a tube well in the caisson well. The tube wells have an aquifer penetration depth of about 5–6 m below the bottom of the caisson well. The discharge of the pumps ranges from 72 to 170 $m^3$/h, and the operating hours of these wells vary from one season to another between 10 and 24 h continuously in a day. A schematic diagram of RBF wells (pumping wells) in Haridwar is shown in Fig. 1. The wells tap the unconfined aquifer of average thickness about 21 m hydraulically connected with the river/canal. Being located in the vicinity of the canal and river network, the wells when pumped induce water from both river and canal at varying rates depending upon the distance of the wells from them.

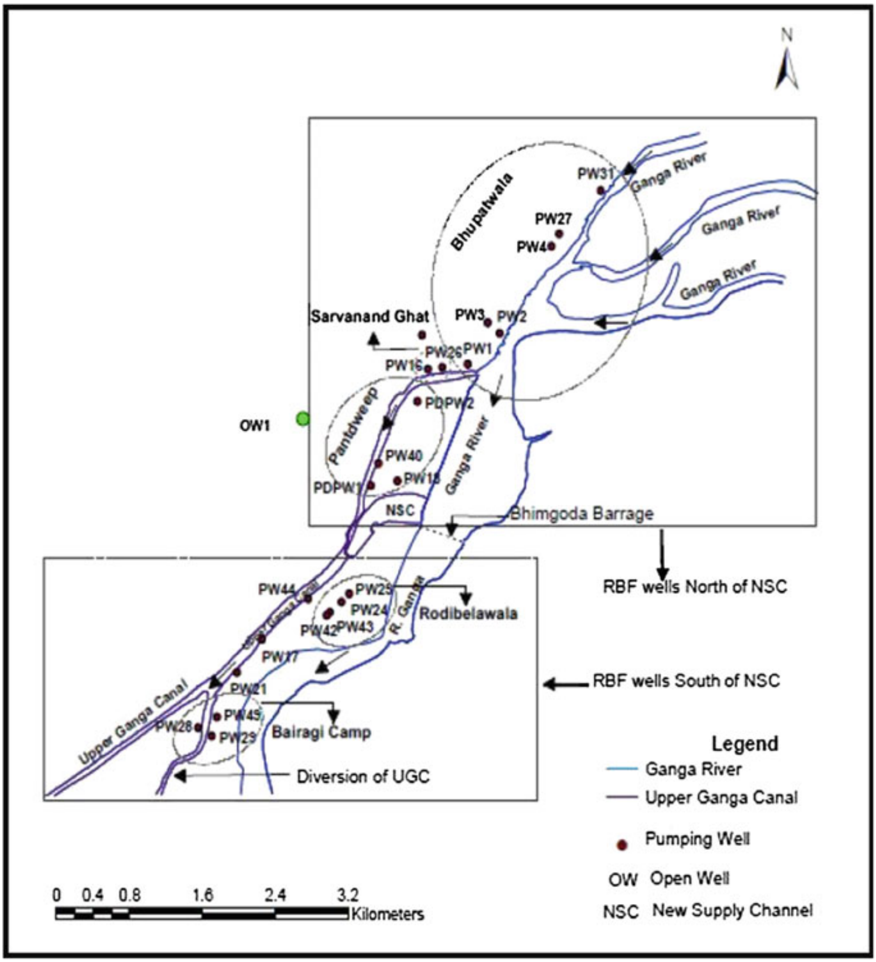


**Fig. 1** Study area representing setting of 22 riverbank filtration wells in the vicinity of the River Ganga and Upper Ganga Canal (UGC) at Haridwar (*dots* also indicate sampling points)

## Hydrogeological Settings

The study area falls under the north-eastern part of Haridwar district which comprises of boulders, pebbles, gravels, sand and clay indicating good recharge zone. Aquifer type is unconfined ranging from 3 to 21 m on which the 22 shallower bottom-entry caisson (RBF) wells are located to pump out water for water supply. The tapping zone of all the 22 RBF wells lies within the unconfined aquifer between depth of 8 and 14 m below the ground surface. Most of the wells have penetrated the aquifer partially, and maintain a considerable gap between the well-bottom and the underneath impervious strata. The hydrogeological formations represented by this unconfined aquifer have a very good hydraulic properties representing hydraulic conductivity (K) value range of 16–50 m/day (Dash et al. 2010).

## Materials and Method

Twenty-seven water samples were collected from 22 wells, River Ganga (upstream and downstream), Upper Ganga Canal (UGC) and groundwater from Haridwar RBF site monthly during monsoon and non-monsoon seasons for the time period 2012–2013 (sample size 8 for monsoon and 10 for non-monsoon). Samples were collected in polyethylene bottles preserved by adding an appropriate reagent (Jain and Bhatia 1988; APHA 1992) and analysed for various water quality parameters as per standard procedures (Table 2) for monsoon and non-monsoon period. The experimental values were compared with standard values recommended by WHO or Indian standards for drinking purposes. Comparison between water samples from RBF wells with River Ganga, UGC and groundwater samples was carried out to indicate the effectiveness of RBF technique for potable water supply in Haridwar district of Uttarakhand.

## Water Sampling and Detailed Methodology

1.0 **Experimental methodology**

1.1 Sampling and preservation
1.2 Chemicals and reagents
1.3 Physicochemical and bacteriological analysis
1.4 Metal ion analysis.

### 1.1 Sampling and Preservation

Water samples were collected from various abstraction wells and River Ganga in clean polyethylene bottles preserved by adding an appropriate reagent (Jain and Bhatia 1988; APHA 1992). The water samples for trace element analysis were collected in acid-leached polyethylene bottles and preserved by adding ultra-pure nitric acid (5 mL/L) Samples for bacteriological analysis were collected in sterilized high-density polypropylene bottles covered with aluminium foils. All the samples were stored in sampling kits maintained at 4 °C and brought to the laboratory for detailed chemical and bacteriological analysis.

## 1.2 Chemicals and Reagents

All general chemicals used in the study were of analytical reagent grade (Merck/ BDH). Standard solutions of metal ions were procured from Merck, Germany. Bacteriological reagents were obtained from HiMedia. De-ionized water was used throughout the study. All glassware and other containers used for trace element analysis were thoroughly cleaned by soaking in detergent followed by soaking in 10% nitric acid for 48 h and finally rinsed with de-ionized water several times prior to use. All glassware and reagents used for bacteriological analysis were thoroughly cleaned and sterilized before use.

## 1.3 Physicochemical and Bacteriological Analysis

The physicochemical and bacteriological analysis was performed following standard methods (Jain and Bhatia 1988; APHA 1992). The brief details of analytical methods and equipment used in the study are given in Table 1. Ionic balance was determined; the error in the ionic balance for majority of the samples was within 5%.

## 1.4 Metal Ion Analysis

Metal ion concentrations were determined by atomic absorption spectrometry using Perkin Elmer Atomic Absorption Spectrometer (Model 3110) using air-acetylene flame. Operational conditions were adjusted in accordance with the manufacturer's guidelines to yield optimal determination. Quantification of metals was based upon calibration curves of standard solutions of respective metals. These calibration curves were determined several times during the period of analysis. The detection limits for iron and manganese are 0.003 and 0.001, respectively (Table 2).

**Table 1** Detailed description of water quality sampling points as plotted in concentration plots/ graphs

| WQ sampling points as shown in study area | Description as in plots/graphs | WQ sampling points as shown in study area | Description as in plots/graphs |
|---|---|---|---|
| PW31→ | BWIW31 | PDPW1 | PDIW1 |
| PW27 | BWIW27 | PW25 | IW25 |
| PW4 | BWIW4 | PW24 | IW24 |
| PW2 | BWIW2 | PW43 | IW43 |
| PW3 | BWIW3 | PW42 | IW42 |
| PW1 | BWIW1 | PW44 | IW44 |
| PW26 | BWIW26 | PW17 | IW17 |
| PW16 | BWIW16 | PW21 | IW21 |
| PDPW2 | PDIW2 | PW49 | IW49 |
| PW40 | PDIW40 | PW29 | IW29 |
| PW18 | PDIW18 | PW28 | IW28 |

*PW* pumping wells or *IW* infiltration wells, *BW* Bhupatwala, *PD* Pantdweep

**Table 2** Analytical methods and equipment used in the analysis

| S. No. | Parameter | Method | Equipment |
|---|---|---|---|
| *A. Physicochemical* | | | |
| 1 | pH | Electrometric | pH meter |
| 2 | Conductivity | Electrometric | Conductivity meter |
| 3 | TDS | Electrometric | Conductivity/TDS meter |
| 4 | Turbidity | Turbid metric | Turbidity meter |
| 5 | Alkalinity | Titration by $H_2SO_4$ | – |
| 6 | Hardness | Titration by EDTA | – |
| 7 | Chloride | Titration by $AgNO_3$ | – |
| 8 | Sulphate | Turbid metric | Turbidity meter |
| 9 | Nitrate | Ultraviolet screening | UV–VIS spectrophotometer |
| 10 | Sodium | Flame emission | Flame photometer |
| 11 | Potassium | Flame emission | Flame photometer |
| 12 | Calcium | Titration by EDTA | – |
| 13 | Magnesium | Titration by EDTA | – |
| 14 | BOD | 5 days incubation at 20 °C, titration | BOD incubator |
| *B. Bacteriological* | | | |
| 15 | Total coliform | Membrane filtration (MF) technique | Filtration assembly |
| 16 | Faecal coliform | | |
| *C. Heavy metals* | | | |
| 17 | Iron | Digestion Atomic spectrometry | Atomic absorption spectrometer |
| 18 | Manganese | | |

## Water Quality Analysis of Physicochemical and Bacteriological Parameters

To determine the water quality improvement of riverbank filtrate, samples of the surface, groundwater and the RBF well water have been collected monthly from May 2012 to October 2013 during the non-monsoon and monsoon seasons. Concentration plots of water quality sample parameters represent average values of each water quality parameter during monsoon and non-monsoon for time period 2012–2013 (sample size 8 for monsoon and 10 for non-monsoon). Comparing different water quality parameters for surface, ground and pumping well water samples enabled the assessment of the natural treatment process of riverbank filtrate, when passing the subsurface. As per the physical process of bank filtration, during pumping, the induced bank filtrate from river water after mixing with the groundwater gets withdrawn, which leads to modification of quality of bank filtrate water by the quality of groundwater. Thus, the quality of extracted water depends on mixing proportion of groundwater with the bank filtrate water.

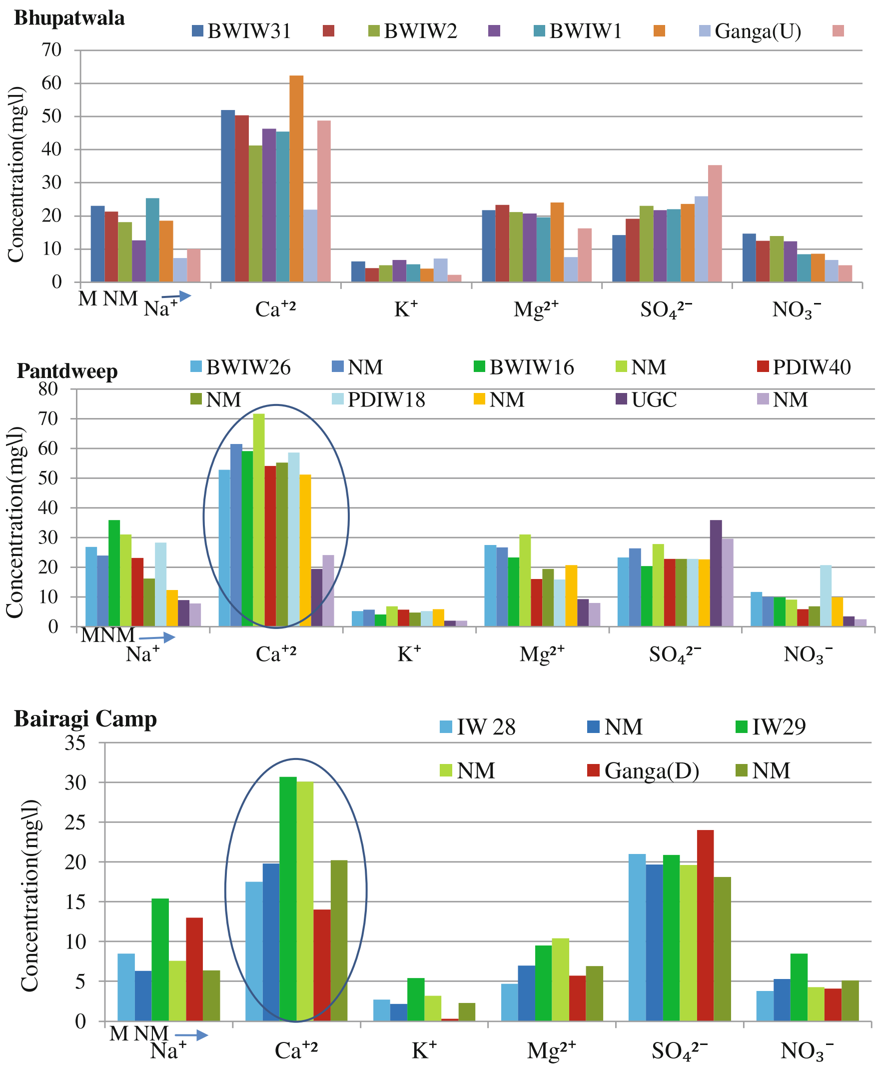


**Fig. 2** Concentration plot of major ions present in pumping wells/infiltration wells and River Ganga (UGC) (*IW* infiltration wells, *M* monsoon, *NM* non-monsoon period for all graphs shown)

Compared results of water quality parameters for surface and groundwater, and pumping (infiltration IW) well showed considerable improvement in the quality of riverbank filtrate water as it moves through the subsurface. Analyses of major ions such as, $Na^{2+}$, $K^{+}$, $Ca^{2+}$, $Mg^{2+}$, $SO_4^{2-}$and $NO^{-3}$ enabled to understand the mineralization process of water during the subsurface passage. Concentration graph showing the major ions present in surface, groundwater and pumping well has been plotted to depict the same for Bhupatwala, Pantdweep and Bairagi Camp area. $Ca^{2+}$

concentration is high in Bhupatwala and Pantdweep as influenced by already mineralized groundwater, whereas Bairagi Camp has low $Ca^{2+}$ concentration due to its near proximity to canal or surface water (Fig. 2).

**Ferrous and manganese** are essential dietary elements present in water, and according to WHO (2011), the recommended health-based limit values for $Fe^{2+}$ and $Mn^{2+}$ are 2 and 0.4 mg/L, respectively. Concentration plot for ferrous and manganese present in river and nearby RBF wells for Bhupatwala, Pantdweep and Bairagi Camp depicts that surface water is having higher concentration of ferrous and manganese ranging from 2.1 to 5.5 mg/L and from 1.9 to 6.7 mg/L, respectively, during monsoon as higher discharge and flow velocities cause erosion of $Fe^{2+}$ and $Mn^{2+}$ which is accumulated in river bed during low flow in river (Fig. 3).

**Turbidity** is the measure of relative clarity of a liquid. Material that causes water to be turbid includes clay, silt, finely divided inorganic and organic matter, algae, soluble colour organic compounds, and plankton and other microscopic organisms. The most important health-related function of turbidity is its use as an indicator of the effectiveness of drinking water treatment processes, particularly filtration, in the

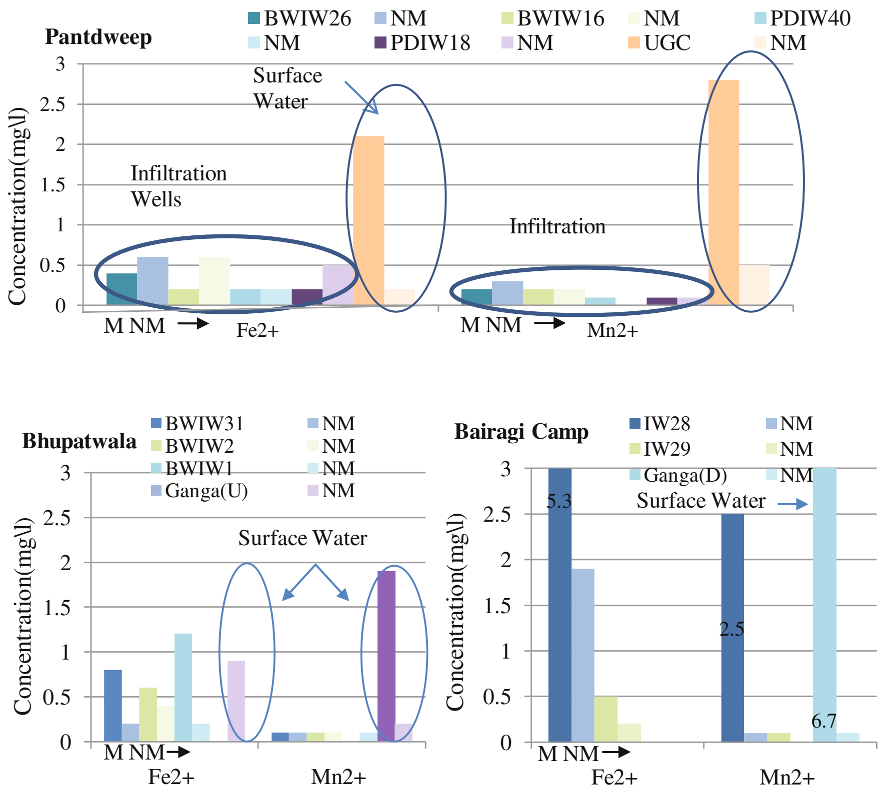


**Fig. 3** Concentration plot of ferrous and manganese present in pumping wells/infiltration wells and River Ganga (UGC)

removal of potential microbial pathogens. There is no precise relationship between the magnitude of turbidity reduction and the removal of pathogens. Compared to groundwater, the turbidity within rivers is mostly higher due to higher flow velocities, which causes erosion of bed material. Microorganisms are typically attached to particulates, and removal of turbidity by riverbank filtration will significantly reduce microbial contamination within water. Turbidity also affects the selection and efficiency of treatment processes, particularly the efficiency of disinfection with chlorine since it exerts a chlorine demand and protects microorganisms and may also stimulate the growth of bacteria (WHO 2011). Turbidity result is visualized in Fig. 4, which shows that the turbidity of Ganga River (upstream and downstream of Bhimgoda Barrage) is 2–15 times more turbid in monsoon season due to high flow velocities, high run-off and erosion of soil and river bed materials, respectively. The turbidity of the abstracted water from RBF wells and groundwater (open well) is below the Indian standard limit of 5 NTU (IS 10500 1993) during monsoon and non-monsoon.

**Electrical conductivity** itself is not a human or aquatic health concern, but because it is easily measured, it can serve as an indicator of other water quality problems. Water with high mineral content tends to have higher conductivity, which is a general indication of high dissolved solid concentration of the water (Mumtazuddin et al. 2012). The electrical conductivity for RBF wells ranges from

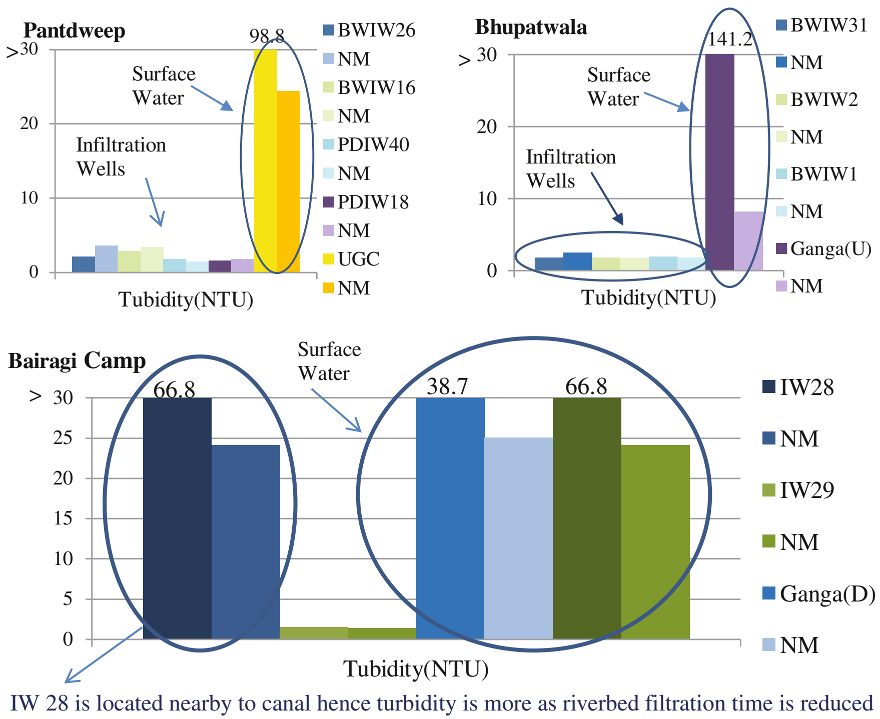


**Fig. 4** Turbidity (NTU) in River Ganga (UGC) and pumping wells/infiltration wells

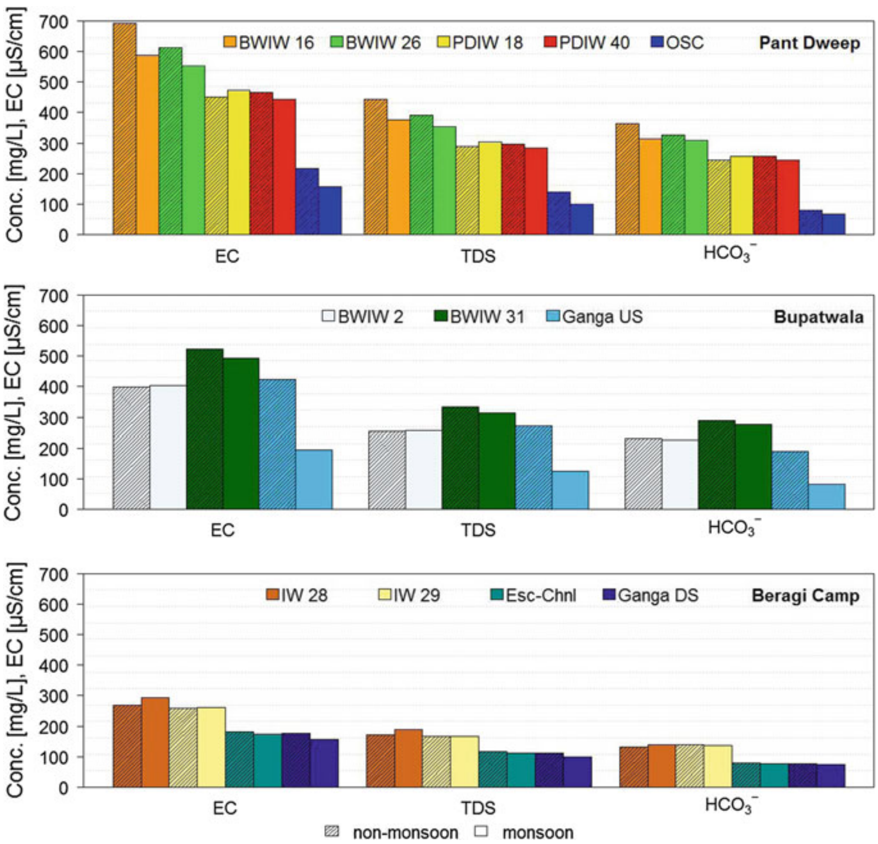


**Fig. 5** River water quality and water quality of pumping wells regarding electrical conductivity (EC), total dissolved solids (TDS) and bicarbonate ($HCO_3^-$)

700 to 400 µS/cm, whereas EC values for canal and Ganga River are 200 µS/cm indicating RBF wells have high mineral content compared to canal/river as influenced by already mineralized groundwater (Fig. 5).

**Total dissolved solids (TDS) and $HCO_3^-$** level in RBF wells, canal and River Ganga are well below the acceptable limit of 500 and 200 mg/L as per Indian Standards (IS 10500). The concentration of $HCO_3^-$ and TDS in RBF wells and groundwater is high due to geogenic sources as TDS refer mainly to inorganic substances that are dissolved in water. The effects of TDS on drinking water quality depend on the levels of its individual components; excessive hardness, taste, mineral depositions and corrosion are common properties of highly mineralized water (Fig. 5).

The count of biological parameters, viz. **total coliform** and **faecal coliform**, although found to be removed considerably in the extracted water, still remained above the acceptable limit, for both non-monsoon and monsoon periods. The per

**Table 3** Min.–Max. and Mean ± Std. count of total coliform and faecal coliform for non-monsoon and monsoon period

| | River and canal water | | | | Extracted water (RBF wells) | | | | Groundwater (Open well) | | | | Acceptable limit (IS:10500) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Non-monsoon | | Monsoon | | Non-monsoon | | Monsoon | | Non-monsoon | | Monsoon | | |
| | (Min.–Max.) | (Mean ± Std.) | (Min.–Max.) | (Mean ± Std.) | (Min.–Max.) | (Mean ± Std.) | (Min.–Max.) | (Mean ± Std.) | (Min.–Max.) | (Mean ± Std.) | (Min.–Max.) | (Mean ± Std.) | |
| TC (MPN/100 mL) | 28–2400 | 897.625 ± 1045.27 | 1000–2400 | 1614.29 ± 735.82 | 64–1305 | 374.27 ± 284.84 | 9.20–2400 | 416.7 ± 524.66 | 1100–2400 | 2140 ± 581.38 | 1100–2400 | 1966.67 ± 750.56 | Must not be detectable |
| FC (MPN/100 mL) | 43–2400 | 686 ± 1004.17 | 93–2400 | 1006.63 ± 1160.3 | 3–498 | 164.45 ± 162.76 | 6.75–2400 | 570.21 ± 698.35 | 150–2400 | 1120 ± 1047.07 | 75–2400 | 1625 ± 1342.34 | Must not be detectable |

**TC* Total coliform, *FC* Faecal coliform cent removal of coliform varied between 78 and 83% for total coliform and between 65 and 85% for faecal coliform in comparison with the quality of groundwater for both the non-monsoon and the monsoon periods (Table 3).

**BOD** content in RBF wells ranged 0.72–2.4 mg\L in M and 0.9–3 mg\L in NM period, respectively. It was noted that in NM period River Ganga BOD content was 18.32 mg\L whereas in M period it ranged 1.81 mg\L. For GW, the BOD content was negligible in M and 1.26 mg\L during NM. For RBF wells and GW, BOD content is within the desirable limit of 5 mg\L for drinking purposes, whereas River Ganga water sample falls beyond this desirable limit.

## Results of Water Quality Analysis

During non-monsoon and monsoon seasons, the extracted water gets mineralized during the subsurface passage through the aquifer, as illustrated by the increasing concentrations of major ions within each well sample (Fig. 2).

The longer the water is held up in the aquifer, the more the concentration of $Na^+$, $Ca^{2+}$, $K^+$ and $Mg^{2+}$ increases. $Ca^{2+}$ concentration is high in Bhupatwala and Pantdweep as influenced by already mineralized groundwater, whereas Bairagi Camp has low $Ca^{2+}$ concentration due to its near proximity to canal or surface water (Fig. 2).

The nitrate and sulphate concentration for each RBF well is below the recommended guideline value (WHO 2011) of 50 and 500 mg/L, respectively. Ferrous and manganese are essential dietary elements present in water, and according to WHO (2011), the recommended health-based limit values for $Fe^{2+}$ and $Mn^{2+}$ are 2 and 0.4 mg/L, respectively. All RBF (pumping) wells except PW28 show $Fe^{2+}$ and $Mn^{2+}$ concentration below recommended health limit (Fig. 3).

Turbidity of Ganga River (upstream and downstream of Bhimgoda Barrage) is 2–15 times more turbid in monsoon season due to high flow velocities, high run-off and erosion of soil and river bed materials, respectively (Fig. 4).

Turbidity of the abstracted water from RBF wells is below the Indian standard limit of 5 NTU (IS10500 2012) during monsoon and non-monsoon. Electrical conductivity (EC), total dissolved solids (TDS) and bicarbonate ($HCO_3^-$) of all RBF (pumping) wells are under the allowable limits (Fig. 5).

For RBF wells and groundwater, BOD content is within the desirable limit of 5 mg\L for drinking purposes whereas River Ganga water sample falls beyond this desirable limit.

The per cent removal of coliform varied between 78 and 83% for total coliform and between 65 and 85% for faecal coliform in comparison with the quality of groundwater for both the non-monsoon and the monsoon periods (Table 3).

## Conclusion

This paper highlights that the physicochemical and microbiological characteristics of the produced water from pumping (RBF) wells, after getting filtered through river bed, subsurface passage and mixing with groundwater, are better than the allowable standards for drinking purposes, hence proving the effectiveness of RBF technique for potable water supply and management in Haridwar. RBF set-up in Haridwar was found to be efficient in removal of turbidity, whereas the biological parameters exceeded the acceptable and permissible limits in the present analysis. Therefore, a post-treatment of the extracted water, particularly disinfection of the biological parameters, would be necessary before supply of water to users for drinking purposes. As post-treatment, Uttarakhand Jal Sansthan (UJS) who is responsible for domestic water supply has been using the appropriate doses of *sodium hypochlorite* (NaClO) solution as disinfectant to remove biological contents in the extracted water.

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# A Study of the Characteristics of Groundwater Solute Transport Parameters

**Biswajit Chakravorty and N. C. Ghosh**

**Abstract** The study is an attempt to evaluate the behaviour of constituents/pollutants moving with groundwater. Three examples having field relevance have been demonstrated in the study. Dispersivity, adsorptivity and decay which are primary parameters affecting the transport phenomena have been considered. The dispersivity which is the main characterizing parameter in groundwater solute transport problems has been considered for sensitivity analysis. It has also been attempted to quantify errors when a when a 3-D problem is simplified to a 2-D problem and a 2-D problem to a 1-D problem for convenience. The result indicated that one-dimensional analytical and numerical solution of transport equation compares well but simplifying a two-/three-dimensional transport problem to a one-dimensional problem leads to error due to transverse dispersion. Close to the source, advection dominates, whereas away from it the dispersion phenomena dominate. It was also seen that transverse dispersivity becomes prominent as distance increases from the source.

## Introduction

Groundwater is a source for fresh drinking water beside its use in industrial, agricultural and other domestic uses. During recent times due to overuse and abuse of groundwater resources, stresses on the groundwater have increased. Apart from its quantitative over exploitation, its qualitative assault has also taken place. This has resulted in depletion of groundwater resources. Once contaminants from the unsaturated zone containing dissolved constituents move to the saturated zone, it is transported due to groundwater flow and spreads in all possible directions.

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Contaminant's transport in groundwater is largely governed by the parameters which shapes the groundwater flow. Therefore, to simulate contaminant transport phenomena, first it is necessary to simulate groundwater flow. Groundwater transport is governed by advection, dispersion, addition/removal of the constituent to/from the system and chemical reaction. The basic concept of solving flow and transport equation is the mass-balance equation. Numerous analytical and numerical models are available to simulate flow and transport phenomena in a groundwater system. Analytical models can be used for solving groundwater flow and transport equation with simple initial and boundary conditions. In most cases, analytical methods cannot represent real field situation because of heterogeneity of aquifer parameters, irregular shape of the domain boundaries and temporal, spatial distributions of the various sink–source functions, etc. Common problems in groundwater transport modelling are the absence of direct means for the determination of dispersivity in the field, lack of knowledge of exact chemical reactions occurring during movement of constituents, etc. To simplify the flow and transport problems, the most common assumptions are as follows: (i) consideration of one-dimensional flow and transport, (ii) constituents are assumed to have same properties, and their decay and absorption/adsorption rates are constant. These simplifications lead to a wide disagreement between observed and computed values of groundwater head and concentration.

## Present Study and Objectives

The present study is an attempt to evaluate the behaviour of constituents/pollutants moving with groundwater. Three examples having relevance to field conditions have been demonstrated in the study. Dispersivity, adsorptivity and decay affecting the transport phenomena have been considered. The sensitivity of parameter mainly dispersivity characterizing the transport problems has been analysed. Attempts have also been made to quantify errors when a 3-D problem is simplified to a 2-D problem and a 2-D problem to a 1-D problem.

The first case example deals with a simple *one-dimensional* transport problem involving advection, dispersion, adsorption and decay. The problem is solved by analytical method. Results obtained from it are compared with the result obtained from well-known numerical flow/transport model MODFLOW/MT3D to quantify the disagreement in solutions. Later, the same problem is extended to a *two-dimensional* case, and the effect of transverse dispersivity is considered. This is to evaluate the quantum of deviation in the concentration profile as compared to the result obtained in one-dimensional case.

The second case example is a *two-dimensional* case with injection of contaminant into a well and subsequently pumping out from the same well. Contaminant is injected for a given time into the aquifer through an injection well is considered as source, and pumped out from the same well is considered as sink. The sensitivity of longitudinal and transverse dispersivities on the concentration profile in time and space has been studied by assigning different values of dispersivities.

The third case example deals with a *three-dimensional* transport of pollutant from a waste dump site. The migration of pollutant is analysed by assuming different longitudinal and transverse (both horizontal and vertical) dispersivities. Here, the aim is to see the effect of transverse dispersivities on the concentration profile both in space and in time. It is also envisaged to see whether transverse dispersivity dominates over the longitudinal dispersivity beyond a certain distance from the source of the waste dump site.

## Mathematical Background

The three-dimensional unsteady movement of groundwater of constant density through porous earth material in a heterogenous anisotropic medium can be described by the following partial differential equation:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t} \tag{1}$$

where $K_{xx}$, $K_{yy}$, $K_{zz}$ = hydraulic conductivity along major axes [$LT^{-1}$]; $h$ = potentiometric head [L]; $W$ = volumetric flux per unit volume and represents sources and/or sinks of water [$T^{-1}$]; $S_s$ = specific storage of the porous material [$L^{-1}$] and $t$ = time [T].

A mathematical model for the transport of solute in groundwater can be derived by taking the mass balance of the dissolved pollutant over a static elementary volume. Expressed in words the equation can be written as:

Change in solute mass *stored* = excess solute mass *diffusion* into volume + excess solute mass inflow over outflow or mass transport by *Convection and Dispersion* + solute mass added by *injection/infiltration* − solute mass lost by *withdrawal* − solute mass lost by *decay* − solute mass lost by *reaction* − solute mass *adsorbed* on solid interface. Mathematically, the above transport equation is expressed as:

$$\begin{aligned}\frac{\partial(nc)}{\partial t}=&\frac{\partial}{\partial x_i}\left(nD_m\frac{\partial c}{\partial x_i}\right)-\frac{\partial}{\partial x_i}(nv_i\,c)+\frac{\partial}{\partial x_i}\left(nD_{ij}\frac{\partial c}{\partial x_j}\right)+q_{3i}\,c_i-q_{3a}\,c\\&-n\,\lambda_c\,c-n\,\zeta_c-\left[\frac{\partial}{\partial t}((1-n)\,\rho_s\,c_a)+\lambda_a(1-n)\,\rho_s\,c_a+(1-n)\,\zeta_a\right]\end{aligned} \tag{2}$$

where $n$ = porosity [−]; $c$ = concentration of dissolved pollutants [$ML^{-3}$]; $t$ = time [T]; $x_i$ = distance tensor [L] (subscript $_i$ = 1, 2, 3. $x_1 = x$; $x_2 = y$; $x_3 = z$); $D_m$ = coefficient of molecular diffusion [$L^2T^{-1}$]; $v_i$ = velocity tensor [$LT^{-1}$]; $D_{ij}$ = coefficient of dispersion tensor [$L^2T^{-1}$] (when $i$ = 1= $x$; $i$ = 2 = $y$;

$i$ = 3= $z$ and when $j$ = 1= $x$; $j$ = 2=$y$; $j$ = 3= $z$); $q_{3i}$ = volumetric infiltration (+= infiltration) [$T^{-1}$]; $c_i$ = concentration of pollutant in infiltrated water [$ML^{-3}$]; $q_{3a}$ = volumetric abstraction (+= abstraction) [$T^{-1}$]; $\lambda_c$ = decay constant for dissolved pollutants [$T^{-1}$]; $\zeta_c$ = volumetric reaction rate of dissolved pollutants [$ML^{-3}T^{-1}$]; $\lambda_a$ = decay constant for adsorbed pollutants [$T^{-1}$]; $\rho_s$ = density of solids (grains) [$ML^{-3}$]; $c_a$ = concentration of adsorbed pollutants [$MM^{-1}$]; $\zeta_a$ = volumetric reaction rate of adsorbed pollutants [$ML^{-3}T^{-1}$].

Equation (2) is the governing equation underlying a solute transport model. The transport equation and the flow equation are linked through the relationship:

$$v_i = -\frac{K_{ii}}{n}\frac{\partial h}{\partial x_i} \tag{3}$$

where $K_{ii}$ = principal component of hydraulic conductivity tensor, [$LT^{-1}$]; $h$ = hydraulic head [L].

In the present study, numerical transport model MT3D (Zheng 1992) compatible with flow model MODFLOW (McDonald and Harbaugh 1988) has been used to solve above flow and transport equations.

Three-dimensional solute transport equation (2) when reduced to *one-dimensional form* (Ogata and Banks 1961) under assumptions of (i) constant porosity; (ii) constant aquifer thickness; (iii) convective velocity 'v' is constant (i.e. steady-state groundwater flow); (iv) since 'v' is constant and $D = \alpha_L|v|$, therefore, 'D' is also constant; (v) molecular diffusion is very small, i.e. diffusion may be neglected; (vi) no decay; and (vii) no reaction becomes:

$$c(x,t) = \frac{1}{2}c_o\,\mathrm{erfc}\left[\frac{x - \frac{v}{R}t}{2\sqrt{\alpha_L\frac{|v|}{R}t}}\right] \tag{4}$$

where $c_o$ = initial concentration of dissolved pollutants [$ML^{-3}$]; 'erfc' is the complementary error function; $x$ = distance in $x$-direction [L]; $R$ = retardation factor [–]; $\alpha_L$ = longitudinal dispersivity [L]; |v| = magnitude of local groundwater velocity [$LT^{-1}$]; $\alpha_T$ = transversal dispersivity [L].

## Case Studies

### 1-D, 2-D Case Problem

One-dimensional steady-state flow domain consists of 100 columns, 1 row and 1 layer. The input parameters for flow and transport simulation are as follows.

For flow:

| | |
|---|---|
| • Cell width along rows ($\Delta x$) | 25 m |
| • Cell width along column ($\Delta y$) | 25 m |
| • Layer thickness ($\Delta z$) | 25 m |
| • Aquifer type | Unconfined |
| • Porosity ($n$) | 0.25 |
| • Homogenous hydraulic conductivity ($k$) | 40 m/day |
| • Constant head cell at (1, 1) and (100, 1) with head | 70 and 60 m respectively |

No external stresses (viz. well, drains, river, evapotranspiration, aerial recharge, stream aquifer relation) considered.

For transport:

- The first column (1, 1) cell is treated as a constant concentration cell with concentration = 1 kg/m$^3$.
- Starting concentration at all other cell = 0 kg/m$^3$.
- Longitudinal dispersivity ($\alpha_L$) = 20 m, retardation factor ($R$) = 5 and decay or the rate constant of the first-order rate reaction ($\lambda$) = 0.002 day$^{-1}$.

First, the 1-D transport problem involving advection; advection + dispersion; advection + dispersion + adsorption; and advection + dispersion + adsorption + decay is solved separately by analytical procedure (Eq. 4) suggested by Ogata and Banks (1961). In this problem, only the *longitudinal dispersivity* is considered. The same problem is also solved numerically using MT3D model. Comparison of results is given in Fig. 1. The result (concentration vs. distance) shows an excellent match between the analytical and numerical solution which eventually shows that the 1-D transport phenomena can well be represented by the 1-D model.

Next, the same example is extended to a 2-D case with 100 × 100 grids. The first and the last columns are assumed to be constant head cells for flow simulation. For simulation of constituent's transport, only cell (1, 51) is assumed to be a constant concentration cell. The transverse dispersivity is assumed to be half the longitudinal dispersivity. All other parameters of flow and transport are kept same. In fact, a real field problem involves spreading of pollutant concentration in all directions. This spreading reduces the concentration at a point as compared to a 1-D problem. The simulated results (concentration profile) advocating the effect of advection + dispersion in a 2-D test case are shown in Fig. 2. The result of 1-D case for advection + dispersion is also shown in the same figure for comparison. The results indicate an appreciable deviation in concentration along 51st row as compared to 1-D case. This difference (reduction) in concentration is due to the spreading of pollutants along the transverse direction. This demonstrates the quantum of errors involved when a 2-D or even a 3-D problem is simplified to a 1-D problem.

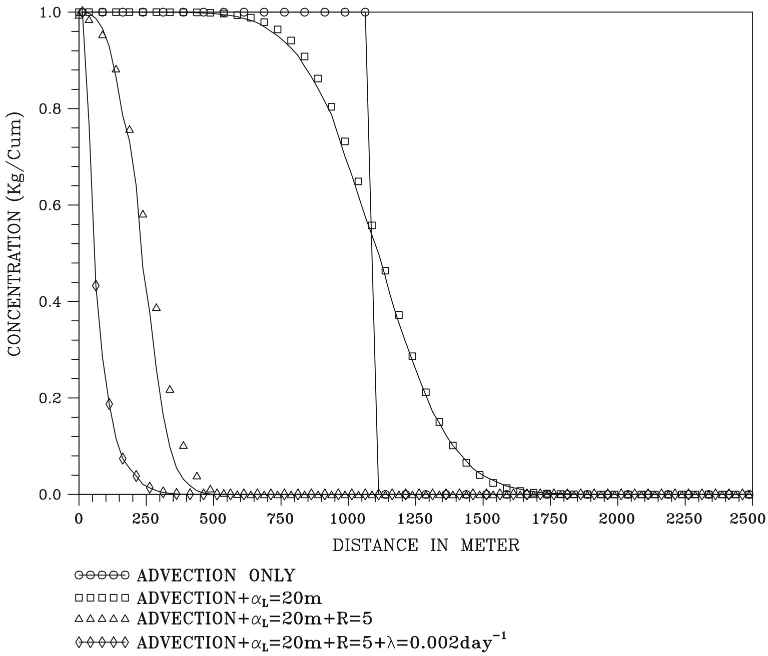


**Fig. 1** Effect of advection, dispersion, adsorption and decay on the concentration profile in an 1-D problem (*line* ⇒ numerical solution and *point* ⇒ analytical solution)

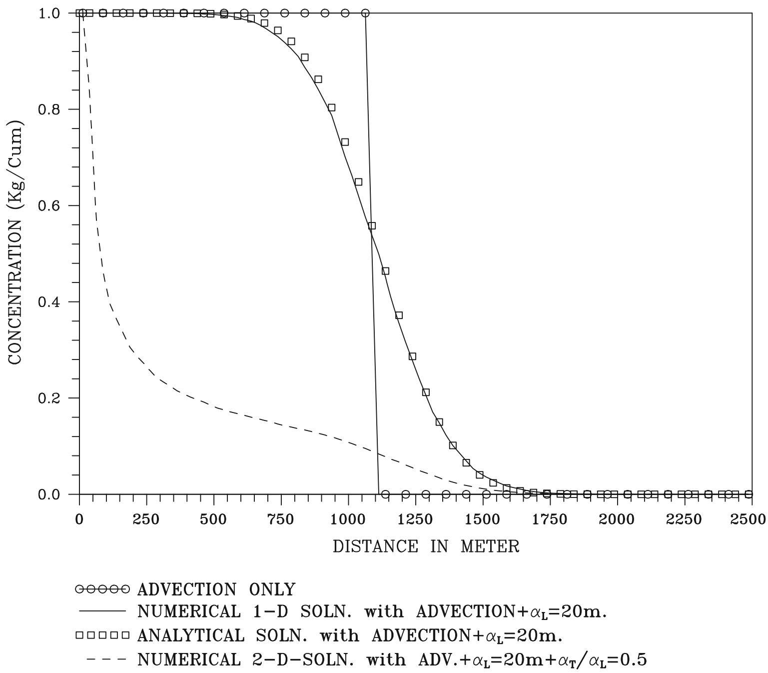


**Fig. 2** Comparison of advection + dispersion on the concentration profile in a 1-D and 2-D problem (*line* ⇒ numerical 1-D solution and *dashed line* ⇒ 2-D solution)

Similar nature of concentration profiles has also been seen from the result of simulation involving advection + dispersion + adsorption and advection + dispersion + adsorption + decay.

## Injection/Pumping Well Problem

A fully penetrating well in a confined aquifer is used for studying the transport behaviour of pollutant injected through it, and later, the same well is used for extraction/sweeping of the contaminants. A pollutant of constant concentration is injected through the well during the first stress period. During the next stressed period, the flow is reversed and the contaminated water is pumped out. The effect of variation of input value of *longitudinal dispersivity* on the simulated concentration versus time profiles in these two stress periods at various distances from the injection/pumping well is seen. The transient 2-D injection/pumping problem taken for analysis consists of 51 rows, 51 columns and 1 layer with a well located at the centre of the area in the cell (26, 26). The input data for flow and transport simulation are as follows.

For flow:

| | |
|---|---|
| • First stress period (injection) | 910 days ≈ 2.5 years |
| • Second stress period (pumping) | 2740 days ≈ 7.5 years |
| • Cell width along rows ($\Delta x$) | 100 m |
| • Cell width along column ($\Delta y$) | 100 m |
| • Layer thickness ($\Delta z$) | 20 m |
| • Top RL = 100 m and Bottom RL | 80 m |
| • Aquifer type | Confined |
| • Porosity ($n$) | 0.30 |
| • Homogenous hydraulic conductivity ($k$) | 50 m/day |
| • Constant head cell at four sides of the boundary | |
| • Injection rate | 2500 $m^3$/day |
| • Pumping rate | 2500 $m^3$/day |
| • Other external stresses are ignored | |

For transport:

- All cells are considered as variable concentration cell with starting concentration as zero.
- In the well package, concentration of the injected water is taken as = 100 g/$m^3$.
- Advective and dispersive transport is assumed. No chemical reaction is considered.
- Longitudinal dispersivity ($\alpha_L$) considered = 10, 50 and 75 m.
- Model is also simulated for $\alpha_T/\alpha_L = 1$, i.e. transversal dispersivity and longitudinal dispersivity are same.

- Observation points are chosen at the well and at 100, 300 and 500 m from the well.

Results of flow simulation reveal that during the injection period, the flow is out of the well towards the boundary sides, and during pumping period, the flow is towards the well. After simulation of flow, transport model is run initially with advective transport and afterwards with different values of longitudinal dispersivity. To examine the effect of transverse dispersivity on the concentration profile, transverse dispersivity is considered to be equal to the longitudinal dispersivity (i.e. $\alpha_T/\alpha_L = 1.0$) and the model is simulated. The breakthrough curves (time–concentration profile) at different observation points located at specified distances from the well are plotted for different values of longitudinal dispersivity and for $\alpha_T/\alpha_L = 1.0$ (Figs. 3, 4, 5 and 6).

From these figures, it is evident that concentration profiles show differences away from the well. This leads one to draw the following inferences.

(i) With increase in value of the longitudinal dispersivity, reduction of concentration of constituents occurs up to a certain distance from the well (up to 300 m in the present case) as is evident from Fig. 5.

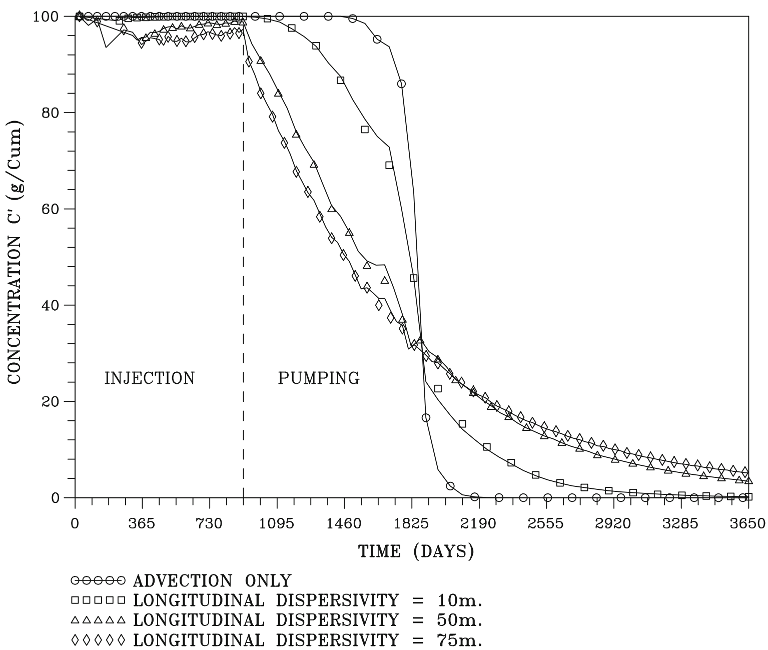


**Fig. 3** Breakthrough curves at the well with advection and different values of longitudinal dispersivity (*line* ⇒ with longitudinal dispersivity; *symbols* ⇒ $\alpha_T/\alpha_L$ = 1.0)

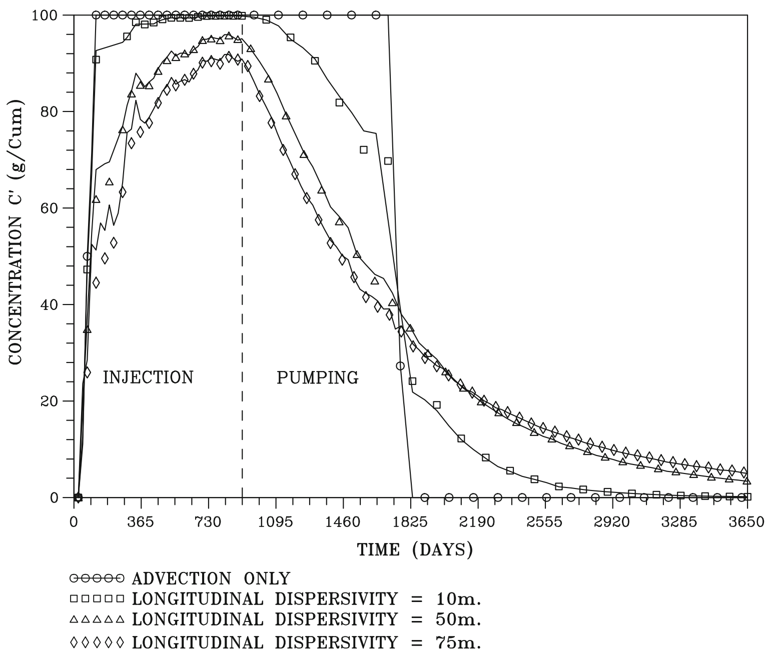


**Fig. 4** Breakthrough curves at 100 m from the well with advection and different values of longitudinal dispersivity (*line* ⇒ with longitudinal dispersivity; *symbols* ⇒ $\alpha_T/\alpha_L = 1.0$)

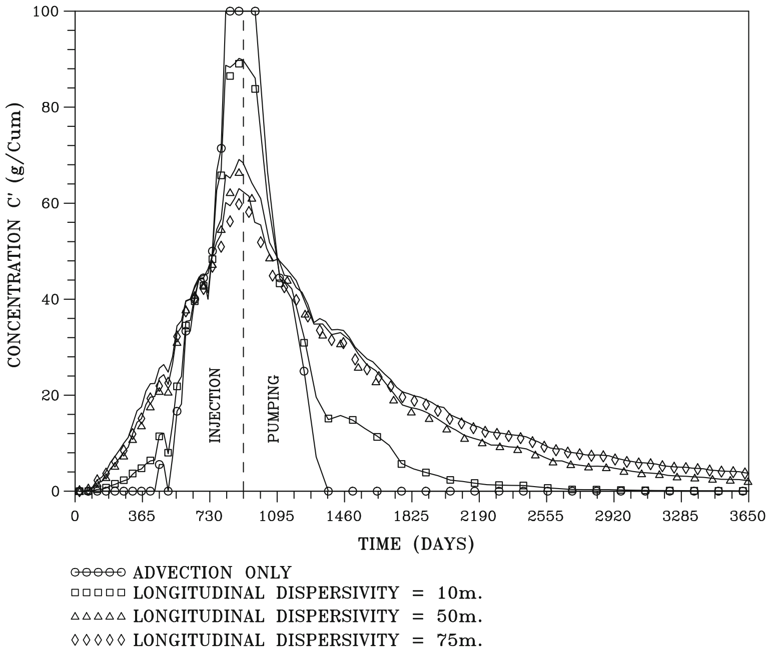


**Fig. 5** Breakthrough curves at 300 m from the well with advection and different values of longitudinal dispersivity (*line* ⇒ with longitudinal dispersivity; *symbols* ⇒ $\alpha_T/\alpha_L = 1.0$)

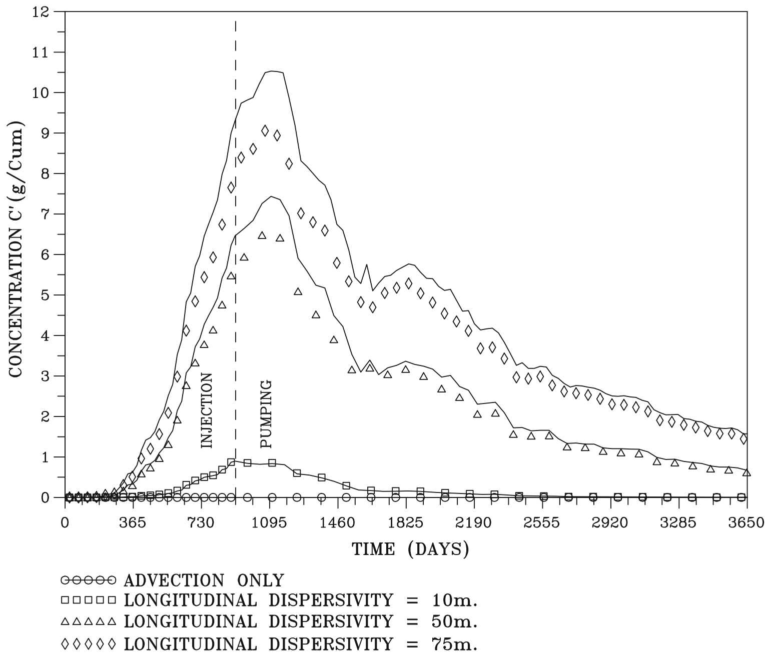


**Fig. 6** Breakthrough curves at 500 m from the well with advection and different values of longitudinal dispersivity (*line* ⇒ with longitudinal dispersivity; *symbols* ⇒ $\alpha_T/\alpha_L = 1.0$)

(ii) For larger value of dispersivity, the fall of concentration during the pumping cycle is gradual, i.e. the concentration reduces at a slower rate for larger value of dispersivity. Thus, concentration profile extends for a longer period for higher value of dispersivity.

(i) Effect of transverse dispersivity, when $\alpha_T/\alpha_L = 1.0$, becomes significant at a longer distance from the well. In the case example, it started becoming apparent at 300 m from the well as shown in Fig. 5. In the closer proximity of the well, the difference in the effect of longitudinal dispersivity and transverse dispersivity is insignificant.

(ii) Closer to the well, the influence of advective transport is dominant and the influence decreases with increase in distance from the well, and for larger distance, it becomes insignificant. Beyond certain distance from the well (in the example case from a distance of 500 m from the well), the dispersion phenomena dominate and the concentration profile shows a reversal of trend; i.e., more the longitudinal dispersivity, more is the concentration. This can well be explained from Fig. 6.

(iii) Dominancy of dispersive transport over the advective transport shifts the peak of concentration profile (Fig. 6).

## 3-D Waste Dump Problem

To study the behaviour of constituent's transport in 3-D, a study area as shown in Fig. 7 is considered. It is assumed that a deposit of benzene in dissolved form lies in the central part of the area covering cells as shown in Fig. 7. The pollutant in dissolved form enters the aquifer system with a concentration equal to 0.0001 kg/m$^3$. Assuming a steady-state condition of flow for the area with the following input data and boundary conditions, the time–concentration profile at a number of observation points located at different distances from the dump site for 20 years after the beginning of benzene migration in the aquifer is analysed.

The aquifer is assumed to have two layers confined in nature. The model area is discretized into 55 rows and 57 columns as shown in Fig. 7. The boundaries of the model area in the north-east, east, south-east and south-west sides are defined by canal which are in full hydraulic contact with the aquifer. They are treated as fixed head boundaries. Other boundaries are defined by streamlines and are therefore impervious (no-flow boundaries). The input data, aquifer parameters and solute properties are assumed constant everywhere as defined below.

For flow:

| | |
|---|---|
| • Thickness of the first aquifer | 8 m |
| • Thickness of the second aquifer | 7 m |
| • Cell width along rows and columns | 100, 25 and 100 m |
| • Porosity (*n*) | 0.2 |
| • Horizontal hydraulic conductivity | 50 m/day |
| • Vertical hydraulic conductivity | 1/20 of Hoz. hydraulic conductivity |
| • Aerial recharge | 0.00216 m/day |

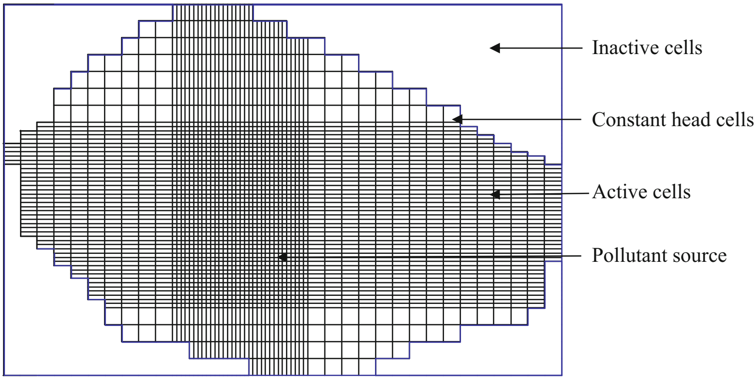


**Fig. 7** Grid network of 3-D model area (number of cells in X-direction = 57 and number of cells in Y-direction = 55)

For transport:

- All cells in the model area are considered as variable concentration cells.
- Concentration of pollutants = 0.0001 kg/m$^3$ entering with the recharge water.
- Advection, dispersion and chemical reactions have been assumed.
- Longitudinal dispersivity ($\alpha_L$) = 5, 10 and 20 m.
- The ratio of horizontal and vertical transverse to longitudinal dispersivity = 0.5.
- Distribution coefficient ($k_d$) of benzene = 0.0002 m$^3$/kg.
- Bulk density of the porous medium in the aquifer = 1700 kg/m$^3$.

The flow is simulated assuming steady-state condition. The computed isolines indicate an outflow towards the south-western side, i.e. towards canal boundaries. To demonstrate the transport behaviour, two observation points at cells (22, 35) and (18, 39) are chosen in both layers of the aquifer.

Responses of concentrations at cell (22, 35) over different time are shown in Figs. 8 and 9 which reveals that:

(i) Increase in longitudinal dispersivity decreases the concentration.
(ii) Combined effect of longitudinal and transverse (horizontal and vertical) dispersivities reduce the concentration further.

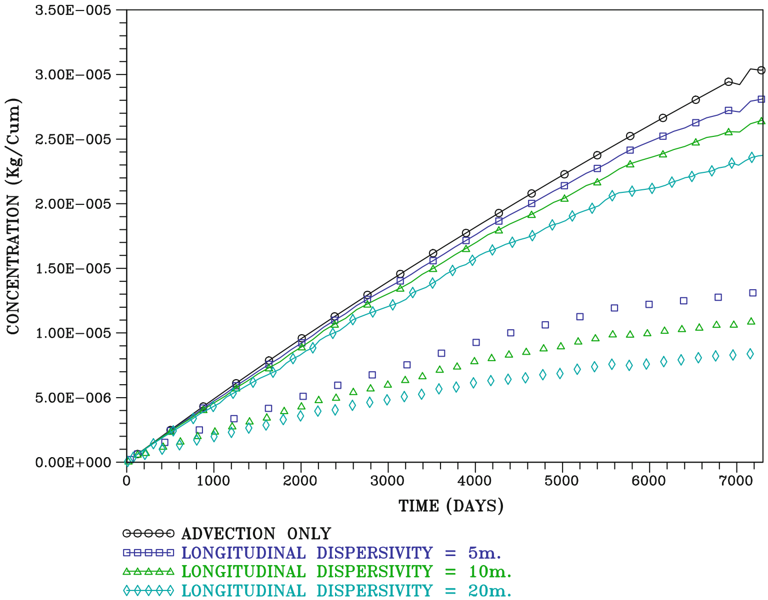


**Fig. 8** Breakthrough curves at cell (22, 35) for the first layer with advection and with different values of dispersivities (*line with symbols* ⇒ with longitudinal dispersivity; only corresponding *symbols* ⇒ $\alpha_T/\alpha_L$ = 0.5 and $\alpha_V/\alpha_L$ = 0.5)

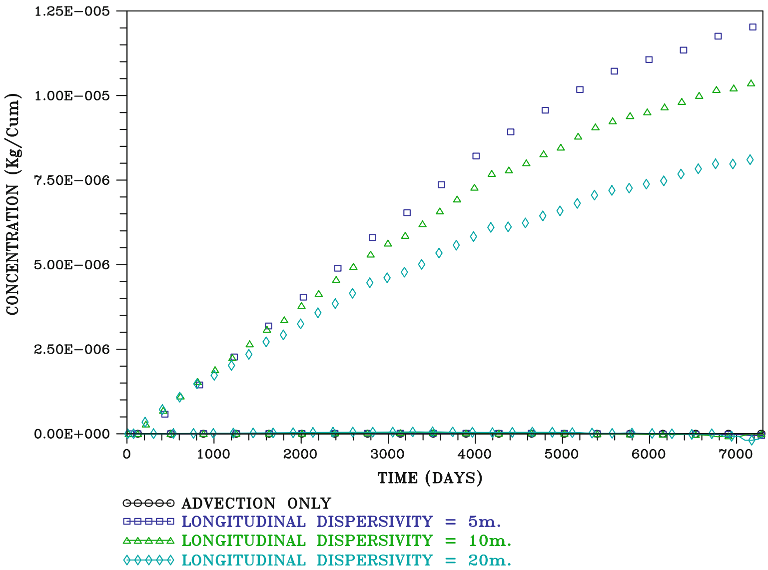


**Fig. 9** Breakthrough curves at cell (22, 35) for the second layer with advection and with different values of dispersivities (*line with symbols* ⇒ with longitudinal dispersivity; only corresponding *symbols* ⇒ $\alpha_T/\alpha_L = 0.5$ and $\alpha_V/\alpha_L = 0.5$)

(iii) In the first aquifer where the dump site is located, the spread of pollutant is influenced both by the longitudinal and by transverse (horizontal and vertical) dispersivities.

(iv) In the second layer, the occurrence of pollutant concentration is dominated by the combined effect of longitudinal and transverse dispersivities. The effect of longitudinal dispersivity alone is negligible.

Away from this cell, similar trend could also be seen excepting that concentration reduces with increase of distance from the dump site.

A reverse trend is observed for cell (18, 39) shown in Fig. 10 in the first layer. In this case, the concentration due to advective transport becomes negligible, and with increase in dispersivities, the concentration also increases. It means the occurrence of pollutant at a farther distance is influenced by the dispersion phenomena, and the concentration is more for higher dispersivity. In the second layer also (Fig. 11), similar trend is observed; i.e., concentration is more due to the effect of horizontal and vertical transverse dispersivities, and it is more for higher dispersivity.

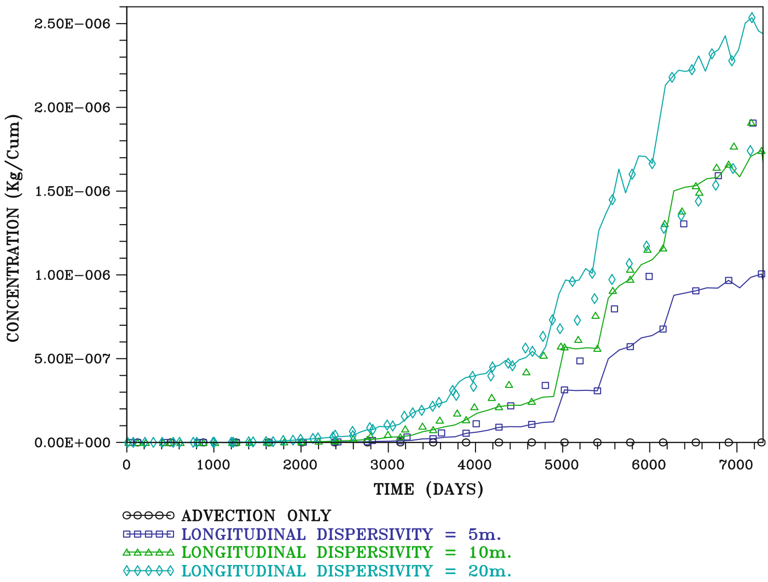


**Fig. 10** Breakthrough curves at cell (18, 39) for the first layer with advection and with different values of dispersivities (*line with symbols* ⇒ with longitudinal dispersivity; only corresponding *symbols* ⇒ $\alpha_T/\alpha_L = 0.5$ and $\alpha_V/\alpha_L = 0.5$)

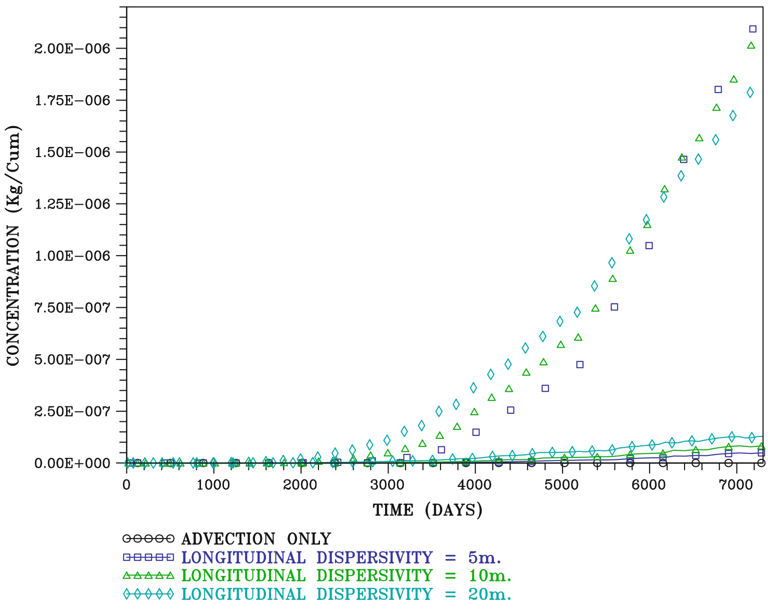


**Fig. 11** Breakthrough curves at cell (18, 39) for the second layer with advection and with different values of dispersivities (*line with symbols* ⇒ with longitudinal dispersivity; *only corresponding symbols* ⇒ $\alpha_T/\alpha_L = 0.5$ and $\alpha_V/\alpha_L = 0.5$)

## Conclusions

(i) One-dimensional analytical solution and results of numerical transport model compare well.
(ii) Visualizing a two- or three-dimensional transport problem as one-dimensional will lead to errors due to transverse dispersion.
(iii) Spreading of pollutant in a transport problem increases with increasing dispersivity.
(iv) Effect of transverse dispersivity becomes prominent as distance increases from the source.
(v) Close to the source, the advection dominates the transport phenomena, and its influence decreases with increase in distance from the source in the direction of groundwater flow.
(vi) When the distance from the source increases, dominancy of dispersive transport over the advective transport shifts the peak of concentration profile.
(vii) Combined effect of longitudinal and transverse dispersivities reduces the concentration further as compared to longitudinal dispersivity considered alone.

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# Prioritization for Management of Groundwater Quality-Related Problems of Rajsamand District of Rajasthan

**K. K. Yadav and P. K. Singh**

**Abstract** A study was conducted during pre- and postmonsoon seasons of the years 2011 and 2012 in Rajsamand district of Rajasthan to prioritize the management of groundwater quality-related problems. The whole district was divided into 6 km $\times$ 6 km square grids, and from each grid, one open dug well was selected randomly. The locations of wells were recorded with the help of global positioning system (GPS). The groundwater samples were drawn from 128 selected open dug wells and analysed for standard water quality parameters, and it was found that the TDS of groundwater of Rajsamand district ranged from 164 to 8600 and 152 to 7840 mg $kg^{-1}$ in premonsoon seasons with the mean value of 1508 and 1425 mg $kg^{-1}$ in the years 2011 and 2012, respectively. In postmonsoon seasons, the TDS varied from 120 to 5810 and 122 to 5980 mg $kg^{-1}$ with the mean values of 1142 and 1154 mg $kg^{-1}$ in the years 2011 and 2012, respectively. The pH of groundwater in premonsoon varied from 6.30 to 8.20 and 6.40 to 8.10 with average values of 7.16 and 7.17 in the years 2011 and 2012, respectively. During postmonsoon seasons, the pH value varied from 6.70 to 8.30 and 6.90 to 8.20 with the mean values of 7.42 and 7.36 in the years 2011 and 2012, respectively. The electrical conductivity of groundwater of Rajsamand district varied from 0.25 to 13.44 and 0.23 to 12.20 $dSm^{-1}$ with the mean values of 2.35 and 2.21 $dSm^{-1}$ in premonsoon, whereas in postmonsoons the EC of groundwater varied from 0.18 to 9.08 and 0.20 to 9.40 $dSm^{-1}$ with mean values of 1.78 and 1.81 $dSm^{-1}$ in years 2011 and 2012, respectively. The minimum EC was found in Kumbhalgarh, whereas the maximum was recorded in Railmagra block in both years.

On the basis of cationic composition of groundwater, it is Na–Mg–Ca type, and as per the anionic composition, the groundwater of the study area is found Cl–$HCO_3$–$SO_4$ type. According to USDA classification of irrigation water, 9.37 and 12.50%

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groundwater samples of Rajsamand district fall under $C_2$ class (medium salinity water), whereas the majority of the groundwater samples (60.94 and 57.81%) fall under $C_3$ class (high salinity water), and 29.69 and 28.91% groundwater samples fall under $C_4$ class (very high salinity water) in premonsoon seasons of the years 2011 and 2012, respectively. In postmonsoon season, 0.78 and 0.78% groundwater samples fall under $C_1$ class (low salinity water), 17.19 and 16.41% samples under $C_2$ class (medium salinity water), 57.81 and 58.59% samples fall under $C_3$ class (high salinity water), and 25 and 24.22% groundwater samples fall under $C_4$ class (very high salinity water). The decreased salinity in postmonsoon period may be due to dilution of groundwater through recharge of aquifers by rainwater.

These findings are highly useful for policy makers or planners for easy illustration and decision making especially for seed minikit distribution, fertilizer distribution and management and prioritization of groundwater quality-related problems of drinking and irrigation water in the different blocks of the district.

## Introduction

Water quality directly affects virtually all water uses. Fish survival, diversity and growth, recreational activities such as swimming and boating, municipal, industrial and private water supplies, agricultural uses such as irrigation and livestock watering, waste disposal and general aesthetics all are affected by the quality of water. Water quality impairment is often a trigger for conflict in a watershed, simply because degraded water quality means that desired uses are not possible or not safe. Hence water quality analysis is one of the most important aspects in groundwater studies.

Normal irrigation water generally has no adverse effect on soil properties. However, irrigation with poor quality water containing high concentration of cations and anions may adversely affect the properties of soil by increasing salt content and exchangeable sodium of soil solution (Lal and Singh 1974). The salt composition of irrigation water may lead to developments of salinity and alkalinity in soil. The assessment of quality of irrigation water especially groundwater is necessary, because it usually varies in their salt content and has a profound impact on soil properties and may ultimately affect the crop yield. The quality of irrigation water in relation to its impact on soil properties is of most interest in arid and semi-arid areas (Khandelwal and Lal 1991). The suitability of water for irrigation is determined by the amount and kind of salts present. With poor water quality, various soil and cropping problems can be expected to develop.

From a policy point of view, the groundwater quality maps are used either for quantifying diffuse groundwater contamination and location-specific background concentrations (in order to assist local contamination assessment) or for input and validation of policy supporting regional or national groundwater quality models. The maps are considered as a translation of point information obtained from the monitoring networks into information on spatial units. The maps enable location-specific network optimization. In general, the maps give little reason for reducing the monitoring network density. The water resources are depleting and deteriorating day by day so the need of research in the field of groundwater quality assessment is becoming more important. Therefore, this study was undertaken to evaluate spatiotemporal variability of groundwater quality of Rajsamand district and to prepare groundwater quality maps of Rajsamand district.

## Description of the Study Area

### *Location*

Rajsamand district is located in the southern part of Rajasthan state and extends between east longitudes 73° 28′ 30″ and 74° 28′ 55″ and north latitudes 24° 43′ 32″ and 26° 01′ 36″. It covers an area of 4768.10 $km^2$. It is bounded in the south and south-west by Udaipur district, in the east and south-east by Bhilwara and Chittaurgarh districts, in the north by Ajmer district and in the west by Pali district. Rajsamand district covers 1.39% of total area of state and is divided into 7 tehsils and 7 blocks (Fig. 1).

## Geomorphology and Drainage

The study area consists of monotonously rolling topography interacted by shallow valleys. Towards the western part of the study area, Aravalli hills, a series of ridges, run diagonally in the direction of NE and SW. The highest portion of Aravalli occurs south of Kailwara near Kumbhalgarh Fort (25°08′:73°35′) with an altitude of 1293 m above m.s.l. A typical gneissic plain bearing irregularly carved gneisses and granites without any alluvium cover is observed to the highest altitude of above 600 m above m.s.l. The central and eastern part of the Rajsamand district is relatively plain area forming the foothill part of Aravalli ranges. This plain gently slopes towards the east and north-east.

Rajsamand district is drained by Banas River and its tributaries, i.e. Khari, Chandrabhaga, Gomati, Kothari and Ahar. The river as well as tributaries is ephemeral and flow only in response to heavy precipitation. The Banas means "the hope of the forest" which rises in Aravalli hills about 5 km. from Kumbhalgarh Fort and flowing southwards meets the Gogunda plateau. It flows through Rajsamand and Railmagra tehsils and then crosses into Chittaurgarh and Bhilwara districts. Chandrabhaga originates from northern and the Gomti from the north-west part of the areas. The predominant drainage pattern in the western hill ranges is rectangular to subrectangular. Drainage pattern in the western hill region is controlled by fractures and joints and in rest of the area by subsurface liniments.

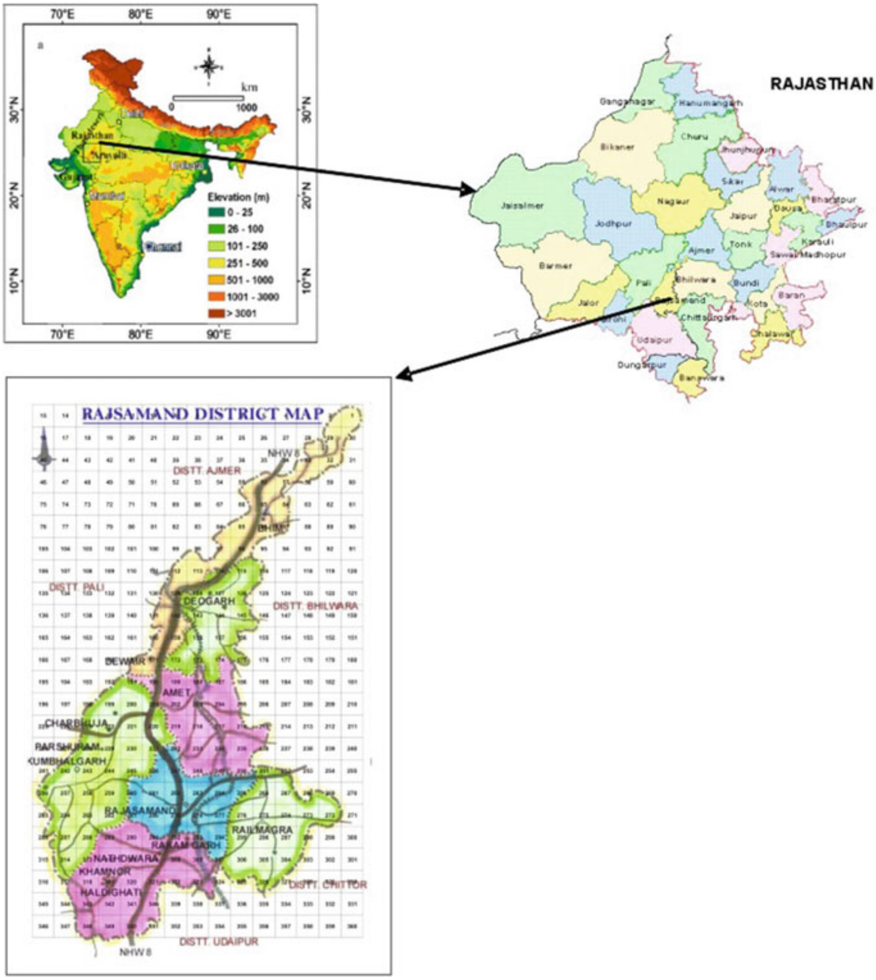


**Fig. 1** Location of the study area showing systematic square grids

## Rainfall and Climate

The study area experiences arid to semi-arid type of climate. Mean annual rainfall of the Rajsamand district is 553.2 mm. Almost 93% of the total annual rainfall is received during the south-west monsoon which enters the district in the third or fourth week of June and withdraws in the mid of September. The highest mean annual rainfall (673.2 mm) is received at Kumbhalgarh, which lies near the south-western boundary of the district. The lowest mean annual rainfall (494.8 mm) is received at Bhim, which lies in the northern part of the district. The rainfall at the

**Table 1** Blockwise rainfall (mm) in Rajsamand district during 2011, 2012 and 2013

| Block | Kumbhalgarh | Bhim | Rajsamand | Railmagra | Deogarh | Nathdwara | Amet | District average |
|---|---|---|---|---|---|---|---|---|
| 2011 | 897 | 716 | 523 | 872 | 739 | 783 | 668 | 743 |
| 2012 | 921 | 735 | 579 | 490 | 686 | 542 | 551 | 643 |
| 2013 | 745 | 592 | 728 | 853 | 767 | 636 | 600 | 703 |


**Fig. 2** Graphical representation of the blockwise average rainfall during 2011–2013

remaining station does not vary much. The rainfall of the area during the study period is given in Table 1 and Fig. 2.

The winter season sets in after about the middle of November, when both day and night temperatures begin to drop steadily up to month of January. January is the coldest month with mean daily minimum temperature of 7.8 °C. The day and night temperatures rise rapidly from February to May. May is the hottest month of the year with mean daily maximum temperature of 38.6 °C. When the south-west monsoon arrives in the district, both day and night temperatures start decreasing appreciably. After the withdrawal of south-west monsoon, there is a slight increase in day temperatures. The night temperature however continues to fall gradually. The day temperature also starts falling in November. The relative humidity is gradually low except during south-west monsoon season. The summer season is the driest part of the year. Winds are generally light with some strengthening in the latter half of summer and south-west monsoon season. In the period from May to September, winds blow from directions between south and west. In the postmonsoon season, the winds are predominantly from the direction between north-west and north-east. The potential evapotranspiration is highest in the month of May and lowest in month of December. Evapotranspiration is more than rainfall in all the month except in July and August.

## Soil, Land Use and Irrigation Practices

The soils of the district vary from sandy loam in Bhim, Deogarh and Amet blocks to heavy clay in Kumbhalgarh block. The types of soil occurring in the district are classified as follows: sandy loam in Bhim, Deogarh and Amet; clay loam Rajsamand, Railmagra and Khamnor; and heavy clay in Kumbhalgarh block (CGWB 2007). The loam soil can support almost all crops. Clay loam is suitable for cultivation of wheat, barley, maize, cotton, sugar cane, jawar, etc, whereas crops such as bajra, moong, moth, guar, groundnut, til, etc., can be grown on sandy loam soils. Wheat, sugarcane and rice are the main crops of clay soils. Broadly, the northern, southern and eastern parts of the district possess loam, foothill soils and black cotton soil with moderate run-off, whereas in the western part of the district lithosols and regosols of hills and rocky outcrops having very high run-off are prevalent. Soil infiltration rate varied from 0.6 to 4.2 cm/h, while the average infiltration rate was found to be 2.35 cm/h. Railmagra and Nathdwara tehsils have the maximum cultivated area of 24,542 hectares and 21,486 hectares, respectively. Kumbhalgarh has the minimum cultivated area of 11,834 hectares. Railmagra and Nathdwara tehsils also top the list in the double cropped area. Net irrigated area in the district is 30,971 hectares. Nathdwara and Railmagra tehsils have the maximum irrigated area.

Agriculture in the district is by and large confined to traditional kharif cultivation depending on monsoon rainfall. Rabi cultivation is prevalent in areas where irrigation facilities are available. The major crops grown are as follows: maize, wheat and jawar, kharif pulses and gram, groundnut, til and mustard, sugarcane and chilly. Since the agriculture is the principal occupation of the population, it is imperative that if the irrigation facilities are extended with good quality water over large area, it will be possible to change the agriculture scenario of the district to a greater extent.

## Physiography and Geology

The area under study is bounded by NE–SW-trending hills whose elevation is more than 700. The general slope of the area is towards SE where the elevation ranges between 500 and 600 m. Banas River is flowing from east to west, and Khari River is flowing from north to east forming other boundaries of area. The major rock type within study area is mainly older gneiss of Bhilwara supergroup. The rocks are comprised of porphyritic and non-porphyritic gneiss complex associated with apatite, amphibolites and gneisses. Gneiss is grey-to-dark brown-coloured medium to coarse-grained rocks.

# Materials and Methods

## *Collection of Groundwater Samples*

The whole Rajsamand district was divided into 6 km × 6 km square grids, and from each grid, one open dug well was selected randomly. The locations of wells were recorded with the help of global positioning system (GPS). Then, the selected wells were given a particular identity indicating the block name and grid number with the help of red paint and brush. After that, cross mark (X) was put at a particular place on the well for measuring well depth and ground level. Then after, the well depth was measured from the marked point with the help of weight-tagged measuring tap and the groundwater level was measured with the help of water level indicator. The groundwater samples were drawn by sampling device and were collected in properly cleaned and labelled plastic bottles and brought to the laboratory for analysis. Total 128 groundwater samples were collected in premonsoon season (first fortnight of June 2011 and 2012) and again in postmonsoon season (first fortnight of November 2011 and in December 2012). The groundwater samples were drawn from the same selected open dug wells.

These groundwater samples were analysed for EC, pH, TDS, $Ca^{2+}$, $Mg^{2+}$, $Na^{+}$, $K^{+}$, $HCO_3^{-}$, $SO_4^{2-}$, $Cl^{-}$ and $CO_3^{2-}$ following the standard analytical methodology.

# Results

Total 128 groundwater samples were collected from all the seven blocks of Rajsamand district of Rajasthan. The blockwise information of the number of samples collected during pre- and postmonsoon seasons of the study period is given in Table 2.

Water containing excessive soluble salts is unsuitable for irrigation. If sodium is the dominating ion, frequent application of such water deteriorates the physical conditions of soil causing soil dispersion, reduced infiltration and poor soil aeration. On the other hand, the presence of soluble salts of calcium plus magnesium in

**Table 2** Blockwise number of samples collected

| Block | Number of samples collected |
|---|---|
| Kumbhalgarh | 22 |
| Bhim | 25 |
| Rajsamand | 13 |
| Railmagra | 21 |
| Devgarh | 10 |
| Nathdwara | 26 |
| Amet | 11 |
| District (total) | 128 |

excess increases the osmotic pressure of soil solution, thereby causing disturbance in the mechanism of uptake of water and nutrients by plants. For the better judgement about the quality of groundwater, it is essential to have a chemical analysis of water. The groundwater samples are analysed following standard methodology for the important water quality parameters (TDS, pH, electrical conductivity, cations: calcium, magnesium, sodium and potassium and anions: sulphate, chloride, carbonate and bicarbonate) in the Groundwater Laboratory of the Department of Soil and Water Engineering.

## Well Depth

The lowest average depth of wells (13.78 m bgl) is recorded in Kumbhalgarh block, whereas the highest average depth of wells (22.12 m bgl) was observed in Railmagra block. The average depth of wells in Rajsamand district was observed as 17.75 m bgl (Fig. 3).

## Water Level

The average value of groundwater level in pre- and postmonsoon seasons in both the years in different blocks of Rajsamand district is compared in Fig. 4. The groundwater levels in postmonsoon season raised up in all the seven blocks of Rajsamand district. The lowest values of average groundwater level in pre- and postmonsoon seasons, i.e. 7.73 and 2.92 and 7.65 and 2.85 m bgl, respectively, in the years 2011 and 2012, were observed in Kumbhalgarh block, whereas the highest values of average groundwater level in pre- and postmonsoon seasons, i.e.

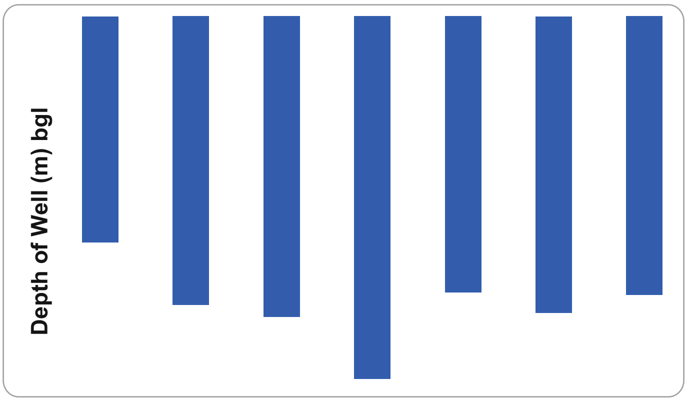


**Fig. 3** Average depth of wells in different blocks of Rajsamand district

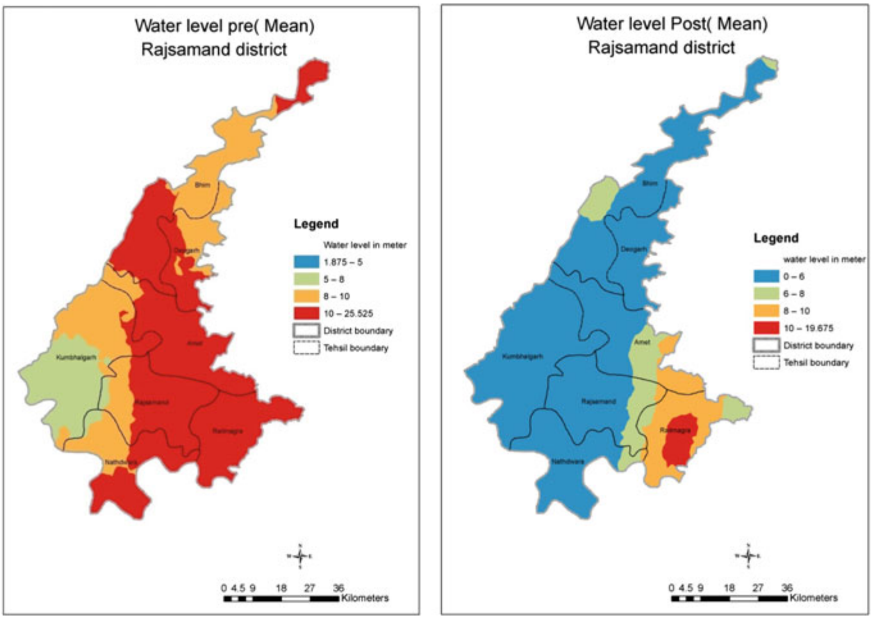


**Fig. 4** Water level fluctuation in pre- and postmonsoon seasons

16.88 and 10.22 and 16.29 and 10.65 m bgl, respectively, were observed in Railmagra block in the years 2011 and 2012, respectively. The average pre- and postmonsoon groundwater levels of Rajsamand district were recorded 11.58 and 5.66 and 11.26 and 5.88 m bgl in both the years, respectively.

## Total Dissolved Solid (TDS)

It is clear that the TDS of groundwater of Rajsamand district ranged from 164 to 8600 and 152 to 7840 mg kg$^{-1}$ in premonsoon seasons with the mean value of 1508 and 1425 mg kg$^{-1}$ in the years 2011 and 2012, respectively. The lowest values of TDS (164 and 152 mg kg$^{-1}$) were observed in Kumbhalgarh block, whereas the highest (8600 and 7840 mg kg$^{-1}$) were recorded in Railmagra block.

In postmonsoon seasons, the TDS varied from 120 to 5810 and 122 to 5980 mg kg$^{-1}$ with the mean values of 1142 and 1154 mg kg$^{-1}$ in the years 2011 and 2012, respectively. The lowest values (120 and 122 mg kg$^{-1}$) were recorded in Kumbhalgarh block, whereas the maximum (5810 and 5980 mg kg$^{-1}$) were recorded in Railmagra block. Hence, a considerable variation in TDS of groundwater in pre- and postmonsoon seasons in both the years in Rajsamand district was observed. The seasonal variation in TDS of groundwater in the study area has also

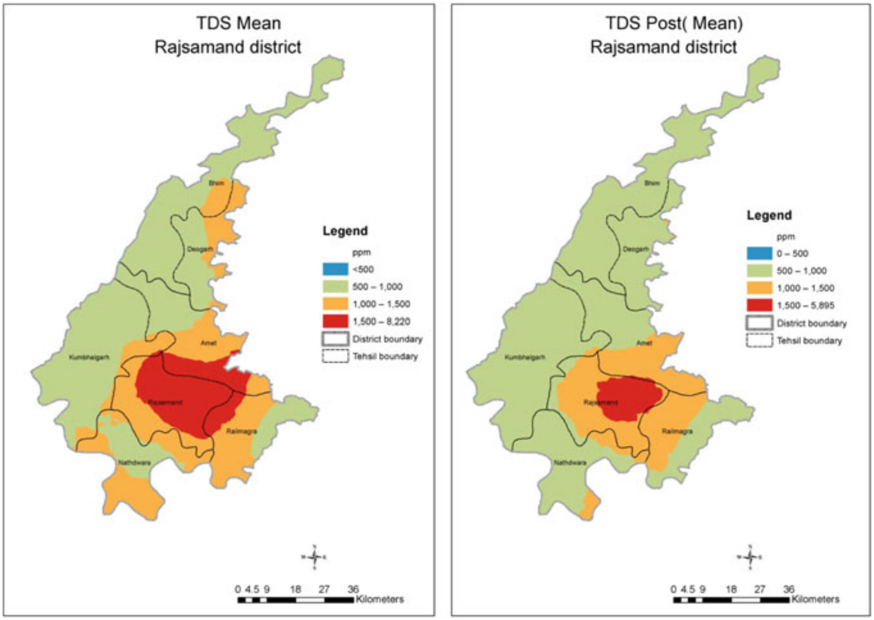


**Fig. 5** Variations in TDS of groundwater of Rajsamand in pre- and postmonsoon

been depicted in Fig. 5. This is clearly indicated that the total dissolved solids of groundwater decreased to a great extent in postmonsoon seasons as compared to premonsoon seasons in both the years. This may be due to dilution effect of rainwater recharge.

The above results are in the close conformity with the findings of Kumar et al. (2007) who reported a significant reduction in TDS of groundwater in postmonsoon season as compared to premonsoon season due to dilution of salts by rainwater. Similar results were also observed by Machiwal et al. (2010).

## PH

The pH of groundwater of Rajsamand district in premonsoon varied from 6.30 to 8.20 and 6.40 to 8.10 with average values of 7.16 and 7.17 in the years 2011 and 2012, respectively (Appendix I). Maximum values (8.20 and 8.10) were recorded in the well water of Deogarh in 2011 and 2012, respectively, whereas the minimum values 6.30 in Railmagra block in 2011 and 6.40 in Nathdwara block in 2012 were observed.

During postmonsoon seasons, the pH value varied from 6.70 to 8.30 and 6.90 to 8.20 with the mean values of 7.42 and 7.36 in the years 2011 and 2012, respectively. Minimum pH values (6.70 and 6.90) were found in Railmagra block, whereas maximum value (8.30) was recorded in Amet block in 2011 and 8.20 in Railmagra block in 2012.

The variation in pH of groundwater of the study area in pre- and postmonsoon seasons indicated that no systematic trend was observed in pH variation in groundwater during both the seasons and years, but in general, a slight increase was observed in postmonsoon seasons as compared to premonsoon seasons.

The results of the present investigation are in line with the findings of Prasad and Minhas (2007) who have reported a slight increase in pH of groundwater in postmonsoon season as compared to premonsoon season in Mahoob Nagar district of Andhra Pradesh. An increase of pH in the postmonsoon suggests that dissolution has been enhanced due to high interaction between soil and rainwater. Similar results were also reported by Kumar et al. (2007) and Ramkumar et al. (2010).

## Electrical Conductivity

The electrical conductivity of groundwater of Rajsamand district varied from 0.25 to 13.44 and 0.23 to 12.20 $dSm^{-1}$ with the mean values of 2.35 and 2.21 $dSm^{-1}$ in premonsoon of the years 2011 and 2012, respectively. The minimum values (0.25 and 0.23 $dSm^{-1}$) were recorded in Kumbhalgarh block, whereas the maximum values (13.44 and 12.20 $dSm^{-1}$) were evidenced in the Railmagra block.

In postmonsoon season, the EC of groundwater of Rajsamand district ranged from 0.18 to 9.08 and 0.20 to 9.40 $dSm^{-1}$ with mean values of 1.78 and 1.81 $dSm^{-1}$ in the years 2011 and 2012, respectively. The minimum EC (0.18 and 0.20 $dSm^{-1}$) of groundwater was found in Kumbhalgarh, whereas the maximum (9.08 and 9.40 $dSm^{-1}$) was recorded in Railmagra block in both years, respectively.

Further, the spatial and temporal variability in groundwater salinity (EC) was explicitly depicted in map in Fig. 6 which clearly indicated that the extent of groundwater salinity was higher in premonsoon seasons as compared to post-monsoon seasons in both the years. The higher average value of EC of groundwater may be due to enrichment of salts because of evaporation effect and due to deeper groundwater levels in the premonsoon. The substantial decrease in salinity of groundwater in postmonsoon season may be due to dilution through good quality rainwater.

The results of the present investigation get support from the studies of Satyanarayan et al. (1967) who observed improvement in groundwater quality by 17% in Kamuruddin Nagar of Delhi after the monsoon rains. Similar results were also reported by Prasad and Minhas (2007) and Rajput et al. (2008).

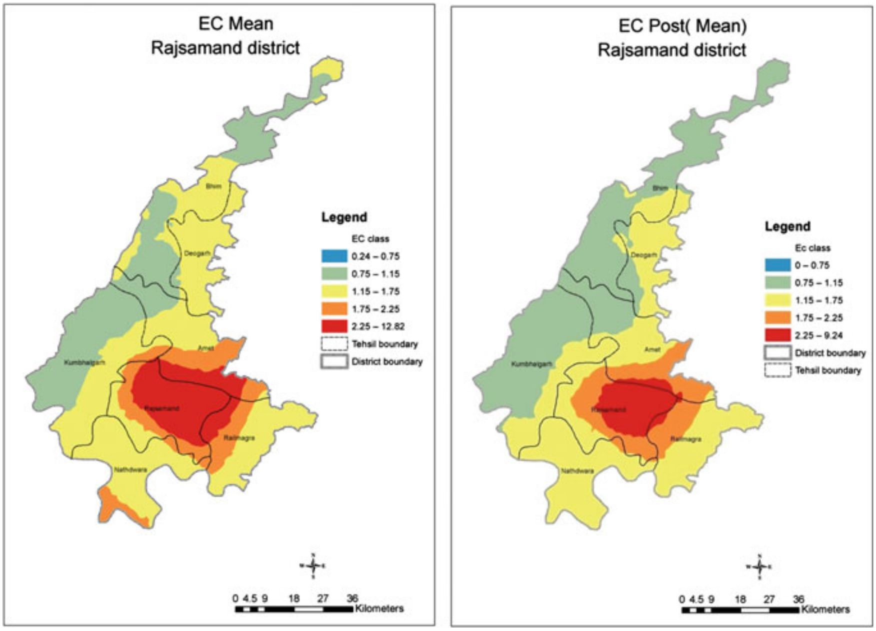


**Fig. 6** Variations in EC of groundwater of Rajsamand district in pre- and postmonsoon

## Cationic Composition

The cationic composition of groundwater of Rajsamand district clearly showed that on the basis of average values of two years the magnesium is the dominated cation followed by calcium, whereas in case of monovalent cations sodium is the dominated cation in groundwater in pre- and postmonsoon seasons in Rajsamand district. Further, it is clearly indicated from the Fig. 7 that the water type of Rajsamand district is Na–Mg–Ca type.

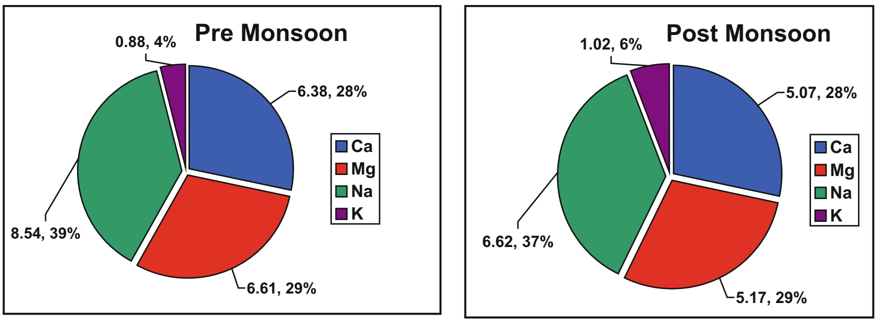


**Fig. 7** Average cationic composition of Rajsamand district

## Anionic Composition

The anionic composition of groundwater of Rajsamand district was also varied with different seasons. In general, postmonsoon groundwater contains less amount of anions as compared to premonsoon season. Chloride was found the dominated anion in groundwater in both the years and seasons followed by bicarbonate, sulphate and carbonate ions (Fig. 8). Further, on the basis of anionic composition of groundwater of the study area is found Cl–$HCO_3$–$SO_4$ type.

## Classification of Groundwater for Irrigation Suitability

A. Salinity

According to USDA classification of irrigation water (Table 3), 9.37 and 12.50% groundwater samples of Rajsamand district fall under C2 class (medium salinity water), whereas the majority of the groundwater samples (60.94 and 57.81%) fall under C3 class (high salinity water), and 29.69 and 28.91% groundwater samples fall under C4 class (very high salinity water) in premonsoon seasons of the years 2011 and 2012, respectively. In postmonsoon season, 0.78 and 0.78% groundwater samples falls under C1 class (low salinity water), 17.19 and 16.41% samples under C2 class (medium salinity water), 57.81 and 58.59% samples fall under C3 class (high salinity water), and 25 and 24.22% groundwater samples fall under C4 class (very high salinity water).

Hence, it is undoubtedly marked from the data that the salinity of the groundwater decreased in postmonsoon seasons and magnitude of decrease was influenced by rainfall characteristics, topography of the area and its drainability. The decreased salinity in postmonsoon period may be due to the dilution of groundwater aquifer by rainwater.

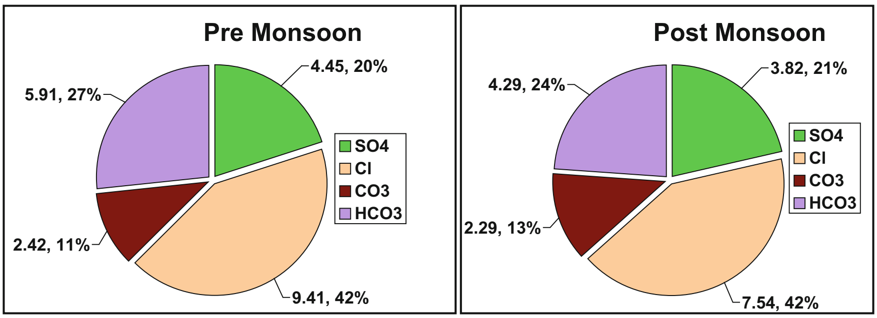


**Fig. 8** Average anionic composition of Rajsamand district

**Table 3** Classification of groundwater of Rajsamand district for irrigation suitability

| Water classes* | 2011 | | 2012 | |
|---|---|---|---|---|
| | No. of water sample in premonsoon | No. of water sample in postmonsoon | No. of water sample in premonsoon | No. of water sample in postmonsoon |
| *Salinity* (*EC*) | | | | |
| $C_1$ (<0.25) | 0 | 1 (0.78% ) | 1 (0.78%) | 1 (0.78%) |
| $C_2$ (0.25–0.75) | 12 (9.37%) | 22 (17.19%) | 16 (12.50%) | 21 (16.41%) |
| $C_3$ (0.75–2.25) | 78 (60.94%) | 73 (57.03%) | 74 (57.81%) | 75 (58.59%) |
| $C_4$ (>2.25) | 38 (29.69%) | 32 (25%) | 37 (28.91%) | 31 (24.22%) |
| *Sodicity* (*SAR*) | | | | |
| $S_1$ (<10) | 126 (98.44%) | 126 (98.44% ) | 125 (97.66%) | 126 (98.44%) |
| $S_2$ (10–18) | 2 (1.56%) | 2 (1.56%) | 3 (2.34%) | 2 (1.56%) |
| *Alkalinity* (*RSC*) | | | | |
| $A_1$ (<1.25) | 124 (96.87%) | 124 (96.87%) | 121 (94.53%) | 120 (93.75%) |
| $A_2$ (1.25–2.5) | 1 (0.78%) | 1 (0.78%) | 1 (0.78%) | 2 (1.56%) |
| $A_3$ (>2.5) | 3 (2.35%) | 3 (2.35%) | 6 (4.69%) | 6 (4.69%) |

*As per criteria suggested by USDA (Richards 1954)

B. Sodicity

Further, out of 128 groundwater samples, 98.44 and 97.66% samples found to have SAR value of <10 (safe for irrigation) and 1.56 and 2.34% samples showed SAR values in between 10 and 18 (moderately safe marginal quality) during premonsoon seasons in the years 2011 and 2012, respectively. In postmonsoon seasons, 98.44 and 98.44% samples found to have SAR value of <10 (safe for irrigation) and 1.56 and 1.56% samples showed SAR values in between 10 and 18 (moderately safe marginal quality) in the years 2011 and 2012, respectively.

C. Alkalinity

Furthermore, it is given in Table 3 that according to USDA classification of irrigation water (Richards 1954), out of 128 groundwater samples, 96.87 and 94.53% samples showed RSC value of <1.25 $meL^{-1}$ (satisfactory for irrigation), 0.78 and 0.78% showed RSC value in between 1.25 and 2.50 $meL^{-1}$ (marginal quality), and 2.35 and 4.69% showed RSC value >2.5 $meL^{-1}$ (unsuitable for irrigation) in both the years in premonsoon seasons, respectively. In postmonsoon seasons, 96.87 and 93.75% samples showed RSC value of <1.25 $meL^{-1}$ (satisfactory for irrigation), 0.78 and 1.56% showed RSC value in between 1.25 and 2.50 $meL^{-1}$ (marginal quality), and 2.35 and 4.69% showed RSC value >2.5 $meL^{-1}$ (unsuitable for irrigation) in the years 2011 and 2012, respectively. Hence, it is clearly evidenced from the data that no trend was found for spatiotemporal variation in residual sodium carbonate in groundwater of Rajsamand district.

Regarding blockwise information, the two-year mean data presented in Table 4 revealed that the maximum water level (16.58 m) in premonsoon season was

**Table 4** Variation in water level and quality parameters in premonsoon season in different blocks of Rajsamand district (mean of two years)

| Block | WL and quality | | | |
|---|---|---|---|---|
| | WL (m) | TDS (ppm) | pH | EC (dS/m) |
| Kumbhalgarh | 7.69 | 666 | 7.05 | 1.04 |
| Bhim | 11.57 | 1127 | 7.37 | 1.76 |
| Rajsamand | 11.07 | 2210 | 7.15 | 3.44 |
| Railmagra | 16.58 | 2092 | 7.03 | 3.25 |
| Deogarh | 9.89 | 1265 | 7.57 | 1.96 |
| Nathdwara | 10.48 | 1798 | 7.08 | 2.79 |
| Amet | 12.70 | 1169 | 7.01 | 1.81 |
| District | 11.43 | 1475 | 7.18 | 2.29 |

**Table 5** Variation in water level and quality parameters in postmonsoon season in different blocks of Rajsamand district (mean of two years)

| WL and quality | Block | | | |
|---|---|---|---|---|
| WL and quality block | WL (m) | TDS (ppm) | pH | EC (dS/m) |
| Kumbhalgarh | 2.88 | 586 | 7.28 | 0.91 |
| Bhim | 5.61 | 792 | 7.25 | 1.23 |
| Rajsamand | 4.28 | 1694 | 7.43 | 2.65 |
| Railmagra | 10.44 | 1682 | 7.43 | 2.63 |
| Deogarh | 5.33 | 1080 | 7.49 | 1.69 |
| Nathdwara | 5.42 | 1412 | 7.50 | 2.20 |
| Amet | 6.02 | 856 | 7.49 | 1.33 |
| District | 5.71 | 1157 | 7.41 | 1.81 |

recorded in Railmagra block, whereas the minimum water level (7.69 m) was found in Kumbhalgarh block. In other words, we can say that minimum energy will be required for pumping/withdrawal of groundwater in Kumbhalgarh and maximum will be required in Railmagra block. The traditional irrigation with Rahat is more common in Kumbhalgarh block which may be due to shallow water level. The pH of groundwater in premonsoon seasons in all the blocks of the Rajsamand district was found near neutral. Perceptible variations were observed in TDS and EC in different blocks in premonsoon seasons. Highest salinity was observed in Rajsamand block followed by Railmagra and Nathdwara blocks which is not suitable for irrigation on long-term basis.

The data presented in Table 5 revealed that the maximum water level (10.44 m) in postmonsoon season was recorded in Railmagra block, whereas the minimum water level (2.88 m) was found in Kumbhalgarh block. As in case of premonsoon seasons, the pH of groundwater in postmonsoon seasons in all the blocks of the Rajsamand district was also found near neutrality. Much variation was observed in TDS and EC in different blocks in postmonsoon seasons. Comparatively, higher salinity was observed in Rajsamand, Railmagra and Nathdwara blocks which is much lower than the values in premonsoon season. This information of the average groundwater levels and its quality may be highly useful in many ways for the selection of the water-lifting devices, selection of the crops for particular block, distribution of seed minikits, management and methodology of application of fertilizers, drinking water supply and other management of quality-related problems on priority basis in the whole district.

## Conclusion

On the basis of the above facts, it can be concluded that the spatiotemporal variations were observed in water quality parameters which indicated that there is improvement in quality of groundwater in postmonsoon. It was observed that the groundwater of Rajsamand district was Na–Mg–Ca and Cl–$HCO_3$–$SO_4$ type. The majority of groundwater samples were in high to very high salinity class on the basis of electrical conductivity (EC), but normal on the basis of sodicity (SAR) and alkalinity (RSC). The quality of groundwater in Rajsamand block was found worst affected followed by Railmagra and Nathdwara blocks. Groundwater quality maps are useful for policy makers or planners for easy illustration and decision making. The maps of average water level can be utilized for the selection of water-lifting devices and their capacity for farmers as well as dealers. The TDS map can be used for prioritization of drinking water supplies, and the EC map can be used for the selection of salt-tolerant crops and varieties and distribution of seed minikits and also for selection of advanced irrigation systems.

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# Effect of Biochar Amendment on Nitrate Leaching in Two Soil Types of India

**Anil K. Kanthle, N. K. Lenka and K. Tedia**

**Abstract** Nitrate leaching from agricultural soils is a major concern to the groundwater, surface water bodies, and environment and also affects the farmers' economy. The present study investigated the effect of native soil organic carbon and biochar amendment on the leaching of nitrate using a laboratory column study. The experiment was conducted taking two soil types of central India (Inceptisol and Vertisol differing in soil texture, viz. Loamy and clay texture). In each soil type, three native SOC levels ($C_1$: high SOC, $C_2$: medium, and $C_3$: low SOC) and four biochar amendment levels were taken in three replications in a factorial design. The four levels of biochar amendment were 0 ($B_0$), 5 ($B_5$), 10 ($B_{10}$), and 20 ($B_{20}$) g biochar $kg^{-1}$ of air-dry soil. There was a significant effect of soil $C$ ($p < 0.01$) and biochar ($p < 0.01$) amendment on the $NO_3^-$-N leached, and the total dissolved salt (TDS) leached in both soil types. In the Inceptisol, $NO_3^-$-N leaching increased with reduction in native SOC content, whereas the reverse trend was observed in the Vertisol. Biochar amendment reduced $NO_3^-$ leaching in both the soils, though the effect was higher in the Inceptisol. In both the soils, a significant effect of SOC level on leachate pH was observed with reducing pH with decrease in SOC level. As compared to control, the extent of reduction in the TDS leaching varied from 13 to 18% under biochar amendment in the Inceptisol and by about 5–6% in the Vertisol.

## Introduction

Nitrate leaching is one of the common concerns reported from intensive agriculture areas. The problem is severe in areas depending heavily on added soil nutrients in form of chemical fertilizers with low supplementation of organic inputs. Because of the less clay content and dominance of less activity clays with low surface areas,

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coarse- and medium-textured soils are prone to nitrate leaching. However, with regular addition of chemical fertilizers and declining soil organic carbon (SOC) content, even clay soils may contribute to nitrate leaching beyond the root zone. Apart from the role of soil texture, the SOC content has a vital role in regulating nitrate leaching. The SOC content is a function of soil properties and soil management. In intensive agriculture systems, poor SOC management in form of low supplementation of organics is the primary reason for reducing soil quality. Of late, biochar has been used as an amendment to improve soil quality and reduce leaching loss of nutrients (Laird et al. 2010; Mukherjee et al. 2014). Biochar application to soil increases the overall sorption capacity, and thus, may influence the soil function to retain nutrients and filter harmful chemicals. However, the role of SOC and soil amendments such as biochar in leaching of nutrients is less studied in Indian soils. Hence, the particular study was conducted to study the effect of native SOC level and biochar on leaching of nitrate in two major soil types of India (Inceptisol and Vertisol).

## Materials and Methods

### *Experimental Details*

The experiment was conducted through a column study in laboratory set up at the Indian Institute of Soil Science, Bhopal, (Madhya Pradesh) during the year 2014–15. The two soil types used for the experiment were: (1) clay soil (Vertisol) collected from Bhopal region (23° 18′ North latitude and 77° 24′ East longitude) of Madhya Pradesh, and (2) loam soil (Inceptisol) collected from Bemetara district (21° 42′ North latitude, 81° 32′ East longitude) of Raipur region of Chhattisgarh. Bulk soil from the surface 0–20 cm layer from different land uses was collected to obtain a SOC gradient with three SOC levels under each soil group. The selected land uses included those under permanent vegetation cover, agricultural land use, and nearby fallow lands. The bulk soil collected was air-dried and ground to pass through a 2 mm sieve, and then stored for use in the column study.

The column study was conducted in two soil types with three native SOC levels under each soil type and four levels of biochar amendment in each SOC level. The three native soil organic carbon levels under each soil type were treated with four levels of biochar as amendment 0, 5, 10, and 20 g $kg^{-1}$ of air-dry soil (0, 11.2, 22.4, and 44.8 ton $ha^{-1}$), resulting in 12 treatments for each soil type. The treatments were replicated thrice in factorial completely randomized design (FCRD), and thus, 03 × 04 × 03 = 36 columns were used for each soil type. The technical program of work is presented in Table 1.

**Table 1** Technical program of work

| S. No. | Treatments | Treatments levels | Detail |
|---|---|---|---|
| 1 | Soil types | 02 | Clay soil (Vertisol)<br>Loam soil (Inceptisol) |
| 2 | Native soil organic carbon | 03 | $C_1$, $C_2$ and $C_3$ representing high, medium and low native SOC status |
| 3 | Biochar as amendment | 04 | 0, 5, 10 and 20 g biochar kg$^{-1}$ soil |
| 4 | Replications | 03 | |
| 5 | Design | Factorial CRD | |
| 6 | Number of treatments in each soil | 03 × 04 = 12 | |
| 7 | Number of columns per soil type | 03 × 04 × 03 = 36 | |
| 8 | Total number of columns for two soil types | 02 × 03 × 04 × 03 = 72 | |

## *Preparation of Soil Columns*

For the column experiment, PVC-made cylindrical pipes were used with assembly for leaching and collection of leachate. The columns were 40 cm long with 11 cm internal diameter (3800 cm$^3$ volume). The columns were provided with an end cap and funnel arrangement for collection of leachate. All columns were packed to a bulk density of 1.2 Mg m$^{-3}$ for both the soil types. Taking into account the bulk density and the volume of each column, 4.562 kg of soil was required for each column. The columns were packed gently with small taps in small layers of about 5 cm followed by scratching with a laboratory spatula so as to maintain natural continuity among the filling soil layers.

## *Biochar Amendment*

Biochar is the carbonaceous product obtained by the heat treatment (300–600 °C temperature) of biomass such as soft/hard wood, grasses, algae, wastes, crop residues, etc., under limited or no oxygen (pyrolysis) conditions. The physical and chemical characteristics of biochar vary depending on the feedstock selected and pyrolysis conditions. In this experiment, biochar made from maize stalks was used. The maize biochar was produced by combusting maize stalks in a closed kiln at a temperature of 350 °C for 3 h under limited oxygen conditions. The biochar was ground in a wooden hammer, and the portion less than 2 mm fraction was separated by dry sieving. The biochar used in the study was measured to have pH (1:10) of 11.2 and electrical conductivity (dS m$^{-1}$) of 4.88 with total carbon varying from 42 to 55%. In the biochar treatment, required amount of biochar as per the treatment was weighed for upper half depth of the soil column (i.e., 20 cm soil depth). Biochar was mixed thoroughly with the soil before filling in the upper half of the soil columns under the biochar treatments. There were four biochar treatments in each soil at the rate of 0, 5, 10, and 20 g $kg^{-1}$ of air-dry soil (equivalent to 0, 11.2, 22.4, and 44.8 ton biochar $ha^{-1}$).

## *Soil Columns Incubation and Leaching*

The leaching experiment was conducted in the laboratory condition at the room temperature during August to November 2014 for the Vertisol (representing standard meteorological week 31–48) and during December 2014 to March 2015 for the Inceptisol (representing standard meteorological week 49–14). Potassium nitrate ($KNO_3$) was added in the 1st, 9th, and 12th leaching in the Inceptisol and in the 1st, 8th, and 11th leaching in the Vertisol, at the rate equivalent to 200 kg N $ha^{-1}$ in each case. The fertilizer was incorporated into the top 3 cm of the soil in the columns by "micro tillage" using a laboratory spatula.

For each soil, 15 leaching events were carried out, approximately at the rate of one event per week. Before initiation of the 1st leaching, the soil columns were pre-wetted to a water-filled porosity of about 60%. This was equivalent to 1200 $cm^3$ in the Inceptisol and 1450 $cm^3$ in the Vertisol. Then for each leaching event, 200 $cm^3$ of water was added on the surface of each soil column. Leachate from each column was collected in 250 ml glass conical flask. The experiment was conducted under limited evaporation conditions by loosely covering of the columns with polythene. The leachate collected per column in each event was filtered in Whatman No. 1 filter paper to remove bypassed sediments, if any. The leachate volume was measured in 50 ml measuring cylinder and then stored for further analysis. The electrical conductivity (EC) value of the leachate was measured by an electrical conductivity meter. Nitrate and ammonium concentrations of the leachate were measured by a Kjeldahl distillation unit, as per the method of Bremner and Keeney, as described in Sparks (1996). The nitrate leached was computed from the product of nitrate concentration and leachate volume. The total dissolved salt (TDS) leached was computed from the EC values using a factor of 640 for EC less than 5.0 dS $m^{-1}$ and 800 for EC greater than 5.0 dS $m^{-1}$. The data obtained for various parameters under study were analyzed by the method of analysis of variance applicable for factorial completely randomized design (FCRD) as described by Gomez and Gomez (1984). The effects of the two factors (native SOC level and biochar amendment level) and their interaction effect were compared at 95% level of significance ($p < 0.05$).

## Results and Discussion

### *Effect of Native Soil Carbon and Biochar on Total $NO_3^-$ Leached in Inceptisol*

The $NO_3^-$-N leached in each of the 15 leaching events in the Inceptisol is shown in Fig. 1. Barring the first two events, the $NO_3^-$-N leaching in general was higher in low carbon ($C_3$) treatment and reduced with increase in native SOC level. Significant effect of both the factors, viz. native soil $C$ ($p < 0.01$) and biochar ($p < 0.01$) was observed. However, the interaction effect of the two factors was not significant. Averaged over biochar treatments, the mean $NO_3^-$ leached in all the 15 events varied from 402 under $C_1$ to 430 under $C_2$ and 538 mg under $C_3$ treatment. As compared to $C_1$, leached $NO_3^-$ was higher by 6.74% under $C_2$ and by 33.66% under $C_3$ treatment. Biochar amendment decreased the $NO_3^-$ leaching. Averaged over native SOC levels, the total $NO_3^-$-N leached in the 15 events were 525, 491, 414, and 398 mg under control, $B_5$, $B_{10}$, and $B_{20}$ treatments, respectively. As compared to control, $NO_3^-$ leached was lower by 6.44, 21.21, and 24.13% under $B_5$, $B_{10}$, and $B_{20}$ treatments, respectively. Temporal variation in the $NO_3^-$ leached was observed, with highest peak in the first leaching event (LE) and drastic decline after 3rd LE. There were secondary peaks in the 9th and 12th LE due to addition of $KNO_3$ salt before initiation of the particular leaching events. The effect of addition of salts before 9th and 12th leaching resulted in an increasing trend of leached $NO_3^-$ even up to the 15th LE, and the increase was much higher in the $C_3$ treatment.

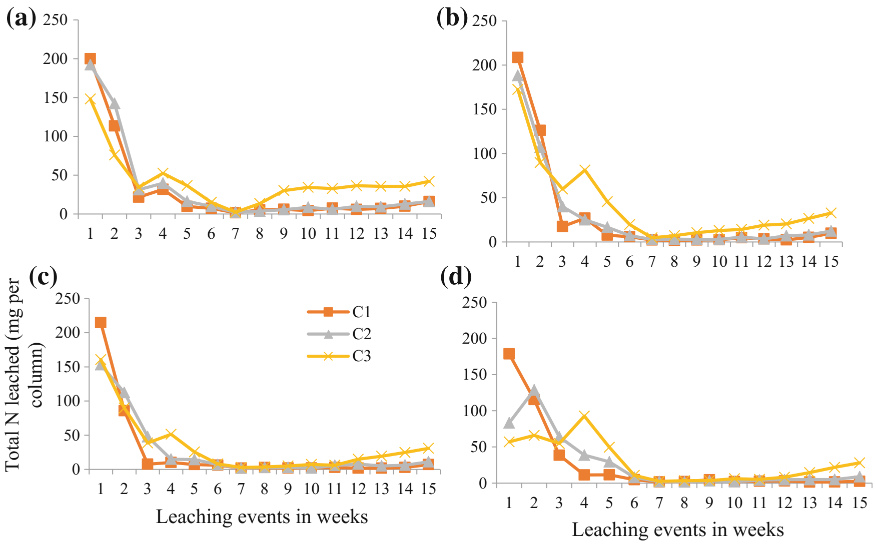


**Fig. 1** Total $N$ leached (mg per column) under different native soil carbon levels ($C_1$, $C_2$, and $C_3$ representing high, medium, and low carbon, respectively) with different biochar amendment rates at 0 (**a**), 5 (**b**), 10 (**c**), and 20 (**d**) g biochar kg$^{-1}$ soil, respectively in the Inceptisol

### *Effect of Native Soil Carbon and Biochar on Total $NO_3^-$ Leached in Vertisol*

The data on the total $NO_3^-$-N leached in the individual LE for the Vertisol are shown in Fig. 2. In most of the 15 individual leaching events, significant effect of both the factors, viz. native SOC ($p < 0.01$) and biochar ($p < 0.01$), and their interaction effect was observed on the total $NO_3^-$ leached. The $NO_3^-$ leaching was much higher under $C_1$ up to 4th LE, and then the effect got either neutralized or reversed. This was due to the high substrate ($NO_3^-$) availability in the $C_1$ soil compared to the $C_2$ and $C_3$ soils. In other words, the $NO_3^-$ present in the $C_1$ soil showed a dominant effect in determining the $NO_3^-$ leached till the 4th LE. Very high levels of $NO_3^-$ leached in the first few LE under the $C_1$ soil resulted in a higher cumulative value over the 15 events, and thus, showed an apparently higher leaching under $C_1$ than $C_2$ or $C_3$ soil. The cumulative data showing higher leaching in the $C_1$ treatment and lowest under $C_3$ treatment were contrary to the trend observed in the Inceptisol. The apparently higher trend of $NO_3^-$ leaching under $C_1$ as compared to $C_2$ and $C_3$ was solely because of the high SOC and the soil $NO_3^-$ present in the former. The difference in the absolute values of $NO_3^-$ leached between $C_1$ and $C_2$ or $C_3$ was highest in the 1st LE and then gradually reduced with successive leaching events. After 12th LE, the trend got reversed completely with significantly higher $NO_3^-$ leaching under $C_3$ or $C_2$ as compared to $C_1$. In other words, the effect of SOC level in regulating $NO_3^-$ leaching got masked due to the

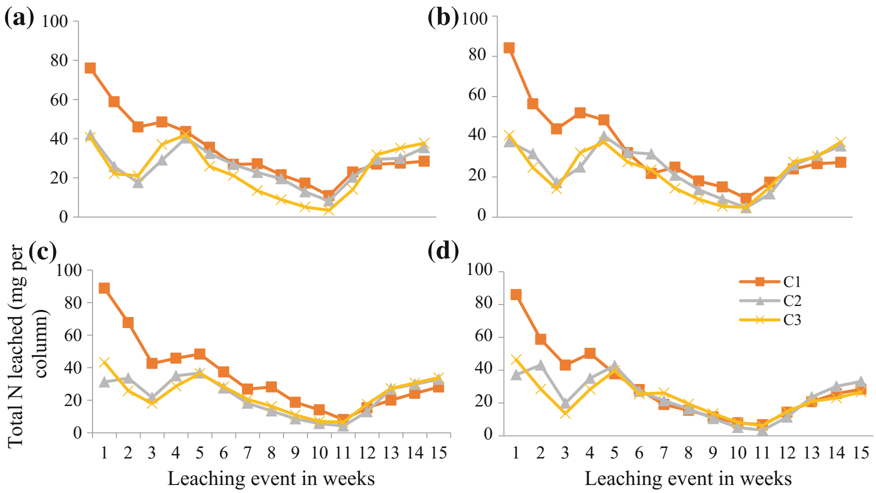


**Fig. 2** Total *N* leached (mg per column) under different native soil carbon levels ($C_1$, $C_2$, and $C_3$ representing high, medium, and low carbon, respectively) with different biochar amendment rates at 0 (**a**), 5 (**b**), 10 (**c**), and 20 (**d**) g biochar $kg^{-1}$ soil, respectively in the Vertisol

substrate effect, i.e., high SOC and high $NO_3^-$ content in the $C_1$ soil. In general, biochar treatment reduced $N$ leaching in all the three native SOC levels, though the effect was smaller than the Inceptisol. The cumulative $NO_3^-$-N leached varied from 424 mg under control to 403, 401, and 385 mg under $B_5$, $B_{10}$, and $B_{20}$ treatments, respectively. As compared to control, $NO_3^-$ leached was lower by 4.74, 5.32, and 9.03% under $B_5$, $B_{10}$, and $B_{20}$ treatments, respectively. Lower leaching losses of $NO_3^-$-N due to biochar amendment as observed in both the soils of the present study have also been shown by earlier workers (Mukherjee et al. 2014; Mukherjee and Zimmerman 2013; Laird et al. 2010).

## *Effect of Native Soil Carbon and Biochar on Leaching of Total Dissolved Salt in Inceptisol*

The effect of native soil carbon and biochar amendment on TDS leached from the soil column over the 15 events in the Inceptisol is shown in Table 2. At the 1st LE, the TDS leached (averaged over biochar treatments) values were 2.54, 2.39, and 2.24 g under $C_1$, $C_2$, and $C_3$ treatments, respectively, where as the values (averaged over SOC treatments) were 3.13, 2.35, 2.46, and 1.63 g under $B_0$, $B_5$, $B_{10}$, and $B_{20}$ treatments, respectively. In all the treatments, the quantum of TDS leached reduced to about half in the 2nd LE and further declined in the successive leaching events. However, secondary peaks were observed in the 10th and 13th LE owing to the addition of fertilizer salts in the 9th and 12th LE. In the secondary peaks, the increase was higher under $C_3$ than other SOC treatments possibly due to lower sorption in the $C$ limiting soil. The data of cumulative total of the 15 events showed a reduction in the TDS with increase in SOC level and biochar amendment having significant effects of SOC, biochar and their interaction. Averaged over biochar treatments, the TDS leached values were 5.63, 6.84, and 7.23 g under $C_1$, $C_2$, and $C_3$ treatments, respectively. This implied an increase in the TDS leaching by 21.5% under $C_2$ and by 28.4% under $C_3$ as compared to $C_1$. Averaged over SOC treatments, the cumulative TDS values were 7.39, 6.45, 6.07, and 6.36 g under $B_0$, $B_5$, $B_{10}$, and $B_{20}$ treatments, respectively. Thus, reduction in the TDS leached was to the extent of 12.7, 17.9, and 13.9% under $B_5$, $B_{10}$, and $B_{20}$ treatments, respectively, as compared to control.

**Table 2** Total dissolved salt (TDS) leached in 15 leaching events under different biochar and SOC level (gram per column)

| SOC/biochar level | $B_0$ | $B_5$ | $B_{10}$ | $B_{20}$ |
|---|---|---|---|---|
| $C_1$ | 6.07 | 5.65 | 5.30 | 5.51 |
| $C_2$ | 7.74 | 6.26 | 6.76 | 6.59 |
| $C_3$ | 8.37 | 7.45 | 6.15 | 6.97 |

**Table 3** Total dissolved salt (TDS) leached in 15 leaching events under different biochar and SOC level (gram per column) in Vertisol

| SOC/biochar level | $B_0$ | $B_5$ | $B_{10}$ | $B_{20}$ |
|---|---|---|---|---|
| $C_1$ | 5.70 | 5.39 | 5.54 | 5.24 |
| $C_2$ | 4.16 | 4.13 | 3.80 | 3.99 |
| $C_3$ | 3.62 | 3.43 | 3.51 | 3.51 |

### *Effect of Native Soil Carbon and Biochar on Leaching of Total Dissolved Salt in Vertisol*

The data showing the effect of SOC and biochar treatment on TDS leached in the Vertisol are given in Table 3. The ANOVA of the total leached salt over the 15 events showed significant effect of both SOC and biochar, but not their interaction. The effect of SOC was contrary to the trend observed in the Inceptisol. Higher TDS leaching was observed under high *C* soil ($C_1$) with reduction with lowering of SOC level. The total TDS leached in the 15 events were 5.47, 4.02, and 3.52 g under $C_1$, $C_2$, and $C_3$ treatments, respectively. Thus, with reduction in SOC level, the TDS leaching reduced by 26.5% and 35.6% under $C_2$ and $C_3$ treatments, respectively, as compared to $C_1$. Averaged over SOC treatments, the absolute values of TDS leached were 4.50, 4.32, 4.28, and 4.25 g under $B_0$, $B_5$, $B_{10}$, and $B_{20}$ treatments, respectively. The three biochar treatments were at par in reducing the TDS leaching but were significantly better than the control. As compared to control, the $B_{20}$ treatment could reduce 5.6% TDS leaching. A reduced TDS with biochar application might be due to higher cation exchange capacity as reported by several workers (Nigussie et al. 2012). Laird et al. (2010) using a column study reported a significant reduction in the leaching of cations like K, Na, and Mg when biochar was added in addition to manure. They reported that the 20 g kg$^{-1}$ biochar treatments reduced total *N* and total dissolved *P* leaching by 11 and 69%, respectively. Thus, increased sorption by biochar amended soils as reported by Mukherjee and Zimmerman (2013) might be responsible for the reduced salt leaching as observed in the present study.

## Conclusion

The study showed that biochar amendment significantly reduced leaching of nitrate and dissolved salt in both the studied soils; however, the effect was conspicuous in the Inceptisol as compared to the Vertisol. The study also showed native soil organic carbon level affecting the action of biochar in mitigating nitrate leaching from soil. Future studies are thus required to investigate the mechanisms of action of biochar in diverse types of soil conditions.

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# Seasonal Variation of Groundwater Quality in and Around Laharpur Reservoir, Bhopal

**Neha Nigam and Shalini Yadav**

**Abstract** Variations in availability of water with respect to time, quantity, and quality are playing a very significant role in the development of economy of a country. For the different uses, one may require different criteria of water quality as well as standard methods for reporting and comparing results of water analysis. Groundwater and other water bodies in the region of central India are getting contaminated due to numerous types of discharge by the human activities, residential, municipal, commercial, industrial, and agricultural activities. Bhopal, the capital of province of the Madhya Pradesh in India, has a number of water bodies. Laharpur reservoir is one of them. An attempt is made to investigate the seasonal variation in groundwater quality in and around the area of the Laharpur reservoir. The study has revealed from the analyzed results of collected groundwater samples that certain parameters, namely EC, TH, TDS, BOD, chlorides, were exceeding the desirable limit throughout the investigation period in all locations. This is due to the leaching of contaminants into the groundwater. Based on the findings, it is suggested to the local government that discharged wastewater from the sewage of residential and local industrial area must be treated properly as per the standard to avoid its adverse impact on the human health of the region.

## Introduction

It is an open truth that freshwater is a finite and limited resource on the planet and its utilization from ages has led to its overexploitation coupled with the growing population along with the improved standard of living as a consequence of technological innovations (Bouwer 2000). Groundwater is one of the renewable resources, and it is directly linked with human welfare and economic development. Around 70% of

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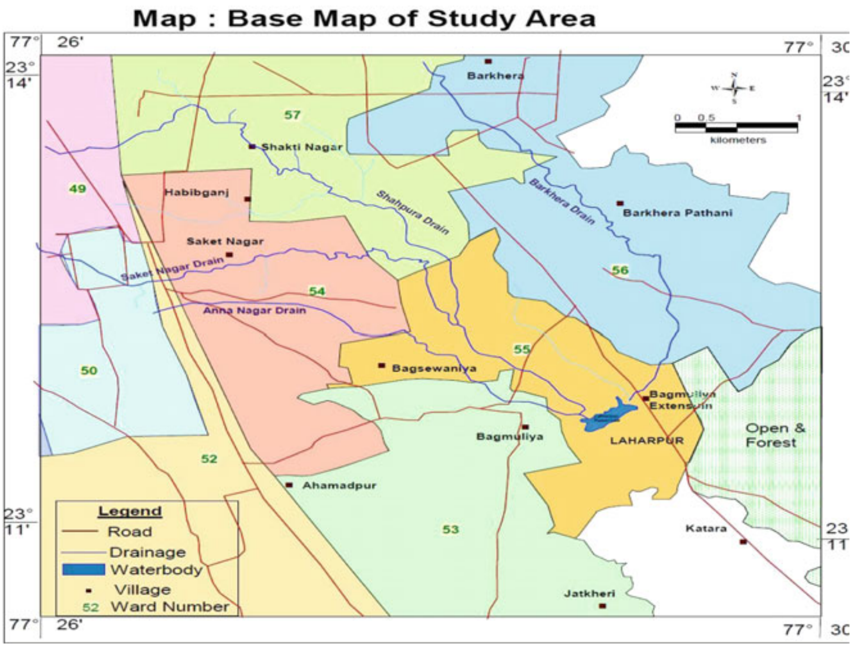
population in India lived in rural area and are dependent on groundwater as it is the only source of drinking water supply (Hajalilou and Khaleghi 2009). Its quality is a vital concern for the mankind.

Bhopal, the capital of the province of Madhya Pradesh, is the home to a large number of lentic water resources, including the famous Bhoj Wetland and the maiden Ramsar Site of the state (Hegde and Kale 1995). Despite having a large number of water bodies in and around it, the city witness decreased water supply, especially during the drier months of the year. The majority of Bhopal's drinking water supply is met by two surface water sources, namely the Upper Lake and the Kolar Reservoir. Besides, there are tube wells, hand pumps, and dug wells.

Laharpur reservoir is situated in the southwest of Bhopal city in the state of Madhya Pradesh, with an objective to store water for irrigational purpose. Over the period of the last few years, the reservoir has been surrounded by habitations with the growth of the city. These developments resulted in anthropogenic pressures on the reservoir which accelerated the eutrophication process, thereby making the water body unfit for human consumption. The higher concentration of bacterial contamination in the water reservoir may possibly contaminate the groundwater also. Therefore, the assessment of the variation of water quality parameter is the first and foremost task of the scientific management of the reservoir and groundwater, and finding out the suitability of the water for multipurpose (Khodapanah et al. 2009). In light of the above, the present study was undertaken to assess the seasonal variations of water quality parameters of groundwater located in and around the Laharpur reservoir.

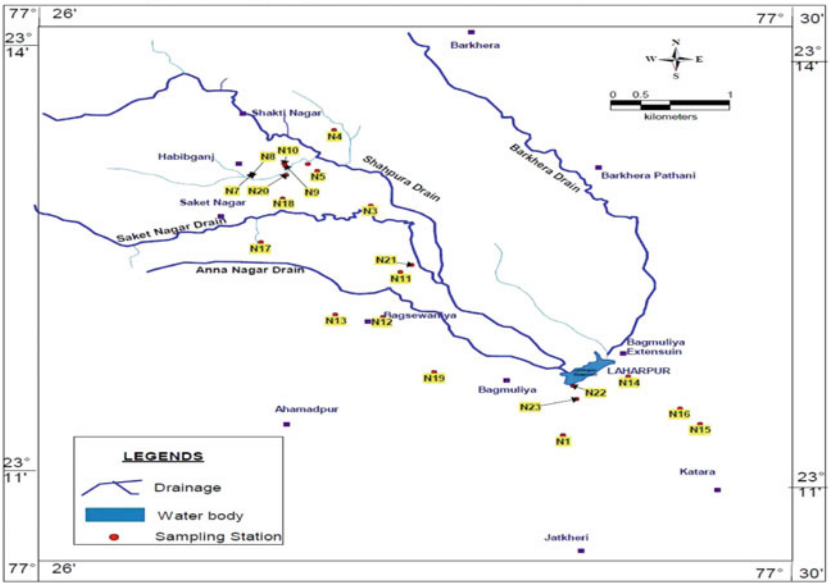


## Materials and Methods

The present study has been designed to take into account the spatial distribution of contaminants accumulating in the Laharpur reservoir and their subsequent transfer in the subsurface aquifer of the neighboring areas. The residential areas adjoining the Laharpur reservoir almost exclusively depend upon the groundwater to suffice the needs of potable and secondary uses of water (Malik and Dubey 2009). Therefore, it becomes pertinent to collect water samples from every important locality for the purpose of the study. It has been taken into account while designing the study to collect representative samples from all the major residential colonies.

The study comprises of collection of water samples from the identified locations, interpretation, and analysis of water samples collected from different stations in and around Laharpur reservoir. Twenty water samples were collected from identified dug wells and bore wells during pre-monsoon and post-monsoon period of the years 2014 and 2015 from the identified twenty sampling points. The water samples were collected in plastic container to avoid unpredictable changes in physicochemical characteristics, and the glass bottles were used for the collection of samples of total coliform. The samples were analyzed within 24 h of sample collection. Physical, chemical, and bacteriological parameters for the all the collected samples were analyzed (Pandey et al. 2010). The parameters that were analyzed during the study are pH, turbidity, conductivity, total dissolved solids, total alkalinity, total hardness, calcium hardness, calcium content, magnesium content, chlorides, dissolved oxygen, biochemical oxygen demand, chemical oxygen demand, sodium, potassium, sulfates, nitrates, total phosphate, orthophosphate, iron, and total coliform.

Map : Sampling Station in the Study Area



All the samples were analyzed in accordance with standard procedure subscribed in APHA. The parameters such as pH, turbidity, and conductivity were measured using standard pH meter, conductivity meter, and nephelometer, respectively. The total dissolved solids were measured using standard laboratory method using hot plate and hot air oven by evaporating the samples at 105 °C. The chemical parameters which include total alkalinity, total hardness, chloride, dissolved oxygen (DO), free carbon dioxide ($CO_2$), biochemical oxygen demand, calcium hardness, magnesium hardness, chemical oxygen demand were analyzed using standard titrimetric methods. The sodium and potassium contents were analyzed using flame photometer technique. The parameters such as phosphate ($PO_4$-P), fluorides, sulfates, nitrate ($NO_3$-N), and iron were measured through wavelength using DR 5000 UV–Vis Spectrophotometer (Hach, USA). The total coliform that present in all the groundwater samples were analyzed through multiple-tube fermentation technique.

## Frequency

Therefore, to take into account the seasonal variations in the water quality of the water sources and also to ensure the reproducibility of the results, samples were collected from the identified sampling stations in different seasons for the period of two years. In this study, the seasonal variability of groundwater quality parameters in and around the residential area in the upstream and downstream areas of Laharpur reservoir was investigated. The analysis was done for pre-monsoon and post-monsoon seasons of the years 2014 and 2015. The following parameters were analyzed during the study viz. pH, turbidity, conductivity, total dissolved solids, total alkalinity, total hardness, calcium hardness, calcium content, magnesium content, chlorides, dissolved oxygen, biochemical oxygen demand, chemical oxygen demand sodium, potassium, fluorides, sulfates, nitrates, total phosphate, orthophosphate, iron, and total confirm.

## Results and Discussion

The water to be used for drinking purpose must meet high standards of physical, chemical, and biological purity. The quality of groundwater is mainly influenced by its physical, chemical, and biological aspects which vary from place to place, with the depth of water table, and from season to season. The occurrence of groundwater is a natural phenomenon attributed to seepage of surface water into subsurface layers of earth. Normally, these impurities removed during trickling down of surface water through biophysical filters of natural soil media. The water retained in capillaries of subsoil strata known as aquifer, which is quite useful for maintaining soil moisture. Because of this popular belief that the groundwater would be relatively uncontaminated, it is being consumed without treatment, but the accumulation of sewage and solid waste at the ground is constantly polluting the groundwater. The anthropogenic activity further deteriorates water quality, especially in case of urban water system. The increasing number of cases related to waterborne diseases in people consuming the groundwater has caused a worry and made it necessary to assess the quality of groundwater being used for potable turbidity point of view season. The groundwater is generally clear with no color during winter and summer seasons when viewed through normal eye, but when compared with bottled water, there is some difference from turbidity point of view.

The pH values of groundwater range from 7.1 to 8.1 during dry and wet seasons, respectively (Fig. 1). The pH values during both seasons fall within the permissible range of 6.5–8.5. Fifty percent of analyzed samples have pH values below 8.0 during dry season, while this increases to 80% during wet season. This indicates that there is more dissolution of pollutants during the rainy season.

The chloride ion concentration values ranged from 39 to 103 mg/L during dry and wet seasons, respectively, and these were found to lie within the permissible level of 250 mg/L (Fig. 2). The higher range of chlorides can be attributed to higher temperature, and the dilution of waste during wet season increases its concentration in groundwater samples.

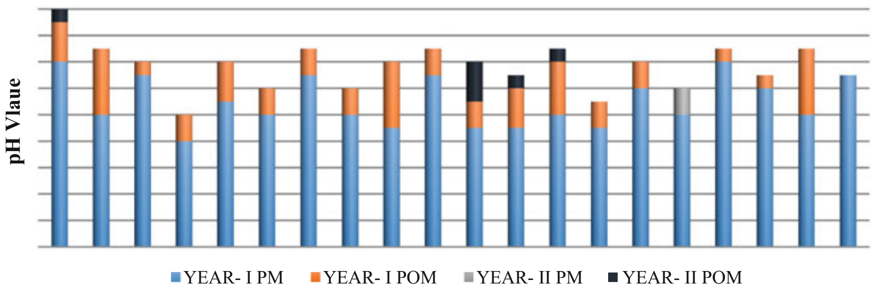



**Fig. 1** Seasonal variation in pH of groundwater

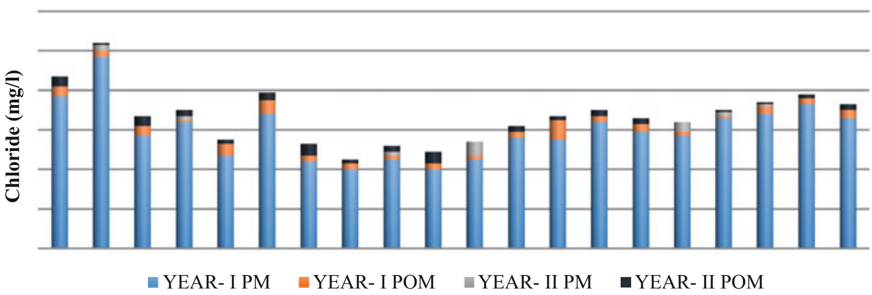



**Fig. 2** Seasonal variation in chloride of groundwater

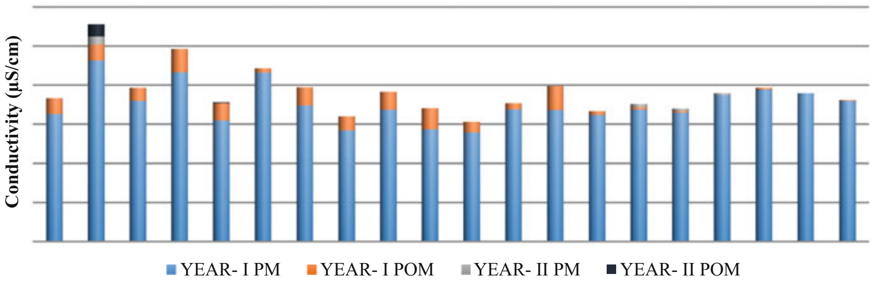



**Fig. 3** Seasonal variation in conductivity of groundwater

Electrical conductivity values range from 558 µS/cm during dry season and 1112 µS/cm during wet season (Fig. 3). The highest value of conductivity was due to the maximum concentration of soluble salts present in the *N*1 and *N*2 during rainy season of the year 2014–15.

The TDS values were 564 mg/L in dry season and 678 mg/L during wet season (Fig. 4). This may be due to leaching of various pollutants through sides and bottom of unlined drain (Pisal and Yadav 2014).

The total hardness (TH) values during dry and wet seasons ranged from 182 to 376 mg/L, respectively (Fig. 5). It is noted that 10% of the water samples fall under "moderate" class while 70% of water samples fall under "hard" class during the dry season. During wet season of sample collection, 45% fall under "moderate" class and 75% fall under "hard" class while the remaining 25% fall under "very hard" class. This may be due to decay of organic matter and weathering of rocks and minerals (Raj 2000). The hardness of water is not a pollution parameter, but it indicates water quality mainly in terms of calcium and magnesium. Water containing excess hardness is not desirable for potable purposes, as it forms scales on water heaters and utensils when used for cooking and consumes more soap during washing clothes.

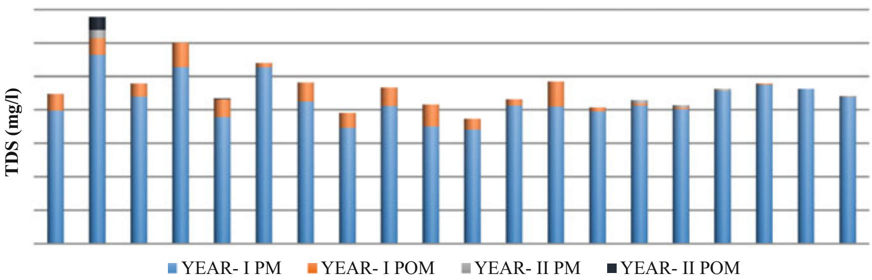



**Fig. 4** Seasonal variation in TDS of groundwater

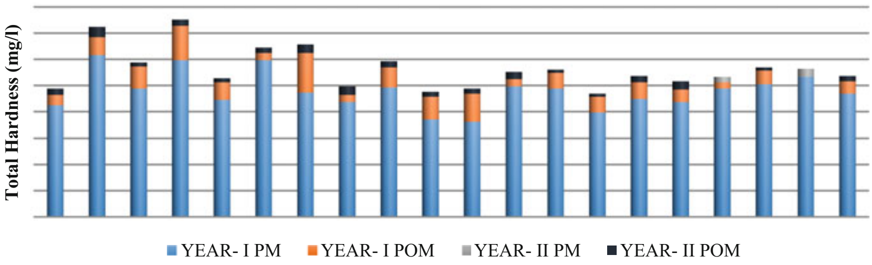



**Fig. 5** Seasonal variation in hardness of groundwater

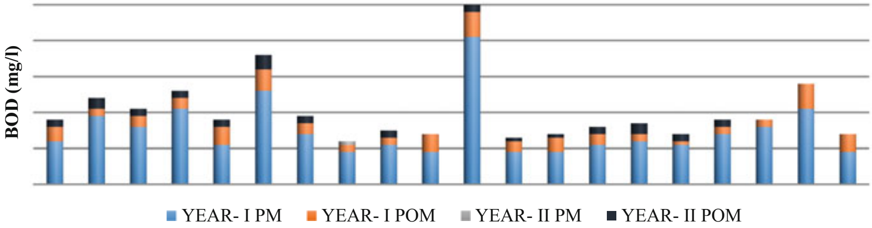



**Fig. 6** Seasonal variation in BOD of groundwater

The concentration of BOD ranges from 1.8 to 2.4 mg/L in dry season and from 8.2 to 10 mg/L during wet season (Fig. 6). The higher concentration of organics can be due to mixing of sewage in groundwater. This concentration increases in rainy season due to increase in flow in the drains which causes dilution of solid waste and its percolation in the nearby aquifers.

The concentration of coliform ranges from 11 to 63 org/100 mL during dry season and from 17 to 108 org/100 mL during wet season (Fig. 7). The major health hazard associated with the consumption of contaminated water is due to the presence of pathogenic bacteria (Todd 1995). The coliform group of bacteria, especially fecal coliform, inhibits intestine of mammals including man and other warm-blooded animals, and their presence in water sample directly reflects the mixing of sewage

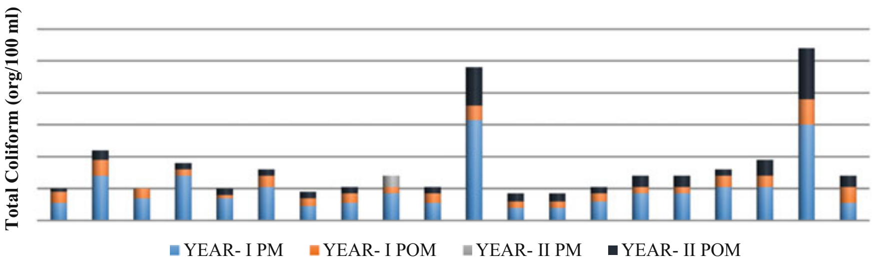



**Fig. 7** Seasonal variation in total coliform of groundwater

with groundwater. The high concentration of total coliform increases the possibility of the presence of pathogenic strains of bacteria such as Schigella, Salmonella, Streptococci, Vibrio, Staphylococcus aureus, thus posing a serious health hazard to its consumers. Almost all water samples have reported a high number of coliform counts exceeding the desired count at all occasions. None of the samples fulfill the potable water quality criteria in terms of coliform. This renders the water unfit for human consumption for potable purpose and poses the threat of waterborne disease to its consumers.

The residential area of the town is surrounded by agricultural area, where agricultural activity and usage of fertilizers are very high throughout the year and also by aquaculture area (Tripathi and Choudhary 2014). The groundwater samples in both seasons have their nitrate values that lie below the limit of 50 mg/L. The open well water is available at shallow depth of 4–5 feet. So seepage of the fertilizers, especially $NO_3$ $PO_4$, from agricultural field to the aquifer is possible, resulting in the contamination of the well water. The very small amount of soluble leachates of organic compounds may also reach the groundwater aquifer, whereas major portions of it may get absorbed by the soil during seepage. Thus, the groundwater aquifers were likely to be contaminated by the use of fertilizers. This may be due to increased hardness of the groundwater.

## Conclusion

It revealed from the analyzed results of groundwater samples that certain parameters, namely EC, TH, TDS, BOD, chlorides, were exceeding the desirable limit throughout the investigation period in all locations. This may be due to the percolation of contaminated water into the groundwater. Thus, it is evident that stagnation of sewage in the surface water drains and, thereafter in the reservoir, it is polluting the groundwater. The Bagmugaliya area and other residential colonies in the proximity of sewage fed drains and reservoir depend largely on groundwater for potable use. The contamination of groundwater is directly related to the health and hygiene of the people; therefore, it majorly causes worry. Based on the findings, it is suggested to the local government that discharged wastewater from the sewage of residential and local industrial area must be treated properly as per the standard to avoid its adverse impact on the human health of the region.

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