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B. S. Chaudhary *Editors*

Geostatistics and Geospatial Technologies for Groundwater Resources in India

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Dedicated to

The Millions of Farmers of India

Foreword

Groundwater is the primary source of freshwater in many parts of the world. Some regions are becoming overly dependent on it, consuming groundwater faster than it is naturally replenished and causing water tables to decline unremittingly. Despite the increasing stress placed on water resources by population growth and economic development, the laws governing groundwater rights have not changed accordingly, even in developed nations. Not only the groundwater depletion is limited to dry climates, but also the pollution and mismanagement of surface water can cause over-reliance on groundwater in regions where annual rainfall is abundant.

In this context, I am delighted to learn that Springer Nature is publishing a book on *Geostatistics and Geospatial Technologies for Groundwater Resources in India*, in the Springer Hydrogeology series. The book is jointly edited by Partha Pratim Adhikary, Pravat Kumar Shit, Priyabrata Santra, Gouri Sankar Bhunia, Ashwani Kumar Tiwari, and B. S. Chaudhary who are eminent scholars and researchers in the field of groundwater and geospatial technology.

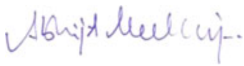
India, arguably one of the most densely populated parts of this planet, hosts about 19% of the world's population, within only $\sim$2.5% of the total global land area. Although, the region encompasses three of the most extensive riverine systems of the world (Indus, Ganges and Brahmaputra river basins) that host several of the high groundwater-producing aquifers of the globe, the availability of safe and sustainable groundwater in the region is not consistent, and there is a growing concern about the accessibility of safe water in many of these aquifers (e.g., Ganges basin) due to presence of geogenic pollutants. Moreover, the groundwater from these trans-boundary aquifers has become a politically sensitive issue. The region is also the most extensive user of groundwater resources on the globe, leading to severe concern of groundwater availability, even for groundwater affluent aquifers. Several anthropogenic activities, particularly irrigation (accounts for >80% of the groundwater withdrawal), lead to groundwater depletion in most of areas within the region. Varying precipitation rates and sub-surface hydraulic condition are providing more challenges to groundwater governance. Further, ongoing and proposed urbanization rate in India has skewed the distribution of population and their water footprint. Unregulated growth of urban areas, particularly over the last two decades, without infrastructural services for proper collection, transportation, treatment, and disposal of domestic wastewater led to increased pollution and health hazards.

This forthcoming book has been very effectively organized into four thematic sections: Section-I covers the fundamentals of geostatistics and geospatial technologies, Section-II represents groundwater availability: exploration, depletion, recharge and storage, Section-III evaluates the groundwater quality and pollution assessment and Section-IV illustrates application of GIS, and geostatistical techniques in groundwater resource management.

It is a cohesive effort of a number of authors, researchers, and experts in the groundwater across the country and other parts of the world. The editors have done an exemplary job in collecting the papers, compiling, and editing them in a book form. The quality of this interdisciplinary research can be realized by readers by going through chapters in this enriched volume. This book will be very beneficial for hydrologists, geographers, soil scientists, students, scientists, agriculturalists, and policymakers.

I extend my warmest greetings to editors, authors, and all those associated with the publications of this book and wish them a wide readership.

Yours truly,



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Preface

India is the largest user of groundwater in the world using an estimated 250 km^3 of groundwater per year. Groundwater contributes 62% in agriculture sector, 85% in rural water supply, and 45% in urban water consumption in India. Therefore, groundwater is inarguably India's single most important natural resource and the foundation of the livelihood security of millions of Indian farmers. However, this precious water resource is under increasing pressure due to the intensification of human activities along with climate change. In India, about 36% of groundwater blocks are semi-critical, critical, or overexploited and the situation is deteriorating rapidly. Not only groundwater depletion is unprecedented, its quality is also deteriorating on an alarming rate throughout India. Therefore, water supply situation from groundwater is expected to become more severe in the future.

Even as groundwater has helped the country to become self-sufficient in food production, the country is now facing a crisis of depleting water tables and water quality. The deep drilling by tube wells that was once part of the solution to the problem of water shortage now threatens to become a part of the problem itself. The country, therefore, needs to pay urgent attention to the sustainable and equitable management of groundwater. The prospects of continued high rates of growth of the Indian economy will depend critically on how judiciously we are able to manage groundwater in the years to come.

Geospatial techniques and tools like geostatistics, remote sensing, and geographic information system play an important role in depicting the spatio-temporal variation of water level and water quality. The advances and applications of RS, GIS, and geostatistical techniques to solve the twin problems of groundwater quantity depletion and quality deterioration are a researchable topic and need further discussion.

The present book entitled *Geostatistics and Geospatial Technologies for Groundwater Resources in India* has covered elucidation-based groundwater problem-solving strategies with the help of geospatial techniques in a precise and clear manner to the research community to achieve in depth knowledge in the field. It will help those researchers who have an interest in this field to keep insight into different concepts and their importance for applications in real life. This book advances the scientific understanding, development, and application of geospatial technologies related to water resource management. Further, it will be helpful in the planning of future research strategies in the field of groundwater management.

We thank all the authors who have meticulously completed their chapters at short notice and contributed in building this edifying and beneficial publication. We believe, this book will be of great value to geographers, geologists, geophysicists, agriculture engineers, hydrologists, soil scientists, ecologists, research scholars, environmentalists, and policymakers.

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The preparation of this book has been guided by several hydrologic pioneers. We are obliged to these experts for providing their time to evaluate the chapters published in this book. We thank the anonymous reviewers for their constructive comments that led to substantial improvement to the quality of this book. Because this book was for a long time in the making, we want to thank our family and friends for their continued support. Dr. Partha Pratim Adhikary thanks ICAR-Indian Institute of Soil and Water Conservation, Research Center, Koraput, Odisha, for its support to edit this book. Dr. Pravat Kumar Shit thanks Dr. Jayasree Laha, Principal, Raja N. L. Khan Women's College (Autonomous), Midnapore, for her administrative support to carry out this project. This work would not have been possible without constant inspiration from our students, knowledge from our teachers, enthusiasm from our colleagues and collaborators, and support from our family. Finally, we also thank the publisher and its publishing editor Dr. Alexis Vizcaino, associate publishing editor Dr. Ali Khan, and production administrator Karthik Raj Selvaraj, Springer Nature, for their continuous support in the publication of this book.

Executive Summary

The book contains four sections. In the first section, we discussed the fundamentals of geostatistics and GIS techniques, which have potential applications for groundwater assessment. Overall, these fundamentals are tried to capture in five chapters of the section. These chapters are essential either to understand the spatial process of groundwater variation or to quantify these variations further. Spatial assessment of groundwater can be done easily if understanding the spatial processes governing the spatial variation of this natural resource is clear. Chapter "Fundamentals of Geostatistics for Assessing Spatial Variation of Groundwater Resources" of the section covers basic fundamentals of geostatistics, e.g., concept of regionalized variable, random distribution, spatial interpolation, semivariogram, autocorrelation, etc. Further, the kriging processes along with its different variants are discussed. The kriging is defined as a spatial interpolation technique in which spatial variation structure of the target variable is utilized and it is quite different from classical interpolation techniques, e.g., inverse distance weighting, spline, etc. In Chapter "Recent Trends in GIS and Geostatistical Approaches to Analyze Groundwater Resource in India," application of geographic information system (GIS) and geostatistics for analyzing the status and changes of groundwater resources is highlighted, which will help the policymakers and managers to implement proper regulations for the sustainability of this precious resource in India. Moreover, the status of availability of groundwater in India along with its present situation in different applications is discussed in the chapter. Recently, artificial intelligence (AI) has been gaining much attention as a computational tool with an impressive performance over conventional techniques. Therefore, Chapter "Concept of Artificial Intelligence and Its Applications in Groundwater Spatial Studies" of the section devotes on the discussion on artificial intelligence and different soft computation methods and machine learning techniques and its applications in groundwater management. For example, artificial neural networks (ANNs), fuzzy logic (FL), wavelet transformation (WT), etc. are discussed in detail in this chapter. Moreover, the combination of one or more of methodologies has resulted in the emergence of new categories like a neuro-fuzzy (NF) technique, which is more powerful than individual methods. We further emphasize on learning the design, implementation, and application of individual and hybrid AI techniques on groundwater studies. In Chapter "Multi-criteria Decision-Making Approach Using Remote Sensing and GIS for Assessment of Groundwater Resources" of the section, multi-criteria decision-making approach in GIS environment for assessment of groundwater potential is discussed. As groundwater recharge and its availability depend on some geophysical factors, multi-criteria decision-making approach can be suitably applied to identify the groundwater potential zones. An example of its application for assessment of groundwater potential in Purulia District of West Bengal, India, is discussed too in the chapter. Chapter "Hydrogeochemical Characterization of Groundwater Using Conventional Graphical, Geospatial and Multivariate Statistical Techniques" of the section deals with graphical, geospatial, and multivariate statistical techniques for characterization of groundwater. In this chapter, cluster analysis, bivariate plots, factor analysis, Wilcox classifications, etc. are discussed which are used as an example study to characterize bore wells. Overall, the section provides suitable information on geostatistics and GIS along with various geospatial analyses for groundwater assessment and their management.

Section two of the book deals with the groundwater availability and its exploration, depletion, recharge, and storage for use in different purposes. As per the report of Central water Commission (2015), the water resource potential of India in terms of natural runoff in the rivers is about 1869 Billion Cubic Meter (BCM)/year. Out of which, the operational water resources have been assessed as 1123 BCM/year, in which 690 BCM/year is shared by surface and 433 BCM/year by groundwater. The net annual groundwater obtainability in India is 398 BCM. With the increase of population in India, the national per capita annual availability of water has reduced from 1816 cubic meters in 2001 to 1544 cubic meters in 2011 which is reduced approximately by 15%. Management of groundwater in future will entail a configuration of forward-thinking governance, innovative public grant, and educated participants. Approximately, 65% of India's overall aquifer is characterized by hard rock aquifers of peninsular India which is a low-storage aquifer system and the water level tends to drop very rapidly by more than 2–6 m over a decade. Alluvial aquifers of the Indo-Gangetic plain have substantial storage spaces and freshwater supply potential. However, due to extreme groundwater withdrawal and low recharge rates, aquifers are at menace of irreparable overexploitation. Aquifers provide a natural infrastructure for collecting, filtering water, and providing long-term and short-term storage without evaporative loses. Aquifers are the inexpensive natural set-up that could be used to deliver a stable water source for generations. However, without proper management, this natural infrastructure can deteriorate and become unstable, requiring substantial financial investments to collect, store, and treat water for use. Recently, groundwater science has grown up vastly through the expansion of novel monitoring tools and amended computational technologies that empower sophisticated modeling. The data sources of groundwater varying from new satellites to low-cost well monitoring have instigated to develop new intuition. Present section of the groundwater book summarizes exploration, depletion, recharge, and storage of groundwater and offers various geospatial approaches in terms of groundwater availability.

The application of geostatistics and other related modern tools for ensuring groundwater availability has been discussed in nine chapters. Chapter "Efficacy of Geospatial Technologies for Groundwater Prospect Zonation in Lower Western Ghats Area of Maharashtra, India" focused on efficacy of groundwater potential zone identification on lower Western Ghats (Central India) using geospatial technology and observed that MCDA approach is most appropriate than MIF. In Chapter "Identifying Suitable Sites for Rainwater Harvesting Structures Using Runoff Model (SCS-CN), Remote Sensing and GIS Techniques in Upper Kangsabati Watershed, West Bengal, India," the Upper Kangsabati Watershed has been considered for constructing rainwater harvesting structures using runoff model. Thirty-three check dams, twenty-eight minor irrigation tanks, and eleven percolation tanks locations were suggested for constructing sustainable rainwater harvesting structures. Chapter "Identification of Groundwater Potential Areas Using Geospatial Technologies: A Case Study of Kolkata, India" focused on the identification of potential zone for groundwater-based weighted overlay technique and summarized that most of the zone of Kolkata Municipal Corporation comes under the low potential zone for groundwater. Chapter "Geospatial Assessment of Groundwater Potential Zone in Chennai Region, Tamil Nadu, India" concentrates on Chennai region for assessing groundwater potential zone and found that western and south western zones are dominant for groundwater storage. Chapter "Identification of Groundwater Potential Zones Using Multi-Influencing Factors (MIF) Technique: A Geospatial Study on Purba Bardhaman District of India" identified the groundwater prospective zone in Purba Bardhaman District using statistical and geospatial techniques, and the outcome of the study suggested that 20.65%, 45.61%, and 33.74% of the total area comes under high potential, moderate potential, and low potential zone. Chapter "Delineating the Status of Groundwater in a Plateau Fringe Region Using Multi-Influencing Factor (MIF) and GIS: A Study of Bankura District, West Bengal, India" described the groundwater potential areas delineation in a plateau fringe region of the tropical environment and result indicates the poor to a fairly good condition of groundwater potentiality in all over the study area that is Bankura District of India. In Chapter "Aquifer Vulnerability Assessment of Chaka River Basin, Purulia, India Using GIS-based DRASTIC Model," DRASTIC model was used after integrating with GIS to identify vulnerable aquifer zones of Chaka river basin and suggested remedial measures for efficient planning and management. Chapter "Assessment of Water Level Behavior to Investigate the Hydrological Conditions of Bokaro District, Jharkhand, India Using GIS Technique" investigated the groundwater level conditions of Bokaro District and find out the relative impact of the different hydrometeorological and hydrogeological factors. Chapter "Investigation of Lineaments for identification of Deeper Aquifer Zones in Hard Rock Terrain: A Case Study of WRWB-2 Watershed from Nagpur District, Central India" has made an attempt to verify the influence of lineaments on groundwater regime in hard rock areas by employing the remote sensing technique and revealed that the yield of the borewells tapping deeper aquifers is highly influenced by the presence of lineaments. Overall, this section emphasized the application of geostatistics to explore and use the groundwater potential in India.

The third section of the book deals with the groundwater pollution and its assessment using geospatial techniques. The quality of groundwater is the appearance of combine influence of numerous physical, chemical, biological and radioactive elements. Polluted water may be hazardous to human health and cause diseases such as cancers, neurological disease, and cardiovascular disease. In India, only 12% of people can access good quality of drinking water and near about 85% of the rural population solely depends on specified groundwater sources, which is depleting at a faster rate. The high fluoride, salinity and arsenic content in groundwater are the major chemical-related problems of the whole of India. Subsequently, the issue of sustainability and maintenance of the standard quality of supplied drinking water and irrigation water is an area of concern for regions where groundwater is the main source.

Seven chapters are there in this section. Chapter "Assessing Contamination of Groundwater with Fluoride and Human Health Impact" elaborately discussed the groundwater contamination by fluoride and its consequently human health impact. Chapter "Primary Concept of Arsenic Toxicity: An Overview" focused on overview of arsenic toxicity and its impact on human organs. Fluoride and arsenic are the two of the most important groundwater contaminants affecting minions of people. Therefore these two chapters will be beneficial to tackle the health affect from these two pollutants. Chapter "Evaluation of Groundwater Quality by Use of Water Quality Index in the Vicinity of the Rajaji National Park Haridwar, Uttarakhand, India" discussed about the groundwater quality in Rajaji National Park and its surrounding regions, Haridwar, Uttarakhand, India using field-based measurement and also focused on the importance of monitoring for proper risk assessment of groundwater contamination. Chapter "Assessment of Groundwater Resource Pollution in Kangsabati River Basin, Paschim Medinipur, West Bengal, India" evaluates the degree of groundwater pollution in Kangsabati river basin, Paschim Medinipur District, West Bengal in India using field-based monitoring and measurement. It also suggested proper management practices to cope up with groundwater contamination in this river basin. Chapter "Effect of Conventional Sand Mining along Heavy Mineral Beach Placers and Its Environmental Impact" discusses the effect of saltwater intrusion in the coastal aquifer and the influence of sand mining on the quality of groundwater in the coastal region of Odisha state in India. The coal mining has a profound effect on groundwater pollution and colliery areas are in general polluted with heavy metals and other minerals are presented in Chapter "Evaluation of Shallow Groundwater Quality Index: A Case Study for a Coal Mining Environment (East Bokaro Coalfield) of Damodar valley, India." In the final chapter of the section, that is Chapter "Spatial and Temporal Categorization of Groundwater Quality for Domestic Use in Hisar District, Haryana, India" deals with the detailed study of groundwater pollution in watershed level and concluded with suitable recommendations to mitigate this problem. Overall, this section has provided the readers with an exhaustive overview of our current understanding of groundwater quality and pollution level through geospatial and geostatistical technology for better management of geographical regions. All chapters cover extensively the literature and present new results and ideas for future work.

The section four of this book specifically deals with the application of GIS and geostatistical techniques in groundwater resource management. Nine chapters have been devoted under this section. Chapters "Mapping Groundwater Level Fluctuation and Utilization in Puruliya District, West Bengal," "Mapping Groundwater Recharge Potential Zones Using GIS Approaches and Trend of Water Table Fluctuation in Birbhum District, West Bengal, India" and "Spatio-temporal Dynamics of Groundwater Resources of National Capital Region, Delhi" of this section deal with the seasonal and annual fluctuation of groundwater level and how to manage this resource under this varying fluctuation condition. The highly exploitative zones were identified and the zones where potential recharge can be possible were also mapped in these chapters. In this context, the efficacy of multi-influencing factor and analytical hierarchy process for groundwater management was established. Chapter "Groundwater Hydrology in Arid Rewari District of Haryana: Assessment, Development and Management Options" assessed the groundwater hydrology of the arid western region of India and discussed different development and management options. The understanding of hydrological dynamics will help toward the design of speedy groundwater management plans such as artificial recharge on large scale through rainwater harvesting, regulation on groundwater development in overexploited and critical areas, development of groundwater sanctuaries, power tariff on withdrawal of groundwater, conjunctive use of water, etc. These measures will certainly bridge the gap between groundwater availability and demand. The use of environmental isotopes to manage groundwater resources was dealt with in Chapter "Environmental Tracers and Isotopic Techniques: Tools for Sustainable Water Management." It will help to understand the use of isotopic techniques and environmental tracers in ecohydrology and groundwater studies. The applicability of the stable isotopes, noble gases as environmental tracers in water flow, and contaminant transport study has been discussed in detail. This chapter will be helpful in designing experiments and field scale observation stations for investigation of groundwater pollution loading and implementation of management plan. Chapter "Integrated Watershed Conservation and Management of Koshalya-Jhajhara Watershed, North India" discussed about the positive impact of integrated watershed management and conservation to augment the groundwater resources of India. The effect of proper implementation of watershed management plans has been visualized in the increase in groundwater resources of the watershed, which is a complex impact of change in land use, geomorphology, vegetation cover, socio-economic condition of the peoples living in the watershed, surface hydrology, etc. Water resources management for irrigated agriculture in perspective of geospatial techniques was discussed in Chapter "Water Resources Management for Irrigated Agriculture in Perspective of Geospatial Techniques." Chapter "Climate Change Impacts on Hydrology of a Small Watershed in a River Valley Project Catchment of Southern India" discussed the modeling technique like the use of SWAT model to manage the groundwater resources under climate change condition. The efficacy of hydrological model like SWAT to deal with the complex hydrological situation of a river basin under various climate change scenario has been discussed in this chapter. This chapter showed the effects of climate change on future agricultural production and alerted us about the required change that we have to undergo to cope up with the future harsh climatic conditions. The last chapter deals with the economic aspect and econometric management of groundwater with India centric considerations. Overall, this section clearly described the importance of geospatial techniques for suitable management of groundwater resources to get sustainable ecological and economical benefit.

Contents

About the Editors

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Fundamentals of Geostatistics for Assessing Spatial Variation of Groundwater Resources

Priyabrata Santra and Partha Pratim Adhikary

Abstract The natural resources on the earth seem to be randomly distributed but their variations over space and time are not all random. They exhibit a spatial correlation. This spatial correlation can be captured by geostatistics. Geostatistics deals with the analysis and modelling of geo-referenced data. The point observations are analyzed and interpolated to create spatial maps. For geostatistical interpolation, first the spatial correlation structures of the parameter of interest are quantified and then spatial interpolation is done using the quantified spatial correlation and optimal predictions at unobserved locations to create a map. In this chapter, the fundamental of randomness and statistical distribution are discussed. The statistical measure of spatial variation is the variogram which characterize the degree of spatial correlation. The quantification of variogram is also discussed in detail. Different interpolation techniques like kriging and its variations are also discussed. The fundamentals of ordinary kriging, indicator kriging and regression kriging are also described and their application aspects are also highlighted. The cross-validation procedure and the errors in geostatistical interpolation have also dealt in detail. The chapter ended with sampling design optimization and stochastic simulation processes, showing their importance and application in groundwater resources. This chapter will help the students, researchers and natural resources managers to understand the fundamentals of geostatistics and their application.

Keywords Cross validation · Kriging · Nugget · Semivariogram · Sill · Stochastic simulation · Range

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1 Introduction

Geostatistics is fundamentally different from classical statistics in the sense that it deals with the analysis and modelling of geo-referenced data. Its main aims are to quantify spatial variability and to create maps from point observations and thus can be easily applied on ground resource assessment. In this chapter, it is emphasized on how the spatial variability is assessed and further geostatistical interpolation is done.

In geostatistical interpolation, the first step is to quantify the spatial correlation structure of the variable of interest; for example, groundwater depth or groundwater quality parameters here (Adhikary et al. 2010). This can be done by examining the spatial observations on groundwater parameters and how these change in spatial domain. In the next step, spatial interpolation is done using the quantified spatial correlation and optimal predictions at unobserved locations to create a map. During the process of prediction, interpolation error is quantified as well, which helps to design optimal spatial sampling schemes that balance data collection costs and map accuracy (Santra et al. 2008). All this will be explained in this chapter, but in order to do so we first need to discuss the statistical theory that underlies geostatistical interpolation followed by representation of the spatial correlation structure, the basics of geostatistical interpolation ('kriging'), kriging extensions and spatial stochastic simulation.

2 The Random Field Model

Geostatistical methods are based on a statistical model of reality. This model treats reality in such a way that it is an outcome or a 'realization' of a stochastic spatial process. To describe the spatial process in detail, there is need to explain few basics of probability theory and statistics. For example, one need to understand about random variable, normal distribution, correlation, covariance etc.

2.1 Random Variables

Random variables are variables whose values depend on the outcome of a probabilistic experiment. A typical example is the throw of a (fair) die. If we denote this outcome by D, then D is a random variable that has six possible outcomes: 1, 2, 3, 4, 5 and 6. Each outcome has equal probability (namely 1/6), which means that D has a uniform probability distribution, as depicted in left side graph of Fig. 1. Now suppose that we perform the experiment and throw the die. Let the outcome be 5. Then $d = 5$ is the realization of D. Note that we introduced notation in which random variables are written in upper case and realizations in lower case. Realizations are just numbers; they are not stochastic but deterministic.

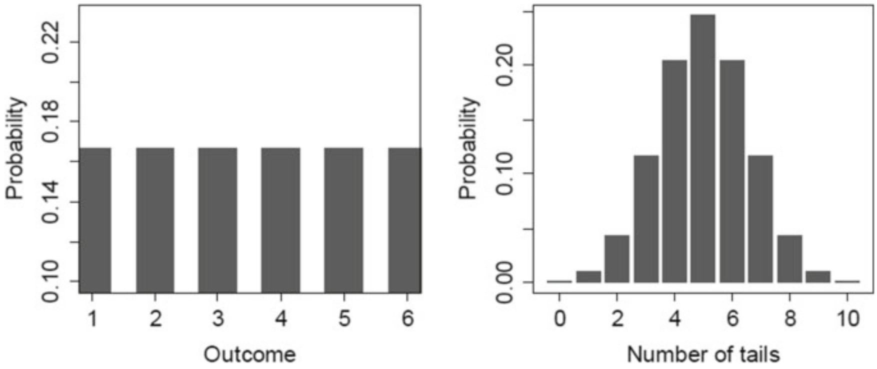

Fig. 1 Probability distribution of the throw with a die (left) and of the number of tails of ten tosses with a coin (right) (Adapted from Santra and Heuvelink, 2018)

Another example of a random variable is the number of tails ('successes') of ten tosses with a coin. The possible outcomes are all whole numbers between zero and ten. The probability distribution is no longer a uniform distribution because the probabilities are not equal for all outcomes, as depicted in right side graph of Fig. 1. For instance, the probability of zero successes is much smaller than that of three successes, and this in turn is smaller than that of five successes. If we denote this random variable by K, then we have probability $P(K = k) = \binom{10}{k}\left(\frac{1}{2}\right)^{10}$ for all k between zero and ten. The probability distribution of K is an example of the binomial distribution.

Key properties of a random variable are its mean and variance. The mean is also known as the expected value. It is calculated by taking a weighed sum of all possible outcomes of the random variable, using the probability of each outcome as a weight. Thus, we can calculate the mean of a throw with a die as:

$$\mathrm{E}[D] = \sum_{d=1}^{6} d \cdot P(D = d) = \sum_{d=1}^{6} d \cdot \frac{1}{6} = \frac{1}{6}\sum_{d=1}^{6} d = \frac{1}{6}(1 + 2 + 3 + \cdots + 6) = 3.5 \tag{1}$$

Here, E[D] stands for expected value. It is custom to denote the mean of a random variable by the Greek letter μ. The mean may be interpreted as the average outcome of a very large (infinite) number of repetitions of the same probability experiment. In other words, if we would throw the die 1 million times, then the average of these 1 million throws would be very close to 3.5.

The variance is the expected value of the square of the difference between the random variable and its mean. It is typically denoted by σ^2. For the throw with a die we get:

$$\sigma^2 = Var(D) = E[(D - E[D])^2] = \sum_{d=1}^{6}(d - 3.5)^2 \cdot P(D = d)$$
$$= \frac{1}{6}\sum_{d=1}^{6}(d - 3.5)^2 = 2.92 \tag{2}$$

The standard deviation is the square-root of the variance (i.e., σ). It is a measure of the spread or variability of the random variable, while the mean is a measure of centrality or central tendency. Other measures of centrality are the median and mode. The median is the value that separates the probability distribution of a random variable in two halves of equal probability mass (e.g., if X is a random variable then $(X < median) = (X > median) = 0.5$). The mode is that outcome of a random variable that has the largest probability.

The two examples discussed so far are examples of a discrete random variable. These are random variables that have a finite number of outcomes (or countably infinite). The opposite are continuous random variables, which have an (uncountable) infinite number of outcomes. For instance, let U be a randomly chosen real number between 0 and 1. Because there are an infinite number of outcomes, each outcome has equal probability and because all probabilities must sum to one, we have $P(U = u) = 0$ for any value of u. This implies that we cannot characterize a continuous random variable by the probabilities associated with each possible outcome. Instead, we must use the concept of probability density. We can calculate the probability that U takes on a value within a given interval $[a, b]$ by mathematical integration:

$$P(a \le U \le b) = \int_a^b f(u)\mathrm{d}u \tag{3}$$

Here, f represents probability density. If you are not familiar with mathematical integration, then it may help to know that the integration sign is nothing else than a twisted letter 'S', which signifies that we sum from a to b, in very much the same way as we used the $\sum$ symbol to represent summation over the outcomes of a discrete random variable. For random variable U, which has a uniform continuous distribution between 0 and 1, we have $f(u) = 1$ for all u in the interval [0,1] and so $P(a \le U \le b) = \frac{1}{b-a}$ (assuming $0 \le a < b \le 1$).

3 The Normal Distribution

The most common continuous probability distribution is the normal distribution. Let X be a normally distributed random variable, then its probability density is given by:

$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}}\mathrm{e}^{\frac{(x-\mu)^2}{\sigma^2}} \tag{4}$$

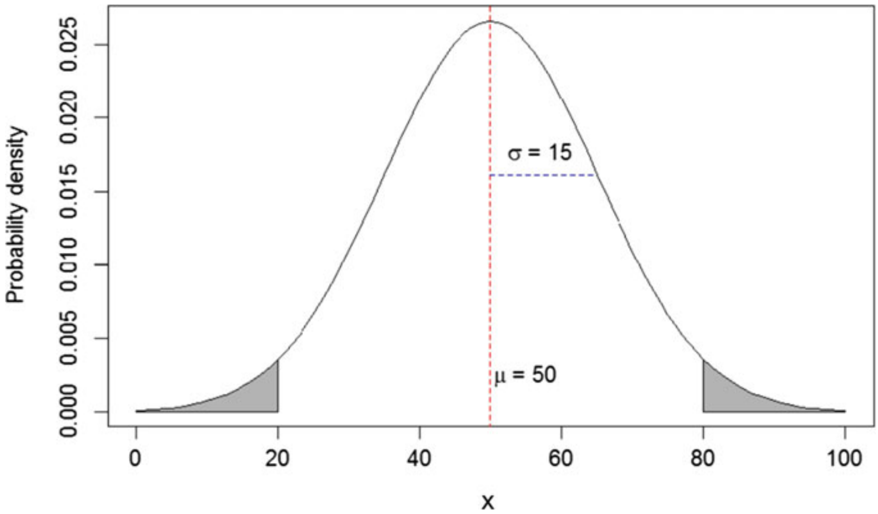

Fig. 2 Probability density of a random variable X that has a normal distribution with mean $\mu = 50$ and standard deviation $\sigma = 15$. The probability of values that deviate more than two standard deviations from the mean (grey area) is about 0.05 (Adapted from Santra and Heuvelink, 2018)

where μ and σ^2 are parameters. If we calculate the mean and variance of X in a similar way as was done for D above (but then using integration instead of summation), we get that the mean of X equals μ while its variance equals σ^2 (this also explains why we used these symbols). The shape of the normal probability density is the well-known bell-shaped curve and an example is given in Fig. 2. Beware not to interpret the numbers on the y-axis as probabilities. In case of continuous random variables, probabilities can only be associated with the surface area below the curve. The total area below the curve must always be equal to one.

The importance of the normal distribution can be realized from the *Central Limit Theorem* of statistics. It states that the distribution of averages of realizations that are randomly and independently drawn from whatever distribution will tend to be the normal distribution. For instance, the height of a person is the cumulative effect of many factors, such as genetic material, food supply and illnesses during childhood, and so whenever we plot the frequency distribution of a person's height from a sufficiently large sample of adults drawn from a population, this distribution will be remarkably normal. This is illustrated also in Fig. 3, which shows that the number of tails with repeated tossing of a coin converges to the normal distribution as the number of tosses increases. Indeed, many variables encountered in the environmental sciences, such as air temperature, clay content of the soil or river water flux, fit the normal distribution curve fairly well. There are also many variables that follow better a *lognormal* distribution, such as the concentration of pollutants in the ground- or surface water. Such variables typically result from *multiplication* instead

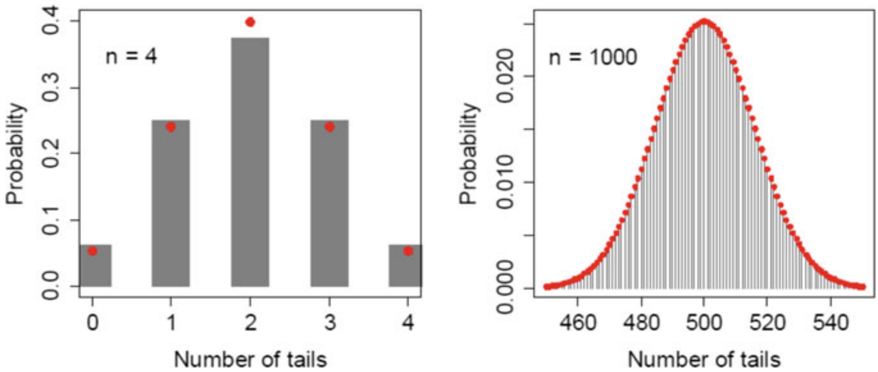

Fig. 3 The probability distribution of the number of tails when tossing a coin progressively approaches the normal distribution with increasing number of tosses (*n*). Grey bars represent the factual binomial distribution; red dots represent the normal distribution (Adapted from Santra and Heuvelink, 2018)

of *summation* of underlying random variables. The lognormal distribution is asymmetric and has a non-zero *skewness*. A random variable is lognormally distributed if its log-transform is normally distributed.

In geostatistics, we mainly work with normally distributed random variables. Not only because the normal distribution is often encountered in the real world, but also because the *statistical inference* associated with normally distributed random variables is much easier than with others. Whenever we come across a variable that deviates substantially from normality, we will look for a *mathematical transformation* (e.g., logarithm, square-root) such that the transformed variable is (approximately) normal.

4 Probability Distribution Versus Frequency Distribution

Above we explained that random variables are characterized by a probability distribution, such as the uniform and normal distribution. The attentive reader might ask, how can the observed data of an environmental variable have a probability distribution? It is not a random variable, it is a data set (i.e., a characteristic measured on a *population* of objects or on a *sample* from such population). Indeed, there is a subtle but important difference between the two. Whereas a random variable has a *probability distribution*, a data set has a *frequency distribution*. A frequency distribution shows how often a certain value (or range of values) occurs within the dataset, while a probability distribution shows the probability of a certain outcome of a probability experiment. Now if we define a random variable as the outcome of a *random draw* from the dataset, then it turns out that the probability distribution of that random variable equals the frequency distribution of the data.

5 Covariance and Correlation

Before we address the spatial extension of random variables in the next section, we must first briefly discuss the concept of *correlation*. The correlation between two random variables X and Y is usually denoted by the Greek symbol ρ and is defined as:

$$\rho(X, Y) = \frac{\mathrm{cov}(X, Y)}{\sqrt{\mathrm{var}(X).\mathrm{var}(Y)}} = \frac{E[(X - \mu_X).(Y - \mu_Y)]}{\sqrt{E\left[(X - \mu_X)^2.E(Y - \mu_Y)^2\right]}} \tag{5}$$

Here, $Cov(X,Y)$ is the *covariance* between X and Y. The correlation is a standardized or normalized covariance. It is dimensionless and always a number between −1 and 1. It is a measure of the joint variability of random variables: if the correlation is positive then highs (lows) of X often coincide with highs (lows) of Y. If the correlation is negative then it is the opposite. This is illustrated in Fig. 4 which shows *scatter plots* of 100 random draws from the joint probability distribution of X and Y for six different correlations. The absolute value of the correlation measures the strength of the (linear) relationship between X and Y. For instance, a zero correlation means that X and Y are not related to each other. In other words, knowing Y does not provide any information about X, and vice versa. In the environmental sciences, most variables are correlated to some degree because everything is related to everything else, but the strength of the correlation is often weak.

6 Random Fields

In geostatistics we deal with variables that vary in space and for this reason we need to extend the concept of a random variable to a *random field*. A random field is defined as a collection of random variables indexed by a geographic coordinate. Let us explore this by considering a soil database of the arid western region of India. If we denote the soil properties at any location x in the geographic domain of interest A (i.e., hot arid ecosystem of India) by (x), then in geostatistics we treat (x) as a random variable, while the collection of all random variables $Z = \{Z(x)|x \in A\}$ is a random field. Similar to random variables, a random field Z is fully characterized by its probability distribution, but such probability distribution can be very complex. It must specify the probability distribution of $Z(x)$ for all locations x in A, and it must also specify the correlations between $Z(x_1)$ and $Z(x_2)$ for all paired locations x_1 and x_2 in A. Now if we also assume that Z is normally distributed, then we have completely characterized Z by the (marginal) probability distributions and the correlations. In practice, we will not be able to specify different distributions for all locations $x \in A$ and different correlations for any pair of locations x_1,$x_2 \in A$, simply because we cannot collect that information from only a sample of observations at measurement

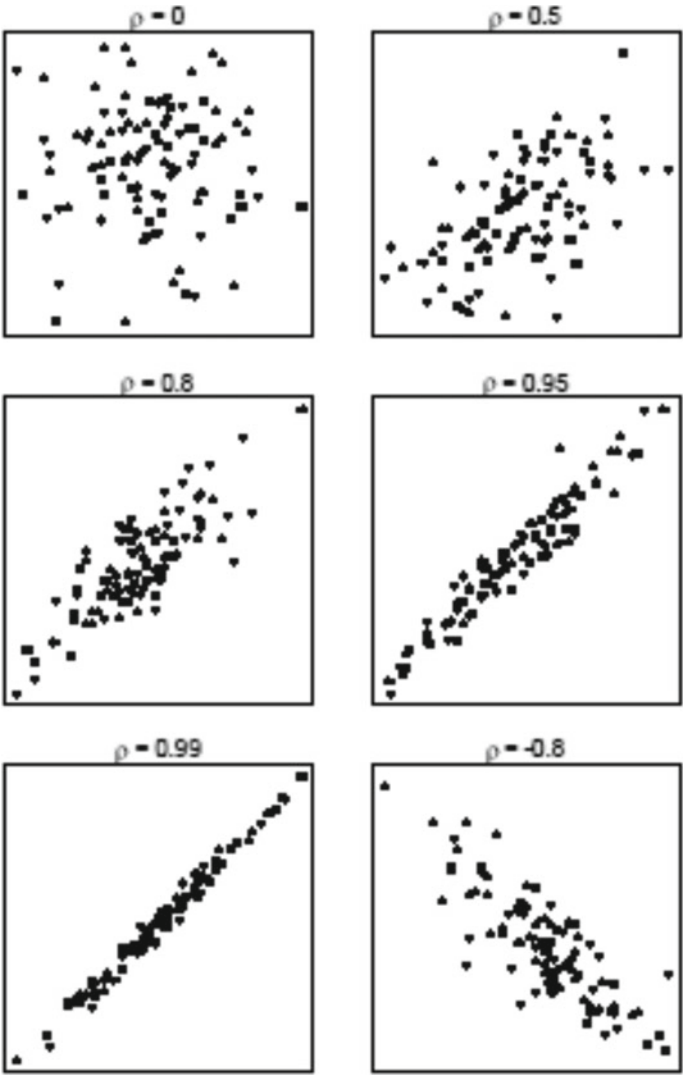

Fig. 4 Scatter plots of 100 paired draws from a bivariate normal distribution with different correlations (Adapted from Santra and Heuvelink, 2018)

locations, and so we have to make certain simplifying assumptions to be able to estimate the distributions and correlations from the available observations. It makes sense to assume that the correlation between $Z(x_1)$ and $Z(x_2)$ only depends on the separation distance $|x_1 - x_2|$ between the two locations. In such case, the correlation becomes a function of just the separation distance and is called *spatial correlation.*

Figure 5 shows twelve realizations of a random field whose probability distribution at every location is a normal distribution with a mean of 50 and a standard deviation

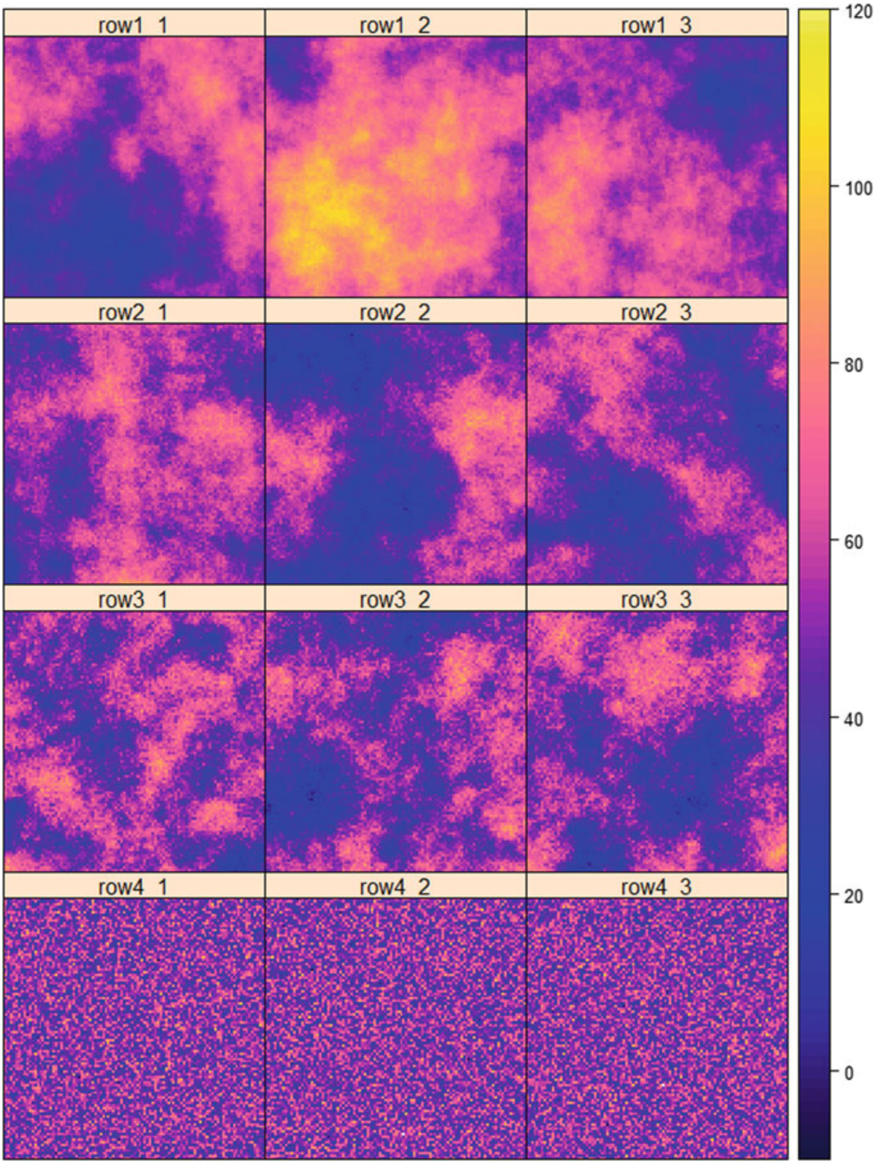

Fig. 5 Twelve realizations of a random field with a constant mean of 50 and standard deviation 15. The degree of spatial correlation is strongest in the top row and decreases from the top to the bottom row. Realizations within a row are all different but have the same spatial structure (Adapted from Santra and Heuvelink 2018)

of 15. The realizations within each row in Fig. 5 have the same spatial correlation, but the spatial correlation is different between rows. It is strongest in the top row and smallest (in fact completely absent) in the bottom row. As we can see the same random field yields different realizations, for the same reason that repeated throws with a die are unlikely to yield the same outcome every time. So, none of the realizations in a row are the same, but we may notice that their 'spatial structure' is. This is because this is controlled by the spatial correlation.

7 Statistical Measure of Spatial Variation: The Variogram

We concluded the previous section with a figure showing different realizations of random fields. The spatial structure of realizations within a row was quite similar, while between rows they were different. This was because the degree of spatial correlation that was used to generate these realizations was different between rows. The top row showed fairly large patches of similar value which reflects strong spatial correlation, the bottom row showed spatial 'noise' which means no spatial correlation at all, and the middle rows showed an in-between situation. What measure can we use to characterize spatial correlation? And how can we estimate this measure from a limited number of point observations? These are the two main questions that we address in this section.

7.1 The Variogram

In geostatistics, the degree of spatial correlation is characterized by the semivariance. Let Z be a random field defined on a geographical domain D. The semivariance is defined as follows (Isaaks and Srivastava 1989):

$$\gamma(h) = \frac{1}{2} E\left[(Z(x) - Z(x + h))^2\right] \tag{6}$$

Here, E stands for mathematical expectation, as before. Thus, the semivariance $\gamma(h)$ is half the expected squared difference between the value of Z at two locations separated by the distance vector h. A graph of the semivariance against distance is called a *variogram* (sometimes also called: semivariogram). Clearly, $\gamma(h)$ cannot be negative because it is the average of a square. Taking a closer look also reveals that it typically increases with distance, because according to Tobler's first law of geography, "Everything is related to everything else, but near things are more related than distant things". In other words, since the difference between $Z(x)$ and $Z(x + h)$ will usually be small for small h, $\gamma(h)$ will also be small for small h.

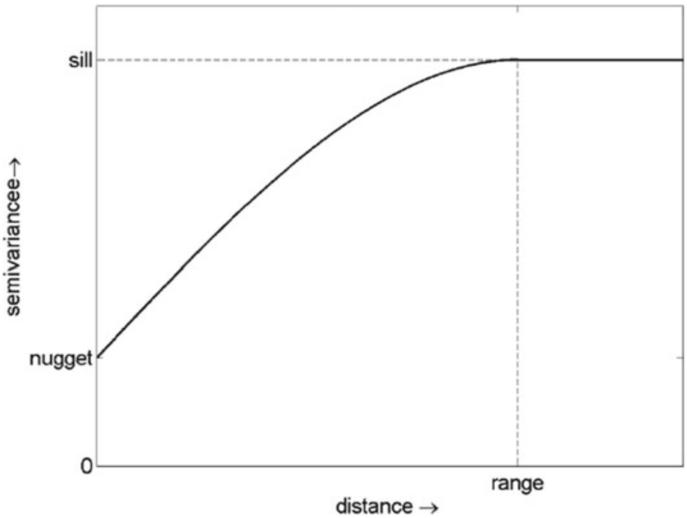

Fig. 6 Typical shape of the variogram with its three key parameters nugget, sill and range (Adapted from Santra and Heuvelink 2018)

The typical shape of the variogram is given in Fig. 6. Many real-world variables have a variogram with such shape. A few observations can be made. First, the semivariance increases with distance. However, note also that at some point the increase comes to a hold and the variogram stabilizes. This happens at a distance which is called the *range*. It identifies the distance up to which there is still spatial correlation. In other words, for distances beyond the range there is no longer any spatial correlation and the semivariance has reached its maximum value. The maximum value is known as the *sill* of the variogram. In fact, it can be proven that the sill is equal to the *variance* of Z, which we introduced before in Section *Random Variables*. Finally, the third key parameter of the variogram is the *nugget*. This characterizes the spatial variability at short distances, also known as the 'micro-scale' variation. Note from the definition of the semivariance that it must be zero for $h = 0$, but apparently it can be greater than zero for distances close to zero. The term 'nugget' stems from mining: if we are lucky we may find a gold nugget at some location in a geologic deposit, while right next to the location there may be no gold at all. Thus, there is much spatial variation at short distances. Apart from micro-scale variation, random *measurement error* also contributes to the nugget variance. This is because repeated measurements of the same variable may yield different outcomes, due to measurement error, and so when calculating half the squared difference, an outcome bigger than zero will result.

The variograms of three out of four random fields that were used to generate the realizations shown in Fig. 5 are given in Fig. 7. It is important that we can link a spatial structure or 'pattern' as shown in Fig. 5 with a variogram. We should understand how the shape of the variogram influences the spatial pattern. A variogram with a small

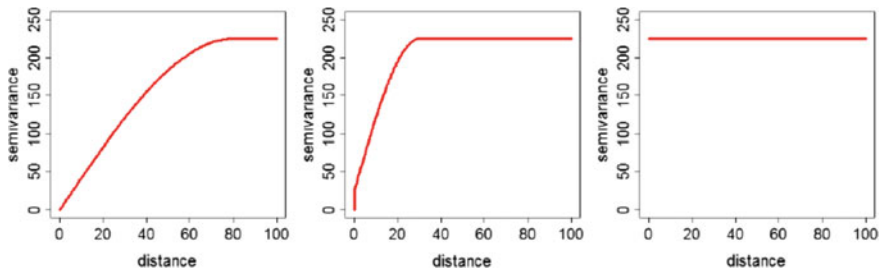

Fig. 7 The three variograms that correspond with realizations shown in Fig. 5 (left: top row; middle: third row; right: bottom row) (Adapted from Santra and Heuvelink 2018)

or zero nugget and large range yields large spatial patterns and no 'noise', while a variogram that has no spatial correlation ('pure nugget') creates patterns that are complete noise.

When we defined the semivariance with Eq. (6), we implicitly assumed that it only depends on the distance h between the locations, and not on the locations themselves. This is known as the *stationarity* assumption. To be more precise, the stationarity assumption has two components, namely that the mean (expected value) of Z is constant and that the semivariance of Z only depends on the distance between locations. Perhaps the stationarity assumption is not realistic in all cases. For example, we know that air temperature is negatively correlated with elevation, so it would be unwise to assume a constant mean for air temperature in mountainous terrain. Another example: we know that spatial variability of soil organic matter depends on land use, so it would be unwise to assume a single variogram for organic matter in an area with cropland, grassland and forest. There are possibilities in geostatistics to relax the stationarity assumption, but for now we will assume that the assumption holds. Moreover, in Fig. 6 we also implicitly assumed that the semivariance only depends on the 'Euclidean' distance between locations, and not on the distance *vector* that also takes account of direction. This is the *isotropy* assumption. The opposite is *anisotropy*. For instance, the variogram of the soil clay content of a river floodplain may be different in a direction parallel to the river than in a direction perpendicular to it. In such case the isotropy assumption is not realistic and an anisotropic variogram should be used instead.

In practice we need to estimate the variogram from a set of observations. The procedure that is used for this is known as the *structural analysis*. We will not explain in detail how the structural analysis works but merely mention that it is based on evaluating the squared difference between observations for each pair of observation locations in the dataset. By averaging these squared differences over multiple distance intervals, a so-called sample variogram is obtained. Using curve fitting techniques, a variogram model (mathematical function) is fitted through the sample variogram. The procedure works well but requires a sufficiently large set of observations. It is generally agreed that stable estimation of the variogram requires at least one hundred observations, which ideally are spread out through the entire study area, and include a few clusters of observations to be able to estimate the nugget reliably (Burgess and Webster 1980).

7.2 Relationship Between the Variogram, Covariance Function and Correlogram

The variogram measures the degree of spatial variation as a function of the separation distance between two locations. We have seen that it typically is a function that increases with distance, due to Tobler's first law of geography. Unlike the variogram, the *covariance function* measures the covariance between the variable of interest at two locations as a function of the distance between the locations. The covariance was defined in Section *Covariance and correlation*, where it was explained that it measures the degree of co-variation of two random variables. In the case of a covariance function of a random field Z, it measures the degree of co-variation of $Z(x)$ and $Z(x+h)$ and is defined as $C(h) = E[(Z(x) - E[Z(x)]) \cdot (Z(x+h) - E[Z(x+h)])]$. The covariance function tends to decrease with distance. This is confirmed by the mathematical relationship between the variogram γ and the covariance function C: $C(h) = \gamma(\infty) - \gamma(h)$ and $\gamma(h) = C(0) - C(h)$. In other words, the covariance function is a 'mirrored' version of the variogram, see Fig. 8.

The *correlogram*, which plots the correlation as a function of distance, is simply a normalized version of the covariance function. It is obtained by dividing the covariance function by the overall variance (i.e., the sill of the variogram). Thus, the correlogram is dimensionless and cannot be greater than $+1$. In Fig. 8, the correlogram starts at 1, but note that it would be a value smaller than 1 if there were a nugget variance greater than 0.

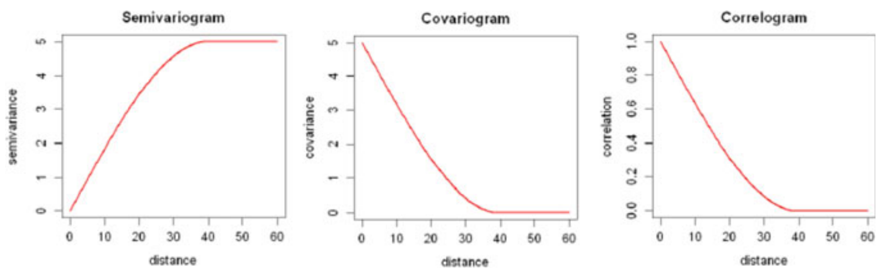

Fig. 8 Variogram, covariance function and correlogram of the same random field (Adapted from Santra and Heuvelink 2018)

8 Kriging

Section *Statistical measure of spatial variation: the variogram* explained how spatial variability can be characterized with a variogram. The variogram is a very useful tool because it provides insight into the degree and structure of spatial variation, which help researchers understand the processes behind spatial variation, but it is also very useful for another reason. This is that it provides the information needed for geostatistical interpolation, also known as *kriging* (after the late South-African mining engineer Danie Krige). There are many versions of kriging. We will discuss some of these in this chapter, beginning with *ordinary kriging*.

8.1 Ordinary Kriging Equations

The idea of ordinary kriging is to predict $z(x_0)$ at a location x_0 where z was not measured as a linear combination of the observations:

$$\hat{z}(x_0) = \sum_{i=1}^{n} \lambda_i . z(x_i) \tag{7}$$

Here, the λ_i are so-called *kriging weights*. We would like to choose these weights such that the *interpolation error* $z\hat{}(x_0) - z(x_0)$ is as small as possible. Now the problem is that we do not know the interpolation error, because in order to calculate it, we need to know $z(x_0)$, which we were aiming to predict in the first place. If we knew it, we would not have an interpolation problem. The solution that is used in geostatistics is that we characterize the interpolation error by a probability distribution. This means that we replace the realization z by its geostatistical model Z and predict $Z(x_0)$ instead of $z(x_0)$. Given the geostatistical model that we have assumed for Z (including its variogram) we can derive the probability distribution of $\widehat{Z}(x_0)$ $-$ (x_0) for any choice of kriging weights, and next we choose the weights such that the variance of the prediction error is the smallest among all possible choices, while also ensuring that the expected value (i.e., mean) of the prediction error is zero. In other words, we choose the kriging weights such that the expected squared prediction error:

$$E\left[\left(\hat{Z}(x_0) - Z(x_0)\right)^2\right] = E\left[\left(\sum_{i=1}^{n} \lambda_i . Z(x_i) - Z(x_0)\right)^2\right] \tag{8}$$

is minimized under the condition that the prediction error is *unbiased*:

$$E\left[\hat{Z}(x_0) - Z(x_0)\right] = E\left[\sum_{i=1}^{n} \lambda_i . Z(x_i) - Z(x_0)\right] = 0 \tag{9}$$

The unbiasedness condition implies that the kriging weights must sum to one: $\sum_{i=1}^{n} \lambda_i = 1$. This also makes intuitively sense: if the weights would add up to a number larger than one, then we would tend to overpredict the value of Z at x_0, while we would on average end up with too small predictions if the weights add up to a value smaller than one.

It was mentioned several times in this chapter that in geostatistics, we pose a statistical model Z of reality and assume that the single, true reality that we are interested in is a realization z of the statistical model Z. We characterize the model and its spatial variability by a variogram. Once this is done, we can derive the probability distribution of the kriging prediction error at any location x_0 in terms of a probability distribution. That distribution will look similar to the one shown in Fig. 2, only with different values for the mean and standard deviation. The 'real' prediction error at x_0 (which we do not know) may now be interpreted as a realization from that distribution. Thus, the ideal shape of the distribution would be the one that has a zero mean and zero standard deviation, because in that case we would be certain that the interpolation error is zero. In practice, it will be impossible to choose the kriging weights such that this is achieved (unless the prediction location is an observation location and there are no measurement errors), so that we try to get as close as possible to it by ensuring that the distribution is centered around zero and has the smallest standard deviation possible. In this way, we achieve that on average, for many locations and for the many kriging exercises, the actual prediction errors made will be closer to zero compared with any other interpolation method. Of course, all this is true under the assumption that the geostatistical model is a correct description of reality. But given this model, kriging is indeed an *optimal interpolator*.

Minimization of Eq. (8) is achieved by working out Eq. (8), treating it as a function of the kriging weights λ_i, and minimizing it by setting its mathematical derivative with respect to each of the λ_i to zero. A slight complication is that the unbiasedness condition Eq. (9) must also be satisfied. For this, a mathematical 'trick' is applied in which an extra unknown, the so-called *Lagrange parameter*, is introduced. For us, it is sufficient to know that finally we end up with $n + 1$ linear equations with $n + 1$ unknowns:

$$\sum_{i=1}^{n} \lambda_i . \gamma\left(h_{ij}\right) + \varphi = \gamma(h_{i0}) \quad \text{for all } j = 1 \ldots n \tag{10a}$$

$$\sum_{i=1}^{n} \lambda_i = 1 \tag{10b}$$

Here, h_{ij} is the geographic distance between x_i and x_j, $h_{i0}$is the distance between x_i and x_0, and φ is the Lagrange parameter.

Equation (10a, b) is known as the *kriging system*. It has a unique solution that is not difficult to calculate, because all equations are linear in the unknowns. However, calculation by hand becomes tedious and error-prone for values $n = 3$ and larger, and so in practice we use computers for that, also because we need to repeat the calculation for each and every prediction location x_0 (which are usually the nodes of a fine grid laid out over the area of interest). The resulting values for the λ_i obviously depend on the variogram and on the spatial configuration of the observation and prediction points, but the general picture is that observations nearby the prediction location get larger weights (because they are more strongly correlated with the variable at the prediction location), and that observations in clusters get smaller weights than more isolated observations (because of redundancy). In general, the smaller the nugget-to-sill ratio, the larger is the diversity in kriging weights.

Once the kriging weights are calculated it is easy to calculate the ordinary kriging prediction, because it just requires substitution of the weights and the actual observations in Eq. (7). An attractive property of kriging is that the accuracy of the prediction is also quantified, by means of the *ordinary kriging variance*. This is nothing else than the expected squared prediction error Eq. (8), which can be worked out into:

$$\sigma_{OK}^2(x_0) = E\left[\left(\hat{Z}(x_0) - Z(x_0)\right)^2\right] = \sum_{i=1}^{n} \lambda_i.\gamma(h_{ij}) + \varphi \tag{11}$$

The square-root of Eq. (11) gives the *kriging standard deviation*, which is easier to interpret than the kriging variance because it has the same measurement units as the kriging prediction. One may also calculate the ratio of the kriging standard deviation and kriging prediction to get the *relative error*, or compute the lower and upper boundaries of an approximate 95% *prediction interval* by calculating $z\hat{}(x_0) \pm 2 \cdot \sigma_{OK}(x_0)$ (see also Fig. 2).

8.2 Cross-Validation

Although the kriging standard deviation map produces a measure of the accuracy of the kriging predictions, it is only valid given the kriging assumptions, which include the used variogram. After all, it is derived from the geostatistical model that was assumed. Instead, a more objective measure of map accuracy would be obtained if an independent data set were available. If this were the case, then we could compare the kriging predictions at the validation locations with the independent observations, and compute summary measures from these, such as the *Mean Error (ME)*, *Root Mean Squared Error (RMSE)* and *Standardized Root Mean Squared Error (SRMSE).* These are defined as follows:

$$ME = \frac{1}{m}\sum_{i=1}^{m}\left[\hat{z}(x_i) - z(x_i)\right] \tag{12}$$

$$RMSE = \sqrt{\frac{1}{m}\sum_{i=1}^{m}\left[\hat{z}(x_i) - z(x_i)\right]^2} \tag{13}$$

$$SRMSE = \sqrt{\frac{1}{m}\sum_{i=1}^{m}\left[\frac{\hat{z}(x_i) - z(x_i)}{\sigma_{OK}(x_i)}\right]^2} \tag{14}$$

where m is the number of validation observations and the x_i are in this case the validation locations. The *ME* should be close to zero, the *RMSE* as small as possible, and the *SRMSE* should be close to one. If *SRMSE* is greater than one, then the 'observed' errors are bigger than the 'anticipated' errors. If *SRMSE* is smaller than one, then the observed errors are smaller than the anticipated errors. Both are undesirable outcomes because we want the kriging standard deviation to be a realistic measure of interpolation error.

Often, we cannot afford splitting the dataset into one set for interpolation and one for validation, because we want to use all available data for interpolation to obtain the most accurate map possible. An often-used alternative then is to take out one or multiple observation(s) at a time for validation purposes and use all other data for prediction. This is called *cross-validation.* If one observation is removed at a time, it is called *leave-one-out cross-validation.*

8.3 Kriging Extensions

8.3.1 Regression Kriging

Optimal spatial prediction using ordinary kriging only makes use of information contained in observations of the variable of interest. However, in many practical situations there is additional information that is useful too and can help improve prediction. For instance, we know that air temperature is correlated with elevation and since we have a DEM of most parts of the world, we might try to include elevation data to help predict air temperature. One way of doing that is through *regression kriging*, which is a combination of regression and kriging. It is also sometimes called *kriging with external drift* or *universal kriging*, although there are subtle differences that we need not discuss here. Before we explain regression kriging, let us first look at linear regression.

In *(multiple) linear regression*, we consider a dependent variable Y that is assumed to be linearly related to a number of independent (explanatory) variables X_i:

$$Y = \beta_0 + \sum_{k=1}^{p} \beta_k . X_k + \varepsilon \tag{15}$$

Here, the β_k are regression coefficients (β_0 is known as the *intercept*), p is the number of independent variables and ε is a zero-mean, normally distributed stochastic residual with constant variance σ^2. The regression coefficients and variance of the residual are estimated from paired observations of the dependent and independent variables. The standard deviation of ε is derived from the spread of the points around the fitted line. It conveys how well we can predict Y with the X_i. If the independent variables are informative about Y, then the variance of ε will be substantially smaller than that of Y. The variance reduction is neatly captured by the so-called R^2 (*R-square* or *goodness-of-fit*), which is a number between zero and one that expresses the *amount of variance explained* by the regression. In case of simple linear regression (i.e., $p = 1$), R^2 equals the square of the correlation between X and Y.

Prediction of Y given the Xi is done as follows:

$$\hat{Y} = \hat{\beta}_0 + \sum_{k=1}^{p} \hat{\beta}_k . X_k \tag{16}$$

In other words, we use the fitted regression line for prediction. This makes sense because the $\hat{\beta}_k$ are our 'best' estimates of the true regression coefficients, and because ε has zero mean, and hence our 'best' estimate of it is simply zero. However, both the estimation errors of the regression coefficients and the stochastic residual of the regression model cause that the prediction differs from the true value of Y. In other words, there will be a prediction error, which has a mean of zero (i.e., the prediction is unbiased), but whose standard deviation is bigger than zero. Multiple linear regression as explained above can also be used to predict a spatially distributed variable (such as air temperature) from other spatially distributed variables (such as elevation). However, the regression model assumes that the stochastic residual is *statistically independent*, while we learnt in previous sections of this chapter that many spatially distributed variables are spatially correlated. This implies that the assumption of statistical independence of the regression residual is often not realistic in case of spatially distributed variables, and this is where regression *kriging* comes in. Under the regression kriging model, the dependent and independent variables are made spatially explicit and the spatial correlation of the regression residual is modelled with a variogram. Since we had characterized the target variable by Z and had used letter x for geographic location, we now write the spatial analogue of Eq. (15) as:

$$Z(x) = \beta_0 + \sum_{k=1}^{p} \beta_k . f_k(x) + \varepsilon(x) \tag{17}$$

Here, the f_k are spatially distributed explanatory variables, such as elevation, slope, vegetation index, land cover and geology. In fact, it could be any variable that is spatially exhaustively available and that is correlated with the dependent variable Z. Note that it must be spatially exhaustive, because otherwise we could not predict at locations where the explanatory variables are not available. Note also that the explanatory variables need not be numeric variables such as elevation and slope, but can also be categorical variables, such as land use and geology. Such variables can still be included in linear regression by treating them as *factors*, effectively replacing them with as many binary dummy variables as there are categories. In Eq. (17), the term $\beta_0 + \sum_{k=1}^{p} \beta_k . f_k(x)$ is known as the *trend*.

The only real difference between Eqs. (15) and (17) is that we now allow for spatial correlation of the stochastic residual ε. We typically assume stationarity, so that its spatial correlation is fully characterized by a variogram. Regression kriging then works as follows:

(i) *Fit regression model*. Select spatially exhaustive explanatory variables (often termed '*covariates*'), overlay these with the locations of observations of the dependent variable, and fit a regression model on the resulting dataset.
(ii) *Variography regression residual*. Subtract predictions of the regression model from the true observations at observation locations, and calculate a variogram of the resulting residuals.
(iii) *Apply regression model*. Apply the regression model at all locations in the study area to generate a regression map of the dependent variable.
(iv) *Krige residuals*. Krige the residuals with ordinary kriging to the same area.
(v) *Combine results*. Add the map with kriged residuals to the map of the regression predictions.

This shows that regression kriging is truly a combination of regression and kriging. If we would do only regression, then we would not include a kriging interpolation of the regression residual. If we would do only kriging, we would only do a spatial interpolation of the dependent variable, without taking the information in the explanatory variables into account. In fact, ordinary kriging is a special case of regression kriging, namely the one where there are no explanatory variables ($p = 0$) and where the trend is assumed constant. From this, you can also see that regression kriging relaxes the assumption of a constant mean or trend, as described in Section *The variogram*. It poses a more realistic model of reality, and it can potentially provide a more accurate prediction map because it uses more information: not only the observations of the dependent variable, but also explanatory covariate information. Thus, if there is explanatory power in the covariates, then the regression kriging variance should be smaller than the ordinary kriging variance.

8.3.2 Indicator Kriging

The previous section mentioned that categorical variables can be used in regression kriging. In that case the categorical variables were used as explanatory variables, but what to do if the dependent variable is measured on a categorical scale? For instance, what if we have observations of vegetation type or land cover at locations in an area, and want to interpolate these observations to create a map of the dependent variable? In such case we can make use of *indicator kriging*. This is done as follows. First, for each category the observations are transformed into observations of a binary 'indicator' variable, which is one if the categorical variable at a location equals the category and zero otherwise. As a result, we get a set of point observations that are either zero or one. Next, a variogram is estimated from the indicator values and used in kriging. This is done in the same way as described in Sections Kriging and Kriging extensions. The resulting prediction map typically has values between zero and one, which is as expected because Eq. (7) shows that the prediction is a weighted average of zeroes and ones. The prediction is interpreted as the *probability* that the category will occur at the prediction location. This is intuitively sensible, because values close to one will result if there are many ones in the local neighbourhood, meaning that the category often occurs in the local neighbourhood, while values close to zero turn up in areas where the specific category is rare or absent. Indicator kriging is then repeated for all other categories, again transforming observations to a binary indicator variable, estimating the variogram and applying kriging (Adhikary et al. 2011).

In practice, it may occur that predictions are smaller than zero or greater than one. In such case a clipping to zero or one is done. Also, it usually happens that the sum of the predictions for all categories do not add up to one, while obviously the probabilities should. This is repaired by scaling the predictions such that they do sum to one. In a way, these corrections show that while indicator kriging may work satisfactory in practice, its theoretical foundation is weak. Many geostatisticians are therefore not in favour of it. Unfortunately, there are not many alternative geostatistical methods and those that do exist are quite involved. Apparently, spatial interpolation of numerical variables is much easier than spatial interpolation of categorical variables.

9 Sampling Design Optimization

We have seen before that one of the attractive properties of kriging is that it quantifies the interpolation error, by means of the kriging variance. This implies that we can compare the interpolation accuracy of different spatial sampling designs, by comparing the associated kriging variance maps. When comparing sampling, it makes sense to select the sampling design that has the smallest average kriging variance, because this yields the smallest overall interpolation uncertainty. Any design is characterized by two components. The first is the total number of observations. Collecting more observations yields a more accurate interpolated map, but at the expense of greater costs. The second is the spatial configuration of the sampling locations. Here, one configuration or design might produce a more accurate map than another, while sampling costs remain the same. This section briefly explores these issues and presents some common sampling design approaches used in geostatistics.

While it makes sense to use the average kriging variance as a criterion to compare sampling designs and select the optimal design, there is a problem. This is that the kriging variance can only be computed after the observations have been taken and a variogram calculated, while the sampling design must be chosen prior to the actual sampling. Indeed, Eq. (11) shows that the kriging variance can only be computed if the kriging weights, the variogram and the Lagrange parameter are known. The kriging weights and Lagrange parameter are computed by solving Eq. (10a, b), which again requires the variogram. This implies that geostatistical sampling design optimization can only be done given the variogram. Note, however, that the observations themselves are not required to compute the kriging variance. Thus, all that we need to be able to optimize the sampling design is the variogram. In practice, two approaches are used to get hold of it prior to sampling for interpolation. The first is to 'borrow' the variogram from a previous, similar study, where the same variable was measured in a comparable study area. The second approach is to conduct sampling in two stages: the first only aiming at estimation of the variogram, the (optimized) second to interpolate the variable of interest with kriging. The disadvantage of the first method is that extrapolation of variograms is risky, the disadvantage of the second is that one needs to do fieldwork and data collection twice. Nonetheless, it may definitely pay off, particularly in large projects and/or when observations (e.g., laboratory analyses) are expensive. It is beyond the scope of this chapter to explain how the actual sampling design optimization is done. We only note that it tends to go for a fairly uniform distribution of observations points across the study area, with slightly higher sampling density in the boundary region of the study area.

In practice, it may frequently happen that we cannot 'borrow' a variogram from another study and cannot afford to do fieldwork twice. In that case we must design a spatial sampling design that will be used both for variogram estimation and kriging. A uniform distribution of points across the study area is preferred for kriging, as we noted above. One practical way of doing that is to sample at the nodes of a regular grid, where the grid mesh is chosen such that the total number of observations stays within the fieldwork budget. However, regular grid sampling is far from ideal for variogram estimation. This is because such design provides no information about the spatial variability at distances smaller than the grid mesh, while kriging is sensitive in particular to the behaviour of the variogram at short distances (i.e., the nugget variance). Therefore, it is recommended to supplement the regular grid with multiple small 'clusters' of points, such as shown in Fig. 9. As a rule of thumb, one might use two-thirds of the total number of observations for regular grid sampling, and the remaining one-third to assess short-distance spatial variation.

10 Spatial Stochastic Simulation

10.1 Spatial Stochastic Simulation Versus Kriging

Kriging makes predictions at points in such a way that the expected squared prediction error is minimized. This ensures that the predicted value is on average closest to the true (unknown) value. *Spatial stochastic simulation* has an entirely different objective. Here, the aim is to generate possible realities from the probability distribution of the uncertain variable. This is done using a *pseudo-random number generator*, while accounting for the shape of the probability distribution, the spatial correlation

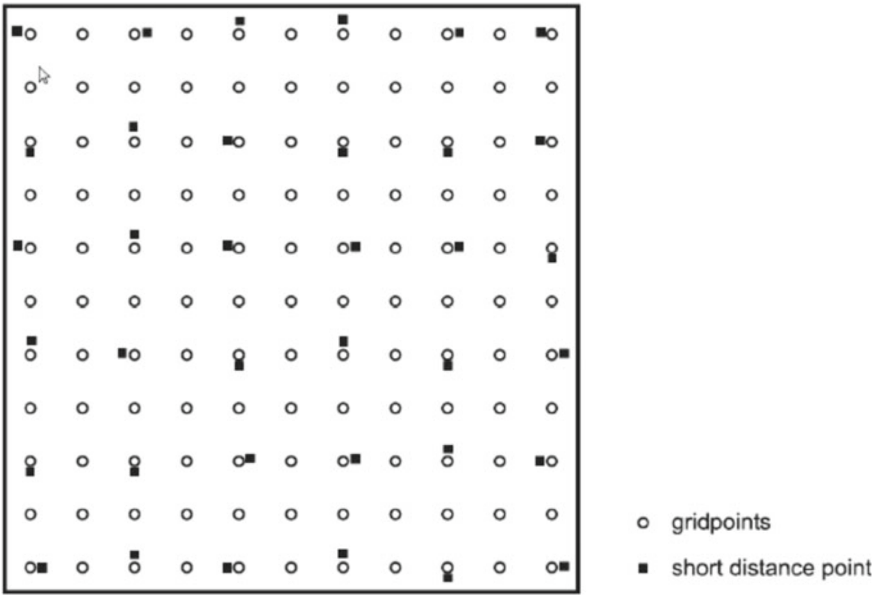

Fig. 9 Regular grid sampling supplemented with short-distance points to achieve a spatial sampling design that works well for variogram estimation and kriging (Adapted from Santra and Heuvelink 2018)

structure and the observations. The result of a stochastic simulation exercise is not unique, because there are an infinite number of possible realities, from which just one or several are taken.

Spatial stochastic simulation is useful for two main purposes. First, visualization and comparison of multiple simulated realities nicely conveys the uncertainty about the mapped variable. Where uncertainty is large the differences between simulated values will be large, where there is little uncertainty the differences will be small. Also, the spatial structure in the simulated maps agrees with that of reality, whereas kriging produces a smoothed version of reality. Second, spatial stochastic simulation is also required in spatial uncertainty analysis studies. The aim of such studies is to analyze how errors and uncertainties in inputs to environmental models (such as interpolated maps) propagate through the model. This can be analysed using a Monte Carlo simulation approach, which requires that realizations of the uncertain inputs are generated using stochastic simulation. For spatially distributed inputs, spatial stochastic simulation must be used.

There are various ways for spatial stochastic simulation. Perhaps the most attractive method is *sequential Gaussian simulation*, which works as follows:

(i) Define a grid of simulation locations across the study area (as also done in kriging).

(ii) Visit a randomly selected simulation location and verify that it does not coincide with an observation or already simulated location (if it does, then select another simulation location).
(iii) Krige to the simulation location, this yields a kriging prediction and kriging standard deviation.
(iv) Use a pseudo-random number generator to sample from the normal distribution with mean equal to the kriging prediction and standard deviation equal to the kriging standard deviation.
(v) Add the simulated value to the data set, in other words treat the simulated value as if it were another observation.
(vi) Go back to step 2 and repeat the procedure until there are no more simulation locations left.

Note that adding previously simulated values to the dataset as required in step 4 causes the kriging system (i.e., the number of equations, see Eq. 10a, b) soon becomes very large so that it will be needed to set a maximum on the number of observations to be used in the kriging (step 3). Usually, one limits the observations to those located in a circular window surrounding the simulation location. If this is done, it is called *local kriging*. The opposite, in which all available observations are used, is called *global kriging*. Local kriging is attractive because it is fast (in the case of spatial stochastic simulation on a fine grid it is imperative for this reason, because global kriging would take 'forever'), and also because the kriging result is more robust against deviations from the stationarity assumption. The disadvantages are that the kriging variance will increase slightly, and that anomalies in the kriging prediction map may result if the local window is chosen too small.

11 Conclusion

Groundwater studies is time consuming and cost-effective and geospatial technology offers a practical way to assimilate several data sources for its favourable groundwater development and sustainable management. The knowledge about the fundamental of geostatistics is helpful to proper management of this natural resource. Understanding of the basics of geostatistics will help the students, researchers and planners to accurately assess the problems and thereby can undertake proper remedial measures to solve the problems.

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Recent Trends in GIS and Geostatistical Approaches to Analyze Groundwater Resource in India

Ch. Jyotiprava Dash and Partha Pratim Adhikary

Abstract India is the largest user of groundwater in the world using an estimated 250 km^3 of groundwater per annum. In India, groundwater contributes 62% in agriculture sector. In rural India, 85% and in urban India, 45% of water consumption has been met from groundwater. However, this precious water resource is under increasing pressure due to intensification of human activities along with climate change. In India about 36% of groundwater blocks are semi-critical, critical, or over-exploited and the situation is deteriorating rapidly. Not only groundwater depletion is unprecedented, its quality is also deteriorating in an alarming rate throughout India. Therefore, groundwater dependent water supply system is expected to hit adversely in the future. In this context, Geographic Information System (GIS) along with geostatistics play an important role in depicting the spatio-temporal variation of water level and water quality. In this chapter work done by various researchers on GIS and geostatistics in groundwater is highlighted, which will help the policy makers and managers to implement proper regulations for sustainability of this precious resource in India.

Keywords Geostatistics · Groundwater pollution · India · Indicator kriging · Ordinary kringing

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1 Introduction

Groundwater is one of the most important sources of water worldwide on which 50% of the world's population depends for their drinking requirement (FAO 2010). Not only domestic use this source also contributes towards 43% of the water used for irrigation globally and 40% of industrial requirement (Foster and Chilton 2003; Seiler and Gat 2007; Siebert et al. 2010). Apart from above mentioned use it plays an important role in replenishment of surface water sources such as streams, rivers and wet lands. India stands first in the world in terms of groundwater use having an estimated 250 km^3 of groundwater per annum, where as China and USA stand second and third, respectively (Margat and van der Gun 2013). In India, contribution of groundwater towards agriculture, rural water supply and urban water consumption are 62, 85 and 45%, respectively indicating massive dependency on this source of water (Mukherjee et al. 2014).

Uncertainties in monsoon, unreliable and inadequate municipal water supplies, and water availability at the point of use are some of the factors which are responsible for inclination of people towards groundwater use over surface water use. With increased use of groundwater, this precious water resource is under threat. In India about 36% of groundwater blocks are semi-critical, critical, or overexploited, and the situation is deteriorating rapidly all over the country (CGWB 2019) and presented in Fig. 1. It has been reported by Central Ground Water Board (CGWB) that in India, 1186 assessment units (approximately 17% of total assessment units) have been classified as 'Overexploited', which indicates that the groundwater extraction in those units is at risk (CGWB 2019). In north west part of India, the over-exploited areas are mostly concentrated in Delhi, Haryana, some parts of Punjab, and Western Uttar Pradesh and the reason behind this overexploitation is due to changing cropping pattern, increase in cropping intensity and free or subsidized power supply (Dash et al. 2010; Aneja 2017; Baweja et al. 2017; Bhalla 2017). Similarly in the western part of India, specifically Rajasthan and Gujarat, overexploitation of groundwater is because of farmers' inclination towards growing more remunerative crops which are water demanding, along with prevalence of arid climate which limits natural groundwater recharge (Panda et al. 2012). In southern India, the inherent aquifer properties of crystalline aquifers are responsible for making less groundwater available in the region, which includes states like Andhra Pradesh, Karnataka, Telangana and Tamil Nadu (CGWB 2019).

Not only groundwater depletion, its quality is also deteriorating in an alarming rate throughout India (Fig. 2). The fluoride concentration of groundwater exceeding the permissible limit for drinking (>1.5 mg l^{-1}) is widely prevalent in many parts of the country (Sankhla and Kumar 2018; Ali et al. 2019). Even fluoride concentration more than 3.0 mg l^{-1} is prevalent in some parts of Punjab, Rajasthan, Madhya Pradesh, and Chhattisgarh (Ali et al. 2019). In Andhra Pradesh, Gujarat, Tamil Nadu and Uttar Pradesh excess amount of fluoride has been detected in drinking water supply system covering more than 50% of the districts in these states. It has also been reported that in India, the fluoride concentration in groundwater is nearly 2 times higher than

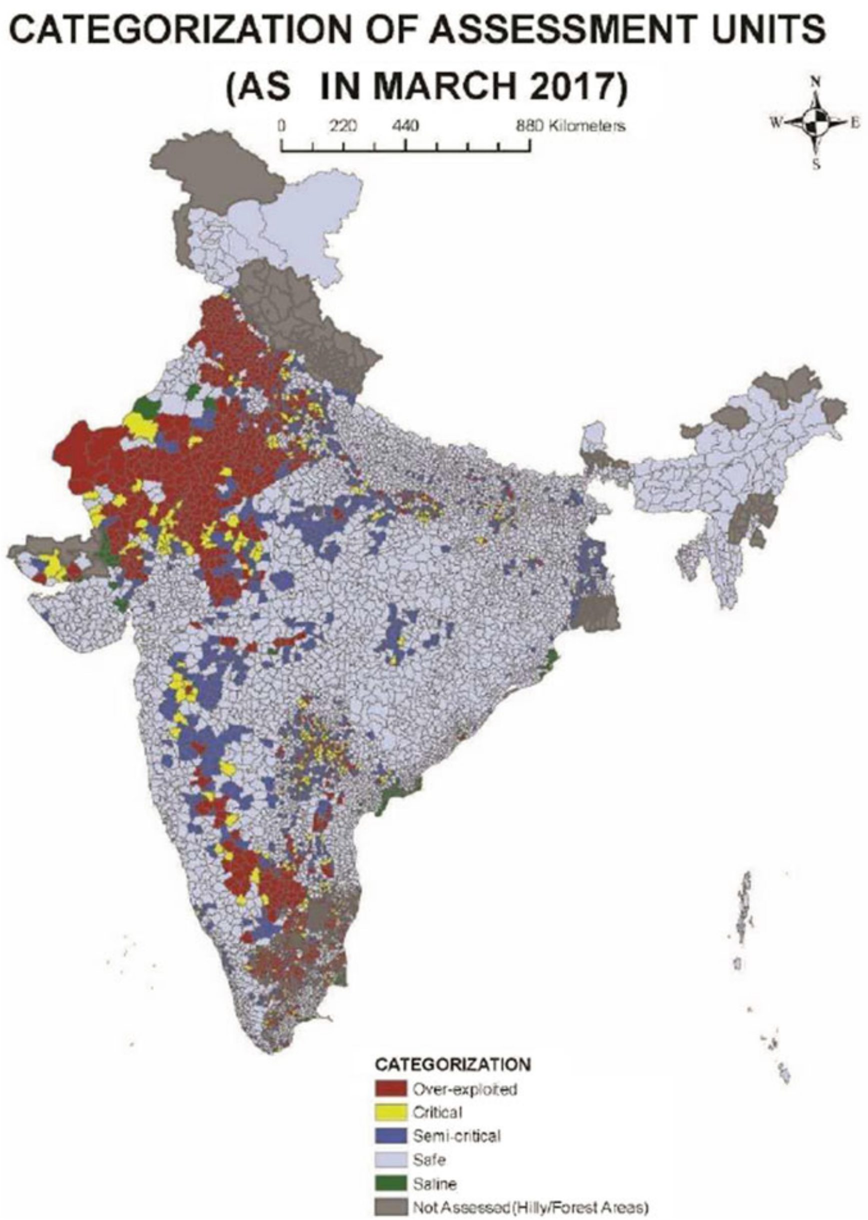

Fig. 1 Categorization of groundwater assessment unit (Adopted from CGWB 2019)

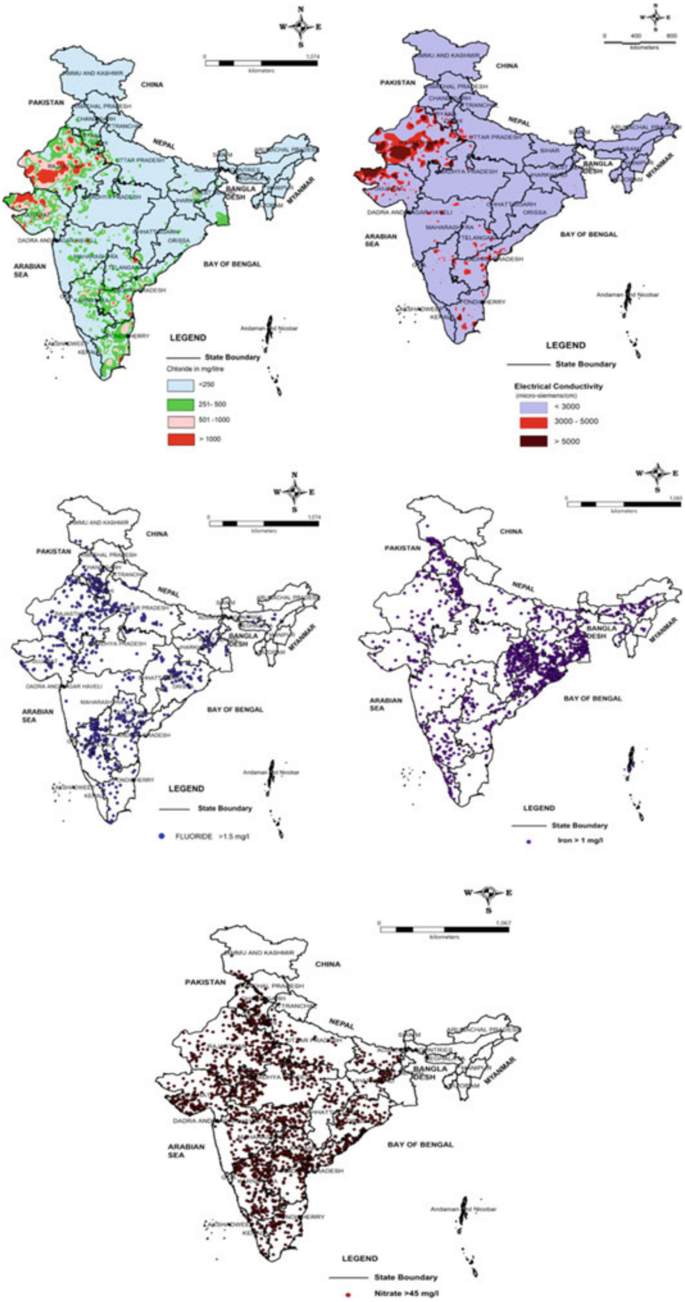

Fig. 2 Spatial variation of groundwater quality in India (Adopted from CGWB 2019)

in the groundwater of urban areas (Ali et al. 2019). High level of arsenic has also been reported by many workers from various states such as Chhattisgarh (Mukherjee et al. 2014), West Bengal (Mazumder and Dasgupta 2011) and Karnataka (Hebbar and Janardhana 2016). As both water quality and groundwater depletion problem are aggravating in India day by day, definitely it will have serious implications on the sustainability of groundwater use in India.

In this regard, modern technologies like GIS and geostatistics play an important role in many issues related to groundwater. GIS has been used as a suitable platform to make strategies for sustainable use of water resources. Therefore, the main objective of this chapter is to give an insight into the role played by GIS and geostatistics in proper management of groundwater resources in India.

2 Geographical Information System

GIS a computer-based information system used for receiving, storing, checking, integrating, retrieving, analyzing and displaying spatial data. In other words, it's a database system having specific capabilities of handling spatially referenced data. Mostly GIS is employed for mapping, through which different layers are integrated and every layer contains information about a particular kind of feature. The main functions of GIS are:

- Data acquisition and pre-processing: It includes digitizing, editing, topology building, format conversion, transformation of projections etc.
- Data management, storage and retrieval: This includes data archival, object-oriented database, hierarchical, network and relational modeling, attribute query etc.
- Spatial measurement and analysis: This include measurement processes, overlay operations, buffering, and connectivity maneuvers etc.
- Product generation through graphic output: This includes scale conversion, simplification, statistical and topological map etc.

The Geographic Information System (GIS) has appeared as a very helpful technique in analyzing and quantifying various aspects of groundwater manifestation. It is very helpful to delineate groundwater prospect and deficit zones, along with groundwater quality.

3 Geostatistics

Geostatistics is a technique in which natural variables can be visualized to be distributed over space and time (Journel and Huijbregts 1978; Isaaks and Srivastava 1989; Dash et al. 2010) are analyzed and predicted. In geostatistical method the analysis of spatial correlations is carried out through covariance and variogram functions, which present the spatial regression among a dataset based on the spatial variability of couple of points at the specific spatial distances (known as lag distances) (Dash et al. 2010; Barca et al. 2017). This method explores the spatial continuity of natural properties and uses this spatial continuity of natural properties to describe the property of a natural parameter some distance away through proper adaptation of regression techniques (Bohling 2005). Semivariance function characterizes the spatial continuity between points. The semivariogram is the graphical representation of the semivariance with respect to the lag distance or separation distance between points (Isaaks and Srivastava 1989). The semivariogram structure can be elucidated by three properties such as the nugget, the range and the sill (Fig. 3). The distance (represented by X-axis) at which the model starts flattening is termed as the range, whereas the value (represented by Y-axis) at which the model starts flattening is sill. The nugget represents the value at which the semi-variogram intercepts the Y-axis. The semivariogram structure helps to quantify spatial dependence between observations and is shown in Eq. 1.

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [z(s_i + h) - z(s_i)]^2 \quad (1)$$

where $\gamma(h)$ is the semivariogram, which can be articulated as a function of the magnitude of the lag distance h, $N(h)$ is the number of observation pairs separated by distance h, and $z(\mathrm{s_i})$ is the spatial variable at location s_i.

Kriging is the highly preferred geostatistical interpolation technique. The advantages of kriging lay in consideration of the distance and the degree of variation between known data points together, while predicting values at unknown points.

The general form of kriging is given below:

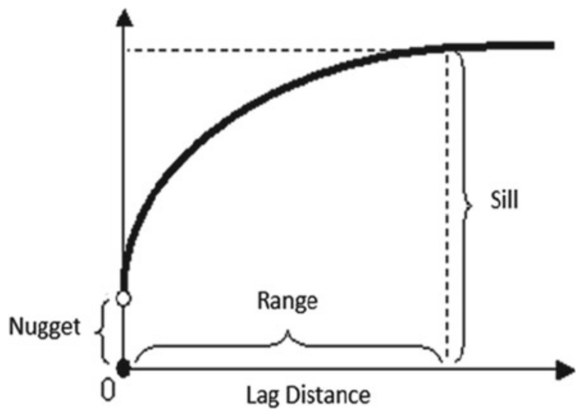

Fig. 3 A typical example of semi-variogram showing different components

$$Z(s) = \sum_{i=1}^{N} \lambda_i Z(s_i) \tag{2}$$

where Z(s) is the measured value at the ith location, λ_i is an unknown weight for the measured value at the ith location, s is the prediction location, and N is the number of measured values. Kriging can be of different types.

3.1 Kriging

There are various types of kriging methods such as ordinary kriging, simple kriging, universal kriging, indicator kriging, probability kriging and disjunctive kriging.

3.1.1 Ordinary Kriging

Ordinary kriging is most extensively used methods among various kriging types. In this method the variance of the estimation error has been kept minimum, to obtain best linear unbiased estimate of a spatial variable at an un-sampled site. Through this method the estimated mean error used to be kept equal to zero so that the reliability and the accuracy of the estimation will be high. In ordinary kriging, the linear relationships between observed parameters are used to estimate the value at unsampled point. The coefficients of this linear regression are focused to determine the weights. The linear distance between the observed and the estimated points is one of the factors that decide the value of weights. Apart from this, the spatial structure of the variable is also considered as another factor. In this method, two assumptions are

(a) The mean of the process is constant.
(b) The mean is invariant within the spatial domain.

The ordinary kriging is represented as

$$z(s) = \mu + \varepsilon(s) \tag{3}$$

where μ is an unknown constant and $z(s)$ is the measured value at any location s, with stochastic residual $\varepsilon(s)$ with zero mean and unit variance. This method is considered as one of the simplest methods for predicting variables at unknown points with a great flexibility in application.

3.1.2 Simple Kriging

Simple kriging is practically similar to ordinary kriging, in which either semivariogram or covariance is used. This method also allows measurement error. To estimate the measurement error, all the parameters and covariant should be known.

The working model for simple kriging is given below:

$$z(s) = \mu + \varepsilon(s) \tag{4}$$

where μ is a known constant.

3.1.3 Indicator Kriging

The concept behind the indicator kriging method is conversion of the data into either 1 or 0 depending upon its relationship to a threshold value. In this method, first indicator function is used to generate indicator codes, which is below a desired threshold or critical value z_{th}. The indicator kriging assumes the model:

$$I(s, z_{th}) = \begin{cases} 1, & \text{if } z(s) \geq z_{th} \\ 0, & \text{otherwise} \end{cases} \tag{5}$$

The indicator kriging estimator, $I^{\wedge}(s_0; z_{th})$ at the location (s_0) can be calculated by

$$I^{\wedge}(s_0; z_{th}) = \sum_{i=1}^{N} \lambda_i I(s_i; z_{th}) \tag{6}$$

and the indicator kriging system given $\lambda_i = 1$

$$\sum_{j=1}^{N} \lambda_j \gamma_i \left(s_j - s_i\right) = \gamma_i (s_0 - s_i) - \mu \tag{7}$$

where γ_i is the semivariance of the indicator codes at the respective lag distance, λ_j is the weighted coefficient, and μ is the Lagrange multiplier.

3.1.4 Probability Kriging

This kriging method is similar to indicator kriging method with some additional features. In this method, the main variable is the indicator code $I(s_i; z_{\text{th}})$ and the auxiliary variable in the cokriging estimator is the uniform value $U(s)$. Deutsch and Journel (1997) call this uniform value as the standardized rank. This can be defined as

$$U(s) \approx \frac{r}{N} \tag{8}$$

where r denotes the rank of the rth order statistic $z(r)$ located at s and N is the total number of observations (Goovaerts 1997).

The probability kriging estimator is defined by

$$I^{\wedge}(s_0; z_{th}) = \sum_{i=1}^{N} \lambda_i I(s_i; z_{th}) + \sum_{i=1}^{N} \lambda_{ui} U(s_i) \tag{9}$$

where λ_i and λ_{ui} are the weights associated with $I(s_i; z_{\text{th}})$ and $U(s_i)$.

In this kriging method, covariance or semivariogram, cross-covariance and transformations are used, however this method restricts the measurement error to occur (Bourgault and Marcotte 1991).

3.1.5 Universal Kriging

This kriging method assumes the model

$$z(s) = \mu(s) + \varepsilon(s) \tag{10}$$

where μ(s) is some deterministic function and ε(s) is random variation (called microscale variation).

The mean of all errors is zero. Theoretically, the autocorrelation is modeled from the random errors ε(s). Actually, universal kriging is one type of regression kriging that is developed by using with the spatial coordinates as the explanatory variables. In universal kriging, the errors ε(s) are modeled to be auto-correlated.

The μ(s) in Eq. 10 is called as drift. The drift can be defined as a simple polynomial function that models the average value of the scattered points (Ahmed 2007).

Goovaerts (1997) has modelled the drift function as:

$$\mu(s) = \sum_{k=1}^{K} a_k f_k(s) \tag{11}$$

where, f_k are the basic functions and a_k are the drift coefficients.

3.1.6 Disjunctive Kriging

This kriging method assumes the model:

$$f(z(s)) = \mu + \varepsilon(s) \tag{12}$$

where f(z(s)) is an arbitrary function of z(s) and μ is an unknown constant. Disjunctive kriging can explain more than ordinary kriging with increased complexity. The functions f(z(s)) is an approximate estimate and can work with the assumption of bivariate normality. In this kriging data transformations are adapted to structure the semivariogram but it excludes the measurement of errors. Therefore, the solutions obtained from this interpolation method are more complex where many assumptions are made.

4 Applications of Kriging in Groundwater

4.1 Mapping of Groundwater Depth

Probably for the first time in India, geostatistical method was applied to map spatial variation of groundwater depth by Dahiya et al. (1986) for an arid region of Haryana. They concluded that these contour maps could serve as a better background for making appropriate decisions in the management of groundwater in the study area. Thereafter many researchers have been used different types of kriging method to map spatio-temporal variation of groundwater depth across India. For Upper Kongal basin, Nalgonda district, Andhra Pradesh, India, Prakash and Singh (2000) used ordinary kriging method to know the spatial distribution of groundwater in the district and also quantified the optimum number of observation wells required for better understanding of groundwater scenario in the study area. Universal kriging technique with a linear drift could be considered as a suitable method to analyse the available groundwater levels in a coupled system of weathered and fractured rock aquifers in a hard rock region of Andhra Pradesh (Kumar and Ahmed 2003). The spatial and temporal variation of groundwater level during 1985–1990 was mapped for some area of Indira Gandhi Nahar Pariyojana (IGNP) canal command area, Rajasthan, India using ordinary kriging by Kumar and Ramadevi (2006). The auto-correlation of groundwater level with distance was quantified by them and reported to be varied between 13.1 and 17.4 km in the study area. They also emphasized on the suitability of ordinary kriging in predicting groundwater levels in the study area, having a low mean error (-0.4 to -0.24 m) and mean square error values (3.6–7.9 m^2). They also pointed out the utilization of estimation errors as a guide to select new observation sites. The application of universal kriging in mapping groundwater level in Rajasthan, India was carried out successfully with minimum mean error (0.06), mean square error (9.79) and kriged reduced mean square error value of 0.98 by Kumar (2007). Dash et al. (2010) mapped water table depth using both ordinary and indicator kriging for National Capital Territory (NCT) of Delhi and also indicated the suitability of indicator kriging over ordinary kriging in mapping spatial variation of water table depth. Machiwal et al. (2012) applied GIS and geostatistics to analyze the spatio-temporal behavior of water table depth in Ahar river basin, Udaipur, Rajasthan, India and identified critical areas, where there is a need of implementation of measures like construction of water harvesting structures and groundwater recharge techniques to protect the underlying aquifer from further depletion. The analysis of spatio-temporal variations of water table depths using geostatistics in aquifers of coastal areas were very helpful (Mini et al. 2014; Sahoo and Jha 2014), in delineating the critical regions where measures like controlled pumping and artificial groundwater recharge needed to be implemented to prevent sea water intrusion by improving groundwater level. Based on the study carried out by Chowdhury (2016) using ordinary kriging in GIS platform, a policy plan was suggested for proper utilization of groundwater resource in Haringhata Block, Nadia district, West Bengal, India. Similarly, Adhikary and Dash (2017) emphasized use of universal kriging for spatial mapping of groundwater depth in NCT Delhi and also reported that there is a greater chance of groundwater exploitation up to a depth of 20 m in the study area. Kaur and Rishi (2018)identified areas prone to groundwater over exploitation in Panipat district, Haryana, India. They used ordinary kriging to reach the above-mentioned conclusions and based on the results they recommended policy plans to protect the groundwater from further exploitation. Recently Anasari et al. (2018) used ordinary kriging to know the spatial and temporal variations of groundwater level from 2010 to 2016 in Banaskantha District, Gujarat, India. Taking up of artificial recharge on large scale through appropriate techniques on a local scale with active community participation was suggested by them.

4.2 Mapping Groundwater Quality

Ahmed (2002) demonstrated accuracy of kriging method to predict Total Dissolved Solids in groundwater. Spatial variability in groundwater quality with respect to different parameters such as chloride, electrical conductivity (EC), fluoride, magnesium, nitrate, potassium, sulphate, and sodium were analyzed using both ordinary and indicator kriging (Adhikary et al. 2010; Dash et al. 2010; Gupta and Sarma 2016) and the probability of exceedence of the threshold value of different water quality parameters were mapped (Adhikary et al. 2010; Dash et al. 2010) for NCT of Delhi. The heavy metals in the groundwater quantified with high precision using indicator kriging (Adhikary et al. 2011). Not only was heavy metal, geospatial variability mapping of fluoride concentration also analyzed for Mathura district, Uttar Pradesh, India using ordinary kriging. It was observed that more than one third of the area of the district comes under moderately to severely polluted as per BIS standard ranging fluoride concentration values from 2.0 to 5.1 mg l^{-1} during the year 2007 (Rawat et al. 2012). Gorai et al. (2013) have used ordinary kriging to study the groundwater quality in Ranchi municipal corporation area. Similarly, Sharma et al. (2015) used ordinary kriging to generate the thematic spatial maps of EC, TDS, total hardness, fluoride, nitrate and chloride in the groundwater in Tonk district, Rajasthan, and a plan was suggested by them to implement special measures to solve the water quality problems in the affected areas of the district. Bayesian kriging method was applied successfully to determine the spatial distribution of fluoride in groundwater in the Tamiraparani river basin (Magesh et al. 2016).They reported that half of the study area has groundwater fluoride concentrations below the threshold level of fluoride concentration that would guard the teeth from the formation of dental caries and only 0.1% of the study area has high fluoride level in excess of the concentrations that would create dental fluorosis. Fehmida and Bindu (2018) assessed groundwater quality in the industrial belt of Eloor in Ernakulum district of Kerala using geographical information system based geostatistical method.

As groundwater pollution is prevailing in many parts of India and one of the burning environmental issues, it's scientific management by taking suitable site-specific measures and aimed to control or reduce the risk of water pollution by contaminants is utmost important. The knowledge about the spatio-temporal distribution of various pollutants in groundwater exceeding the threshold or critical limit for particular purpose, will definitely be helpful to policy makers to make strategies for sustainable management of groundwater resources.

4.3 Mapping of Groundwater Potential Zone

In NCT, Delhi the groundwater potential zones were delineated using geostatistics in GIS environment (Mallick et al. 2014), and the delineated zones showed good correlation with observed discharge and groundwater depth data. Jasrotia et al. (2016) delineated the groundwater potential zones of Devak and Rui watersheds of Jammu and Kashmir using aquifer parameters in GIS environment. They depicted the groundwater potential zones into five categories namely excellent, good, moderate, low and runoff zone. Similarly, in the semi-arid region of YSR Kadapa district, Andhra Pradesh, India, Rajasekhar et al. (2018)identified groundwater potential zones of using GIS. Their study will be useful for planning and development of integrated water resources management.

5 Conclusions

Groundwater is an important source of water supply around the world. The knowledge about the spatio-temporal distribution of this precious source along with its quality is utmost important for proper planning and management. Geostatistics is one of the advanced tools used to know the both the spatial and temporal distribution of natural variables in any area in GIS environment. Geostatitics along with GIS has gained a momentum in field of groundwater across India. Thus, information obtained from these techniques can be potentially used for planning, management, and policy-making for sustainable use of groundwater so that it can be conserved for our future generations.

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Concept of Artificial Intelligence and Its Applications in Groundwater Spatial Studies

Gouri Sankar Bhunia, Pravat Kumar Shit, and Partha Pratim Adhikary

Abstract As a computational method with impressive performance over traditional methods, Artificial Intelligence (AI) has recently gained great attention. It is a consortium of different soft-computational methodologies including artificial neural networks (ANNs), Fuzzy Logic (FL), Wavelet Transformation (WT) and so forth. AI recently begun to explain complex and non-linear problems in geoscience and hydrology in a clear and satisfactory manner. The combination of one and more approaches has created, rather than applying one approach, new categories such as Neuro-Fuzzy (NF), which are more effective than distinct approaches. Considering the recognition and huge application and promotion of AI procedures in geoscience and hydrology since last few years, it would be an vital chore to deduce the distinctive new use of the AI techniques in groundwater investigation. It was therefore our goal to exhibit the use of AI to take care of the perplexing and nonlinear issues in the field of groundwater research. In this chapter we have attempted to emphasize the learning of individual and hybrid AI techniques in groundwater studies, introduce and apply them. We mainly described different individual and combined soft-computing tools like Fuzzy logic, Sugeno fuzzy logic, Neurofuzzy, Gradient-based groundwater model, Artificial Neural Network, Support Vector Machine, and Wavelet transform

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to assess and monitor groundwater resources. Long-term applications and advancement of AI procedure for precise appraisal of groundwater assets is additionally proposed.

Keywords Artificial neural network · Fuzzy logic · Neuro fuzzy · Sugeno fuzzy logic · Support vector machine · Wavelet transform

1 Introduction

The spatial and temporal variation of hydrogeological properties, landscape conditions, climate properties, land use, pumping and so on influences groundwater dynamics. The increase in agricultural activities contrarily influences the groundwater due to global warming and the growing population. Groundwater rates are typically modeled with process-related models that rely on the deep knowledge of the system dynamics observed. To classify the aquifer characteristics, spatial and thematic data on geological and hydrological properties are needed. The complexity of the system challenge accurate physical simulations because of the criteria for model creation and calibration of large agricultural and hydrogeological data. Many physical models worldwide use default modeling tools and their precision depends on the availability of detailed and accurate data (Adhikary et al. 2019).

Machine learning algorithms detect trends embedded in past data and use them to model situations for the future. Input variable selection is important for the creation of data driven models and is especially important when modeling water resources (Quilty et al. 2016; Galelli et al. 2014). In spite of the fact that, the physical models show a noteworthy setback as they required exact characterization and measurement of physical properties and common conditions inside the framework beneath thought. Compared to the physical/non-parametric model, the advantage of parametric models is that data on original and boundaries or aquifer characteristics are not required (Nourani et al. 2014). Artificial Intelligence (AI) models benefit from being used with a high level of detail to address a wide variety of groundwater challenges, both in quantity and in quantity(Govindaraju and Rao 2000; Mohanty et al. 2010). Hence, an appraisal of machine learning application in groundwater management recommends that majority of the methods can attain performance analogous to or may be more precise than the numerical models.

2 Applications

In the twenty-first century, the Artificial Intelligence (AI) applications became an imperative aspect of research in several areas. The use of AI in water resource management contributed to the development of expert frameworks for problem-solving and decision-making, which was done mainly in computer science and cerebral thinking. The areas of groundwater management using this technology is expected to demonstrate through modeling and simulation, qualitative and quantitative information integration, theoretical growth etc. The control of water supplies today relies increasingly on complex machine learning, high performance computing for coherent network simulation and spatial grid computing. According to Millington (2006), "the Artificial Intelligence (AI) is about making computers capable of performing the tasks of thought that humans and animals can do".

Since the last decades, the uses of various AI techniques, such as ANNs and SVM in hydrological applications are being used continuously incurring relatively less cost and effort (Chen et al. 2008). ANNs are the computing system and their construction simulates the neural structure of the data and information to produce the output values according to input by creating non-linear relationships (Suykens et al. 2012). Figure 1 showing a conventional AI life cycle in groundwater investigations: 'Operations', 'Data Accumulation', 'Data finalization', 'Machine learning' and 'Decision making'. 'Operations' implies the phenomenon of interest, such as each aspect involves separate tasks of the groundwater studies. As the procedures interchange to the virtual space, various output are in the forms of 'digital exhaust' which is trace data on numeral actions that may use to build employing algorithms. Groundwater investigation is most difficult field for estimation that most of the cases indirect measurements are taken care. Data accumulation has to be extracted from multiple databases, figures, statistics etc. There are growing availability of standard

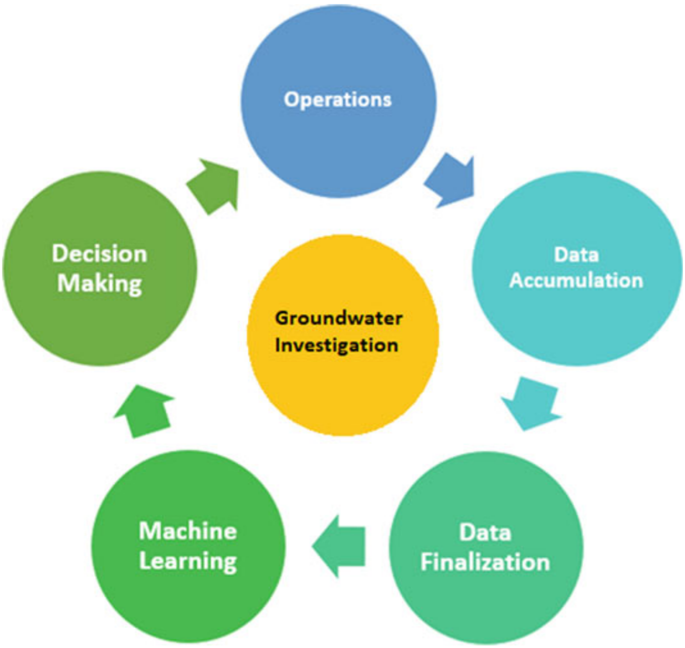

Fig. 1 Life cycle of an AI-supported groundwater resource practice

data format, including ICR, transcription, voice and image archives, weather data and logistics data. Various spatial and thematic data including topographic, land cover, and forest maps were collected and utilized through data processing.

"Finalization of data" transformed all of these data into a standard format, scale fixing and combined before analysis can take place. 'Machine Learning' refers to a wide range of techniques which can adapt and learn to produce algorithms, which usually perform best, typically prediction. Consequently, "scaled-up" algorithms such as recurrent neural networks and deep learning are powering the breakthrough of AI. Therefore, the supply of massive data from several sources like social media, industry, e-commerce, science and government has improved the approaches and algorithms to machine learning. "Decision making processes" is about how we use computer model perspectives in daily operations. AI today relies entirely on the creation, use and dissemination of Big Data (Burggräf et al. 2018). AI also developed into a data first approach with improved transparency of real time data and the expanding method to maximize vast volumes of data in seconds. A principle that forms the foundation for land conservation and environmental protection around the world, water supply management has given rise to the notion of sustainable development. The fundamental complexity of natural resources will overcome these problems in the field of ground water management using AI technologies like genetic algorithms, neural networks, multi-agent systems, cellular automata, forecasting systems, swam intelligence etc. Numerous AI tools and techniques including mathematical optimization, logical, classification, statistical learning and probability-based methods have been used (Nourani et al. 2014). Most of the AI based models that have been used in groundwater modelling are as follows:

3 Models

3.1 Fuzzy Logic

Fuzzy structures are used for the logistic purpose to describe ambiguity. A Fuzzy set includes part membership from '0' to '1' (Zadeh 1965). Fuzzy rule-based techniques accept impression and ambiguity of hydrological parameters when modeling fuzzy input file (Dixon 2005; Umamaheswari and Kalamani 2014), and to explain inherently imprecise pollution of groundwater quality. A conceptual framework for fully logic in groundwater research is illustrated in Fig. 2. The fuzzy c-means (FCM) is one of the most suitable clustering methods suggested by Pang and Lee (2004) to fill multidimensional spaces in a selected cluster of numbers. For example, Fijani et al. (2013) used FCM algorithm for *Vul* approximation, a fuzzy if-then rule *i*can be articulated as:

$$Rule\ i : If(D\ belongs\ to\ MF_D^i) and (R\ belongs\ to\ MF_R^i) and (A\ belongs\ to\ MF_A^i)$$
$$and (S\ belongs\ to\ MF_s^i) and (T\ belongs\ to\ MF_T^i) and$$

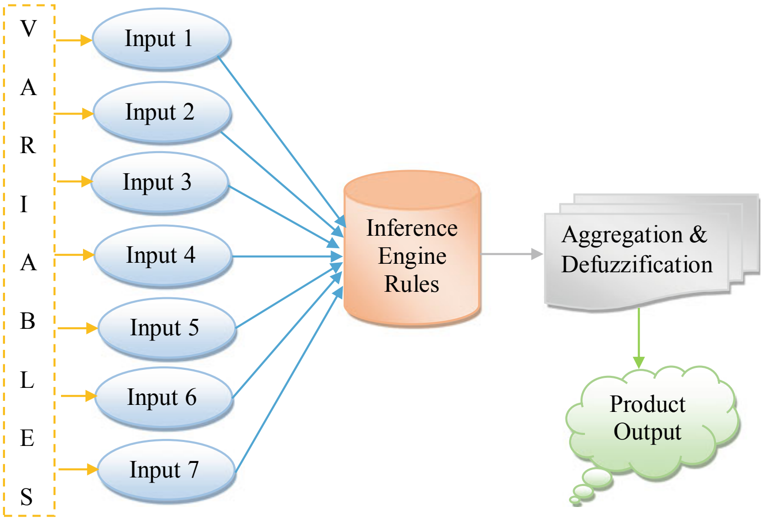

Fig. 2 Conceptual framework for fuzzy logic

$$(I\, belongs\ to\, MF_I^i) and (C\, belongs\ to\, MF_C^i), then (vul\, belongs\ to\, MF_{vul}^i),$$

where, Vul_i is the output of the rule i, MF_D^i is the membership function of the ith cluster of input D, MF_R^i is that the membership function of the ith cluster of input R, and so forth. The operator among the input MF is "and" (lessen) operator and therefore the output of the principles is accumulated *via* the "or" operator (maximize).

3.2 *Sugeno Fuzzy Logic*

Sugeno fuzzy logic (SFL) model developed by Lohani et al. (2006) uses output membership linear (first order) or constant (zero order) functions. The clustering method removes the input clusters and the output membership functions. The assignment radius of the value from '*0*' to '*1*' is the fundamental parameter of the subtractive clustering that governs the cluster number and the laws of '*if then*' (Li et al. 2000). For groundwater risk assessment, a fuzzy if-then rule i can be stated as:

$$Rule\ i : If (D\, belongs\ to\, MF_D^i) and (R\, belongs\ to\, MF_R^i) and (A\, belongs\ to\, MF_A^i)$$
$$and (S\, belongs\ to\, MF_s^i) and (T\, belongs\ to\, MF_T^i) and$$
$$(I\, belongs\ to\, MF_I^i) and (C\, belongs\ to\, MF_C^i), then$$

$$Vul_i = m_i D + n_i R + p_i A + q_i S + u_i T + k_i I + l_i C + c_i$$

where, Vul_i is the productivity of rule i, MF_D^i is the membership role of the ith cluster of input D, MF_R^i is the membership function of the ith cluster R, and so forth m_i, n_i, p_i, u_i, k_i, l_i, and c_i are co-efficient to be governed by linear least square approximation. The final outcome of the weighted average of entirely rule outputs is as follows:

$$Vul = \frac{\sum_i w_i Vul_i}{\sum_i w_i}$$

where, w_i is the firing strength of rule i, which is obtained via "*and*" operator.

3.3 Neurofuzzy (NF)

In many hydrological research works with a combination of Fuzzy set theory and ANN is carried out(Nauck and Kruse 1999; Nayak et al. 2004). A schematic NF configuration diagram is shown in Fig. 3. NF model is an authoritative method that operates with the GIS and can be used effectively to determine the vulnerability of groundwater. The architecture of NF operations is as following:

Step 1: Generate input data membership function. The neuron output is defined according to $O_i^1 = \mu_{ji}(X) \quad i = 1 \ldots 7 \ldots$

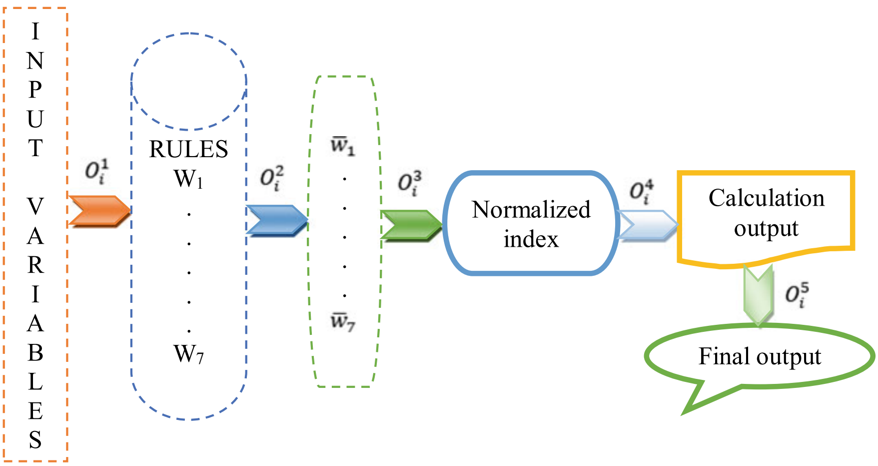

Fig. 3 Schematic diagram of Neurofuzzy model

where, j is Input number and 'i' is an index of membership functions. X = {DRASTIC} is a set of input. $\mu_{ji}(X)$ is a fuzzy set related with neuron i given a membership function.

USA has developed the DRASTIC model with seven geological and hydrological parameters in particular (Aller et al. 1987). Such factors are measured according to a numerical rating system weighted in accordance with its relative rank within the model. Such scores and weights are worn in the estimation of the DRASTIC Index (Rahman 2008; Fijani et al. 2013) using the following equation:

$$DRASTIC\ Index = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w$$

where, the capital letters designate the consistent constraint and the subscript "r" and "w" denote to the ratings and weights, respectively. The GIS integrates, manipulates, interprets and portries all these elements of the model. The result is a geographically based dataset viewing the hydrogeological environment and groundwater-sensitive areas of adulteration.

After this, the creation of membership functions must be regarded as a trapezoidal membership.

Step 2: Calculate GW vulnerability strength w_i for the i^{th} rule via multiplication:

$$O_i^2 = w_i = \mu_{1i}(X)\mu_{2i}(X)\mu_{3i}(X), \ldots \mu_{7i}(X)$$

Step 3: Normalized GW vulnerability strengths for the ith neuron can be computed as:

$$O_i^3 = \bar{w}_i = \frac{w_i}{\sum_i w_i} \quad i = 1, \ldots, 7$$

Step 4: The contribution of ith the rule in the model performance based on the SFL process of the first order is calculated as:

$$O_i^4 = \bar{w}_i Vul = \bar{w}_i(m_i D + n_i R + p_i A + q_i S + u_i T + k_i I + l_i C + c_i)$$
$$for\ i = 1, \ldots 7$$

Step 5: The final output can be calculated based on the weighted average of all rule outputs:

$$o_i^5 = Vul = \sum \bar{w}_i Vul_i$$

3.4 Gradient-Based Groundwater Model

Reinecke et al. (2019) proposed a groundwater model (G^3M) gradient based illustrated with a bucket-like 5′ (arcminutes) linear groundwater reservoir. G^3M is based on information on hydrogeology, topography, pumping wells, position and type of hydraulic surface water and ground water heads and follows the principles of MOD Flow ground water modeling (Harbaugh 2005).

3.5 Artificial Neural Network (ANN)

The ANN method has a composite process calculation which includes a long time and requires a number of input parameters (Zhang et al. 2014). The general ANN structure was derived from the biological neural system, but was first suggested by McCulloch (1984), in smaller sizes and dimensions. An ANN is a black box model, which is formed by studying the hidden relationships between phenomena. Within systems of ANN there are three layers—(i) input layer, (ii) hidden layer, and (iii) output layer. Figure 4 reveals a standard ANN structure for predicting the future zone for groundwater. The network obtains signals by neurons from the *input layer*, and the output of the network is provided by the neurons on an *output layer*. There may

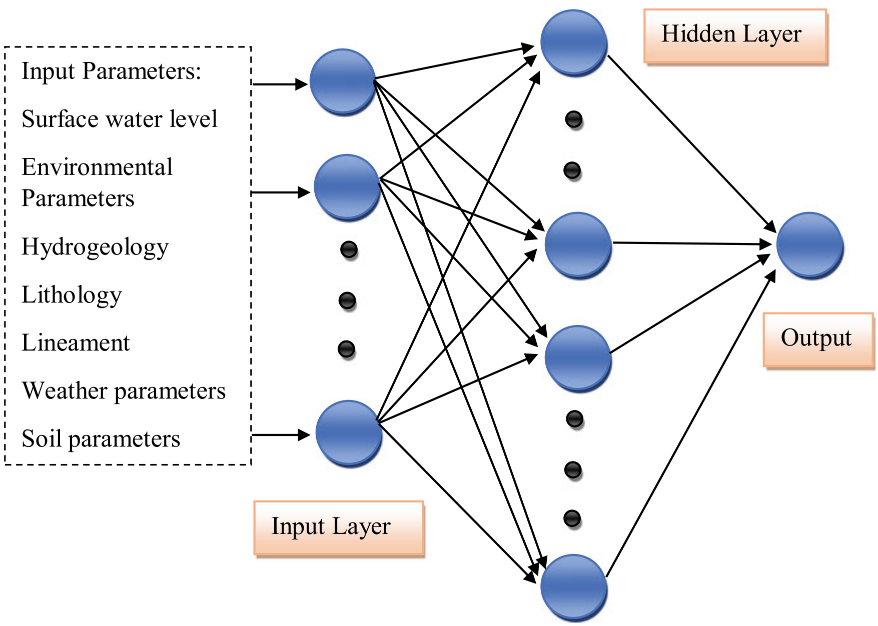

Fig. 4 Typical ANN structure for groundwater prediction (*source* Modified after Wang et al. 2018)

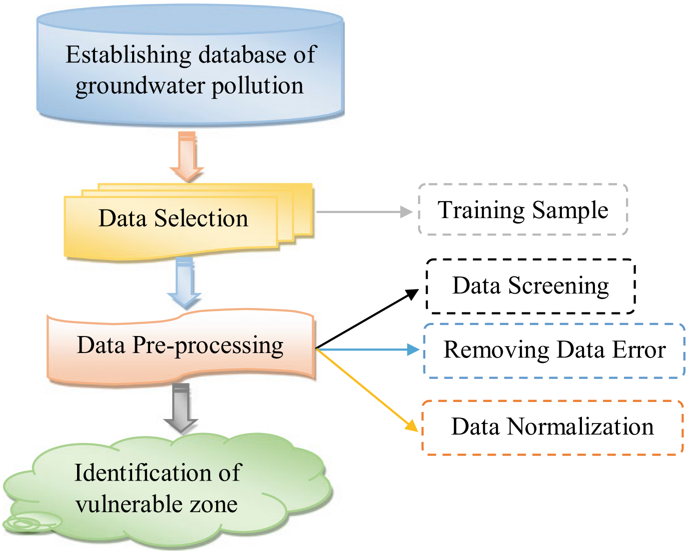

Fig. 5 Flow chart of SVM method for groundwater vulnerable zone identification (*source* Modified after Wang et al. 2018)

be more transitional *hidden layers*. The nodes of processors are located in the secret layers. Each network can have several layers hidden and each layer hidden may have several nodes. Results showed that each node represents a certain output function, and the relation between two nodes can be demonstrated by the hidden layers that suit ANN's memory. The ANN model's predictive performance is simpler than linear and other nonlinear models.

3.6 Support Vector Machine (SVM)

The SVM technology is better applicable and longer than the ANN method, but is not able to deal with major problems (Jiao et al. 2017). This approach refers to regression problems once the ε-insensitive loss function is implemented. The typical flow chart of SVM method is illustrated in Fig. 5.

3.7 Wavelet Transform

The transforming wavelet (WT) has become much more achievable and admirable since it was started in the early 1980s until the Fourier transformation (FT) has not been practiced as extensively. WT should reliably avoid AI algorithm failures in the treatment of non-stationary signal behaviour. It provides a time-scale process location, with accurate, long-term low-frequent information and high-frequency information for shorter regions (Sang 2012). The time-scale WT of a incessant time signal, x(t), is demarcated as (Mallat 1998):

$$T(a,b) = \frac{1}{\sqrt{a}} \int_{-\propto}^{+\propto} g^{*}\left(\frac{t-b}{a}\right) x(t) \cdot \mathrm{d}t$$

where, 'a' is the dilation aspect, 'b' is the chronological translation of the function '$g(t)$', which permits for the study of the signal around 'b', * resembles to the multifaceted conjugate and '$g(t)$' is the wavelet function or mother wavelet.

Sang (2012) has highlighted multi-faceted knowledge, including characterization and understanding of multi-temporality scales of hydrologic sequence, seasonal and pattern detection and data noise, in its analysis of WT's application in hydrological time series modeling. Therefore, the ability of WT to break down non-stationary signals into subsignals at different time scales helps to better construct hydrological processes (Sang 2012; Kisi 2010; Adamowski 2008). The use of WT to pre-process input data provides an example of a signal time frequency in various stages in the time domain, along with significant evidence of the physical structure of the data (Fig. 6).

Most of AI works are concerned mainly with the occurrence and expansion of soil water (Data management/Communication), spatial and temporal variability trends (Data Analysis) and with policy development to achieve soil water resources. The AI model for hydrological studies was used by Alagha et al. (2013). Emamgholizadeh et al. (2014) found the Artificial Network for the Prediction of Groundwater Level (ANN) and Adaptive Fuzzy Inference (ANFIS). For forecasting groundwater levels on a monthly basis, Adamowsk and Chan (2011) used ANNs and discrete wavelet transforms. Heesung et al. (2011) studied two nonlinear model time series used by ANNs and Support Vector Machines (SVM) for predictive groundwater level functions. For groundwater level prediction use was made of the neural feed-forward network (FFNN), Auto Regressive Moving Average (ARIMAX) (Nourani et al. 2015). The development of models for artificial neural network prediction in time

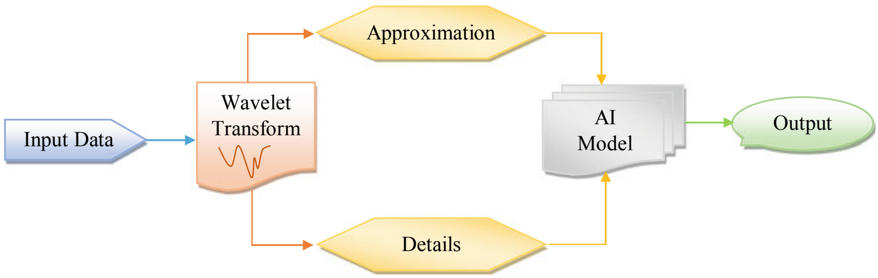

Fig. 6 A schematic diagram of wavelet transform in hydrological model

series prevision is based on a multilayer feedback perception (FFMLP) (Kouziokas et al. 2016). Guzman et al. (2015) recommended the ANN for regular groundwater levels as well as the help of vector regression (SVRThe new hybrid Wavelet-ANFIS model with multiple inputs and mother wavelets is adopted by Zare and Koch (2018), which is planned to pretend and envisage improvements in the floodplain in Iran in the Miandarband. Table 1 shows few examples of application of AI in groundwater assessment.

Groundwater contamination has a number of serious implications for the human and natural environment. Berkeley Labs have developed the AI system used in the Kalman filter framework to estimate groundwater quality through the provision of real-time sensor monitoring systems(Schmidt et al. 2018). Estimating water quality is difficult and data sets are often nonlinear. Artificial neural networks deliver prevailing regression analysis inference engines, nonlinear literature mapping frameworks. The competence of ANNs to estimate the level of dissolved oxygen (DO) and biochemical demands for oxygen in the Gomati River of India were investigated by Singh et al. (2009). For estimating the mean water quality values at ungauged sites Khalil et al. (2014) have been using a set of three models including ANNs and canonical correlation analysis. AI methods are used as an intermediate control feature, such as design of the dam reservoir valve system, flood analysis flow and precipitation projections. Consequently, different optimization and modelling schemes coordinated with other technical branches may be considered in several engineering projects to make many of them practical and lengthier, and different optimization and modeling plans coordinated with other science branches can be considered.

4 Conclusion

As the deep learning is becoming more prevalent in different fields, we need to analyze and improve the strategies mentioned in the literature of water management practices. Applications of the AI in groundwater studies and interpretations of the AI model without further data and commitment have become the trend without further details. Various research projects focused on the analytical predictive approach of the soil studies have been undertaken and most work indicated great potential in widespread water resource engineering for the use of the AI system. Further studies are required to investigate the applications of other network structures (e.g., recurrent network, radial basic network), learning algorithms (SVM regression, kNN, multilayer perception…) as well as the sensitivity of mapping scale to evade over prediction and to enhance the model performance. In addition, IoT technology requires the creation of a wide variety of prediction models within the field of groundwater management. Hence, exploration on hybrid models that assimilate AI and other practices is considered to be talented field that use smallest data, time and exertion for ground water search and analysis.

Table 1 Examples of AI applications in groundwater studies

Objectives	Methods	Product output	Reference
Predict the level of ground water in an unstable aquifer with pump and different weather conditions	The artificial neural network (ANN) and quantitative models	ANN models are perfect for karst and leaky aquifer simulations	Coppola et al. (2003)
Modelling of the Kentucky River (USA) rainfall runoff cycle	The ANNs model is based on daily average rainfall and stream flow data for rainfall-runoff processes	Comparison of various algorithms for the preparation. Real coded genetic algorithm (RGA) out performed than other algorithms	Srinivasulu and Jain (2006)
Study impacts on groundwater level of hydrology, temperature, and humidity	Artificial neural network (ANN)	The average error of 0.37 m or less was highly accurate to predict ground water levels with ANN's model	Taiyuan et al. (2007)
Niangziguan fountain, China's groundwater quality assessment	Model SVM was used for water quality parameters classification	SVM offers high precision analysis and a workable evaluation process	Junping et al. (2009)
Modelling of water level in Beysehir Lake, Turkey	Different ANN models developed based on Rainfall and evaporation data	Comparisons were observed between different models. The best results were obtained through the adaptive neuro-fuzzy inference system (ANFIS)	Yarar et al. (2009)
Groundwater level forecasting in Towaco aquifer, New Jersy, USA	SVM and ANN models for transit groundwater levels have been established in a complex groundwater system with different prediction horizons	For longer prediction horizons, particularly when less data are available, the SVM slightly outperformed ANNs	Behzad et al. (2010)
Prediction of groundwater level	Time-series models based on historical groundwater level, precipitation and tide level were developed using SVM's, ANNs.	The SVMs model is better than the ANN model generalization efficiency	Yoon et al. (2011)

(continued)

Table 1 (continued)

Objectives	Methods	Product output	Reference
Clustering technique for the consistency of groundwater models	Modeling of groundwater quality by Artificial Neural Networks and Support Vector Machine (SVM)	Improving the simulation accuracy of AI technologies will make decisions for groundwater management more reasonable and efficient	Alagha et al. (2013)
Groundwater flow equations in Ghaen and Karaj aquifers in Iran	Adaptive neural fuzzy inference system (ANFIS) and genetic programming (GP)	Across such case studies, the implementation of ANFIS and GP models illustrates the superior consistency between GP and ANFIS across time series modeling. A less root mean squared error (RMSE) is the error criterion for the water table lifting results	Fallah-Mehdipour et al. (2014)
Simulation of groundwater level	Simulation of groundwater by the Artificial Neural network (ANN) and the Neurofuzzy adaptive inference system (ANFIS)	The model ANFIS provides better results for soil water estimation than the standard ANNs	Khaki et al. (2015)
Estimation of groundwater level along the left bank of the Danube River, in the Province of Vojvodina	Adaptive neuro fuzzy inference system (ANFIS) and ANN model used to forecast monthly water table	Both these techniques represent useful tools for modelling hydrological processes in agriculture, with similar computing and memory capabilities	Djurovic et al. (2015)
Groundwater level simulation in Punjab	Different types of Network and Training Algorithms (ANN) are tested and compared to consider model efficiency and accuracy	The division of boreholes/observation pools into different groups of data and the design of separate networks validated by the ANN technique and the degree of accuracy of the ANN model in the forecast of the groundwater level are to be achieved in an acceptable limit	Lohani and Krishan (2015)

(continued)

Table 1 (continued)

Objectives	Methods	Product output	Reference
Prediction of groundwater level	The experience of the artificial neural network is used to estimate groundwater levels	An increased prediction accuracy of the developed Artificial Neural Network Models	Kouziokas et al. (2017)
Groundwater contamination estimation	Kalman filter framework to create an in situ real-time system of surveillance for groundwater contamination based on observable variables of in situ water quality	Such contaminant concentrations can be calculated using in situ observable variables which are accurate when contaminant concentrations are less frequent or not measured directly	Schmidt et al. (2018)
Groundwater modeling with machine learning techniques	Internet of things (IoT) was used for the collection of data; computer methods of learning are implemented with strongly correlated physical parameters as input variables (linear regression, decision trees, random forests, and gradient boosting)	Modeling methods based on data should work well enough in predicting changes in groundwater levels	Kenda et al. (2018)
Prediction of groundwater level of Reyhanlı region in Turkey	Radial basis neural network (RBNN), SVM-RBF support vector machine (svm-pk) support, multilinear regression (MLR) adaptive neural fuzzy inference system (ANFIS). Type of software to the poly-kernel support vector machine (PK) type	The most reliable groundwater level prediction were for SVM–RBF and SVM-PK models	Demirci et al. (2019)
Groundwater remediation	For optimizing pumping schedules to fix a polluted aquifer using the Pump, Treat and Inject process, the Optimum Control of artificial information (OCAI) is used	Results include OCAI "proof of concept"; strategies for the monitoring of pollutants and the remediation of polluted feathers have been developed based on the optimum PTI plan	Sadeghfam et al. (2019)

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Multi-criteria Decision-Making Approach Using Remote Sensing and GIS for Assessment of Groundwater Resources

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Abstract In the field of groundwater investigation, integrated remote sensing and geographical information system (GIS) has become a significant approach to explored groundwater resources, its assessment, monitoring, and conservation. The present study of Purulia district in West Bengal, India, tries to assess the potential groundwater zones using remote sensing and GIS technique. As groundwater recharge and its availability depend on some geophysical factors, a multi-criterion decision-making approach (MCDA) has been adopted to recognize the potential zones in the studied district. Thus, most significant factors viz. geomorphology, lithology, slope, lineament, drainage, soil, and land-use land-cover have been considered and assigned weights in respect to their relative importance to find out groundwater potential zones. Thematic maps of these selected factors were transformed to raster data using raster converter tool in ArcGIS. The groundwater prospective zones were obtained through weighted overlay analysis technique and categorized into six sub-classes viz., unavailable, very poor, poor, moderate, good, and very good zones. The outcome shows that about 7.5, 36.86, and 27% areas have very high, high and moderate potentiality respectively whereas, about 19.54 and 8.56% areas are under poor to very poor condition in terms of groundwater potentiality of the study area. The recharge and availability of groundwater are mainly depending on surface topography, slope, underlying rock composition, and lineaments as these factors determine the porosity, permeability, and rate of infiltration.

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Keywords Groundwater potential zone · Multi-criteria decision-making approach · Physical determinants · Weighted overlay analysis

1 Introduction

Groundwater is defined as the water found below the surface of the earth in conditions of 100% saturation, which accounts for 30 of freshwater of the earth available. It is about 60 times as plentiful as the freshwater found in lakes and streams. Groundwater is a very important natural resource and has a significant role in the economy of any nation. For a long period, people from all over the world use subsurface water to supply themselves for various purpose for example use as drinking water, which accounts almost half of the world's population (WWAP-UNESCO 2009). Therefore, the exploitation of groundwater is gradually increasing as it contributes significantly to the irrigation and food industry (Smith et al. 2016). About 70% of both the surface and sub-surface water is withdrawn for irrigation purpose at a global scale (Liu and Yang 2010). All around the world, exploitation of groundwater has started booming from the twentieth century ('the silent revolution') since the people enjoy huge benefits from groundwater than ever before (Llamas and Martínez-Santos 2005). As a result, it triggered unprecedented changes in the state of groundwater level. The groundwater is pumped out faster than it can replenish itself through underground recharge. This imbalance of groundwater extract and recharge creates the problems of drawdown, a lowering of the sub-surface water (Chenini and Mammou 2010). Consequently, the crisis of groundwater is a contemporary issue at the local level as well as a global concern. Globally this issue needs to address to make surethat the sustainable use of groundwater resources and maintain depletion of reserved groundwater (reducing water levels). If this valuable resource can't be managed properly, it will be a threat to living being very soon. Therefore, for the optimal utilization and preservation of this treasured, the recognition of groundwater prospective zones is extremely important. In India, increasing demand for water emerges extremely (Black and Talbot 2005) as the population grows rapidly. About 80–90% uses of domestic water in rural areas heavily dependent on groundwater, beyond that, more than 50% irrigation is also dependent on groundwater source (Central Ground Water Board 2014). For the greater interest, ameasurement of groundwater resource is really significant for the sustainable management and remote sensing and GIS tools are widely used in favour of this purpose (Dar et al. 2010; Krishna Kumar et al. 2011; Magesh et al. 2012; Kumar et al. 2014; Thapa et al. 2017; Nasir et al. 2018).

Remote sensing and GIS act as an efficient tool for delineating the potential zones of groundwater of a particular area. Satellite information along with conventional maps and statistics are commonly been used and made it effortless to establish the basic information regarding potential groundwater zones (Das et al. 1997; Thomas et al. 1999; Muralidhar et al. 2000; Gupta and Srivastava 2010; Rashid et al. 2012; Selvam et al. 2015; Nasir et al. 2018). It is further more using to characterize the features of the earth surface (like land-use, lineaments, and stream patterns) in addition to identify the zones of groundwater recharge (Sener et al. 2005; Magesh et al. 2012). To determine the location of aquifers beneath the surface, experimental drilling and geological stratigraphic analysis are one the conventional and dependable techniques, but may not be applied everywhere as it is very costly and lengthy (Zemo et al. 1994). Therefore, remote sensing and GIS technologies have appeared as an essential tool for map-making the existing groundwater resources (Jha et al. 2007). Many determinants, for instance, geomorphology, geology, topography, climatic condition, soil, land use land cover, etc. manage the availability of underground water. To assimilate of these factors, researchers have recognized that multi-criteria decision-making approach (MCDA) which effectively works under GIS environment. Thus, it was used for modelling the potential groundwater zones in various terrains (Mukherjee et al. 2012, Fashae et al. 2014; Ghosh et al. 2016; Islam et al. 2017) as well as in administrative units (Chowdhury et al. 2009; Selvam et al. 2015; Thapa et al. 2017) and groundwater resource evaluation (Srinivasa Rao and Jugran 2003; Jha et al. 2010; Fashae et al. 2014; Nag and Kundu. 2018). This technique provides the most advantageous solution in which the uncertainties related to the evaluating criteria that are ranked based on the overall performance of various input related to objectives (Nag and Chowdhury 2019). In MCDA, to every decisive factor a weightage has given to represent its valid consequence towards groundwater potentiality (Magesh et al. 2012) and provides competent spatial analysis functions (Yeh et al. 2009).

Delineation of potential groundwater zones with a proper approach is indispensable to manage the problem of water insufficiency in drought-prone areas. Purulia district is a drought-prone area of West Bengal and only a few works have been completed regarding groundwater prospect. Therefore, the present study tries to identify the zones of potential groundwater in Purulia district using MCDA weightage overlay analysis and remote sensing-GIS techniques.

2 Study Area

Purulia district an eastern part of Chota Nagpur plateau is located in the western part of West Bengal. The study area extended between 22° 42′ 35″ N to 23° 42′ 00″ N and 85° 49′ 25″ E to 86° 54′ 37″ E (Fig. 1). The district covered with a total 6259 km^2 area with 20 Community Development blocks. Mainly igneous and metamorphic rocks (i.e. granite and granitic gneiss) are the dominant lithological formation of the study area and sculpted a unique physical setting and topographical variations in the entire district. Therefore, permeability and porosity are mostly very poor in nature over this hard-crystalline rocky terrain. Consequently, this kind of impervious crystalline rocks is the major obstruction to the proper aquifer development. Roy (2014) and Das et al. (2018) reveal that deep weathered mantle and shallow fractures in the bedrocks with the unconfined or semi-confined condition may generate available groundwater beneath the surface. Although some deep fractures about 50–60 m under the ground are observed (Das et al. 2018), there are certain limits of fractures development and

Fig. 1 Location of the study area (Purulia district)

well-developed weathered mantle (Dolui et al. 2016, 2018) due to the existent geo-environmental setting of Purulia district. Therefore, the district is suffering severe water crisis for a long period. Purulia is the most backward district of West Bengal regarding socio-economic development and water scarcity is one of the significant and responsible issues. The surface drainage systems and available water bodies in this district are completely depend on atmospheric rainfall and as a result, all types of sources of surface water dries up during the dry summer. Therefore, the uses of water in domestic, irrigation and other necessary purposes are mostly depending on groundwater. So, groundwater as a significant resource for the local people's daily life of this district is to be delineated and managed with proper evaluation and planning.

3 Materials and Methods

Recently several methods such as hydro-geological, geophysical and remote sensing and geographical information system have been applied to determine the groundwater potential zone (Selvam et al. 2016; Sharma and Baranwal 2005; Chowdhury et al. 2010; Adhikary et al. 2015). The occurrence and movement of groundwater in a particular area is affected by many determinants, including landscape, geology, rock structures and extent of fractures, depth of weathering, primary and secondary porosity, slope, drainage patterns, existent geomorphological features and landforms, land use/land cover, and climate (Mukherjee. 1996; Jaiswal et al. 2003; Jha et al. 2007; Machiwal et al. 2011; Kumar et al. 2014; Senanayake et al. 2016; Maity and Mandal. 2017; Singh et al. 2019). Therefore, multi-criteria based decision-making approach (MCDA) using remote sensing and GIS is a significant method for delineating groundwater potential zones.

3.1 Generation of Thematic Maps

In order to delineate the groundwater potential zones in Purulia district, seven thematic maps, viz., geology geomorphology, slope, soil texture, lineament density, drainage density, and land use and land cover (LULC) were generated by using conventional information and remote sensing data by employing the GIS software (ArcGIS). Out of these thematic layers, the slope and stream density maps were prepared from Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER) data, while the remaining maps were prepared using collected secondary data like geology, geomorphology, lineament density and soil texture. The detail database is provided in Table 1.

3.2 MCDA Based Weight Assignment Modeling

Based on the understanding of hydro-geological importance of the selected parameters for the occurrence of groundwater in Purulia district, suitable weights have assigned against the seven thematic layers and their individual sub-class attribute. These weights were assigned employing the weighted overlay method which is a technique of multi-criteria decision-making approach (MCDA) using the spatial analysis tool in ArcGIS. During exercising the weighted overlay, the rank has been assigned for every individual sub-parameters of each thematic map according to the multi influencing character. Interrelationship between these aspects and their consequence over each other's is shown in Fig. 2. The representative weight of a factor of the possible zone is the summation of all weights as of every one factor. The factor with a higher weightage value indicates a greater impact on the other hand a factor with

Table 1 Details of data used in groundwater potential analysis

Data	Sources	Type	Purpose
Digital elevation data	Earth Explorer—USGS https://earthexplorer.usgs.gov	Satellite-borne sensor ASTER	Slope mapping
Land-use data	https://landsat.usgs.gov	LANDSAT 8 OLI	Landuse mapping
Geology	Geological Survey of India https://www.portal.gsi.gov.in	Reference type	Geological mapping
Soil texture	N.B.S.S. and L.U.P. https://www.nbsslup.in	Reference type	Soil texture mapping
Drainage network	https://earthexplorer.usgs.gov http://www.surveyofindia.gov.in https://earth.google.com	GDEM, SOI Top sheets and Google image	Drainage density mapping
Lineament	Geological Survey of India https://www.portal.gsi.gov.in	Reference type	Lineament density mapping
Geomorphology	N.B.S.S. and L.U.P. https://www.nbsslup.in	Reference type	Geomorphological mapping

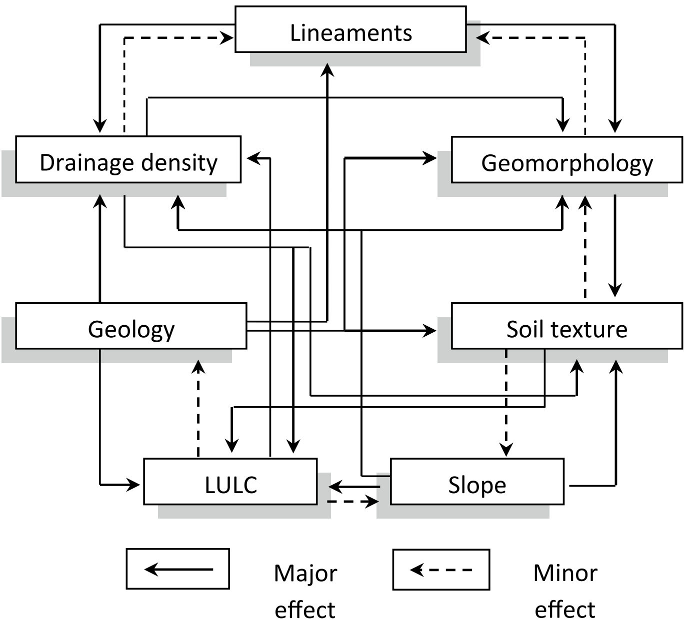

Fig. 2 Interrelationship between the factors influencing the occurrence of groundwater (modified after Magesh et al. 2012)

a lower weight age value indicates minimum effect on potential groundwater zones. Based on major and minor effects, the total weightage of the individual features has estimated using the formula given below adopted from Magesh et al. (2012).

$$W_i = \left[\frac{(A+B)}{\sum(A+B)}\right] \times 100 \tag{1}$$

where, (W_i) is the total proposed weightage score of each factor, A is the major effects and B is the minor effects of the factors on groundwater potentiality.

The Thematic layers of the certain attributes have incorporated in the GIS environment for making groundwater potential index (GWPI). The GWPI has been estimated by the weighted linear combination method of Malczewski (1999) given as given:

$$\mathrm{GWPI} = \sum_{w=1}^{m}\sum_{i=1}^{n}(\mathrm{W_i} \times \mathrm{R_i}) \tag{2}$$

where, (m) is the entire number of parameters, (n) is the total number of sub-classes in each parameter, $(\mathrm{W_i})$ represents map weight, $(\mathrm{R_i})$ represents the ranking for each map layer and GWPI is the Ground Water Potential Index. The entire methodology is presented in a flowchart given as follows (Fig. 3).

The individual class weight $(\mathrm{W_i})$ is multiplied by its own class rank $(\mathrm{R_i})$. After that, all the thematic maps were transformed into raster layout and reclassified according to individual preference $(\mathrm{R_i})$, collectively in a linear combination equation in GIS raster calculator in ArcMap. The equation used to investigate the ground water potential zones as:

$$\begin{aligned}\mathrm{GWPI} = \sum\Big\{&\big(\mathrm{W_{Geomorphology}} \times \mathrm{R_{Geomorphology}}\big) + \big(\mathrm{W_{Geology}} \times \mathrm{R_{Geology}}\big)\\ &+ (\mathrm{W_{Soil}} \times \mathrm{R_{Soil}}) + \big(\mathrm{W_{Lineament\ density}} \times \mathrm{R_{Lineament\ density}}\big)\\ &+ \big(\mathrm{W_{Drainage\ density}} \times \mathrm{R_{Drainage\ density}}\big) + \big(\mathrm{W_{Slope}} \times \mathrm{R_{Slope}}\big)\\ &+(\mathrm{W_{Landuse}} \times \mathrm{R_{Landuse}})\Big\}\end{aligned} \tag{3}$$

4 Results and Discussion

4.1 Weightage Overlay Analysis

The multiple factors which influence the potentiality of ground water are namely lithology, lineaments, geomorphology, drainage, soil, slope, and land-use. These factors were inspected and a proper weight has been assigned and is revealed in Table 2. The selected factors and their direct and indirect effects may contribute to demarcate the groundwater potential zones of the studied district. However, these

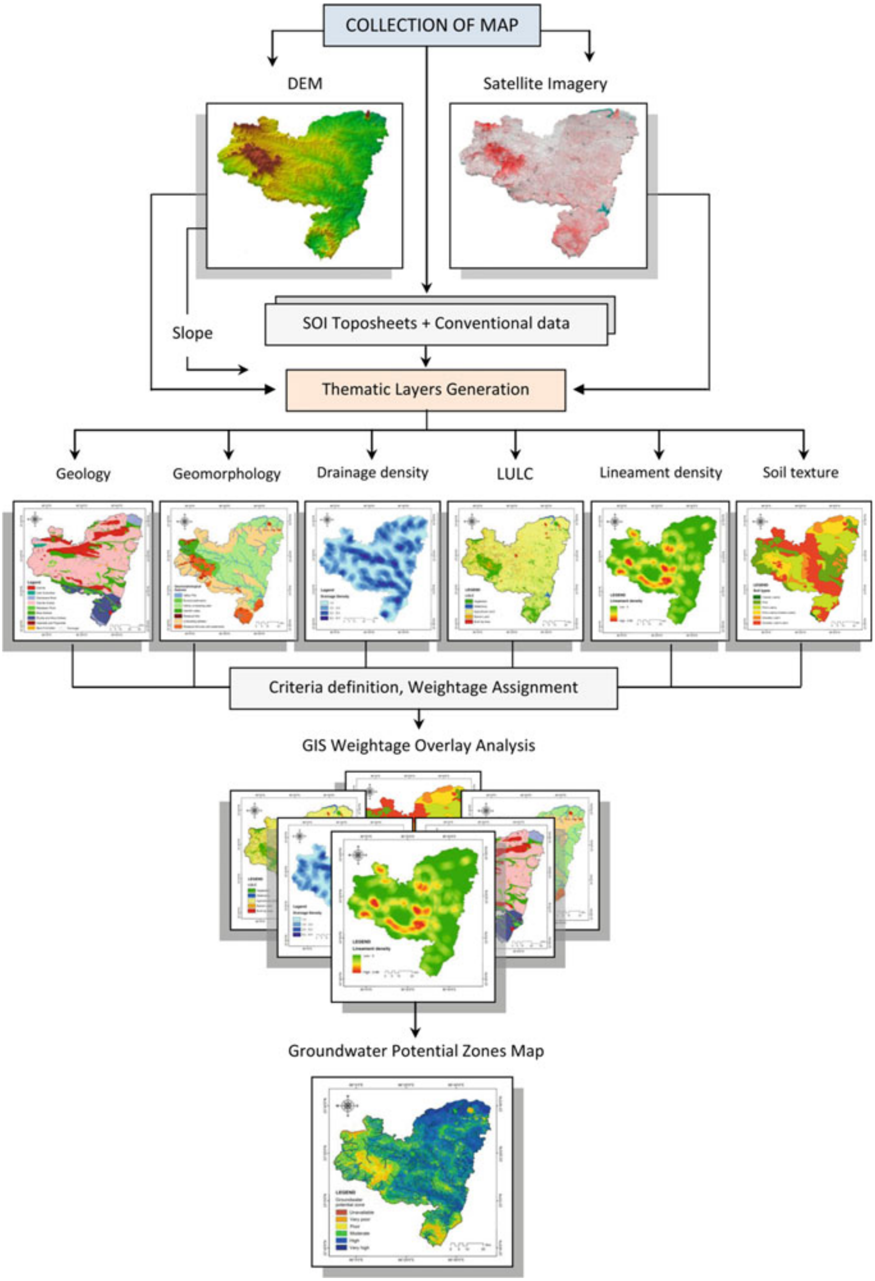

Fig. 3 Methodological flowchart of mapping groundwater potential zones

Table 2 Effect of controlling factors, relative rates and total weightage for each potential factor

Factors	Major effects (A)	Minor effects (B)	Proposed relative rate (A + B)	Proposed score of each controlling factor (W_i)
Geomorphology	1	0.5	1.5	9
Geology	1 + 1 + 1 + 1	0	4	24
Soil texture	1	0.5 + 0.5	2	11
Lineaments	1 + 1	0	2	12
Drainage density	1 + 1	0.5	2.5	15
Slope	1 + 1 + 1	0	3	18
LULC	1	0.5 + 0.5	2	11
			$\sum$ 17	$\sum$ 100

physical factors are mostly interdependent with each other. According to Magesh et al. (2012) the major and minor effects of these parameters (Fig. 2) were assigned a weightage of 1.0 and 0.5 respectively. Those respective weightages of minor and major effects were combined for estimating the total weightage score of individual controlling factors based on the Eq. 1. The resultant total weightage score (Table 2) of each influencing factor was further used to demarcate the rank of each sub-classes of the selected parameters.

4.2 *Evaluation of Physical Factors Controlling Groundwater Occurrence*

4.2.1 Slope

Slope is the most significant factors which controls the surface runoff and the rate of infiltration from surface to subsurface. Basically, steep slope has greater rate of surface runoff whereas, gentle slope to plain surface has significantly lower rate of surface runoff. Consequently, gentle slope may provide more times than steep slope to infiltrate the water into the subsurface zone. In Purulia district, the surface elevation broadly ranges from 150 to 300 m (Das et al. 2018) and undulating topography including some dissected and scattered residual hills are located in the major part of the district. Slope map was prepared using SRTM DEM data in GIS environment. The result shows that the decline of slope is basically from west to east direction. In the western part, Ajodhya hills and dissected hills of Jhalida are main elevated landforms which influenced the inclination of topography of this region. Normally, slope ranges from 2° to 5° in the major part of the central and eastern areas of the district. The steep slope is observed in the western and southern hilly regions of the district (Fig. 4). This hilly tract and associate elevated topography is the significant

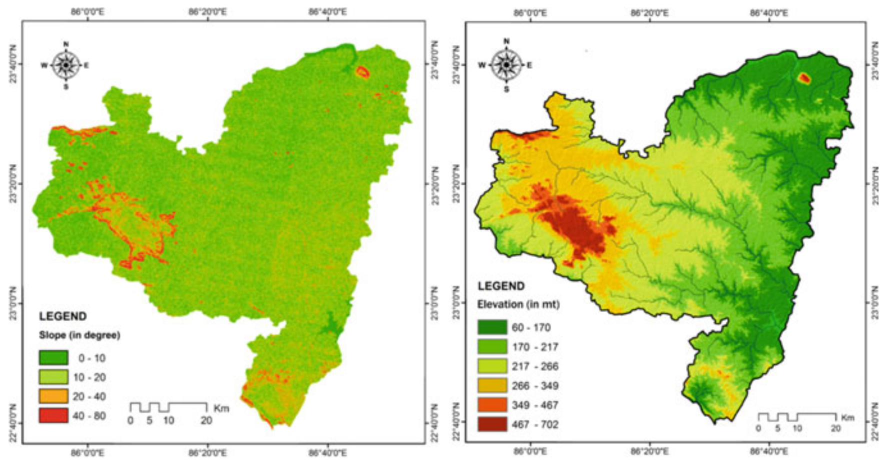

Fig. 4 Slope and elevation of Purulia district

hindrance to groundwater recharge on the other hand surface with gentle slope is favourable.

4.2.2 Geology

Regionally Purulia district is a part of Chota Nagpur Gneissic Complex of eastern Indian peninsula, covering to the north of Singhbhum craton. Purulia district habitually associates with intrusive granite and granitic gneiss rocks including meta-sediments of Precambrian age (Dolui et al. 2016). A deep stratigraphic sequence of predominantly Archaean granitic gneiss is exhibit in Purulia district (Geological Survey of India 2001).Various types of rocks and minerals like Pre-cambrian massive granites and quartzite, gneiss, phyllite, mica-schist, Permo-carboniferous sandstone shale, china clay and some recent alluvium sediments deposition are present in the district (Fig. 5a). These geological formations have significant controls over the groundwater potentiality. A detail of the significant rock formation and their location has provided in Table 3. Areas with hard rocky terrain are obstacle to subsurface infiltration, but the areas with highly fractured and/or weathered creates available surface for underground percolation. Along the courses of the channels a stripe of alluvium sediments deposition is occurred which may be a good groundwater potential zone.

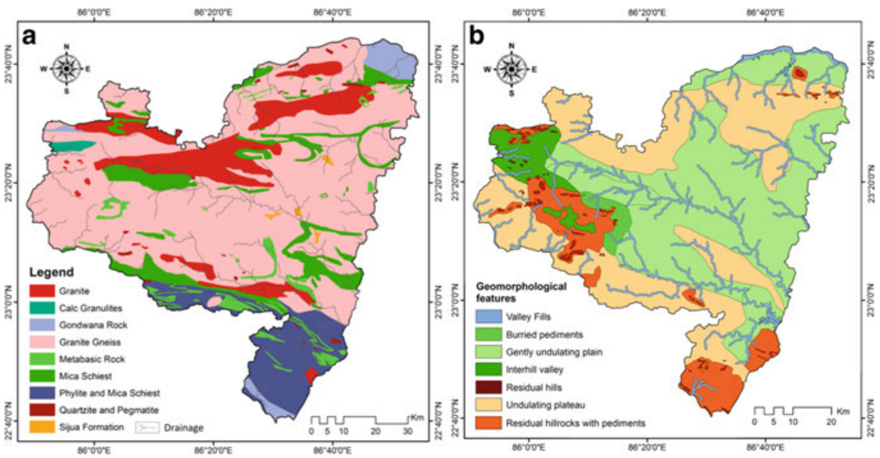

Fig. 5 Physical features of Purulia district: **a** geological formation and **b** major geomorphological features

Table 3 Distribution of significant rock formation in Purulia district

Sl. No.	Major geological formation	Areal coverage (km^2)	Areal coverage (in %)	Location in Purulia district
1	Intrusive granite	844.34	13.49	Mostly northern and western part
2	Granitic gneiss	4032.67	64.43	Throughout the whole district
3	Phyllite and Mica-schist	950.12	15.18	Mostly in southern part and in some patches over the north-western part
4	Metamorphic rocks	301.06	4.81	Scattered in the southern and eastern part
5	Gondwana sedimentary rocks	130.81	2.09	North-eastern part in a small extent

Source Das et al. (2018)

4.2.3 Geomorphology

Geomorphology illustrates the various types of landform and topographical features of an area. Thus, it is one of the essential criteria to demarcate the groundwater potential zone. Surface water as a geomorphological agent acts on the shaping and development of landscape and associate landforms and consequently different geomorphic features are developed in a particular region. In various geomorphic features the rate of infiltration and resultant groundwater availability is different. As Purulia district is a part of the south eastern Choto Nagpur plateau, the nature of terrain and its geomorphic characteristics signifies that except hilly areas the district has general height ranges between 200 and 300 m. Besides these, over the undulating and rolling topography, the monadnocks with rocky out crops are common morphological features (Mukhopadhyay 1980). The sub-aerial and pedological processes have enormous influence on distinctive landforms and types of soil and their distribution (Banerjee 1983). Landform pattern thus matched with particular soil pattern. The major geomorphic unites are plain and sprinkled with residual hills, hillocks, dome shaped mounds, dissected valleys etc. The entire frontal south, west and north section are covered with residual hillock and undulating plateau (Fig. 5b). However, middle and eastern parts of the district covered with gently undulating plain, buried pediments and valley fills which influences the subsurface water percolation and potential zone of groundwater.

4.2.4 Lineament Density

Lineaments are structurally inhibited linear or curvy linear features, which are basically recognized from the satellite images based on their reasonably linear alignments (Prasad et al. 2008). Lineaments illustrate the underground structural characteristics over the surface topography. Mainly, lineaments form in the tensional faulting and fracturing zones and its improved inferior porosity and permeability. Consequently, those areas are hydro-geologically extremely significant for groundwater recharge as it provides pathways of surface water infiltration. In this study, lineament density was calculated by the equation of Greenbaum (1985) and total length of the lineaments was extracted from the hydro-geological map of Geological Survey of India.

$$L_d = \left(\sum_{i=1}^{i=n} L_i \right) / A$$

where, $(\sum_{i=1}^{i=n} L_i)$ designates the overall length of lineaments, and 'A' designates the unit area. A high value of lineament density (L_d) indicates high-intensity secondary porosity; in consequence demarcate the areas of high potential groundwater recharge. The result shows that more than 0.4 km/km^2 lineament density are occurred in central and western parts while moderate density (0.15–0.4 km/km^2) is observed as fragmented patches throughout the studied district (Fig. 6). Very poor lineament density (<0.15 km/km^2) is observed in the majority of the areas which may be indicate the poor groundwater recharge potentiality (Haridas et al. 1998).

4.2.5 Drainage Density

The proximity of spacing between stream channels is defined as drainage density. Basically, it's a ratio between total lengths of the streams of different orders with

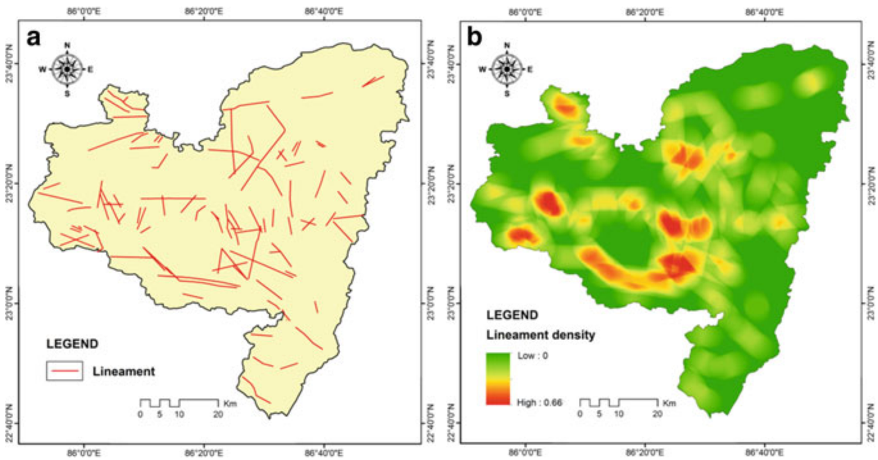

Fig. 6 Geophysical characteristics of Purulia district: **a** occurrences of lineaments and **b** lineament density

unit area (Greenbaum 1985).

$$D_d = \left(\sum_{i=1}^{i=n} S_i\right)/A$$

where, $(\sum_{i=1}^{i=n} S_i)$ indicates the total length of drainage. The (D_d) is drainage density which considerably correlated to the groundwater recharge.

The drainage density is normally controlled by the rock types; this influences the permeability and the rate of infiltration of particular areas. The slope of the surface topography also has direct and positive relation with drainage density as it increases the velocity of surface runoff and reduces the degree of subsurface infiltration. Therefore, drainage system of any area helps in identifying the areas which has a higher intensity of groundwater recharge. As a result, steep slope with low permeability can be developed higher drainage density, thus poor infiltration with higher surface runoff which is occurred in the western part of the district. The 'line density analysis tool' in ArcGIS has used to delineate the drainage density map of the area. The drainage density of the Purulia district is classified into five categories and assigned the quality in terms of the probability of groundwater availability, i.e. 'very good' (0.00–1.00 km/km^2), 'good' (1.00–1.20 km/km^2), 'moderate' (1.20–1.40 km/km^2), 'poor' (1.40–1.60 km/km^2) and 'very poor' (>1.60 km/km^2). High drainage density (2.02 km/km^2) is observed in the western hilly parts near Ajodhya hills (Fig. 7a).

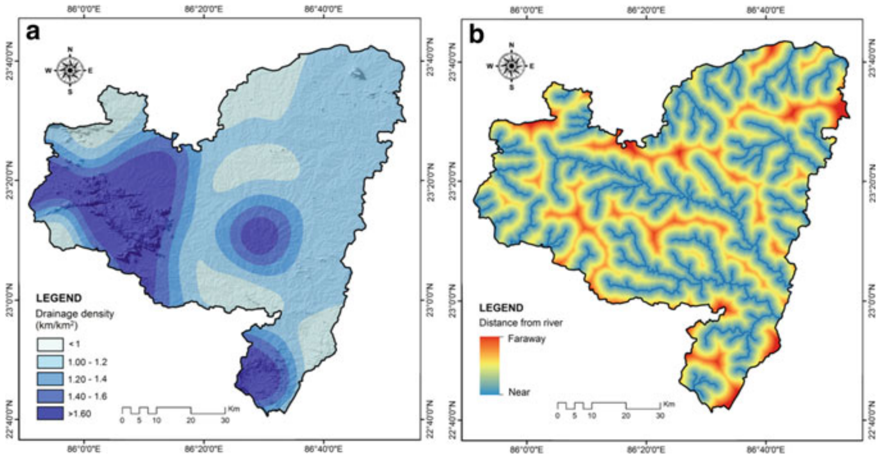

Fig. 7 Drainage characteristics of Purulia district: **a** drainage density and **b** distance from rivers

4.2.6 Soil Texture

Potential infiltration of rainfall is highly depends on the soil texture which is also influenced directly the nature of porosity and permeability. Normally, fine-grained soil has comparably low infiltration rate than coarse-grained soil because of difference in porosity. In the entire district, hard granite and gneiss rocks in bedrocks may interrupt to develop thick soil layers over the surface. Therefore, coarse and gravelly loamy soils are highly dominant in Purulia district (Fig. 8a). The granitoid bedrocks help to develop the acidic soil with low fertility (National Bureau of Soil

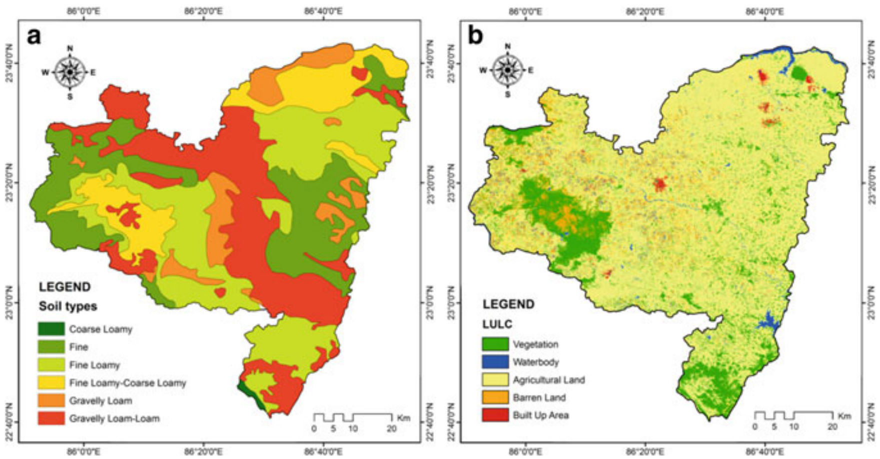

Fig. 8 **a** Pattern of soil texture and **b** Land use land cover in the study area

Survey and Land Use Planning 2010). Besides there, the lithological variation can help to develop a variety of soil types in the district. Dominant gravelly-loam and coarse-loamy soil constitutes about 28.11% (1759.4 km^2) and 12.45% (779.25 km^2) areas of western and central segments of the district respectively. On the other hand, scattered fine and fine-loamy soil covers about 21.47% (1343.81 km^2) and 29.59% (1852.04 km^2) areas of the district respectively.

4.2.7 Landuse Landcover (LULC)

Land use and land cover is one of the essential factors, which control the occurrence of groundwater beneath the surface. Different land use types operate differently in the capability of infiltration of water from the surface. Normally, the areas with natural vegetation cover and agricultural activities are suitable for groundwater recharge with higher infiltration rate, whereas, the areas with built-up cover and fallow land enhance the run-off capability and act as hindrance for subsurface infiltration. The rivers and other water bodies of the plain and surface with gentle slope can increase the volume of groundwater but the monsoon dependent non-perennial nature of drainage may not be helpful for sufficient groundwater recharge in this area. Land use land cover map was prepared form Landsat 8 OLI satellite imagery using maximum likelihood classification algorithm to obtain five major land use classes. Most of the forest cover land is covered with deciduous type's natural vegetation. Having significant area under agriculture land, most of the land remains vacant over the years as the farming practice highly dependent on seasonal rainfall. Mostly disperse types of rural settlements with very fewer concentrated urban settlement are observed in Purulia district (Fig. 8b). Thus, open and barren lands in the central to western part are unfavourable for groundwater recharge as evapotranspiration process is highly active over this area.

4.3 Delineating the Groundwater Potential Zone

Based on multi-criteria decision-making approach the weightage has been assign to the selected parameters to recognize the priority and rank of the parameters and their associate sub-classes (Table 4). The potential groundwater zones of Purulia district has been derived by the integration of various thematic layers viz., slope, geology, geomorphology, lineament density, drainage, soil texture, and land-use/land cover using the Eqs. 2 and 3. The process has been carried out in ArcGIS through weightage overlay analysis tool. The resultant ground water potential map demonstrates the diverse nature of spatial variation of ground water distribution zone in the entire district and the results were reclassified in to six classes with groundwater potentiality from unavailable to very high potential zones (Fig. 9). Higher potentiality of groundwater is found in the valley fills and gently undulating plain where concentrations of lineament intersections are significantly dominant. Therefore central to the north

Table 4 Classification of thematic layers influencing the groundwater potential zones and their rank

Thematic layer	Weightage (W_i)	Class	Ground water potentiality	Rank (R_i)
Geomorphology	9	Burried Pediments	Moderate to poor	1
		Gently Undulating Plain	Very good	2
		Interhill Valley	Moderate to poor	0.5
		Residual hillrock with pediments	Moderate to poor	0.5
		Undulating Plateau	Moderate	2
		Valley fills	Very good	2.5
		Residual hills	Very poor	0.5
Geology	24	Calc Granulites	Very poor	0.5
		Gondwana rocks	Very good	3
		Granite	Moderate to poor	1
		Granite Gneiss	Moderate	2.5
		Meta Volcanic	Very poor	0.5
		Metabassic	Good	3
		Mica schist	Very good	4
		Phylite mica schiest	Very good	4
		Quartzite	Moderate	2.5
		Sijun Formation	Good	3
Soil	11	Fine	Very poor	0.5
		Geravelly loam	Very good	3
		Fine loamy coarse loamy	Good	2.5
		Fine loamy	Moderate to poor	1
		Gravelly loam loam	Good	2.5
		Coarse loam	Moderate	1.5
Lineament density (km/km^2)	12	0–0.1	Good	5
		0.1–0.2	Moderate	4
		0.2–0.3	Moderate to poor	2
		0.3–0.68	Very poor	1
Drainage Density (km/km^2)	15	0.00–1.00	Very good	5
		0.10–1.20	Good	4

(continued)

Table 4 (continued)

Thematic layer	Weightage (W_i)	Class	Ground water potentiality	Rank (R_i)
		1.20–1.40	Moderate	3
		1.40–1.60	Very poor	2
		>1.60	poor	1
Slope (in degree)	18	0–10	Very good	8
		10–20	Good	5
		20–40	Moderate to poor	3
		40–80	Very poor	1
LULC	11	Agricultural Land	Good	3
		Barren Land	Moderate to poor	0.5
		Builtup area	Very poor	0.5
		Vegetation	Moderate	3
		Waterbody	Very good	4

and north-eastern segments are found to be very good potential zone, whereas, hard rock terrain with a steep slope and undulating surface in the western and southern parts shows a poor potentiality as there shallow depth of water level is indicating. The hilly tract of Ajodhya is the area of very poor potential zone as the region has a greater rate of surface runoff and insignificant capabilities of subsurface infiltration.

5 Conclusion

Rapid reducing nature of groundwater storage is the prime issue of monsoonal countries such as India because of the increasing demand of water in multipurpose activities which are mostly depend on groundwater. Increasing population pressure creates demand for their domestic uses and the irrigation practices are completely depends on groundwater. But uncertainty of rainfall, climatic variability affected the natural environmental processes including groundwater recharge. Purulia district has gone through an immense crisis of surface as well as underground water sources.

In this recent work, an integrated approach has been adopted to evaluate the potential groundwater zones using multi-criteria GIS technique. The final outcome of this study delineates the probable groundwater available zones of Purulia district. Classified groundwater potential zones show that 7.5 and 36.86% areas of Purulia district have very high and high potentiality in central and northern region of the district, respectively. Thus, it is clear that permeable geological setting beneath the gentle slope topography with supporting permeable soil texture, vegetative cover and lineament density helps to increase the availability of water under the surface.

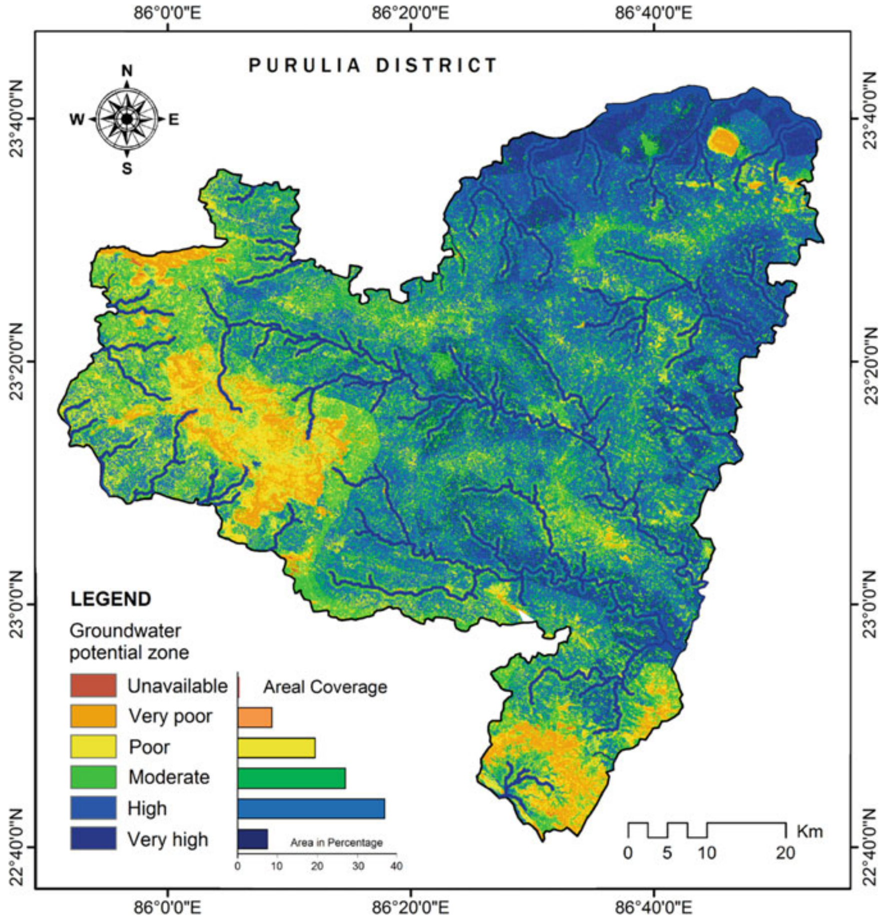

Fig. 9 Groundwater potential zones with percentage of coverage area of Purulia district

About 27% areas of the district have moderate potential groundwater zones, which are located, scattered in the entire district. On the other hand, about 19.54 and 8.56% areas are under poor to very poor condition in terms of potential groundwater and this result completely depend on impervious geological formation, high slope and associate higher drainage density. Very little amount of areas (0.43%) would have no available groundwater which are located in the hill tops. So, the western and extreme southern hilly tract of undulating plateau with intense surface runoff due to higher drainage density creates a strong obstruction for potential groundwater recharge. Depending on the result, this work can assist the concerned decision makers and planners to prepare an effective and successful plan intended for irrigation and other activities, sustainable water resource utilization and management for the people of Purulia district.

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Hydrogeochemical Characterization of Groundwater Using Conventional Graphical, Geospatial and Multivariate Statistical Techniques

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Abstract Groundwater from 25 bore wells of Nagari area were obtained and assessed for physico-chemical characteristics and the major ion concentrations in the pre-monsoon period of 2018. From the results it is found that groundwater has elevated levels of SO_4^{2-}(64%), Cl^-(24%), Ca^{2+} (28%) and Na^+ (3%) which are unsuitable for drinking purposes. The spatial distribution diagrams show that the ions were highly concentrated in both NE and Eastern directions. Cluster analysis in Q-mode results four clusters which are fresh, nearly fresh to brackish, moderately brackish and brackish in nature, while the R-mode cluster analysis shows that weathering of silicates, chloride and sulphate minerals which are caused by agricultural fertilizers, sewage and industrial discharge are the main factors regulating groundwater chemistry in the study area. Factor analysis results three factors, in which Factor 1 is a hardness-controlled factor, factor 2 is an unaffected and low mineralised factor and factor 3 shows high mineralisation due to the impact of each and every ion in groundwater. In accordance with the WHO standards, 52% well samples are unfit for drinking purposes. Parameters such as the sodium percent (%Na), sodium adsorption ratio (SAR), Kelly's ratio (KR), magnesium ratio (MR) and permeability Index (PI) show that 22 well samples (88%) are satisfactory for irrigation uses with exceptions such as KR (2 samples) and MR (1 sample). A total of 15 well samples (60%) are suitable for irrigation when USSL and Wilcox classifications are considered. Bivariate plots show that weathering of silicates is the major governing mechanism of groundwater hydrochemistry. The Indices of base exchange (IBE-I and IBE-II) reveal that the reverse ion exchange prevails in groundwater of investigated region.

Keywords Bivariate plots · Indices of base ion exchange · Geospatial and multivariate statistical techniques · Groundwater · MINITAB · Nagari

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1 Introduction

In a hard rock terrain, groundwater is the major resource that can be used for drinking and irrigation practices. Generally, groundwater in a crystalline rock formation is a finite resource which is influenced by geological processes such as weathering and fracturing. Generally, groundwater quality is controlled by rainfall proportion, recharge water quality, surface water accessibility, hydrogeochemical processes occurring between groundwater and aquifer system and human induced activities such as unplanned irrigation, mining, and water resource management (Domenico 1972; Schuh et al. 1997; Grag et al. 2009; Singh and Kumar 2010; Venkateswaran and Vediappan 2013; Nagaraju et al. 2015; Balaji et al. 2018, 2019a). In addition, the recharge and revival of groundwater plays a crucial task, especially in dry lands owing to lack of surface water resources apart from rivers (Tizro and Voudouris 2008). Recently, the groundwater consumption has risen rapidly as a result of growing population, agricultural, mining and industrial activities. Consequently, water bodies have been polluting at a high rate. Groundwater has a certain amount of dissolved solvents in it which is primarily regulated by the nature of recharge water, underlying lithology and the time of water in contact with aquifer material. Excess dissolved ions in groundwater may adversely affect the quality of water for drinking and irrigation. The hydrogeochemical investigation is explicitly helpful in evaluating, protecting and managing water resources in terms of identifying the mechanisms that changes groundwater chemistry, and in assessing the quality of water for potable and agricultural purposes. Hence, proper knowledge of hydrogeochemical processes is essential for sustainable utilization of water resources (Sappa et al. 2013). The spatial interpolation tool in GIS acts as a powerful tool in pollution mapping. Hence it is used in this study to identify the pollution hot spots in a glance which helps in managing sustainable utilization of water resources of Nagari.

Earlier, many workers focused on the water quality evaluation for drinking and irrigation uses as it helps to manage water resources effectively (Adhikary et al. 2012; Srinivasa Reddy 2013; Nag and Das 2014; Nagaraju et al. 2015; Balaji et al. 2016; Nagarju et al. 2017; Balaji et al. 2018; Adimalla and Qian 2019; Adimalla et al. 2020). Multivariate statistical methods are comprehensive data reduction strategies that help to handle and distinguish the complex hydrogeochemical data sets by pointing out a major interrelation among them. And also helps in utilizing of water resources in a efficient manner, as well as in finding realistic solutions to the problem of pollution. Multivariate statistical techniques have been employed in this study to have proper knowledge of hydrogeochemistry dealing with large data sets. Many workers have worked in dealing multivariate statistical techniques in groundwater studies (Noshadi and Ghafourian 2016; Islam et al. 2017; Boufekane and Saighi 2018; Balaji et al. 2019b; Etikala et al. 2020).

Hence, the hydrochemical analysis and the multivariate statistical techniques were performed in this study to know water quality evaluation for potable and agricultural uses and to interpret the complex hydrogeochemical data sets in a comprehensive manner.

2 Study Area

The Nagari falls between 13°15′ and 13°24′ North latitudes and 79°32′ and 79°39′ East longitudes of Chittoor District, Andhra Pradesh, India (Fig. 1). The extent of Nagari is 151.06 km^2 and the mean elevation is 115 m above the mean sea level. The annual precipitation is about 1031 mm. Geologically, Nagari area is covered by Archaean age granites and gneisses, Proterozoic age quartzites and basic intrusives and Recent alluvium along the main streams. A River named "Nagari" is passing in the middle of the study area. The piezometric levels vary from 5 to 15 m below ground level. The shallow fractured zones encountered at a depth of 16 m below ground level which discharges trace amounts of water and the deep fractured zones encountered from 115 to 116 m below ground level which yields a good amount of water (CGWB 2013).

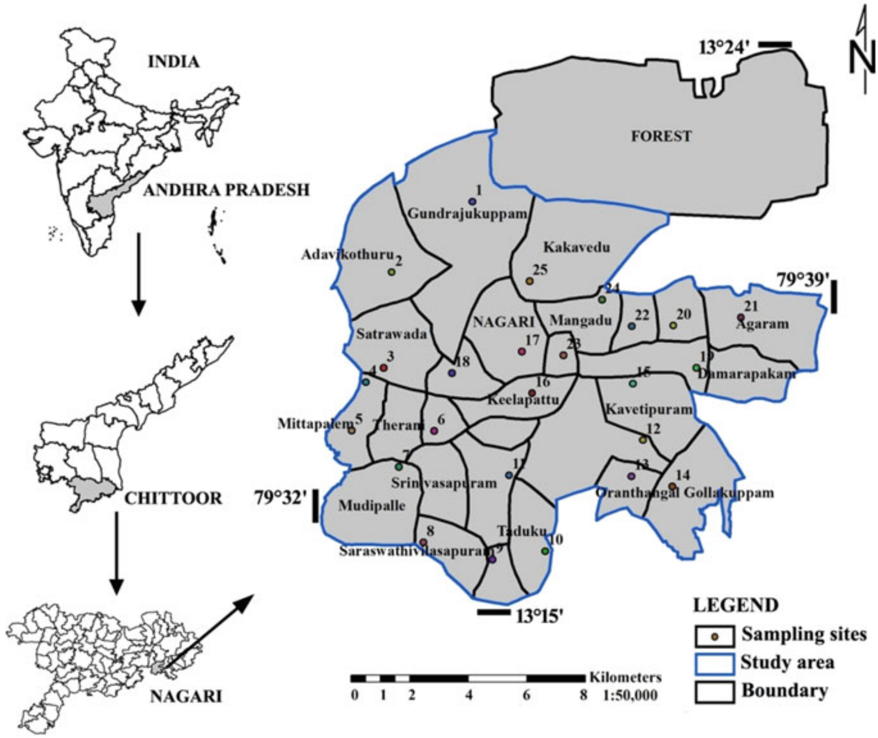


Fig. 1 Location map of the study area with bore well points

3 Materials and Methods

Groundwater from 25 existing regularly used bore wells were collected in a pre-sterilized polythene bottles and assessed for pH, EC and major ions in the laboratory using established standard practices (APHA 2012). The spatial distribution diagrams were generated by inverse distance weighted (IDW) interpolation in Arc GIS 10.1. Based on the analysed data, the irrigation suitability of groundwater was evaluated. The formulas for calculation are given below

$$SAR = Na^{+}/\left(Ca^{2+} + Mg^{2+}\right)/2 \quad (1)$$

$$\%Na = 100 \times \left(Na^{+} + K^{+}\right)/\left(Ca^{2+} + Mg^{2+} + Na^{+} + K^{+}\right) \quad (2)$$

$$Kelly's\,ratio = Na^{+}/\left(Ca^{2+} + Mg^{2+}\right) \quad (3)$$

$$PI = 100 \times (Na^{+} + \surd HCO_{3}^{-}/(Ca^{2+} + Mg^{2+} + Na^{+})) \quad (4)$$

$$MR = 100 \times \left(Mg^{2+}/\left(Ca^{2+} + Mg^{2+}\right)\right) \quad (5)$$

(Here, all ion values were shown in meq/L).

Then the data was executed to statistical analysis in MINITAB 18 interface to know the principal regulating factors of chemistry of groundwater. The summary statistics of the hydrochemical studies are shown in Table 1.

4 Results and Discussion

4.1 Hydrochemical Facies

The study of hydrochemical facies is to know the chemical nature of water that is linked to aquifers lithological and hydrological behaviour. Chadha (1999) proposed a new classification system which can be plotted by taking the meq/L values of (Ca^{2+} + Mg^{2+}) and (Na^{+} + K^{+}) on X-axis and the meq/L values of ($CO_3{}^{2-}$ + $HCO_3{}^{-}$) and (Cl^{-} + $SO_4{}^{2-}$) on Y-axis in one of the four possible subfields. The study revealed that the chief facies were Ca–Mg–Cl followed by (Ca–Mg) > (Na–K) and (Cl–SO_4) > (HCO_3) water types respectively (Fig. 2).

Table 1 Summary statistics of various components in groundwater and their suitability for drinking and irrigation use in accordance with guidelines

S. No	Constituents	Min	Max	Average	PL[a]	SEPL[b]
1	Calcium (Ca^{2+}) (mg/l)	104	366	195	200	7
2	Magnesium (Mg^{2+}) (mg/l)	11	117	35	150	0
3	Sodium (Na^{+}) (mg/l)	83	301	123	200	3
4	Potassium (K^{+}) (mg/l)	3	15	8	N.G[c]	0
5	Bicarbonate (HCO_3^{-}) (mg/l)	92	1043	405	N.G	–
6	Sulphate (SO_4^{2-}) (mg/l)	163	582	333	250	16
7	Chloride (Cl^{-}) (mg/l)	124	348	197	250	4
8	Specific conductance (μmhos/cm)	650	3960	1922	1500	14
9	Total dissolved solids (TDS)	416	2534	1230	1000	14
10	Hardness	344	1054	634	500	17
11	Sodium adsorption ratio (SAR)	1.17	4.32	2.47	18–26	0
12	Percent sodium	15.12	49.89	32.49	40–60	0
13	Kelly's ratio	0.18	1.03	0.52	<1	2
14	Mg ratio	8.63	53.07	22.58	<50	1
15	Permeability index	27.35	65.57	46.18	–	0
16	pH	7.1	7.9	7.3	–	0
17	Chloro alkaline indices—I	−1.71	0.43	−0.21	–	–
18	Chloro alkaline indices—II	−0.32	0.31	−0.02	–	–

*[a]Permissible limits: [b]samples exceeding permissible limits: [c]no guideline
*According to WHO (2011), Wilcox (1948), Eaton (1950), Kelly (1951), Todd (1980), Doneen (1964), Paliwal (1972), Schoeller (1977) and Karanth (1987), respectively

4.2 Assessment of Water Quality for Drinking

In general, water quality is mostly influenced by the geochemical processes occurring within the aquifer and anthropogenic activities. The summary statistics and suitability categorisation of groundwater for potable uses based on WHO (2011) criteria were shown in Table 1. By comparing the analyzed parameters with the standards, 56% well samples are unfit for drinking owing to high salinity (>1500 μmhos/cm) and high total dissolved solids (>1000 ppm). The majority of the wells (68%) are hard in nature making water unfit for drinking. By comparing the ionic concentrations with standards, it is found that groundwater has elevated levels of SO_4^{2-}(64%), Cl^{-}(24%), Ca^{2+}(28%) and Na^{+}(3%) which is unsuitable for drinking purposes. The spatial distribution of physicochemical specifications and major ion concentrations was prepared by using the spatial interpolation module such as inverse distance weighted (IDW) in GIS. The result shows that the major ions were concentrated in NE and Eastern directions which make water unfit for drinking and irrigation practices. Continuous monitoring of water resources and the implementation of water

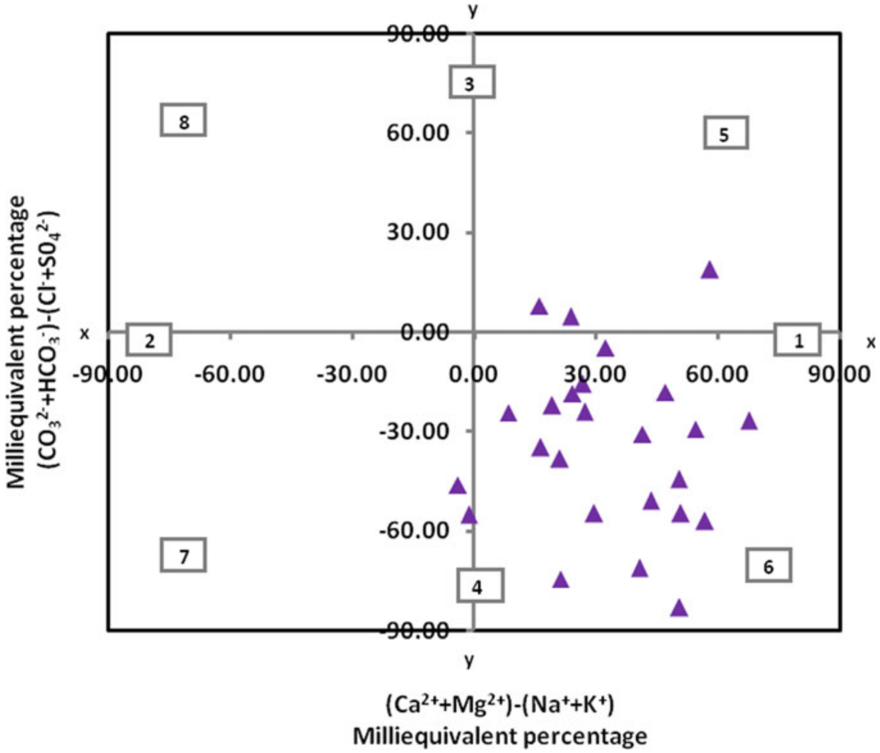


Fig. 2 Chadha's diagram showing the groundwater facies

quality protection policies is required for sustainable management in these regions (Fig. 3a–k).

4.3 Assessment of Water Quality for Irrigation

The statistics of ions were shown in Table 1. Moreover, USSL and Wilcox classifications have been used to classify groundwater to know the suitability for agricultural use.

4.3.1 USSL Classification

The USSL diagram shows the suitability of water for agricultural purpose and it can be framed by placing EC values on X-axis and SAR values on Y-axis. (Richards 1954). The result shows that the majority of the well samples (64%) fell in C3S1 segment which is permissible for irrigation use and can irrigate with certain semi-tolerant

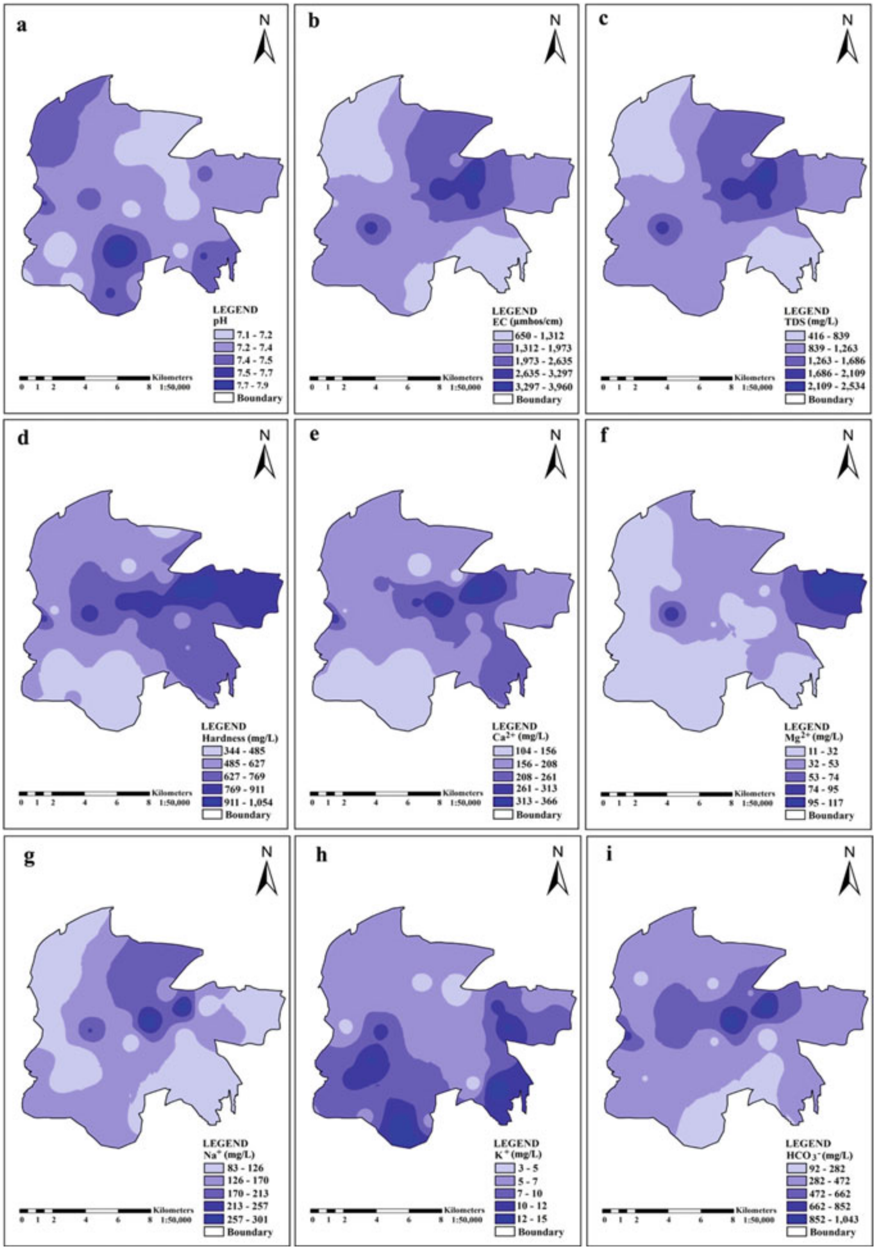
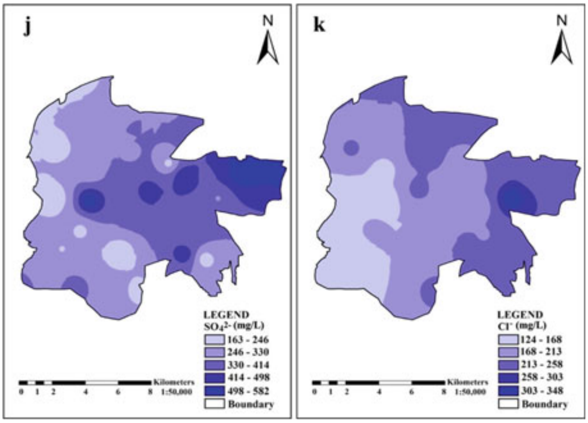


Fig. 3 **a**–**f** Spatial distribution of pH, EC, TDS, hardness, Ca^{2+} and Mg^{2+}. **g**–**k** spatial distribution of Na^{+}, K + , HCO_3^{-}, SO_4^{2-} and Cl^{-}

Fig. 3 (continued)



crops. The remaining samples fell in C4S2 segment (12%) and C4S1 segments (24%) which were not suitable for irrigation use (Fig. 4).

4.3.2 Wilcox Classification

Wilcox (1948) proposed a diagram which is adapted for the groundwater classification for irrigation use and it can be framed by taking EC values on X-axis and % Na on Y-axis. The result shows that the major (56%) groundwater samples fell in good to permissible category followed by excellent to good (4%), doubtful to unsuitable (28%) and unsuitable (12%) categories respectively (Fig. 5). In general, the crop yield is typically low where the lands harvested with water belong to doubtful and doubtful to unsuitable categories. This may be due to elevated sodium salts in the plant-soil system that affects the osmotic process.

4.4 Statistical Analyses

4.4.1 Cluster Analysis in Q-Mode

The Q-mode clustering has given four clusters (Fig. 6). Cluster 1 comprises the well numbers 1, 4, 9, 11 and 14 which are fresh in nature with TDS values (416–851 mg/l). The principal hydrochemical facies were Ca–Mg–Cl followed by Ca–Mg–HCO_3 and Na–Cl water types. Cluster 2 comprises the well numbers 2, 3, 5, 6, 7, 8, 10, 12, 13, 15, 16, 24 and 25 which are nearly fresh to brackish in nature with TDS values (736–1732 mg/l), the principal hydrochemical facies were Ca–Mg–Cl followed by Na–K and Cl–SO_4 water types. Cluster 3 comprises the well numbers 17, 18, 19, 20 and 21 which are moderately brackish in nature with TDS values (2900–3000), the chief hydrochemical facies are Ca–Mg–Cl type and the remaining two wells 22 and

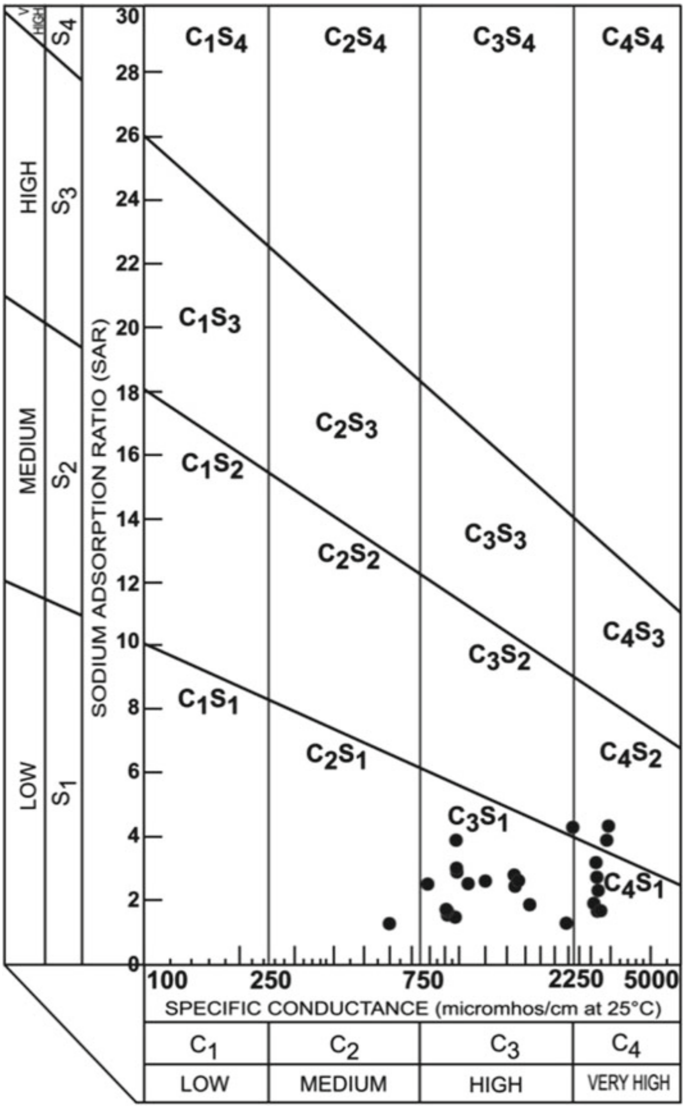


Fig. 4 Diagram shows the USSL classification (USSL 1954) for groundwater quality

23 forms cluster 4 which is brackish in nature (>3000) and highly polluted among the four clusters. The major water facies were Ca–Mg–HCO_3 type.

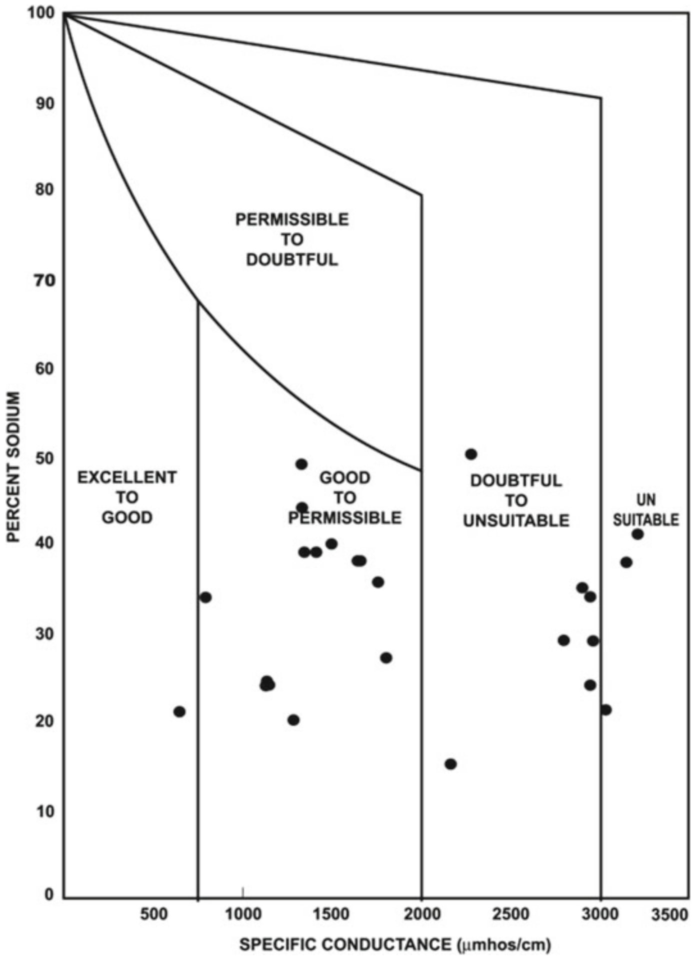


Fig. 5 Wilcox diagram (Wilcox 1951) to show the groundwater quality

4.4.2 Cluster Analysis in R-mode

The R-mode clustering results in three clusters (Fig. 7). Cluster 1 comprises of pH, K^+, and Cl^- which relates to disintegration of feldspars, mica minerals and weathering of Cl^- minerals in addition to agricultural fertilizers, sewage and discharge from industry (Rao et al. 2012). Cluster 2 comprises of EC, TDS, Mg^{2+}, SO_4^{2-} which are due to the relative impact of all ions in the groundwater in addition to magnesium sulphate rich fertilizers. Cluster 3 comprises of Ca^{2+}, hardness, Na^+ and HCO_3^- which represents the rock-water interaction in addition to hardness owing to the presence of Ca^{2+}, HCO_3^- ions in groundwater.

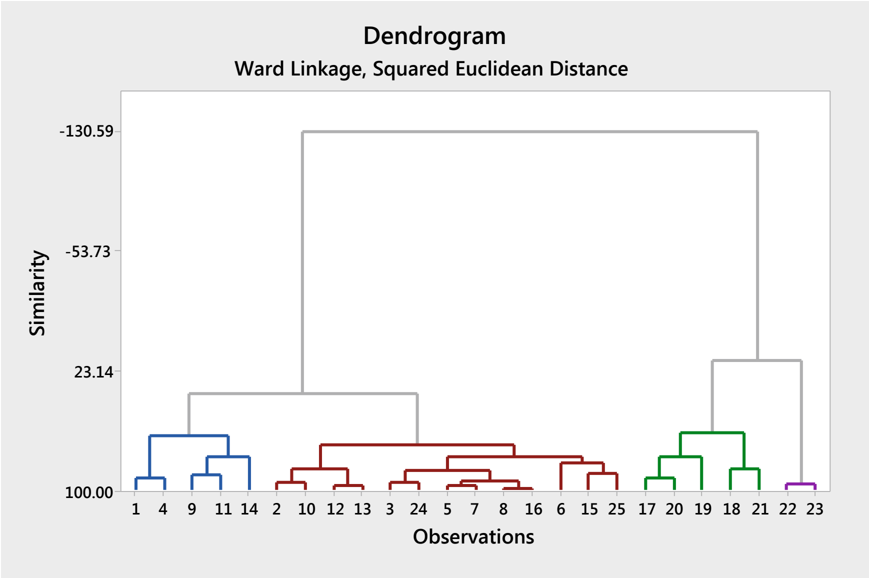


Fig. 6 Dendrogram of Q—mode cluster analysis

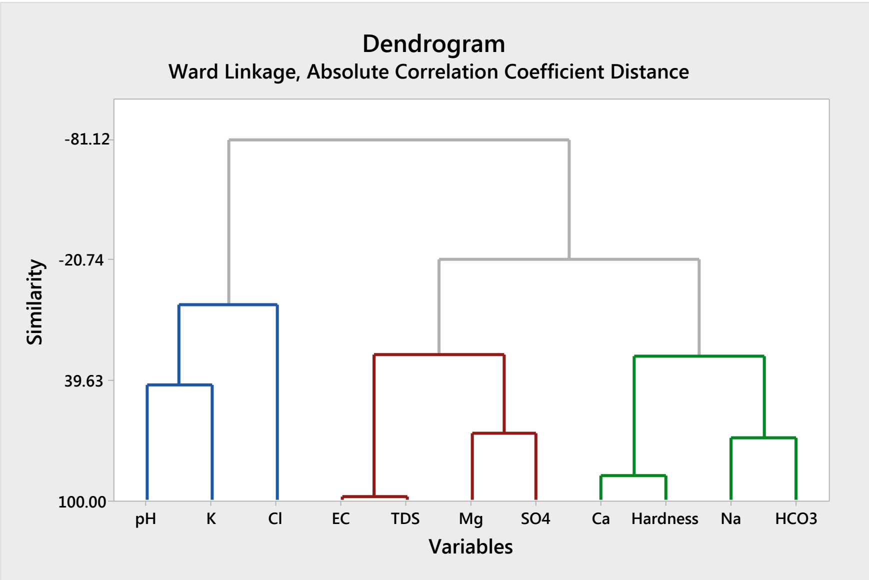


Fig. 7 Dendrogram of R-mode cluster analysis

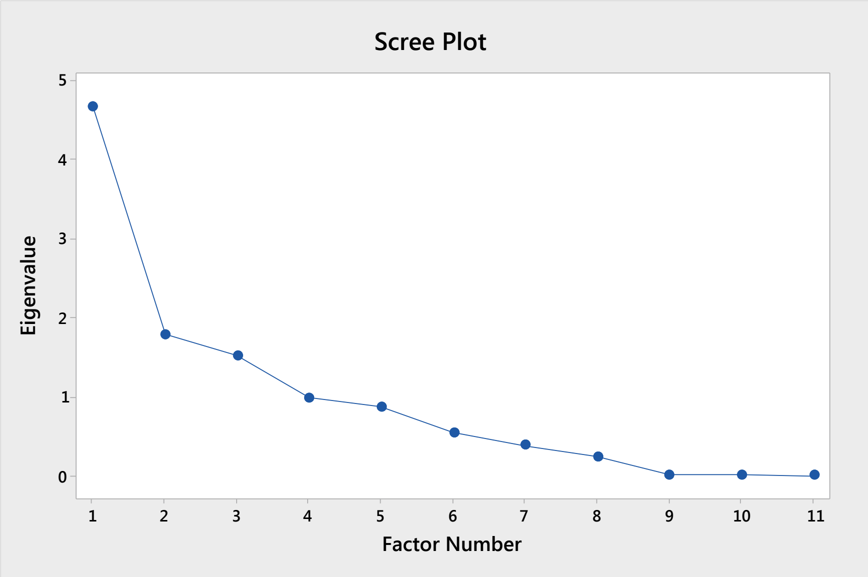


Fig. 8 Scree plot of Eigenvalue versus factor numbers

4.4.3 Factor Analysis

The factor analysis (varimax rotated) has given 11 factors, among those the first three factors with Eigenvalue >1 or equivalent to 1 are considered as they explain the variance in the data (Cattell 1966) (Fig. 8). Factor 1 shows high positive loadings with Ca^{2+}, HCO_3^- and hardness which is a hardness-controlled factor due to the combination of $Ca^{2+} + HCO_3^-$ in addition to dissolution of feldspar and carbonates. Factor 2 results in negative loadings with all variables which are unaffected and low mineralisation in groundwater. While factor 3 is positively loaded with EC and TDS which shows high mineralisation due to the influence of each and every ion in groundwater (Table 2).

4.5 Bivariate Plots

The normalized bivariate plots (Fig. 9) reveals that the entire groundwater samples fall under silicate-weathering zone which may be attributed to the influence of silicate minerals in the aquifer systems.

Table 2 Varimax rotation factor loading matrix with values of variance and % variance

Variable	Factor 1	Factor 2	Factor 3
pH	0.086	0.165	−0.017
EC	0.318	−0.873	0.224
TDS	0.251	−0.880	0.220
Ca	0.966	−0.186	−0.086
Mg	0.046	−0.241	0.955
Na	0.177	−0.322	0.008
K	−0.009	−0.046	−0.003
HCO3	0.731	−0.242	0.006
Cl	0.005	−0.084	0.105
SO4	0.285	−0.346	0.523
Hardness	0.853	−0.278	0.395
Variance	2.4806	2.0236	1.4583
% Var	0.226	0.184	0.133

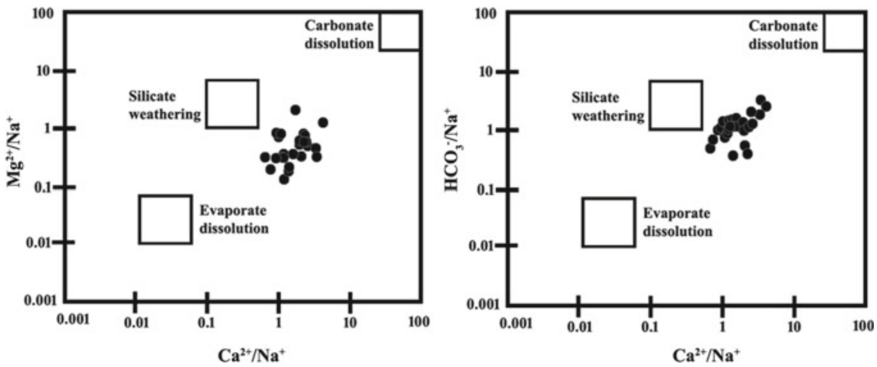


Fig. 9 Bivariate plots to show the groundwater ion chemistry

4.6 *Indices of Base Exchange*

Schoeller (1977) proposed a method to interpret the ion exchange mechanism in groundwater which is in contact with aquifer material during its time of travel and residence. The Indices of base exchange (both I & II) were determined using formulas given below.

$$\text{Indices of base exchange IBE} - \text{I} = \left(\text{Cl}^- - \left(\text{Na}^+ + \text{K}^+\right)\right)/\text{Cl}^-$$

$$\text{Indices of base exchange IBE} - \text{II} = (\text{Cl}^- - \left(\text{Na}^+ + \text{K}^+\right)/\left(\text{SO}_4^{2-} + \text{HCO}_3^- + \text{CO}_3^{2-} + \text{NO}_3^{2-}\right)$$

If the IBE is negative, ion exchange is in between ($Na^+ + K^+$)with ($Ca^{2+} + Mg^{2+}$), whereas the ratio is positive, the reverse ion exchange takes place. From the results, about 57% of well samples shows reverse type of ion exchange.

4.7 Conclusions

Based on the comparison with the water quality standards, the majority of the wells (68%) are hard in nature with high amounts of SO_4^{2-}(64%), Cl^-(24%), Ca^{2+}(28%) and Na^+(3%) in groundwater making water unfit for drinking purposes. According to the parameters like %Na, SAR, KR, MR and PI a total of 22 well samples (88%) are suitable for irrigation use with few exceptions such as Kelly's ratio (2 samples) and magnesium ratio (1 sample). While considering USSL and Wilcox classifications a total of 15 well samples (60%) are suitable for irrigation use. The chief hydrochemical facies were Ca–Mg–Cl followed (Ca–Mg) > (Na–K) and (Cl–SO_4) > (HCO_3) water types respectively. The spatial distribution diagrams reveal that the ions were highly concentrated in NE and Eastern directions. The multivariate statistical techniques such as Q-mode cluster has given four types of groundwater namely fresh, nearly fresh to brackish, moderately brackish and brackish. The R-mode cluster has given three regulating factors for hydrogeochemistry such as silicate weathering, influence of major ions and the dissolution of chlorides and sulphates due to fertilizers, sewage and industrial seepages. Whereas the factor analysis has given three possible sources of hydrogeochemistry, they are of hardness-controlled factor, unaffected and low mineralised factor and high mineralisation factor due to the influence of each and every ion in groundwater. Moreover, the bivariate plots show that silicate weathering is the dominant process, whereas the IBE shows the majority wells shows reveres ion exchange. Proper monitoring of water resources in terms of quality is required as majority (68%) wells are unfit for drinking purposes.

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Efficacy of Geospatial Technologies for Groundwater Prospect Zonation in Lower Western Ghats Area of Maharashtra, India

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Abstract The importance of groundwater potential zone (GWPZ) is a vital aspect for the society as directly or indirectly it sustains and supports the urban, crop irrigation and industrial activities. This study involves multi-parametric comparative geospatial modelling for delineation of potential groundwater zones. The Remote Sensing based and supplementary data were processed in the GIS environment to obtain the raster/vector layers of various themes such as land-slope, litho-units, stream density, lineaments, surface run off and land utilization. The thematic layers thus derived were subsequently divided into sub-criterion and suitable weights were assigned according to the degree of influence on groundwater dynamics using multi-parametric evaluation methods namely Multi-Criteria Decision Making (MCDM) and Multi-Influencing Factors (MIF). Furthermore, the outputs of both the techniques are superimposed to delineate more precise delineation of GWPZ in the study area. The validation of results reveal that the MCDM technique output map has total 160 wells i.e. around 96% falling in good—excellent zones. Whereas, MIF technique predicted 137 wells (about 83%) covering the same range, while the combination of

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both the techniques revealed 148 wells out of 166 wells (89%) falling in favourable zones.

Keywords Geospatial technology · Groundwater · Lower Western Ghats · MCDA · MIF

1 Introduction

Groundwater is considered as a safe consumable water source due to its less chances of contamination while comparing with the surface water (Thakur et al. 2011; Li et al. 2018). The rapid industrialization and over-population growth have led to continuous and enhanced extraction of groundwater resources, coupled with deterioration of groundwater quality worldwide (Kumar and Krishna 2018; Doell et al. 2014; Jha et al. 2014; Adhikary et al. 2010; Magesh et al. 2011; Murthy 2000). Currently, near about 85% of the population in rural India suffice their domestic needs through groundwater(CGWB 2011; Nampak et al. 2014).The recharge process begins when the precipitation or snowmelt water percolates down through vadose zone into the phreatic aquifer (Yeh et al. 2016).The availability and the flow groundwater area function of lithological set-up, structures (lineaments), topography, soil, landforms, meteorological factors, etc. (Naghibi et al. 2015; Thapa et al. 2017; Mishra et al. 2019). Therefore, the scientific study encompassing all these aspects is vital for assessing the potential for groundwater in an area (Adji and Sejati 2014).

The field-based approach to generate the hydrogeological database in this regard is time taking, expensive, cumbersome and many times not feasible in the catchment zones (White et al. 2003). Eventually, due to the advancement of GIS, GPS and remote-sensing techniques, groundwater prospects mapping has been accelerated, and became a powerful and cost-efficient alternative (Jasrotia et al. 2013; Kaliraj et al. 2014; Balamurugan et al. 2017). Many hydrogeologists, scientists worldwide have studies potentiality of groundwater resources employing RS-GIS-GPS techniques (Chowdhury et al. 2009; Ballukraya and Kalimuthu 2010; Chenini and Mammou 2010; Machiwal et al. 2011; Malekmohammadi et al. 2012; Gumma et al. 2012; Deepaet al. 2016; Senanayake et al. 2016; Golkarian and Rahmati 2018; Patra et al. 2017; Singhai et al. 2019). In the present work, the Shivganga basin, situated in the low elevation parts of Western Ghats, Maharashtra is explored with respect to integrated approach of MCDA, MIF and weighted sum techniques to arrive at verification of best fit method in the prediction of GWPZ. It is expected that the outcome of the work will be significant in efficient planning of the precious water resource and establish the equilibrium between demand and supply side management of the study area.

2 Study Area

The watershed covers a geographical area of 176.92 km^2 and is situated on lower elevations of the Western Ghats of Maharashtra, India (Fig. 1). It is drained by river

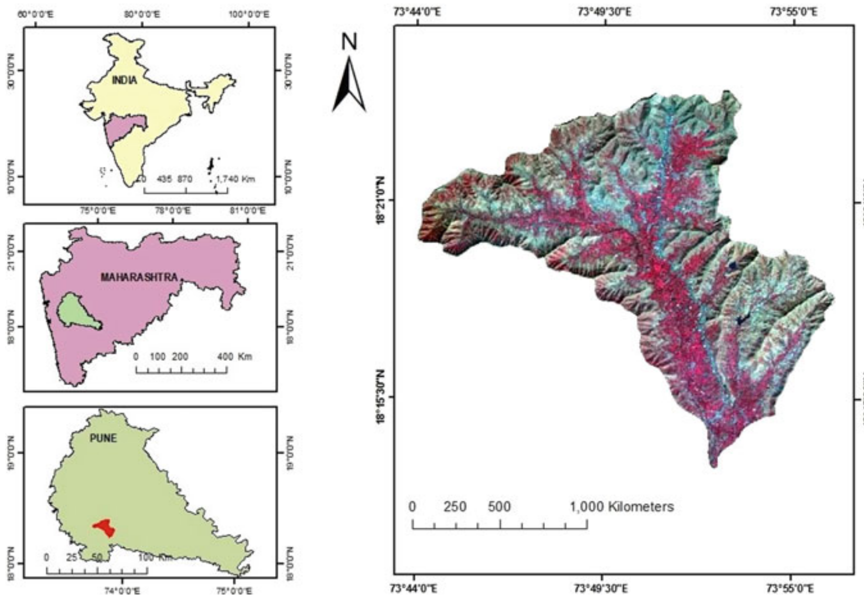

Fig. 1 Index map of Shivganga basin, Maharashtra

Shivganga that originates at Sinhagad fort covering the foot hill region. The area falls in toposheet 47F/15 and F/16 published by Survey of India. The region receives an average annual rainfall of 2604 mm, in which almost 85% precipitation occurs during June upto September. The watershed falls in sub-tropical climate zone, having average temperature of about 18 °C during winter to 36 °C in summer. The study area depicts an elevation difference of 674 m, in which the highest and the lowest elevation readings of 1264 and 590 m (above AMSL) is noted in western and easternmost parts respectively (Kadam 2018).

3 Methodology

The utilized material, implemented techniques and the procedures adopted for the GWPZ-mapping of the watershed is illustrated in Fig. 2. Initially, the demarcation of study area and the natural streams were marked from the topographical map, and further the stream density was obtained from the same. Further, the land slope map was created from contour lines. The land cover map was generated by classifying the free downloaded LANDSAT satellite imagery and validated using latest Google images. All thematic layers (land slope, soil, land cover patterns, surface runoff, geology, landforms and drainage density) were projected to Universal Transverse Mercator (UTM) and World Geodetic System (WGS)-84 co-ordinate systems. These layers were superimposed using raster overlay tool for delineating the GWPZ.

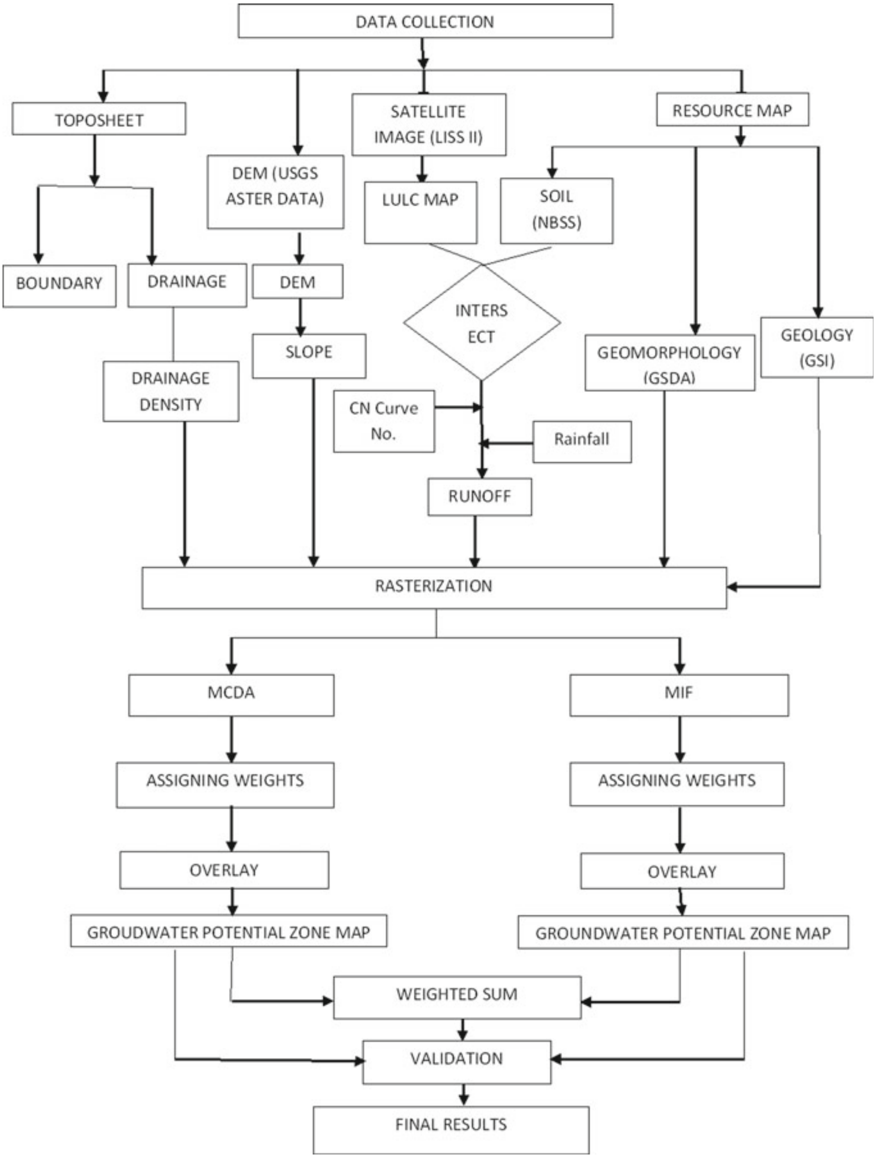

Fig. 2 Methodology adopted to delineate GWPZs

The GWPZ in the study area was identified using two approaches and compared to find out the best fit method amongst them. In the first approach, as per significance of the theme and the domain experience, weight was assigned to each theme and ranks were allocated to each feature class of theme under consideration. In second approach, MIF technique was used to give weights, where weights were allocated based on the reliance of the parameters on each other. The weights were allotted using MIF and weighted overlay analysis was performed on ArcGIS 9.3 platform. The results of weighted sum calculations, obtained by deploying MIF and MCDA methods were used to derive a final GWPZ output of the study area.

4 Results and Discussion

4.1 Slope

Slope of land governs the runoff-recharge process of any region therefore considered as a key parameter for identifying groundwater potentiality. The land slopes with high degree cause instant surface runoff vis-a-vis poor infiltration resulting into 'poor' groundwater storage, while flat areas or with gentle slopes permit rainwater to reside for longer duration, thus give a scope for infiltration. The slopes were reclassified in five classesfor the Shivganga watershed (Fig. 3).

It has been observed that the slopes in the area varies from 0 to 25º. The high slopes are reported from the peripheral/borders of the watershed, resulting into less

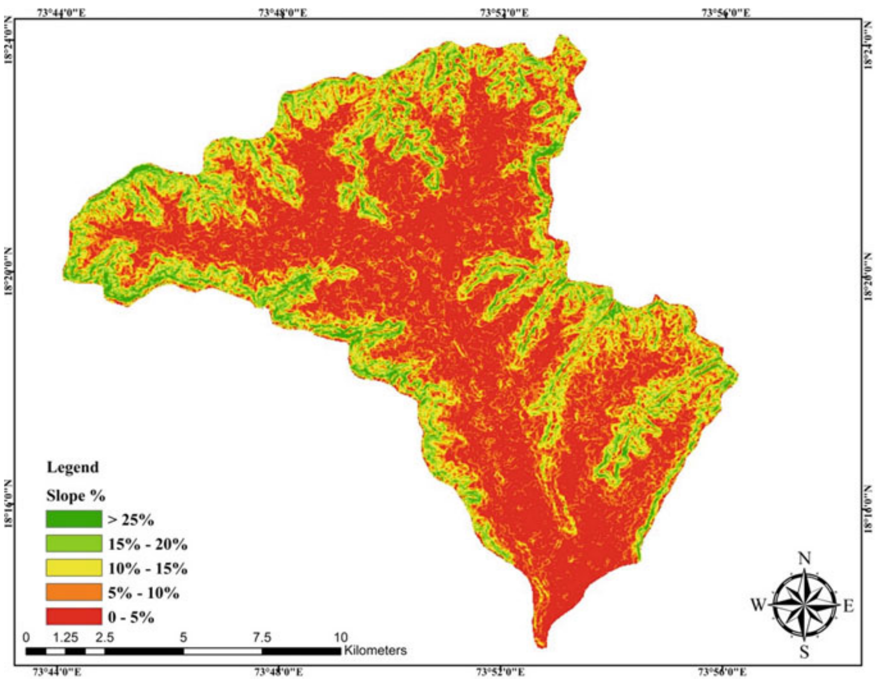

Fig. 3 Slope map of Shivganga basin

percolation while flat to gently sloping lands are scattered all over the area (0°–10°). The large portion of studied region was inferred in slope class 0–5°, occupying around 40% of area, indicative of favourable situation for recharge due to high percolation scope.

4.2 Geomorphology

Geomorphology provides the information on landforms, the processes and the sediment products. The weather and ecological parameters influence the landforms of any area. In view of this, the geomorphological set-up in the area was studied, which shows five geomorphological classes (Fig. 4). The weathered-shallow/weathered landforms are found to be suitable; whereas, moderately dissected plateau has moderate groundwater potential.

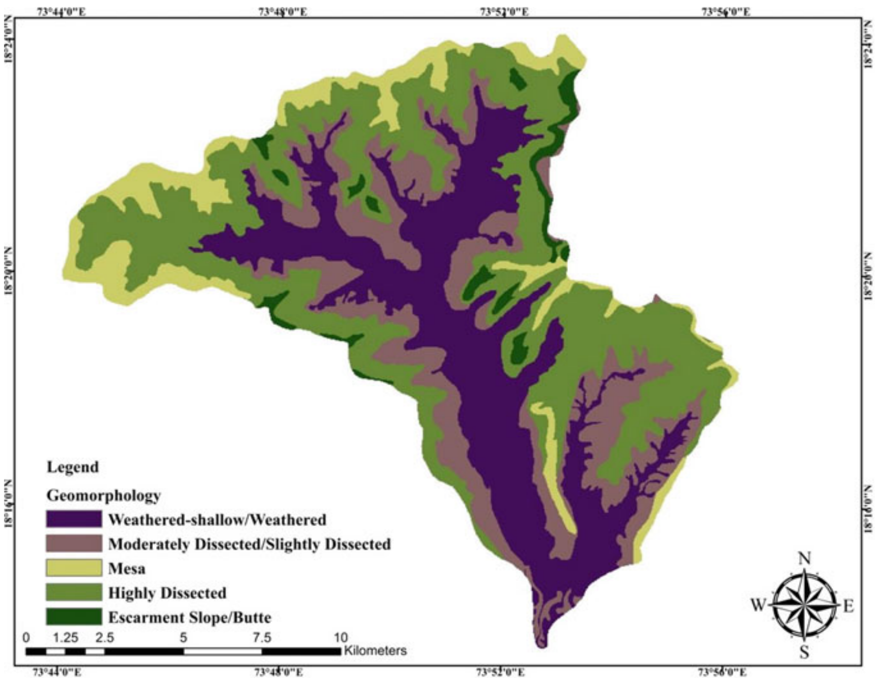

Fig. 4 Geomorphological set-up of Shivganga area

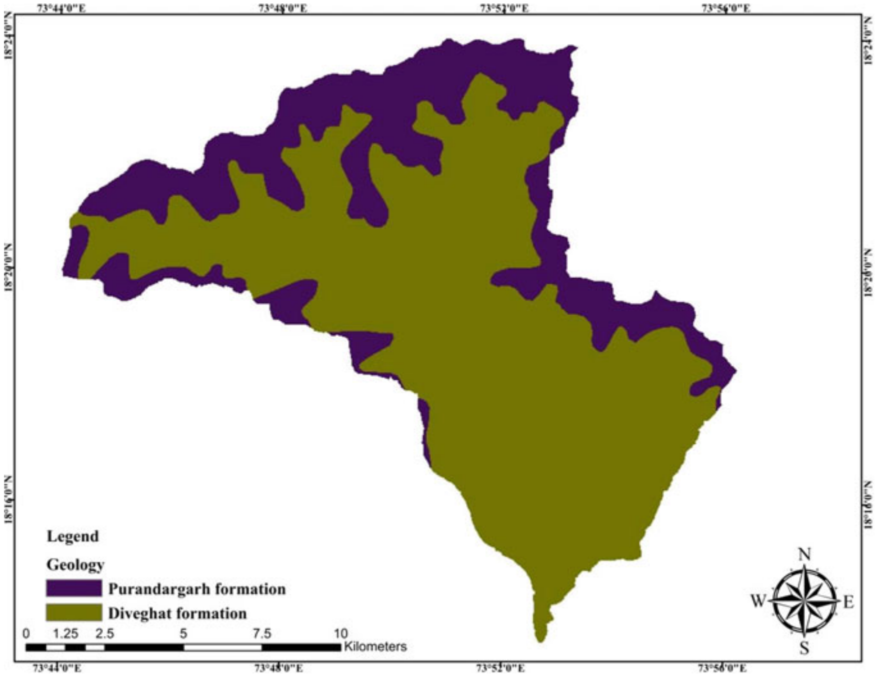

Fig. 5 Geological map of Shivganga basin

4.3 Geology

The watershed area is covered with thick pile of basaltic lava flows of Purandargarh Formation and Diveghat Formation of Sahyadri Group *representing pahoehoe, aa* types, and few exhibit mixed characteristics. These flow units are characteristically display sheet joints, columnar joints and pipe amygdales. The Diveghat Formation displayed compound pahoehoe flow with predominant vesicles covering majority of the basin area (Fig. 5). The dug well sections, stream/river sections and ghat sections were studied to understand the hydrogeological properties of the flows and it has been observed that there is alternate vesicular and compact basalts with varying degree of weathering, jointing and fracturing.

4.4 Land Use and Land Cover

The land utilization pattern is rapidly changing in the process of urbanization and as a result land initially being favourable for recharge is getting converted to impervious type. The southern part of the basin is experiencing haphazard urbanization and

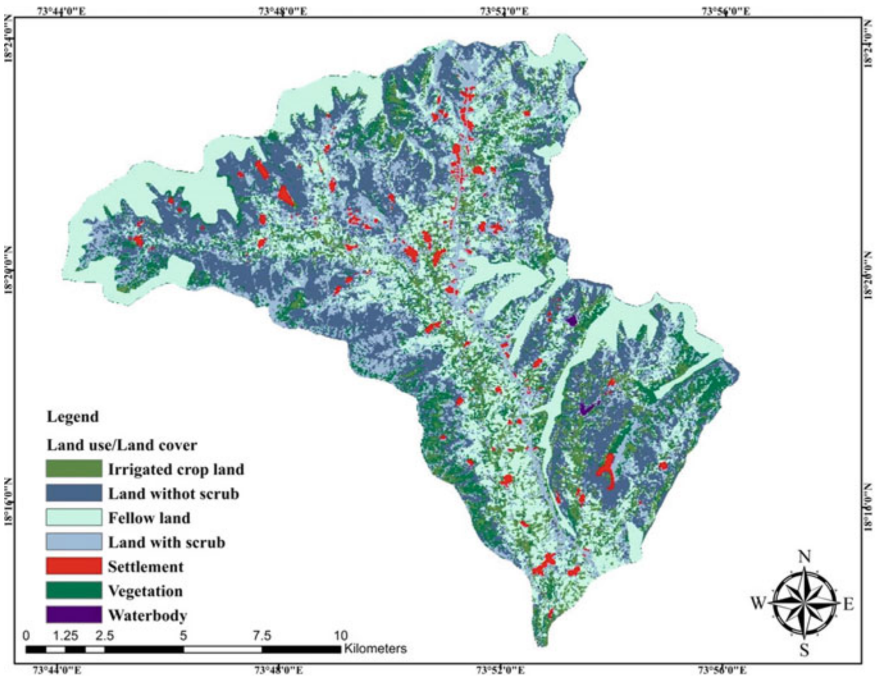

Fig. 6 Land use land cover map of Shivganga basin

industrialization causing imbalance in rainfall—runoff pattern (Selvam and Sivasubramanian 2012). The Shivganga watershed area has been categorized into major land use class types that include fallow land, water bodies, forest, crop land and built up area (Fig. 6). The forest area, water bodies, tree plantation and cropland generate low surface runoff, therefore these land use types have been designated as 'good' zones for GWP in contrast with the built-up urban areas.

4.5 Drainage Density

It is the ratio of total stream length of all orders within a basin to the total basin area, which is expressed in terms of km/sq km that manifests due to the variety of landforms, rock types, rainfall, land slope and land cover (Horton 1932; Bali et al. 2012). Drainage density is the reflection of land use type and the hydrological response time between precipitation and surface discharge. A low drainage density indicates high infiltration rates and hence few channels are required to carry the surface runoff.

The map depicts very low drainage density in the central part of the watershed that increases outward. The categorize of this parameter covers five classes namely

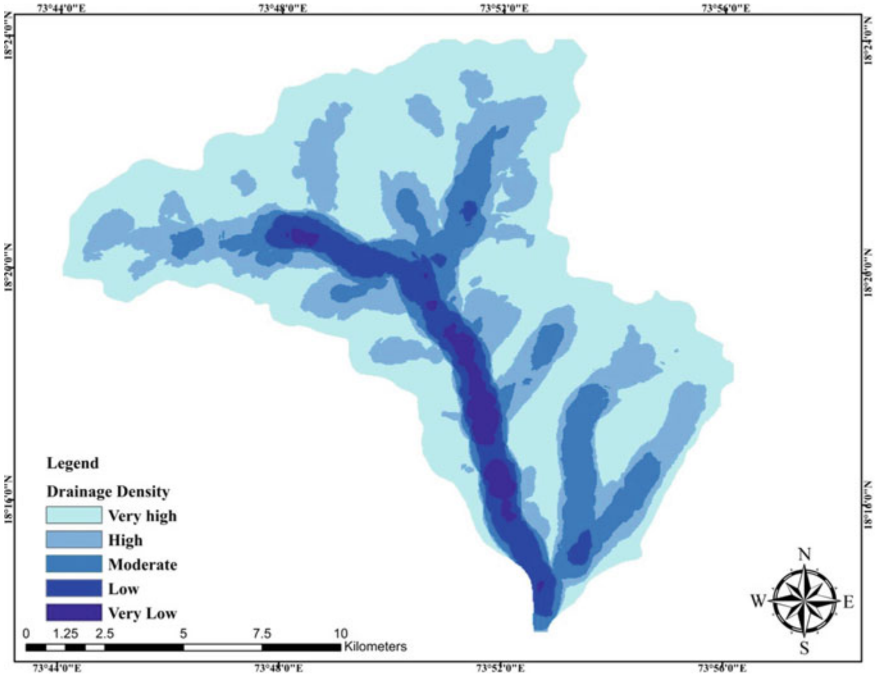

Fig. 7 Drainage density map of Shivganga basin

'Excellent' (0–0.467 km/km^2), 'Very good' (0.467–1.236 km/km^2), 'Good' (1.236–1.841 km/km^2), 'Moderate' (1.841–2.46 km/km^2) and 'Poor' (>2.46 km/km^2) as shown in Fig. 7. Higher values are indicative of poor groundwater potential whereas the lower values assure higher chances of groundwater recharge.

4.6 Runoff

It is the portion of the water cycle that moves over the land as surface water instead of absorbed into subsurface water is evaporating. The runoff is a function of precipitation, slope, land cover, soil, lithology and its permeability characteristics. The runoff map shows that the maximum runoff in the study area occurs at north-eastern and eastern parts of the region with their values ranging between 774.49 m and 958.89 m (Fig. 8). The lower runoff, having values 36.86–221.27 m, is seen at central part of the watershed and recognised as the most favourable zone for groundwater occurrence.

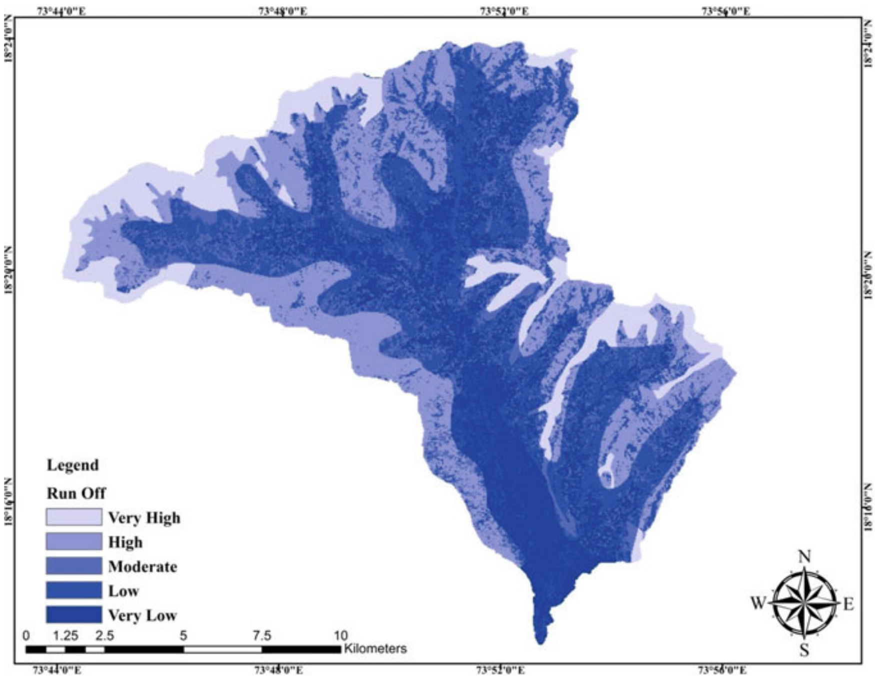

Fig. 8 Runoff map of Shivganga basin

4.7 Soil

Soil being the sensitive top cover of the earth, has an important role in supporting the biota and green growth (Umar et al. 2009). The hydrogeological properties of soil govern infiltration and percolation of rainwater. The NBSS classification (Bhattacharyya et al. 2013) reveals that study area possess sandy loam, loam and clayey soils (Fig. 9). Most of the area is underlain by sandy loamy (48%) and loam clay (43%) soils. The sandy soil depict higher infiltration and permeability capacity due to greater porous nature, therefore it has been designated with highest priority, whereas clayey soils are compact and impermeable therefore low priority.

4.8 Multi Criteria Decision Analysis (MCDA)

The GIS facilitated MCDA technique primarily concerned in combining geographical data (map criteria) on the basis of value findings (expert opinion preferences) to organize them into a one unique guide of assessment, from which decision makers can make the final choice (Malczewski 2006). Therefore, MCDA has been conducted

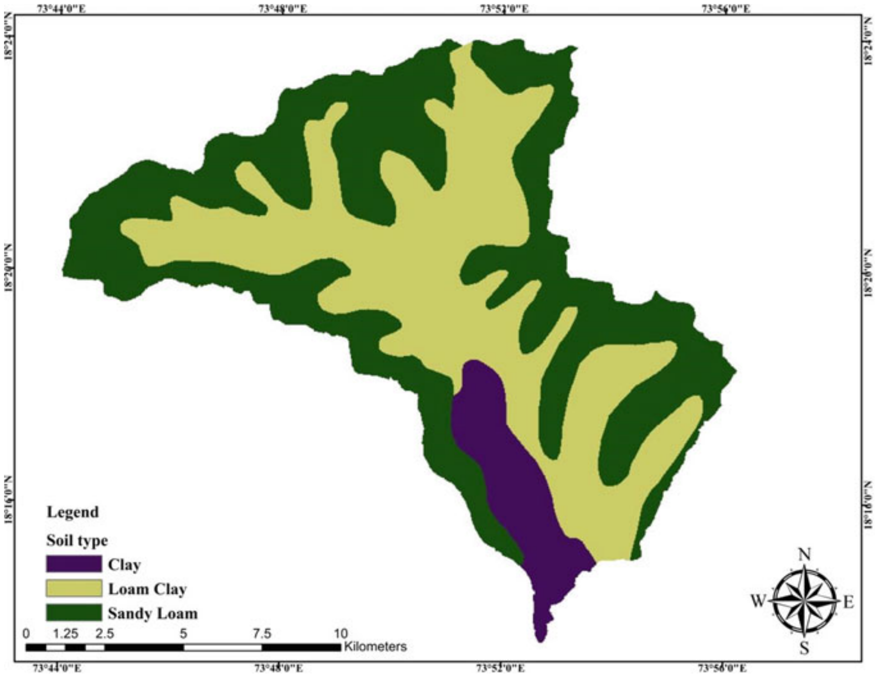

Fig. 9 Soil types of Shivganga basin

to obtain relative weights of various determining factors relating to thematic maps for GWPZs (Table 1).

The respective weights were assigned to groundwater influencing parameter based on expert opinion, literature review and local experience (Jenifer et al. 2017). For this study, the GWPZ map was generated using weighted sum overlay tool within the framework of ArcGIS software (Fig. 10). The area falling in various MCDA categories indicating groundwater favourability are provided in Table 2.

4.9 Multi Influencing Factor

Multi-influencing factor (MIF) method has been recognized as an important technique, in which the appropriate weights are assigned to different influencing parameters affecting the groundwater potentiality (Chandio et al. 2013). In the present work, the major influence factor on subsurface recharge (A) was given a score value of 1.0 whereas, a score of 0.5 given to negligibly influencing factor. In case of no influence, null or zero weight was given assigned (Table 3). The collective score i.e. $A + B$ of main (A) and minor (B) influential factors are applied to calculate the relative effect (Table 3). The comparative influence is additionally considered to determine

Table 1 Categorization of factors influencing recharge potential in Shivganga basin

Sr. No	Criteria	Weight class	Ranks	Influence (%)
1	Slope	0–5%	5	15
		5–10%	4	
		10–15%	3	
		15–25%	2	
		>25%	1	
2	Geomorphology	Weathered-shallow/weathered	5	15
		Moderately dissected	4	
		Highly dissected	3	
		Escarpment slope/Butte	2	
		Mesa	1	
3	Geology	Purandargarh	3	15
		Diveghat	2	
4	Land use/land cover	Irrigated crop land	5	20
		Waterbody/vegetation	4	
		Fallow land	3	
		Land with scrub/land without scrub	2	
		Built up	1	
5	Drainage density	Very low	5	10
		Low	4	
		Moderate	3	
		High	2	
		Very high	1	
6	Soil	Sandy loam	5	10
		Loam clay	4	
		Clay	3	
7	Run off	Very low	5	15
		Low	4	
		Moderate	3	
		High	2	
		Very high	1	

the score of affecting criterion. The projected score of each affecting parameter was determined by applying the following equation;

$$\frac{A+B}{\sum(A+B)} \times 100.(1)$$

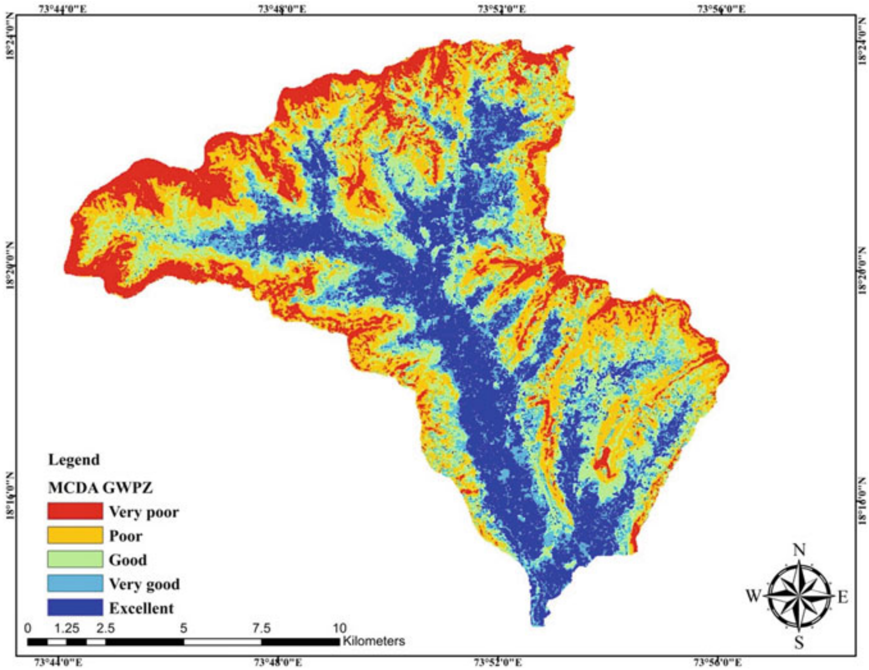

Fig. 10 Groundwater potential map derived by MCDA

Table 2 Statistics of MCDA groundwater potential map

MCDA GWPZ	Area (km^2)	Area (%)
Excellent	30	17.3
Very good	49.2	28.4
Good	51.8	29.7
Poor	33	19
Very poor	9.1	5.2

where: ***A***- major affecting factor and ***B***- minor affecting factor.

The flow chart of the interrelationship between various factors influencing groundwater potentiality surveyed in the current research is represented in Fig. 11. Subsequently, the influential thematic map layers along with computed score were combined using raster calculator in GIS environment to derive the sub-surface recharge probable zone (Fig. 12). The area under MIF based GWPZs is shown in Table 4.

Table 3 Effect of influencing factor, relative rates and score for each potential factor

Criteria	Major effect (A)	Minor effect (B)	Proposed relative rates (A + B)	Proposed score of each influencing factor
Soil	1	0	1	7
Land use/land cover	1	0.5 0.5 0.5	2.5	17
Geomorphology	11	0.5	3	21
Geology	111	0.5	3.5	24
Slope	11	0.5	2.5	17
Run off	1	0.5 0.5	1	7
Drainage density	1	0	1	7
			∑14.5	∑100

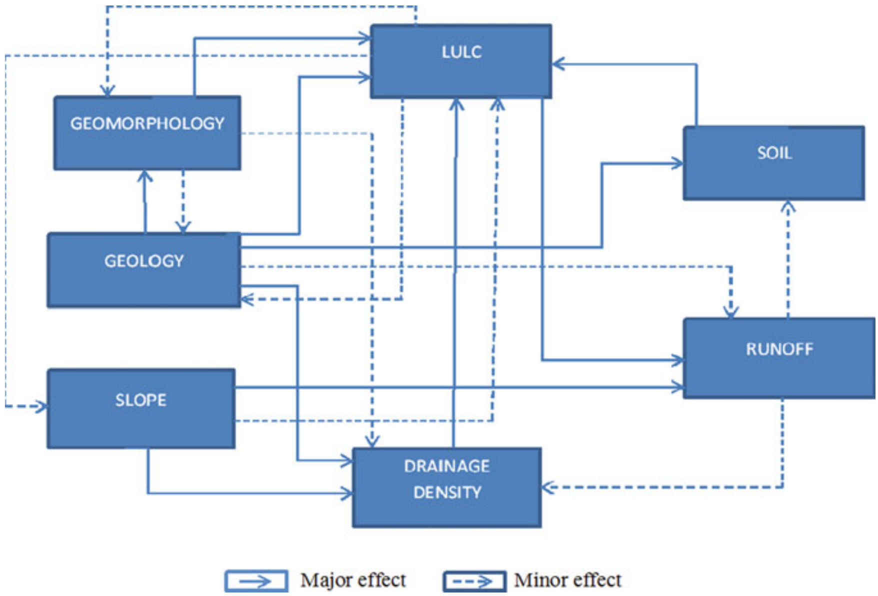

Fig. 11 Interrelationship between the multi-influencing factors concerning the GWPZ (Magesh et al. 2012)

4.9.1 Weighted Sum

The weighted sum technique uses the several raster's for multiplying each other by their given weight and adding them together. The technique offers the capability to weight and group many inputs to make a combined analysis. Since two different techniques have been used to find out the potential zones of groundwater, weighted

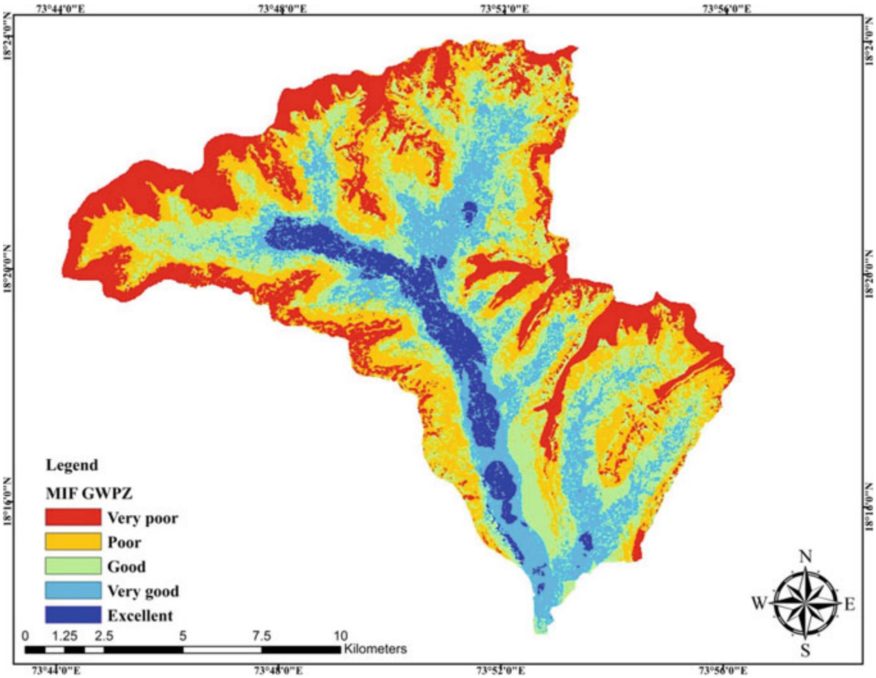

Fig. 12 MIF groundwater potential map

Table 4 Statistics of MIF groundwater potential map

MIF GWPZ	Area (km^2)	Area (%)
Very poor	36.03	20.7
Poor	51.69	29.7
Good	45.88	26.4
Very good	31.65	18.2
Excellent	8.23	4.7

sum tool was used to see if the results could be better when the two techniques are integrated. The raster of GWPZ by MCDA technique was integrated to the raster of GWPZ by MIF technique. Hence a final output of weighted sum and their respective areal spread is shown (Table 5; Fig. 13).

4.9.2 Validation

The existing 166 dug well inventoried data have been utilized for verification of GWP map obtained from MCDA, MIF and weighted sum techniques in Arc GIS environment. The depth to the water table within the study region varies from 3

Table 5 Statistics of weighted sum groundwater potential map

Weighted sum GWPZ	Area (km^2)	Area (%)
Excellent	7.4	4.6
Very good	32.8	18.9
Good	44.1	25.4
Poor	51.4	29.7
Very poor	37.6	21.7

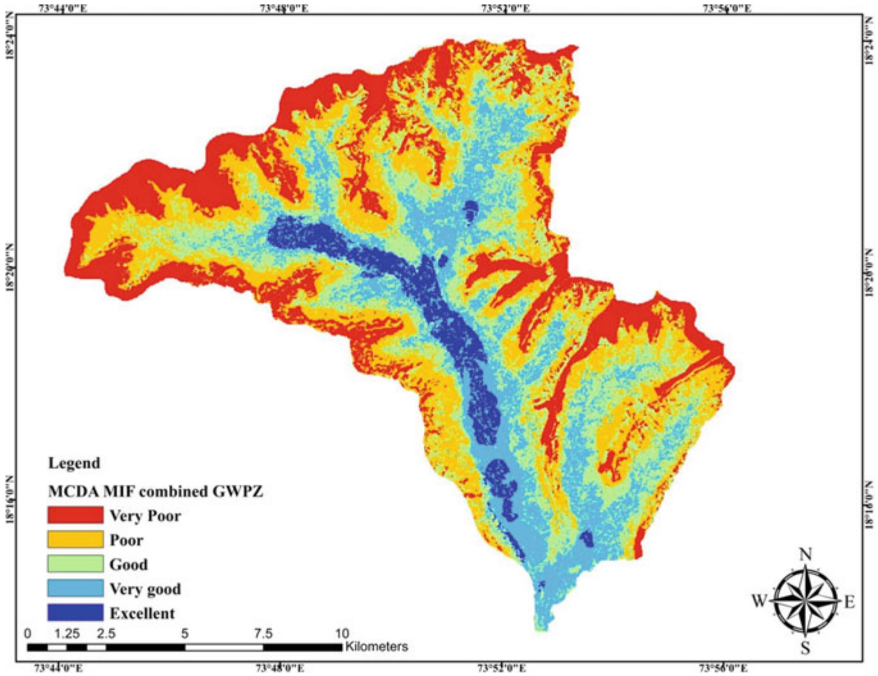

Fig. 13 Weighted sum groundwater potential map

to 15 m, which were further categorized into five classes, viz 'Excellent' (0–3 m), 'Very Good' (3–6 m), 'Good' (6–9 m), 'Poor' (9–12 m) and 'Very Poor' (12–16 m) respectively. The existing well sites were further utilized as reference sample to determine the classification accuracy.

Validity of MCDA—GWPZ Map with Well Information

Figure 14 shows the validation with MCDA GWPZ map. The validation results reveal that 11% of the wells are in 'excellent' depth GWPZ, 7% of the wells fall under 'very good' depth GWPZ, 38% of the wells under 'good' depth GWPZ, 17% of the wells

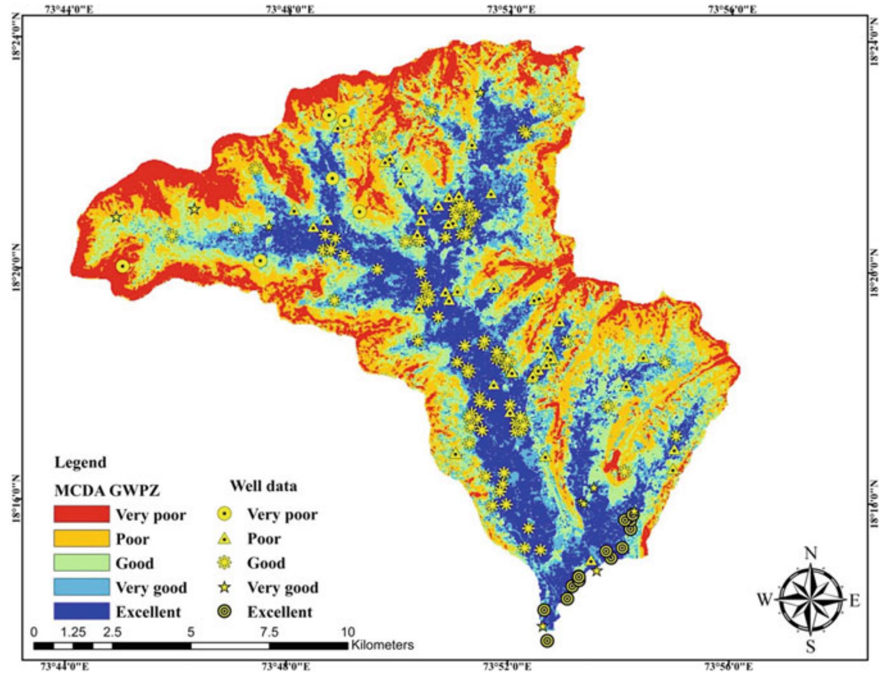

Fig. 14 Validation with MCDA groundwater potential map

Table 6 Comparison of accuracy assessment in % of the developed from different techniques groundwater potential maps

Groundwater potential zone	Percentage of groundwater by		
	MCDA (%)	MIF (%)	Weighted sum (%)
Excellent	11	0	0
Very good	7	4	4
Good	38	45	42
Poor	17	50	41
Very poor	100	100	100

are in 'poor' depth GWPZ and the remaining 27% of the wells are found in 'very poor' depth GWPZ category respectively (Table 6).

Validity of MIF- GWPZ Map with Well Information

The validation of MIF with GWPZ map shows 4% of the wells under 'very good' depth GWPZ, 45% of the wells under 'good' depth GWPZ and 50% of the wells in

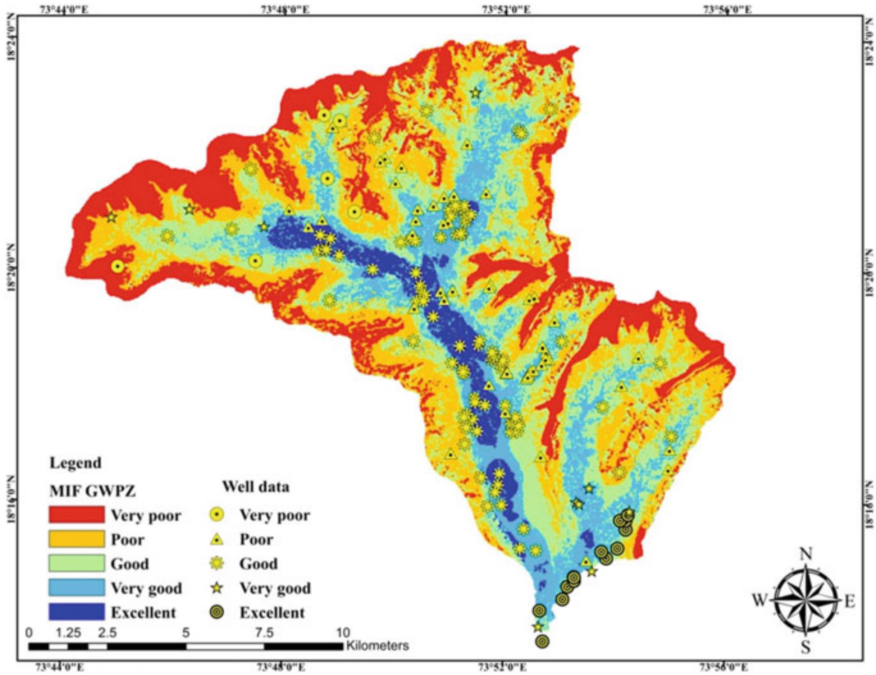

Fig. 15 Validation of MIF-GWPZ map

'poor' depth GWPZ. Remaining 1% of the wells belongs 'very poor' depth GWPZ category (Fig. 15; Table 6).

Validity of Weighted Sum—GWPZ Map with Well Information

The validation of weighted sum with weighted GWPZ map shows 4% of the wells under 'very good' depth GWPZ, 42% of the wells are in 'good' depth GWPZ, 41% of the wells are found in 'poor' depth GWPZ. Remaining 13% of the wells are found in 'very poor' depth GWPZ category respectively (Fig. 16; Table 6).The groundwater potential zone with different techniques were compared to ground validation and presented in Fig. 17.

5 Conclusion

The present study identifies the GWPZ in Shivganga river basin representing semi-arid zone of Western Ghats applying MCDA, MIF and weighted sum technique. The thematic layers in raster format were generated using imageries, topographical

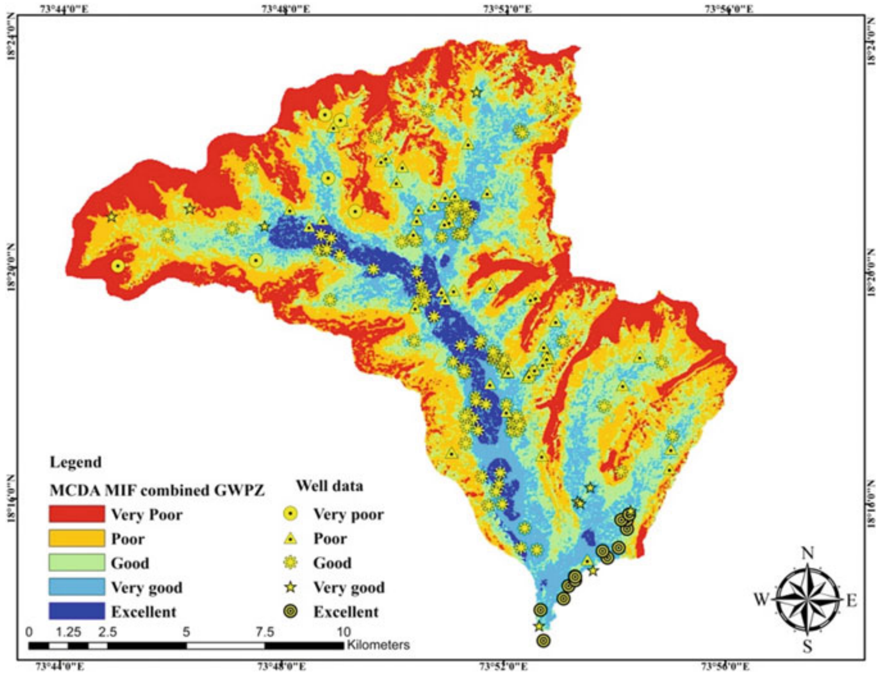

Fig. 16 Validation with weighted sum groundwater potential map

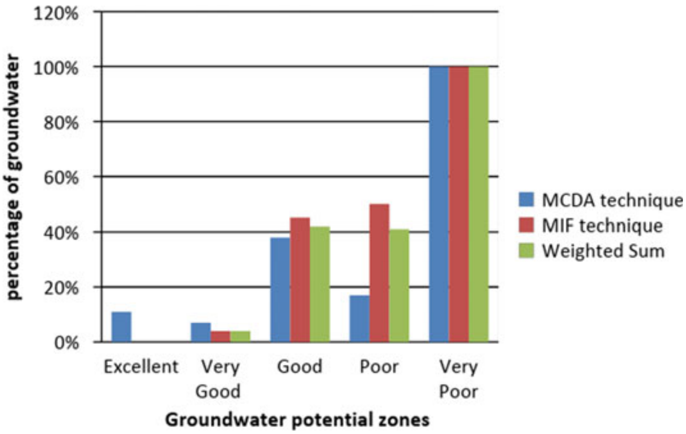

Fig. 17 Groundwater potential zone with different techniques compared to ground validation

maps and resources maps viz. gradient, lithology, drainage density, surface runoff, landform classification, land cover class and soil. These derivative layers were allocated appropriate weightages in MIF and MCDA approaches based on its important on influence of occurrence for groundwater. The outcomes of all these methods are compared from its accuracy in determination of GWPZs.

The GWPZs were classified into five classes of varied potential zones. The results in MCDA shows that 17.3% (30 km^2) show outstanding GWPZ with 28.4% (49.2 km^2) and 29.7% (51.8 km^2) of GWPZ, while 19% (33 km^2) area present as a poor, 5.2% area under very poor zones. Hence, the study area is having 75.40% (131.0 km^2) as good to excellent potential. The results in MIF technique shows that 20.7% (36.03 km^2) show excellent zone with 29.7% (51.69 km^2) and 26.4% (45.88 km^2) of very good and good GWPZ, while 18.2% (31.65 km^2) area present as a poor, 4.7% (8.23) area under very poor zones. Hence, the study area is having 76.8% (133.6 km^2) as good to excellent GWPZ. The results in weighted sum technique shows that only 4.6% (7.4 km^2) having excellent zone with 18.9% (32.8 km^2) and 25.4% (44.1 km^2) of GWPZ respectively. The 29.7% (51.4 km^2) area present as a poor, 21.7% (37.6 km^2) area under very poor zones. Hence, this method shows the distinct results than above two methods. The outcomes maps were validates using wells overlays, the results divulge that output of MCDA method have 160 wells in good, very good and in excellent zone which is around 96% wells, MIF have 137 wells and 83% and when both these techniques combined it gives 148 wells and 89% out of 166 wells so it was found that MCDA technique is more suited in comparison to other two techniques in the present study area.

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Identifying Suitable Sites for Rainwater Harvesting Structures Using Runoff Model (SCS-CN), Remote Sensing and GIS Techniques in Upper Kangsabati Watershed, West Bengal, India

Asish Saha, Manoranjan Ghosh, and Subodh Chandra Pal

Abstract The Upper Kangsabati Watershed (UKW) is a drought-prone region where the scarcity of water risk has been leading to the serious potential human problems. To mitigate this water scarcity threat, watershed management in the forms of construction of rainwater harvesting (RWH) structures to trap the rainfall and unused surface runoff has become the main priorities. Watershed has been chosen as one of the principal planning units for water resources management in a sustainable way. The rainfall induced runoff always play vital role of the availability of surface, sub-surface and groundwater recharge within a particular watershed. The aims of our present research work are (a) to estimate the surface rainfall-runoff using Soil Conservation Service Curve Number (SCS-CN) analysis and geospatial (GIS) technology, and (b) to identifying favorable sites for collection of rainwater using guiding principles given by Integrated Mission for Sustainable Development (IMSD) in conjunction with overlay analysis of weighted parameters in GIS platform of UKW. The different environmental parameters i.e. land use land cover (LULC), soil classes (texture), geomorphic, lineament, weathering profile, slope, hydrologic soil group (HSG),rainfall, runoff depth, and stream orders have used to analysis surface runoff and delineating different RWH structures of UKW. However, it has noticed that the deepness of average annual runoff is 979.45 mm and runoff volume is 280.85 m^3. Being a part of the Chhotanagpur plateau, the study area is covered with hard rock terrain and having undulating rugged topography; thus, average annual runoff depth is significantly high. In addition, total thirty-three check dams, twenty-eight minor irrigation tanks, and eleven percolation tanks locations have identified for sustainable rainwater harvesting structures. Hence, this study will help planners to conserve the water, land and other natural resources of UKW.

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Keywords Geographic information system · Hydrologic soil group · Rainfall-runoff · Rainwater harvesting structure · SCS-CN method · Upper Kangsabati watershed

1 Introduction

Water is one of the most primary natural resources in our daily life. As a noteworthy natural resources, water plays an important role for human needs in terms of food security, industrial development, and sustainable ecosystem services along with the socio-economic progress of a nation (Sinha et al. 2015; Singh et al. 2017). In recent times, the widespread scarcity and the gradual diminution of the surface and groundwater along with environmental degradation have been making the major problems to all the living being on the earth surface. Looking into the current phenomena regarding the rising problems of water deficiency and misuse of groundwater across the world, it is a well-established fact by many scholars that world's 67% population and its gradually increasing rate will be harshly affected by the water scarcity within the forthcoming time periods (Alcamo et al. 2000; Wallace and Gregory 2002; Tiwari et al. 2009). Therefore, an emphasis has been giving on the development and management of water resources for maximum utilization of natural water resources, which is a challenging and most difficult task (Biswas and Tortajada 2009). In the developing country like India, an excessive number of population put immense pressure on water resources; as a result, per capita water utility is gradually decreasing over the time (Singh et al. 2017).However, considering this recent phenomenon like widespread scarcity and the gradual depletion of the water resources, increasing demand of per capita water availability, and lack of proper management, there is a necessity to manage the water resources effectively. Thus, in the hydrological point of views, runoff estimation of a particular watershed is necessary to know the rainfall-runoff deviation, development and sustainable management of natural water resources. The estimation of rainfall-runoff is one of the most significant hydrologic variables in water resource studies of a particular watershed (Nagaraja and Poongothai 2012; Ningarahu et al. 2016).The SCS-CN method helps to understand the hydrological behavior of a watershed through surface runoff estimation and helps the stakeholders to make some suitable plans for sustainable watershed management and water resource planning (Schulze et al. 1992; Gajbhiye 2015; Saha et al. 2020). SCS-CN method has been generally used to estimate rainfall-runoff rate due to its large acceptance and reliability, and this method was developed by the United State Department of Agriculture's (USDA) National Resources Conservation Service (USDA 1972, 1986). The remote sensing technique and GIS tool have been extensively used and has an advantage over the conventional method to rainfall-runoff estimation of a particular watershed due to it enhancing the accuracy in results. On the basis of SCS-CN method, several scholars have worked out to estimate the rainfall-runoff such as Hauser and Jones (1991); Durbude et al. (2001); Amutha and

Porchelvan (2009); Rao et al. (2010); Shi et al. (2009); Jung et al.(2012); Sindhu et al. (2013); Pal and Chakrabortty (2019).

The construction of RWH structures is necessary and appropriate ways for watershed management to overcome the water shortage and scarcity problems. For reduced the rate of surface runoff, renew of groundwater, reduced the sedimentation, and reuse the water whenever it required, the RWH structures always play an important role (Prasad et al. 2008; Gavit et al. 2018). RWH is the techniques through which surface runoff are effectively trapped and used it for daily livelihoods activity, mainly agricultural and domestics purposes (Naseef and Thomas 2016; Gavit et al. 2018). Water storage facilities are very much essential to overcome the water scarcity threat particularly in the region where runoff potential is very high. Natural resources like land and water, which is depleting at a faster rate day by day may conserve in a precious way through water harvesting structures (Bamne et al. 2014; Das and Pal 2019, 2020). Rainwater harvesting structures not only collect rainwater but also prevents flood and most necessarily acts as a hindrance to soil erosion (Naseef and Thomas 2016). The recognition of suitable sites for RWH is avital footstep towards utmost of water availability and maximizing land production of an area (Adham et al. 2018). Several scholars throughout the world have studies on suitable site selection for RWH structures such as Padmavathy et al. (1993); Singh et al. (2009); Tumbo et al.(2014); Naseef and Thomas (2016); Ammar et al. (2016); Mugo and Odera (2018).

The very first objective of this research study is to estimate the rainfall-runoff dynamics of Upper Kangsabati Watershed (UKW). The rainfall-runoff dynamics has estimated during the last fourteen years of rainfall data (2007–2017) using the SCS-CN analysis and geospatial techniques. In addition to potential rainfall-runoff estimation, appropriate sites for RWH structures in UKW have recognized using the guiding principles of IMSD. In this study, mainly emphasis has given to three types of rainwater harvesting structures i.e. check dams, percolation tanks, and minor irrigation tanks. Additionally, the findings of the present rainfall-runoff estimation and RWH site suitability map of UKW would help the watershed planners for proper development and sustainable management of water resources in an appropriate way.

2 Materials and Methods

2.1 Study Area

The present study area of Upper Kangsabati Watershed (UKW) in the western part of Puruliya district of West Bengal has codified by 2A2B5alpha-numeric codification system of Soil and Land Use Survey of India (CWC and NRSC 2014). The study area is extended between 23°13′25"N to 23°28′36"N and 85°57′5"E to 86°11′46"E with the total geographical area of 286.74 km^2 (Fig. 1).The study area belong to hot dry sub-humid tropical types of climate with the annual average rainfall is about 1393 mm and annual mean temperature of 25.6 °C (Saini et al. 1999). However, temperature

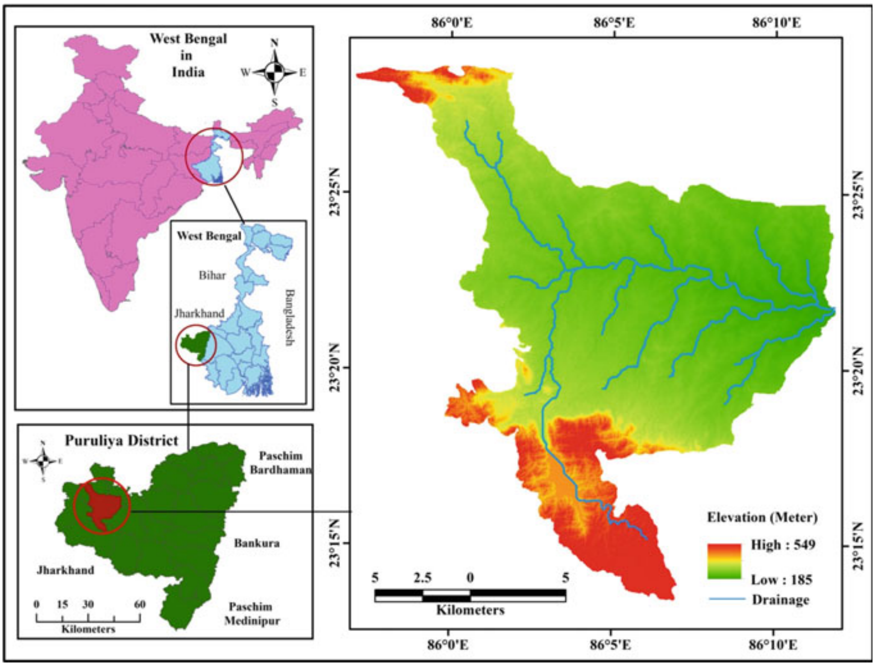

Fig. 1 Location map of the study area

is very high in summer and low in winter season and its range fluctuates in between 7 °C in winter and 52 °C in summer with the mean summer and winter temperature is 29 and 21.3 °C respectively (Saini et al. 1999; Sarkar and Sahoo 2006). Geologically, the study area is a part of Chhotanagpur Gneissic Complex (CGC) of Peninsular India and the dominant rock types of this area are granite, gneissic, mica-schist, and recent to sub recent-alluvium. As a consequence of the presence of hard rock terrain, water percolation rate is very low and as a result surface runoff of the seasonal rainfall is very high in this area. Thus, in the current situation water shortage has been taken a devastating form due to its distinct physical and anthropogenic factors which also largely effect the socio-economic development of Puruliya district.

2.2 Data Source

Several types of secondary data have used to fulfill the objectives of the present research work. The basic database used in this studies consist of topographical mapson 1:50,000 scale from Survey of India (SOI), map of soil texture from National Bureau of Soil Survey and Land Use Planning (NBSS and LUP), Shuttle Radar Topographic Mission (SRTM v3) Digital Elevation Model (DEM) of 30 m resolution by United State Geological Survey, LISS III satellite imagery from Indian Space

Table 1 Information of the data sources used in the present study

Description of data	Year	Scale/spatial resolution	Source
Topographical map (73E/15)	1982	1:50,000	Survey of India (SOI), Kolkata
Topographical map (73I/3)	1977		
Topographical map (73I/4)	1975		
Soil texture map	1991	1:500,000	National Bureau of soil survey and land use planning (NBSS and LUP)
Rainfall data	2004–2017	–	India Meteorological Department (IMD)
NRCS technical release (TR)-55	1986	–	United State Department of Agriculture (USDA)
Saprolite (Weathering profile) data	2010	–	Central Ground Water Board (CGWB), Eastern Region, Kolkata
LISS-III imagery	2015	23.5 m	www.nrsc.gov.in
SRTM-DEM	2017	30 m	https://earthexplorer.usgs.gov

Research Organization (ISRO), ISRO's Geoportal Bhuvan for lineaments mapping, weathering profile data has collected from Central Ground Water Board (CGWB), rainfall data from India Meteorological Department (IMD), report of United State Department of Agriculture Technical Release-55 (1986) and guiding principles of IMSD for site suitability of RWH structures. Table 1 shows the details about the different data sources and necessary information.

2.3 Data Processing

2.3.1 LULC

The LULC map of UKW has been prepared after the details study of SOI's topographical maps and LISS III satellite imagery by visual interpretation techniques and spectral reflectance of each pixel value using ERDAS IMAGINE 2014 platform. The present study area have been classified into ten types of LULC namely dense forest, forest clearing, open scrub forest, double crop land, single crop land, pond, reservoir, river, settlement, and wasteland.

2.3.2 Slope and Drainage

The DEM work was analyzed in the ArcGIS 10.3 platform. Slope map was prepared using slope sub tool under surface tools and reclassified the slope map into percentage classes using spatial analyst tool in the ArcGIS platform. Drainage map of the study area was obtained from SRTM-DEM using different hydrology tools like Flow Accumulation, Flow Direction, Flow Length, Snap Pour Point and Stream Order tools under the ArcGIS spatial analyst tools. Line density tool was used to mapping drainage density for this study area.

2.3.3 Lineaments

LISS III satellite image was used to prepare lineaments map using Geometica 2017 software. In the Geometica platform, for the extraction of lineaments Line Module Control Panel was used. In addition to this, ISRO's Geoportal Bhuvan site was also used to prepare lineaments map. Line density tool under spatial analyst tools was used to mapping lineaments density in ArcGIS platform (Mugo and Odera 2018; Chakrabortty et al. 2018).

2.3.4 Soil and HSG

Soil texture map has prepared from the NBSS&LUP's soil report for this study area by digitization in the GIS platform; after that, generated soil texture map has transformed into hydrologic soil group map in ArcGIS platform using curve number (CN) values. Finally, for obtaining the merged LULC-HSG map with the new polygon layers, the LULC map has overlies on the HSG map in the GIS platform. Table 2 shows the SCS soil classification system in details based on USDA-SCS 1974.

2.3.5 Rainfall Analysis

In the entire Puruliya district, five identifiable IMD rainfall measure stations are identified, namely Raghunathpur, Bazrabzar, Puruliya, Manbazar, and Jhalda. To analyze the rainfall pattern of last fourteen years (2004–2017) rainfall data have collected from IMD stations. To the lack of rainfall station within the study area of UKW, nearest station has considered for the rainfall analysis. In ArcGIS platform, Inverse Distance Weightage (IDW) tools have used to generated rainfall map under geo-statistical analysis tools.

Table 2 USDA-Soil Conservation Service (SCS) classification system, 1974

Hydrologic soil group (HSG)	Soil textures	Runoff potential	Final infiltration rate (mm/h)
Group A	Deep, well-drained sands and gravels	Low	>7.5
Group B	Moderately deep, well-drained with moderately fine to coarse texture	Moderate	3.8–7.5
Group C	Clay loams, shallow sandy loam, soil with moderate to fine texture	Moderate	1.3–3.8
Group D	Clay soil that swells significantly when wet, heavy plastic and soil with a permanent high water table	High	<1.3

2.4 Rainfall-Runoff Modeling (SCS-CN)

Runoff estimation is an important parameter which impact on water storage (surface and groundwater) capacity as well as erosion rate of a watershed and helps the planners to taking appropriate action for planning purposes (Shi et al. 2009; Pal and Chakrabortty 2019). Among the various types of rainfall-runoff method, SCS-CN method has been frequently used to estimate direct runoff from a watershed (USDA 1972). The curve number provided by SCS is a reliable and conceptual techniques commonly used to estimate surface runoff (Ponce and Hawkins 1996). To estimate the rainfall-runoff rate by using SCS method following equation has been used

$$Q = [\mathrm{P} - \mathrm{I_a}]^2/(\mathrm{P} - \mathrm{I_a} + \mathrm{S}) \tag{1}$$

where, Q represent runoff rate in mm, P represent rate of rainfall in mm, I_a represent early abstraction in mm, in terms of all the losses before the runoff start (Allen and Hjelmfelt 1991).

The early abstraction i.e. I_a was calculated based on following experimental relation,

$$I_a = 0.3S \tag{2}$$

$$S = (25,400/CN) - 254 \tag{3}$$

where, CN = Curve Number.

Substituting the value of I_a (Eq. 2) in the generalized runoff equation (Eq. 1), the equation can be rewritten as,

$$Q = (\mathrm{P} - 0.3\mathrm{S})^2/(\mathrm{P} + 0.7\mathrm{S}) \quad (4)$$

where, Q represent runoff rate in mm, P represent rate of rainfall in mm, S represent possible utmost retention of water by soil.

The Antecedent Moisture Condition (AMC) indicates wetness of soil surface; it means the existence of water in the soil at a specified time (USDA 1974). The AMC is defined as the soil moisture availability earlier than the rainstorm which has a noteworthy effect on runoff volume (Singh et al. 2017).Three types of antecedent moisture conditions have developed by the SCS of USDA, and these are, for dry condition AMC I, for normal or average condition AMC II, and for wet condition AMC III. The value of AMC I and AMC III for the present study area have calculated using the following equations.

$$CN(I) = (\mathrm{CN(II)})/(2.281 + 0.0128\ \mathrm{CN\ (II)}) \quad (5)$$

$$CN(III) = (\mathrm{CN\ (II)})/(0.427 + 0.00573\ \mathrm{CN\ (II)}) \quad (6)$$

where, $CN(I)$, CN(II) and $CN(III)$ represent curve number for dry condition, normal condition and wet condition respectively.

$$CN_w = \sum CN_i * A_i/A \quad (7)$$

where, CN_w represent weighted curve number, CN_i represent Curve number from 1 to any number N, A_i represent area with curve number CN_i and A represent total watershed area.

2.5 *Weighted Overlay Analysis*

Applications of Remote Sensing and geospatial technology along with geomorphological knowledge have used to estimate appropriate sites for RWH structures. The guiding principles of IMSD, National Remote Sensing Agency (NRSA) and Indian National committee on Hydrology (INCOH) have taken for selecting sites of different RWH structures (Kumar et al. 2008; Singh et al. 2009). Table 3 shows the details

Table 3 IMSD guidelines for rainwater harvesting structures

Structure	Slope in degree	Permeability	Runoff	Stream order
Check dam	<15	Low	Medium/high	1–4
Percolation tank	<10	High	Low	1–4
Minor irrigation tank	0–5	Low	Medium/high	1–2

about the IMSD suitable site selection criteria for RWH structures. In the site suitability of rainwater harvesting structures different factors have their own peculiar characteristics. Thus, all such factors do not have the same importance and they differ from one another depending upon their own characteristics. Therefore, on the basis of the characteristics of various factors different weights were identified accordingly. Here, weight assignment of different factors has been done based on primary knowledge and they are integrated and analyzed through weighted overlay analysis (Mugo and Odera 2018). The construction of rainwater harvesting structures is largely depending on the slope character because various slope classes influences the runoff and infiltration rate. The soil texture is another important factor for rainwater harvesting because it defines the capacity of storage of the water and infiltration rate in the soil (Mibilinyi et al. 2007). The site suitability of RWH structures also depends on LULC, lineament density, geomorphology, weathering profile, runoff depth, stream order (Singh et al. 2009; Nketiaa et al. 2013; Jha et al. 2014; Mugo et al. 2018).

3 Results

3.1 *Land Use Land Cover (LULC)*

It is a well-established fact that depending on the types of LULC the rainfall induced runoff and the infiltration capacity take action in a different way (Das et al. 2019). The area of fallow land with built-up area increases the run off rate and minimizes the infiltration capacity, and the area with dense forest cover generally increases the infiltration rate (Owuor et al. 2016; Das et al. 2018). There are ten types of LULC classes (Fig. 2) within the present study area of UKW. The different LULC types along with the percentage of area are dense forest (11.17%), forest clearing (1.19%), open scrub forest (9.39%), double crop land (7.95%), single crop land (61.19%), pond (0.78%), reservoir (0.30%), river (0.89%), settlement (4.93%), and wasteland (1.6%). From the percentage of different LULC types it has shown that the area of single crop land (61.19%) is the leading form of land use among the others LULC types. The supremacy of single crop land is due to the lack of adequate water and hard rock terrain cover which is unfavorable for agricultural point of view. The area of dense forest cover (11.17%) is also significantly low due to the man-made changes of land cover through degradation.

3.2 *Hydrologic Soil Group (HSG)*

Three types of soil texture (Fig. 3) have found in the present study of UKW. The different types of soil texture along with their area are as coarse loamy (37.72 km^2),

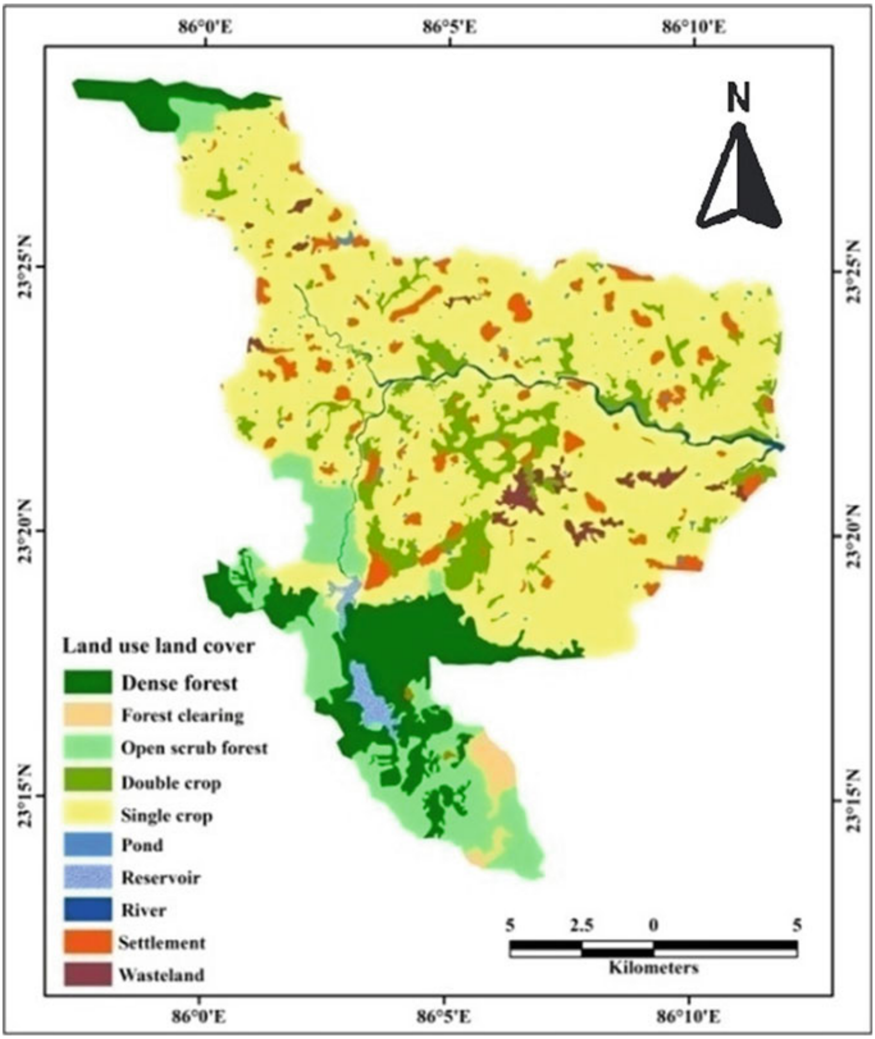

Fig. 2 Land use land cover map of UKW

fine loamy (106.28 km^2), and loamy skeletal (142.74 km^2). The USDA-Soil Conservation Service (1974) have developed four types of hydrologic soil groups namely A, B, C, and D in the soil classification system. On the basis of soil texture classification map in the present study of UKW, two types of HSG have identified namely B and C (Fig. 4). In the category of 'B' hydrologic soil group different LULC classes along with their areal allocation are as dense forest (0.82 km^2), open scrub forest (0.76 km^2), double crop land (10.24 km^2), single crop land (84.53 km^2), pond (1.07 km^2), river (1.66 km^2), settlement (5.99 km^2), and wasteland (1.25 km^2). On the other side, in the category of 'C' hydrologic soil group different LULC classes along with their

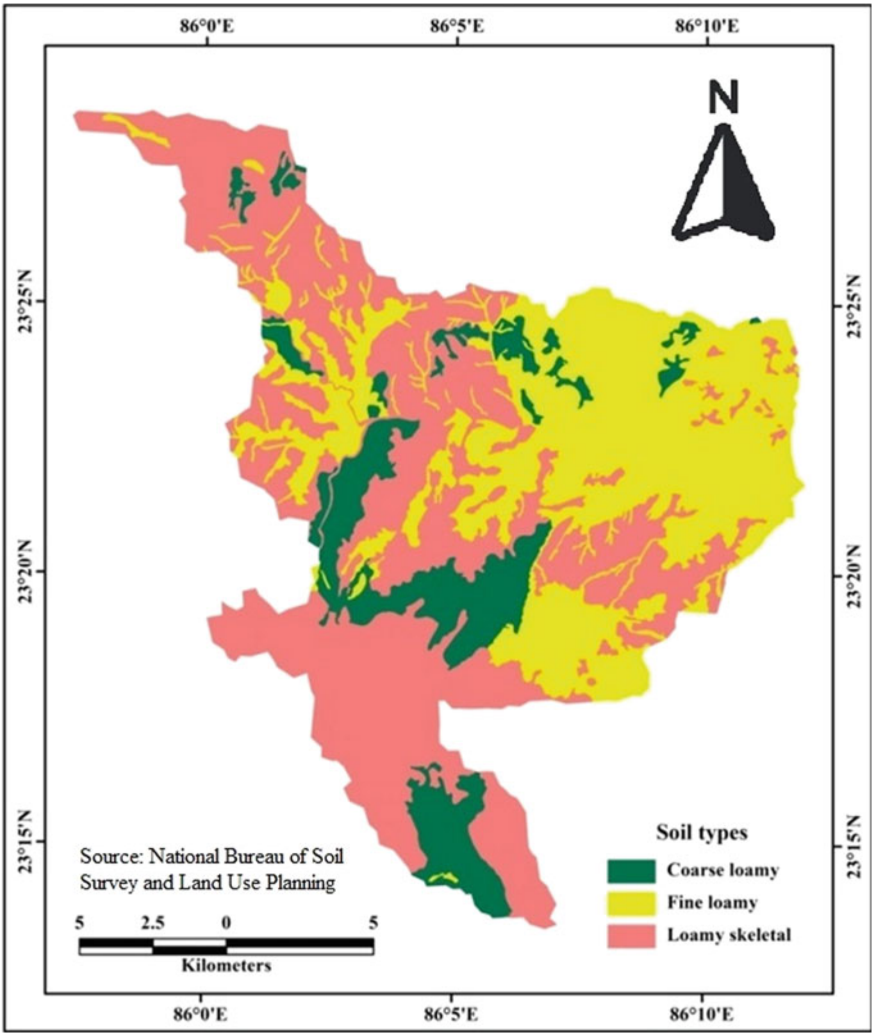

Fig. 3 Soil texture map of UKW

areal allocation are as dense forest (31.08 km^2), forest clearing (3.423 km^2), open scrub forest (26.14 km^2), double crop land (12.55 km^2), single crop land (90.92 km^2), pond (1.18 km^2), reservoir (2.74 km^2), river (0.88 km^2), settlement (8.17 km^2), and wasteland (3.34 km^2).

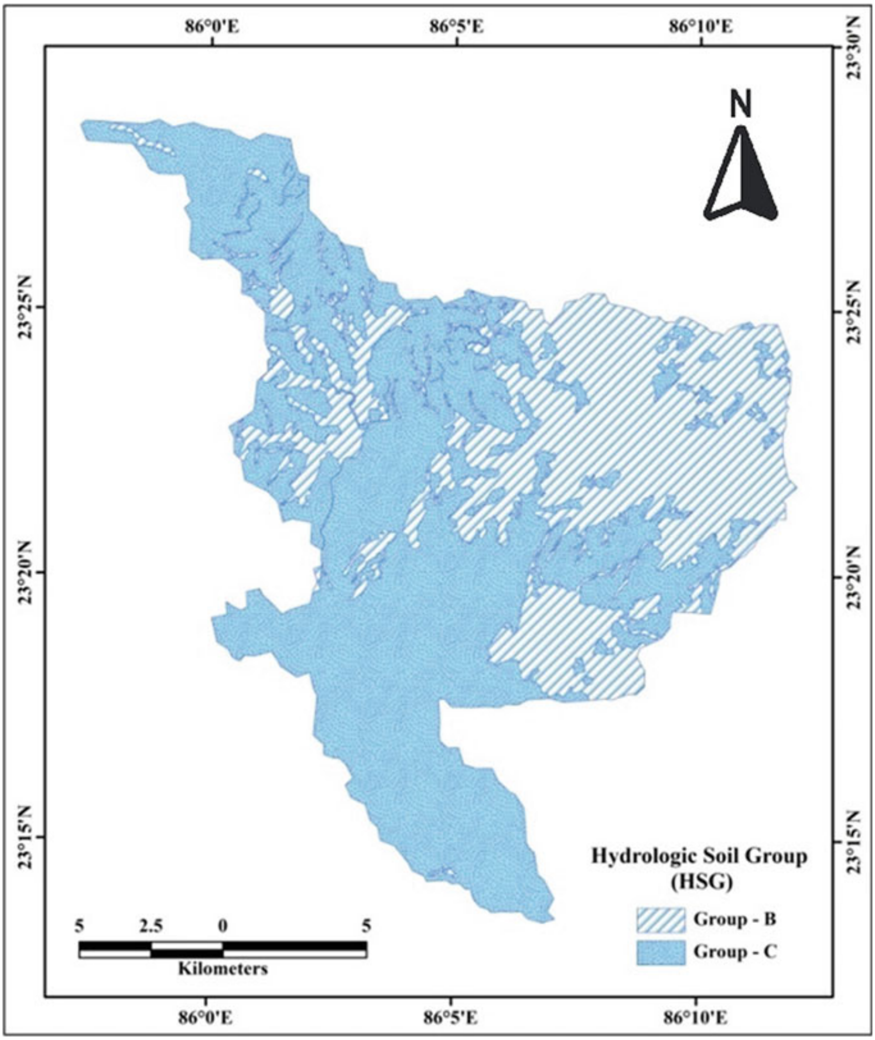

Fig. 4 Hydrologic soil group map of UKW

3.3 Curve Number (CN)

The possible runoff rate of a particular watershed has been estimated using SCS-CN method in which CN values have been taken as an empirical parameters (Gitika and Ranjan 2014; Satheeshkumar et al. 2017; Raju et al. 2018; Pal and Chakrabortty 2019). In the present research work of UKW, the CN values have been estimated on the basis of LULC classes of hydrologic soil groups B and C, and the CN ranges vary between 40 and 100 (Fig. 5). It has found that the weighted curve number value

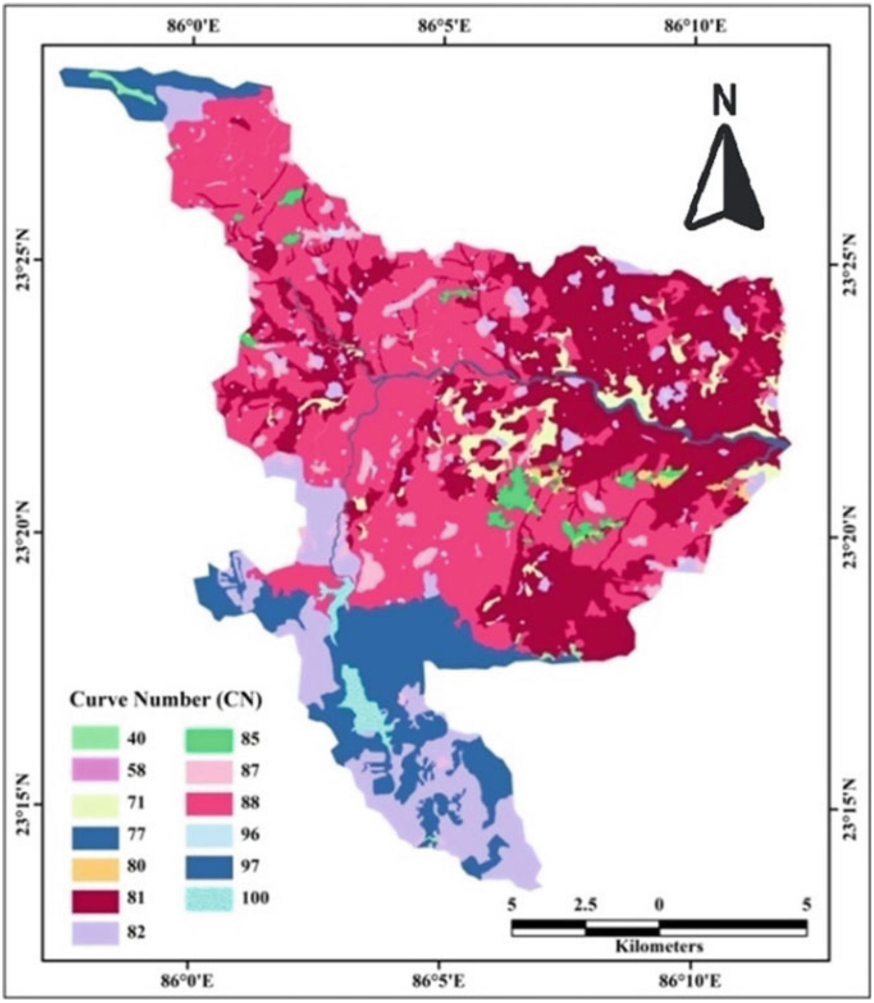

Fig. 5 Curve numbers map of UKW

for normal soil moisture condition (AMC II) is about 81.1. The curve number value of AMC I for dry condition is 65.25 and AMC III for wet condition is 90.95.

3.4 Rainfall

Rainfall is an important parameter which indicates the erosive power of soil surface at the time of rainstorm phase (Pal and Shit 2017). Depending on the amount of rainfall, runoff rate varies and thus, the positive relationship has been found among the amount of rainfall and runoff (Pal and Chakrabortty 2018). In the study area of UKW, the annual rainfall ranges between 901.3 and 1783.8 mm. The rainfall map (Fig. 6) of UKW has shown that the amount of rainfall gradually decreases from east to west. The area towards the north-west received lowest amount of rainfall throughout the year. This area is characterized by hilly terrain with undulating rugged topography thus, maximum rainfall in this area flow as surface runoff. The area towards the east of UKW received maximum rainfall throughout the year. This area basically consists of flat to moderately undulating terrain with dominant of single crop land

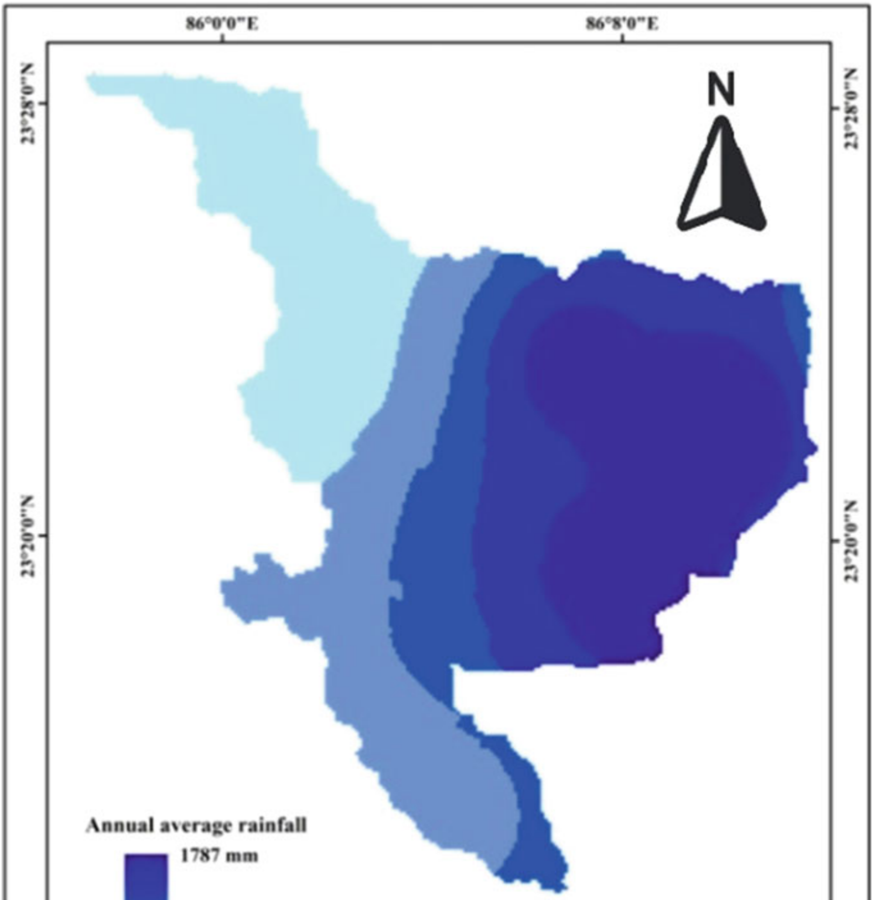

Fig. 6 Spatial distribution of rainfall map of UKW

and settlement areas. In the eastern part of this area, due to the presence of hard rock terrain with moderate weathering profile zone low to medium surface runoff occurred.

3.5 Slope

The slope is a major controlling factor which determines the surface runoff and infiltration rate (Das et al. 2018). The maximum surface runoff along with less infiltration has been occurred in the area of steep slope whereas in the gentle slope area surface runoff is low which also allows more time to percolate thus, infiltration capacity is high (Das et al. 2018). The study area of UKW being a part of the Chhotanagpur plateau is characterized by undulating rocky hilly terrain with general elevation ranges between 185 and 549 m. Figure 7 shows the slope map of UKW and the whole watershed classified into nearly level to very steep slope classes. The different slope classes along with their percentage values in the study area are as follows Level to nearly level (32.49%), very gentle (43.98%), gentle (8.52%), moderate (7.22%), steep (6.69%) and very steep (1.1%). On the basis of the sloping character it has found that low to high rate of rainfall induced runoff occurred in the nearly level surface and steep slope of hilly areas respectively.

3.6 Lineaments Density

In the present study of crystalline structural rugged topography cover area, lineament or fractural zone is an important factor for ground water recharge. Lineaments are straight and slightly curved or curvilinear composite linear features which play an important role in groundwater movements and occurrences (Rao 2006; Prasad et al. 2008). In areas where lineaments representing fracture zone or fault lines are not suitable for construction of water storage structures due to underground seepage factor. On the contrary, where lineaments represents dyke rock may act as a barrier in flow of ground water and suitable for water storage structures (Chakrabarti 2002). The lineament density of the present study area is shown in Fig. 8. The very high lineaments density is found (>1.0) in the southern portion of UKW area. That means this portion is not suitable for water storage capacity because water will be drain through the fracture zone. The lineament density of some patches of the study area is moderate (0.20–1.0) and rest of the portion is low (<0.2). The area of low lineaments density is most suitable for water storage capability because this area is free from cracks or fracture zone.

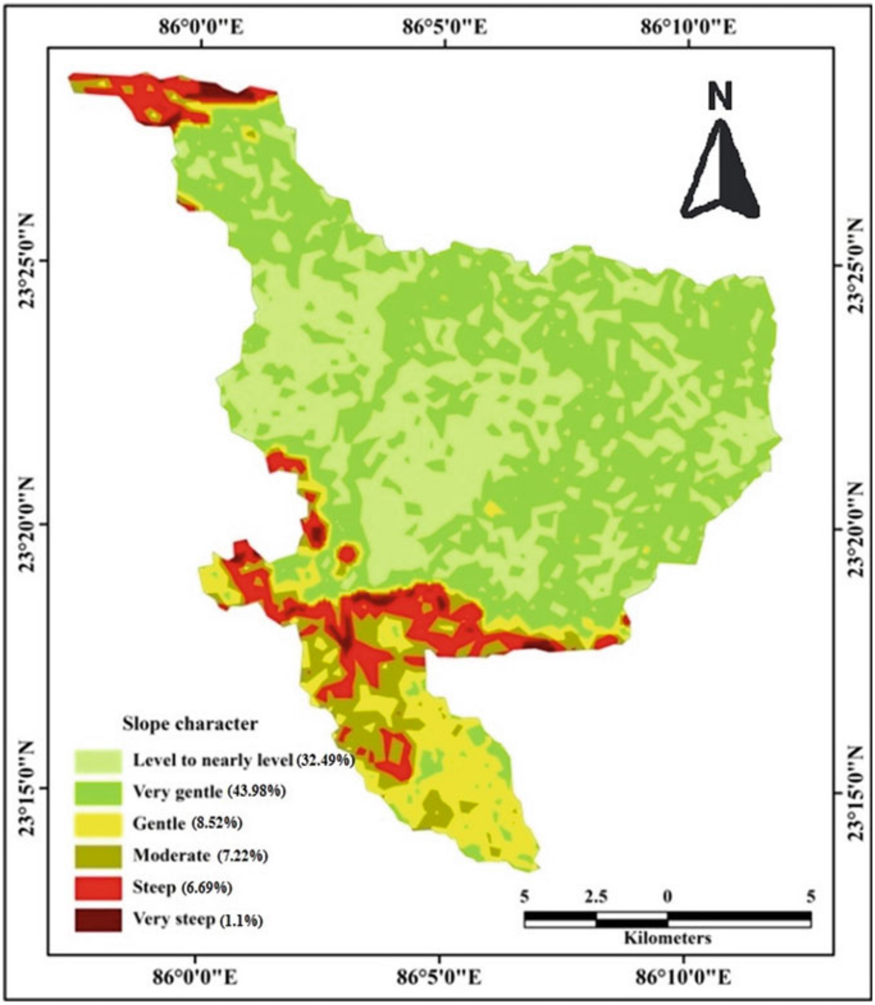

Fig. 7 Spatial distribution of slope map of UKW

3.7 *Drainage*

In the present study area, stream ordering map (Fig. 9) indicates that the area is largely possessed with first and second order streams and the whole area represent fifth order stream. The lower order streams have higher permeability and infiltration capacity rate and thus stream order analysis is an important task for constructions of rainwater harvesting structures (Adham et al. 2018). Basically, lower order streams are also favorable for generation of runoff along with rainwater storage capacity in a watershed (Mugo and Odera 2018). Site suitability analysis of RWH structures largely depends on drainage density. Therefore, high drainage density prone area is

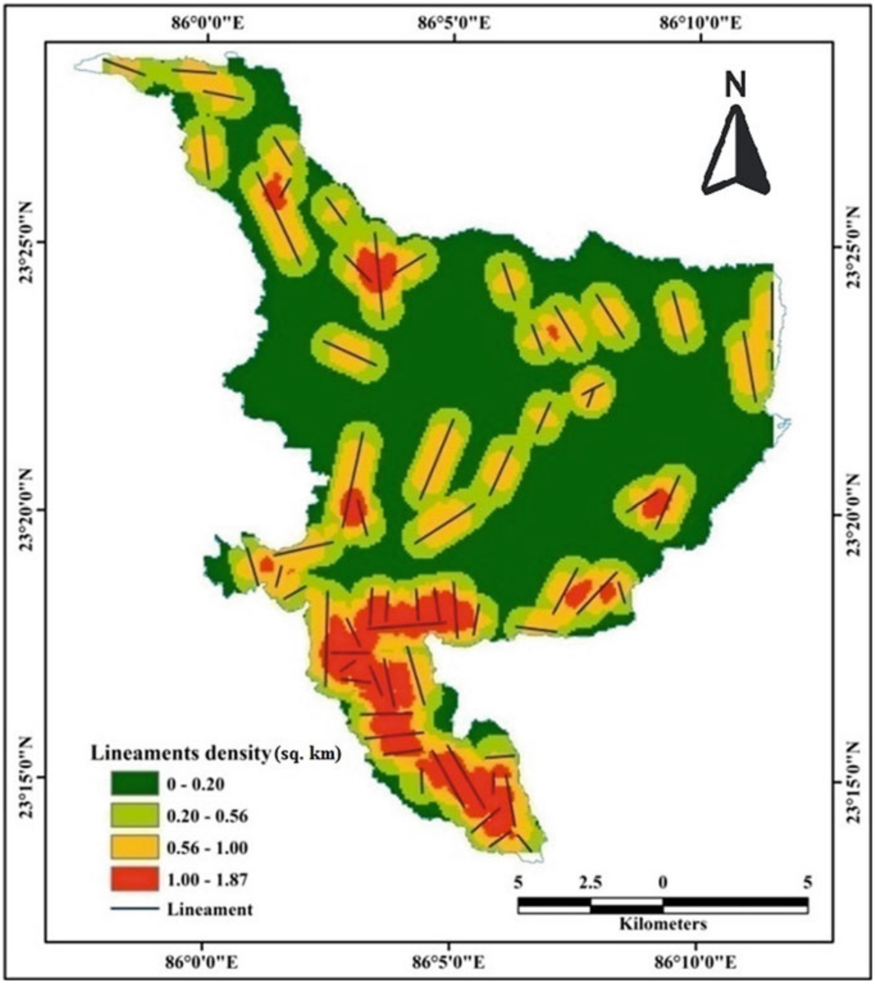

Fig. 8 Lineaments density map of UKW

more suitable for RWH structures. The drainage density map of this area is shown in the Fig. 10. North, north-western and eastern part of UKW area has a high drainage density and as a results this portions have high runoff generation, and thus this area is more favorable for construction of RWH structures.

3.8 Geomorphology

Geomorphologically, the study area of UKW can be divided into two units; units of denudational origin and units of fluvial deposition. The upper part of the watershed in

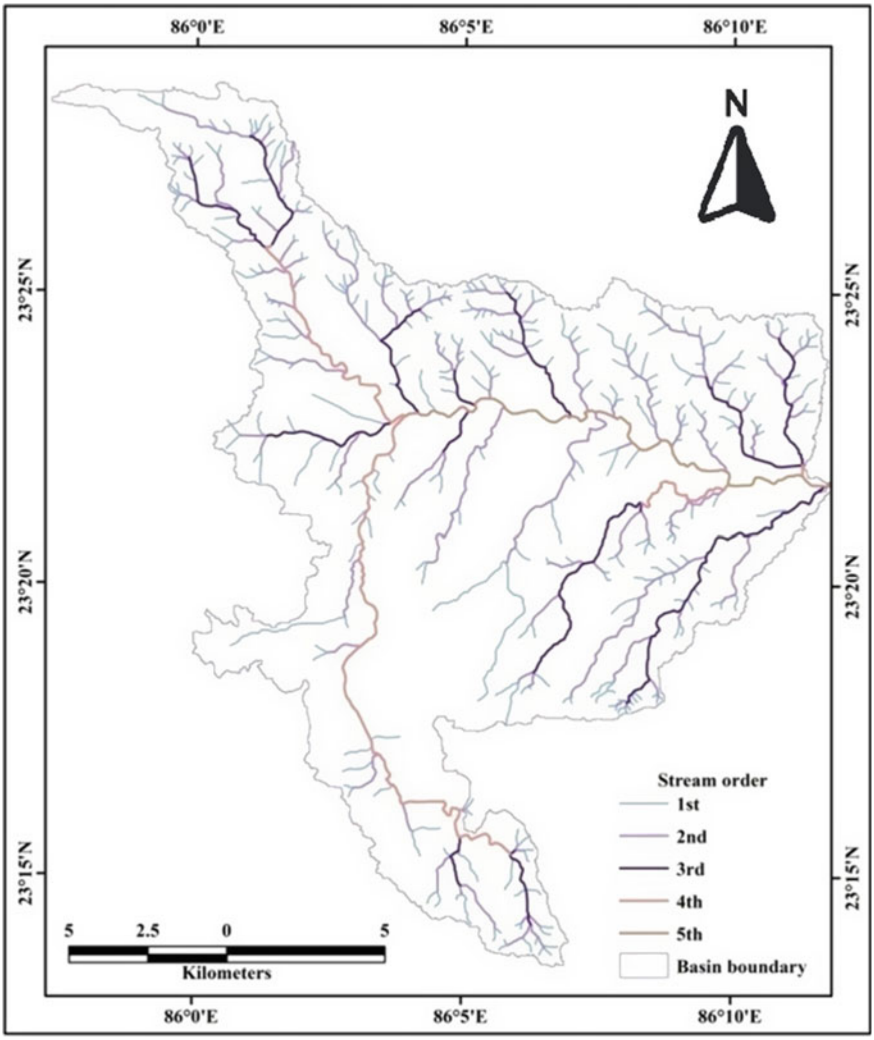

Fig. 9 Stream ordering map of UKW

Puruliya district is characterized by an undulating upland topography with a number of isolated hillocks such as Jhora Pahar (Δ662 m) and Guru Pahar (Δ579 m). The rocky upland surface in this area is the products of erosional activities, while the rest of the surface is a product of a gradational activity mainly by fluvial processes. In the present study area of UKW, six types of geomorphic units are found and these are hill, pediment, bajada, buried pediment medium, buried pediment shallow and valley fill (Fig. 11). Each geomorphic unit has different groundwater prospects such as hill has poor to nil, pediment has modest to poor, buried pediment shallow has moderate to poor, buried pediment medium has good to moderate, valley fill has good

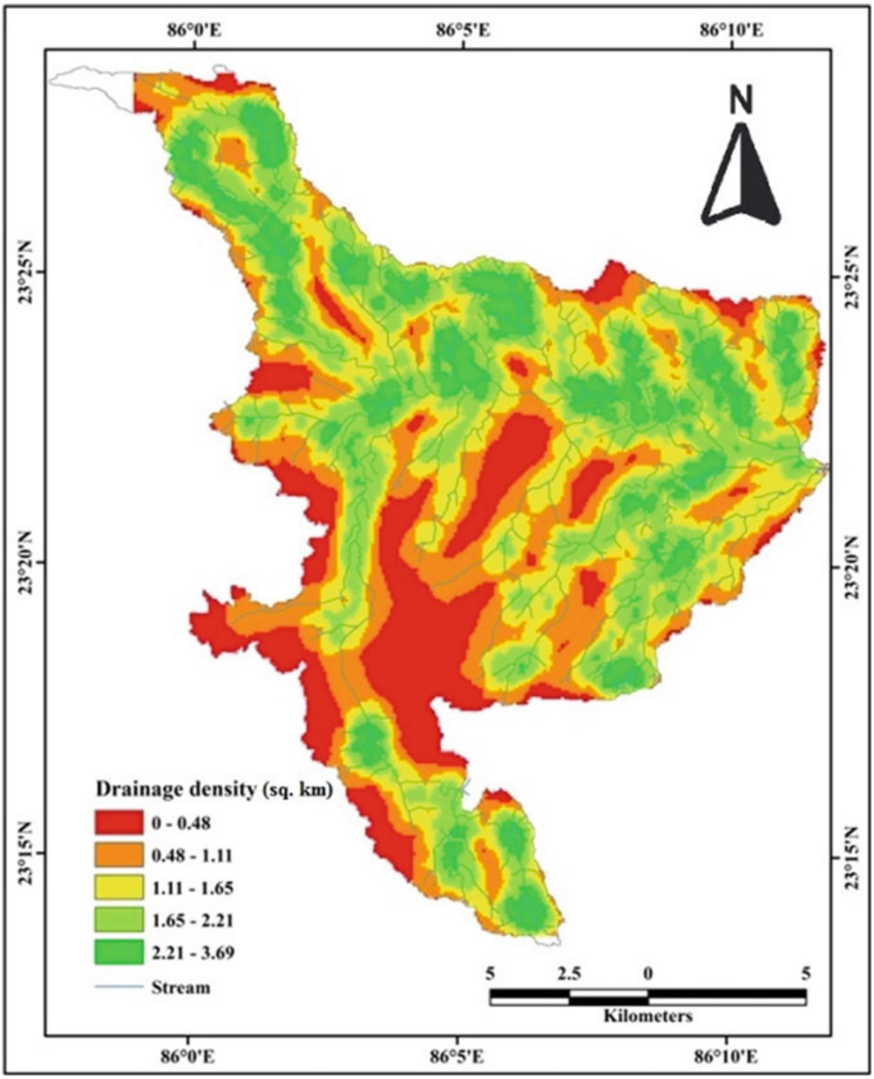

Fig. 10 Drainage density map of UKW

to moderate and hill wash deposition has good to very good depending on thickness of soil.

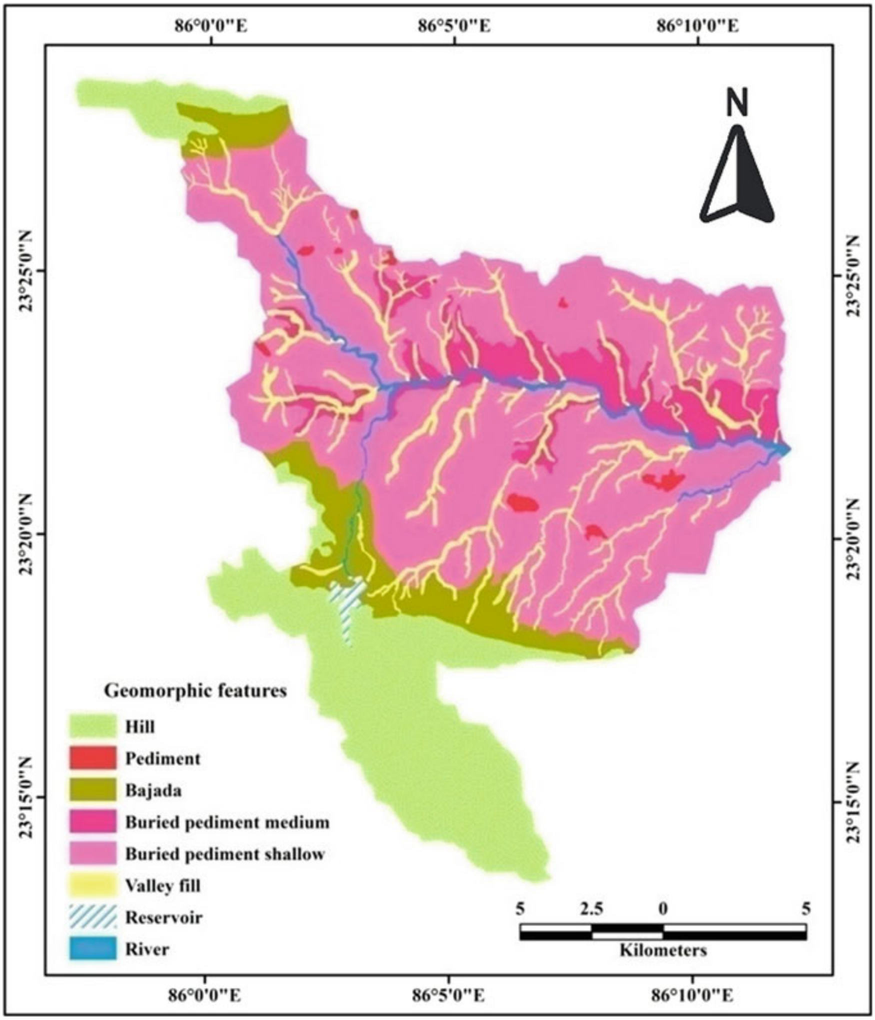

Fig. 11 Spatial variation of geomorphic characteristics of UKW

3.9 Weathering Profile

Weathering profile or saprolite zone is a sandwiched between weathered matter and un-weathered granitic rocks. The body of in situ weathered rock referred to as saprolite may comprise a number of zones depending on the relative rates of weathering, erosion and the composition and hydromorphic characteristics of regolith (Goudie 2004). In the present study area of UKW, depth of weathered zone varies from 7 to 14 m (Fig. 12). Thick weathered layer (11–14 m) occupied at middle portion of North, West and middle part of the watershed and this portion is not

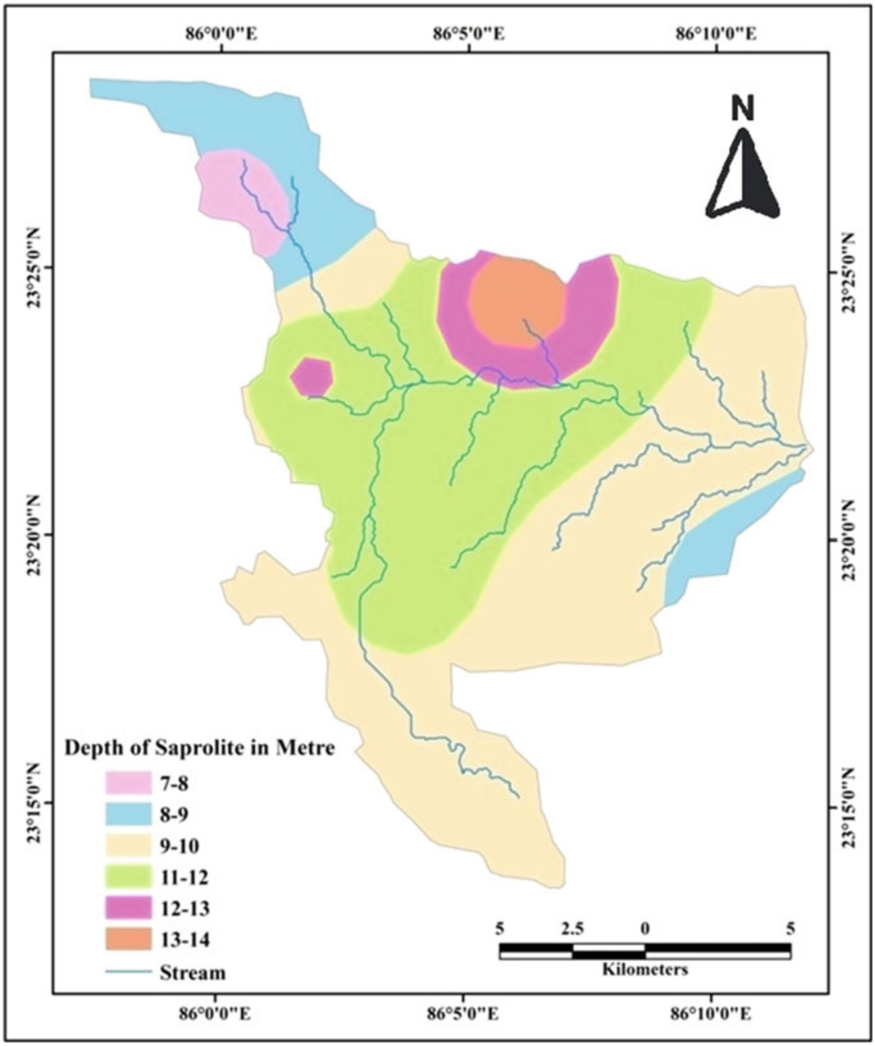

Fig. 12 Weathering profile map of UKW

suitable for RWH structures because water will be percolate and infiltrate through deep weathered layer. Comparatively thinner weathered layer found North-Western along with South-Eastern portion of the watershed and this area is more suitable for construction of RWH structures.

3.10 Estimation of Rainfall-Runoff

The average annual surface runoff depth as determined by using the SCS-CN method. It has reveals from the last fourteen years (2004–2017) of rainfall data in this region that the mean annual rainfall is about 1341.59 mm and the annual rainfall varies between 901.3 and 1783.8 mm. By using the equations number (3) and (4) of the SCS-CN method, it is estimated that runoff rate varies between 506.22 and 1360.77 mm (Fig. 13). It has also found from the fourteen years (2004–2017) of rainfall data that average annual runoff rate is 979.45 mm and runoff volume is 280.85 m^3. From the Fig. 13 it has indicated that higher rainfall leads to higher rate of runoff. The co-relation between rainfall-runoff has shown in Fig. 14 of the UKW which shows that rainfall-runoff strongly positively correlated ($R^2 = 0.96$). The co-relation results indicated that if the rainfall increased the runoff rate will also be increased and vice-versa. The runoff depth map (Fig. 15) of the present study area shows that north-western along with southern part of the hilly area has the highest runoff generation at >1100 mm/year and north-eastern and middle portion of the watershed has runoff generation at <900 mm/year.

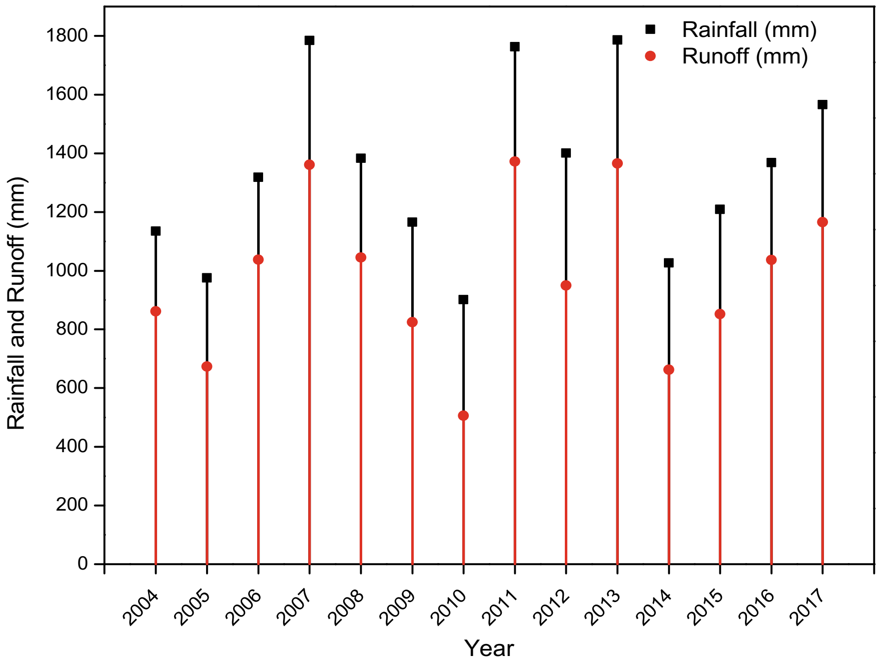

Fig. 13 Average annual rainfall versus annual runoff of UKW

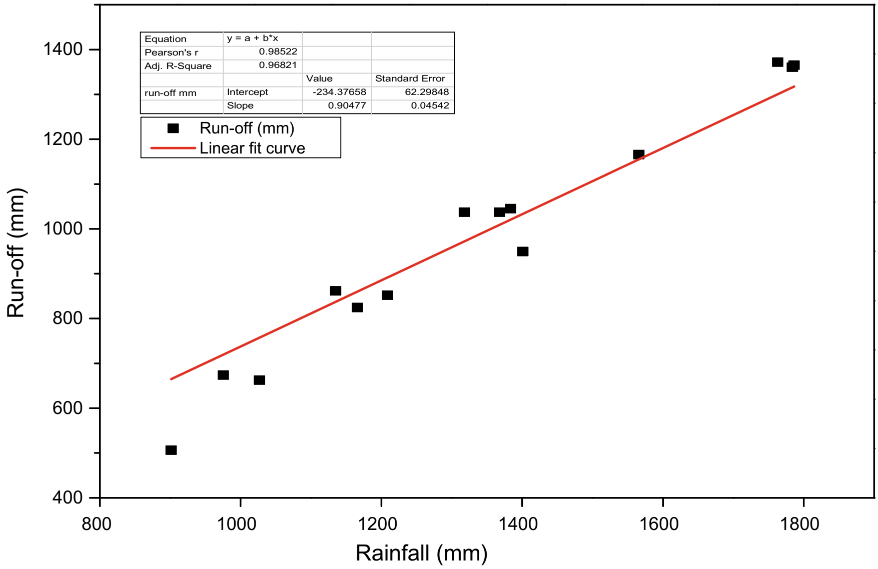

Fig. 14 Rainfall-runoff relationship of UKW (2004–2017)

3.11 Weighted Overlay Analysis and Sites for RWH Structures

Different thematic layers i.e. LULC, slope, soil texture, lineament density, geomorphology, weathering profile, runoff depth, and stream order have been taken to find out suitable location for RWH structures. Weight of these layers is given on the basis of general available knowledge in controlling the occurrence, storage space and allocation of ground water. Each and every layer used in this study again further divided into several classes. Finally, scores of different classes have been calculated on the basis of product of weight (Table 4). Weighted aggregation method has been applied to integrate all of these thematic layers with each other in ArcGIS 10.5 platform. It is a well-known fact that RWH structures generally set up along the lower order streams. The location of RWH structures should be in such a way that those structures should get sufficient amount of water to fulfill the daily needs of livelihood. It is also to remember that the structures should be neither too closes nor not too far from the agricultural filed and as well as from settlement area. This is due to abstain of sudden flash flood during the peak season of monsoon and from destruction of property. The resultant map of different RWH structures is shown in Fig. 16.

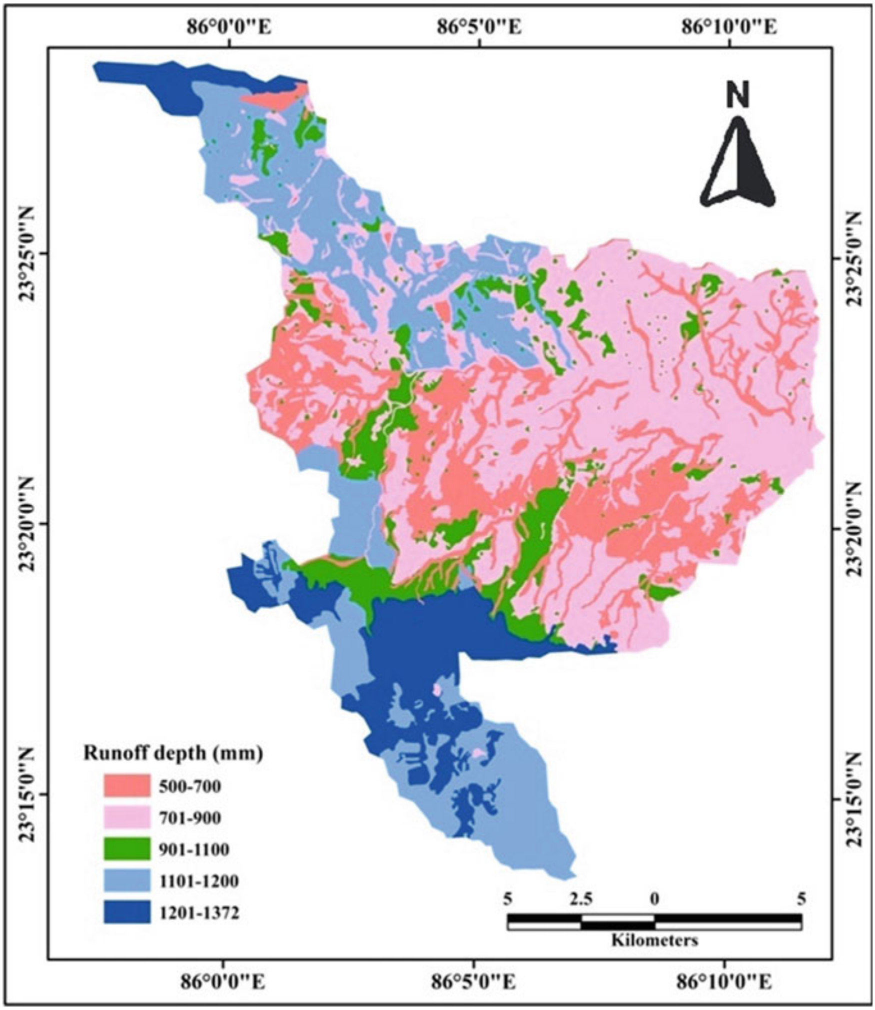

Fig. 15 Runoff depth map of UKW

4 Discussion

Guzha et al. (2018) and Owuor et al. (2016) has rightly mentioned that land use of a particular region play a crucial role to determining the runoff rate as well as the infiltration rate which has also fluctuate due to the progressively land use changes. In the UKW, the rate of surface runoff flow is comparatively high because of the present LULC pattern vastly dominated by single crop land. In addition, the HSG map of the UKW also indicate moderate rate of water transmission. The runoff curve number (CN) as an indicator of empirical parameter which has been used for

Table 4 Weightage criteria for site suitability of RWH structures in the present study area

Criteria	% of influence	Class	weightage	Criteria	% of influence	Class	weightage
Land use land cover	12	Dense forest	6	Runoff depth	21	1201–1372 mm	9
		Forest clearing	2			1101–1200 mm	9
		Open scrub forest	4			901–1100 mm	8
						701–900 mm	7
		Double crop	6			500–700 mm	5
		Single crop	5	Slope	14	Level to nearly level	9
		Pond	9				
		Reservoir	9			Very gentle	7
		River	7			Gentle	6
		Settlement	1			Moderate	5
		Wasteland	2			Steep	3
Geomorphology	8	Hill	1			Very steep	1
		Pediment	8	Weathering profile	10	7–8 m	3
		Bajada	6			8–9 m	4
		Buried pediment medium	8			9–10 m	6
						11–12 m	7
		Buried pediment shallow	7			12–13 m	8
						13–14 m	9
		Valley field	9	Drainage density	12	0–0.48	3
		Reservoir	9			0.48–1.11	5
		River	7			1.11–1.65	6

(continued)

Table 4 (continued)

Criteria	% of influence	Class	weightage	Criteria	% of influence	Class	weightage
Soil	13	Coarse loamy	8			1.65–2.21	7
						2.21–3.69	8
		Fine loamy	7	Lineament density	10	0–0.20	9
						0.20–0.56	7
		Loamy skeletal	5			0.56–1.00	5
						1.00–1.87	3

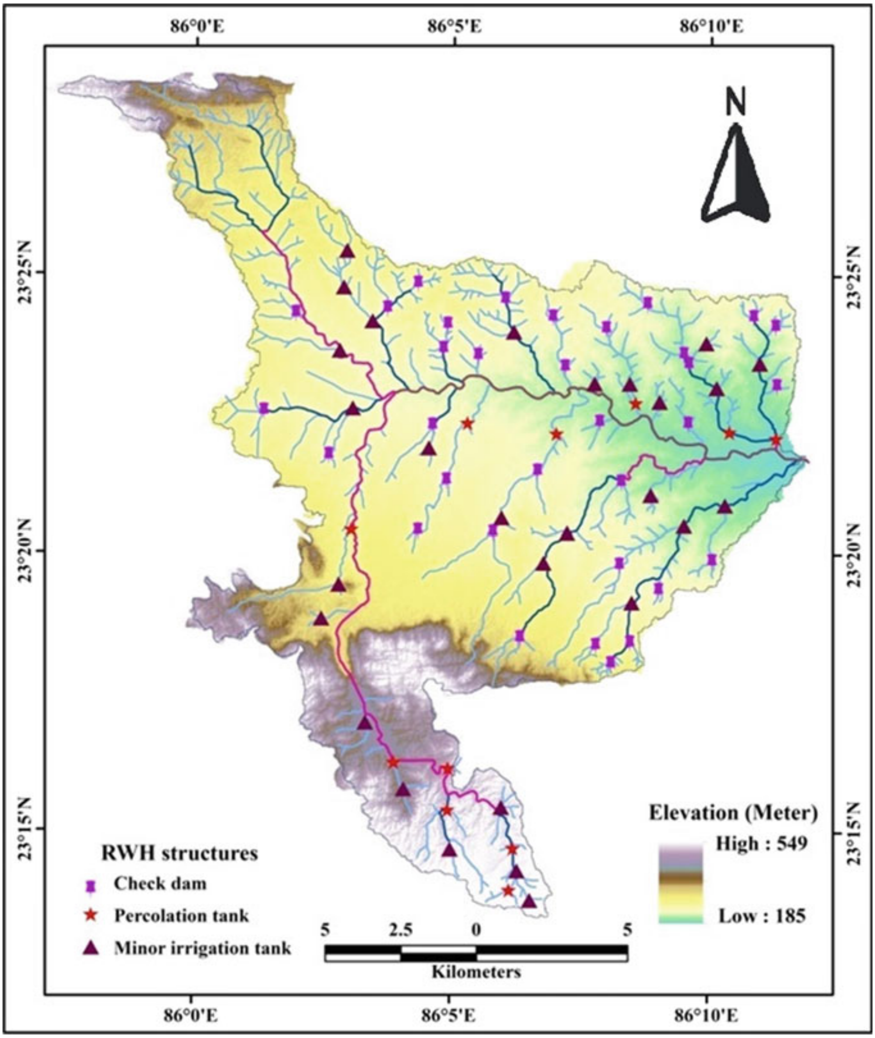

Fig. 16 Proposed sites for rainwater harvesting (RWH) structures of UKW

estimating the rainfall-runoff of a watershed. The result shows that in UKW, the CN varies from 40 to 100 in different location; which indicate normal moisture soil to dry soil in different respective locations. In addition, Mahmoud and Alazba (2015) and Prasad et al. (2008); Rao (2006) highlighted the importance of slope and lineament density regarding surface water flow. In the UKW, the slopes fall in the category of nearly level to very steep slope classes and in contrary, it is also a very high lineaments density region. However, Mugo and Odera (2018) has mentioned that lower order streams are most favorable for rainwater storage capacity and drainage density fundamentally emphasis on suitability of RWH structures. The high drainage density in the northern, north-western, and eastern part of UKW showed exactly the same potential zone of building of RWH structures.

Moreover, each geomorphic unit of UKW is the product of different aspect of slope, soil, weathering profile and fluvial erosional activities. The rocky upland surface in UKW is the products of erosional activities, while the rest of the surface is a product of a gradational activity mainly by fluvial processes. Middle northern and South-Eastern part of the UKW is more suitable for construction of RWH structures. On the other hand, depth of runoff in this UKW area indicate that north-western and southern portion of the hilly area has the highest runoff generation and north-eastern and middle portion of the watershed has runoff generation at <900 mm. Finally, overlay of different thematic layers i.e. LULC, slope, soil texture, lineament density, geomorphology, weathering profile, runoff depth, stream order has indicating the suitable site for RWH structures in UKW. All of these thematic layers are divided into different classes and given them individual scores on the basis of product of weight. To facilitating RWH structures, scale values of 1 to 9 are assigned individually. The score value 1 indicated lowest Weightage and score value 9 indicated highest weightage. In this research study, different parameters were used which are mentioned in technical guidelines of IMSD, NRSA, and INCOH for suitable sites of RWH structures. Parameters for different RWH structures are as follows-

1. Check dams—constructed in lower orders stream up to 3rd order streams, slope ranges between 2 and 5% with deep soil cover.
2. Percolation tanks—basically, constructed lower portion of the check dam i.e. in the downstream segment, slope ranges between 3 and 5% and soil having adequate permeability.
3. Minor irrigation tanks—availability of sufficient catchment area in the upstream side, slope of <8%.

5 Conclusions

The space technology along with GIS techniques can be used effectively for sustainable watershed development and water resource management purposes. It has widely recognized that site suitability analysis for identification of RWH structures using runoff (SCS-CN) model, remote sensing and GIS techniques has an advantage over the conventional method. This is due to the GIS platform has the capability to integration of different layers of variety parameters and as a result which give a composite layer for suitability units. It is necessary to estimate surface runoff in relation with rainfall within a watershed to manage water resources, particularly in drought-prone areas. Whereas, the UKW belong to drought prone region, therefore, sustainable water resource conservation and uses is important for all kind of development activities. The results of present study suggest that the rate of water percolation and ground water recharge are low compare to the annual rainfall due to the high rate of surface runoff. Thus, excessive rate of runoff degraded natural resources like land degradation through soil erosion and severe water scarcity all over the UKW. Therefore, to overcome these problems, formation of artificial recharge structures is very much necessary. Thus, in this analysis site suitability of check dams, percolation tanks, and minor irrigation tanks were assigned. The site suitability of RWH structures map will be very much helpful to watershed planners and hydro for sustainable watershed management and water resource planning.

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Identification of Groundwater Potential Areas Using Geospatial Technologies: A Case Study of Kolkata, India

Sushobhan Majumdar, Uday Chatterjee, Pravat Kumar Shit, and Gouri Sankar Bhunia

Abstract The problem regarding the uses of groundwater and daily needs is very high in the third world countries like India. Kolkata is one of the metropolitan cities in India, facing several problems, like lack of drinking water, lack of water for daily uses etc. This study is focus to delineate groundwater potential areas of Kolkata with the help of geospatial techniques. Weightage indices have been calculated with the help of few criteria's like geo-morphological map, hydro-logical map, land use and land cover map etc. Results show most of the area in Kolkata city comes under the low potential zone for groundwater. This type of study will throw a new light over the future studies in the field of groundwater management. Side by side efforts has been made to recommend few suggestive measures to mitigate the problems of groundwater in Kolkata city.

Keywords Groundwater potential zone · Kolkata metropolitan · Sustainable planning · Weighted indices

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1 Introduction

Groundwater is playing a major role in any developmental activities. In urban areas, the major source of water is groundwater. In the tropical regions like India, there is uncertainty of rainfall, the inhabitants of the urban areas and the poor farmers in rural areas have to be depending on the groundwater resources for their drinking purposes and cultivation purposes respectively.

Geospatial technologies and its tool like Remote Sensing (RS) and the Geographical Information System (GIS) is one of the essential tools for groundwater management due to its synoptic coverage, repetitive activity, analyzing spatio-temporal characteristics of the data. In the groundwater study, RS and GIS are not directly helped, but aids to identify the potential areas for the groundwater potential area based on the environmental variables (Remesan and Panda 2008; Subramani et al. 2012). Geophysical techniques along with other previous methods like physical techniques and photo-geological techniques have been employed to identify the groundwater potential zones (Taylor and Howard 2000; Srivastava and Bhattacharya 2006; Adhikary et al. 2015). Recently various types of satellite data has been used for the mapping of ground water potential zones with the help of old maps mainly used for the ground truth verification (Muralidhar et al. 2000; Chowdhury et al. 2010). In Taiwan, first groundwater potential study has been carried out using geo-informatics with the help of several physical factors like lithological features, land use types, lineament and its types with distribution, drainage characteristics and slope (Musa et al. 2000). Kumar et al. (2012) makes an effort to find out the groundwater potential zones in the south western part of India, Kerala. Tiwai et al. (2017) has been conducted a study about the different processes of ground water recharging in the Damodar river valley area in India. Behzad et al. (2015) makes an attempt to find out the different categories of ground water potential areas in the hilly areas of India using remote sensing technologies.

The weights of factors contributing to the groundwater recharge are derived using aerial photos, geology maps, a land-use database, and field verification. For mapping of groundwater zones soil, land use and land cover, geology, geomorphology, rainfall, drainage density were derived from the high-resolution satellite images (Sciences 2013).

2 Study Site

Kolkata is one of the major metropolitan cities in India, have been flourished from the period of the British era. Kolkata is under the jurisdiction of Kolkata Municipal Corporation (KMC), extending between 22° 34′ North latitude and 88º21′ E longitude (Fig. 1). Kolkata and its surroundings are known as Kolkata Metropolitan Area (KMA). The total numbers of wards in KMC are 144. After 2012, few areas of Joka I and Joka II panchayats have been added with KMC and total areas of KMC

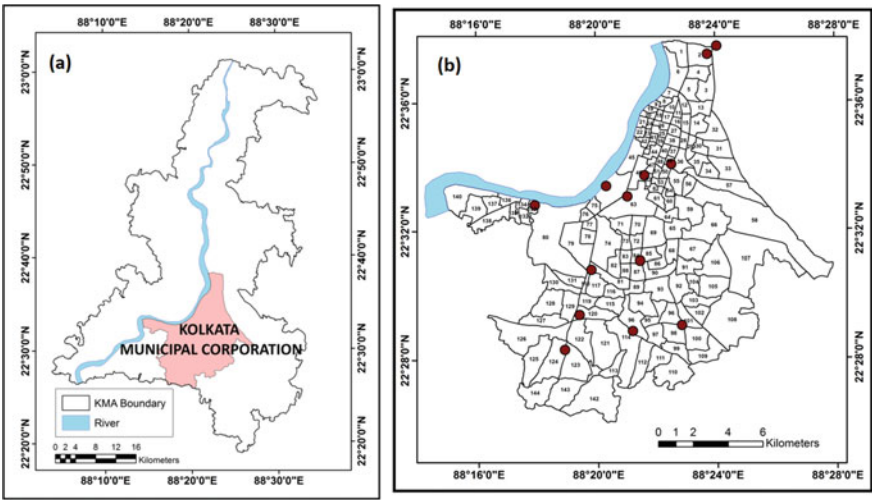

Fig. 1 **a** Location of Kolkata Municipal Corporation. **b** Network stations in KMC

has been increased into 200 km^2. Kolkata city is located in the eastern bank of the Hooghly River and on the large alluvial plain of the delta. The heights of Kolkata city ranges from the 0 to 9 m from the sea level (United States Geological Survey). The population of KMC is 4.54 lakhs with a growth rate of −0.38% from 2001 to 2011 census. The Climate of Kolkata is under the monsoonal climate. The temperature of Kolkata is maximum in the month of May–June (ranges from 35° to 45 °C) and minimum in January–February (ranges from 15° to 20 °C) month. July and August month are the rainy season and also the ideal time for groundwater recharge. The soil of Kolkata is mainly alluvial as this city is located on the thick alluvial deposit of Hooghly River and also a major part of the moribund delta.

Total number of boroughs in KMC is 16. There are few pumping stations in Kolkata from where groundwater has been collected (Fig. 2).

3 Data and Methods

An earlier study reported that the groundwater of Kolkata city is depleting very rapidly (KMC 2012). To find out the potential areas of groundwater various physical maps like slopes, elevation, drainage characteristics, land use and land cover types, geomorphology, hydrological, hydrochemical map have been used. Drainage map, geo-morphological map, hydrochemical zonation map etc. have been collected from the Kolkata Municipal Corporation from Dharmatala Area with a scale of 1:38,000, KMDA offices in Salt lake with a scale of 1:42,000 etc. After Collection of those maps, those maps have been digitized with the previously geo-referenced map with the same topographic scale.

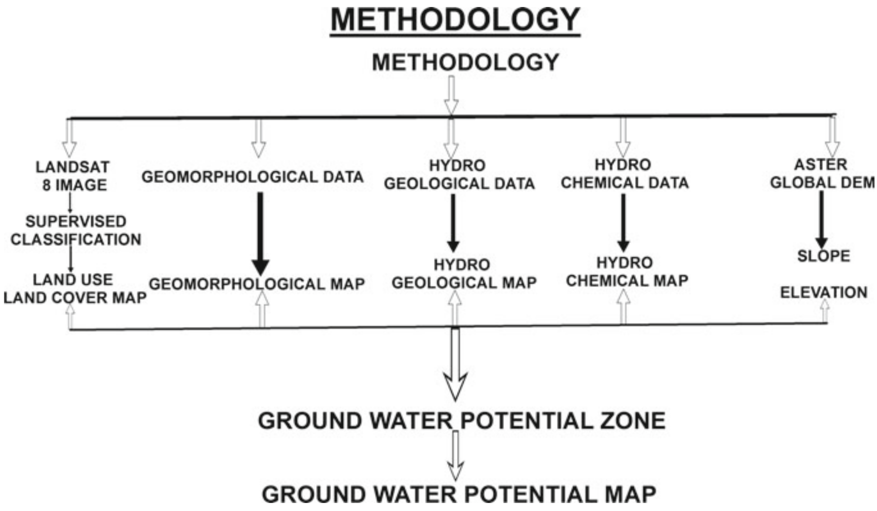

Fig. 2 Framework of research methodology

Uses of land and land cover types of Kolkata were prepared from Landsat OLI 8 satellite images of 2019 (138/44, Date of Pass 12.03.2019) of Kolkata based on supervised classification. The Advance Space Thermal Emission Radiometer (ASTER) DEM has been collected from Jet Propulsion Laboratory, California Institute of Technology (https://asterweb.jpl.nasa.gov/gdem-wist.asp) to prepare the elevation and slope map. DEM was generated through 5 m contour interval. Slope and elevation map are collected from the United States Geological Survey from Advance Space Thermal Emission Radiometer (ASTER) DEM global land cover data.

Field verification has been carried out during the period between March–April month and September–October month (i.e. before and after the rainy season) to scrutinize the reason for depletion of groundwater. For image processing, Erdas Imagine software v14 has been used.

All the thematic layers are finally integrated and overlapped using ArcGIS desktop software v14 to yield groundwater potential areas (Table 1). All the thematic layers were overlaid to delineate an integrated output of groundwater potential zone map of Kolkata city.

4 Results and Analysis

From the various maps and reports, it has been found that the groundwater of Kolkata city has been depleting very rapidly. The condition of groundwater in the few areas is so poor that the percentage of groundwater has been totally depleted. As a result, the groundwater layer of Kolkata city has been transformed into a shallow layer which can cause land subsidence in any area.

Table 1 Weighted indices of the indicators

SL. no	Criteria	Classes	Rank	Weights (%)
1	Geomorphology	Deltaic plain	1	20
		Inter-distributary Marsh	2	
		Older Levee	3	
		Younger Levee	4	
2	Hydro-geological map	A group	1	15
		B group	2	
3	Hydro-chemical map	Ca–Mg–Cl type	1	7
		Ca–Mg–HCO_3 type	2	
		Na–Cl type	3	
		Na–HCO_3 type	4	
4	Land use and land cover map	Vegetation	4	20
		Water bodies	3	
		Barren land	2	
		Built-up area	1	
5	Drainage network	Less than 30 m	1	25
		30–60 m	2	
		60–90 m	3	
		90–120 m	4	
		More than 120 m	5	
6	Slope	Low	1	5
		Medium	2	
7	Elevation	Low	1	5
		Medium	2	

Figure 3 shows the geo-morphological map of Kolkata Municipal Corporation (KMC). From the geo-morphological map of KMC, it has been found that Kolkata is located mainly in the alluvial plain of the Hooghly River. The geo-morphology of this area has been classified into four categories. Those are Deltaic Plain, Inter-distributary Marsh, Older Levee and Younger Levee. The percentage (Table 2) of the older levee (15.05%) is high in the upper i.e. the northern portion of Kolkata and the younger levee (17.01%) can be found in the southern portion of the KMC. Because of the presence of the alluvium layer, the infiltration of water below the ground is very high, but now the layer of groundwater is depleting very rapidly because of low infiltration of water in the subsurface layer and over-exploitation or excessive use of the groundwater. Soumen (2014) opined that the amount of groundwater concentration is high in the low lying area and alluvial plain area, but it is low in the mountain area or the residual hilly area.

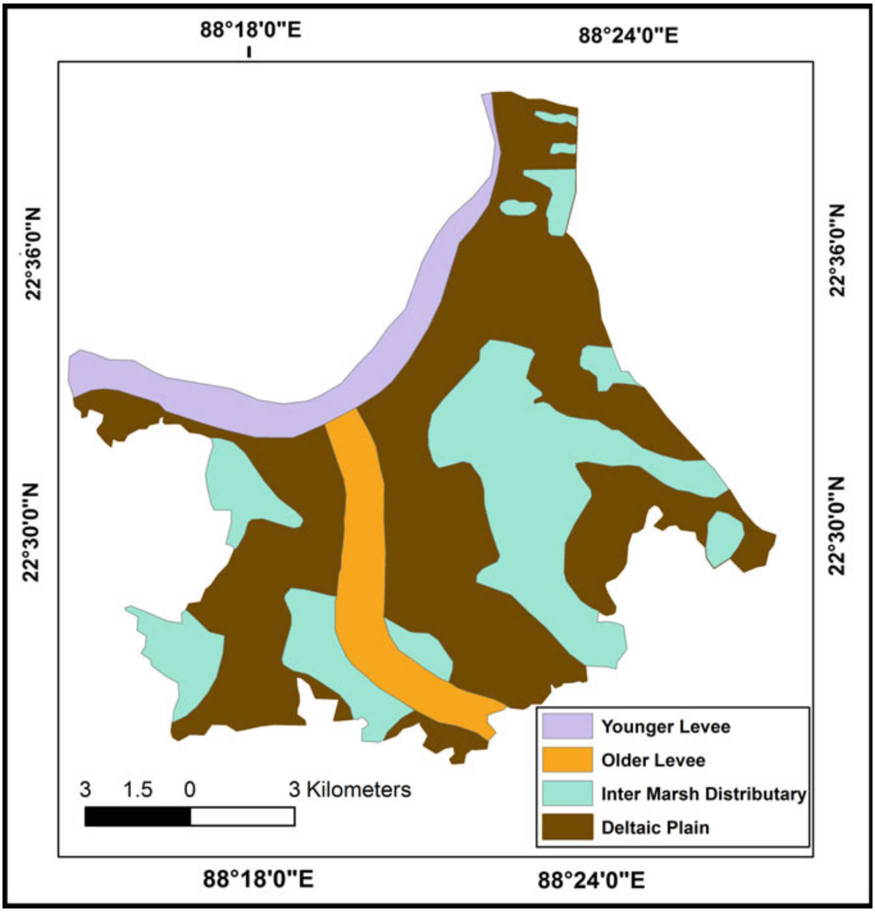

Fig. 3 Geo-morphological map of Kolkata

Table 2 Weighted indices of the geomorphological indicators

Class name	Area (km^2)	%	Description	Weightage
Younger Levee	31.45	17.01	Mainly beside the Hooghly river because of the deposit of aluvium	7
Older Levee	27.87	15.05	Mainly beside the Tolly Nallah towards the southern parts of Kolkata	6
Interdistributary Marsh	59.65	32.24	Areas beside the east Kolkata wetland areas and in the southern parts of Kolkata	4
Deltaic plain	66.51	35.95	In the northern and central part of Kolkata i.e. part of the Morbund delta	3

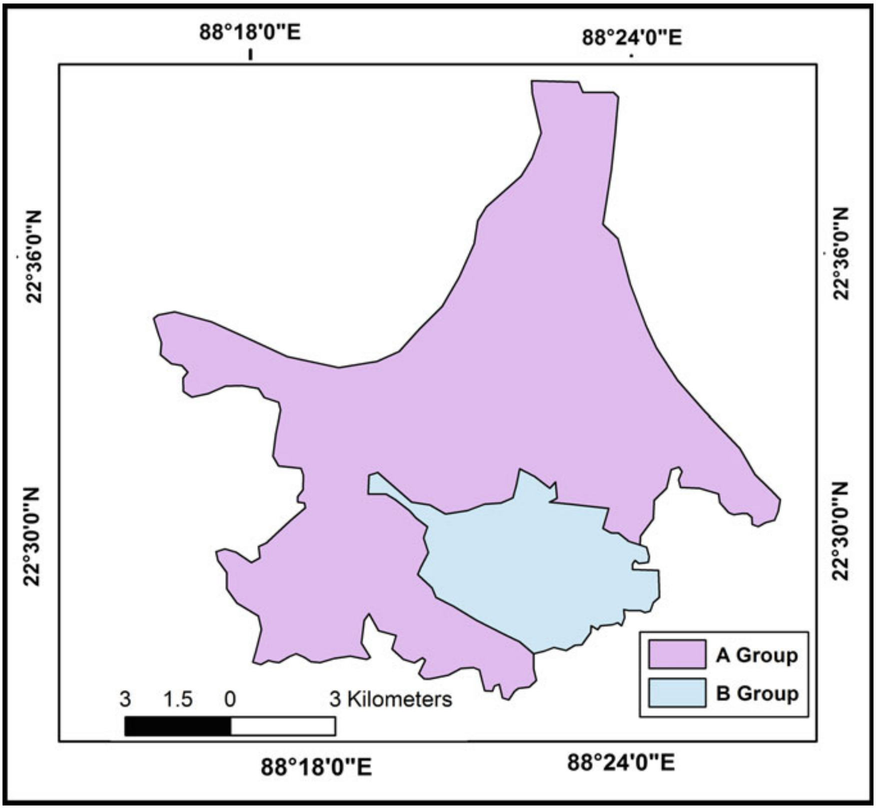

Fig. 4 Hydro-geological map of Kolkata

Figure 4 shows the hydro-geological map of Kolkata Municipal Corporation shows that most of the land in this area belongs to the quaternary and upper tertiary time period. Alluvium, clay, silt, sand, gravel and pebble are the major lithological characteristics of the area. The layer of this area is thick in nature with confined aquifer of 360 m. These are the major hydrological characteristics of the area. In this map, group A indicates the area where fresh water is overlain by saline groundwater and group B indicates that area where fresh groundwater is underlain by saline groundwater. Most of the area of KMC is under the subgroup A, which covers almost 75% of the total area and it is followed by group B which covers only 45% of the total area (Table 3). The area under B group is high in the southern parts of Kolkata. So,

Table 3 Weighted indices of the hydro-geological indicators

Class name	Area (km^2)	%	Description	Weightage
A group	139.39	75.35	Whole parts of KMC except Southern Part	8
B group	45.61	24.65	Only Southern Part	7

most of the areas in the southern Kolkata is under the saline water or arsenic prone areas. There are two types of pipelines in the southern parts of Kolkata one is from the KMC and another is a direct pipeline from the Garden reach pumping station. Most of the people prefer the water from Garden Reach pumping station areas as the quality of water is relatively high than the KMC pumping stations.

Figure 5 explains the hydro-chemical conditions of the groundwater of the Kolkata Municipal Corporation. There are two types of hydro-chemical layers are present in Kolkata. Firstly, the area where fresh water is underlined by the saline water and secondly the area where the saline water is underlain by the fresh water. These two are the typical types of hydro-chemical composition can be seen in this area. Other than these types of characteristics there is four compositions of water has been found here those are Chemical Ionization of Calcium-magnesium (Ca–Mg–C_i) type, Calcium-magnesium hydrogen carbonate $(Ca–MgHCO_3)_2$ type, Sodium Chloride (Na–CI) type and Sodium-bicarbonate $(Na–HCO_3)$ type (Table 4).

Figure 6 explains the characteristics the patterns of land use and land cover in the Kolkata Municipal Corporation (KMC) Area. From the overview of types of land use and land cover features, it has been found that urban area or the built-up area is

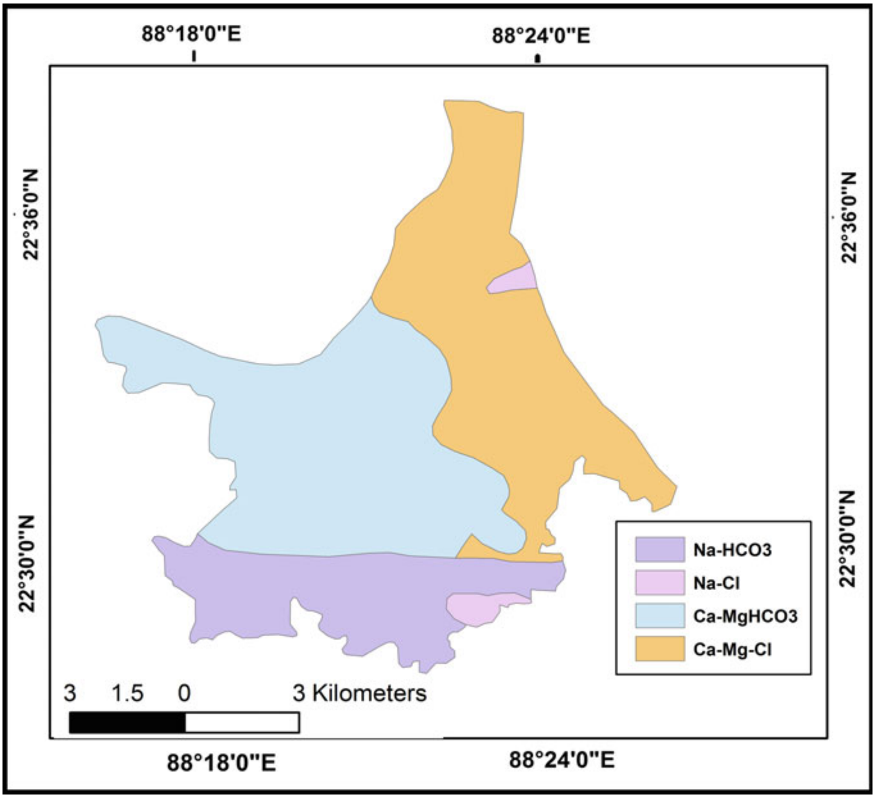

Fig. 5 Hydro-chemical map of Kolkata

Table 4 Weighted indices of the hydro-chemical indicators

Class name	Area (km^2)	%	Description	Weightage
(Ca–Mg–C_i) type	78.05	42.19	Chemical ionization of Calcium-magnesium	3
$(Ca–MgHCO_3)_2$type	71.37	38.58	Calcium-magnesium hydrogen carbonate	2
(Na–CI) type	5.42	2.93	Sodium chloride	1.5
(Na–HCO_3) type	31.05	16.78	Sodium-bicarbonate	0.5

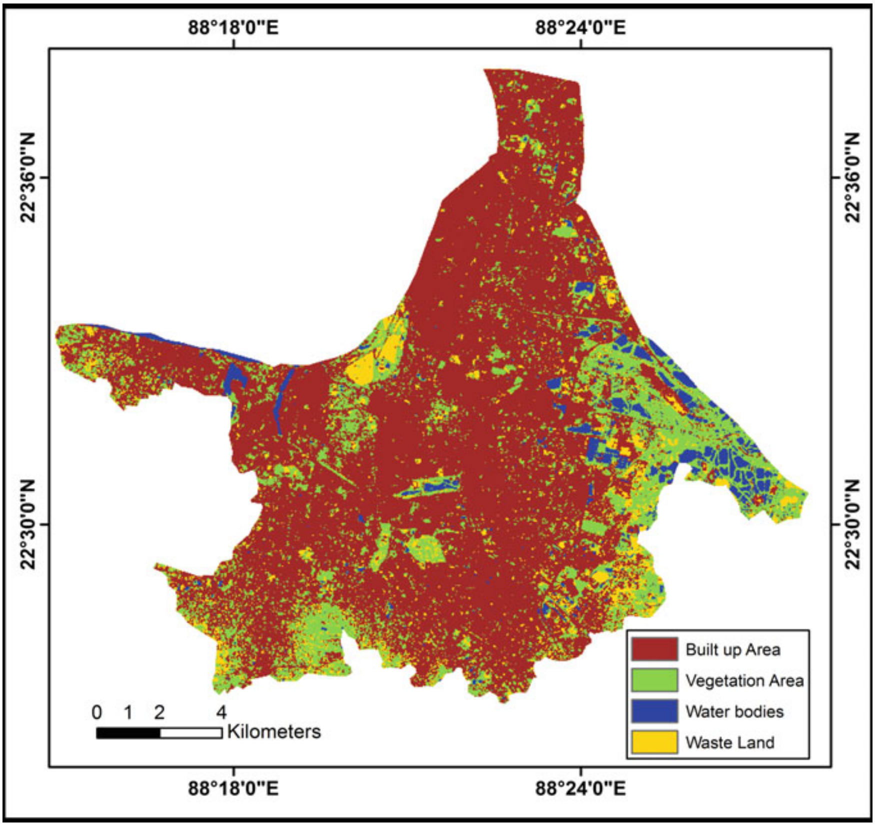

Fig. 6 Land use and land cover map of Kolkata municipal corporation

the major land use and land cover in this area (Table 5). It is followed by vegetation area, water bodies, barren land and a very small amount of urban agriculture mainly towards the eastern part of the KMC area. The percentage of built-up area in this area is very high which creates an adverse impact on the local land resources. Because of the increase in impervious surfaces, the infiltration of rain water is very less in this

Table 5 Weighted indices of the LULC indicators

LULC class name	Area (km^2)	%	Description	Weightage
Vegetation	29.01	15.68	Outside the CBD areas	9
Water bodies	18.06	9.762	Mainly eastern parts	7
Waste land	34.32	18.55	Scattering all over the KMC	3
Built up area	103.61	56.01	Mainly Central Part (CBD) and Northern Area (older Part)	1

region. For this reason, groundwater recharge is not successful properly. According to the Chowdhury et al. (2010) the infiltration of ground water is high in the waterlogged or forest area and it is very low in the urban area.

In the southern part, the conditions of the drainage system are very poor, the elevations of the area are very low and the drain is not properly clean regularly which makes this area completely waterlogged in the rainy season or any certain amount of rainfall in a short time period. Figure 7 shows the height of water in the KMC area which indicates that the height of water in the northern portion of KMC is very less as this is the most older parts in this area. Other than these the height of groundwater is slightly high in the southeastern and southwestern part of the area as these area has been flourished later and these areas are the newly added area of KMC (Table 6).

Figures 8 and 9 show slope and elevation map of KMC respectively. Results show that the elevation is high in northern part than the southern parts. The whole region is slightly tilted towards the southern direction because of the presence of Ganga delta and Bay of Bengal (Table 7).

The potential areas of groundwater are identified by overlapping all the maps produced in this study using weighted overlay method by using a spatial analysis tools and techniques of ArcGIS software. During this analysis, the ranks have been assigned based on the influence of the different parameters. After that, all the thematic maps were converted into raster format through "Reclassification" technique in ArcGIS software.

From potential areas (Fig. 10) of groundwater, it has been found that most of the area in Kolkata city is low groundwater potential zones (Table 8). As most of the areas in Kolkata city is under the impervious area. The rate of infiltration of groundwater is very less in this area.

From the above study, it has been found that in Kolkata because of the increase in the impervious surfaces the rate of infiltration of water in the ground is very low which creates extreme pressure in the urban ecological conditions of the city. Other than these from the field verification, it has been found that because of the urban expansion most of the wet lands and water bodies have been converted into the urban area or residential area, which indirectly reflects on the urban environmental conditions of the city. In some areas near the southern part of the KMC (Like Behala, Metiaburuz) the layer of groundwater is totally depleted, for this reason the inhabitants of those areas have to be depend on the municipal car services for the consumption of drinking

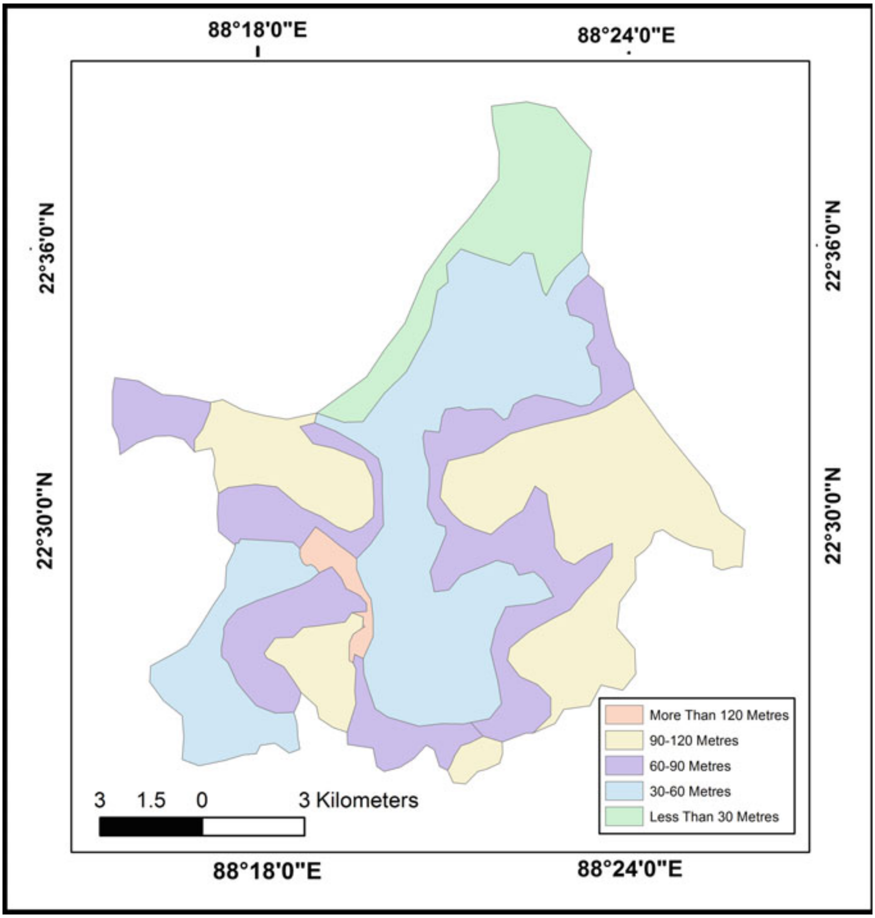

Fig. 7 Height of water level in Kolkata

Table 6 Weighted indices of the height of water level indicators

Height of water level	Area (km^2)	%	Weightage
Less than 30 m	5.75	3.11	7
30–60 m	39.41	21.30	6
60–90 m	45.37	24.52	5
90–120 m	63.24	34.18	4
More than 120 m	31.23	16.88	3

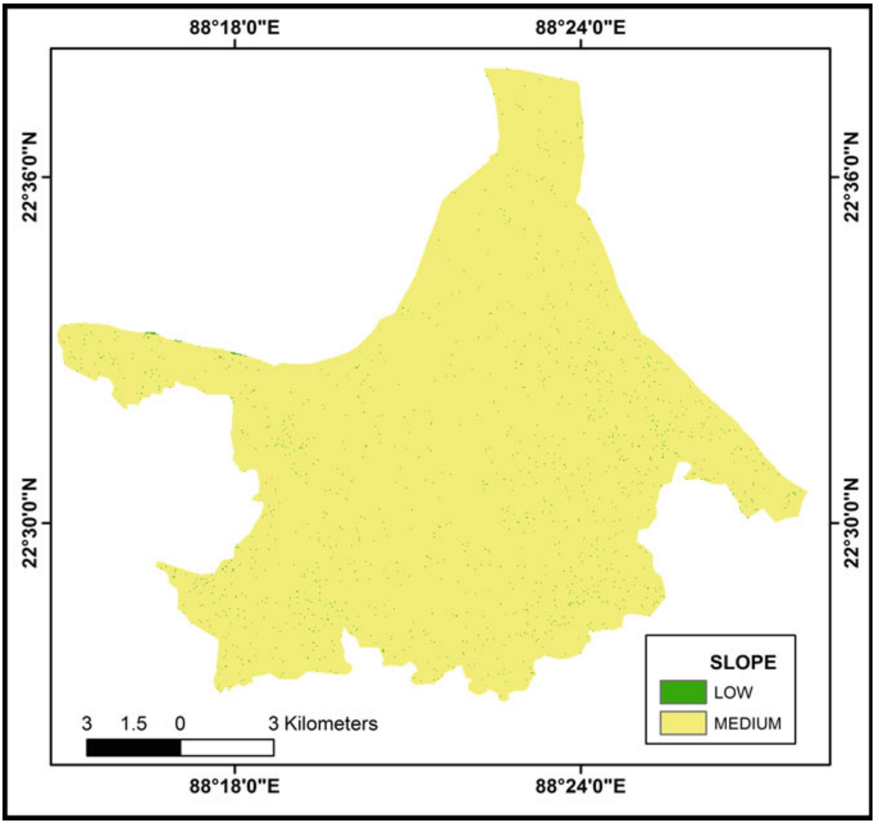

Fig. 8 Slope map of Kolkata

water. From this study, it has been found that the potential zone with low groundwater is high in the northern parts of the Kolkata as those areas are the old city areas in Kolkata. The percentage of area of high groundwater potential is high in the southern parts of Kolkata and those areas are the newly added areas of Kolkata.

5 Discussion and Recommendation

To save the groundwater of KMC area, overuse, misuse or exploitations of the groundwater should be strictly stopped. Otherwise future generations have to depend on the rain water for their daily needs. There are no master plans for the Kolkata city. So, Govt. Officials and policymakers should prepare a strict master plan to protect and save the groundwater from its misuse. Most of the drainage network systems in Kolkata city are very old in nature which was mainly developed by the Britishers. So, decision-makers and urban planners have to make a well-planned drainage system

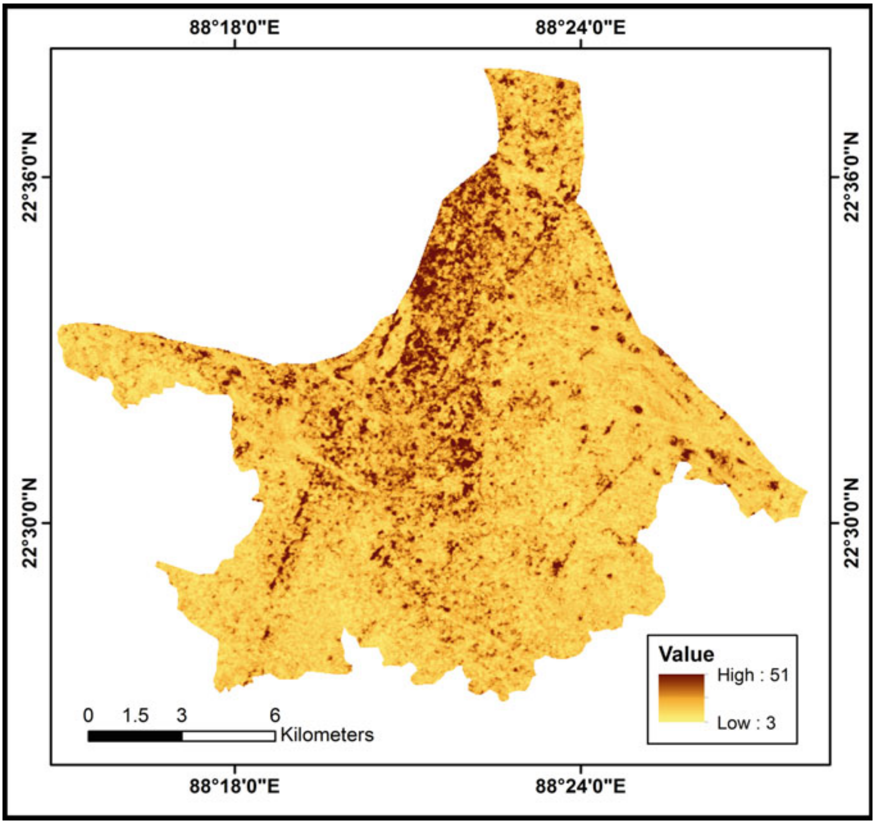

Fig. 9 Elevation map of Kolkata

Table 7 Weighted indices of the slope and elevation

Slope	Description	Weightage	Elevation	Description	Weightage
Low	High infiltration	3	High elevation	Low infiltration	2
Medium	Low infiltration	2	Low elevation	High infiltration	3

network to prevent Kolkata city from waterlogging and for the groundwater recharge. Kolkata Municipal corporation authorities should restrict the uses of the groundwater and the authorities should give subsidies to the inhabitants who are using natural water for their daily uses. The authorities should increase water tax to prevent the misuse of the groundwater. Lastly, awareness among the people should be increased to know about the importance of groundwater.

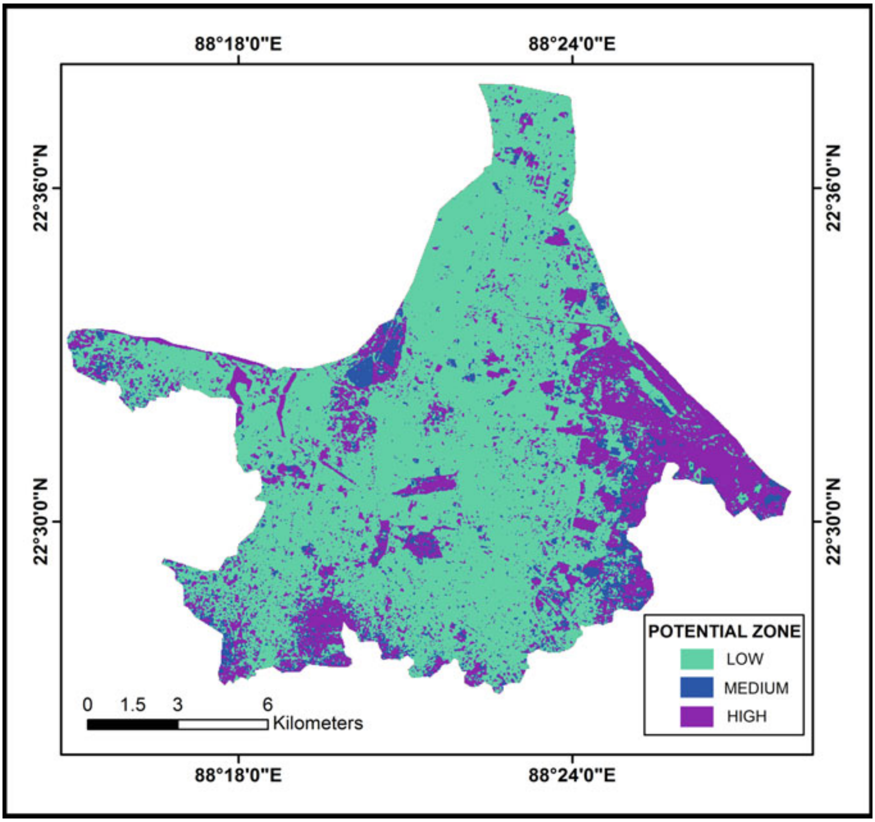

Fig. 10 Potential zone of groundwater in Kolkata

Table 8 Groundwater potential areas in KMC

Potential zones	Area (km^2)	%	Description
Low	94.61	51.14	Mainly in the CBD areas and Northern Parts
Medium	41.32	22.34	Scattering all over the areas
High	49.07	26.52	Mainly in the east Calcutta Wetland areas and fewer areas in southern parts

6 Conclusion

Kolkata is one of the cities in West Bengal which have experienced rapid development mainly because of the rapid influx of refugees and major infrastructural development. Because of the huge increase in an urban area or built-up area the rate of infiltration of rain water has been decreased in this area very rapidly. This is the major reason behind the decline of groundwater level. The groundwater potential zones with high possibilities are very low in this area and most of the area is under the very low groundwater potential area. In the area of high potential of groundwater, the infiltration rate of groundwater will be high and vice versa. The percentage of the low potential zone is high in this area just because most of the area is under the urban land area or built-up area. So, water cannot penetrate over the low potential zones. Govt. officials and policymakers should take immediate measure to solve the problem of groundwater in Kolkata city. Otherwise, it will make a natural disaster which leads to the destruction of the city also. These types of study will throw a new light over the future study. It will help other policymakers to take immediate planning measures to mitigate the problem of groundwater of Kolkata city. The study which has been done over the Kolkata city can also be applied to the other major cities also. As the importance of water and groundwater is very high in our daily life, so it is one of our duties or responsibilities to save the water for future generations.

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Geospatial Assessment of Groundwater Potential Zone in Chennai Region, Tamil Nadu, India

K. S. Vignesh, P. Thambidurai, and V. N. Indhiya Selvan

Abstract The major source of drinking water is Groundwater for human life. The current study utilized the geospatial techniques, to identify the groundwater potential zones in Chennai region. The calculable parameters used to conduct this study such as soil, land use/land cover, geomorphology, geology, slope, rainfall, lineament, drainage density, lineament density and NDVI which has been derived to identify the groundwater potentiality in the research area. The weighted overlay technique determines the influence of various parameters based on the assigned weights. The study highlighted the groundwater potential zones in five categories such as very low, low, moderate, high and very high. The result reveals that western and south western zones of the Chennai region records 60% dominant in groundwater. The study will also enhance the stakeholders for the purpose of planning, resource management and other developments in the study area.

Keywords Groundwater potential zone · Thematic layers-Weighted overlay analysis · GIS and remote sensing · Chennai region · Tamil Nadu · India

1 Introduction

Globally, two third of groundwater is considered to be the freshwater resources (Chilton et al. 1995). It is a substantial part of ecosystem and environments. Groundwater plays a major role for all the purpose of water requirements preferably for drinking, agriculture, industrial and ecological function in the hydrological system

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(Varma and Tiwari 1995; Takem et al. 2011). According to Howard (2002) urbanization, in particular, groundwater resources are being increasingly exploited to meet this growing demand and can make a serious constraint on quality and local resource in later. Due to high population in the metropolitan cities, there occurs a serious threat to groundwater and its quality (Thambidurai et al. 2014). A technical report published by Central Groundwater Board (CGWB 2017) was stated that the 70% of groundwater is utilized for agricultural purposes and whereas in urban areas 90% is utilized for domestic water consumption. Due to population growth, urban areas are facing extensive water scarcity which is indirectly declines the groundwater resources. According to the UNESCO (2000), the death rate tolls around 2.2 million per year in the world due to lack of safe drinking water. Comparatively it's a natural phenomenon that the groundwater is clearer safer than the surface water. Due to population growth, urban areas are facing extensive water scarcity which indirectly declines the groundwater resources (Takem et al. 2010). The Government is facing serious problem in managing the groundwater resources, particularly with the aquifers available around the areas in the country.

The enormous usage of groundwater for domestic and an irrigation purpose declined the level of water resource and also cause devastating damage to the aquifer by water contamination and pollution. One of the main problems is groundwater pollution in India and the issues of water quality for various physical and chemical parameters were reported (Thambidurai et al. 2013; Moharir et al. 2017). Todd and Mays (1980) strongly addressed that geophysical, hydrogeological, and drilling methods are suitable to identify the groundwater zone. Nowadays, advancement of technology and satellite-based information are used extensively to access the baseline information of potential groundwater zones and sustainable management of resources (Magesh et al. 2012; Sener et al. 2005).

The Geographical Information System (GIS) facilitates wide range of user friendly support on spatial data management and spatial analysis (Burrough 1986) and also it can offer precise spatial information which overcomes the traditional methods like hydrological and geological surveys. Furthermore the authors Saraf and Choudhury (1998) reported the integration of geographical information system and remote sensing as an effective tool for exploring groundwater prospective zones. Adding, Sander et al. (1996) highlighted the feasibility of identifying the groundwater zones using various influential parameters.

The concept of ascertaining the potential groundwater zones through geographical information system and remote sensing were studied by the researchers around the globe however the influential parameters varies and depends on the topography of the study area (Nagarajan and Singh 2009; Imran et al. 2010; Oh et al. 2011; Magesh et al. 2012; Nag and Ghosh 2013; Bagyaraj et al. 2013; Kumar et al. 2014; Selvamet al. 2015; Yeh et al. 2016; Kanagaraj et al. 2019). For an effective identification of groundwater potential zone, the present study includes various influencing factors are (1) Geology which facilitates precise information on primary rock layers. (2) Geomorphological study enriches the information on surface landforms. (3) Soil texture provides information on downward movement of water to determine the groundwater potentiality. (4) Slope regulates the surface water infiltration. (5)

Elevation determines the availability of groundwater. (6) Rainfall is unique factor for groundwater recharge. (7) LU/LC influences forecasts the rate of surface runoff and infiltration. (8) Drainage density also regulates the surface water infiltration into the soil. (9) Lineament density governs movement of groundwater with respects to geological faults and fractures. (10) Normalized Difference Vegetation Index (NDVI) contributes the assessment crop stage condition precisely. Probably for the first time, the current study attempted to identify an effective groundwater potential zone using geo-spatial technology integrated with multi-influencing factors in Chennai region, Tamil Nadu.

Every year there is an increasing demand of water in Chennai region which led to a direct scarcity of freshwater. Notable population utilizes groundwater for their daily needs which led to groundwater crisis during summer season. Another challenges faced in the study area is the vital growth of industrialization led to an impactful changes in climate over the decades has levied intense stress on groundwater resources. Based on the report of Central Groundwater Board (2019), the major reservoirs that supply drinking water to this region have dipped far below the zero level and hold not even 1% of their capacity. The area is now critically dependent on neighboring states and also certain policy framework is required to solve the problem efficiently. The initiation of Information Technology (IT) corridor and Technology Park with enormous floor space benefits has no piped water supply for their use which faces serious threat to employability.

2 Materials and Methods

2.1 Study Area

The Chennai region is situated in the North Eastern part of Tamil Nadu (Fig. 1) and it covers 426 km^2 which lies between 15° 59′ and 13° 08′ north latitude and 80° 12′ and 80° 18′ east longitude. The eastern side of study area bounded by Bay of Bengal, where the coastal stretch is covered 43 km. The landscape of the research area is terrain with a slight alteration of 2 m above the mean sea level (MSL). The study area comprises 15 zones with the population of 66,72,103 (Census India, 2011).The month of January is the coolest part of the year which records 18–20 °C followed by March is warm which records 25–32 °C and from May to June is the hot and humid with the temperature ranges from 38 to 42 °C. The average annual rainfall is 750 mm.

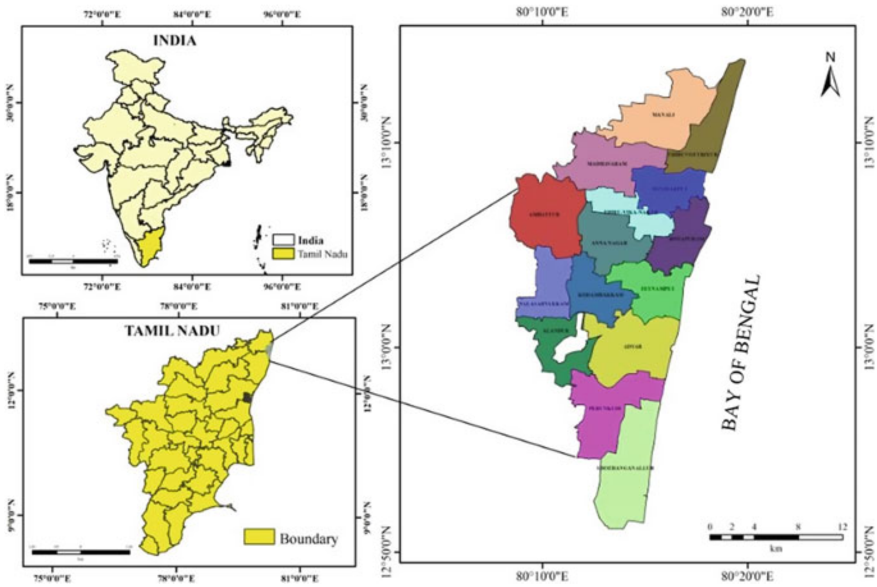

Fig. 1 Location map of the study area

2.2 Methodology Framework

Due to the lack of research study and continuous groundwater issues alarmed the authors to undergo the research study in Chennai region. The methodology adopted for the study is framed in the Fig. 2. Baseline topography of the study area was derived from topographical sheets No. 68 C/1, 68D/1 and 68D/5, Survey of India (SOI) with scale 1:50,000. Subsequently, geology and geomorphological data were derived from Geological Survey of India. The other thematic layers include, lineament density, elevation, slope, LU/LC, NDVI and drainage density were prepared from satellite imagery in various resolutions. All the thematic layers as a raster file were overlaid to process the final results. The spatial analyst tool in GIS platform is used to execute the weighted overlay analysis based on the weights assigned for various influential parameters. In a research study, during the execution of weighted overlay analysis assigned suitable weights to each parameter and subsequently, ranks to each subclass of that parameter based on the hydrogeological condition of the study area. As a result of potential zone for groundwater is demarcated in the study area in terms of 05 categories viz. very low, low, medium, high and very high.

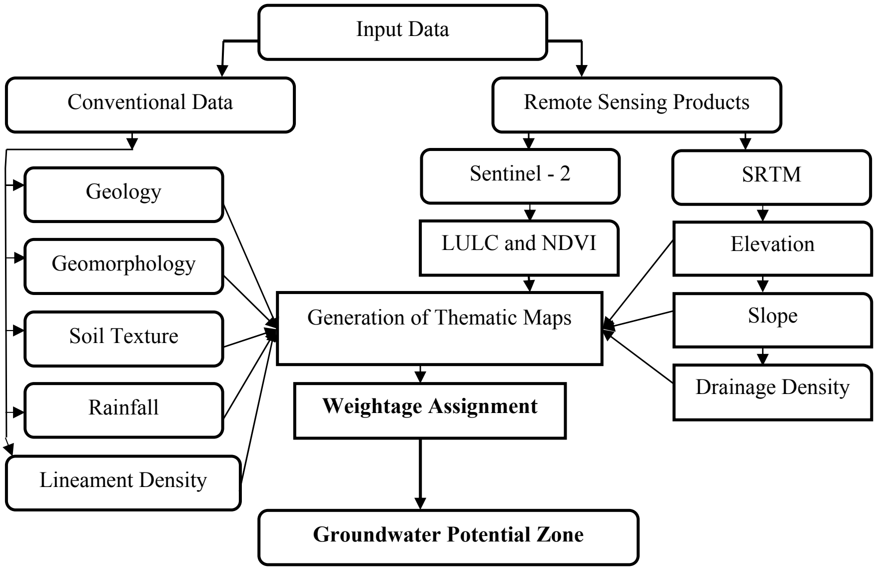

Fig. 2 Methodology flowchart

2.3 Data Used

The spatial and non-spatial datasets were extracted from various sources based on the suitability and availability. Table 1 lists the dataset used for the study. The extracted data are processed in Arc Map 10.3 for the purpose of analysis.

3 Results and Discussion

3.1 Geology

The geological formation is classified into seven categories namely crystalline rocks, Khondalite Group, Peninsular Gneiss (Bhavani group), Cuddalore Formation and Sathyamangalam Fluvial-marine-mangrove swamps and Alluvium—fluvial. The area is dominant on crystalline rocks of 43% distributed in north western side subsequently, alluvium–fluvial along the coastal side covers an area of 130.11 km^2. The traces of Khondalite Group are seen in the western side of area in 2.2 km^2 followed by Cuddalore Formation with 1.26 km^2.

Other groups such as fluvial-marine-mangrove swamps are present in 17 km^2, Peninsular Gneiss in 80.1 km^2 and Sathyamangalam Group in 8.07 km^2 are present in the study area. Figure 3 represents the geological formation of the study area and Table 2 highlights the area accommodated for each subclasses. The dominant

Table 1 Data used for the study

Sl. No.	Input data	Source	Year/path/row	Scale/resolution
1	Geology	Geological Survey of India, Chennai, Tamil Nadu	2005	1:50,000
2	Geomorphology	Geological Survey of India, Chennai, Tamil Nadu	2005	1:50,000
3	Soil texture	National Bureau of Soil Survey and Land Utilization Planning, Nagpur, Maharashtra	1996	1:50,000
5	Slope	USGS—Shuttle Radar Topographic Mission STRM 1 Arc Second Globe	23-09-2014	30 m
6	DEM	USGS—STRM	23-09-2014	30 m
7	Drainage density	USGS—STRM	23-09-2014	30 m
8	LU/LC	Sentinel—2 (ESA) Band combination (Blue, Green, Red, NIR and SWIR)	05-07-2018, R-142, P-51	10 m
9	NDVI	Sentinel—2 (ESA) Band Combination (NIR and Red)	05-07-2018, R-142, P-51	10 m
11	Lineament density	Bhuvan (https://bhuvan-app1.nrsc.gov.in/thematic/thematic/index.php)	NA	1:50,000

crystalline rocks are capable of water movement rapidly through fractures and joints which determines the groundwater potential zones.

3.2 Geomorphology

The geomorphological features of study area is comprises of old coastal plain, pediment, young coastal plain, flood plain, alluvial plain and pediplain. The maximum area of 137.01 km^2 is covered by alluvial plain along the north and western side of the study area which is 32% of total area. In addition, coastal plains are dominant in the study area in two categories namely old coastal plain and young coastal plain with 83.53 km^2 and 136.2 km^2 respectively. The pediplain traces are found in the western side of the area with the moderate percentage of 15.49%.

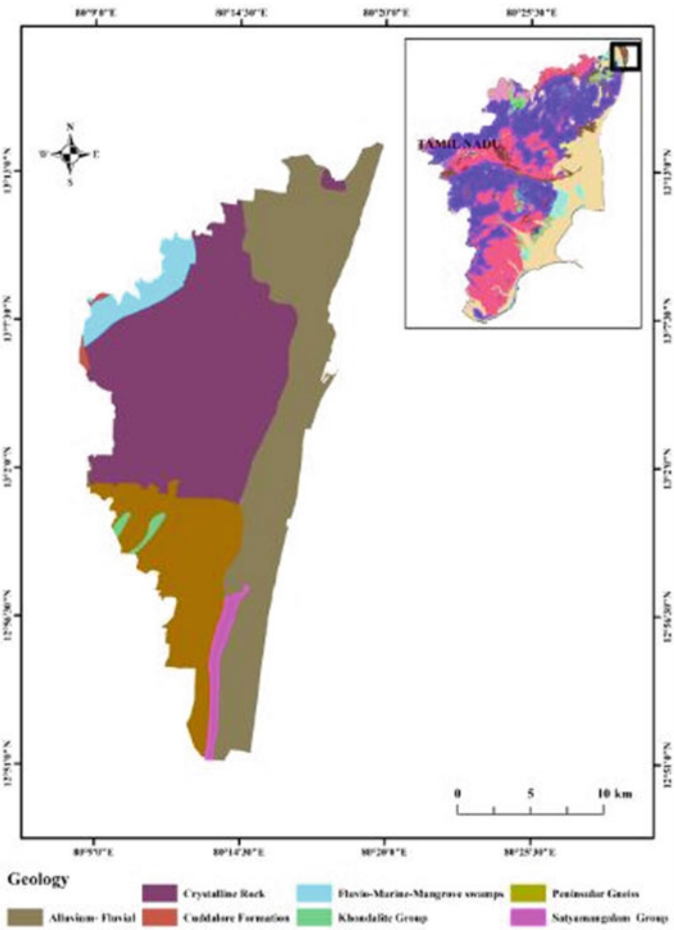

Fig. 3 Geology map of the study area

Table 2 Geology classification of the study area

Class	Potentiality	Area (km^2)	Area (%)
Alluvium-fluvial	Very high	130.11	30.53
Khondalite group	Low	2.02	0.51
Crystalline rock	Low	187.03	43.96
Fluvial-marine-mangrove swamps	Very high	17.00	3.99
Peninsular genesis	Very low	80.01	18.80
Cuddalore formation	High	1.26	0.29
Sathyamangalam group	High	8.07	1.89
Total		426.04	100

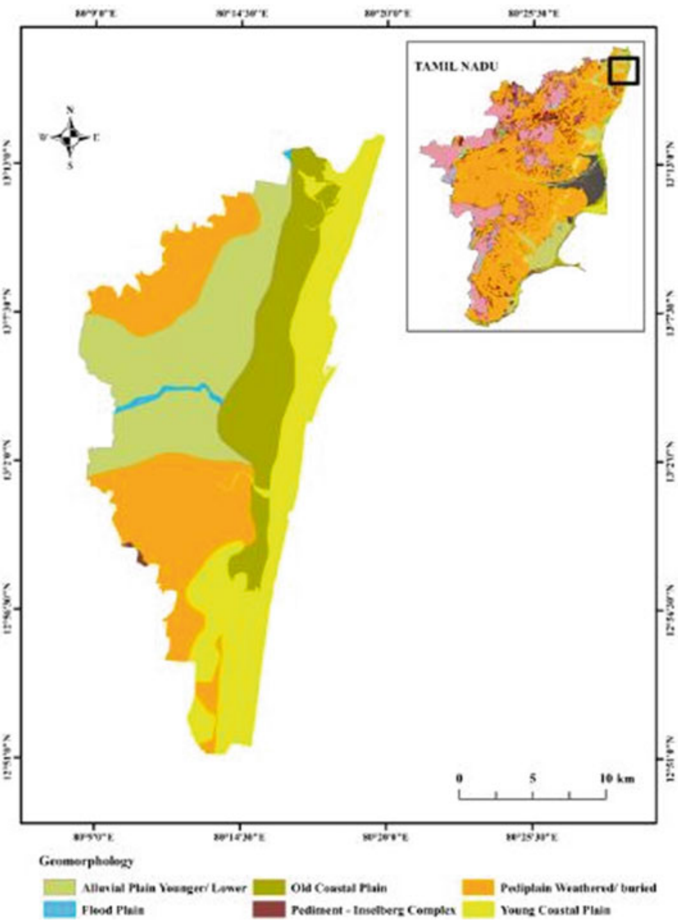

Fig. 4 Geomorphology map of the study area

The flood plains are delineated from western side to eastern side with least area of 0.66%. Figure 4 shows the geomorphological features of the study area and Table 3 illustrates the area calculation for each geomorphological class respectively. The alluvial plains are generally formed by deposition of running water. Hence, presence of alluvium deposits along the course trends for groundwater potential zones.

3.3 Soil Texture

The soil texture of study area were classified into eight groups namely clay loam, loamy sand, water body, clay, sandy loam, habitation, sandy clay, sandy clay loam.

Table 3 Geomorphology classification of the study area

Geomorphology	Potentiality	Area (km^2)	Area (%)
Old coastal plain	Low	83.53	19.61
Pediment—inselberg complex	Medium	0.05	0.12
Young coastal plain	Very low	136.02	31.97
Flood plain	Very high	2.08	0.66
Alluvial plain younger/lower	Very high	137.01	32.16
Pediplain weathered/buried	Medium	66.00	15.49
Total		426.04	100

The maximum area is covered by clay with 149.4 km^2 followed by habitation with 125.07 km^2. Adjacently, loamy sand and sandy clay are also dominating 15% and 11% respectively. The area is accommodated with higher percentage of clay which records nearly 35% of the total area.

Apparently, the least percentage falls in the category of sandy loam with 0.8%. Figure 5 exposes the categories of soil texture in Chennai region. The presence of clay reduces the water infiltration rate comparatively with the sand. But the traces of sand around region have a tendency to increase the groundwater potential. For further understanding, Table 4 highlights the region accommodated by different soil texture group.

3.4 Land Use/Land Cover

LU/LC produced using Sentinel-2 satellite data and classified the study area into five classes namely vegetation, built-up, dense vegetation, barren land and water bodies. The study area records higher percentage of built-up with an area 158.63 km^2 and followed by barren land with an area of 150.31 km^2. Comparatively, the vegetation in the study area is moderate with 21% and traces of dense vegetation are scattered along the course with an area of 23 km^2. The Chennai region is expanding in all sectors and transferring predominantly into a metro city, therefore the built-up records at higher percentage. The water bodies available in the study area are only 0.8% provides a crystal evident for the need of study. Figure 6 depicts the LU/LC for the study area and Table 5 highlights the area accommodated by each feature class of the region.

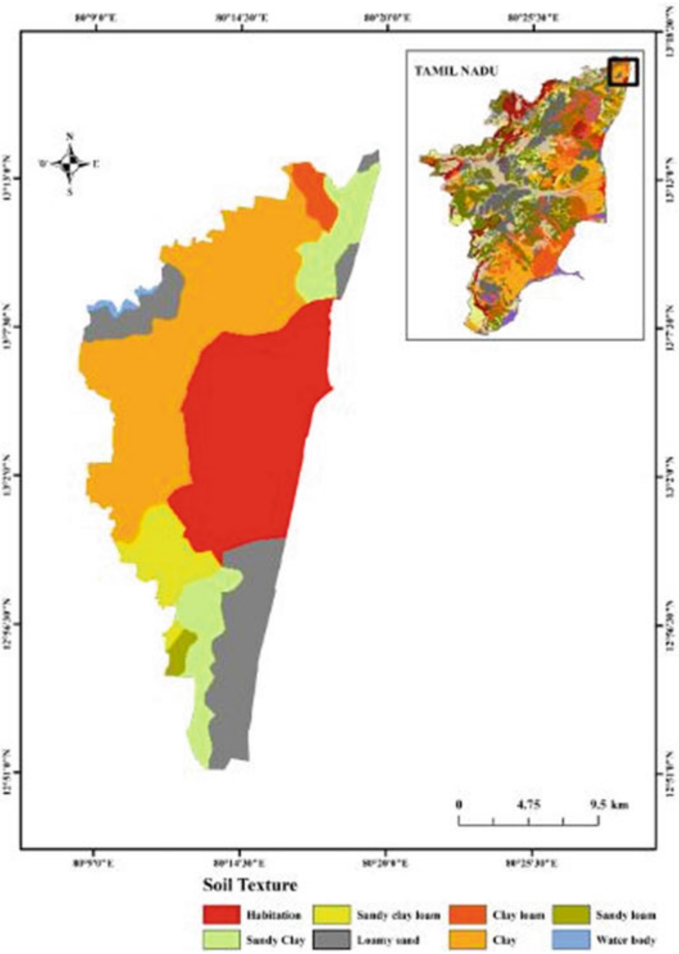

Fig. 5 Soil texture map of study area

Table 4 Soil texture classification of the study area

Class	Potentiality	Area (km^2)	Area (%)
Clay loam	Medium	7.08	1.83
Loamy sand	Medium	65.08	15.44
Water body	Very high	2.01	0.49
Clay	Very low	149.04	35.06
Sandy loam	Medium	3.05	0.82
Habitation	Very low	125.07	29.35
Sandy clay	Low	47.02	11.07
Sandy clay loam	Medium	25.02	5.91
Total		426.07	100

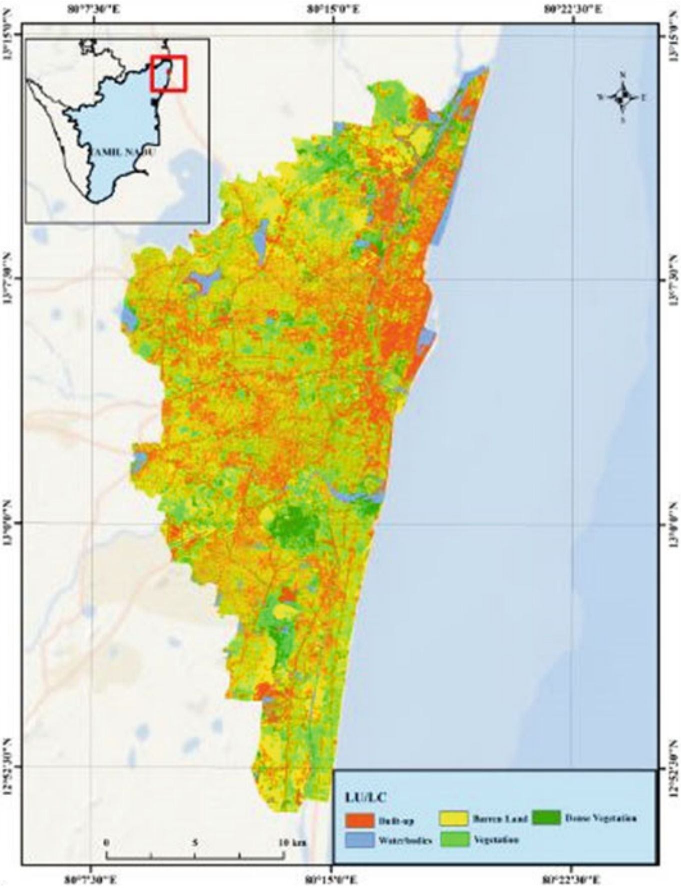

Fig. 6 LU/LC map of the study area

Table 5 LU/LC classification of the study area

Class	Potentiality	Area (km^2)	Area (%)
Built-up	Low	158.63	37.23
Water bodies	Very high	3.41	0.80
Vegetation	High	90.07	21.28
Dense vegetation	High	23.00	5.39
Barren land	Medium	150.31	35.27
Total		426.05	100

3.5 Slope

The Slope is determined by rise or fall of the land surface. The slope plays a vital parameter for demarcating the groundwater potential in the Chennai region. It ranges between 0° and 42° which is categorized in different subclasses. The maximum area is covered between the slope angle 0° and 7° which accommodates 407.12 km^2 and 95% of total area. The angle between 7° and 14° is distributed along the study area with 4%. The remaining part of the region are scattered with higher slope angle with coverage of area in least percentage. Figure 7 represents slope variation in the study area. The area is predominantly covered with gentle slope angle (0°–15°) which is suitable for groundwater potential. Table 6 highlights the area lodged in each sub classes.

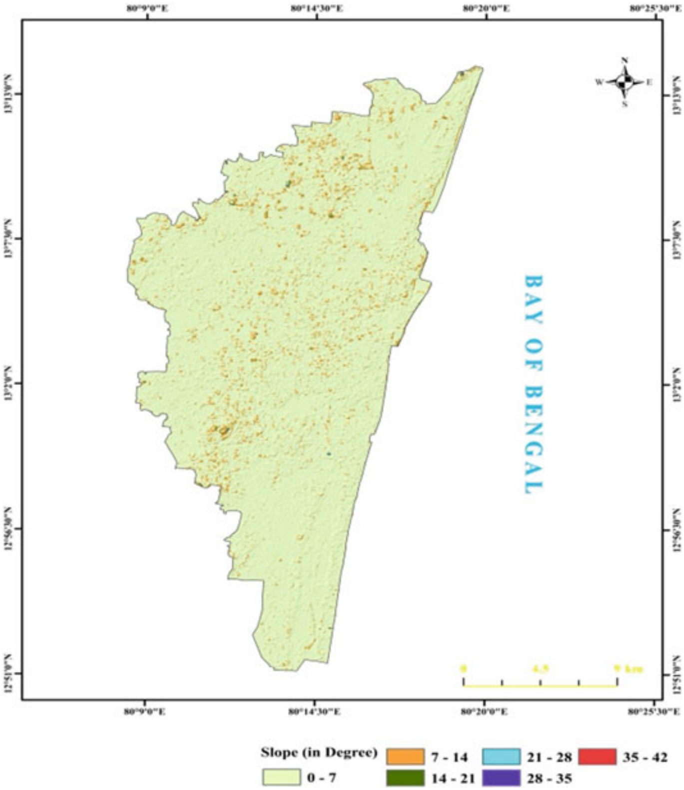

Fig. 7 Slope map of the study area

Table 6 Slope classification of the study area

Class (degree)	Potentiality	Area (km^2)	Area (%)
0–7	Very high	407.12	95.55
7–14	High	18.18	4.26
14–21	Medium	0.64	0.15
21–28	Medium	0.11	0.02
28–35	Low	0.02	0.00
35–42	Low	0.00	0.00
Total		426.07	100

3.6 Elevation

The elevation is very important in analyzing the topography which can influence the groundwater in terms of its flow, storage and discharge. The concept of elevation determines the availability of surface water in according to the elevation. On considering the Chennai region most of the areas are dominant with lower elevation and hence identification of groundwater potential zone is quite tedious task. The maximum area of 232.93 km^2 is covered with an elevation of 14–28 m and 187.69 km^2 is covered with an altitude of 0–14 m. Predominantly, 90% of total area is between 0 and 28 m elevation. On the other side, considerable patches of high elevated area are found in 2%. Figure 8 presents the elevation map of the Chennai region. The moderate elevation of 14–28 m determines the suitability of groundwater potential in the research area. Table 7 elucidates the classification of elevation for individual subclasses.

3.7 Rainfall

Rainfall is a predominant factor for groundwater potentiality as it directly induces the water runoff and infiltration rate in the study area. As a baseline data, it has been identified that there are two rain gauge stations namely Nungambakkam and Meenambakkam which is used primarily by India Metrological Department (IMD) for recording rainfall values. The annual rainfall for the year 2018 shown in the Fig. 9, was plotted using Inverse Distance Weighted (IDW) interpolation method (Chen and Liu 2012; Kumar et al. 2014). The rainfall is distributed between 280 mm and the maximum of 711 mm annually. The maximum rainfall showers in northeast monsoon during the period from October to November. The maximum area of 170.56 km^2 experiences a moderate rainfall of 539–625 mm. The highest rainfall ranges from 625 to 711 mm in the south western side of the Chennai region enhances the best possibility of suitable groundwater zones. Table 8 highlights the rainfall values and its area covered in different ranges.

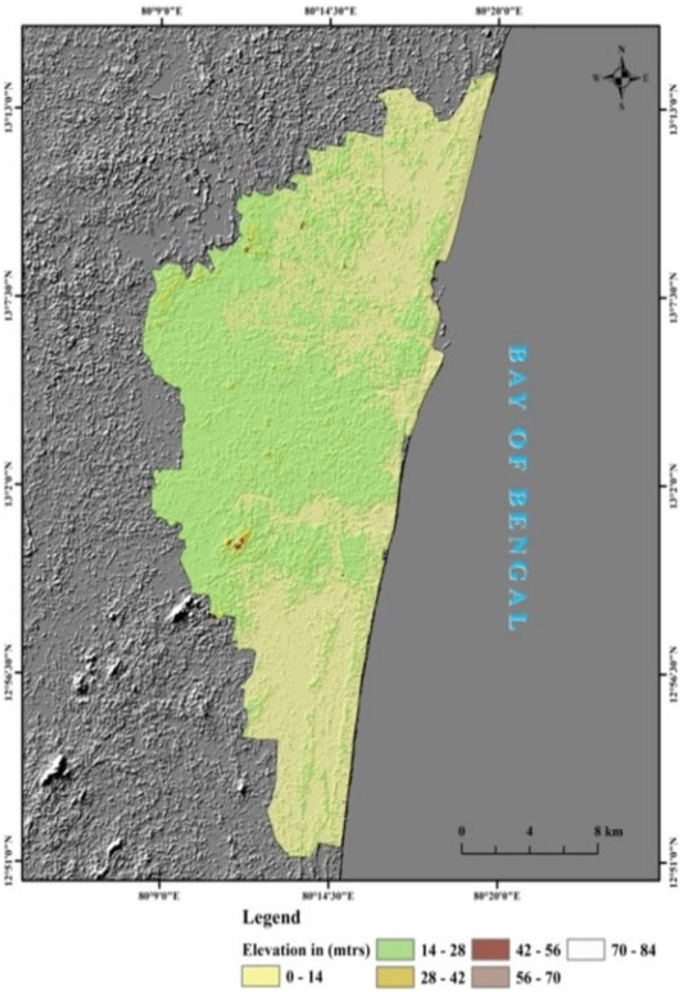

Fig. 8 Elevation map of the study area

Table 7 Elevation classification of the study area

Class (m)	Potentiality	Area (km^2)	Area (%)
0–14	Very high	187.69	44.04
14–28	High	232.93	54.65
28–42	Medium	5.14	1.20
42–56	Medium	0.31	0.07
56–70	Low	0.07	0.01
70–84	Low	0.02	0.00
Total		426.15	100.03

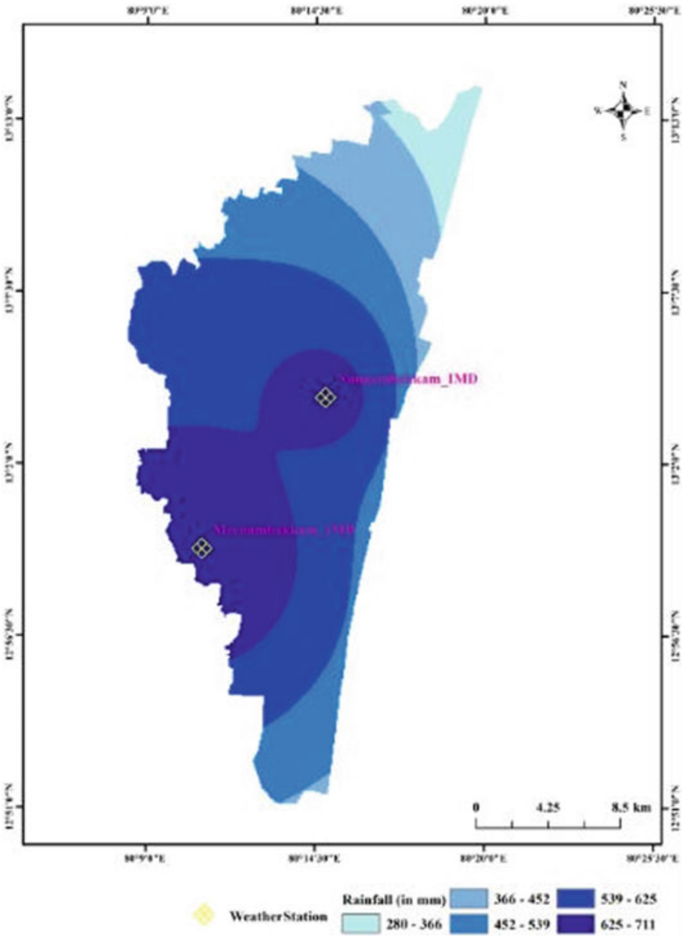

Fig. 9 Elevation map of the study area

Table 8 Rainfall classification of the study area

Class (mm)	Potentiality	Area (km^2)	Area (%)
280–366	very low	18.29	4.31
366–452	Low	43.55	10.28
452–539	Low	90.30	21.17
539–625	Medium	170.56	40.01
625–711	High	103.36	24.23
Total		426.06	100

Table 9 Drainage density classification of the study area

Class (km/km^2)	Potentiality	Area (km^2)	Area (%)
0–0.70	Very low	68.95	16.18
0.70–1.40	Low	149.28	35.04
1.40–2.11	Medium	122.54	28.76
2.11–2.81	High	30.16	7.08
2.81–3.52	Very high	55.12	12.94
Total		426.05	100

3.8 Drainage Density (DD)

Drainage Density (DD) shall be considered as one of the parameter which can be calculated as the ratio of length of the channel to the basin area (km/km^2). The groundwater potential zone suitability is indirectly proportional to the DD because of permeability and runoff factors (Chowdhury et al. 2010). It is to be noted that the permeability is the converse factor of drainage density which means, if the permeability of rock is very less and it is obvious that infiltration rate also will be reduced. This in turn increases the surface runoff from an elevated region. The study is accommodated with regular drainage pattern from various sources such as Adayar River, Coovum River, Jawahar Canal and Buckingham Canal. The higher drainage density values are recorded for an area of 4.61 km^2 which determines the lowest groundwater potential. Contradictorily, the maximum area of 171 km^2 is covered with very low drainage density which in turn governs the potentiality of groundwater. Table 9 highlights the area covered with suitable drainage density and Fig. 10 portrays the density drainage map of the study area. As the elevation gradually decreases from the west to east (towards sea), the flow direction is also highly concentrated on the same side. Further adding, the higher concentration of drainage is found near the river starting from the North Kosasthalaiyar River, Coovum River (Central), Adyar (South Central) and which is exceptional in southern side due to the presence of freshwater marsh land.

3.9 Lineament Density (LD)

Lineaments are explored from satellite imagery by their structurally controlled curvilinear or linear features, which also depicts the topography of the surface and its underlying features. The movement of groundwater depends on the lineament density. According to Haridas et al. (1998), the high lineament density area have considerable amount of groundwater potential. Figure 11 reveals very low lineament density for the 80% of total area. The traces of good lineament density are seen along the coastal side of the study area which is of nearly 20% only. Figure 11 calculates the area accommodated for each sub-classes of lineament density in the study area.

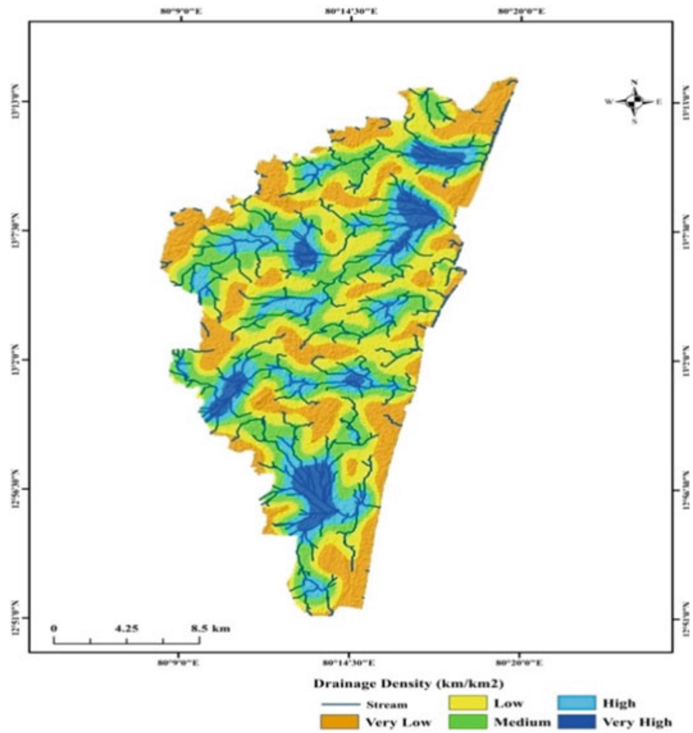

Fig. 10 Drainage density map of the study area

3.10 Normalized Difference Vegetation Index (NDVI)

In general, NDVI parameter is interconnected to the proportion of photo-synthetically absorbed radiation. If the NDVI value tends to be zero value determines the absence of green vegetation and when the value is close to 0.8–0.9 determines the possibility of green leaves at high density. The calculation of NDVI is done on a basis of per pixel as the normalized difference (Patra and Mishra 2018).

$$\text{NDVI} = (\text{NIR} - \text{RED})/(\text{NIR} + \text{RED})$$

The identification of NDVI is considered is to assess the crop stage condition which gives precise estimation of effective groundwater potential zone. Table 10 highlights the classification of NDVI classes and Fig. 12 displays the accessibility of vegetation in the Chennai region.

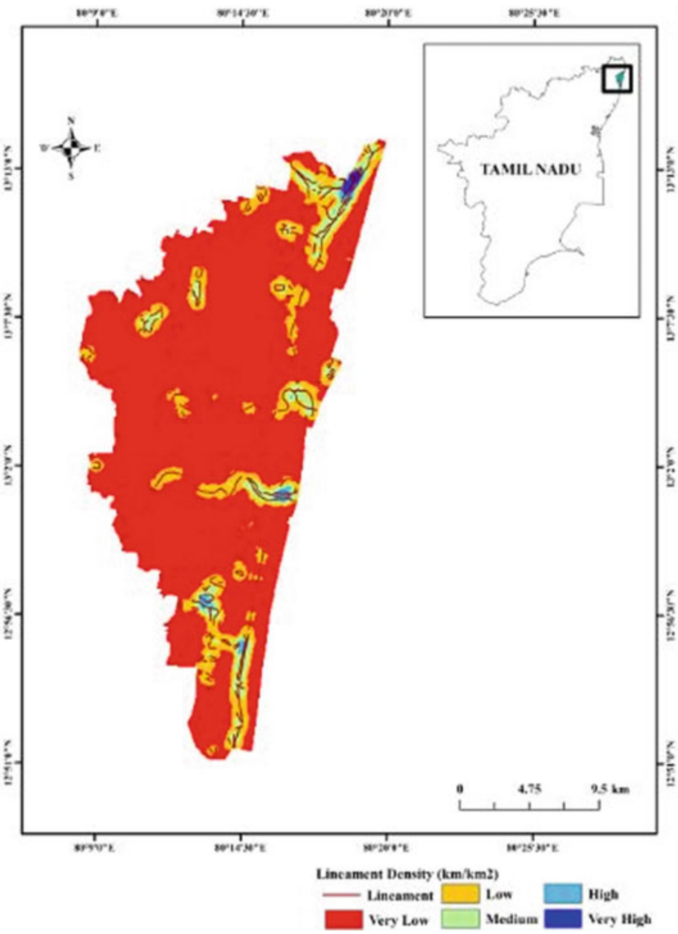

Fig. 11 Lineament density classification of the study area

Table 10 NDVI classification of the study area

Class	Area (km^2)	Area (%)
Very low	68.95	16.18
Low	149.28	35.04
Medium	122.54	28.76
High	30.16	7.08
Very high	55.12	12.94
Total	426.05	100

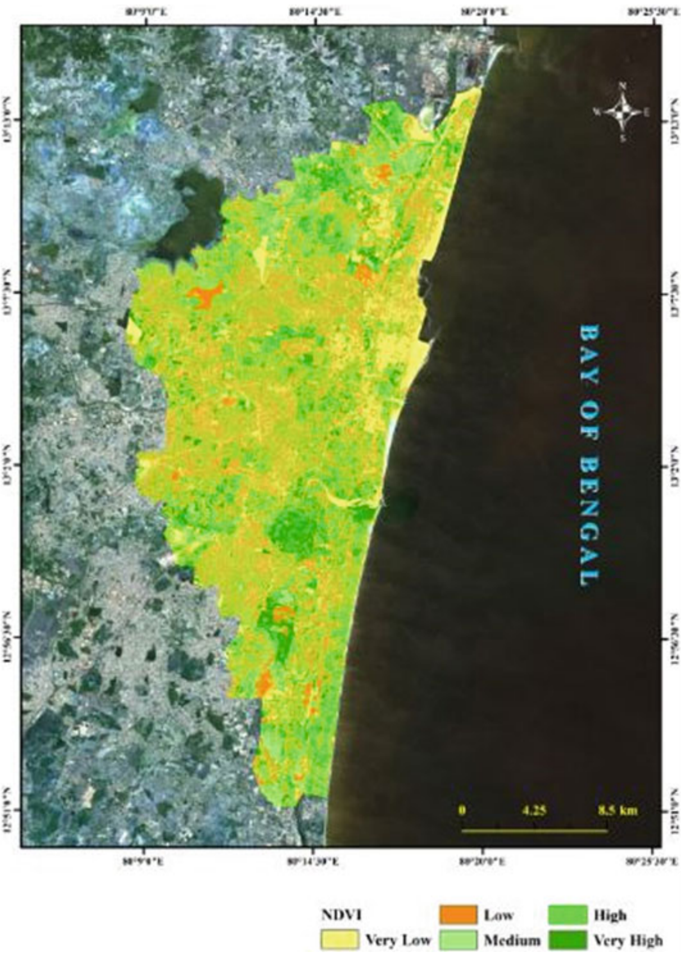

Fig. 12 NDVI map of the study area

3.11 Weightage Calculation

The multiple influencing factors such as geomorphology, geology, soil texture, slope, elevation, lineament and drainage density, rainfall, LU/LC, and NDVI are used for demarcating the groundwater potential area.

These parameters are apportioned to a suitable weight and subsequently, rank for the potentiality are shown in Table 11. The parameters considered for the study are independent and have a unique contribution to identify the groundwater potential zones in Chennai region.

Table 11 Classification of weighted factors influencing the potential zones

Parameter	Sub classes	Potential	Weightage	Rank
Geology	Alluvium-fluvial	Very high	20	5
	Crystalline rock	Low		2
	Fluvio-Marine-Mangrove swamps	Very high		5
	Cuddalore formation	High		4
	Peninsular gneiss	Very low		1
	Khondalite group	Low		2
	Sathyamangalam group	High		4
Soil texture	Habitation	Very low	10	1
	Sandy clay	Low		2
	Sandy clay loam	Medium		3
	Loamy sand	Medium		3
	Clay loam	Medium		3
	Clay	Very low		1
	Sandy loam	Medium		3
	Water body	Very high		5
LU/LC	Water bodies	Very high	5	5
	Built up	Low		2
	Vegetation	High		4
	Dense vegetation	High		4
	Barren land	Medium		3
Geomorphology	Young coastal plain	Very low	10	1
	Old coastal plain	Low		2
	Flood plain	Very high		5
	Alluvial plain younger	Very high		5
	Pediplain	Medium		3
	Pediment	Medium		3
Slope	0–7°	Very high	5	5
	7–14°	High		4
	14–21°	Medium		3
	21–28°	Medium		3
	28–35°	Low		2
	35–42°	Low	5	2
Elevation	0–14 m	Very high		5
	14–28 m	High		4
	28–35 m	Medium		3
	35–42 m	Medium		3

(continued)

Table 11 (continued)

Parameter	Sub classes	Potential	Weightage	Rank
	42–56 m	Low		2
	56–83 m	Low		2
Drainage density	0.004–0.663 km/km^2	Very low	15	1
	0.663–1.1022 km/km^2	Low		2
	1.102–1.554 km/km^2	Medium		3
	1.554–2.122 km/km^2	High	10	4
	2.122–3.296 km/km^2	Very high		5
Lineament density	0–0.70	Very low		1
	0.70–1.40	Low		2
	1.40–2.11	Medium		3
	2.11–2.81	High		4
	2.81–3.52	Very high		5
Rainfall	280–366 mm	Very low	15	1
	366–452 mm	Low		2
	452–539 mm	Low		2
	539–625 mm	Medium		3
	625–711 mm	High		4
NDVI	0.5–0.07	Very low	5	1
	0.07–0.16	Low		2
	0.16–0.27	Medium		3
	0.27–0.40	High		4
	0.40– 0.72	Very high		5

3.12 Demarcation of Groundwater Potential Zone

As discussed earlier, the groundwater potential zone for the Chennai region is demarcated using weighted overlay analysis through GIS platform. As a result of groundwater potential zone, the Chennai region is categorized into five grades such as very low, low, medium, high and very high. The potential zone displayed in Fig. 13 exhibits the high potentiality in the eastern side of Chennai region, whereas the coastal side showed the low potentiality due to various anthropogenic activities. The coastal region is ranked as very low prospective zone due to the proximity towards the sea. The northern part of the area are dominantly falling under the category of moderate and high potential zones due to the distribution of soil texture which intends to recharge the groundwater table. On considering the southern part of the study the potentiality is high due to the presence of subsurface properties. The moderate potentiality is seen along the study area accommodating an area of 129.36 km^2 followed by very high potentiality scattered in an area of 37.17 km^2. However, the study area

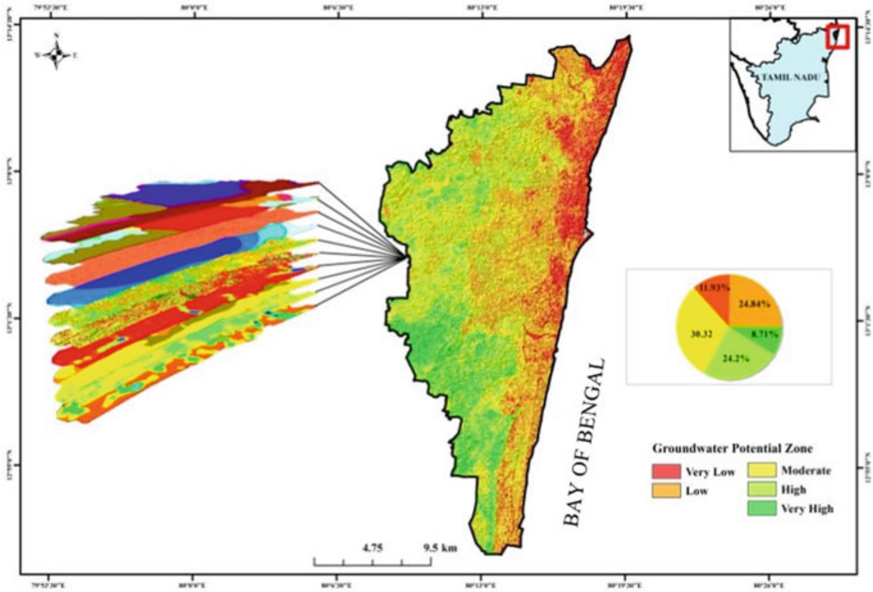

Fig. 13 Groundwater potential zone of the study area

is also dominant to low groundwater potentiality in higher percentage of 24.80% due to urbanization.

The assigned weightage for individual parameter is grounded on holding capacity of water and landforms. The geology is a prioritized parameter which is assigned with a highest weightage value because of the water storing capacity based on the nature of porosity and permeability. Geomorphology intended to assess the groundwater based on the landforms available in the research area. Taking slope and elevation in account at lowest weightage is due to suitability of holding the water and the generic movement of water on the surface. Considering the soil texture which determines the infiltration capacity of the region whereas lineament density is derived from lineament which is a natural phenomenon included shear zones, fracture faults, veins and dykes where the storage of water is feasible.

Rainfall dominates the supply of freshwater and also regulates the water cycle in an eloquent manner which is considered as one of the dominating parameter based on the annual rainfall of the study area. Drainage density is a predominant factor concentrated to delineate the water flow for the study area. Comparatively, LU/LC and NDVI is considered as the parameters of lowest weightage to assess of the layer of interaction and the intensity of vegetation respectively. LU/LC is also considered as a controlling factor for the recharge process. Table 12 highlights the classification of groundwater potential zone in the research area.

Table 12 Classification of groundwater potential zone

Groundwater potential	Area (km^2)	Area (%)
Very low	50.60	11.88
Low	105.68	24.80
Moderate	129.36	30.36
High	103.26	24.24
Very high	37.17	8.72
Total	426.07	100

4 Conclusion

The delineation of groundwater potential zone in Chennai region using geographical information system and remote sensing effectively manages the time and money which in turn enhances the water resources management to implement quick decision making for sustainability. The data collected as topographical sheets and satellite imageries from various resources were utilized efficiently to generate the thematic layers such as geomorphology, geology, slope, texture of the soil, elevation, drainage and lineament density, LU/LC, rainfall and NDVI. These layers were integrated in GIS platform though weighted overlay analysis by assigning suitable rank and weightage to an individual parameters. The research study highlighted the groundwater potential zones in 05 categories such as very low, low, moderate, high and very high. The result reveals that very high (8.71%), high (24.24%), moderate (30.36%), low (24.80%) and very low (11.88%). Subsequently, the majority area (129.36 km^2) is classified as moderate groundwater potential zones followed by high (103.26 km^2) and very high (37.17 km^2) potential zone. The results also indicates that western and south western zones of the study area are dominant to groundwater. However, the eastern side of the study area is determined as coastal zone which have a least potentiality for groundwater. As a conclusion, the conventional method adopted for the research study, will enhance the stakeholders for the purpose of planning, resource management and other developments in different sites around the world in a sustainable way.

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Identification of Groundwater Potential Zones Using Multi-influencing Factors (MIF) Technique: A Geospatial Study on Purba Bardhaman District of India

Niladri Das, Prolay Mondal, Subhasish Sutradhar, and Ranajit Ghosh

Abstract In the present era, the resource crisis and the deterioration of quality of resources is the primary concern of the geographical study. Groundwater resource is the primary depleted resource today due to massive population pressure and indiscriminate use in agriculture. Hence, proper planning and strategies are needed to facilitate groundwater recharge. Therefore, a study, like the delineation of potential groundwater zones, is one of the prime tasks of the geographer, the environmentalist, and the scientist also. Present research involves the assessment of potential groundwater recharge zone by using a popular statistical method, i.e., multi-influencing factors (MIF) along with the application of GIS. Based on the study, three major potential zones have been identified viz. high potential zone, which comprises 20.65% area, moderate potential zone with 45.61% area, and low potential zone covering 33.74% area out of the total geographical area of the Purba Bardhaman district of West Bengal, India. High potential zones are predominantly observed in the extreme west and east of the test area as well as along the river course. Moreover, low potential zones are found in the middle and the southern part of this concerned region. In the end, validation of these potential zones has been made by taking actual yield from the field observation and comparing it with the prepared potential model. Therefore, this kind of study for the delineation of potential groundwater zones is very much relevant for the improvement of groundwater status in the era of the water crisis. The validation of this model proves that this model is 73.17% accurate for the identification of the potential groundwater zones.

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Keywords Geographic information systems · Groundwater potential zones · Multi-influencing factors · Remote sensing · ROC curve

1 Introduction

With the march of time, various sectors like agriculture, industry, and urbanization have seen rapid development in developing countries like India, increasing the demand for water (Venkateswaran and Ayyandurai 2015). In the present world, groundwater is one of the precious resources, which pulling the chariot of human civilization (Magesh et al. 2012). It is also one of the largest sources of fresh water. To meet the daily need, like drinking and other domestic activities, nearly 90% rural population and 30% urban population of India depends on groundwater (Reddy et al. 1995; Bhunia et al. 2012)

The demand for groundwater is increasing day by day, leading to a groundwater crisis. In this crisis phase, we must delineate groundwater potential zones to use this precise resource sustainably. Now, with the advent of advance Remote Sensing and GIS techniques, it has become cost-effective and time-saving work (Das and Mukhopadhyay 2020; Thapa et al. 2017; Chaudhary and Kumar 2018; Adiat et al. 2012; Verma and Singh 2012). In the era of advanced science and technology, it has become very much easy to access spatial, spectral, and temporal data of the entire world within a few minutes (Sener et al. 2004; Gupta and Srivastava 2010; Panahi et al. 2017). GIS techniques are useful tools to capture, manipulate, store, analyze, manage, and represent various kind of spatial data (Chowdhury et al. 2008; Gupta and Srivastava 2010). Although it cannot directly be identified, but integrating multiple layers in a single frame such as geology, soil type, rainfall, lineament density, aquifer thickness, drainage density, Land use and Land cover, slope, NDVI, etc., groundwater potential zones can be demarcated (Dar et al. 2010; Agarwal et al. 2013; Thapa et al. 2017; Magesh et al. 2012; Das and Mukhopadhyay 2020; Bhunia et al. 2012; Panahi et al. 2017).

To detect groundwater potential zones, different quantitative techniques have been used by various researchers viz. Analytic hierarchy process (AHP) is one of the standard quantitative methods (Ajay Kumar et al. 2020; Arulbalaji et al. 2019; Mohammadi-Behzad et al. 2019; Murmu et al. 2019; Nithya et al. 2019; Siva et al. 2017; Phukon et al. 2004; Chowdhury et al. 2009; Murthy and Mamo 2009; Adiat et al. 2012; Panahi et al. 2017; Das and Mukhopadhyay 2020), frequency ratio model (Manap et al. 2014; Oh et al. 2011;Razandi et al. 2015) and multicriteria decision evaluation (Machiwal and Singh 2015; Murthy and Mamo 2009; Jothibasu and Anbazhagan 2016). After consideration of the previous studies, recognition of potential groundwater zones, Multi-influencing factors (MIF) method is rather simple and easy to apply (Magesh et al. 2012; Thapa et al. 2017; Das et al. 2017; Biswas et al. 2013).

Purba Bardhaman district is agriculturally endowed, and groundwater plays a significant role in maintaining its status in agriculture. But over-exploitation of groundwater is bringing the region under threat. According to the report of The Telegraph, April 2016, a joint survey was done by the Central Ground Water Board and the State Water Investigation Directorate, which identified Katwa-I, Katwa-II Kalna-I, Kalna-II, and Manteswar community development blocks under threat. Before the survey, Purbasthali-I and II community development blocks were demarcated to be having toxic groundwater. Overexploitation of groundwater leads to a very slow recharge. Water resources development ministry of West Bengal has said that more than 1, 62,000 water bodies' viz. canals, Ponds, and lakes have already silted up. Although the region gets sufficient rainfall, the dead water bodies cannot store water, and these water bodies cannot act as recharge potential as these are silted up. Therefore, for optimum use of groundwater, it is essential to demarcate the potential groundwater zones, so that policymakers, planners and local government and local people can identify the suitable and unsuitable borehole locations (Thapa et al. 2017; Das et al. 2017).

2 Materials and Methods

2.1 Study Area

Purba Bardhaman district is a newly formed district of West Bengal, divided from the previous Bardhaman district. This district is extending from 22° 56′ 00″ N to 23° 51′ 00″ N latitude and 87° 26′ 00″ E to 88° 25′ 00″ E longitude, occupying 5416 km^2 area and contains 23 C.D. blocks (Fig. 1).

This district is bounded by Paschim Bardhaman district (newly created) in the west, Birbhum District in the north, separated by Ajoy river, Murshidabad in the north, and the Bhagirathi river forms eastern boundary separating Nadia District from Purba Bardhaman district. In the south-east direction, the Damodar River flows dividing the Bankura district from it, and in the south-west side of this district, Hugli district is located. Geographically Purba Bardhaman district is characterized by Ganga-Brahmaputra alluvial plain both in the northern part and in the eastern region.

2.2 Data Used

To prepare thematic layers, conventional data and satellite data have been utilized from different sources. The administrative map of India and West Bengal has been downloaded from the DIVA-GIS portal. The Community Development blocks of the Purba Bardhaman district have been digitized from the map derived from the official website of the Purba Bardhaman district (http://Purbabardhaman.gov.in/burdwan/for_citizen/maps.php). The geological variety of the Purba Bardhaman district

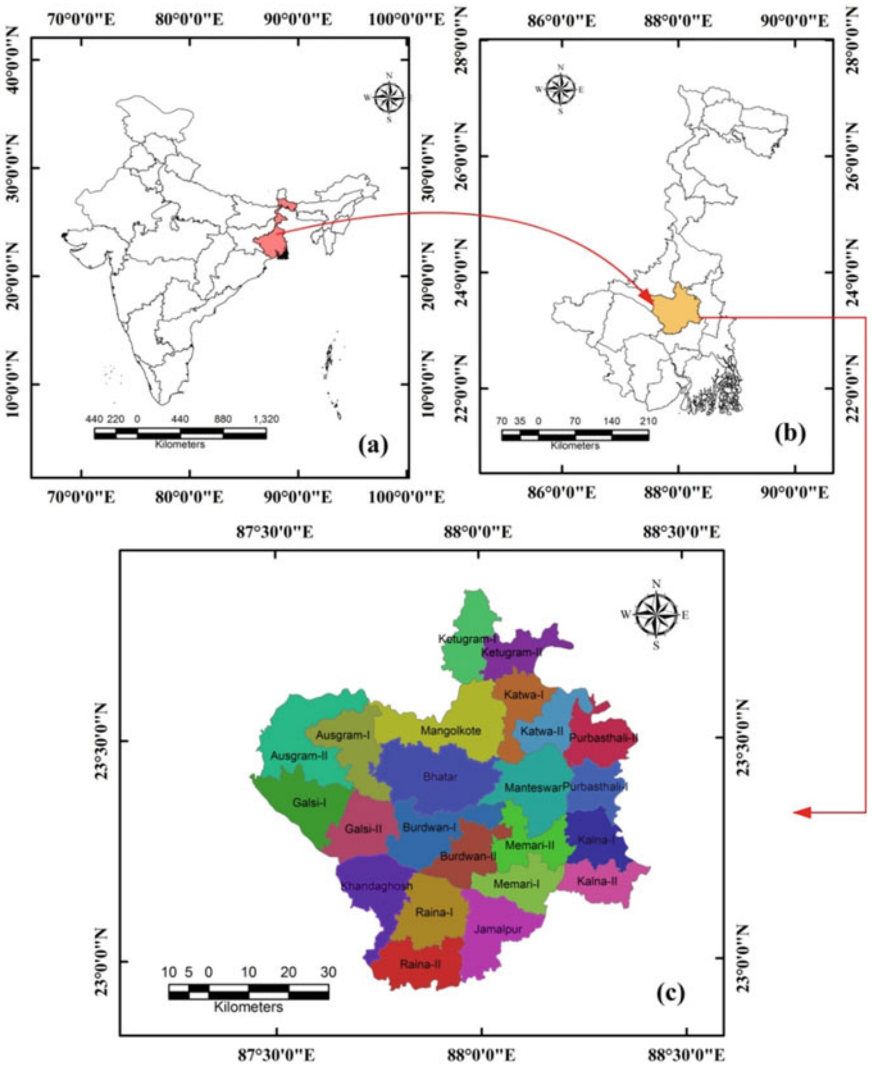

Fig. 1 **a** India. **b** West Bengal. **c** Purba Bardhaman

has been collected from the district resource map of Burdwan. Rainfall map and soil type map have been digitized from the district planning map of the NATMO. Aquifer thickness map has been digitized and prepared as a thematic layer in Arc GIS 10.5 from India-WRIS Web map services. The map of lineament density has been collected from BHUVAN Portal, and this map is made in ArcGIS 10.5 software using the line density tool. Land use/Land cover (LULC) map has been prepared from LANDSAT 8 OLI images (Table 1) of USGS EarthExplorer (https://earthexplorer.usgs.gov/) and supervised classification has been done in Arc GIS 10.5 using image analysis tool.

Table 1 LANDSAT 8 OLI images utilized in this study

Sl. no.	Image ID	Row/Path	Acquisition date	Spatial resolution (m)
1.	LC81380442018139LGN00	138/044	2018/05/19	30
2.	LC81390442018114LGN00	139/044	2018/04/24	30

Normalized difference vegetation index has been made using the above LANDSAT 8 OLI images of band 4 and band 5. To prepare slope and drainage map, SRTM DEM of 30 m resolution has been used and made in the Arc GIS 10.5 environment.

2.3 *Multi-influencing Factors (MIF) for Weightage*

To delineate potential groundwater zones, ranks were assigned to all the parameters statistically, using the MIF technique based on a literature review (Fig. 2). Factors which has dominant control on groundwater potentiality has been assigned as major effect and on the other hand, factors having less control assigned as a minor effect. A major factor has been assigned as weight 1, and minor factor has been assigned as weight 0.5, which is plotted in Table 2 based on Fig. 3 (Magesh et al. 2012; Thapa et al. 2017). Proposed Relative rates have been calculated by summing up the ranks of minor and major effect (Table 3). Then the proposed score of each factor has been calculated using this formula

$$PoposedScore = \left[\frac{(X_1 + X_2)}{\sum (X_1 + X_2)}\right] \times 100$$

where X_1 is Major effect and X_2 is minor effect.

With the help of the MIF, we can get weight for each parameter (Table 4). After reclassification with weightage, we made an overlay of all these selected layers with the help of Weighted overlay tool in spatial analyst in Arc GIS 10.5 software (evaluate copy) to delineate the potential zones.

3 Result and Discussion

To delineate the potential zones of Purba Bardhaman district, nine influencing factors of the groundwater recharge and storage have been considered viz. geology, lineament density, rainfall, soil type, slope, drainage density, aquifer thickness, land use/land cover and NDVI. All the factors have been studied individually concerning groundwater production and storage (Das et al. 2017).

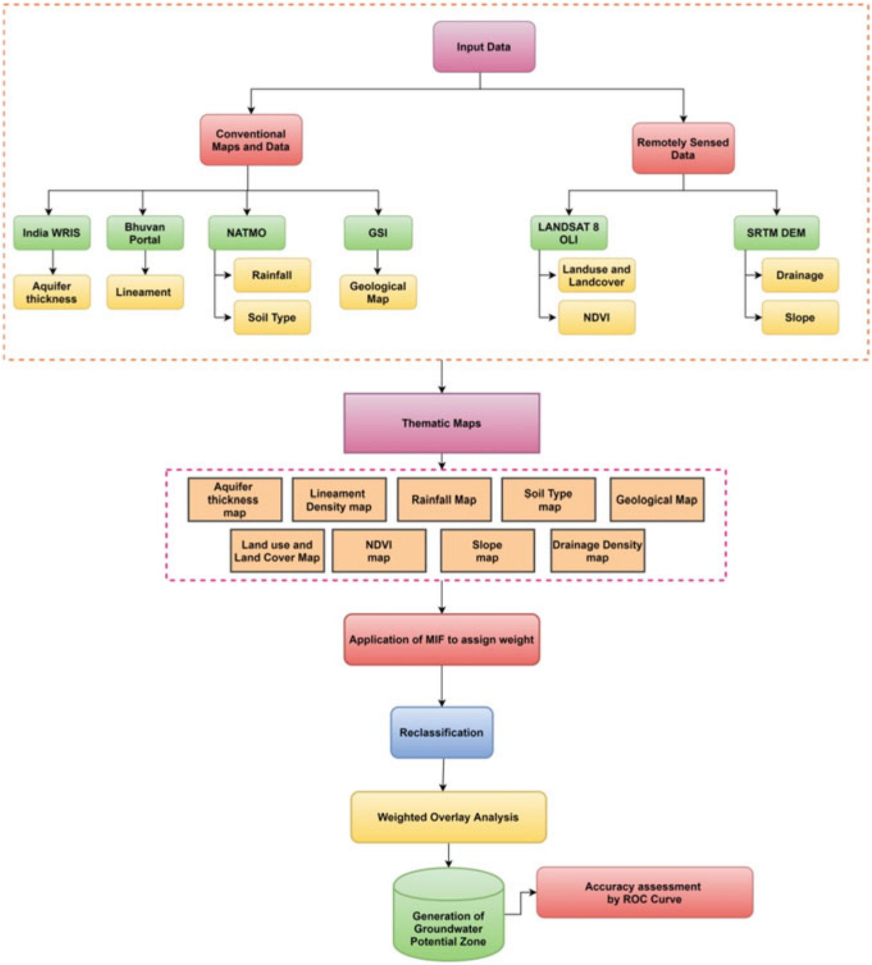

Fig. 2 Flowchart of the methodology of delineation of groundwater potential zones

3.1 Influencing Factors of Groundwater Potentiality

3.1.1 Slope

The slope is another significant physiographic factor and one of the best indicators for the identification of potential zones (Al Saud 2010; Ettazarini 2007). Slope controls the runoff process and infiltration rate of the groundwater (Gouri et al. 2019). Therefore, it strongly influences the groundwater recharge (Adiat et al. 2012; Bhunia et al. 2012; Kumar et al. 2014). Slope morphology explains that groundwater recharge is adversely related to it (Rahmati et al. 2016). Hence, the higher the degree of slope, the lower weightage has been assigned and vice versa. The slope map has been made

Table 2 Major effect and minor effect, proposed relative rates and scores for influencing factors (Magesh et al. 2012)

Factor	Major effect (X_1)	Minor effect (X_2)	Proposed relative rates ($X_1 + X_2$)	Proposed score of each influencing factor
Aquifer thickness	1	0.5	1.5	6
Geology	1 + 1 + 1 + 1	0.5	4.5	19
Lineament density	1	0.5	1.5	6
Rainfall	1 + 1	0.5 + 0.5	3	13
Drainage density	0	0.5	0.5	2
Soil type	1 + 1	0	2	9
Slope	1 + 1 + 1 + 1	0.5 + 0.5	5	21
LULC	1 + 1	0.5 + 0.5	3	13
NDVI	1 + 1	0.5	2.5	11
			$\sum 23.5$	$\sum 100$

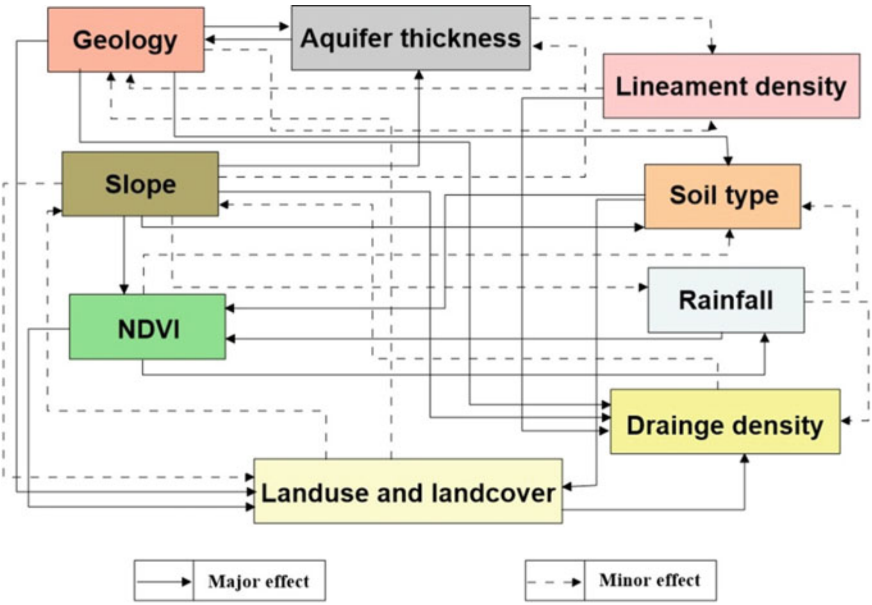

Fig. 3 Interrelationship and interdependence between influencing factors affecting the groundwater potential zone

Table 3 Factors assigning weightage concerning groundwater potential

Thematic map	Weightage	Groundwater potentiality
Geology	Clay alternating with silt & sand	Moderate
	Clay with caliche concretion	Very poor
	Laterite	High
	Sand, silt and clay	Poor
Rainfall	High (>1400 mm)	Good
	Moderate (1200–1400 mm)	Moderate
	Low (<1200 mm)	Poor
Soil	Alfisoils older alluvium	Poor
	Entisoils younger alluvium	Moderate
	Lateritic utisoils	Good
Slope	High	Poor
	Moderate	Moderate
	Low	High
Drainage density	High	Unsuitable for groundwater potential
	Moderate	Moderately suitable for groundwater potential
	Low	Suitable for groundwater potential
Lineament density	High	Suitable for groundwater potential
	Moderate	Moderately suitable for groundwater potential
	Low	Unsuitable for groundwater potential
Aquifer thickness	High	Good
	Moderate	Moderate
	Low	Poor
NDVI	High	Good
	Moderate	Moderate
	Low	Poor

from SRTM DEM of 30-m spatial resolution provided by USGS Earth Explorer, and it has been processed in Arc GIS 10.5 software (Fig. 4a). This region comprises with moderate category of the slope, which ranges between 1.27° and 2.97°.

3.1.2 Geology

Geology is the fundamental parameter that strongly influences groundwater recharge and helps to determine the potentiality of the groundwater. So, the groundwater storage initially depends upon the geological structure (Hachem et al. 2015). Geological formations ascertain the recharge and storage capacity of groundwater (Ayazi

Table 4 Thematic layers with its classes, ranks and weightage

Layers	Classes	Assigned ranking	Weightage
Geology	Clay alternating with silt & sand	14	19
	Clay with callche concretion	4	
	Laterite	19	
	Sand, silt and clay	9	
Rainfall	High (>1400 mm)	13	13
	Moderate (1200–1400 mm)	9	
	Low (<1200 mm)	5	
Soil Type	Alfisoils older alluvium	3	9
	Entisoils younger alluvium	6	
	Lateritic utisoils	9	
Slope	High	21	21
	Moderate	14	
	Low	7	
Drainage density	High	1	2
	Moderate	1	
	Low	2	
Lineament density	High	6	6
	Moderate	4	
	Low	2	
Aquifer thickness	High	6	6
	Moderate	5	
	Low	4	
	Very Low	3	
NDVI	High	11	11
	Moderate	7	
	Low	3	
LULC	Built up area	3	13
	Sandy area	9	
	Current fallow	5	
	Vegetation	11	
	Cultivated land	7	
	Water bodies	13	

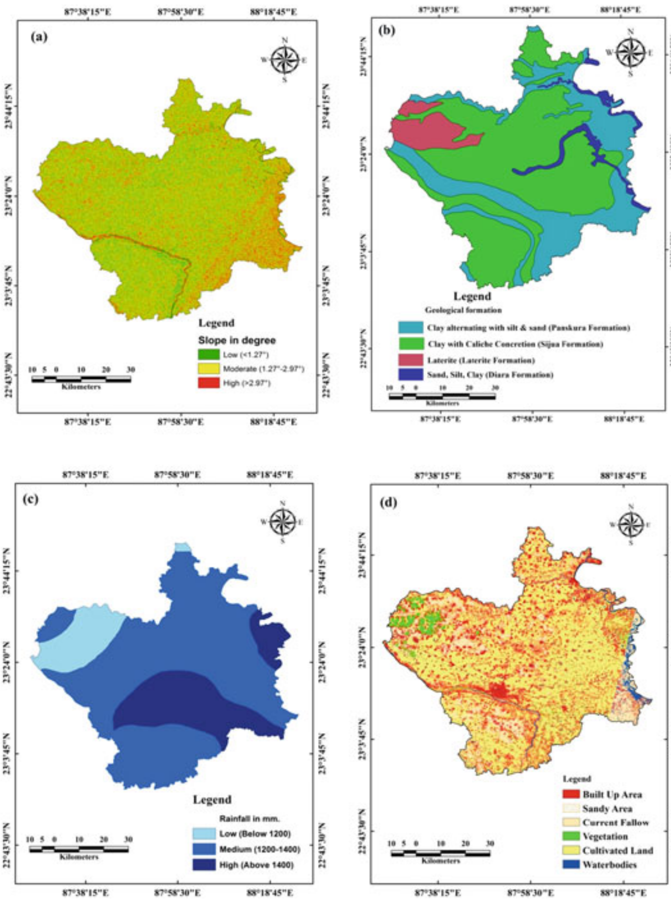

Fig. 4 Thematic maps: **a** Slope. **b** Geology. **c** Rainfall. **d** Land use and land cover. **e** NDVI. **f** Soil type. **g** Aquifer thickness. **h** Lineament density. **i** Drainage density

et al. 2010; Chowdhury et al. 2009; Jhariya et al. 2016). This region is characterized by four significant geological formations viz. sand, silt and clay formation, clay with caliche concretion formation, clay alternation with silt and sand formation, and laterite formation (Fig. 4b).

The concretion is a kind of hard and compact mass of materials formed by the precipitation of minerals and cemented pore spaces of the soil. Therefore it discourages the recharge of groundwater, and hence this formation leads to very low potentiality to groundwater availability. Laterite supplies productive groundwater storage because of good permeability (Das and Mukhopadhyay 2020). Thus it creates an excellent potential zone of groundwater storage. Therefore, laterite is given more weightage than other geological formation. Clay alternation with silt and sand also moderately influences groundwater potentiality.

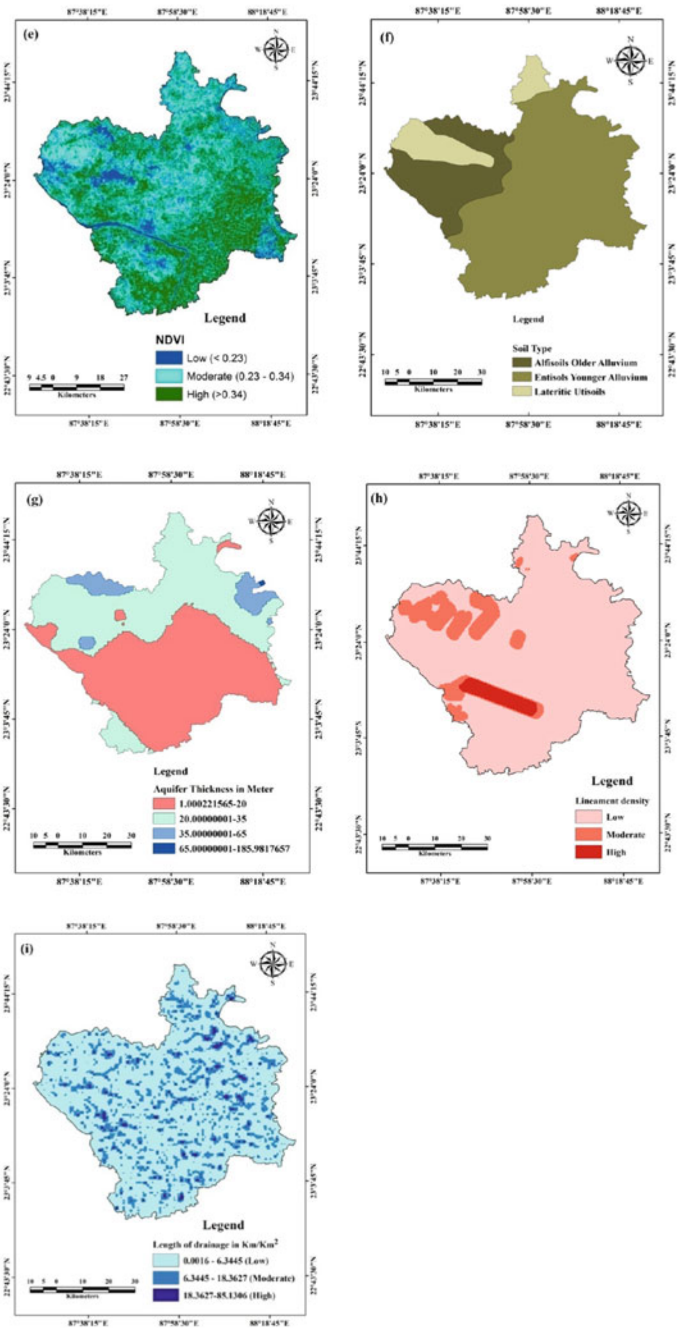

Fig. 4 (continued)

3.1.3 Rainfall

In the hydrological cycle, rainfall plays an important role in groundwater retention, which ultimately determines the groundwater potentiality and fluctuation (Magesh et al. 2012; Agarwal et al. 2013). The study region receives nearly 80% rainfall from south-west monsoon from June to September. Rainfall map has been digitized from the district planning map of NATMO, which has been categorized into three subclasses viz. High (Above 1400 mm), medium (1200–1400 mm), and low (less than 1200 mm). The southeastern portion of the region receives more than 1400 mm rainfall, which carries out 22%. The western part receives below 1200 mm rainfall with 10% areal coverage. The rest part of the study area has experienced a medium category of rain, which ranges from 1200 to 1400 mm and covers 67% area (Fig. 4c).

3.1.4 Land Use and Land Cover

LULC is also an important parameter to identify the extension of the need and use of groundwater (Jhariya et al. 2016). It helps to understand the variation of recharge in different units of land use (Singh et al. 2011). The LULC map has been prepared with Landsat-8 satellite images, which are downloaded from the USGS earth explorer portal, and supervised classification has been done using the maximum likelihood method in ArcGIS 10.5 software. Six types of classes have been extracted in this test area viz. built up, sandy area, current fallow, vegetation, cultivated land, and water bodies (Fig. 4d). As the Waterbody is the best-known source of the unit of groundwater recharge, the highest weightage is assigned for this parameter. Vegetation also acts as an important parameter as the recharger of the groundwater; hence it has been given good weightage after water bodies. Low weightage has been assigned for Built-up areas as this zone has a meager infiltration rate. In the study area, 23.33% area is under the built-up area, 55.59% area is under cultivated land, only 3% is underwater bodies, 2.85% is under the converge of vegetation. As this area belongs to the riverine floodplain, hence major part of the district is under cultivable land.

3.1.5 NDVI

For the identification of vegetation quality, NDVI is an important index, and it has been widely used in the present era of RS & GIS. To identify the potential groundwater zones, NDVI has been considered an important parameter. The values obtained from NDVI ranges from -1 to $+1$, and if the value is >0.4, it indicates as dense vegetation. If the value is <0.1, there is no vegetation i.e., barren land. Moreover, if the value is 0 or less than it, it may be water bodies, wet areas. NDVI map has been prepared from Landsat-8 satellite image in ArcGis 10.5 environment with the help of this formula

$$NDVI = \frac{NIR - RED}{NIR - RED}$$

where NIR denotes Near-Infrared band, and RED denotes the band 4 of Landsat image.

Figure 4e explains that the southeastern part of the test area is characterized by higher NDVI value, which indicates vegetation covers over this part. Moreover, the central and northwestern parts of this district are experienced medium to low NDVI value that means this part has less or no vegetation cover.

3.1.6 Soil Type

Soil type is one of the necessary natural elements that significantly determine the water infiltration rate. The study region is characterized by three types of soil viz. Older Alluvium, Younger Alluvium, and Laterite (Fig. 4f). About 70% area of the region is covered by younger alluvium due to high deposition by the rivers almost every year. This soil is mainly found in the western part of this district. About 19 and 10% of the area are under older alluvium and laterite, respectively. Both the soils are found in the western and northern parts of the district. Newer alluvium is more influencing for groundwater recharge than older alluvium. Moreover, laterite soil strongly accelerates the groundwater recharge due to its high porosity. Hence laterite soil has been given more weightage followed by younger alluvium and older alluvium.

3.1.7 Aquifer Thickness

An aquifer is a layer of unconsolidated porous rock that allows water to flow through it. Aquifer thickness of any area plays a vital role in controlling the groundwater potentiality. As aquifers contain water, therefore areas having higher aquifer thickness will have more groundwater potential. In this area, the width of the aquifers varies from 1.000221565 to 185.9817657 m. The region having lesser aquifer thickness is found in the majority of this district. Some parts of the eastern and northern parts have higher aquifer thickness (Fig. 4g). 51.23% has very little aquifer thickness of 1.000221565 to 20 m, 43% of the study area has 20.00000001–35 m aquifer thickness, 5.71% has 35.00000001–65 m, and only 0.06% has 65.00000001–185.9817657 m aquifer thickness.

3.1.8 Lineament Density

Lineament is tectonically originated features of linear, rectilinear, curvilinear shape, and can be extracted from the satellite image (Magesh et al. 2012; Jhariya et al. 2016). The number of lineaments influences the infiltration rate and hence sufficient groundwater recharge. Spatial data of lineament has been collected from the Bhuvan Geoportal (Das and Mukhopadhyay 2020). An area having higher lineament density is more conducive for the potentiality of groundwater. Therefore, in this study, classes of higher lineament density have been assigned higher weightage and vice versa. Figure 4h depicts that in the study region, the lineament density is very high only along the Damodar river valley, and the rest of the area has experienced very little lineament density.

3.1.9 Drainage Density

Drainage density means the length of stream per unit area (Horton 1932; Strahler 1952; Das and Mukhopadhyay 2020). Drainage density has a dominant influence on the groundwater potentiality as it has an inverse relation with infiltration (Chowdhury et al. 2009; Agarwal et al. 2013; Magesh et al. 2012; Das and Mukhopadhyay 2020). Higher the drainage density value, the higher will be the surface runoff, and hence lower will be the recharge of groundwater and vice versa. So, higher weightage has been given to the lower drainage density and lower weightage for higher drainage density. In this district, almost above 90% area is under low drainage density zone (Fig. 4i).

3.2 Delineation of Groundwater Potential Zones

Based on Multi-Influencing Factors technique, and arrangement of the pixel of all influencing factors like, rainfall, drainage density, soil type, slope, lineament density, aquifer thickness, LULC and NDVI, the groundwater potential zones map has been prepared (Fig. 5) and three potential zones have been identified which are high, medium and low. Each potential zone has a certain area, i.e., low potential zone covers 1815.1 km^2, moderate potential zone occupies 2453.18 km^2 and high potential zone covers 1110.83 km^2. The percentage of area covered under potential zones is shown in the following Table 5.

Based on the pixel arrangement of all the thematic layers, a final map has been extracted which depicting groundwater potential zones. This map reveals that groundwater potentiality has strongly been influenced by physical factors like geology, river, slope, lineament, etc. (Das and Mukhopadhyay 2020). From Fig. 5, it is observed that a high potential zone is a characteristic feature of laterite formation and clay alternating with silt and clay because it allows a high rate of percolation of groundwater and large storage of groundwater. Moreover, the high potential zone can also be found along the riverside due to the continuous supply of surface water.

In this present context, identification of groundwater potential zone is very much important because the potentiality of any resource provides a new dimension to rethink for sustainable use of that resource to the planner. Therefore, the delineation of these zones of Purba Bardhaman district will help to formulate a suitable regional level plan (Das and Mukhopadhyay 2020).

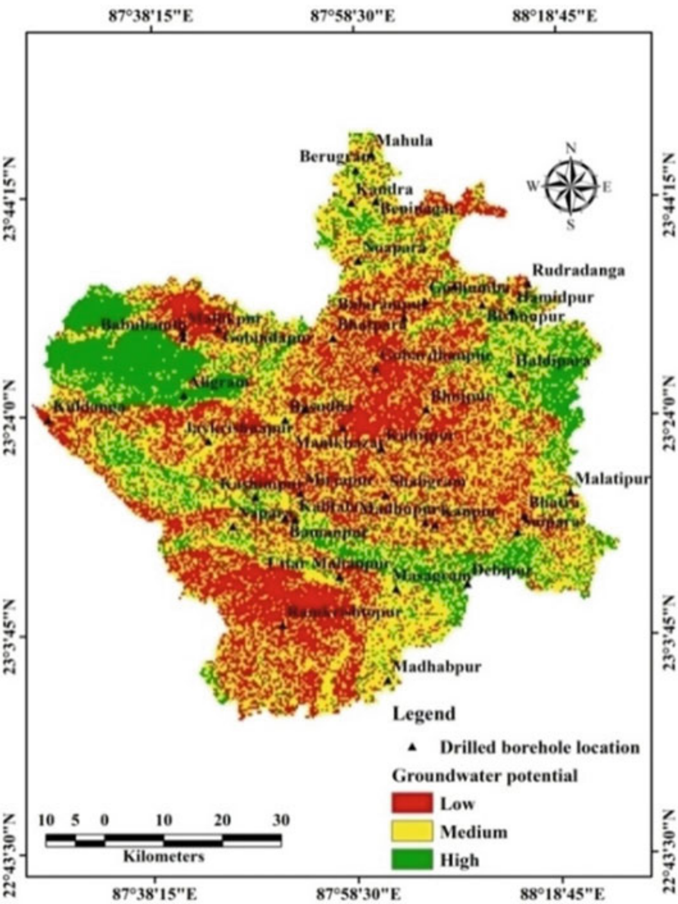

Fig. 5 Groundwater potential zones of Purba Bardhaman district

Table 5 Area under different Groundwater potential zones

Groundwater potential zone	Area (km^2)	Percentage of area
Low potential zone	1815.1	33.74
Moderate potential zone	2453.19	45.61
High potential zone	1110.83	20.65

3.3 Validation of the Groundwater Potential Zones

To validate the finally extracted groundwater potential zones map, 41 drilled boreholes have been selected from where boreholes yield data have been collected. Borehole locations have been plotted in Fig. 6 and actual yield data have been tabled in Table 6. Based on the field data, the yield ranges have been categorized into 3 groups

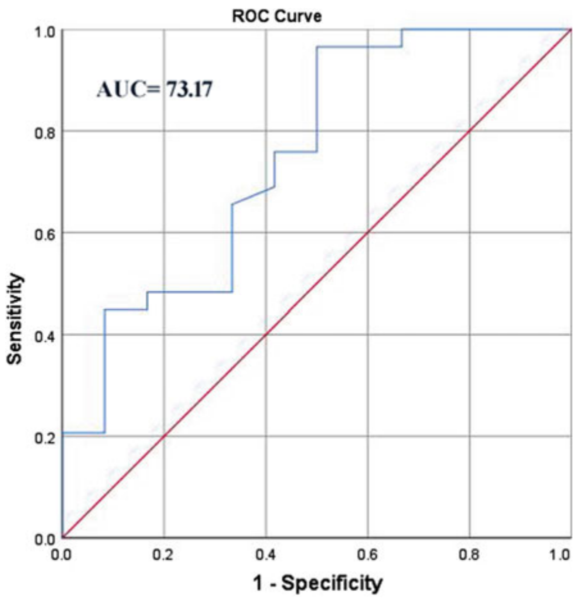

Fig. 6 Receiver Operating Characteristic (ROC) to validate the potential zones

viz. less than 3 lps as low yield zone, 3–6 lps as medium yield zone, and more than 6 lps as high yield zone. The actual yield and expected yield that is predicted from the groundwater potential zones map have been shown in Table 6 and agreement between actual and expected yield have been tabled to explain the remark of agreeing and disagreeing, which represents the consistency between actual yield and predicted yield. For the accuracy assessment of the map following steps have been followed

i. Bore hole surveyed = 41
ii. Number of surveyed boreholes under agreement = 30
iii. Number of surveyed boreholes under disagreement = 11
iv. The accuracy prediction =

$$\frac{\text{No. of boreholes under agreement of coherence}}{\text{Total number of borehole surveryed}} \times 100$$

$$= \frac{31}{41} \times 100$$

$$= 73.17\%$$

The accuracy value 73.17% indicates that the Multi-Influencing Factors technique with the help of remote sensing and GIS can be successfully applied to generate a successful result.

To understand the level of accuracy graphically, Receiver Operating Characteristic (ROC) curve is mostly used (Das and Mukhopadhyay 2020). The area under curve has been drawn against the real and expected yield of groundwater, which represents

Table 6 Accuracy assessment of groundwater potential zones by comparing of actual groundwater yield with the obtained groundwater potential zones

Sl. no.	Location	Latitude	Longitude	Actual yield from drilled borehole (lps)	Actual yield remark	Expected yield predicted from the map	Agreement between actual and expected
1	Berugram	23° 46′ 48″	87° 58′ 40″	3.75	Medium	Medium	Agree
2	Basudha	23° 23′ 40″	87° 51′ 27″	6.87	High	High	Agree
3	Babubandh	23° 31′ 23″	87° 41′ 24″	0.33	Low	High	Disagree
4	Bamanpur	23° 14′ 38″	87° 51′ 22″	1.62	Low	Low	Agree
5	Aligram	23° 25′ 59″	87° 41′ 20″	1.6	Low	Low	Agree
6	Jaykrishnapur	23° 21′ 46″	87° 43′ 47″	5.28	Medium	Medium	Agree
7	Manikbazar	23° 22’ 59″	87° 57′ 9″	3.8	Medium	Medium	Agree
8	Mallikpur	23° 31′ 60″	87° 41′ 30″	1.38	Low	High	Disagree
9	Kandra	23° 43′ 45″	87° 58′ 13″	1.13	Low	High	Disagree
10	Bhatpara	23° 31′ 7″	87° 55′ 52″	6.57	High	High	Agree
11	Napara	23° 13′ 54″	87° 46′ 11″	4.02	Medium	Medium	Agree
12	Kanpur	23° 13′ 57″	88° 6′ 22″	3.92	Medium	Medium	Agree
13	Kashimpur	23° 16′ 35″	87° 48′ 26″	3.63	Medium	Medium	Agree
14	Kubijpur	23° 22′ 14″	87° 59′ 19″	7.2	High	High	Agree
15	Gobindapur	23° 32′ 8″	87° 44′ 40″	3.89	Medium	Medium	Agree
16	Kuldanga	23° 23′ 33″	87° 27′ 37″	3.52	Medium	Medium	Agree
17	Uttar Mahanpur	23° 9′ 25″	87° 56′ 45″	6.7	High	High	Agree
18	Mahula	23° 48′ 15″	88° 0′ 14″	4.12	Medium	Medium	Agree
19	Beninagar	23° 43’ 52″	88° 0′ 38″	6.67	High	High	Agree
20	Natungram	23° 36′ 3″	88° 8′ 7″	7.88	High	High	Agree
21	Hamidpur	23° 33′ 40″	88° 14′ 9″	5.63	Medium	Low	Disagree
22	Balarampur	23° 32′ 45″	88° 2′ 37″	6.63	High	High	Agree
23	Goshumba	23° 33′ 54″	88° 4′ 41″	6.35	High	High	Agree
24	Gobardhanpur	23° 28′ 24″	88° 0′ 59″	1.92	Low	Medium	Disagree
25	Haldipara	23° 27′ 46″	88° 14′ 6″	9.35	High	High	Agree
26	Bishnupur	23° 34′ 12″	88° 11′ 12″	4.12	Medium	Medium	Agree
27	Shaligram	23° 16′ 43″	88° 1′ 24″	3.85	Medium	Low	Disagree
28	Bhojpur	23° 24’ 35″	88° 5′ 33″	4.02	Medium	High	Disagree
29	Masagram	23° 8′ 2″	88° 2′ 24″	7.53	High	Medium	Disagree
30	Debipur	23° 8′ 32″	88° 9′ 31″	5.13	Medium	Low	Disagree
31	Rudradanga	23° 36′ 8″	88° 15′ 56″	7.65	High	High	Agree

(continued)

Table 6 (continued)

Sl. no.	Location	Latitude	Longitude	Actual yield from drilled borehole (lps)	Actual yield remark	Expected yield predicted from the map	Agreement between actual and expected
32	Kalitala	23° 14’ 36″	87° 52′ 20″	3.73	Medium	Medium	Agree
33	Chandipur	23° 24′ 46″	87° 53′ 30″	8.18	High	High	Agree
34	Noapara	23° 38′ 30″	87° 58′ 44″	7.72	High	High	Agree
35	Ramkrishtopur	23° 5′ 47″	87° 49′ 41″	7.62	High	High	Agree
36	Malatipur	23° 16′ 51″	88° 19′ 51″	4.52	Medium	Medium	Agree
37	Madhupur	23° 14′ 10″	88° 5′ 22”	3.37	Medium	Medium	Agree
38	Mirjapur	23° 16′ 56″	87° 52′ 55”	3.05	Medium	Low	Disagree
39	Bhatra	23° 14′ 41″	88° 15′ 12″	4.37	Medium	Medium	Agree
40	Suipara	23° 13′ 13″	88° 14′ 32″	4.45	Medium	Medium	Agree
41	Madhabpur	22° 59′ 34″	88° 1′ 32″	4.92	Medium	Low	Disagree

0.731 or it compared to 73.1% accuracy. So, it can be remarked that this method can be used here to generate a precious result of the groundwater potential map.

4 Conclusion

The delineation of groundwater potential zones with the aid of advanced approach of remote sensing and GIS using multi-influencing factors (MIF) technique in the Purba Bardhaman district may be very much helpful for the sustainable development planning of underground water resources. The result depicts that about 20.65% area is in the category of the high potential zone, and with the help of the ROC curve, it has been proved that this method is about 73% accurate for the assessment of groundwater potential zones. Moreover, Purba Barddhaman is an agriculturally endowed region, so for the better management of groundwater resources, especially for agricultural purposes, this kind of study is very much relevant and justified. Common people can also be benefited from the map because, with the help of this, they can easily identify the proper drilling area to extract water for a long time.

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Delineating the Status of Groundwater in a Plateau Fringe Region Using Multi-influencing Factor (MIF) and GIS: A Study of Bankura District, West Bengal, India

Avijit Mahala

Abstract Present study tries to identify the groundwater potential areas in a plateau fringe region of the tropical environment. Groundwater is an essential natural resource of any region and it also bears the hydrogemomorphological conditions of that region. The availability of groundwater indicates the geomorphological, hydrological, pedological as well as vegetal characteristics of a particular area. The current study evaluates the status of groundwater of Bankura district, West Bengal which located in the eastern slope of Precambrian Chota Nagpur plateau dominated by granite gneiss and Gondwana deposits. Major groundwater potential zones are confined within residual weathered rocks of the district. The present study, therefore, was undertaken to identify the significant groundwater development with the help of remote sensing data. The original data sets like Landsat 8 multispectral data, aster DEM data, toposheets has been used to evaluates the hydrological, geomorphological, pedological and landuse landcover characteristics of Bankura district. Ten features (geology, geomorphology, pedology, soil texture, lineament density, relief, slope, drainage, aridity and landuse landcover) which delineates the groundwater potentiality have been analysed and integrated. The weighted raster has been created after assigning the relative weight derived from Multi-Influencing Factor (MIF) analysis. All the features have been integrated into a GIS environment. The weighted index overlay method has been followed after assigning the certain weight derived from MIF to each class of each feature. The result indicates the poor to a fairly good condition of groundwater potentiality in all over the district. The whole district has been categorized into four distinct groundwater potential zones. Very poor groundwater potential zone constitutes 6% of the total district area, covered by unweathered granite gneiss geological formations mostly. This is the area of plateau proper also. Poor groundwater potential zones occupy 39% of the total area covering proper plateau fringe region. This is the area of crystalline gneiss rock of dissected plateau. High slope and undulating characteristics of the terrain helps less infiltration of rainwater. The reasonably good condition of groundwater potentiality occupies a

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majority of the block, covering 46% of the total area of the district. This is the area of significant rivers interfluvial area covered by upper alluvium geological formations. Less relief and slope with high drainage density helps in easy groundwater recharging creates good groundwater potential zone. The very good potentiality of groundwater covers floodplains of major river basins in the districts occupy 9% of the whole area. This is the area of newly deposited alluvial soil helps easy recharging of groundwater.

Keywords Chotanagpur plateau · Groundwater potential · Multi-influencing factor (MIF) · Plateau fringe · Remote sensing · Tropical environment · Weighted index overlay

1 Introduction

Groundwater is one of the essential flow resources available under the surface of the earth. It available in the aquifer zones of porous rock system bounded by aquiclude. The groundwater can be grouped saturated (sufficient availability), unsaturated (Insufficient availability), and types of groundwater available in vadose zone. The importance of groundwater is not only in providing the largest sources of irrigation water worldwide but also to sustain the important sources of drinking water. It is the only sources of drinking water in prolonged dry areas of the world. Groundwater is the sources of 85% of the domestic households in rural areas (Nag and Kundu 2018). The importance of groundwater can be stressed from the fact that the countries development can be judged by the use of groundwater of that country. The water stress conditions are becoming due to the overexploitation of groundwater to fulfil the growing needs. This situation is becoming more hazardous because of unscientific groundwater exploration techniques (Nag and Ghosh 2013). Some parts of the world are facing severe groundwater stress specially high yielding areas. India, a part of tropical world also faces the problem of overexploitation of groundwater. The arrival of green revolution had further accelerated the groundwater depletion. The situation is alarming in northwestern parts of the country, i.e. Punjab, Hariyana and western parts of Uttar Pradesh. Though India has large porous aquifer rock systems in her geological settings imbalance situation in groundwater recharging creates water stress problems. This situation is more prolonged in large plain areas (Ganga, Sindh, Godavari, Narmada basin etc.) of the country due to overexploitation for irrigation. There is an urgent need for groundwater management and development to call off this problematic situation. It needs a large volume of data from various sources.

An integration of different factors influencing groundwater availability in the GIS environment is the best way for managing groundwater development. The GIS and remote sensing have the advantage of covering temporal, spatial and spectral data for large and inaccessible areas in minimum times. It helps in convergent analysis of multidisciplinary data (Nag and Ghosh 2013). Several attempts have been made to provide the groundwater potential areas through the use remote sensing data

(Pande et al. 2018; Das 2017; Adhikary and Dash 2017). Remote sensing offers a time-efficient and extensive coverage of parameters controlling the occurrence and movement of groundwater such as geological formations, stratigraphy, lineaments, soils, geomorphology, landuse landcover etc. (Yeh et al. 2016). Therefore the systematic study of all these factors can provide a better groundwater prospective zones of any area. The combination of remote sensing and GIS offer a suitable platform for analysis of large volume multidisciplinary data. Jagannathan et al. (1996) have used GIS platform for delineating groundwater potential zones Marudaiyar basin of south India. Similar work has been done for Burdur province of Turkey (Sener et al. 2005) and Occidental Lebanon (Shaban et al. 2006). The application of remote sensing and GIS in groundwater hydrology provides the opportunities of hydrogeologic data analysis, distribution of natural recharge zones, artificial recharge site and assessment of groundwater resource (Peiffer 2007).

The different study has used different methods to identify groundwater prospect zones. Most of the study access groundwater potential zones by integrating the geophysical data with geospatial data (Jagannathan et al. 1996; Yeh et al. 2016). Study of Sener et al. (2005), Shaban et al. (2006) have identified groundwater potential zones through the interpretation of geological, lineament and landuse characteristics after the integration of different thematic layers like, annual rainfall, LULC, topography, slope, drainage density, lithology, lineament density etc. Many studies used artificial recharge site as an important indicator for groundwater prospect zone identification (Saraf and Choudhury 2010). Study of Gupta and Srivastava (2010), Nag and Ghosh (2013) gave more importance to lineament density in identifying groundwater prospect zones. Guru et al. (2017) have used ER model in determining groundwater zones of cold desert, India. Presence and movement of groundwater depend upon many factors like geological formations, geomorphological features, soil characteristics, lineament density, drainage density, slope characteristics, aridity condition, landuse landcover characteristics etc. Most of the study tried to integrate all this factors in GIS environment (Jaiswal et al. 2010; Sar et al. 2015; Das 2017; Thapa et al. 2017). So, the integration of different factors which influences the occurrence and movement of groundwater in GIS environment can identify the groundwater prospective zones better.

Nowadays, most parts of the world across the different morpho-climatic areas are facing the groundwater shortage due to the overexploitation. The tropical world though receives high rainfall but due to its overdependence on agriculture also faces groundwater shortage. The tropical world needs special attention from a groundwater perspective due to its agricultural dependence. India as a part of the tropical world also need attention. India has different morpho-climatic regions. It ranges from high mountain areas in northern parts to the ancient plateau areas in middle and southern parts. The large river basin areas are located in between. Plateau area should be given special attention due to its less rainfall receive and dry prone regions. Plateau fringe areas have special characteristics like undulating landform, occasional hills, sloppy surface (Mahala 2017). The areas also suffer from heavy agricultural land expansion in previously forested area (Mahala 2018a, 2018b). This is also causing massive groundwater extraction. This area suffered substantial groundwater shortage due to less groundwater recharge except for the regions of a valley fill and lineament intersect (Nag and Ghosh 2013). Most of the study evaluates the groundwater potentiality of plateau proper (Magesh et al. 2012; Ghosh et al. 2016; Das 2017). There is very less study available on plateau fringe region.

2 Study Area

The study area, Bankura district of West Bengal is a part of tropical plateau fringe region of eastern Chotanagpur plateau. The district is located in the southwestern parts of West Bengal adjoining Jharkhand and Orrisa (Fig. 1). The district covers the latitudinal extent of 22° 37′–23° 38′ N and longitudinal extent of 86° 36′–87° 44′ E. The granite gneiss geology, undulating plateau upland with inter-fluvial lateritic upland, eastern flowing river system, low to medium precipitation (100–140 cm), high temperature (35–40 °C), tropical dry deciduous forest cover makes the Bankura district a true representative of tropical plateau fringe (Mahala 2017). Geologically Bankura district is situated in the transition zone between western granite gneiss Chotanagpur plateau and eastern Gangetic alluvial plain. The gneiss and schist types of rock system spread in western half parts of the district. Medium to high relative

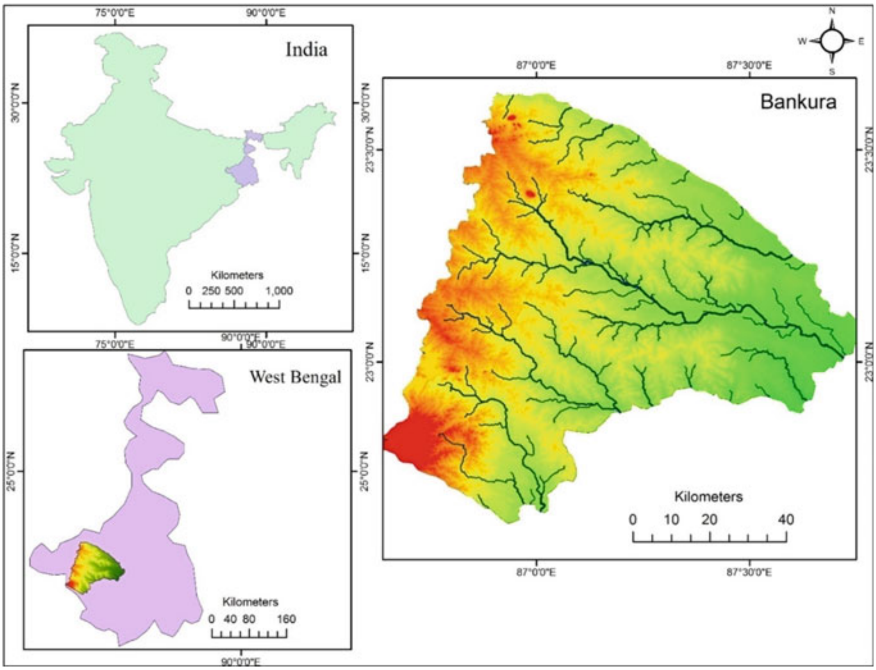

Fig. 1 Location of Bankura district, West Bengal, India

relief and undulating topography are the general characteristics of this formation. The sandstone and gabbro distributed in north-western part around Damodar Valley is an area of mining. The eastern half of the district is covered by alluvium geology. *Undulating plateau area* distributed in the western half of Bankura district has the characteristics of undulating, open plateau plain. Medium relative relief, dissected forest cover, longspur, undulating upland, dissected highland, pediments and isolated hillocks are the common physiographic unit in this division. Old granite is exposed in most parts of the premises (Mahala 2018a, 2018b). *Upper undulating alluvial plain*, distributed primarily in the interfluvial area of the plateau margin, characterized by 100–200 m. Elevation, 5–8 m. Relative Relief and >5° slope. *Damodar River* originated from Chotanagpur hill the river flows in farther north of the region. Damodar flows northern parts of Bankura district marks the boundary of the area. *Dwarakeshwar River* originated from Chotanagpur plateau. The river flows through undulating plateau upland of Bankura district. Dwarakeshwar River flows through the middle of Bankura district. Kangsabati River flows through the southern extent of district (Mahala and Pani 2018).

3 Data Used and Methodology

Remote sensing data have provided the most efficient tool for successfully exploring the groundwater potential zones. Most of the study conducted for identifying the groundwater prospect zones have used multispectral remote sensing data (Acharya et al. 2019; Pande et al. 2018). For the present study, the significant databases used are:

1. Landsat 8 OLI 30 m. resolution multispectral data.
2. Aster DEM 30 m. data.
3. SOI toposheets of the scale of 1:50,000.

3.1 Preparation of Thematic Map

The sources of database and detailed methodology for factor map creation used for the present study has been outlined in Table 1. ArcGIS 10.1 has been used extensively for factor map creation and raster conversion. The base map of Bakura district has been prepared from the Census of India database. The geological formations have been mapped form the Geological Survey of India (GSI) map. On-screen digitisation and vector map creation have been conducted. Geomorphological features have been stressed from Aster DEM (30 m) data and Landsat 8 OLI (30 m) multispectral image. Soil or pedological map has been prepared from National Bureau of Soil Science (NBSS) maps. Lineaments of the study area have been extracted from Aster DEM (30 m) data and density map has been prepared after applying fishnet tools of ArcGIS. The elevation and slope characteristics are identified from Aster DEM (30 m) data.

Table 1 Data sources of major factors of ground water prospects

Factors	Data sources	Techniques
Geological formations	Thematic map of GSI	Digitization and vector data creation
Geomorphological features	Aster DEM 30 m; Landsat 8 OLI 30 m. multispectral data;	Feature identification and vector data creation
Soil characteristics	Thematic map of NBSS	Digitization and vector data creation
Lineament density	Aster DEM 30 m; Landsat 8 OLI 30 m. multispectral data	Lineament extraction through GIS
Relief	Aster DEM 30 m	Relief classification through GIS
Slope	Aster DEM 30 m	Slope classification through GIS
Drainage density	Aster DEM 30 m	Raster calculation through GIS
Aridity (P/PET)	IMD data	Point kriging in GIS
Land use land cover	Landsat 8 OLI 30 m multispectral data	Maximum likelihood supervised classification
Soil texture	Primary field data	Point kriging in GIS

The drainage density map has been prepared from DEM data after applying raster calculation tools in ArcGIS. The aridity condition of the study area has been stressed by the IMD data. The landuse landcover map has been prepared from Landsat 8 OLI (30 m) multispectral data after applying supervised classification techniques.

3.2 *Assigning of Weights and Ranks*

The statistical techniques of multi-influencing factor (MIF) has been applied for computing the rates of each factor. The knowledge-driven approach has been applied for assigning the ranks of each subclass. The interrelationship among different factors and assigning of weights for each sub-classes has been done by author's prior knowledge supported by a detailed literature review (Thapa et al. 2017; Magesh et al. 2012; Arkoprovo et al. 2013; Senanayake et al. 2016). The factors which have a major influence on groundwater availability has been marked as a major effect and assigned a weight of 1.0. Whereas, the minor influence was marked as a minor effect with a weight of 0.5 as shown in Table 2 (Thapa et al. 2017; Magesh et al. 2012). Table 3 represents relative rates of each factor calculated by the cumulative sum of both major and minor effect followed by proposed score calculation of each influencing factor using the formula as follows:

$$\text{Proposed Score} = \left[(X + Y)/ \sum(X + Y)\right] * 100$$

Table 2 Multi-influencing factor score of each influencing factor

Criteria	Score	Classes	Weightage	Criteria	Score	Classes	Weightage
Geology	17	Alluvium	17	Slope	12	<1	12
		Schist and Gneiss	13			1–2	11
		Unclassified crystalline mainly Gneiss	10			2–3	10
		Anorthosite Gabro (Ultrabasic)	7			3–4	9
		Epidiorite/Metabasalt/Metagabro/Ophiotites	4			4–5	8
		Sandstone Shale Grit and Conglomerate	1			5–6	7
Geomorphology	14	Water body	14			6–7	6
		Flood plain	13			7–8	5
		Lower alluvial plain	10			8–9	4
		Upper undulating alluvial plain	7			9–10	3
		Dissected plateau	4			10–11	2
		Residual hillocks and mountains	1			11–12	1
Pedology	14	Water Body	14			>12	1
		Typic ustipsamments	13	Drainage density	5	<1.8	1
		Vertic haplaquepts	12			1.8–1.9	2
		Ultic haplustalfs	11			1.9–2.0	3
		Typic ustifluvents	10			>2.0	5
		Udic ustochrepts	9	Aridity (P/PET)	7	<0.65	1
		Typic Haplaquepts	8			0.65–0.67	2
		Typic ustorthents	7			0.67–0.69	3
		Udic haplustalfs	6			0.69–0.71	4

(continued)

Table 2 (continued)

Criteria	Score	Classes	Weightage	Criteria	Score	Classes	Weightage
		Lithic ustochrepts	5			0.71–0.73	5
		Ultic Paleostalfs	3			0.73–0.75	6
		Lithic ustrothents	1			>0.75	7
Lineament density	12	<0.05	1	Landuse landcover	7	Built up land	1
		0.05–0.10	3			Barren rocky area	2
		0.10–0.15	6			Sands-riverine	7
		0.15–0.20	9			Gullied or Ravenous land	3
		>0.20	12			Fallow land	4
Relief	10	<50	10			Cropland	5
		50–99	9			Forest (Degraded)	5
		100–149	8			Forest (Dense)	6
		150–199	7			Water bodies	7
		200–249	6	Soil texture			
		250–299	5		2	Coarse	2
		300–349	4			Fine	1
		350–399	3				
		400–449	2				
		>450	1				

Table 3 Weightage of different parameters for ground water prospects

Factors	Major effect (A)	Minor effect (B)	Proposed relative rates (A + B)	Proposed score of each influencing factor
Geological formations	3	0.5	3.5	17
Geomorphological features	3	0	3	14
Soil characteristics	3	0	3	14
Lineament density	2	0.5	2.5	12
Relief	2	0	2	10
Slope	1	1.5	2.5	12
Drainage density	0	1	1	5
Aridity (P/PET)	1	0.5	1.5	7
Landuse landcover	1	0.5	1.5	7
Soil texture	0	0.5	0.5	2
Total			$\sum 21$	$\sum 100$

where X represents the major effect of factors and Y represents the minor effect of factors.

3.3 *Weighted Overlay Method*

All the factor maps have been integrated into the GIS environment through the weighted overlay method after assigning the ranks and weight to each factor and subclasses derived from MIF analysis (Table 3).

Where GWPZ represents the groundwater potential zonation, 'x' and 'y' represents factor maps and factor subclass, respectively, G represents geology, GM represents geomorphology, S is soil, LULC is landuse landcover, DD is drainage density, Sl is slope, E is elevation, R is Rainfall, FL is fault and lineament density and ST is the soil texture.

4 Results and Discussion

4.1 Input Parameters for MIF

4.1.1 Geological Formations

Geology is a dominating factor in determining the groundwater potentiality of any area (Shaban et al. 2006). The land surface condition i.e., relief, slope, geomorphology also controlled by geology. The soil, groundwater storage, drainage condition, available mineral depends on geology which indirectly controlled the total aquifer. Granite and gneiss dominate the Archean rock system is the area of the world where the soil is not developed properly, creates less groundwater prosperity.

The district comprises dominant geological formation of Archean Dharwarian rock system (covered 40% of the total area of the district) (Fig. 2). This is the extension of the peninsular Chotanagpur rock system. The rock system includes granite, gneiss, schist and quartzite covered mostly large western parts of the district. The lower Gondwana sandstone, shale, grit, conglomerate and anorthosite gabbro are observed along the Damodar River or northern parts of the district. Alluvium of Holocene period together with laterite was vastly deposited around the eastern parts of the district. It covers more or less 50% of the total area of the district. The primary and secondary laterite is developed around this system. The archean gneiss and schist are characterized by vast open land, infertility, less matured or underdeveloped soil, rock outcrops. This is the main characteristics around the vast western parts of the district causes less water recharge. The less depth soil is unable to infiltrate water. The vast undulating surface causes hindrance in water percolation. The small hillocks with dissected plateau truly cause water stress condition. The Archean geology not permitted to percolation and infiltration causes less groundwater recharge. The undulating surface also decreases the percolating capacity of land. The immature soil is not permitted to grow vegetation cover which in turn causes less humus content in soil makes water stress. The Gondwana rock system in the north-western parts of the district is suffered from mining and related land degradation. The eastern part of the district is mainly covered by alluvium with the lateritic profile. The primary and secondary laterite developed greatly in this region. The interfluvial basin with undulating upper alluvial plain is covered by laterite profile. The greater slope with high rainfall causes intense leaching in this region which in turn causes intense rill and gully formation. The vast interfluvial upper undulating surface with lateritic cover in Dwarakeshwar, Silabati and Kangsabati river basin is prone to rill and gully erosion of the district (Shit and Maity 2012a, 2012b). This phenomenon causes less groundwater recharge and high overland flow.

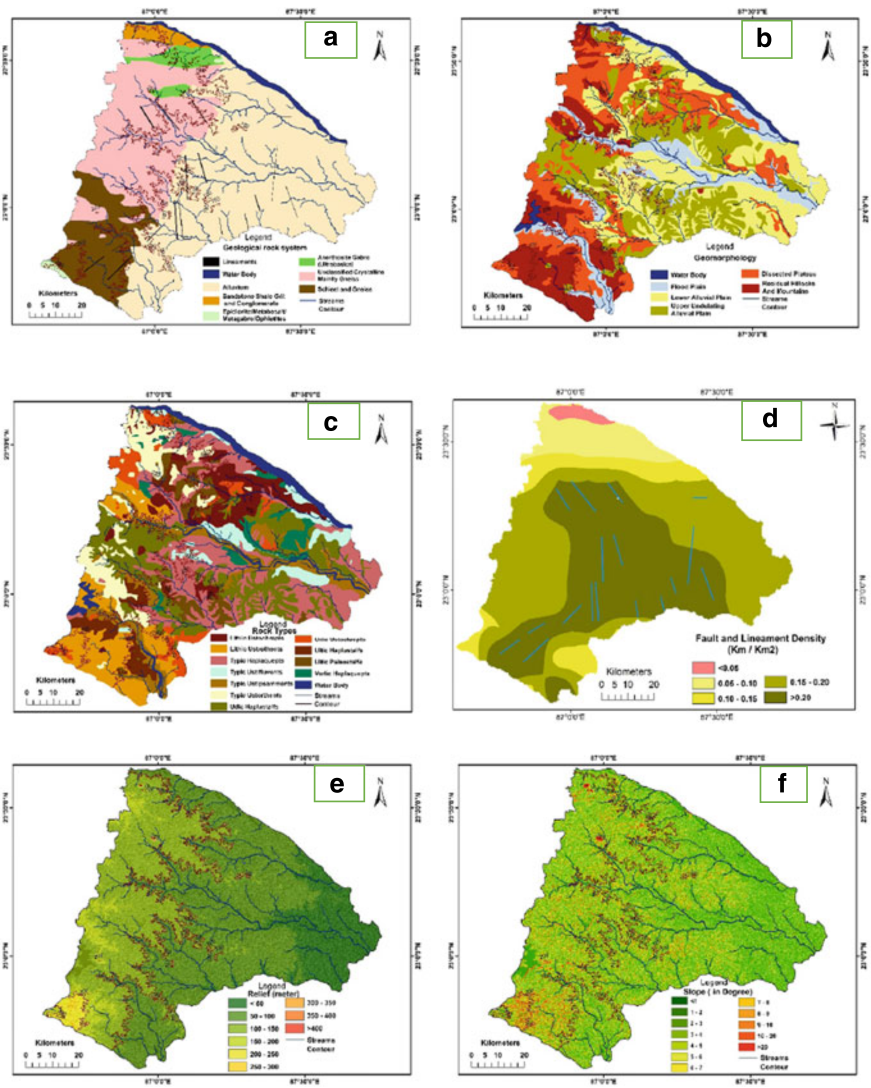

Fig. 2 Factors delineating the ground water potentiality of Bankura district—**a** Geological formations **b** Geomorphological characteristics. **c** Soil characteristics. **d** Lineament Density. **e** Relief characteristics. **f** Slope characteristics. **g** Drainage density. **h** Aridity conditions (P/PET). **i** Landuse Landcover

4.1.2 Geomorphology

The geomorphological features are other surface parameters control the occurrence and movement of groundwater. The different geomorphic features and their associative configuration delineate the groundwater potentiality (Thapa et al. 2017). Highly

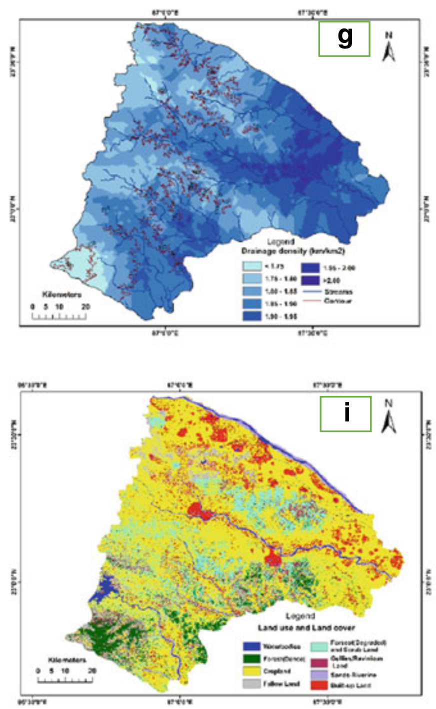

Fig. 2 (continued)

elevated mountainous land with high slope and closely spacing contours create high slope causes less groundwater recharge. The undulating topography with rugged terrain causes high overland flow (Shit and Maity 2012a, 2012b). The dissected and isolated hillocks cause less groundwater infiltration. This problem is dominated by the peninsular region of Asia and Africa (Nyssen et al. 2008). The gently sloping upland and pediments in the feet of undulating plateau suffers from the water stability and soil erosion related problems (Taye et al. 2013). The high relief with an intense amount of rainfall causes high gullied and ravenous erosion in the humid plateau areas. The Aeolian geomorphology with low land causes high water recharge. In one hand the geomorphology controls the water percolation directly and on another hand it controls indirectly by controlling the vegetation cover, climate, soil characteristics, etc.

The geomorphology of the Bankura district shows a transitional zone between vast alluvial Gangetic alluvial plain in the east and Chotanagpur plateau in the west (Fig. 2). The total geomorphology of the Bankura district can be divided into two broad categories (i) Granite gneiss, it includes residual hillocks and mountains and dissected plateau in the west and southern portion of the district. And (ii) Alluvial landforms, it includes upper undulating alluvial plain and lower alluvial plain. And flood plain in riverside. The residual hillocks and mountains of granite gneiss formation is an elevated unproductive area causes less water infiltration. The less-developed soil, the open surface is the general nature of the area. The dissected plateau around the northern and southern portion of the district is a medium elevated indurated plateau area. The sloped characteristics, less vegetation cover, and less soil development cause this area less groundwater potential. The upper undulating alluvial plain and lower alluvial plain is the area of intense rill and gully erosion makes high leaching and less infiltration. This is the area where soil eroded promptly (Shit and Maity 2012a, 2012b).

4.1.3 Soil Characteristics

Soil or the interactive zone of biosphere and lithosphere is the important parameter to delineate the groundwater potentiality. The soil physical characteristics i.e.: soil texture, soil structure, colour, temperature determine the land productivity (Askari et al. 2015). The high and low bulk density soil cause specific types of water stress condition (Bready and Well 2005). The different soil series and their associative controls the groundwater recharge all over the world. The frozen soil of the polar region is unable to infiltrate water. The podsol soil of high mountains area with a low pH suffers from low humus causes water stress. The low organic content soil of desert region causes less soil moisture. Less developed soil of mountain region unable to any types of groundwater recharge. High soil erosion of high slope area causes low infiltration. The coarse-textured soil of desert area is less suitable to capture water whereas the high clay content soil of plain area suffers from water accumulation related problems (Zaffar and Sheng-Gao 2015). The highly compact soil leads to infiltration problems in the mountains area whereas the less compact soil of plain area causes water holding problems. The high and low carbon content soil causes a specific type of water tress problem (Lal 2004). Moisture content capacity of soil controls the other physical and chemical characteristics (Cosby et al. 1984).

The Bankura district is situated in a transition zone of the western plateau and eastern plain land. The soils of Bankura district have distinguished two types of soil series, from middle to western part covers large textured sandy soils of granite gneiss and schist series. And in the eastern half of the district covered by the alluvium and laterite soil (Fig. 2). The lithic ustochrepts and lithic ustorthents covered southern part of the district is a high elevated area soil. The Typic Haplaquepts, Typic Ustifluvents, Typic Ustipsamments distributed through the southern portion of the district is an alluvial soil with laterite profile (Ghosh and Guchhait 2015). The udichaplustalfs and udicustochrepts are laterite deposited inter fluvial soil (Sarkar et al. 2014). The ultic and vertic soil distributed in dissected patches of the district. The lithic ustochrepts and lithic ustorthents distributed in the southern highlands suffer from the less profile development, immature soil, and large soil textural characteristics. The mountainous characteristics of these soils make it infertile. The little soil profile development does not permit water to percolate (Mondal 2012). A typical undulating surface, low permeability causes groundwater depletion. This area is the less habitable part of the district. The typic haplaquepts, typic ustifluvents, typic ustipsaments, and typicustothentslargely distributed in the river valley side of the eastern part of the district is suffering from soil erosion related problems. These types of soil are more or less fertile soil covers around the riverside of the district. The udichaplustalfs and udicustrochrepts developed in the interfluvial region is a laterite type of soil. The high Fe content, intense leaching, low pH and high soil erosion causes this soil-less infiltrative. This types of soils largely cover the interfluvial upper undulating surface. The high erosional characteristics with the sloppy nature of surface cause these types of soil more eroded. The ultichaplustalfs, ulticpaleostalfs, and vertichaplaquepts developed in interfluvial area are also more or less lateritic nature cause less water infiltration.

4.1.4 Lineament Density

The intensity of tectonic activity in hard rock terrain affects the groundwater occurrence and movement (Nag and Ghosh 2013). The evolution of groundwater in hard rock terrain is restricted to interconnected fracture system. Lineaments are natural, linear surface element can directly be interpreted from satellite image. The linear features of geological rock structure are assumed to be the zone of fractured rock system and profound groundwater sources. The hard rock aquifer has the importance of overall availability of groundwater. Thapa et al. 2017 have pointed out that groundwater recharge and availability zone in hard rock terrain is very much concentrated around lineaments and fractured fault zones. Lineament density can directly related to groundwater potentiality (Magesh et al. 2012).

Lineament can be easily identified by tracing out the satellite imagery. The lineaments are usually appeared in straight lines which can be easily identified by tonal differences within the surface materials (Nag and Ghosh 2013). The lineament density map has been prepared after calculating the ratio between the length of lineament to the area of each 1 km $\times$ 1 km grid of the study area. The kriging techniques have been applied for final preparation of the map. The lineament map has been categorised into 5 distinct densities (Fig. 2). It shows a higher density in the middle of the district.

4.1.5 Relief

The surface Relief is an essential parameter of the physiography of any region to determine the groundwater potentiality (Nag and Kundu 2018). The groundwater occurrence and movement get slowed down with increasing relief (Pande et al. 2018). The high relief region (>600 m.) have characterized by high sloped surface have created landslide, avalanches, glacial hazard, debris flow related problems. The high relief causes river drifting in this region. The surface water gets less time here to infiltrate (Ghosh et al. 2016). The soil profile could not develop in this region causes less water holding capacity (Lenka et al. 2014). The high relief areas of Himalayas are a typical example of these types of land degradation (Rashid, et al. 2011). The plateau region (600–300 m) have characterized by medium relief with undulating topography.

The Bankura district situated in the transition zone of eastern plain and western Chotanagpur plateau has typical relief characteristics. The 100 m contour goes through the middle of the district, divided the district broadly in north-south. The relief characteristics of Bankura district can be divided (i) <50 m; covers further eastern part of the district. (ii) 50–100 m.; covers east to the middle half of the district (iii) 100–150 m; covers northwestern part of the district (iv) 150–200 m.; covers the westernmost parts of the district. And (v) >200 m.; covers the south-western parts of the district (Fig. 2). The >300 m elevated areas are occasionally distributed from south to northern side of western half of the district is an isolated hilly area. In the north-western parts the "Susunia" hill region and the south-western the "Mukutmanipur" hill area is characterized by >300 m elevation area. This dissected hillock makes barrier in groundwater recharge. The 200–300 m relief areas distributed mainly in the south-western and isolated patches of western parts of the district is characterized by undulating surface, high relative relief, rock outcrop, less developed soil profile, poor organic matter content which ultimately helps poor groundwater recharge. The high relief with steep slope causes the water to flow makes low infiltration for groundwater recharging. Due to its steep slope characteristics, the vegetation does not grow much causes low surface cover, which in turn causes less rainfall. The 100–200 m. relief areas of the district create an open vast land with undulating characteristics. The less soil profile development is caused by these types of relief characteristics produce less groundwater recharge.

4.1.6 Slope

The slope characteristics of any region determine the stability of materials delineates groundwater condition. The high slope areas >30° have less potentiality to infiltrate the water causes rapid water drain and less groundwater recharge. The high slope areas of the mountainous region have faced slope failure, failure of share strength, landslides, and related problems. Most of the study used the slope factor for groundwater condition (Thapa et al. 2017; Magesh et al. 2012; Ghosh et al. 2016). The infiltration processes are hindered in these types of the sloped surface causes less recharge of groundwater which in turn adversely affect the cropping system of the region. Different irrigation works also hindered in these types of undulating sloped surface. The greater parts of Indian, African and American peninsular have faced these types of land degradation. The low to the medium sloped surface (5°–10°) is suitable for any types of anthropogenic activity.

The slope characteristics of the Bankura district can be subdivided into the following parts (i) >20°; the very high slope areas are concentrated in the south-western parts of the district and northern isolated hillocks areas. (ii) 10°–20°; the high slope areas have distributed around the dissected patches in south-western parts of the district. (iii) 5°–10°; the medium slope areas cover large parts of the district have distributed in interfluvial areas of the district. (iv) 0°–5°; the low slope areas cover large parts of floodplains in northern and eastern parts of the district have profound groundwater recharge zone (Fig. 2). The very high slope (>20°) areas on granite gneiss formation are the area of the rock outcrop and least groundwater recharge zone. The high slope (10°–20°) areas have also suffered from these types of problems. Geomorphologically this area is pediment in nature. The medium slope (5°–10°) areas cause undulating landforms in interfluvial areas of Damodar, Dwarakeshwar, Silabati and Kangsabati River of the district. The high dissected nature of slope and river valley side situation causes less groundwater recharge.

4.1.7 Drainage Density

The drainage network characteristics of any region control the groundwater recharge directly and indirectly. Drainage characteristics broadly determine the regions slope, accumulation and erosion characteristics. The drainage network of any region is the reflectance of all geomorphic and geologic characteristics. The different characteristics of drainage (Drainage density, frequency, length, profile, eroding capacity, and basin shape and basin forms) determine the water infiltration condition of the region (Frankl et al. 2013). High drainage density causes greater groundwater occurrence and movement. The high sloped surface with intense contour spacing formed high-density drainage causes high soil erosion (Girmay et al. 2009). Studies indicate the potential groundwater formation of high drainage density region (Pande et al. 2018; Guru et al. 2017). The basin characteristics determine important characteristics of the river. The large basin areas have collected a large amount of water causes good groundwater recharge. The different basin shapes (Elongated, circular) and forms determine the sediment flow characteristics which in turn delineates groundwater potentiality.

The Bankura district situated transition zone in western plateau and eastern plain have typical types of drainage density condition. The very high Drainage density (>2 km/km^2) have shown in the northeastern lowlands of the districts (Fig. 2). The relatively high gradient of an interfluvial plateau in comparison to River flood plain has given origin high amount of 1st and 2nd order streams which ultimately flows through the plains region to join the main streams. Consequently, this region is covered by lateritic soils causes' high rill and gully erosion leads the land degradation. The high drainage density (1.9–2.0 km/km^2) region broadly distributed along the rivers of Damodar, Shilai, Kangsabati causes high upslope erosion. The interfluvial highlands have largely eroded and create badland topography by this high-density river erosion. The lateritic badlands have developed in this region causes less groundwater recharge.

4.1.8 Aridity (P/PET)

Rainfall plays a prime role in recharging the groundwater. High rainfall areas have the general tendency to acquire prosperous groundwater table. Rainfall and temperature determine the water balance condition of any region. The climatologist used to calculate the water balance condition through the precipitation and evapotranspiration ratio (P/PET) of any area (Kafle and Bruins 2009). The high evapotranspiration than precipitation causes desertification and drought condition (Boschetto et al. 2010). The solar radiation determines the vegetation productivity which in turns controls the other environmental condition. The temperature is also an important climatic parameter determine the soil characteristics and weathering phenomena which ultimately determines the groundwater potentiality. The study used (P/PET) and rainfall condition for groundwater potentiality estimation (Senanayake et al. 2016; Nag and Ghosh 2013).

The climate of the Bankura District is the tropical dry sub-humid, with normal annual rainfall ranging from 1100 mm. in the northern part and 1400 mm. in the southern and eastern part of the district. The mean daily maximum temperature ranges from 40 °C in May to 15 °C in January. The variation in the no. of rainy days and soil moisture variation is common in large parts of the district. The drought periods lasting for weeks adversely affect the cropping practice of the district. The average annual rainfall is higher (>1420 mm) in southern hilly region and towards the north the rainfall decreases dramatically. At the northwestern portion, it is below (<1200 mm.) The Aridity map shows low ratio (<0.60) of P/PET in northern parts of the district causes less groundwater potentiality (Fig. 2). The medium to the high ratio (>7.0) of P/PET shows in southern and eastern parts leads effluent groundwater condition.

4.1.9 Land Use Land Cover

The land degradation characteristics of any region are better to understand groundwater potentiality (Das 2017). The land use characteristics of any region affect groundwater recharge directly and indirectly (Senanayake et al. 2016). The agricultural land use affects groundwater recharge positively as well as negatively. The more the agricultural land more water extraction causes fall in groundwater table on the other side agricultural land also source of groundwater recharge.

The Bankura district situated between the western plateau and eastern plain has a typical land use characteristics (Fig. 2). The water bodies account 2.29% of the total area of the district. This is low in comparison to other areas causes less groundwater recharge. The major source of water is eastern flowing Damodar, Dwarakeshwar, Silabati and Kangsabati River. The dense forest land covers 5.01% of the total area of the district largely distributed in interfluvial highlands. Cropland covers 54% of the area distributed mainly on major river basins. Fallow land accounts 5.64% of the area is the result of continuous forest cutting. The degraded forest and scrubland account 13% of the area is placed in the previously occupied dense forest area. Gullied and ravenous land account 4.5% of the total area largely concentrated on interfluvial lateritic upland and high slope areas. The sands and riverine accounted 2.705 of the area distributed in the riversides. The total built-up area of the district is 9.05% and it is increasing in nature. In the discussion of landscape sensitivity, the anthropogenic activities as an external force to groundwater recharge condition. The land use and land cover status and change greatly delineate the groundwater recharge of Bankura district. Previously occupied water bodies have been changed to built-up areas effect the occurrence of groundwater. The continuous change in LULC categories causes changes in groundwater potentiality. The relative dependence on forest land have cleared out the dense forest and converted to open forest in Bankura district. The continuous pressure on land helped to convert the previously occupied open and dense forest land to agriculture land. The faulty agricultural practice, excessive use of fertilizer, high irrigation causes fall in groundwater table. The high elevated zones have greatly sensitive to any types of LULC change, causes groundwater table decline. The high elevated zone in the southern parts of the district has faced this problem. The high slope with extensive agriculture in inter fluvial upland and riverside of the district faces a high rate of soil erosion. The high rate of vegetation extraction has also helped to form the gullies and riverine. The continuous increase in population helped to built-up land expansion. This expansionis accelerated in the major towns like Bankura, Bishnupur, Raipur and vast northern plain region. This causes concretization of surface and related less groundwater infiltration.

4.1.10 Soil Texture

Soil texture has a greater influence on groundwater recharging. The large texture soil has the facility of easy recharging and flowing of groundwater. Whereas the fine texture soil like clay and silt have less capacity of easy flowing and recharging of groundwater. Thapa et al. (2017) have used soil texture important parameters for groundwater occurrence and movement.

Bankura district as a part of eastern Chotanagpur plateau fringe region has the different soil texture characteristics in different parts of district. The lithic ustochrepts, lithic ustorthents types of soil in western parts of district have large soil texture. The interfluvial areas of the district have greater water infiltration facilities. Whereas the flood plain areas have greater clay content causes less groundwater potentiality.

4.2 Groundwater Potential Zones

The groundwater potential zones of the Bankura district has been computed after Weighted index overlay analysis (WIOA). This is simple and straight forward method for combined analysis of the multiclass map. The human judgement can be incorporated in these types of analysis. The assigning weight depends upon the relative importance of parameters vis-a-vis the classes. The WIOA takes into consideration the relative importance of parameters and the classes belonging to each parameter. The current study has taken the idea of the previous study for criteria selection and assigning the importance to each parameter (Magesh et al. 2012; Nag and Kundu

2018; Thapa et al. 2017). All the factor maps (Geology, geomorphology, soil, drainage density etc.) has been converted into rater layer. The individual layers and classes are assigned by score and weightage (Table 3). The higher weight indicates the greater potentiality of groundwater. The GIS modelling techniques of index overlay method was then applied to produce groundwater potential map.

The final output map has been classified into 'very poor', 'poor', 'good', 'very good' according to the pixel arrangement of the histogram in ArcGIS (Fig. 3). The 'very poor' groundwater potential areas fall in the rocky western parts of district. It covers 438 km^2 or 6% of the total area of district (Table 4). This region covers with ancient granite gneiss geological formation and characterizes by undulating geomorphology helps less water infiltration. The 'poor' groundwater potential areas acquire 2689 km^2 or 39% of the total district distributed mainly whole western and

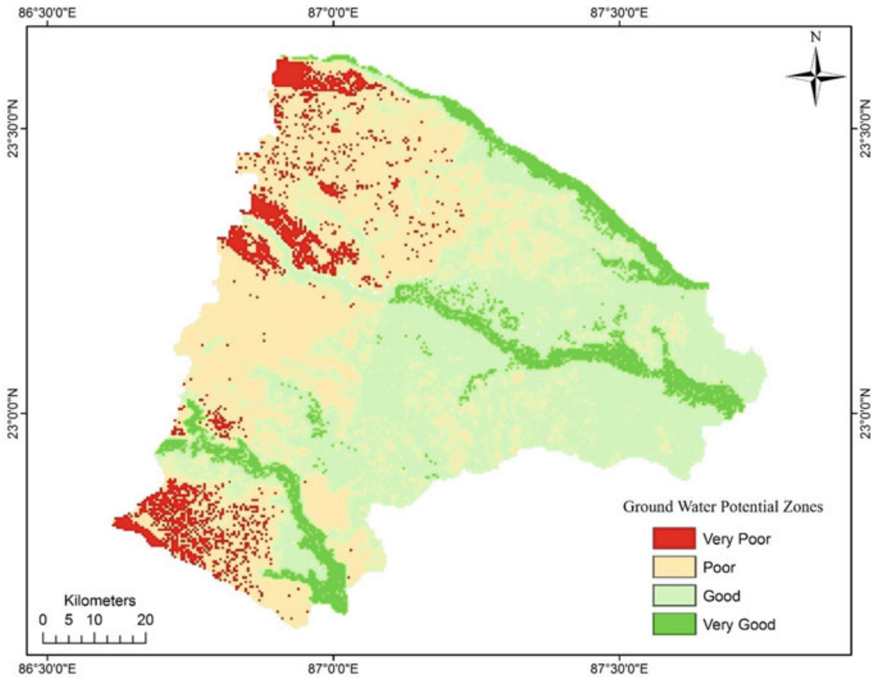

Fig. 3 Major ground water potential zones of Bankura district

Table 4 Area shearing by different ground water potential zones of Bankura district

Zones	Weightage value	Area (km^2)	Area (%)
Very poor	<40	438	6
Poor	40–55	2689	39
Good	55–70	3177	46
Very good	>70	586	9

middle parts of the district. This is covers by unclassified crystalline mainly gneiss geological formations with dissected plateau. The less-developed soil cover with high elevation slope makes the region less potential for groundwater occurrence and movement. The less rainfall and higher aridity help in creating this situation. The ‘good’ groundwater potential area has covered 3177 km^2 or 46% of the total area of district. This area is largely distributed in upper interfluvial areas of eastern parts of district. The region is covered by upper undulating alluvial plain. The higher concentration of lineaments and relatively low elevation and slope, as well as thick soil cover, make the region suitable for water percolation and related groundwater potential. The ‘very good’ groundwater potential area covers 9% of the total area of district or 586 km^2. This is the area of major river basins with thick alluvial cover deep soil profile make the region suitable profound groundwater storage. The very low slope and relief with high rainfall and drainage density help to increase the groundwater table.

5 Conclusion

The current study finds remote sensing, GIS and MIF techniques are efficient tools in delineating and characterising the groundwater potential zones of a plateau fringe region in tropical environment. The current tool is efficient in terms of time, cost and efficiency. The recent study involving in delineating the groundwater potential areas of plateau fringe of tropical environment. The plateau fringe region has the unique characteristics of the archean geological formations, undulating surface with occasional hills of eroded plateau. The gradient elevation differences with sloppy terrain of erosional plateau fringe make the region unique. The declining vegetation cover with increasing aridity creates the region profound area for studying the groundwater potentiality estimation. The different thematic layers like geology, geomorphology, soil, drainage density have been prepared and converted into raster format after assigning weightage according to the importance of groundwater potentiality. The integration of raster layers has been done after applying WIOA techniques in GIS environment. The district has been divided into ‘very poor’, ‘poor’, ‘good’, ‘very good’ according to the groundwater potentiality of the district. The ancient hard rock system with high elevation and sloppy area shows low groundwater potentiality due to its less water infiltration capacity. Whereas the major river basin areas of alluvial low plain and thick soil cover area showing high groundwater potentiality. The results of the present study can use for future groundwater recharge project for sustainable utilization of groundwater.

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Aquifer Vulnerability Assessment of Chaka River Basin, Purulia, India Using GIS-Based DRASTIC Model

Amit Bera, Bhabani Prasad Mukhopadhyay, and Swagata Biswas

Abstract The quality of groundwater, the vast freshwater reserve, is degrading and deteriorating with rapid increase in urbanization and industrialization. Anthropogenic activities are highly responsible for pollution and contamination of groundwater; this, in turn, poses a serious threat to the environment as a whole. For efficient management of this water resource mapping, the vulnerable aquifer zones are a necessity. The study conducted on Chaka watershed aims to delineate the vulnerable aquifer zones of the region using GIS-based DRASTIC model. This model uses 7 parameters for assessing groundwater vulnerability namely Depth to water level (D), Recharge (R), Aquifer media (A), Soil media (S), Topography (T), Impact of vadose zone (I), and Hydraulic conductivity (C). The study area is mainly an agricultural watershed which incorporates the heavy usage of insecticides, pesticides and fertilizers of various kinds. The rainwater that seeps underground thus enriches itself with such chemicals and contaminates the underlying aquifer. The aquifer vulnerability map was generated using overlay analysis and the study area is classified into 5 aquifer vulnerability zones. The validation was done using the physical parameter Total Dissolved Solids (TDS). Few villages with very high vulnerability are Kamta, Takaria, Babuijor, Deorang etc. The output map can be used for future references for efficient planning and management and carrying out research work as well.

Keywords Aquifer vulnerable zone · Chaka basin · DRASTIC · GIS · Groundwater contamination · TDS · Thematic layers

1 Introduction

Groundwater contamination and pollution is a burning issue of the hour. Groundwater is essential for maintaining a proper ecological balance and sustaining life forms on Earth. A major source of potable water is groundwater. Extracted groundwater is also

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required for development of industries, agriculture and meeting the daily domestic requirements. Rapid urbanization and industrialization are highly responsible for contamination of these huge underground freshwater reserves. In India, 396 km^3 of groundwater per year is estimated to be utilizable annually, 80% being domestic water needs and greater than 45% accounts for irrigational purposes (Kaur and Rosin 2011).

Recently, the groundwater quality has drastically deteriorated because of various anthropogenic issues such as improper farming, sewage disposal, landfill wastes, and chemical effluents from industries etc. these pollutants pollute the underlying water reserves and poses a serious threat to mankind (Adhikary et al. 2010). A fundamental approach for proper utilization and management of groundwater and its resources is vulnerability mapping of Aquifer. Aquifer vulnerability is of two types (a) Intrinsic Vulnerability (b) Specific Vulnerability. Intrinsic vulnerability depends on environmental conditions, Specific vulnerability is caused by the transported and waterborne contaminants.

Various approaches had been made by previous researchers to assess the aquifer vulnerability such as GOD (Foster 1987; Ibe et al. 2001; Ghazavi and Ebrahimi 2015), SIGA (Vrba 1991), DRAV (Zhou et al. 2010), fuzzy rule-based approach (Dixon 2005), SINTACS (Civita and De Maio 1997; Al Kuisi et al. 2006; Kumar et al. 2013; Majandang and Sarapirome 2013), IRISH (Daly and Drew1999), AVI (Raju et al. 2014; Jilali et al. 2015), EPIK (Doerfliger and Zwahlen 1997; Doerfliger et al. 1999; Awawdeh and Nawafleh 2008). For assessing the vulnerability of the aquifer of the present study area DRASTIC model was used. Aller et al (1987) used the DRASTIC methodology for evaluating Groundwater Pollution potential with the help of hydrogeological setting. This model is widely accepted and a reliable approach for delineating the contaminate zones. Various researchers have worked on this model previously (Rahman 2008; Assaf and Saadeh 2009; Saidi et al. 2010; Prasad et al. 2011; Huan et al. 2012; Sener and Davraz 2013; Neshat et al. 2014; Singh et al. 2015; Lathamani et al. 2015; Tiwari et al. 2016; Al-Abadi et al. 2017; Ahada and Suthar 2018; Mondal et al. 2019). The geospatial study helps in temporal, spectral, and spatial analysis of data accurately over a large areal extent within a short time (Jackson 2002). Chaka basin covers a large area of agricultural land. Here, irrigation for farming is practiced in dry season. The present study focuses on the identification of Aquifer vulnerability zone in Chaka river basin, Purulia using DRASTIC model and GIS techniques for the monitoring and sustainable management of groundwater resources.

2 Study Area

Chaka river, a left-bank tributary of the Kumari river is situated in Purulia district of West Bengal. The total area of the river basin is 190.92 km^2. Geographically, the study area is located between the latitudes 23° 3′ 8″ N to 23° 13′ 49″ N and longitudes 86° 19′ 41″ E to 86° 33′ 51″ E (Fig. 1). Majority of the study area (37.22%)

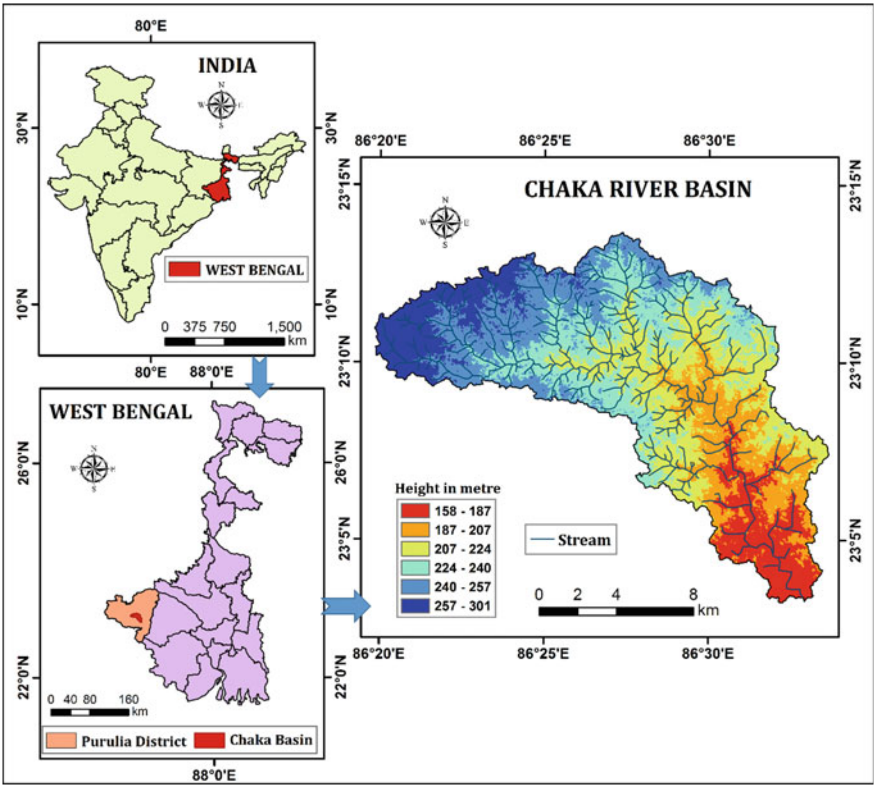

Fig. 1 Location map of the study area

lies in the Manbazar-1 block along with Puncha, Puruliya-1, Barabazar and Arsha blocks. Chaka river originates from Bungara Pahar of Kumari upland and flows towards the east and then flows southeasterly from the village Birjidi of Manbazar-1 block, then finally joins the Kumari River near Bamni and Janra village. The basin mainly comprises hard rock so the primary porosity and permeability are very low. Chotanagpur Granite Gneiss Complex is the major rock type of the study area although some sparsely located mica schist, alluvium and shale were seen. Severe water scarcity affects the region since it is a semi-arid region. The annual rainfall of the region varies from 1265 to 1328 mm, the maximum precipitation occurs during the months of June–September. The study area is an agriculture dominated watershed and the agriculture is largely dependent on the monsoons. Typic Endoaqualfs and Ultic Haplustalfs can be seen in the upper part of the basin, and Typic Ustorthents dominate in the lower parts.

3 Methodology

A widely used procedure of assessing groundwater vulnerability of the aquifer of the region is DRASTIC model. This model is used for delineating groundwater zones which are vulnerable to pollution and contaminants, over a large areal extent. This helps in clear determination of the fact, whether the groundwater is safe for consumption and industrial usages. This model requires 7, both hydrogeological and geomorphological parameters namely Depth to water level (D), Recharge (R), Aquifer media (A), Soil media (S), Topography (T), Impact of vadose zone (I), Hydraulic conductivity (C). These parameters help in better understanding of percolation and infiltration of water. The parameters were ranked accordingly with a specific weight (W_i), and rating (R_i) (Table 1). The parameters were multiplied with their weights and the DRASTIC Index (DI) was computed using the formula:

$$DI = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w$$

where, D, R, A, S, T, I, C represents the 7 parameters, r is the rate and w is the weight assigned to the respective parameters.

24 locations were selected in the study area for measuring the depth to water level, and for validation, the TDS data of the tube wells from the same sites were noted. HANNA HI 98192 (EC/TDS/NaCl/Resistivity) was the instrument used for measuring the physical parameters of the groundwater sample. The collected data were then used for generating the output map in ArcGIS 10.0 environment using IDW Interpolation Method. Rainfall data were collected from Indian Meteorological Department (IMD), the data were used for generating the recharge map and the calculations done were based on the methods of Chaturvedi (1973). The geological map from GSI was used for preparing the Aquifer Media map. The soil texture data from NBSS and LUP was used for preparing the Soil media map. NBSS & LUP, and litholog data from CGWB were used for generating the vadose zone media and Hydraulic Conductivity map. The slope map was produced using ASTER DEM and has been used as the Topography map. The thematic maps were then reclassified into 30 × 30 m cell size. The main thematic layer consisting of the sub-criteria were assigned equivalent weights and ratings and reclassified again. With the help of overlay analysis method the final aquifer vulnerability map was produced. The methodological flow chart is presented in Fig. 2.

4 Results and Discussion

4.1 Depth to Water Level

The distance of the groundwater level from the surface is referred to as depth to water level. Measured in meters, this factor plays a major role in determining the

Table 1 DRASTIC rating and weighting values for the various hydrogeological settings in the study area

DRASTIC parameters	Range	Rating	Weight	Total weight (rating × weight)
Depth to water level (feet)	15.22–18.10	9	5	45
	18.10–19.94	7		35
	19.94–22.82	5		25
	22.82–27.34	3		15
	27.34–34.43	2		10
Net Recharge (in/year)	8.284–8.335	9	4	36
	8.232–8.284	8		32
	8.180–8.232	6		24
	8.129–8.180	3		12
	8.077–8.129	2		8
Aquifer media	Alluvium	8	3	24
	Mica schist and shale	6		18
	Hornblende schist	5		15
	Granite gneiss	3		9
Soil media	Sandy skeletal	9	2	18
	Coarse loamy	7		14
	Loamy	6		12
	Mixed fine loamy	5		10
	Fine loamy	3		6
Topography (Slope in %)	0–3.36	10	1	10
	3.36–7.07	9		9
	7.07–11.28	7		7
	11.28–16.84	5		5
	16.84–42.96	2		2
Vadose zone media	Sand and gravel	9	5	45
	Coarse loamy	7		35
	Loamy	5		25
	Sandy silt	3		15
Hydraulic conductivity (m/day)	40.20–50	9	3	27
	30.40–40.20	7		21
	20.60–30.40	5		15
	10.80–20.60	3		9
	1–10.80	2		6

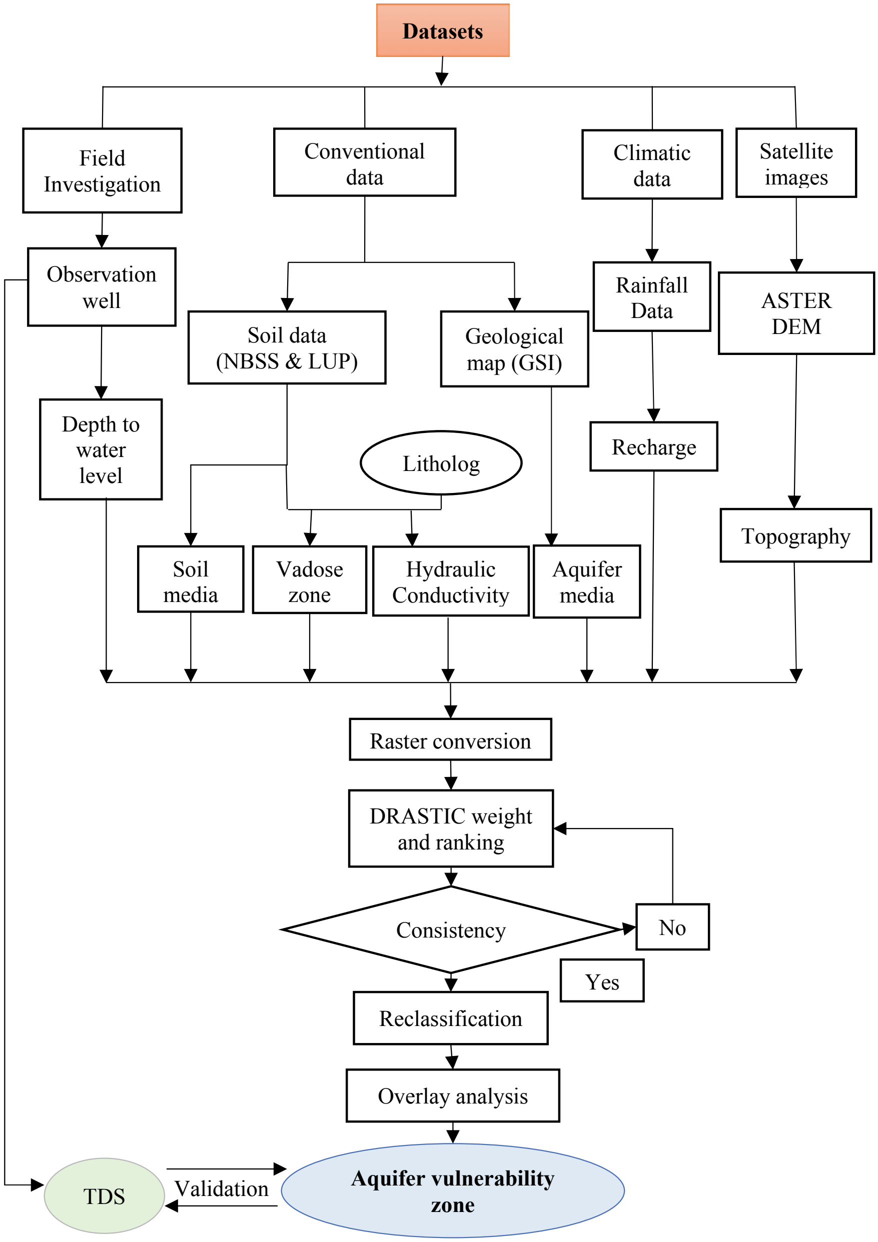

Fig. 2 Methodological flow chart for AVZ mapping

extent of contamination of an aquifer. Depth to water level is inversely related to the contamination and pollution of groundwater. A greater soil depth requires more time for the contaminants to percolate downwards. Loosely packed gravels and larger grains aids in quicker percolation of the contaminants rich water, on the other hand, smaller grains and finer particles check on the pollutants due to their higher density. Deeper aquifers are less vulnerable to contamination since higher percolation time helps in getting rid of the dissolved particles. Shallow aquifers, on the contrary, reduces the time for the reactions that take place otherwise such as sorption, oxidation, dispersion, attenuation (Ahada and Suthar 2018) and allow easy mixing up of the pollutants with the groundwater. Northwestern part of the study area is characterised by deeper aquifers covering 22.03% area, southeastern part has moderate water level covering 40.64% of the study area (Fig. 3). The lowermost catchment area has shallow water level. 37.33% of the study area has shallow water levels indicating the areas are at a higher risk of infiltration and subsequent contamination.

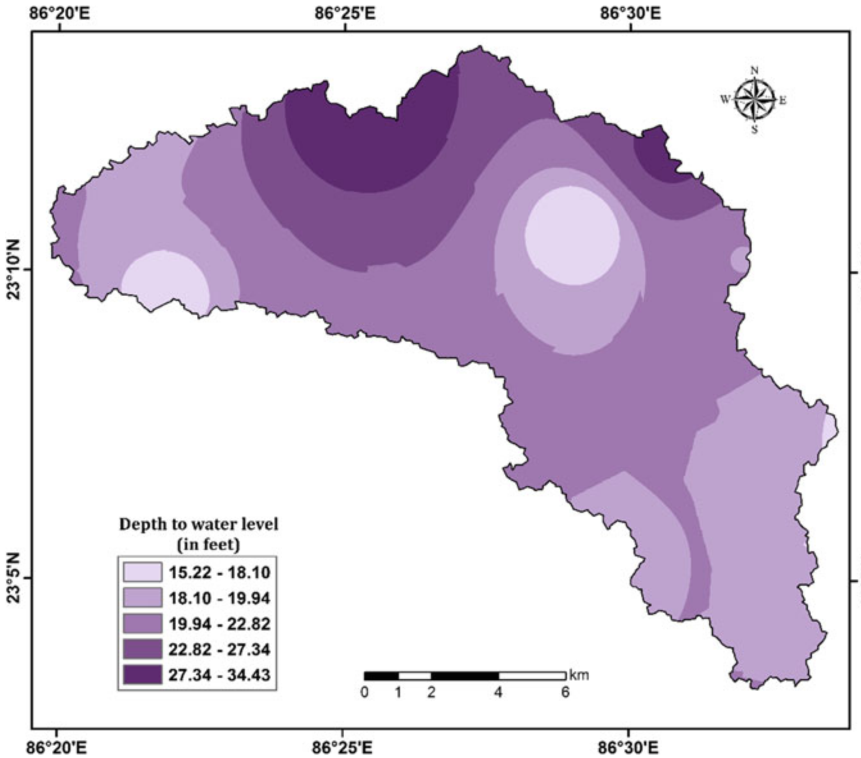

Fig. 3 Depth to water level map of Chaka River Basin

4.2 Net Recharge

The total amount of water percolating per unit area of soil and recharging the water table is referred to as the net recharge. Recharge mainly takes place through rain-water percolating ground surface, however, other factors such as artificial tanks and reservoirs, surface water bodies help in recharging the aquifer. Recharge is directly proportional to contamination. Therefore, an area receiving higher rain-fall and having higher net recharge is more vulnerable to pollution. Contaminants dissolve in the recharge water and percolates through the soil layers. The equation used for calculating the net recharge is R = 1.35 (P-14) 0.5 (Chaturvedi 1973). The net recharge of the area was classified into 5 classes ranging from very low (8.077–8.129), low (8.129–8.180), moderate (8.180–8.232), high (8.232–8.284), very high (8.284–8.335) inch/year covering 18.23, 51.88, 48.68, 38.40, 33.69 km^2 respectively (Fig. 4).

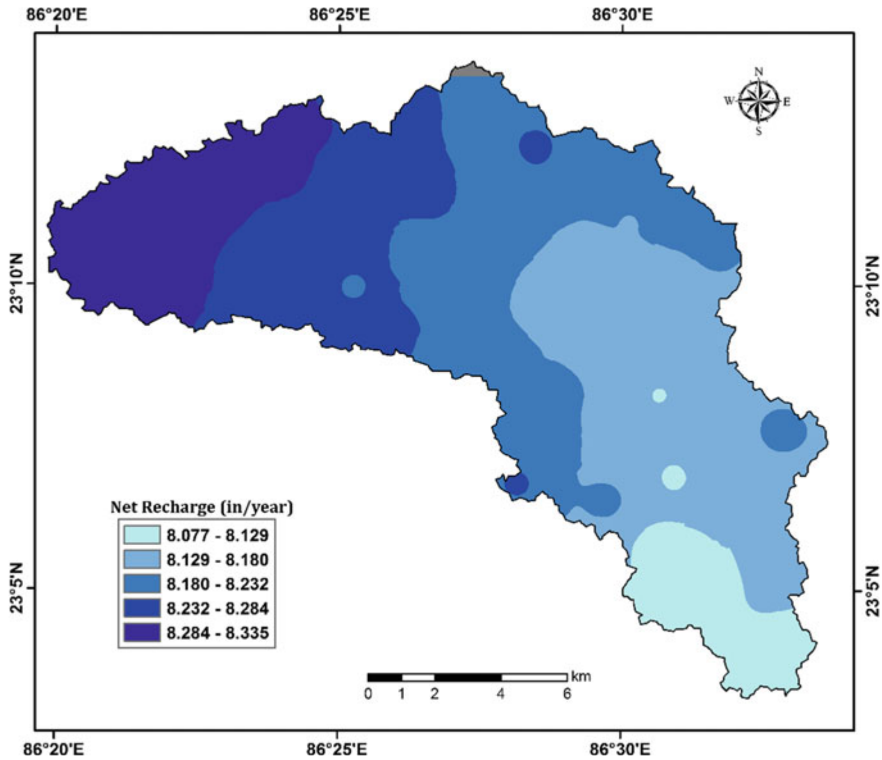

Fig. 4 Net recharge map of Chaka River Basin

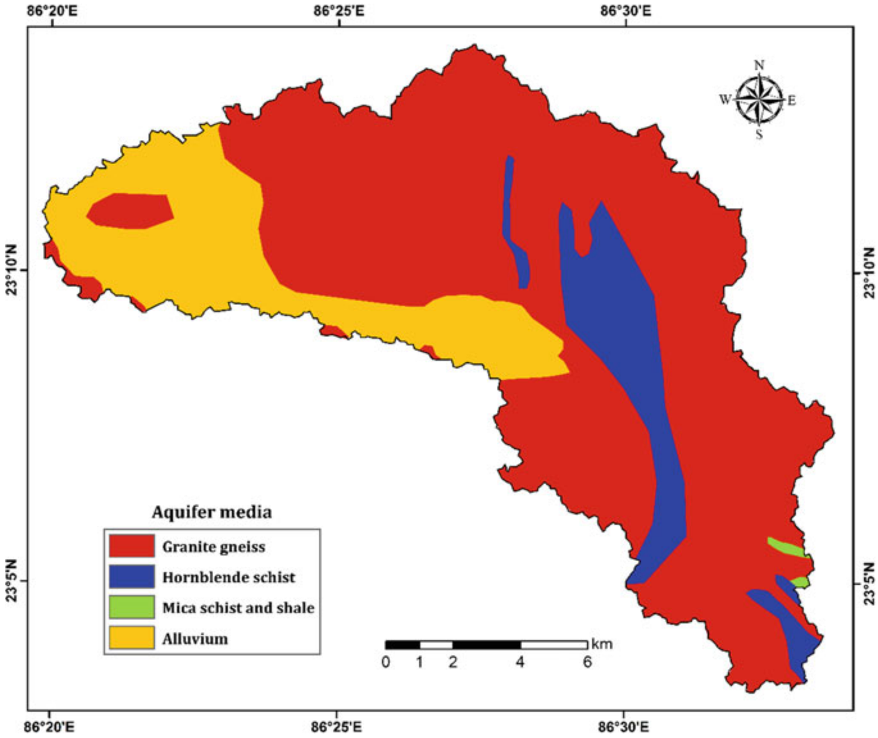

Fig. 5 Aquifer media map of Chaka River Basin

4.3 Aquifer Media

The consolidated or unconsolidated geologic formation hosting an aquifer is an aquifer media. The aquifer media is a vital factor governing the transportation and passage of the contaminants. Larger grain size, fracture prone rocks with weak zones, interconnected pore spaces, porous and permeable layers help in easy passage of contaminants by lowering the attenuation process. Hence such types of aquifer media are at a greater risk of pollution. The study area consisted of 4 types of aquifer media namely granite gneiss, hornblende schist, mica schist and shale, alluvium covering 70.88%, 9.71%, 19.16%, 0.25% areas respectively (Fig. 5).

4.4 Soil Media

The weathered uppermost surface of the Earth is referred to as soil media. Soil media imposes a serious impact on the net recharge of the aquifer. Infiltration through a thicker soil media increases the processes of attenuation. Pollutants interact with the

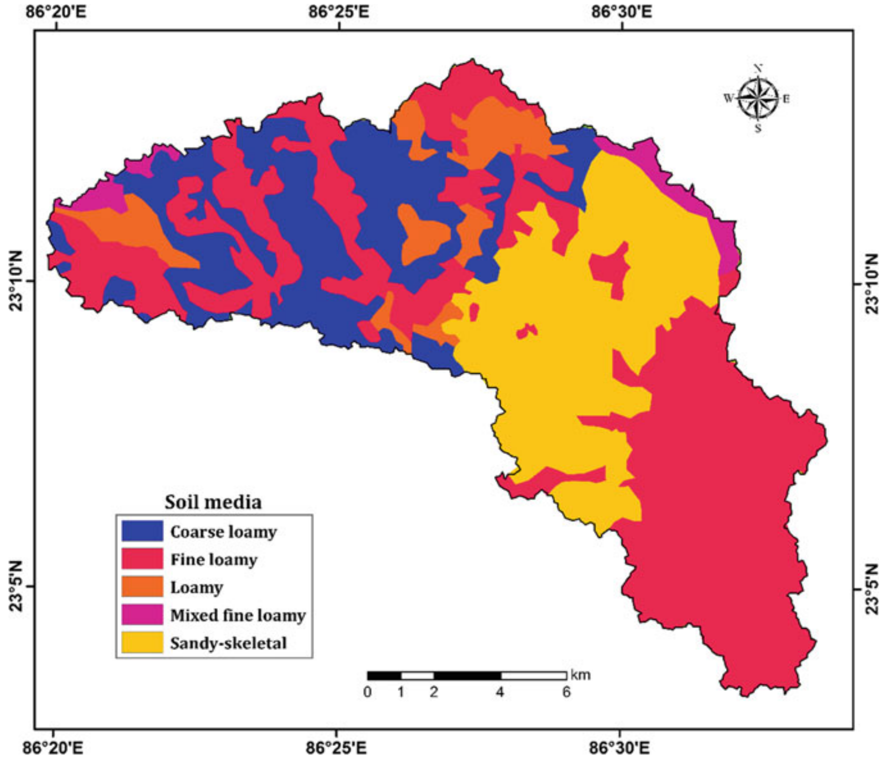

Fig. 6 Soil media map of Chaka River Basin

soil media before passing to the aquifer. Hence, soil media acts as a sieve for the pollutants. Finer particles such as silt, clay acts as a barrier for the pollutants. Large grained particles help in easy permeability of the water (Bera et al. 2020; Biswas et al. 2020). The study area comprised 5 soil types namely Coarse loamy, Fine loamy, Loamy, Mixed fine loamy, Sandy skeletal covering 20.43, 45.45, 6.88, 2.60, 4.64% areas respectively (Fig. 6). Two dominant soil types covering the eastern side of the lower catchment basin area are Sandy skeletal and Fine loamy. In the upper basin region, loamy soil occurs sparsely. Sandy skeletal is the most vulnerable soil type allowing easy percolation of water, followed by Coarse loamy, Loamy, Mixed fine loamy, Fine loamy.

4.5 Topography

Topography represents the slope of a region. This helps in predicting the vulnerability of an aquifer of the region, since the slope of the region helps in determining the infiltration and runoff rate. Regions with higher slopes tend to have a higher runoff

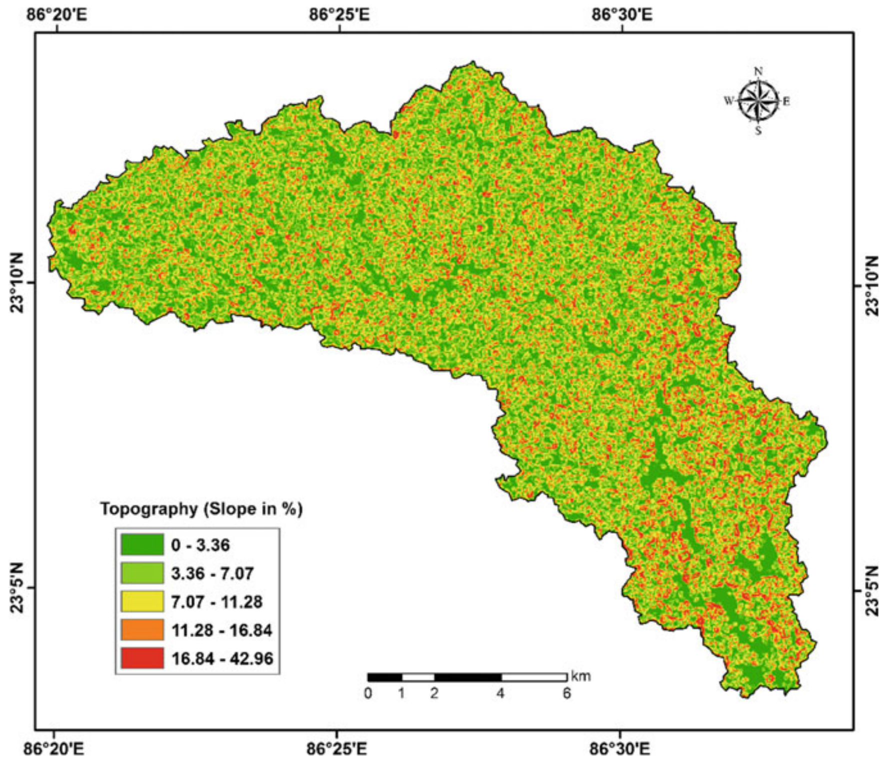

Fig. 7 Topography map of Chaka River Basin

rate and regions with low slope values have a higher infiltration rate and seepage of the pollutant rich water. The residence time of water is highly affected by the topography of the region. The slope values of the region were classified into 5 categories which ranged from 0–3.36, 3.36–7.07, 7.07–11.28, 11.28–16.84, and 16.84–42.96% covering 52.89, 58.85, 47.10, 25.06, 6.90 km^2 respectively (Fig. 7).

4.6 Impact of Vadose Zone

The zone lying between the soil surface and the aquifer is termed as the vadose zone. The thickness of the vadose zone combined with the coupled effects of the regional topography and aquifer media helps in determining the amount of contaminants passing through the vadose zone media. This implies more thickness is responsible for more attenuation and lesser contamination. Vadose zone with high permeability is at a greater risk of contamination. The vadose zone consists of sand and gravel, coarse loamy, loamy, sandy silt covering areas of 24.64, 20.42, 6.88, and 48.06% respectively

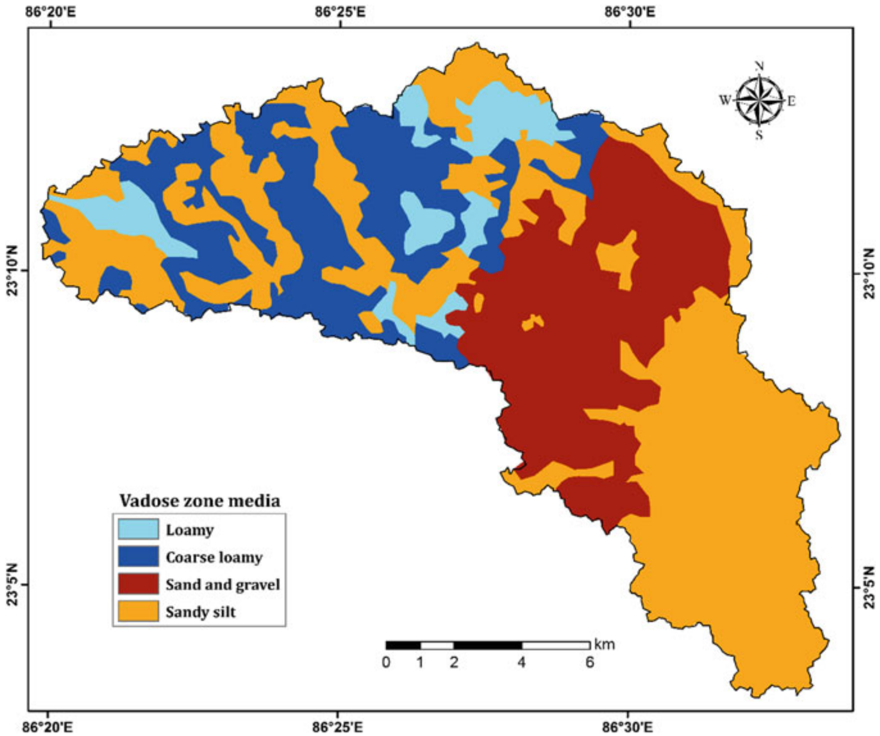

Fig. 8 Vadose zone map of Chaka River Basin

(Fig. 8). Sand-gravel and coarse loamy vadose media are usually associated with high aquifer vulnerability due to the high infiltration rates.

4.7 Hydraulic Conductivity

The property of an aquifer media to transmit water is the hydraulic conductivity of the media. Hydraulic conductivity is directly proportional to contamination of the subsurface water resources. Hence, more the conductivity of the concerned aquifer more is the risk of contamination. Increasing conductivity implies increase in the velocity of the contaminants rich water. The hydraulic conductivity of the region varies from 1 to 50 m/day. They were classified as very low (1–10.8), low (10.8–20.6), moderate (20.60–30.40), high (30.40–40.20), excellent (40.20–50) covering 43.83, 13.21, 10.92, 15.07, 16.97% of the study area respectively (Fig. 9).

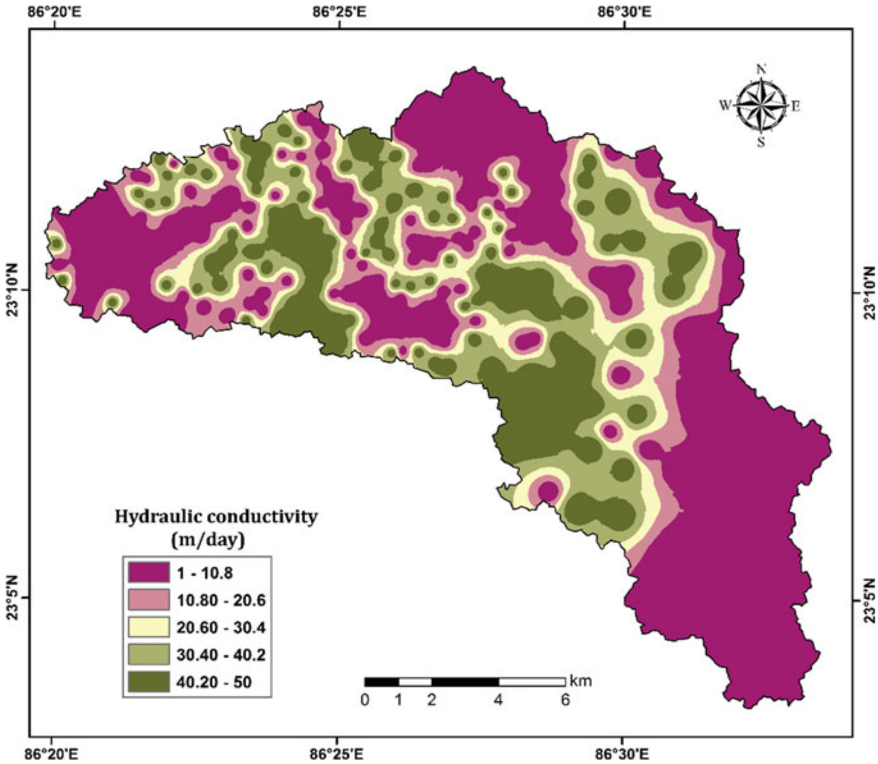

Fig. 9 Hydraulic Conductivity map of Chaka River Basin

4.8 Aquifer Vulnerability Zone

The aquifer vulnerability map thus generated by integrating the various thematic layers gives an insight of the vulnerability of the aquifers of the study area. The study area was classified into 5 aquifer vulnerability zones namely 'very low', 'low', 'moderate', 'high', 'very high', with their Drastic Index (DI) ranging from 56–90, 90–110, 110–134, 134–159, 159–192 and covering 11.34, 25.78, 29.54, 20.35, 12.99% respectively (Fig. 10). The map shows very high aquifer vulnerability zones lie on the mid-east and south eastern regions of the study area. Some villages with high aquifer vulnerability zones are Tukya, Mohandi, Kuda, Durku, Kamta Bajraetc (Fig. 11). North and north western parts of Chaka basin have very low aquifer vulnerability. Few villages such as Darodi, Kenda, Dhanara, Palma etc. show very low aquifer vulnerability.

The scatter plots (Fig. 12) shows the factors having a positive correlation with the AVZ. The graphs are plotted based on random points generated on the basin area map, for which values of the influencing factors for aquifer contamination and the Aquifer vulnerable zone (AVZ) are plotted. The main factors which have the probable

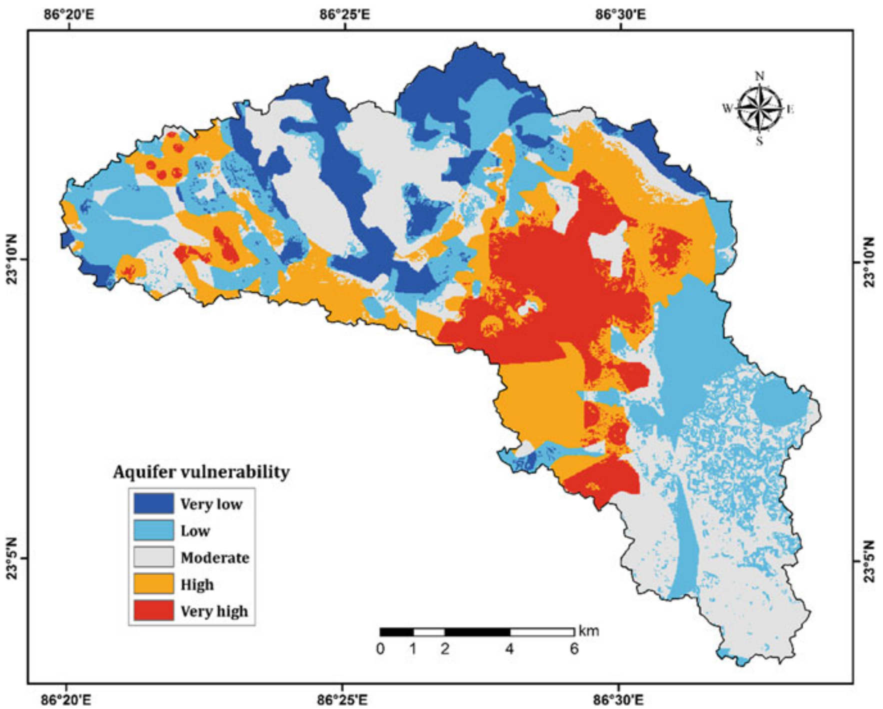

Fig. 10 Aquifer vulnerability zone of Chaka River Basin

influence on the aquifer contamination in this region are Hydraulic conductivity, Aquifer media, Soil media and Impact of vadose zone. This conclusion can also be tallied with the scatter plots and bar graph.

4.9 Validation

For checking out the accuracy of the DRASTIC model validation was done. Verification and validation of samples collected from 24 sites were done using the physical parameter TDS. Previously researchers have worked on their respective study areas and also validated using the parameter TDS such as (Mato RRAM 2002; Garewal et al. 2016; KardanMoghaddam et al. 2017; Ahada and Suthar 2018; Mondal et al. 2018). The present study area mainly consists of agricultural lands and fallow lands falling under considerably high vulnerability zones so the parameter TDS is an appropriate approach for validating the DRASTIC model applied. The TDS values recorded ranged from 122.88 to 860.45 ppm. WHO (2017) guidelines permit TDS values ranging from 600 to 1000 ppm, a TDS value <600 ppm is considered very good for consumption and other applications and values exceeding 1000 ppm is

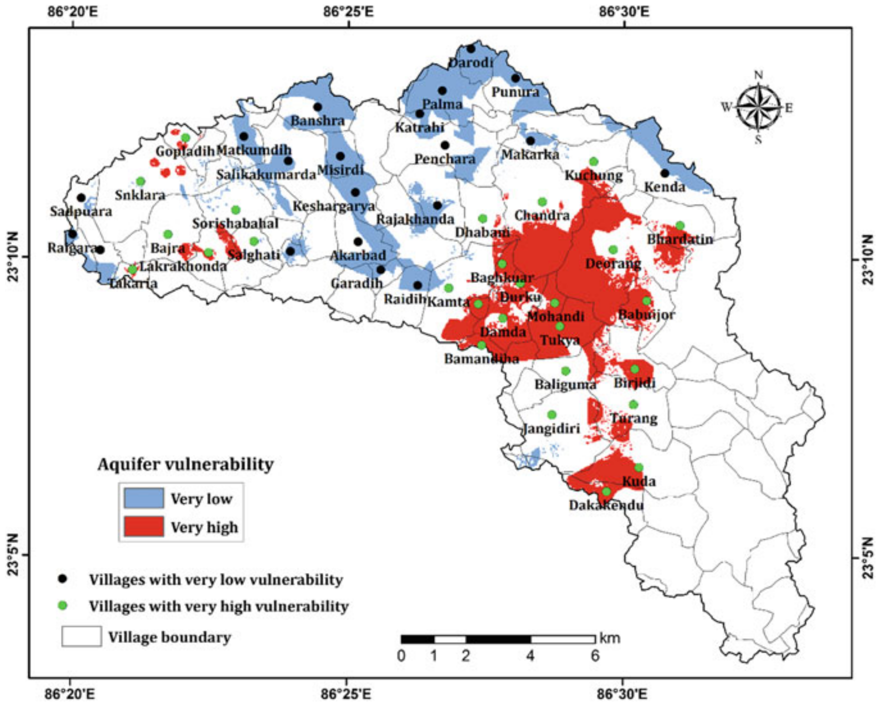

Fig. 11 Villages with high and low vulnerability zone of Chaka River Basin

considered unfit for usages. The results were analysed and an output map was generated using spatial interpolation method (Fig. 13). The output map was correlated with the aquifer vulnerability map generated using DRASTIC. The obtained results show there's a strong relationship between the regions with high vulnerability and high TDS. Regions with high vulnerability have high TDS values and vice versa. Figure 14 shows that locations such as Basudebpur, Mohandi, Birjidi, Kuda had TDS values ranging from 551.36 to 860.45 ppm, as a result of which these regions were categorised as high vulnerability zones. On the contrary, locations such as Darodi, Misirdi, Akarbad, Dhanara had low TDS values ranging from 122.88 to 128.02 ppm and were categorized as low vulnerability zones. The values were further statistically analysed and the scatter diagrams show there's a positive relationship between the TDS and aquifer vulnerability map (Fig. 15). This leads to an inference that surface water rich in chemical and contaminants as runoff from agriculture, industries and household seeps underground, thus contaminating the underlying aquifer.

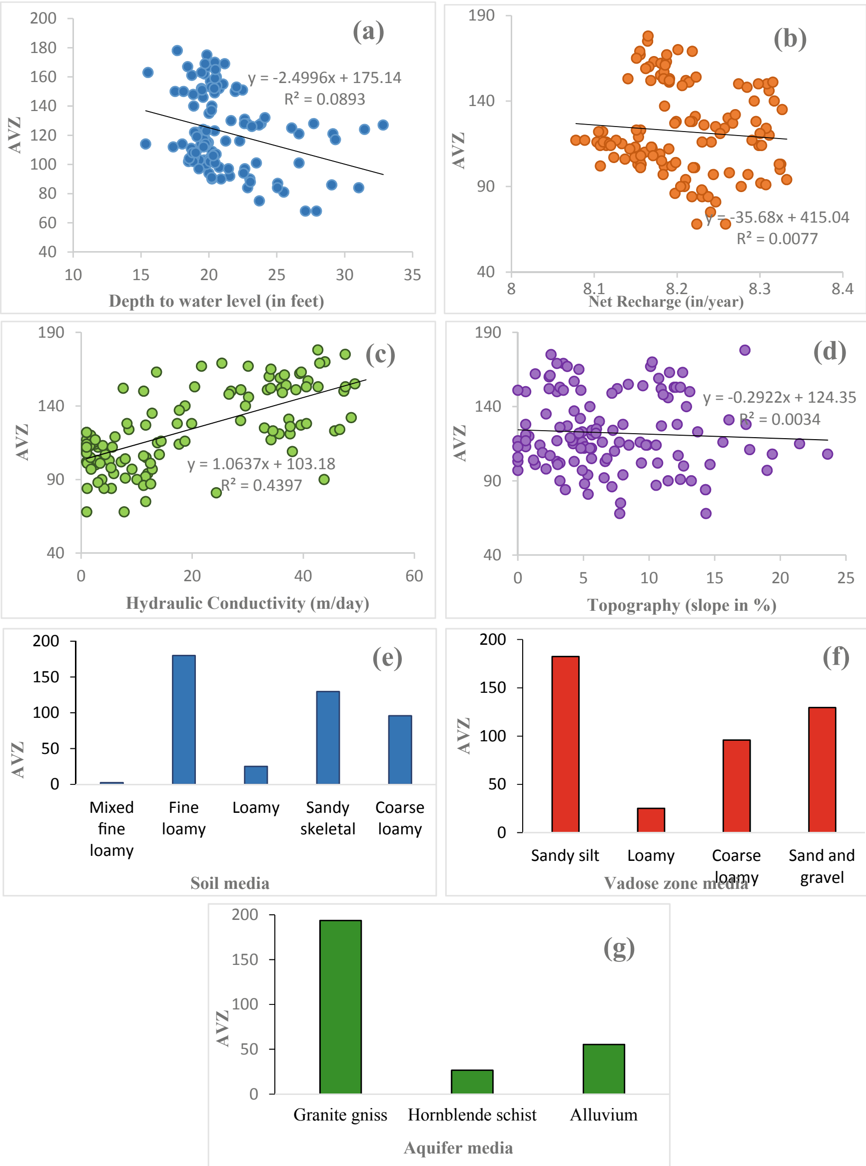

Fig. 12 **a–d** Relationship between the influencing factors for Aquifer vulnerability (grid based) and the Aquifer vulnerability zone (AVZ). **e–g** Bar graphs represent the mean AVZ values for each influencing (vector based) factors and each sub-category

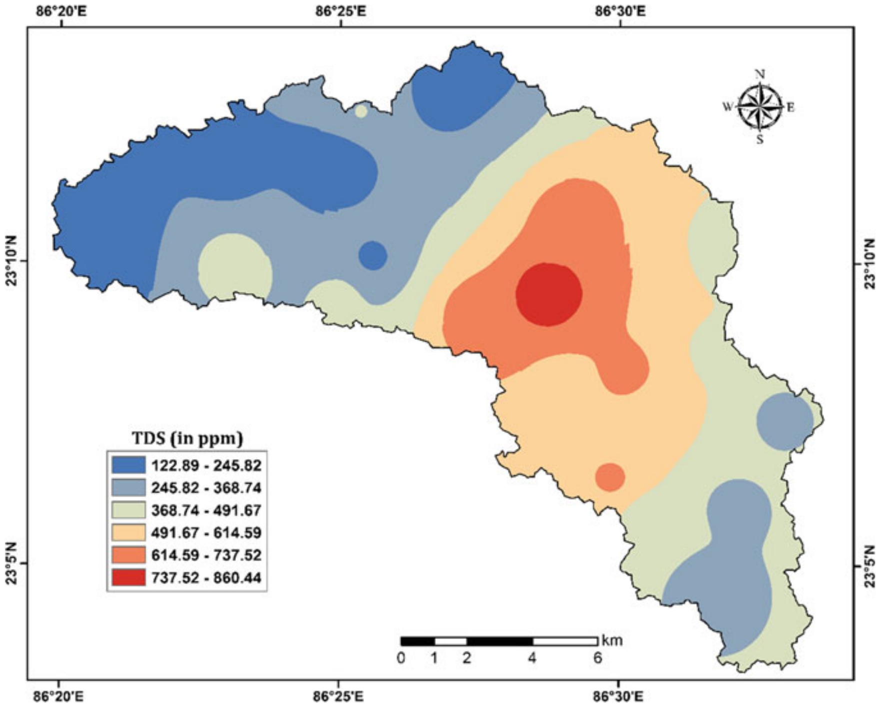

Fig. 13 Spatial distribution of Total Dissolved Solids (TDS) of Chaka River Basin

5 Conclusion

For this research work, 7 hydrogeological parameters were selected, which were used for preparing the aquifer vulnerability map via overlay analysis and DRASTIC. The mid part of the study area has been categorized as a high vulnerable zone with high hydraulic conductivity value as well as a higher proportion of sand and gravel as the vadose zone media. The study area shows a DI value ranging from 56 to 192. Some areas of the selected study area show higher TDS values which lie closer to the upper limit of WHO (2017) guidelines, indicating the water quality is unfit for consumption and other usages. With increasing demands on food and its productivity, farmers are using high yield variety of crops with an increased use of chemical fertilizers. Since the area is mainly an agricultural land, the chemical contaminants easily dissolve into the surface water and leaches underground to the aquifer through the vadose zone. The study area comprises a large stretch of barren/fallow land alongside the agricultural lands, and the diurnal temperature variation being high causes significant amount of physical and chemical weathering which subsequently increases the TDS. Hence, the parameters such as vadose zone media, depth to water level, net recharge play a vital role in determining the degree of contamination of an aquifer. For efficient management of groundwater resources and effective mitigation

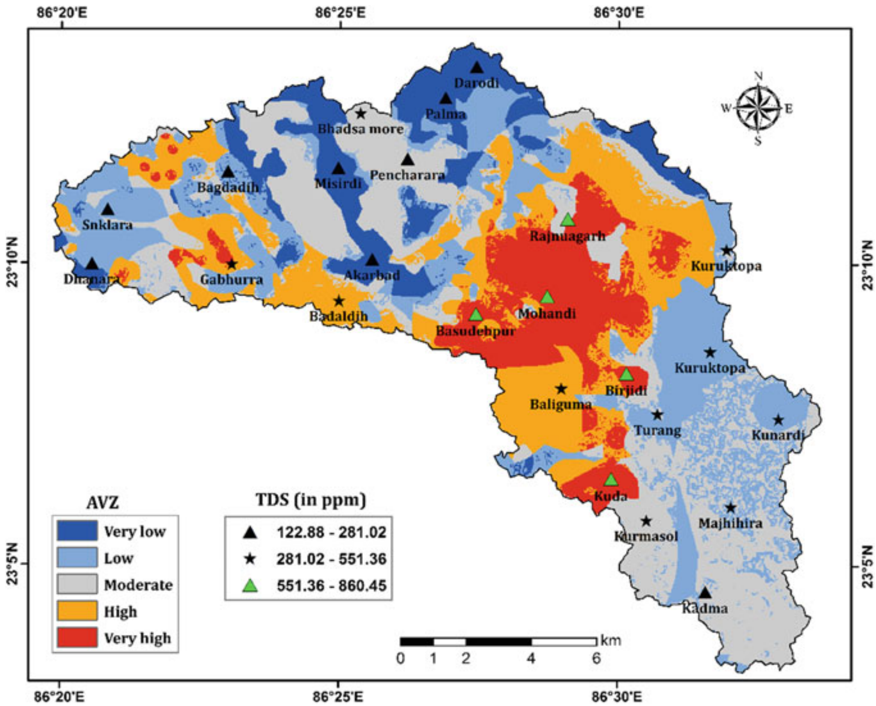

Fig. 14 Aquifer vulnerability zone with their respective TDS values of Chaka Basin

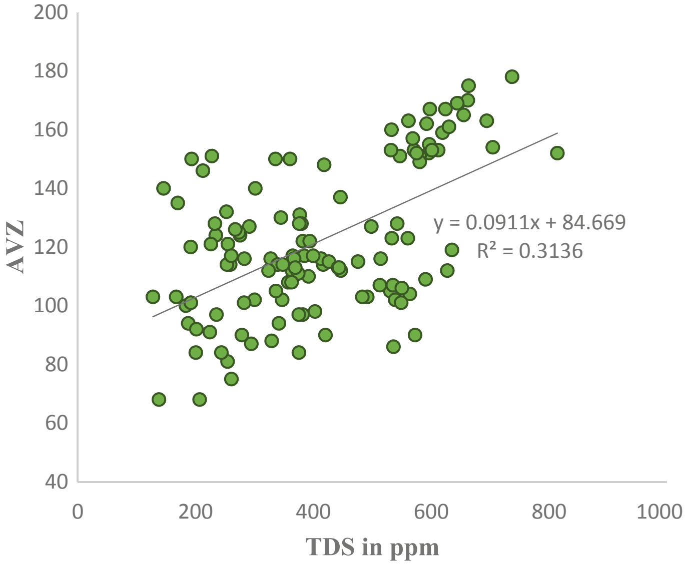

Fig. 15 Relationship between the TDS and the Aquifer vulnerability zone (AVZ)

an alternative approach of using organic fertilizers and farming in scientific methods is recommended especially in the high aquifer vulnerability zones. So, it can be deduced that DRASTIC is an effective, reliable and accurate method for assessing and monitoring the aquifer vulnerability of vast agricultural lands, mining regions, landfills etc.

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Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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Assessment of Water Level Behaviour to Investigate the Hydrological Conditions of Bokaro District, Jharkhand, India Using GIS Technique

Poornima Verma, Prasoon Kumar Singh, and Ashwani Kumar Tiwari

Abstract Groundwater is a highly valuable resource. But, due to non-stop withdrawal and exploitation of groundwater resource to fulfil the human needs impose a major problem to rapidly decreasing groundwater resources of India. To understand the behaviour of groundwater resource, water level fluctuation assessment is an important feature. Therefore, water level measurement and analysis are essential for sustaining groundwater availability. Variation in water level is a consequence of the nature of hydrogeological and meteorological factors and their study helps to define the hydrogeological condition. Hydro-geologic factors influencing water level fluctuation in geomorphology, geological formations, soil types and elevation has been investigated in Bokaro district. In this paper water level of 30 observation wells in a typical fractured and weathered granitic environment of Bokaro district has been monitored. WLF for the different categories were ranked and plotted against the cumulative percentage of wells. Thematic contour map has been plotted for spatial variation of water level and comparative analysis of WLF for the study area. Further, Statistical study has been done to identify the relative impact of the different hydrometer logical and hydrogeological factors. On the basis of the analysis of these water level data, it has been observed that the water level fluctuation has influences of various hydrogeological factors.

Keywords Aquifer recharge · Groundwater · Hydrogeological factors · Water level fluctuation

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1 Introduction

Groundwater is not static; it is a vital and rechargeable natural water resource. However, in hard rock terrain area, its accessibility is of the restricted extent and that occupies nearly two-third part of India (Srivastava et al. 2012). To understand the mechanism of groundwater resources like its availability, flow and physical characteristic of an aquifer or groundwater system, water level behaviour is an important indicator which facts towards effective management of groundwater resources in hard rock terrain area. Consistently, water level is being declined day by day due to overall development in different fields like rapid industrialization, urbanization and extent agricultural activities to fulfil their needs. The groundwater quantity and recharging condition of any area depend on the permeability of rocks which developed by weathering and disintegration of hard rocks. Permeability of rocks depends on the degree of weathering, joint and fracture due to various natural processes like temperature, humidity, rainfall etc. acting on these hard rocks. According to permeability differences, the groundwater storage and occurrence also becomes inadequate in an area as poor, moderate and good, respectively. These circumstances are reflected by many factors including topography, slope, lithology, geological structure, fracture system, weathered-zone thickness, drainage pattern, landforms, land use/cover and climate which affects the groundwater movement and occurrence in a region (Mukherjee 1996; Jaiswal et al. 2003; Bhuiyan 2010). Groundwater availability in hard rock terrain region is mainly limited to fracture and shallow weathered and groundwater recharge primarily dependent on the infiltration of rainfall and geological factors that are interconnected and spatially diverse, and fluctuations of water levels is the change between supply (recharge) and withdrawal (discharge) of groundwater (Chandra et al. 2015). Fluctuations in water tables reflect changes in groundwater storage within aquifers due to the combined effect of hydrometer logical and geological factors. In the present study, the temporal and spatial variation of the water level and water level fluctuation is carried out by using different classes/ranges of various terrain parameters such as elevation, soil, geological formation, geomorphology and climatic parameter like rainfall. The information derived from GIS (Geographic Information System) techniques can be beneficial for identifying the location prone to water level depth in the study area for taking quick and decision by policymakers and stakeholders (Singh et al. 2013). Analysis of water level is important to understand the groundwater regimes with reference to hydrological and geological factors in space and time domain. This work may help for the maintenance of the water level, and provides a valuable awareness about the regional hydrological conditions.

2 Study Area

Bokaro district is highly industrialized coal belt district in Jharkhand. In the north side of the Bokaro district is Giridih while in south side it's bounded by Purulia (West Bengal), Dhanbad in the east and Hazaribagh in the west. It covered over an area of about 2861 km^2 and it lies between 23° 24′ 27″ N to 23° 57′ 24″ N latitude and 85° 34′ 30″ E to 86° 29′ 10″ E longitude of the Jharkhand state (Fig. 1). The area comes in Survey of India (1:50,000 scale) topo sheet No. 73/E/9, E/10, E/13, E/14, 73 I/1, I/2, I/5 and I/6. It contains eight administrative blocks, namely (1) Chas (2) Gomia (3) Nawadih (4) Bermo (5) Petewar (6) Kasmar (7) Jaridih and (8)

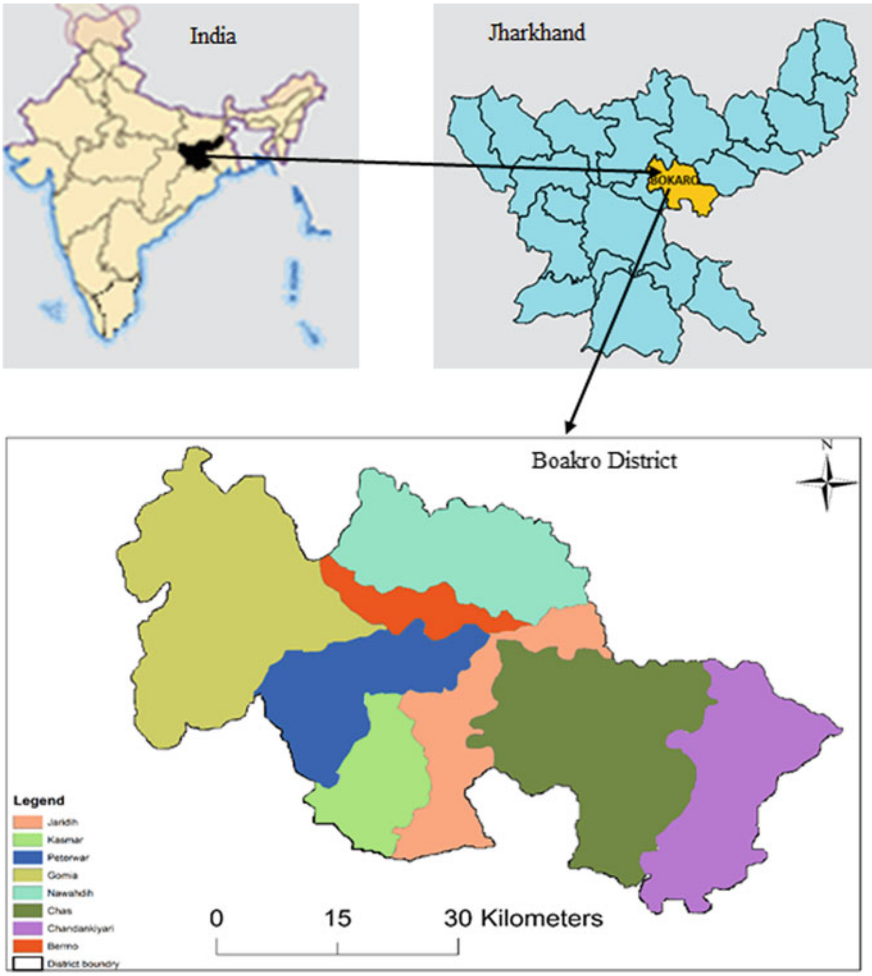

Fig. 1 Location map of the Bokaro district

Chandankiyari. In the central part of the district, the Damodar River flows from west to east on which two important reservoirs Tenughat in the southwestern and konar in the north-western region of the district are situated. As well, Bokaro, Konar and Jamuniya are the major tributaries which originate from Hazaribagh plateau, flow through Hazaribagh to Bokaro and finally encounter to Damodar river while Isri, Gobai, Tashrkhan, Kadwa, Khanju are the major tributaries.

2.1 Rainfall and Climate

The average annual rainfall of the district is 1363.3 mm/year. Chandankiyari block of the district receives maximum rainfall i.e. 1669.58 mm and minimum rainfall was received by Bermo block of the district i.e. 1093.70 mm. The normal rainfall of the district is 1185 mm. The maximum rainfall about 95% happens during monsoon season i.e. mid-June and lasts till the end of September and the rest amount of rainfall takes place during summer and winter seasons (CGWB 2013). The climate of the study area is humid to subtropical. It is described by summer from March to October during which higher temperature varies from 42 to 46 °C and winter from November to February during which the January is the coldest month with average minimum temperature varies from 25.9 to 10.2 °C (Satapathy and Syed 2015). The average humidity of the area is about 60%.

2.2 Geology and Hydrogeology

Lithological study of an area is significant to know about the behaviour and distribution of water-bearing capacity of an aquifer (Fetter 1994). The geological map can generally provide the information of the distribution of rock type and lithological structure. Geological map of the study area has been prepared by using IDW technique which is shown in (Fig. 2). A general geological map from the Government of Jharkhand (https://archive.jharkhand.gov.in/) has been referred to digitize the geological map. A major part of the study area, about the three-fourth area, is covered by granitic gneiss and other metamorphic rocks and remaining part of the study area is covered by sandstone, shale and coal (Satapathy and Syed 2015). A thin layer of alluvium deposit occurs in along the course of Damodar River. Based on different rock properties, the area is categorized into three distinct classes: (1) consolidated rock formation in which groundwater occurs under confined to semi-confined conditions. (2) Semi-consolidated formation, in this region groundwater occurred under confined to semiconfined formation which covered the central part of the district and (3) Unconsolidated formation: in this region, groundwater occurs under water table condition which covered major part of the area with recent alluvium deposited mainly by the Damodar, Konar and Jamunia rivers (CGWB 2013).

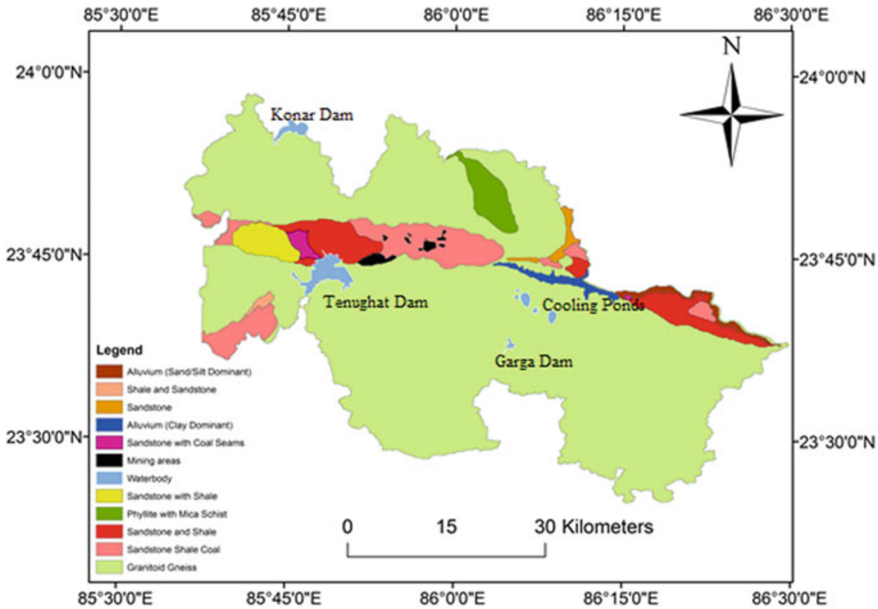

Fig. 2 Geological map of the Bokaro district

The stratigraphic sequence of the various geological formation of the study area is presented in Table 1 and hydrogeological map of the study area is shown in Fig. 3.

2.3 Geomorphology and Soil

The Bokaro district is located on the eastern part of the Chota Nagpur Plateau and has highly undulating all over the district. The important geomorphic units and landforms of the study area are inselberg, pediment, Cuesta, Pediplain, alluvial plain, piedment slope, plateau dissected, plateau undissected, Escarpment Slope and Denudational hill as shown in Fig. 4. For this study, the geomorphological map has been referred from the Government of Jharkhand (https://archive.jharkhand.gov.in/) using IDW technique. Generally, Pediplain structures are developed over granite gneiss which is found in Chas, Chandankiyari and major area of Nawadih, Jaridih, Kasmar and Peterwar Block. Cuesta is developed over the semi consolidated formation and sandstone shale and coal deposit and are found in the central-western part of the district in Bermo and Gomia Block. Inselberg is developed over the unclassified meta-sedimentary and meta-sedimenties rocks are found north western and south-western part of the district. Pediment is developed over metamorphic rock are found Peterwar, Gomia and Kasmar Block. Plateau dissected are developed along with alluvial deposit and are found south-eastern region of the district. The slope of the

Table 1 Geological succession of the study area (CGWB 2013)

S. No.	Age	Series	Lithology	Hydrogeological conditions	Formation	Groundwater potential
1	Upper carboniferous to middle Jurassic	Gondwana supergroup	Sandstone, shale, grit, coal Seams Amphibolite, epidiorite	Moderately thick regionally extensive confined/unconfined aquifers	Fissured/Semi-consolidated	Limited yield prospects below 10 Cu m/h
2	Middle to upper proterozoic	Chota Nagpur granite gneiss	Granite and granite gneiss, micaschist and phyllite	Groundwater restricted to weathered residuum and fractured zone down to 125 m	Fissured/Consolidated	Limited yield prospects below 30 Cu m/h
3	Lower to middle proterozoic	Unclassified metasediments	Quartzites, fine to coarse grained sand, silt, clay, recent stream sediments	Moderately thin restricted unconfined aquifers down to 50 m	Porous/unconsolidated	Limited yield prospects below 30 Cu m/h

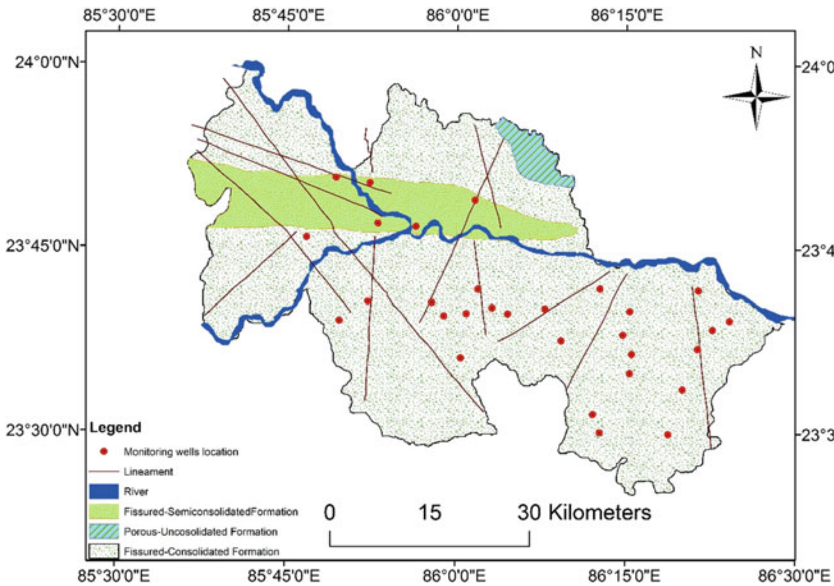

Fig. 3 Location map of the monitoring wells and hydrogeological condition for Bokaro district

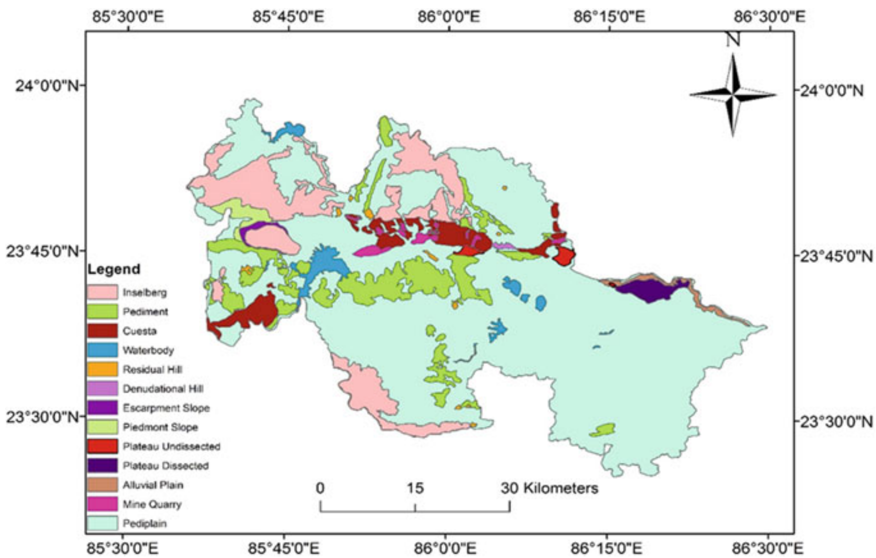

Fig. 4 Geomorphological map of the Bokaro district

study area is from west towards east and an average elevation of the study area ranges from 200 to 350 m above MSL. Gomia is highest hill prominent block in western region while Chas and Chandankiyari in eastern region of the district are low upland where agricultural activities are done. The soil of the Bokaro district is classified into three soil order namely (1) Entisols (2) Inceptisols and (3) Alfisols according to the information from the National Bureau of Soil Survey and Land Use Planning. Alfisols are the dominant soil order, which covers about 62% of the total area, followed by Inceptisols and Entisols, covering around 21.4 and 12.7% of the study area respectively (Satapathy et al. 2015). The detail of different geomorphological structure and their hydrogeological and groundwater condition has been discussed in Table 2.

3 Materials and Methods

Binary correlation of mean seasonal WLF with mean monsoon precipitation, mean monsoonal potential evapotranspiration, and gross groundwater draft couldn't light up the overall changes in WLF (Bhuiyan 2010). It implies different factors likewise impact to infiltration rate and aquifer recharge. Bhuiyan (2010) articulated that infiltration of rainwater and gravity stream to the aquifers are coordinated by different land surface and subsurface components. In this way, information about the distinctive land factors and physical parameters at the well areas has been acquired through ground-based insights and remote-sensing information (Chandra et al. 2015). Siddiqui and Parizek (1971) plotted estimations of well yield under various hydrogeological classes in descending order of magnitude. The cumulative percentage (or frequency) of wells with a yield equal to or greater than the state value P_m has been calculated as

$$P_{\mathrm{m}} = [m/(N_t + 1)] \times 100 \tag{1}$$

where m is the order number of a well, N_{t} is the total number of wells. Thirty wells were selected to monitor the water level depth from different part of the district which is shown in Fig. 3. Water level data were monitored during the pre- (May) and post-monsoon (December) period for the year 2014 using a sensor-based water level recorder (Table 3). Five factors whose influences on WLF have been considered i.e. elevation, geomorphology, geological formation, soil and rainfall for this study. The WLF values for the year under different geological and meteorological parameter classes have been tabulated in descending order of magnitude. Each of these factors has been categorised into classes or ranges based on the observant and range of variation. For comparative analysis, mean and median fluctuation values under different classes have been used. A GIS method has been applied to understand the spatial distribution of water level depth for both the seasons by plotting thematic contour map (Chandra et al. 2015).

Table 2 Geomorphologic units in the study area (Satapathy et al. 2015)

S. No	Geomorphologic units	Description about units	Groundwater condition
1	Cuesta	A mountain or edge with a delicate incline on one side and an abrupt incline on the other opposite is known as cuesta	Poor
2	Pediment	It is a plain of windswept bedrock created in middle of mountain and basin areas	Poor
3	Pediplain	Because of persistent disintegration, pediments merge to pediplains features	Moderate to Good
4	Inselberg	These are separated hills transcending the general portions of a pediment	Moderate
5	Alluvial plain	These are made out of alluvial deposits of sand, silt and clay. Alluvial plains are found on the eastern part of the study area near the Damodar river course	Moderate to Good
6	Denudational hill	Denudational hills are formed due to dynamic procedure of weathering, mass squandering and erosion. These are found in the central part of the study area	Moderate
7	Water body	These are surface water bodies in the district	Good
8	Piedmont slope	The dominant gentle slope at the foot of a mountain; generally used in terms of intermontane-basin terrain in arid to subhumid regions	Moderate to Good
9	Plateau dissected	These are formed due to weathering, erosion and denudation of the former upland areas and are cut by innumerable rivers and rivulets with small vales and dales	Good
10	Plateau undissected	A plateau or other relatively level surface that has not been deeply cut by streams	Moderate to Good
11	Residual hills	The hard rocks left behind after erosion are called residual hills	Poor

Table 3 Data of monitoring wells in the Bokaro district for the year 2014

S. No.	Latitude (N)	Longitude (E)	Elevation (ft)	Pre-monsoon DTW (mbgl)	Post-monsoon DTW (mbgl)	WLF (mbgl)
GW1	23.653	86.403	497	3.87	2.21	1.66
GW2	23.615	86.356	589	3.75	2.37	1.38
GW3	23.641	86.378	520	4.46	3.19	1.27
GW4	23.56	86.334	589	5.05	3.9	1.15
GW5	23.499	86.313	619	4.32	2.88	1.44
GW6	23.582	86.256	716	6.99	6.02	0.97
GW7	23.602	86.007	701	4.54	2.82	1.72
GW8	23.626	86.155	742	4.77	4.05	0.72
GW9	23.608	86.259	794	8.07	5.87	2.2
GW10	23.526	86.202	806	1.92	1.66	0.26
GW11	23.501	86.212	749	6	2.22	3.78
GW12	23.694	86.357	533	7.67	2.47	5.2
GW13	23.666	86.256	785	4.24	2.54	1.7
GW14	23.662	86.076	763	4.56	3.72	0.84
GW15	23.669	86.131	710	10.11	5.55	4.56
GW16	23.67	86.053	909	4.05	2.71	1.34
GW17	23.662	86.015	882	9.34	4.75	4.49
GW18	23.659	85.982	1010	9.3	3.2	6.1
GW19	23.678	85.87	1134	8.3	3.6	4.7
GW20	23.652	85.828	1279	11.95	6.45	5.5
GW21	23.677	85.964	1095	7.4	7.4	4.3
GW22	23.695	86.032	866	8.66	5.56	3.1
GW23	23.78	85.94	748	2.1	1.8	0.3
GW24	23.784	85.884	634	7.56	5.16	2.4
GW25	23.765	85.779	886	3.1	3	0.1
GW26	23.839	85.872	779	3.7	2.5	1.2
GW27	23.696	86.212	731	9.2	6.39	2.81
GW28	23.846	85.822	845	6.34	4.5	1.84
GW29	23.816	86.027	686	7.23	4.1	3.13
GW30	23.634	86.246	637	9.12	3.8	5.32

4 Results and Discussion

4.1 Graphical Analysis of WLF Under Different Factors

4.1.1 Soil Factor

In the study area, out of three main soil classes (Entisols, Inceptisols and Alfisols) wells under Entisols soil class displays the highest fluctuation of 6.1 mbgl fallowed by Inceptisol soil class which displays second-highest fluctuation (Fig. 5). Fluctuation under Alfisols soil class has the lowest value and such behaviour of water level fluctuation in alfisols was due to its distribution pattern in the study area. The maximum WLF are found in the study area may be affected by anthropogenic and mining activities like extraction of groundwater for various purposes such as agriculture, construction, industrial and domestic activities however the regions where WLF are minimum due to their geographical setting which increase the recharge capacity of an aquifer through well-distributed network of river, canal and perfect catchment area on which Tenughat, Konar and Garga reservoirs and cooling ponds are located. Form the frequency plot, it can be observed that under alfisols class show minimum water level fluctuation and entisols class shows higher water level fluctuations.

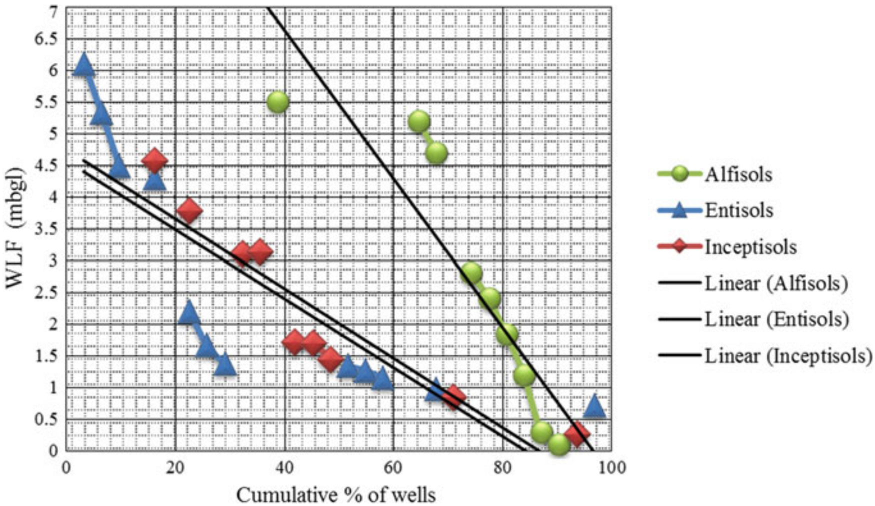

Fig. 5 Value of WLF under different soil class

4.1.2 Rock Formation

The nature of rocks significantly affects groundwater availability of an area (Shaban et al. 2006). Geographically, the study area comprised with grantoid gnesis, sandstone, sandstone with coal seams, sandstone with shale coal, quartzites, mica schist, phyllites and alluvium deposits in which about three fourth part of the study area is covered by rocks of Chota Nagpur granite gneiss. Maximum observing wells are situated within the consolidated rock formation class which mainly consists of granitoid gneiss and then semi-consolidated formation class which is consist of sandstone with coal seam and sandstones with shales. The highest WLF is up to 6.1 mbgl in consolidated formation class, followed by 3.13 mbgl in semi-consolidated rock formation class and lowest WLF is 0.1 mbgl in the semi-consolidated formation class fallowed by 0.26 mbgl in consolidated rock formation class (Fig. 6). The maximum fluctuation within the consolidated rock formation class is in the Jarindih block in Bokaro district. The wells connected with consolidated rock formation show high to moderate fluctuations in most of the regions except some regions of Chas and Chandankiyari Block. The consolidated rock formation is generally massive and forbid precipitation into subsurface, thus increasing the chance of runoff generation, which results in higher fluctuations of wells located with it. Though, a small number of wells within consolidated rock formation class display higher WLF in the Jaridih and Chas blocks due to variation in geographical conditions of the study area owing to anthropogenic actions along with changes in land use pattern.

The semi consolidated rock formation class which is mainly comprised with sandstone coal and shale display minimum inclination of fluctuations owing to their geographical pattern inside the study area which is delimited with Damodar Rivers

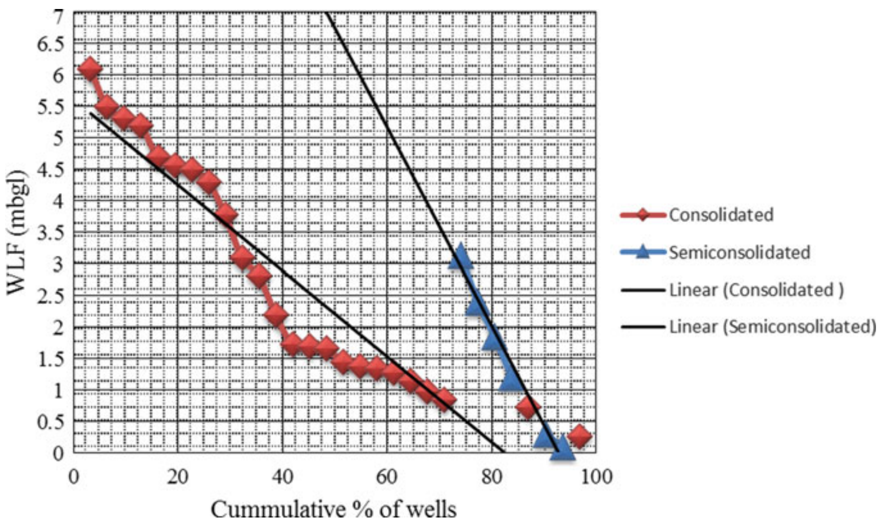

Fig. 6 Value of WLF under different geological structures

and raises the recharge process in this region. However, most of the wells associated with semi consolidated rock formation which is in Gomia and Bermo blocks display moderate to minimum WLF which is due to the point is the sandstone is resultant from the sedimentary rocks with sandstone which generally permits percolation of infiltered water and permeable i.e. sufficient to supply large quantity of water into the aquifer and creating them valuable aquifer (Chandra et al. 2015). Consequently, semi-consolidated rock formations contribute to good groundwater potential and recharge condition. From the frequency plot analysis, it can be observed that under semi consolidated rock formation class, the WLF shows the minimum and consolidated rock formation shows maximum water level fluctuations.

4.1.3 Geomorphic Structure

According to variation in geomorphic structures of the study area wells are divided into four class: (1) Pediment (2) Cuesta (3) Pediplain, and (5) Inselberg. These structures are sympathetic for groundwater existence and groundwater situation differs for different geomorphic structures. Most of the monitoring wells are associated with Pediplain and then followed by pediment, inselberg and Cuesta. Few wells located in pedipalin and pediments have maximum water level fluctuation than Cuesta and inselberg (Fig. 7). Though Pediment and Pediplain structure construct good recharge structure in the area as given in Table 2 however, this condition can be seen that at some wells located in these structures are displaying higher fluctuations which may be due to thin layer of vadose zone and anthropogenic events. Wells associated with Cuesta and inselberg structure show steadily lower fluctuations, which may be

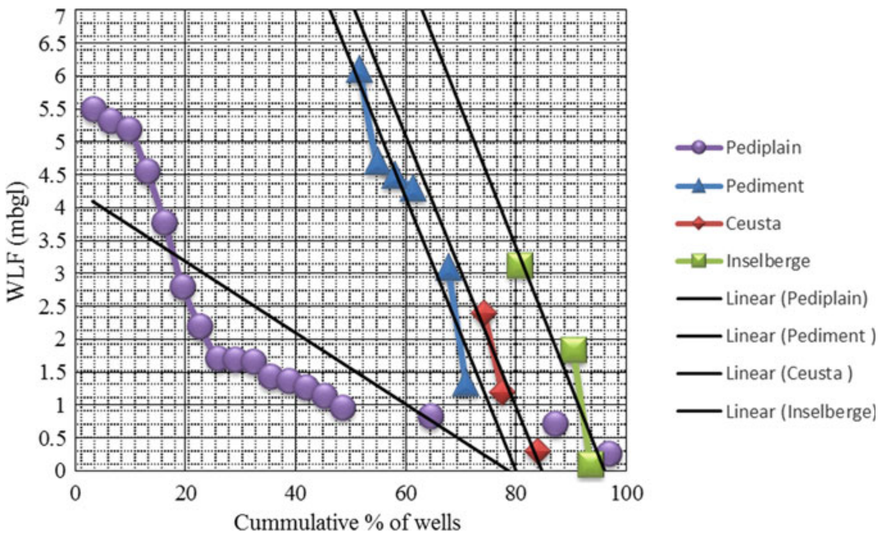

Fig. 7 Value of WLF in wells under different geomorphic units

due to the thick overburden layer of material or thick vadose zone (Chandra et al. 2015). The physical characteristic of the geomorphic structure significantly affects the recharging capacity of aquifers. Pediment and Pedipalin structure display higher WLF in Jaridih and Chas block area may be due to anthropogenic events that have changed the geomorphologic structure of the study area along with pediplain structure which is generally found in the Chas and Chandankiyari blocks i.e. good for aquifer recharging. Jaridih block shows higher WLF due to physical properties of pediment structure which develop runoff zone due to their gentle slopes causes a small amount of rainwater infiltration to the aquifers and construct poor recharge structure for aquifers.

4.1.4 Elevation Factor

Slope, elevation and surface topography of an area plays a significant role in groundwater recharge and water level fluctuation. WLF of any area is directly proportional to the elevation of the land surface. Rise in WLF with elevation indicates the certain positive effect of elevation on groundwater recharge (Bhuiyan 2010). Maximum observing wells are found within 600–800 ft elevation class. The elevation of the study area ranges from 400 to 1300 ft and for this study, elevation map is prepared from GPS data using IDW technique (Fig. 8). The elevation range of 1000–1300 ft has maximum water level fluctuation which in Peterwar and Jaridih block of Bokaro district and in the range of 400–600 ft has minimum water level fluctuation which is in Chas and Chadankiayri block as shown in Fig. 9. All of the well associated with the higher elevation class show maximum WLF which is in Peterwar and Jaridih block may be due to higher elevated area cause more runoff and decreases the chance for

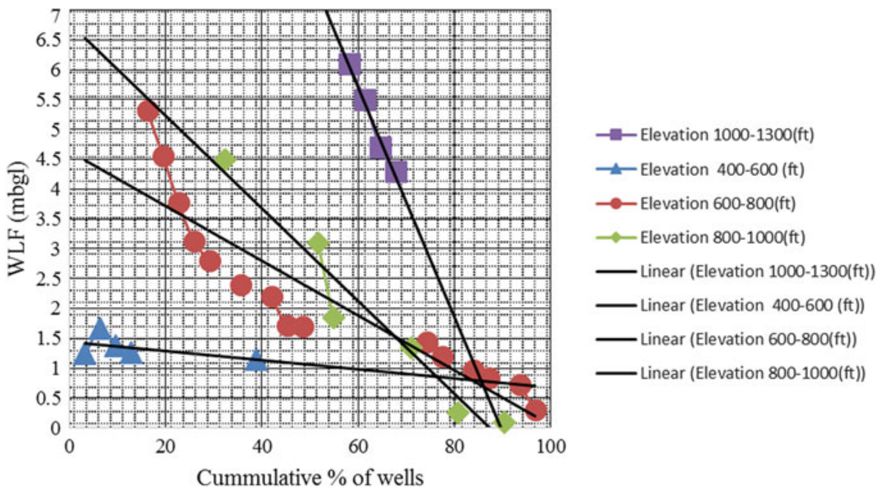

Fig. 8 Value of WLF under different elevation units

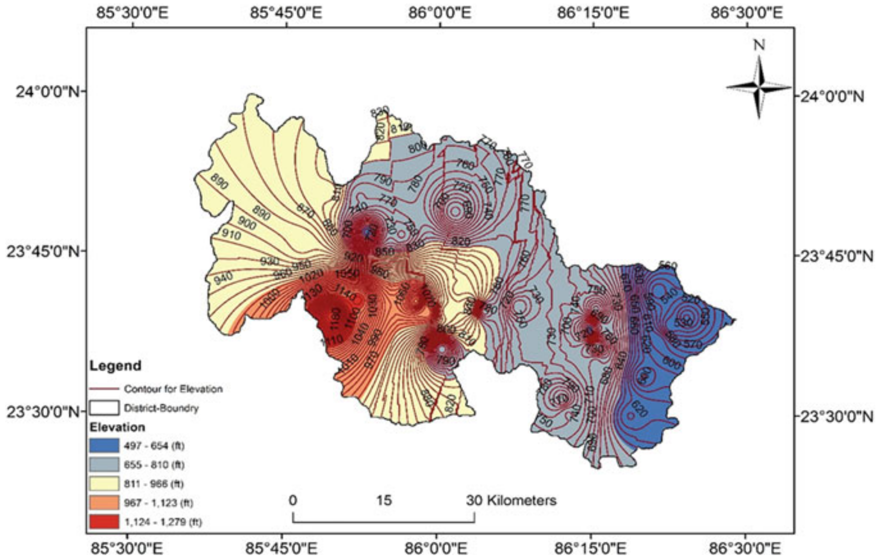

Fig. 9 Elevation map of the Bokaro district

rainwater infiltration. The lower elevation class display lower fluctuation which is in Chas and Chandakiyari block may be due to the higher infiltration rate of rainfall water and low runoff potential towards lower elevation. Regional slope of the study area is from the west towards the east. In the study area, Jaridih block located on the western part of the district has the maximum elevation whereas Chas and Chnadankiyari block on the eastern side have minimum elevation. Lower elevated areas are considered a good recharge zone; however, the higher elevated areas have a low potential for rainfall recharge (Murthy 2000). Form the frequency plot analysis, it can be seen that wells located in the higher elevation class display maximum water level fluctuation than those in lower elevation class.

4.1.5 Rainfall Factor

Rainfall is an important and natural factor for groundwater recharge and plays a significant role in WLF behaviour of any area. According to rainfall variation in the study area wells are classified into three classes: (1) Good (2) Moderate (3) Poor. The rate of infiltration process increases due to higher intensity of rainfall which increases groundwater availability of an area. Increase in WLF with rainfall show optimistic effect of rainfall on groundwater recharge. The average annual rainfall of the study area for the last 35 years ranges from 742.1 to 1849.54 mm and for this rainfall map is prepared from the station using IDW technique (Fig. 10). Wells located in the good rainfall class show minimum fluctuation (Fig. 11) which in Chandankiyari block of Bokaro district due to high infiltration rate and low rainfall runoff which

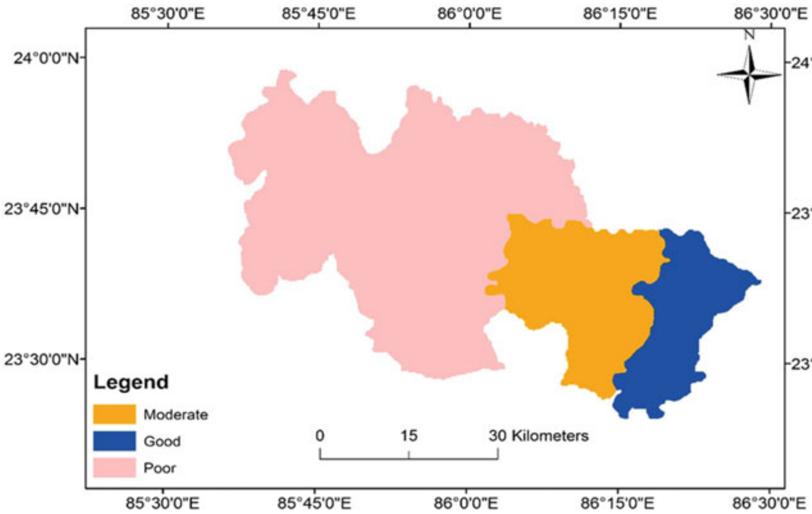

Fig. 10 Rainfall map of the Boakro district

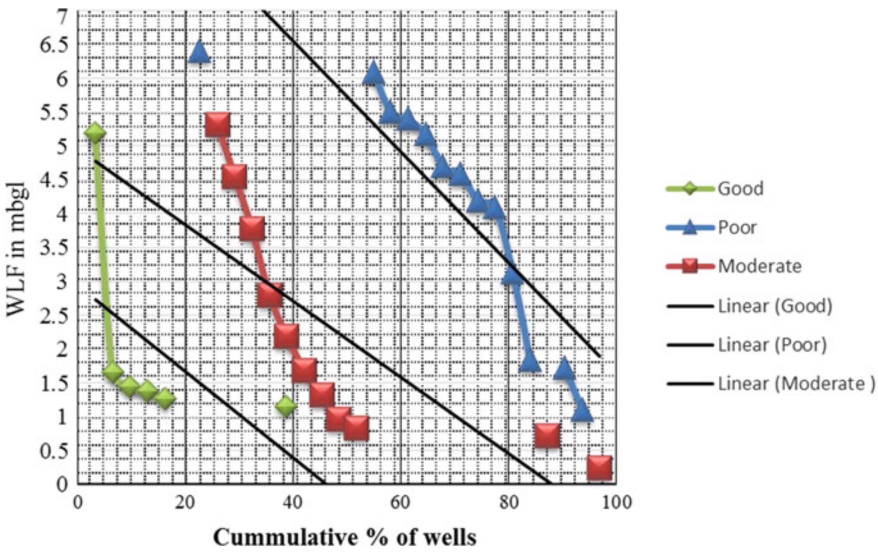

Fig. 11 Value of WLF under different rainfall amount

form good groundwater recharge zone in the study area. Most of the well associated with poor rainfall area show higher WLF due to minimum amount of rainfall causes lower infiltration rate while few well show lower WLF may be due the presence of Tenughat reservoir on the southwestern region and Damodar River in the central part of the study area. From the rainfall map, it can be seen that Chandankiyari block in the eastern region of the study area receives the maximum amount of rainfall, whereas the Peterwar, Gomia, Bermo, Kasmar, Jaridih, and Nawadih receive less amount of rainfall comparatively Chas and Chnadankiayri blocks in western region. Consequently, the rainfall amount shows a positive correlation with groundwater recharge.

4.2 Comparative Analysis of WLF Using GIS Technique

The impact of various hydrogeological factors on WLF has been deliberated individually in the above part. For this study, thirty wells have been monitored to examine the water level depth for both seasons (pre and post-monsoon) in the study area. In the month of May values of water level depth had been collected for pre-monsoon season and these values have been planned on thematic contour map to see the spatial distribution of water level depth in the study area as given in Fig. 12. After analysing the contour map, it can be seen that the lower water level depth is 1.92 mbgl and higher is about 11.95 mbgl during pre-monsoon season. The eastern and western part of the district has lower values of water level depth and higher in the southern part while during post-monsoon season as given in Fig. 13, it can be seen that minimum water level depth values in the eastern and western region of the study area, while maximum water level depth values can be noticed in the southern area and central

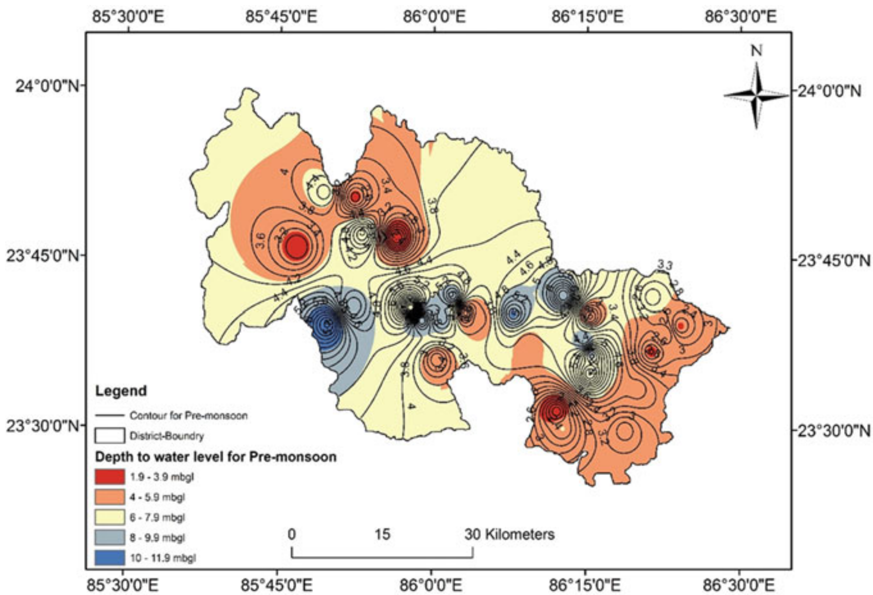

Fig. 12 Contour diagram for depth to water level of Bokaro district for pre-monsoon period for year 2014

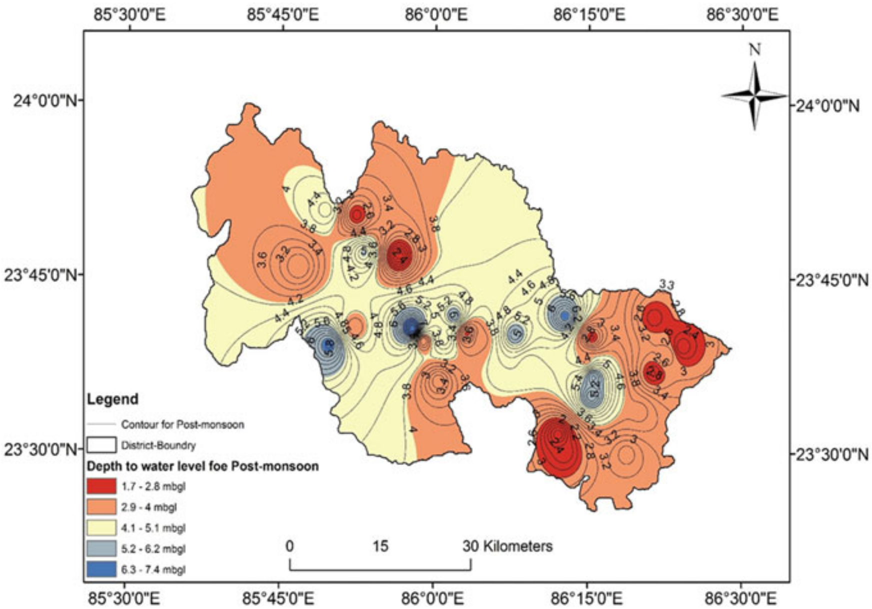

Fig. 13 Contour map for depth to water level of Bokaro district for post-monsoon period for year 2014

part of the district. After analysing the contour maps for both seasons, it has been found that the value of wells noticeable for displaying higher water level depth values for the period of post-monsoon season is relatively lower than for the pre-monsoon season for the similar number of wells; it means those areas have good recharging conditions of an aquifer in the eastern and western part of the district. From the WLF contour map as given in Fig. 14, it can be observed that maximum WLF up to 6.1 mbgl has been shown by the wells situated in the southern part of the district. This may be due to the mutual effect of these factors are soil, elevation, geological formation, geomorphology, rainfall, mining and anthropogenic activities which have been discussed individually already to each factor in the previous part. The minimum WLF can be seen in the western and eastern part of the district which may be due to mutual effect of hydrogeological and meteorological factors and occurrence of some major basin and water reservoirs like Tenughat and Konar on Damodar river in the southwestern and north-western boundary of the study area and two cooling pond and Garga Dam in eastern region of the district. Hence, the assumption can be made from the above discussion that the southern region of the district facing water scarcity due to minimum accessibility of groundwater, however the western and eastern part of the district adequately accessible groundwater resources.

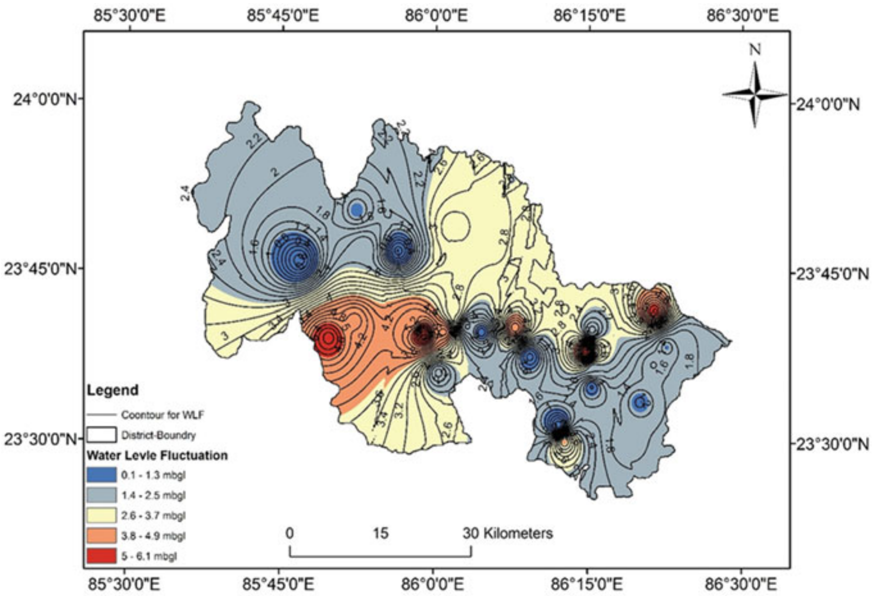

Fig. 14 Contour map of WLF of Bokaro district for year 2014

4.3 Comparative Statistical Analysis

Form statistical study, mean, median and standard deviation have been calculated for the individual number of wells to evaluate the comparative impact of various classes/ranged under different parameters on groundwater recharge capacity. On the basis of the median value of geological formation classes, consolidated formations have higher mean and median values (Table 4), while semi consolidated formations have lower mean and median values. In consolidated rock formation, granitoid gneiss occurred in which movement of in filtered water inside the rock be influenced by secondary porosity and internal connection between rocks by the formation of faults and cracks for displaying maximum median value by it (Chandra et al. 2015). Among the elevation classes (Table 5), the median WLF values in elevation (1000–1300 ft) and elevation (800–1000 ft) have a higher value, respectively while lower median value has been observed by elevation (400–600 ft) class which displays a definite positive correlation between elevation and WLF. Between the geomorphic classes, pediments, inselberg and Pedi plain have maximum mean and median values than the

Table 4 Statistical analysis for geological structures

Geological class	N	Min.	Max.	Mean	Median	SD	Variance
Semi consolidated	6	0.1	3.13	1.49	1.52	1.08	1.17
Consolidated	24	0.26	6.1	2.77	1.96	1.78	3.17

Table 5 Statistical analysis for elevation (m)

Elevation (ft)	N	Min.	Max.	Mean	Median	SD	Variance
400–600	5	1.15	5.2	2.43	1.27	0.17	2.38
600–800	15	0.3	5.32	2.28	1.71	1.42	2.01
800–1000	6	0.1	4.49	1.97	1.59	1.54	0.69
1000–1300	4	4.3	6.1	5.17	5.1	0.69	0.48

cuesta (Table 6). This is because of Pedi plain, inselberg and pediment from moderate to good groundwater potential zone, while cuesta form poor groundwater recharge zone. Among the soil classes, alfisols soils have higher mean and median values than entisols soil class (Table 7). On the basis of the median value of rainfall classes, poor rainfall class have maximum mean and median value while good rainfall class have lower mean and median values (Table 8) which indicate that rainfall amount indirectly proportional to WLF.

Table 6 Statistical analysis for geomorphology

Geomorphic classes	N	Min.	Max.	Mean	Median	SD	Variance
Pediment	6	1.34	6.1	4.005	4.395	1.47	2.18
Cuesta	3	0.3	2.4	1.3	1.2	0.86	0.74
Inselberg	3	0.1	3.13	1.69	1.84	1.24	1.54
Pedi plain	18	0.26	5.5	2.3	1.68	1.68	2.82

Table 7 Statistical analysis for soil type

Soil classes	N	Min.	Max.	Mean	Median	SD	Variance
Entisols	12	0.72	6.1	2.57	1.52	1.83	3.35
Inceptisols	9	0.26	4.56	2.28	1.72	1.34	1.81
Alfisols	9	0.1	5.5	2.67	2.12	1.75	3.08

Table 8 Statistical analysis for rainfall amount

Rain fall amount	N	Min.	Max.	Mean	Median	SD	Variance
Good	6	1.15	5.2	2.306	1.15	1.43	2.05
Moderate	11	0.26	5.32	2.31	1.7	1.60	2.58
Poor	13	1.1	6.4	4.096	4.59	1.64	2.72

5 Conclusions

The hydrogeological and hydrometer logical factors affecting the water level fluctuation behaviour in the Bokaro district are difficult, and they act together to develop the distribution of aquifer properties observed. To analyse the aquifer recharge capacity under different parameter classes, a graphical analysis through frequency plot has been used which proved, it is an efficient tool to evaluate the comparative effect of various hydrogeological and meteorological parameters on groundwater recharge capacity. Based on frequency plot, it has been observed that in the study area, WLF differ steadily, constantly and logically with elevation and rainfall whereas geomorphology, geological formation, soil types have small fluctuation differences, showing their insignificant effect on groundwater recharge. Water level behaviour and WLF can be simply understood by using GIS technique. From the spatial analysis, it has been found that in southern part of the district has higher WLF due to different hydrogeological and meteorological which are further increased by anthropogenic activities. From, statistical analysis, it has been found that elevation (1000–1300 ft) and rainfall class are the highest mean and median values, indicating their positive effect on WLF whereas geomorphic units, geological structure and soil type class showing less reliable fluctuations. Consequently, on the basis of frequency plot, spatial analysis and statistical analysis, this is concluded that rainfall and elevation are the most significant factors for seasonal WLF in the Bokaro district. Other important but slightly significant factors on groundwater recharge in the study area is geomorphic units, geological formation and soil type. WLF is not only influenced by these factors, it is also effectively influenced by mining and anthropogenic activities in the study area such as unsustainable withdrawal of groundwater by people for different purposes like agricultural, domestic construction and industrial area etc. Anthropogenic and mining activities have slightly influenced the hydrogeological factors which are directly affected by WLF in the study area.

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Investigation of Lineaments for Identification of Deeper Aquifer Zones in Hard Rock Terrain: A Case Study of WRWB-2 Watershed from Nagpur District, Central India

Abhay M. Varade, Y. D. Khare, Mukesh Sakhare, Sandipan Das, Atul Doad, Uday Chatterjee, and Bhushan R. Lamsoge

Abstract In current scenario, the groundwater resources are gaining much attention due to enhanced demand of rising population, urbanization, agricultural expansion, etc. The groundwater condition in hard rock terrain, specifically in Deccan trap basaltic region of Maharashtra state, is highly uncertain due to anisotropic aquifer system. In addition, high evaporation and run-off limits the natural recharge to the groundwater. Therefore, the unsustainable distribution of water from the dug wells and bore wells in basaltic region is common which altogether results in acute scarcity of drinking water in the event of drought. In order to mitigate this situation the state groundwater departments often resorts to tapping of deeper aquifers to meet the drinking water demand. However, it is found that the percentage of high yielding borewells is very low due to anisotropic hydrogeological condition of basaltic terrain, and also due to lack of primary porosity unlike sedimentary formations. In view of this it is pertinent to understand the role of lineaments and fractures on the yield of the borewells, as the lineaments i.e. weaker zones, plays vital role in groundwater movement. The current study focuses on the influence of lineaments on groundwater regime in hard rock areas by employing the remote sensing technique. For this study the WRWB-2 watershed of the district of Nagpur, Maharashtra, Central

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India has been investigated. The aim of the study is to understand the importance of lineament mapping in groundwater prospecting. The satellite image of the area was studied to decipher the geomorphological setup and lineament fabrics through visual interpretation. The study area is characterized by basaltic hard rock which forms the multiple aquifer system, wherein wide variations in yield of the borewells are expected. Under this situation the controlling factors such as geomorphological set-up and lineament fabrics have been analysed with respect to yield of the borewells. The overall study revealed that the yield of the borewells tapping deeper aquifers are highly influenced by presence of lineaments as out of the total 143 borewells, 30 are very high yielding with yield >4500 l/h, which is uncommon in Deccan trap terrains. The study demonstrates utility of lineament mapping in the hard rock regions mainly to target productive aquifer system. The decision maker, therefore, should use this technique for successful harnessing of potential groundwater pockets in hard rock areas to achieve the sustainable groundwater availability.

Keywords Central India · Deccan traps · Groundwater · Lineament · Nagpur · Remote sensing

1 Introduction

Groundwater plays a crucial role in the availability of potable water, agriculture and industrial uses particularly in hard-rock regions (Lamas and Santos 2005). Groundwater shares 34% of distribution of total annual water supply (Maggirwar and Umrikar 2011). The occurrence of groundwater is mainly governed by climatic conditions, topography, lithology, degree of weathering and structural fabric, etc. The periodic scarcity situation has adversely affected the water table aquifer system, which often results in scarcity of drinking water in the event of drought (Singh et al. 2017; Pande et al. 2018). The situation compels to explore deeper aquifer for sustainable groundwater source. Under the situation, it is extremely crucial to identify potential deep seated groundwater zones for the management of sustainable groundwater resources (Kulkarni et al. 2000).

The groundwater resource in hard rock terrain is multivariate due to heterogeneous nature of the aquifers. Such heterogeneity is resulted because of degree of weathering of near-surface rocks, variation in tectonic set-up and density of fracturing (Barker et al. 2001; Gopinath and Seralathan 2003; Maggirwar and Umrikar 2011; Varade et al. 2014). Hence, targeting of groundwater in hard rock terrain, specifically in Deccan trap basalt, is complicated and highly uncertain. The thick weathered zones or delineated fractures constitute aquifer in such hard rock terrain, thus being exploited for groundwater extraction.

Recently, remote sensing (RS) technology has shown promising results in the context of assessment and monitoring of groundwater exploration (Ritchie and Rango 1996; Saraf et al. 2004; Chowdhury et al. 2010; Adhikary and Dash 2017; Arulbalaji et al. 2019; Indhulekha et al. 2019). The various literatures highlighted the use of different criteria for delineation of groundwater potential zone (Krishnamurthy et al. 1996; Kamal and Midorikawa 2004; Sreedevi et al. 2005; Nag 2005; Sener et al. 2005; Srivastava and Bhattacharya 2006; Gustavsson et al. 2006; Hajkowicz and Collins 2007; Madrucci et al. 2008; Dar et al. 2011, Varade et al. 2011a, b, 2012). In this study, the efficacy of lineament mapping in the hard rock regions is evaluated, mainly to target productive aquifer system (Varade et al. 2017a, b).

The lineament identification by remote sensing is vital component of groundwater exploration. Lineaments acts as a passage for the movement of groundwater hence are important in the hydrogeological studies (Mehr et al. 1989; Gyoo-Bum et al. 2004; Kim et al. 2004; Das et al. 2019). Several authors advocated satellite imageries as a useful tool in interpretation and delineation of lineaments for the purpose of groundwater potential zone assessment (Odeyemi et al. 1985; Edet et al. 1994; Sander 2007; Varade et al. 2017a, 2018). The present remote sensing based approach highlights the significance of lineaments in groundwater studies in basaltic terrain, in which, the WRWB-2 watershed of Nagpur, India has been investigated extensively.

2 Study Area

The WRWB-2 watershed lies between latitudes 20° 57′ N and 21° 12′ N and longitudes 78° 40′ E and 78° 48′ E, covering a geographical area of 148.32 km^2 in the eastern parts of Maharashtra, Central India (Fig. 1). The watershed includes parts of Katol and Hingna Tehsil. The Survey of India toposheet Nos. 55K/12, K/16, L/9 and L/13 covers the area of study. The area has semi-arid monsoon climate.

The mean annual rainfall is about 1154 mm and falls under assured rainfall zone. The temperature in the study area varies from 45 °C in summer to 10 °C in winter. The topography of the study area is an undulating plain developed over the basaltic terrain with sporadic occurrences of basaltic hillocks. The average slope of the watershed is towards south-west direction and depicts moderate to gentle gradient. The major river system in the study area is river Bor, which is an ephemeral river. The River Bor flows in the south direction, which is a tributary of the River Venna. The drainage patterns in the watershed reflect sub-dendritic to dendritic and rectangular patterns at some places. The geomorphology of the study area shows hard and compact massive type in the bottom unit and vesicular type in the upper unit.

3 Materials and Methods

The present work deals with delineation of lineaments of basaltic terrain and understanding its significance in the groundwater regime. The toposheets no. 55K/12, K/16, L/9 and L/13 of Survey of India were used for preparation of the base map

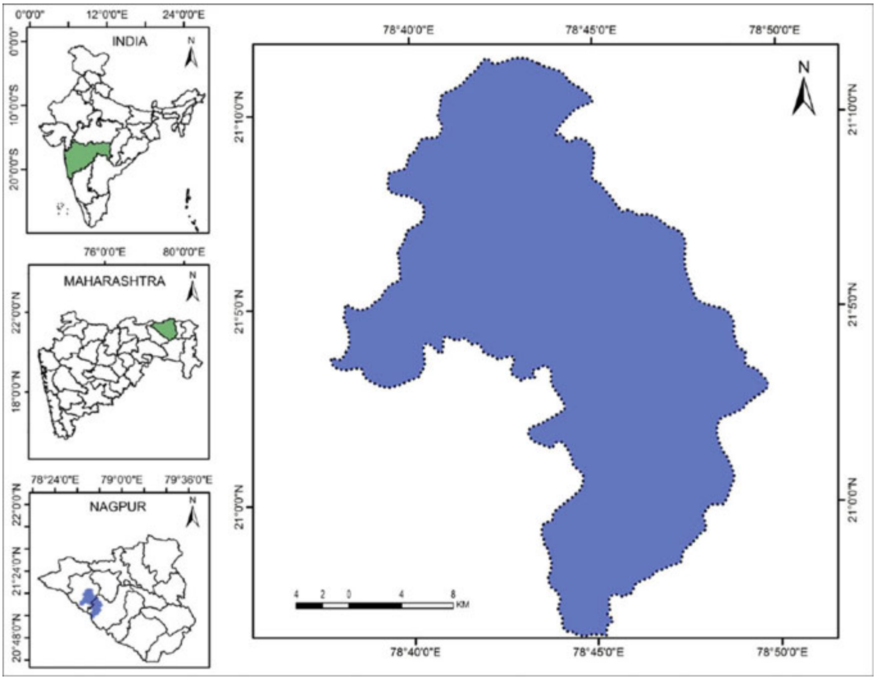

Fig. 1 Index map of the study site

of the study area. Subsequently, interpretation of False Colour Composite, generated by linear stretching (bands 2, 3 and 4: 1:50,000 scale), IRS-1C satellite image of February 1996 (path and row 99–58) for delineation of hydro-geomorphological units and lineaments were carried out by using the visual interpretation technique (Table 1). The map so prepared was studied in conjunction with performance of available bore well data of State Government Agency i.e. Groundwater Surveys and Development Agency (GSDA) to understand the relationship of lineaments and the yield of the borewells. The methodology of the flow chart (Fig. 2) and the findings of the studies are discussed below. In order to understand spatial distribution of aquifer system the geomorphological setup coupled with lineament fabrics is eminent. Therefore, the geomorphological and lineament maps of the area have been derived through interpretation of satellite image to understand the geomorphological and lineament control on the groundwater regime of deeper aquifer system. The bore well yield data of each village is collected from Groundwater Surveys and Development Agency (GSDA) were studied and analyzed with reference to lineament map. The influence of lineament features on borewell yield is investigated.

Table 1 Geomorphological details and image identification characteristics

S. No.	Geomorphological unit	Image characteristics	Associated features	GW Potential
1	Denudational slope	• Rough texture • Brighter tone	• Steep slope surrounded by vegetation, • High drainage density • Rocky surface,	Poor
2	Alluvial plain	• Smooth texture, • Red tone indicating agricultural practices	• Intensive agriculture, • Thick soil cover, • Very gentle slope, • Poor drainage density	Good
3	Moderately dissected plateau	Smooth texture Grayish tone	• Moderate drainage density • Moderate soil density	Moderate
4	Undissected plateau	• Coarse texture • Red and dark tone,	• Weathered mantle • Poor drainage density • Gentle slope • High soil density • Predominantly agricultural land	Good
5	Plateau top	• Smooth texture • Dark bright tone surrounded by steep slope	• Moderate soil thickness and gentle slope • Single cropping pattern primarily Kharif	Poor
6	Highly dissected plateau	• Bright tone, • Coarse texture	• Steep slope • High drainage density • Forest vegetation, • Rocky surface	Poor

4 Results

4.1 Geomorphological Set-Up

LISS III satellite imagery was used for the preparation of geomorphological map of the study area (1:50,000 scale), as geomorphological units directly influence the groundwater conditions. The map shows presence of six geo-morphological units viz. alluvial plain, moderately dissected plateau (MDP), undissected plateau (UDP), highly dissected plateau (HDP), denudational slope and plateau top developed over the Deccan basaltic plateau (Fig. 3).

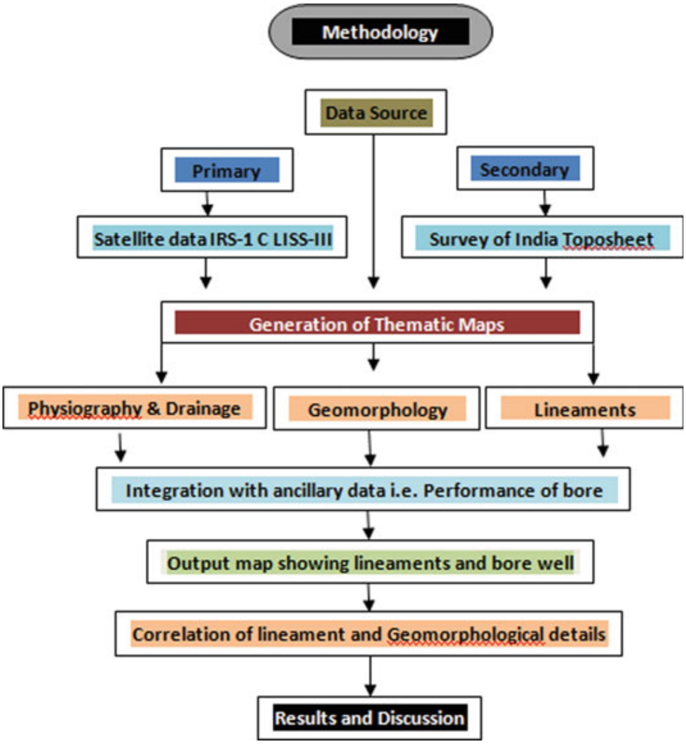

Fig. 2 Flow chart of methodology

4.1.1 Alluvial Plain

The north eastern region of the watershed area along major river Bor is occupied by the alluvial deposit. The groundwater situation in the area is expected to be good because of its gently slope and sandy nature of the aquifer.

4.1.2 Undissected Plateau (UDP)

The intensive agricultural practice in undissected plateau of narrow valleys was identified by pink smooth texture tone on the satellite imagery. Its low drainage density and very gentle slope have been considered to classify it as un-dissected plateau feature. The good groundwater condition of this unit is well reflected through intensive agriculture practices. This unit has occupied a small portion of watershed i.e. ~10 km^2.

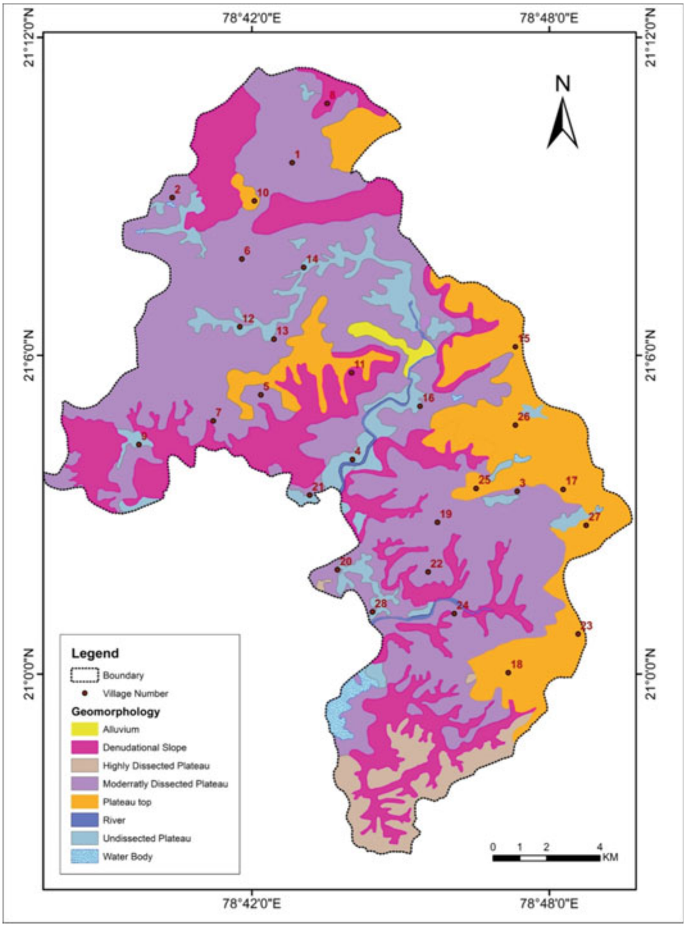

Fig. 3 Geomorphological details of watershed WRWB-2

4.1.3 Moderately Dissected Plateau (MDP)

Moderately Dissected Plateau feature is developed due to stream erosion and is associated with shallow valleys/gullies with gently sloping land. This unit is predominantly found on the middle reaches of the watershed which has moderate slope and weathered thickness. The unit is depicted on the satellite image as a rough texture with bright grey tone. MDP is the most prominent geomorphic unit occurring in the middle region of the study area covering 90 km^2. The groundwater condition for this unit is inferred to be moderate. The *kharif* cultivation is the prominent agricultural practice in the study area which is supported by groundwater irrigation. The characteristic of MDP is not suitable for good groundwater prospect. The sustainable shallow groundwater zones are not expected in this zone and hence tapping of deeper aquifer assumes a great importance.

4.1.4 Highly Dissected Plateau (HDP)

The Highly Dissected Plateau (HDP) covers the southern part of the study area (8 km^2). On satellite imagery, it is identified with its pinkish tone developed due to presence of scanty vegetation. The thickness of weathering in this zone is very shallow and therefore this zone act as runoff zone hence not suitable for groundwater development. The unit is characterized by moderate to high sloping physiography with serrated margins. The groundwater condition of such geomorphological unit is usually very poor.

4.1.5 Denudational Slope (DS)

The highly dissected plateau or plateau top bordered by steep sloping feature is considered a denudational slope. The steep slope features of this region exhibit poor groundwater potential. This unit occurs in scattered patches throughout the watershed area and covers an area of 2.29 km^2. The *Denudational Slope* of this region facilitated water conservation structures construction which can restrict surface run-off.

4.1.6 Plateau Top

The very gently sloping area with thick soil cover and underlain by dissected plateau has been classified as plateau top and occurs along the eastern boundary of study area. The satellite image reveals absence of vegetation with darker tone features. The study area is surrounded by steep sloping surface expression. On satellite image, the feature is demarcated by darker tone. Lack of vegetation cover is identified as associated feature, which is surrounded by steep sloping. The unit shows *rainfed* agricultural crop indicating poor availability of groundwater. The unit covers a geographical area of about 30 km^2. The geomorphology of the watershed indicates moderate availability of groundwater due to Moderately Dissected Plateau covering 63% of the area.

This is attributed to the physical characters such as, moderate slope and moderate thickness, which restricts recharge to groundwater. The same is further corroborated by groundwater assessment studies carried out by the Groundwater Surveys and Development Agency (GSDA 2008) (Table 2). It shows that the annual recharge in the watershed is 1526.7 ha m whereas, the current withdrawal is 335.22 ha m i.e. just 21.96% of the total recharge. The low withdrawal of groundwater in the watershed indicates that the area is not very suitable for groundwater development through open dug wells tapping the unconfined aquifer systems.

Table 2 Groundwater budgeting (6th) for the watershed WRWB-2 (GSDA 2008)

Watershed No	WRWB-2	Gross draft (ha m)	335.22
Total watershed area (ha)	14,832	Stage of development (%)	21.96
Area suitable for groundwater recharge (ha)	12,416	Water table trend	Rising
Total annual groundwater recharge (ha m)	1607.06	Category of watershed	Rising
Natural discharge (ha m)	80.35	For year 2025 Domestic + Industrial	Safe
Net annual groundwater availability (ha m)	1526.70	Net Groundwater Availability for future irrigation use (ham)	196.19

4.2 Lineaments

In view of the unfavorable unconfined aquifer system, the government has drilled number of borewells tapping deeper aquifers in the study area mainly to supply drinking water to the local population in the event of drought. The performance of these borewells has been studied in conjunction with lineaments to understand potentials of deeper aquifers in the region. Lineaments are linear features having enhanced secondary porosity which enables them as a suitable conduit for the groundwater movements (Mabee et al. 1994). Lineament infers presence of structural features like joints and faults in hard rock areas.

Many researchers have identified that lineament features of the area significantly impact groundwater flow and its yield (Zakir et al. 1999; Senthilkumar et al. 2015). Thus understanding the significance of lineament mapping, the satellite image of the watershed has been visually interpreted to delineate prominent lineaments. In hard rock terrain visual technique is the best method as the linear features are directly discernible on the image due to their typical pattern, colour, contrast and vegetation alignment. It has been observed on satellite imagery that lineaments are oriented in E–W, NE–SW, NW–SE, NNE–SSW, WNW–ESE, and NNW–SSE directions. Most of the lineaments show E–W alignment.

Lineaments directions have been shown in the rose diagram (Fig. 4). In this study, it has also been observed that the drainages are largely controlled by lineaments which are well reflected through rectangular drainage patterns. The total length of the lineaments is 278 km (Table 3). The ratio of lineaments total length with respect to total number in the study area is observed to be 3.40 km (~3 km), which categorizes this lineament features as medium to high average in length. Moderate to high lineament frequency (i.e. ~0.55 km^2) is found in the study area having high lineament density of 1.87 km/km^2. The watershed has moderate to high lineament frequency (i.e. ~0.55 km^2). The lineament density of the watershed area is observed to be high i.e. 1.87 km/km^2. Under such circumstances, the influence of lineaments is expected on the yield of borewell.

Fig. 4 Lineament directions shown in rose diagram

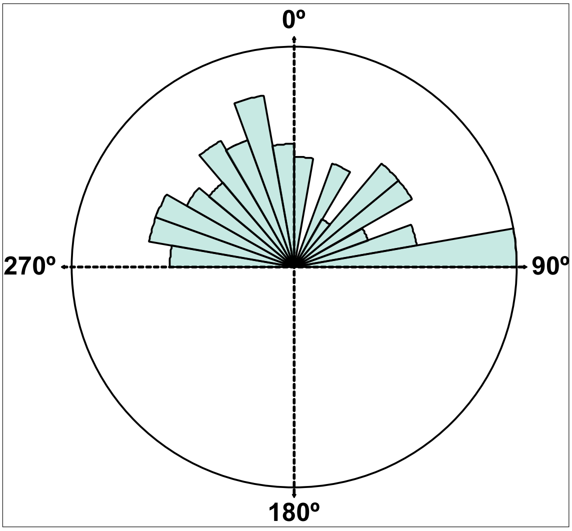

Table 3 Lineament aspects calculation

S. No.	Lineament aspect	Result
1	Average Length of Lineament = Total length/Number of lineaments in the area	3.40 km (~3 km)
2	Total Length of Lineament = Summation of length of all lineaments	278 km
3	Lineament Density of Lineament = Total length of lineaments/Total study area in km^2	1.87 km/km^2
4	Lineament Frequency = Number of lineaments in the area/Total study area in km^2	0.55 km^2

5 Discussion

The Deccan trap basalt is a unique hard rock in terms of possessing a multilayered aquifer system due to piling of flows over one another having two distinct units. The thickness of individual flow ranges between 6 and 20 m. The bottom flow consists of hard and compact basalt, whereas the upper unit shows vesicular and amygdaloidal nature (Naik and Awasthi 2007).

Under this situation the borewells tapping deeper aquifers pierces through two to three flows encountering vesicular units of each flow. This condition of Deccan trap basalt leads to formation of unconfined and confined type of aquifer systems. Hard nature of this formation leads to heterogeneous hydrogeological situation in which the productivity of aquifer system depends upon the geomorphological set-up, fracture porosity, weathering thickness and nature of flows.

The present work revealed the significant impact of lineaments on overall groundwater situation in the region. The village wise bore well data (GSDA 2008) has been evaluated with respect to the geomorphology, lineaments and drainage for above purpose (Fig. 5). The study area hosts a very small proportion of the undissected basaltic plateau, which sustains perennial irrigation through dug wells taping the unconfined aquifer. As a result this area is moderately suitable for groundwater prospect, which is supported by the geomorphology of the area. The most part of the watershed exhibits moderately favorable geomorphic situation in the form of moderately dissected plateau. The highly dissected plateau and denudational slope show absence of irrigation practices during *rabi* season indicating non availability of productive aquifer system. As a result of which the area experiences acute drinking water problem during scarcity period.

In order to solve drinking water scarcity, the state administrator have executed borewells drilling program on a large scale since 1980, in which, about 143 borewells

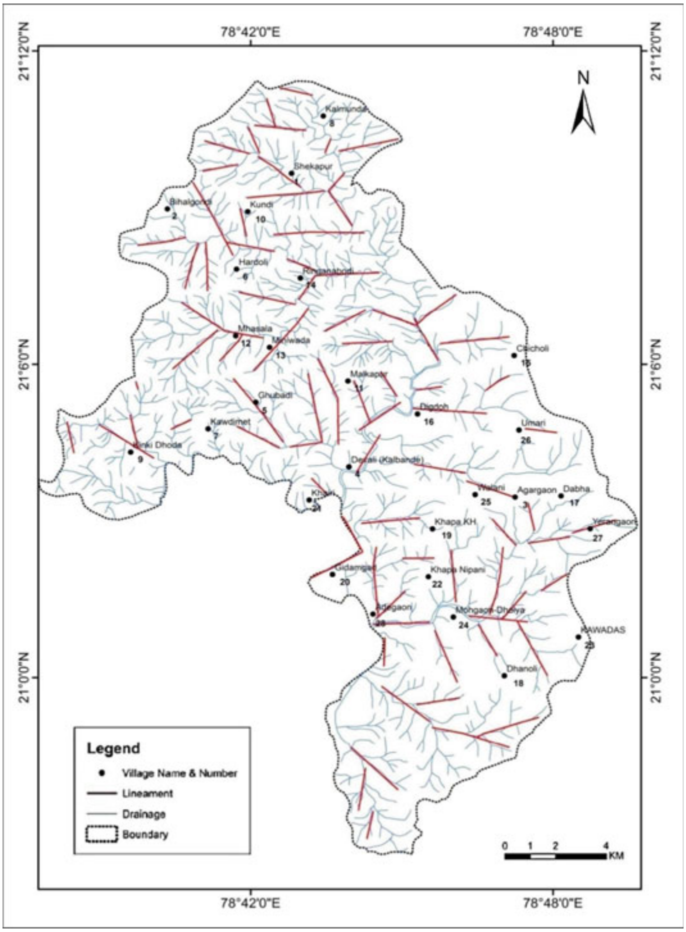

Fig. 5 Relationship of bore wells of the study area with respect to drainage and lineaments

have been drilled in 28 villages (Table 4). The depth of these bore wells ranges between 11 and 92 m. It is observed that the depth of weathering by and large varies between 6 and 12 m as assessed through length of the casing pipes.

Similarly, the water level in the borewell ranges between 6 and 12 m. The analyses of yield of bore wells show that, out of the total 143 borewells, 58 borewells have the yield of above 700 L/h. Such a ratio which is considered a successful ratio is observed to be just 40.56%; however, surprisingly the yield of 30 borewells found to be very high (with yield above 4500 lph), against the adverse groundwater situation.

The contribution of high yielding borewells to successful borewells is ~52.00%. Therefore, the performance of borewells has been further analyzed in relation to their proximity with the lineaments. All these villages have aerial extent of 1–2 km^2 in which varied geological conditions in terms of lithology, physiography, weathering thickness is not expected. However, some of the borewells are exceptionally high yielding (in the range of 5800–45,000 lph in villages like Shekapur, Agargaon, Dabha, Khairi, Dholya and Devali Kalbande) which is attributed to presence of lineaments in the form of weaker zones along its proximity. This phenomenon is very uncommon in basaltic terrain and thus clearly indicates the influence of lineaments on the deeper aquifers.

6 Conclusions and Recommendation

The current study significantly proves that permeable lineaments influence the deeper aquifers and forms infiltration gallery by virtue of development of secondary porosity due to fracturing, which facilitates the movement of groundwater. The extraction of groundwater in the Deccan trap aquifer system is a challenging task because of its heterogeneous nature and lack of primary porosity. Therefore, in the context of groundwater targeting, lineament mapping has significant importance. The present study demonstrated the efficient application of remote sensing technology in identification of prospective groundwater pockets.

The case study has significantly illustrated the efficiency of remote sensing technology in the identification of prospective groundwater pockets with emphasis on lineament identification. The study has a great relevance in Maharashtra State since its area is greater than 300,000 km^2, in which Deccan trap occupies nearly 83%. The state is drought prone and frequently results in scarcity of drinking water. Therefore, to mitigate the drought situation the state agency often embarks upon drilling of bore wells and implementation of water conservation programmes on a large scale, which puts extra financial burden on the state exchequer. The approach adopted in the current paper will surely help the state administrators for implementation of drilling of bore wells and water conservation programmes on cost effective basis. It is, therefore, recommended to widely use this technique for improving the success ratio of the borewells tapping deeper aquifers in hard rock terrain.

Table 4 The success ratio/yield performance of borewell

S. No.	Tehsil	Village	Total No. of Borewells	Depth (m)	Successful borewells (≥700 lph)	High yielding borewells (≥4500 lph)	Range of high yielding borewells (lph)
1	Katol	Shekapur	4	11.10–55.00	03	03	13,500–27,950
2		Bhilgondi	4	61.00–76.20	00	00	–
3		Agargaon	7	50.29–80.77	05	03	5200–5800
4		Devali (Kalbande)	6	37.30–61.00	04	03	5900–45,460
5		Ghubadi	3	60.00–90.00	00	00	–
6		Hardoli	6	41.15–86.00	02	02	4930–7770
7		Kawdimet	1	60.96	00	00	–
8		Kalmund	3	62.50–82.00	01	00	–
9		Kinkindhoda	2	91.40–92.7	00	00	–
10		Kundi	5	15.25–60.00	03	01	9200
11		Malkapur	6	58.70–90.00	01	00	–
12		Mhasala	5	60.00–86.50	00	00	–
13		Miniwada	3	67.00–86.20	00	00	–
14		Ringnabodi	4	61.00–91.44	01	00	–
15	Hingna	Chincholi	5	39.62–74.50	04	01	4930
16		Digdoh	13	32.60–82.50	03	01	4545
17		Dabha	7	32.91–67.80	06	03	4500–13,754
18		Dhanoli	5	42.50–60.00	02	02	43,480
19		Khapa Khurd	1	39.20	01	00	–
20		Gidamgad	3	52.00–61.00	02	00	–
21		Khairi	5	57.90–76.20	03	03	4930–5800
22		Khapa Nipani	3	21.35–85.34	01	00	–
23		Kawdas	12	38.71–81.00	04	04	7770–9200
24		Dholya (Mohgaon)	3	60.00–60.96	02	02	7770–15,950
25		Walani	5	54.00–87.40	01	01	18,900
26		Umri Wagh	10	51.80–88.30	04	00	–
27		Yerandgaon	4	37.19–67.00	02	00	–
28		Adegaon	8	56.70–91.70	03	01	13,500
			143	11.00–91.70	58	30	4545–45,460

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Assessing Contamination of Groundwater with Fluoride and Human Health Impact

Somnath Rudra

Abstract All over the world, groundwater is considered as the prime source for drinking water, but this water may be contaminated though various elements, among which fluoride is most common in many developed as well as developing countries. By consuming these fluoride contaminated water various types of fluorosis disease sets in socioeconomically backward rural people of arid and semi-arid areas where groundwater occurs in hard rock structure. Purulia district of West Bengal state of India is such an ideal area which drags attention to execute some research work to analyse the inherent causes of fluoride contamination of groundwater and its spatial variation as well as assessment of various types of fluorosis diseases people have been suffering with. Here people consume fluoride contaminated water even up to the level of 8.28 mg/Land it is well above the maximum permissible limit (1.5 mg/L), leading to dental, skeletal as well as various non-skeletal fluorosis diseases. It needs urgent attention from the academicians, planners, as well as administrative persons for implementation of medical measures, interventions through supply of safe drinking water, and training and awareness programmes to mitigate the problem.

Keywords Dental fluorosis · Fluoride · Groundwater contamination · Human intervention · Skeletal fluorosis

1 Introduction

Most of the people in the rural areas of developing countries like India use groundwater as the main source of drinking water (Bhattacharya et al. 1997; Mondal and Kumar 2017; Selvakumar et al. 2017), but this water becomes contaminated with various elements like fluoride, arsenic, iron, nitrate etc., and by consuming this contaminated water, considerable damages occur on human health, animal and plant life, soil as well as on the environment. The polluted and poor drinking water quality is

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the major factor for the onset of around 80% diseases in India (Olajire and Imeokparia 2001).

Fluoride (F^-) is a compound form of fluorine which is light yellow-green colour highly toxic and corrosive gas. The enrichment of F^- in groundwater is controlled by several factors among which the underlying geological formations and climatic conditions of the region are most important while other factors are rock-water interaction, pH, temperature, ion exchange capacity of the aquifer media, groundwater flow velocity through the aquifer, solubility and availability of fluoride (Kim et al. 2012). F^- exists in a great variety of minerals, like fluorspar, apatite, cryolite, mica and fluorapatite. In atmosphere, fluorine is found as Chlorofluorocarbon (CFC), Hydrochlorofluorocarbon (HCFC) and Hydrofluorocarbon (HFC) gases, which when wash down by precipitation may increase the fluoride content in surface and groundwater. Volcanic ashes released due to volcanic activities are also responsible for fluoride pollution of the soil and water through precipitation of these ashes and the accompanying rainfall.

Though F^- is naturally present in groundwater and soil, some human activities like industrial waste released from iron, glass, aluminium industries, or certain pesticides and phosphate fertilizers used in agricultural activities intensify the F^- concentration (Gupta et al. 2019).The high concentration of fluoride in soil may lead to excessive intake of F^- resulting into dental and skeletal fluorosis (Ropelewska et al. 2016).

Contamination of F^- in groundwater is now a global problem and it is now endemic in at least 25 countries which are spread over all the continents (Fawell et al. 2006; Adhikary et al. 2014). High amount of F^- concentration in ground water are mostly accompanying with igneous and metamorphic rocks particularly granite and gneisses and these are found in China, India, Pakistan, Sri Lanka, Thailand, West Africa and South Africa (WHO 2006). India and China are the worst affected two most populous countries, where considerable impact of fluoride on human health is noticed.

Fluoride bearing minerals such as fluorite (CaF_2), cryolite (Na_3AlF_6), fluor-apatite ($Ca_5(PO_4)_3F$) etc. are found in granite, granite gneisses and pegmatite rocks, which are mainly responsible forfluoride in groundwater (Deshmukh et al. 1995; Rao 2009; Thapa et al. 2017). In India during 1937, first problem of excessive F^- was first reported from Andhra Pradesh (Short et al. 1937). It is estimated that 65% of Indian villages are endangered to high fluoride risk (UNICEF 1999) and 65 million people, out of which 6 million are children, are already suffering from fluorosis as a result of intake of fluoride contaminated water (Susheela 1993).

Nalhati-I Block of Birbhum District is the first place where fluoride was first identified in West Bengal during 1996. In 2005, it was found that 43 Community Development blocks (CD blocks) of seven districts have fluoride contaminated groundwater at the level of above 1.5 mg/L. Among the districts, Purulia, Bankura and Birbhum districts rank first, second and third respectively in groundwater contamination with fluoride. Other districts are South Dinajpur, Malda, North Dinajpur and South 24 Parganas (Table 1). Many of the people mainly from rural areas of different districts of West Bengal are suffering from fluorosis disease caused by consumption of fluoride contaminated water.

Table 1 Fluoride affected CD Blocks of West Bengal

District	CD Blocks
Purulia (17 blocks)	Santuri, Neturia, Jaypur, Baghmundi, Purulia-I, Purulia-II, Raghunathpur-I, Raghunathpur-II, Jhalda-I, Arsha, Puncha, Manbazar-I, Hura, Barabazar, Para, Kashipur and Balarampur
Bankura (10 blocks)	Bankura-II, Raipur, Taldangra, Indpur, Hirbandh, Chatna, Shaltora, Simlapal, Gangajalghati and Barjora
Birbhum (7 blocks)	Khairasol, Nalhati-I, Rampurhat-I, Suri-I, Mayureswar, Sainthia and Rajnagar
South Dinajpur (5 blocks)	Gangarampur, Kumarganj, Tapan, Khusmandi and Banshihari
Malda (2 blocks)	Ratuya-II, Bamangola
North Dinajpur (1 block)	Intahar
South 24 Parganas (1 block)	Baruipur

Source West Bengal Public Health and Engineering Department, 2009

The major objectives of this study are the analysis of the spatial variation of fluoride contamination in the groundwater-based drinking water sources, finding the probable causes of fluoride contamination and fluorosis diseases, and quantitative evaluation of the various types of fluorosis diseases suffered by the people of the rural areas of Purulia district.

2 Material and Method

2.1 Study Area

For the present study of groundwater F^- contamination and its impactonhuman health, Purulia district in general and five villages of Purulia particularly have been selected.Purulia, the westernmost district of West Bengal, lies between 22°41′35″ N and 23°42′00″ N latitudes and 85°49′25″ E and 86°54′37″ E longitudes covering a geographical area of 6259 km^2. The district is surrounded by Bankura and Jhargram districts from the east, and by West Burdwan district of West Bengal and Dhanbad district of Jharkhand from north, while it is bordered by Bokaro, Hazaribagand Ranchi districts on the west and on the south by Saraikela and East Singhbhum districts of Jharkhand state (Fig. 1).

In West Bengal, out of seven districts which are reported to have F^- contaminated drinking water, Purulia district is the worst one with respect to intensity as well as the spatial extent of F^- contamination in drinking water where out of 20 CD blocks 17 CD blocks have been detected. Many of the people are suffering from the disease of dental and skeletal fluorosis as well as other diseases due to drinking of F^- contaminated water.

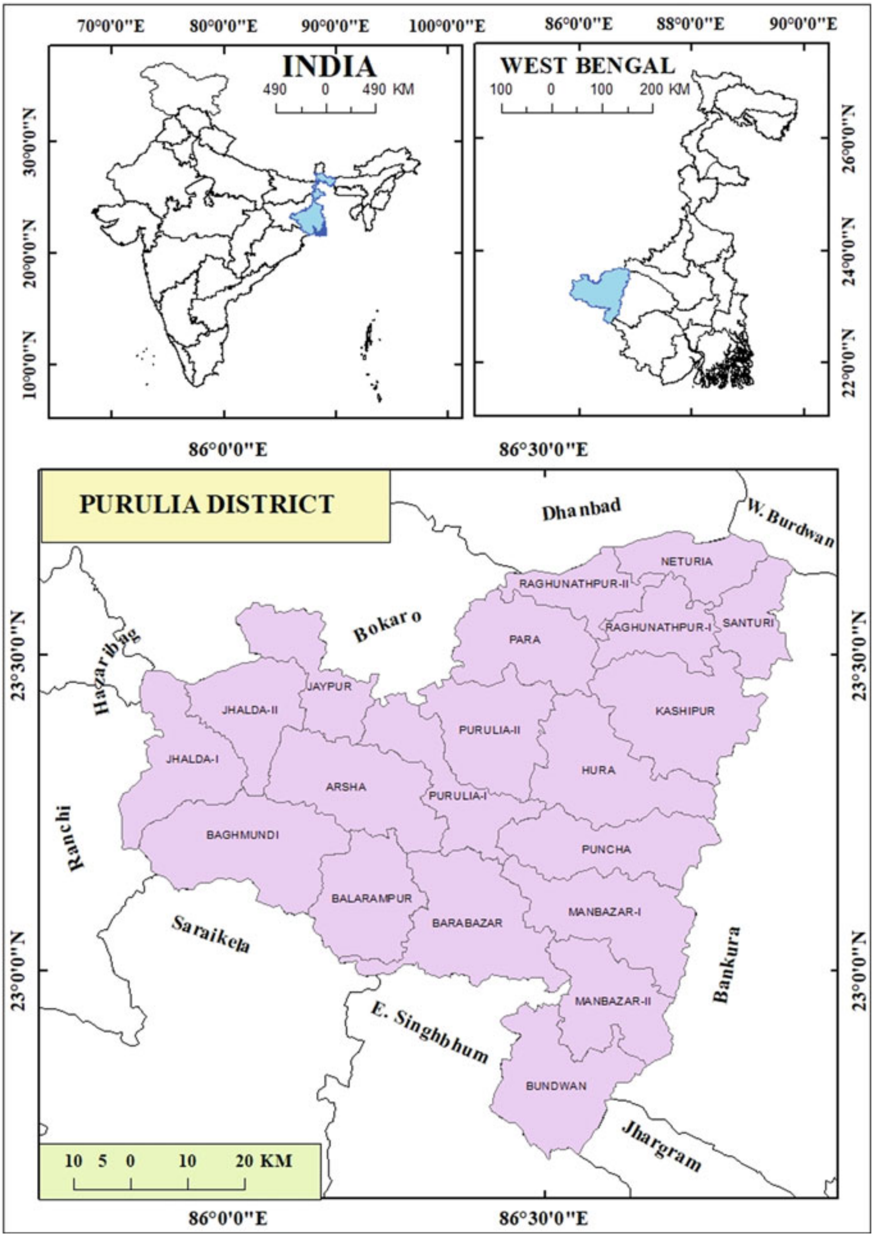

Fig. 1 Location of the study area

Purulia district is considered as the socio-economic backward district with low rate of literacy and lack of modern facilities and amenities. As a result, the problems emerging from fluoride contamination in drinking water has become much aggravated.

For in depth impact analysis, five villages have been selected purposively and detailed household survey has been conducted to find out the intensities of various forms of fluorosis diseases in the affected families. The five selected villages are Bhul, Kharai, Patamputra, Rugri and Juludi.

Bhul village is located at Dimdiha gram panchayat of Purulia-I CD block and hereout of five tube wells tested, four tube wells were F^- contaminated with an above permissible level of 1.5 mg/L. F^- level of this village is highest in Purulia-I CD block of Purulia district which is 5.74 mg/L. No human intervention has been taken so far from any sources to tackle the problem and the people are suffering very much from the fluorosis diseases and facing health as well as socio-economic problems acutely. Kharai village is located at Beko gram panchayat of Kashipur CD block of the district and here, F^- levelwas highest in the district (8.28 mg/L). The villagers use the contaminated water for drinking and other domestic use like cooking and they suffer from the severe problems of fluorosis. In Patamputra village of Garafusra gram panchayat, modern infrastructure, facilities and amenities are very poor and accessibility to the village is very less. F^- concentration level of tube wells at Rugri village of Beko gram panchayat of Kashipur CD was 5.48 mg/L whereas in Juludi village, a tribal village of Babugram gram panchayat of Raghunathpur-I CD it was 4.08 mg/L.

2.2 Data Collection and Analysis

The Gram panchayat level fluoride contamination data of the groundwater-based tube-wells and dug-wells used for drinking, cooking purposes have been collected from the West Bengal Public Health Engineering Department and some water samples from the selected villages were also tested to verify the results with published data.

For the socio economic and fluorosis disease data, primary survey has been conducted. For that purpose, 50 numbers of households from each of the five villages are selected by purposive stratified sampling method taking different socioeconomic group of people.

In the present study, detailed health survey for each and every member of those households has been executed with the help of local doctors and the guidelines of Doctor's Handbook for the on-field detection of fluorosis patients. Their family status in terms of socio-economic conditions, education, food habits, amount of daily intake of water, source of that water, level of awareness about the problem etc. have been documented to correlate these factors with the onset of fluorosis disease.

Spatial mapping of fluoride contamination was performed with the ArcGIS 10.3 software using the location of the gram panchayat and respective fluoride contamination data.

3 Results and Discussion

3.1 Spatial Variation of Fluoride Contaminated Groundwater

Among the different CD blocks of Purulia district, the highest percentage of fluoride contaminated tube wells are found in Purulia-II block, where more than 9% tube wells are fluoride contaminated above the level of 1.5 mg/L followed by Raghunathpur-I, Purulia-I, Joypur and Para. On the other hand, there is no fluoride contaminated tube well in Manbazar-II, Bundwan and Jhalda-II CD blocks (Fig. 2). A very low percentage of F^- contaminated tube wells are found in Santuri where only 0.48% of tube wells are F^- contaminated, followed by Arsha and Baghmundi where less than 1% tube wells are F^- contaminated at the level of above 1.5 mg/L (Table 2).

3.2 Block-Wise Distribution of Fluoride Level

The highest level of F^- contamination is found in Kashipur block, where 8.28 mg/L of F^- concentration is observed, followed by Baghmundi, Jhalda, Purulia-I and Raghunathpur-II. High F^- contamination in these areas is related to underground geology. Geological Structure shows that the rock structure of the Kashipur block is mainly dominated by Granitic Gneiss and Mica Schist of Archaean Era and in Baghmundi, Jhalda, Purulia-I and Raghunathpur-II block, the major geological structure are Granite of Precambrian era and Granitic Gneiss and Mica Schist of Archaean Era. On the other hand, a low level of F^- contamination is observed in Balarampur block followed by Puncha and Manbazar-I (Fig. 3).

3.3 Gram Panchayat Wise Distribution of Fluoride Contamination

Spatial distribution of F^- contamination in different Gram Panchayats (GP) of the Purulia district has been mapped in Fig. 4. The GP-wise variation in three study blocks of Purulia-I, Kashipur and Raghunathpur-I shows that Garafusra and Dimdiha GP are highly F^- contaminated in Purulia-I CD block. Here, in the present study villages, i.e. in Bhul village of Dimdiha GP and in Patamputra village of Garafusra GP, above 5 mg/l F^- contamination level was recorded. The lower level of F^- contamination

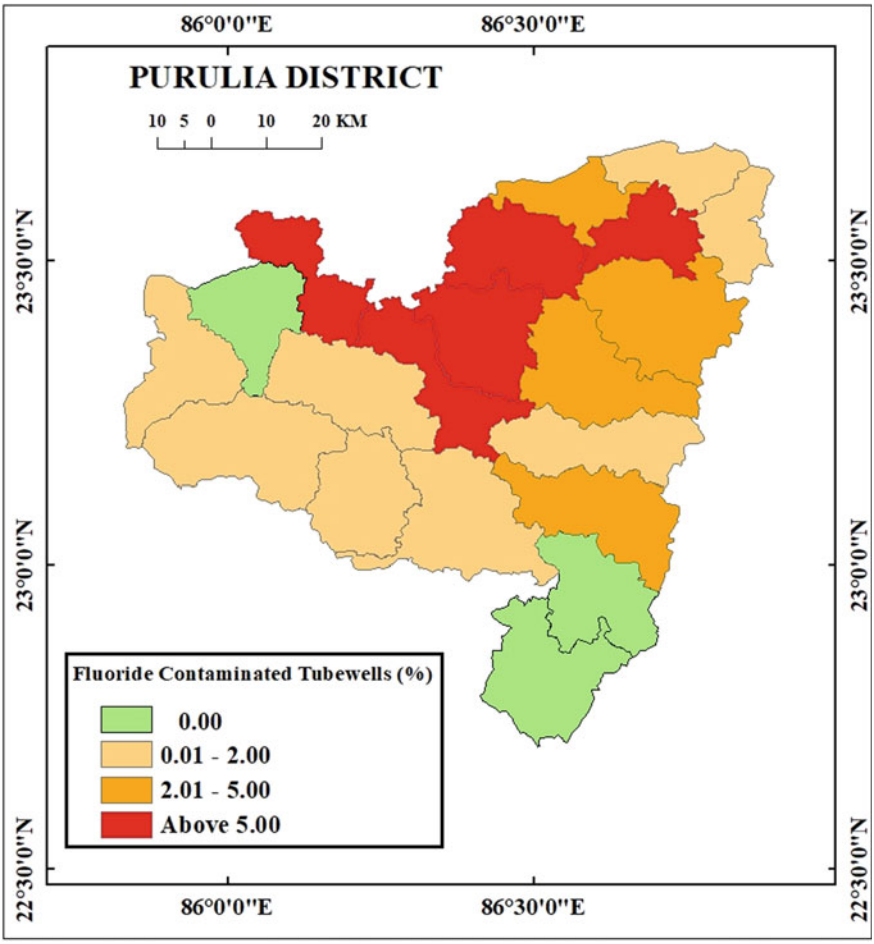

Fig. 2 Percentage of fluoride contaminated tube wells in different CD blocks of Purulia district

Table 2 Percentage of fluoride contaminated tube wells

Above 5%	2–5%	Below 2%
Purulia-II (9.09%) Raghunathpur-I (8.20%) Purulia-I (7.38%) Joypur (5.93%) Para (5.41%)	Raghunathpur-II (3.85%) Hura (3.70%) Kashipur (2.51%) Manbazar-I (2.29%)	Balarampur (1.41%) Barabazar (1.39%) Puncha (1.39%) Jhalda-I (1.26%) Neturia (1.09%) Baghmundi (0.96%) Arsha (0.91%) Santuri (0.48%)

Source Calculated by author from the *WBPHED data*

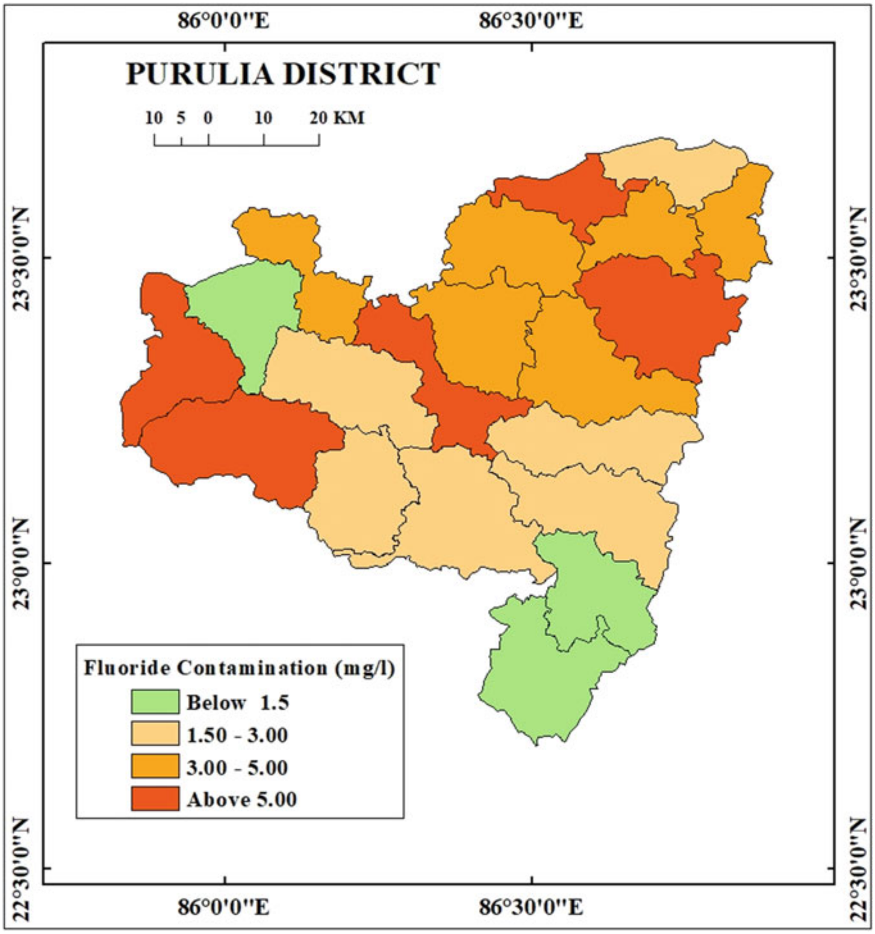

Fig. 3 Fluoride contamination level in various CD blocks of Purulia district

with below 3 mg/l F^- is found in Chakoltore, Sonaijuri, Durku and Lagda gram panchayats (Fig. 5).

In Kashipur CD block, Beko GP is highly contaminated with F^-, where 8.28 mg/L fluoride contaminated tube-wells are found in Kharai village. The lower level of F^- is found in the tube wells of Barrah, Agardih Chitra and Sonathali GP, where F^- levels are less than 1.5 mg/l (Fig. 6).

In Raghunathpur CD block, Babugram GP is mostly affected by F^- contamination in drinking water, where above 4 mg/LF^- level is found at Rangametya and Juludi villages. In Nutandih gram panchayat, F^- level is at a safe level of below 1.5 mg/L (Fig. 7).

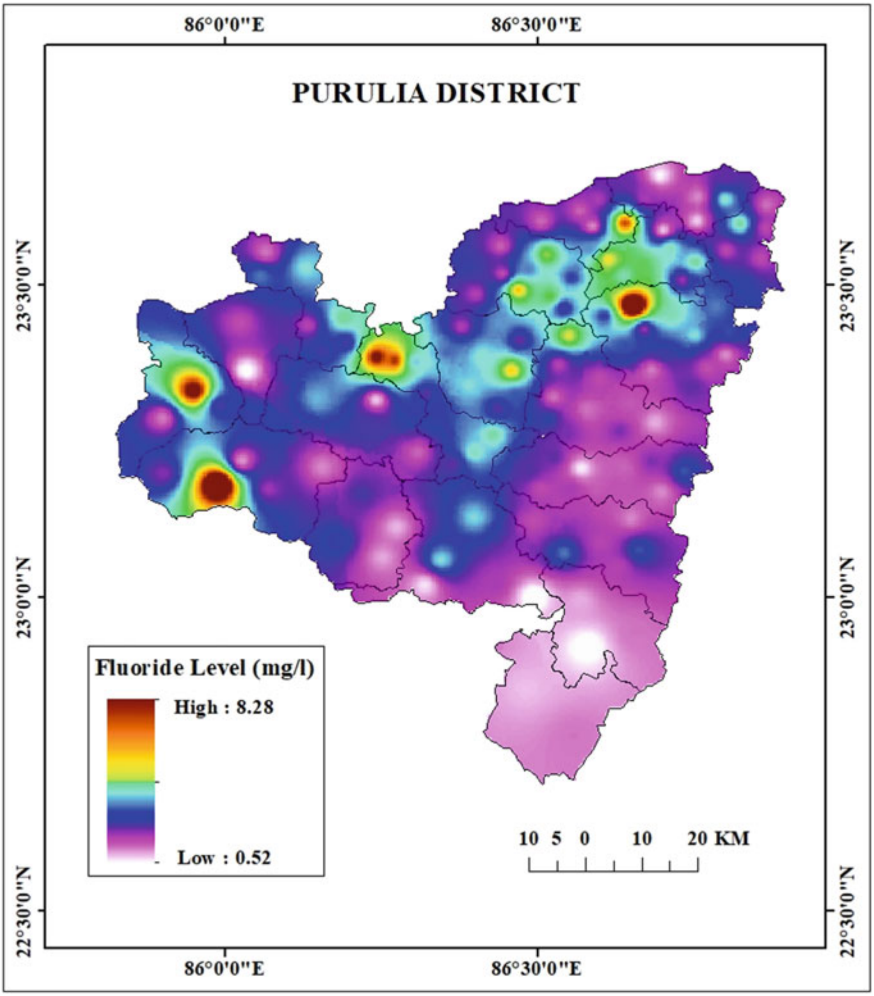

Fig. 4 Spatial variation of fluoride contamination of groundwater based on GP wise distribution data

3.4 Factors of Fluoride Contamination in Ground Water and Onset of Fluorosis

Since long time before geologic environment has great influence on human health adversely by intruding F^- to groundwater and contaminating it. Human being takes F^- from drinking water, food, air, cosmetics, drugs etc. out of which, drinking water is the major source of F^- in human health.

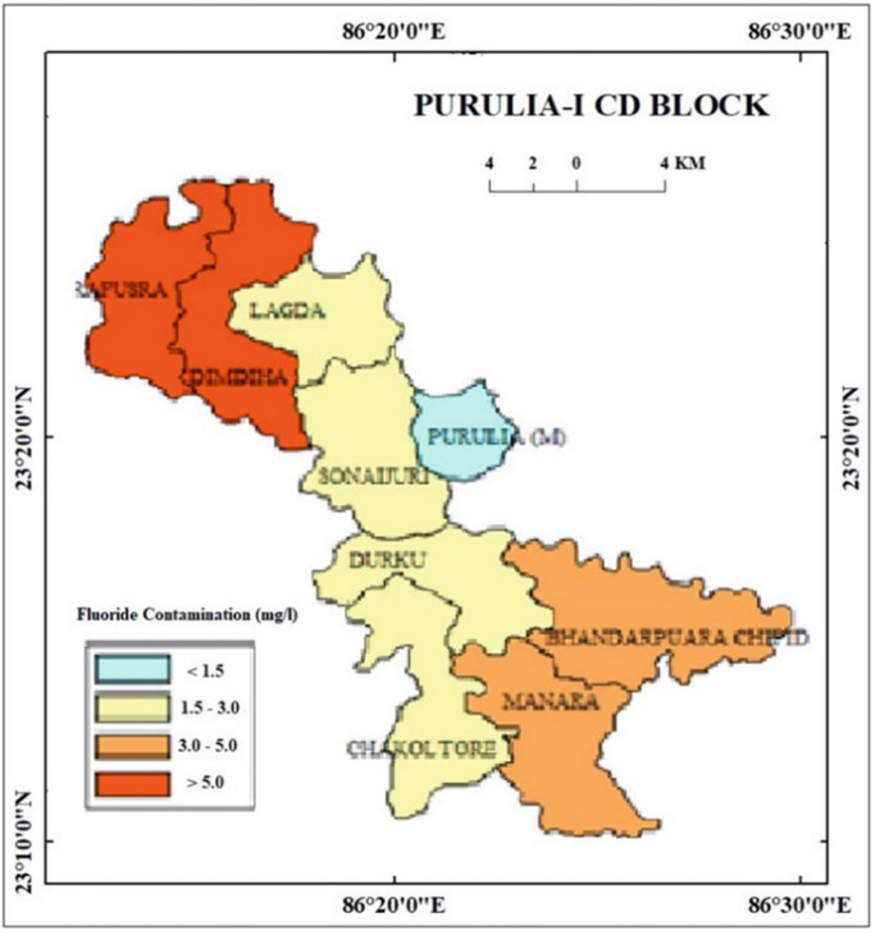

Fig. 5 Spatial variation of fluoride contamination in Purulia-I CD block

Several natural, socioeconomic and habitual factors combinedly contribute to the F^- contamination in drinking water, food, air, environment and to make adverse effects on human health (Fig. 8).

3.4.1 Natural Factors

The natural concentration of F^- in ground water is determined by geology, climate, chemical composition of groundwater and contact time. Geology is the most important factor of F^- concentration which differs greatly in the groundwater depending on the geological structure for groundwater formation and type of rocks through which it passes. Therefore, F^- contamination tends to appear in places where fluorite, apatite

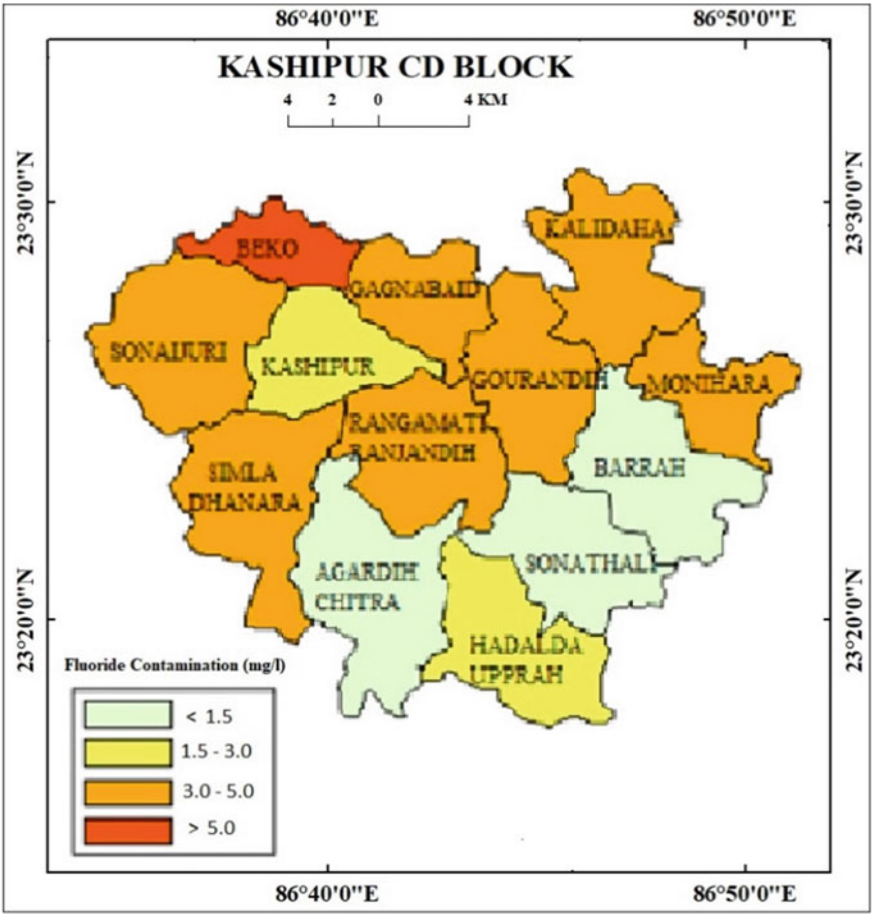

Fig. 6 Spatial variation of fluoride contamination in Kashipur CD block

or mica minerals are most abundant. Within the igneous and volcanic rocks, fluorine concentration ranges from 100 ppm to more than 1000 ppm depending on the acidic level of the rock like ultramafic to alkali rock whereas, sedimentary rock limestone contains less fluorine than the shales (Frencken 1992). Again, in metamorphic rocks fluorine concentration varies from 100 ppm to more than 5000 ppm in regional to contact metamorphism (Frencken 1992). Climatic condition is also important factors for F^- concentration in ground water. Generally, arid dry regions with slow groundwater flow and long reaction time with rocks are prone to high F^- concentrations. But it in humid tropical climate it is less prominent because the groundwater chemical composition is diluted with high rainfall inputs.

In Purulia district, F^- exists in naturally occurring mineral called 'apatite', which presents in composite gneisses, meta-sedimentary, meta-basics and intrusive granite rocks of Late Archean to Proterozoic age. The interaction between rock and water

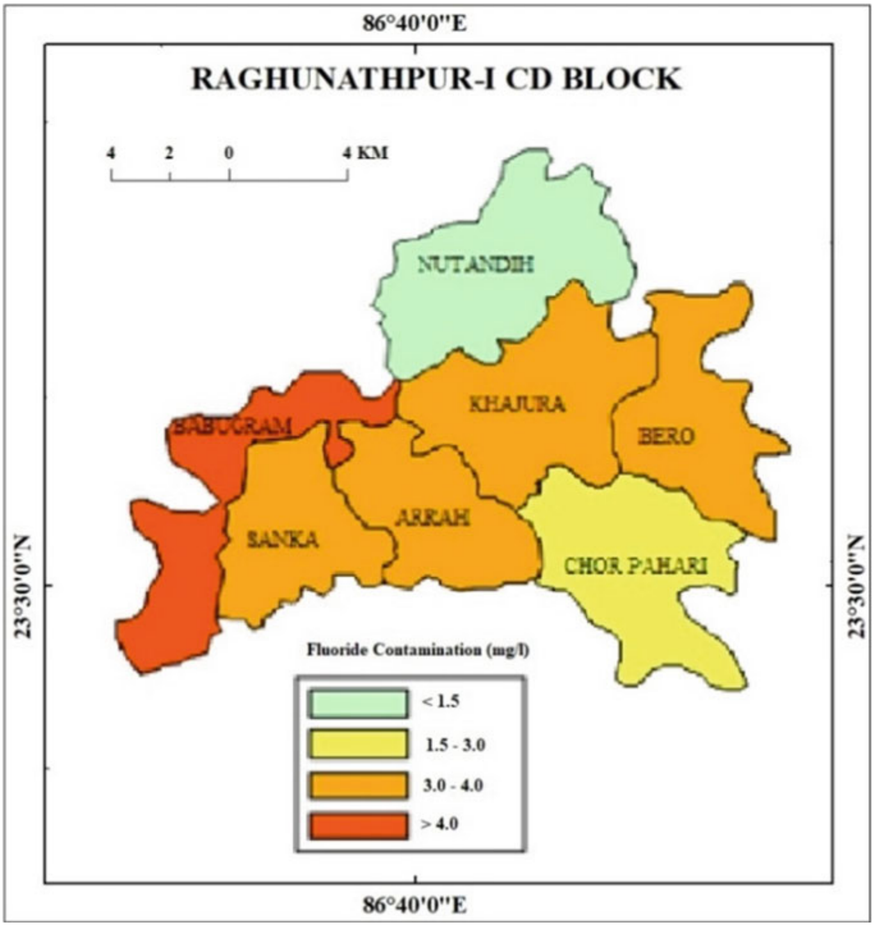

Fig. 7 Spatial variation of fluoride contamination in Raghunathpur-I CD block

acts a significant role behind the enrichment process of fluoride. Fast recession of the water table due to excessive groundwater withdrawal and long spells of drought has prompted the gradual leaching of F^- into the circulating groundwater.

Geological structure (Fig. 9) shows that the rock structures of the study areas are mainly dominated by Granite of Precambrian era and Granitic Gneiss of Archaean Era in Purulia-I and Raghunathpur-I block and Granitic Gneiss and Mica Schist of Archaean Era in Kashipur block. All these rocks are rich in F^- containing minerals which cause F^- contamination in groundwater. Therefore, the water from hand pumps-based tube wells and both the dug and bore wells are greatly contaminated with F^-.

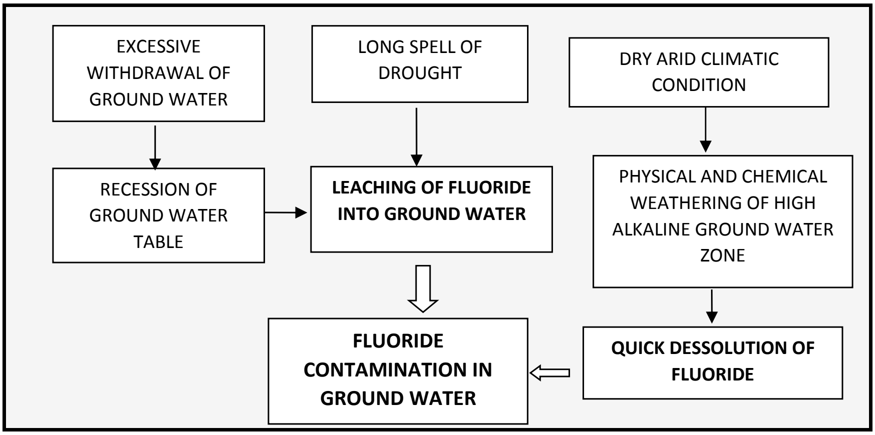

Fig. 8 Factors affecting fluoride contamination in ground water

3.4.2 Economic Factor

Economic activities, as well as economic conditions of the people of any region, also have an important bearing on F^- contamination and associated health hazards. Population increase may exert pressure on the agriculture sector to produce more crops to supply food for the growing population. In this process, excess withdrawal of groundwater for irrigation leads to F^- enrichment in groundwater. Due to excess use of phosphate fertilizer and F^- pesticide, the amount of F^- in the land, soil and surface water increases. On the other hand, F^- containing raw materials are used in aluminium industries, cement industries, phosphate fertilizer industries, brick and ceramic industries. Due to processing of these raw materials huge amount of F^- is released to environment and this F^- pollutes the soil, water, air and environment. Although the typical industrial activities are responsible for creating fluorosis disease in the society, but in the study areas, this kind of industries are not available. So, such kind of contamination does not take place in the sample villages.

On the other hand, the economic conditions of the people of any region also determine the impact of F^- on their health. The poor people do not have sufficient amount of money to treat the fluorosis patients and to procure nutritional food to support the health. They are generally less educated and are not aware of the problems and the procedure to overcome the problems. In the under developed areas, people have poor access to the modern infrastructure, facilities and amenities. That is why, in the district like Purulia people suffer much from the fluorosis diseases.

3.4.3 Social Factor

Social factors like caste status, belief, tradition etc. play an important role to the onset of fluorosis. People from high caste social group are able to combat fluorosis

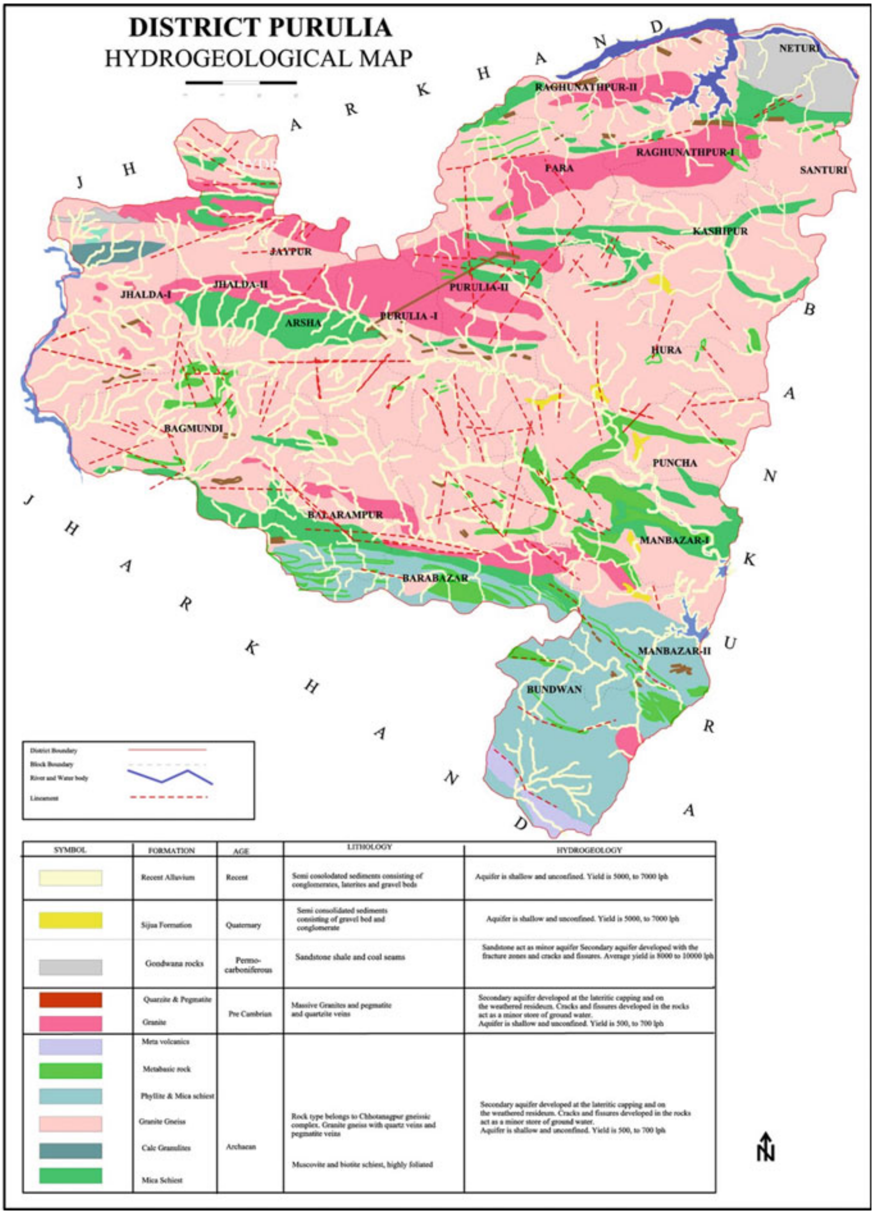

Fig. 9 Hydro-geological Map of Purulia district. *Source* NBSS & LUP Regional Centre, Kolkata

with their better economic condition, social influence, power to receive the benefits of planning and management but poor destitute people have no mean to combat the disease. Social belief or habits of the people also play an important role to retain in their old way of life and take the contaminated water long time. For example, in Rugri village, F^- free drinking water supply through pipeline have been initiated to reduce the fluorosis diseases, but people use the contaminated water from tube wells for drinking and cooking purpose. In this way fluorosis disease persists long time in the village. On the other hand, people have an erroneous concept that contaminated water is safe for cooking, as boiling of this water may reduce the level of contamination. But it is not true and F^- contamination water is not safe for both drinking and cooking purpose because cooking or boiling of it increases the concentration level.

3.4.4 Habitual Factor

Several bad habits of the people of the F^- affected rural areas of Purulia district may enhance the fluorosis risk. People of the affected villages of the study area have the habit of munching *supari*, *pan masala*, *gutkha*, tobaco etc. which have a high amount of F^- content. Tea contains high amount of F^-. So, drinking of tea prepared in F^- contaminated water causes high F^- ingestion to human body. The amount of F^- ingested from tea may range from 0.04 to 2.7 mg/person/day (Murray 1986). Therefore, along with the natural causes of F^- contamination of drinking water, the several social, economic and habitual factors help to propagate the onset of fluorosis in the wide areas of the district in an alarming situation.

3.5 Impact on Human Health

From a long time, it is recognised that the geological environment has great impact on human health and it is probably by Chinese physicians in the fourth century (Appleton 1996). The human health status depends upon the presence of F^- in drinking water in a definite limit and its excess and deficiency both are detrimental. Low intake of F^- causes dental caries buthigh levels F^- consumption can cause dental or skeletal fluorosis subject to the levels of concentration (Table 3).The BIS (Bureau of Indian Standards 2012) and ICMR (Indian Council of Medical Research 1975) specified the highest desirable limit of F^- at 1.0 mg/L and the maximum permissible limit of it is 1.5 mg/L. WHO (2011) also defined the permissible limit for F^- as 1.5 mg/L, whereas according to USPHS (1962), it varies depending on the climatic conditions of a region as the amount of water consumption varies on air temperature.

Drinking water is the major source of F^- for human body but it also derives from other sources like food, air, industrial exposures, cosmetics and medicine (Jha et al. 2010). The food items rich in F^- are vegetables, grains, meat, eggs and milk products, tea, tobacco, betel etc. (Murray 1986; Susheela 1993).

Table 3 Concentration of fluoride in drinking water and its effects on human health

Fluoride concentration (mg/L)	Effect
Nil	Limited growth and fertility
<0.5	Dental caries
0.5–1.5	Promotes dental health, prevents tooth decay
1.5–4.0	Dental fluorosis (mottling and pitting of teeth)
4.0–10.0	Dental fluorosis, skeletal fluorosis (pain in neck bones and back)
>10.00	Crippling fluorosis

Source International Drinking Water Standards (1971), WHO, Geneva

It is estimated that within the body, 90% of the F^- is deposited in skeleton and bone which is important for tooth and bone formation (National Research Council 2006). For the production and maintenance of healthy teeth and bone, 0.5–1.0 mg/Lof fluoride is beneficial (Wood 1974; Dey and Giri 2015). It is especially effective on children who are still developing their teeth (WHO 2006). Excess F^- intake causes diseases of dental fluorosis, skeletal fluorosis and other non-skeletal fluorosis like muscular problem, gastrointestinal, neurological problem, painful skin rashes and allergy, abnormal thyroid function and other hormonal disturbances (Ayoob and Gupta 2006; Zohoori et al. 2015).

The community living in rural areas of Purulia district are most severely affected by F^- as they are dependent on ground water drawn by hand pumps, open or dug wells, tube wells, for consumption. Water quality is seldom tested in rural areas because of the strong belief that water drawn from the deepest crust of the earth is to be pure. Dietary habit of the people is also an important factor for the effectiveness of fluoride on human health. The person who have balanced diet are exposed to less risk than the person not having balanced diet because food with high calcium reduce the risk of fluorosis. People of the district Purulia are more susceptible to develop fluorosis because of mal-nutritional status with poor food condition.

Many of the people in rural areas of Purulia district are suffered from different types of fluorosis diseases due to drinking of F^- contaminated water. The present study indicates that the percentage of fluorosis patients to total population is highest in Bhul villages (44.20%), followed by Patamputra (44.06%), Kharai (33.93%), Rugri (32.03%) and Juludi (30.18%) village.

Intensity of fluorosis diseases in the villages is determined by the F^- concentration level in the drinking water, socioeconomic conditions, food habits and human intervention through supply of alternate safe drinking water (Rudra 2016a, b). Percentage of fluorosis patients increases with increasing F^- concentration in drinking water. Food habits of the people of the five villages are more or less same but it varies with socio-economic condition. On the other hand, human intervention through supply of

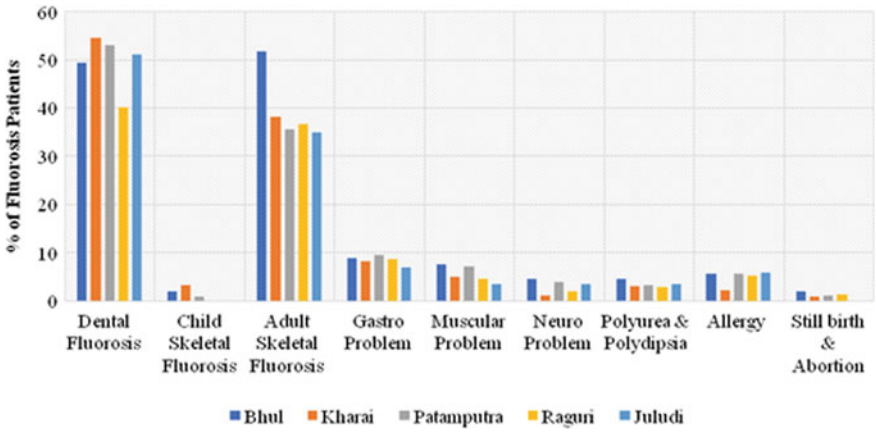

Fig. 10 Comparison between proportions of different fluorosis diseases

alternate safe F^- free drinking water reduces the proportion of fluorosis patients as well as intensity of diseases and problems suffered by the people as it is observed in Kharai and Rugri villages. But, in Bhul and Patamputra villages, due to having no alternate fluoride free drinking water supply, the proportions of fluorosis patients are higher.

3.5.1 Comparative Analysis of Various Forms of Fluorosis Diseases

Among all types of fluorosis diseases, dental and skeletal fluorosis patients are dominating than other types of non-skeletal diseases. The study indicates that in Bhul village, the proportion of skeletal fluorosis for adult persons is highest of all the fluorosis diseases, where nearly 52% patients are suffering from skeletal fluorosis followed by dental fluorosis having the share of above 49% patients of total fluorosis patients. In all other villages, most of the people are affected by dental fluorosis then skeletal fluorosis. While moderate proportions of patients are affected by non-skeletal fluorosis like gastrointestinal, muscular problems, allergy, neurological and polyurea and polydipsia diseases. In contrast, skeletal fluorosis for children, neurological problems and problems of still birth and repeated abortion of women are the rare categories of diseases by which relatively smaller proportion of population are affected (Fig. 10).

3.5.2 Dental Fluorosis

Dental fluorosis mainly occurs in children exposed to levels of F^- greater than 1.5 mg/L affecting their teeth (Levy and Zarei 1991). As the Purulia district is

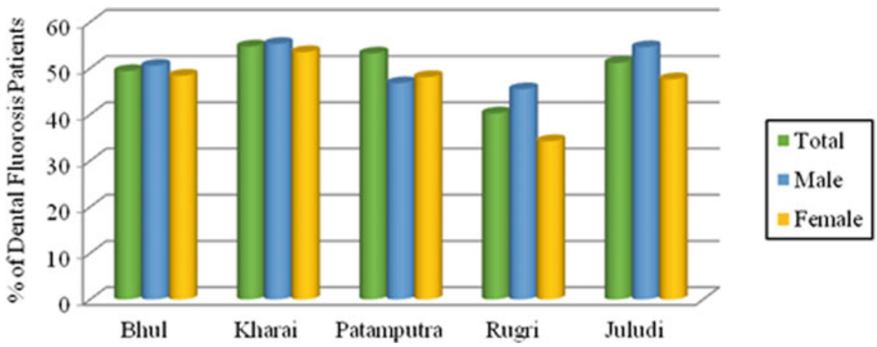

Fig. 11 Proportion of dental fluorosis patients

warmer area more water is consumed and dental fluorosis may occur even at lower concentrations of fluoride in the drinking-water.

Dental fluorosis is classified into six categories based on the stages or intensity like *normal, questionable, very mild, mild, moderate* and *severe* dental fluorosis (Dean 1942).The teeth appear chalky white in the early stage, and then it becomes gradually yellow, brown or black (Dey and Giri 2015) depending on the dose of fluoride, duration of consumption and age of the individual (Bergc 2015).

In the case of dental fluorosis, gender-wise variations of dental fluorosis patients have been observed in different areas (Fig. 11).

3.5.3 Skeletal Fluorosis

Both the young and old people can be affected by skeletal fluorosis where bones and skeleton of the body are degraded. At the initial stage, people feel simple aches and pain in the joints and it becomes difficult to walk or even movements for them but are not easily detectable which may be confused with rheumatoid arthritis (National Research Council 2006) but ultimately the joints become rigid or stiff (Wang et al. 1994; Jha et al. 2011).

If we consider the spatial distribution of skeletal fluorosis patients of five villages in the study area, we find that in Bhul village highest proportion of fluorosis patients suffers from skeletal fluorosis followed by Kharai, Rugri, Patamputra and Juludi (Table 4). Some patients bent forward. A patient with skeletal fluorosis in the final stages may be bent forward, crippled and paralysed. An attempt has been taken to find out sex-wise distribution pattern of fluorosis patients.

3.5.4 Non-Skeletal Fluorosis

The F^- not only affects the hard tissues like teeth or bones but the other organs of the body are also hampered by excessive intake of F^-. The accumulation of F^-

Table 4 Percentage of Adult Skeletal fluorosis to total fluorosis patients

Name of the villages	Total	Male	Female
Bhul	51.88	52.69	50.75
Kharai	38.14	35.19	41.86
Patamputra	35.71	32.43	40.38
Rugri	36.59	38.64	34.21
Juludi	34.88	31.82	38.10

in soft tissues of the body like liver, kidney, lung, musculature, spleen, thyroid, and pituitary gland has also been reported (Oelschlageret al. 1972; Jimenez-Cordova et al. 2019). These are called non-skeletal fluorosis. The patients may feel gastro-intestinal complaints, loss of appetite, constipation, pain in stomach, and even intermittent diarrhoea (Rasool et al. 2018). Muscle weakness and neurological problem with excessive thirst and frequent urination are common among the affected people.

3.5.5 Gastrointestinal Problems

Gastrointestinal problem is one of the significant non-skeletal fluorosis diseases faced by the people of the F^- endemic areas. The F^- from drinking water and diet is ingested through gastrointestinal tract (Kabir et al. 2019). F^- contaminated water effect adversely on stomach, liver and entire digestive systems and people face the problems of nausea, loss of appetite, pain in stomach, gas formation and blotted feeling, constipation and intermittent diarrhoea (Sidhu and Kimmer 2002). Nearly 1/10th of the fluorosis patients suffer from gastro-fluorosis problem (Table 5). Another interesting observation has been revealed that the females are more prone to attack by gastro-fluorosis disease than the male in the same area. This is due to the physiological and social factors. The health awareness among female is less than male while time schedules for taking food is not regular and they belief in old customs and tradition leading to unscientific fasting which along with fluoride contaminated water induce gastro problem much more in female (Rudra 2016a).

Table 5 Percentage of Gastro-fluorosis patients to total fluorosis patients

Name of the villages	Total	Male	Female
Bhul	8.75	7.53	10.45
Kharai	8.25	7.41	9.3
Patamputra	9.52	8.11	11.54
Rugri	8.54	6.82	10.53
Juludi	6.98	6.82	7.14

Table 6 Percentage of fluorosis patients with muscular problems

Name of the villages	Total	Male	Female
Bhul	7.50	8.60	5.79
Kharai	5.05	6.13	4.02
Patamputra	7.17	9.25	6.01
Rugri	4.54	6.36	3.26
Juludi	3.49	4.55	2.38

Table 7 Parentage of fluorosis patients with polyurea and polydipsia problems

Name of the villages	Total	Male	Female
Bhul	4.88	4.55	5.26
Kharai	3.09	3.70	2.33
Patamputra	3.17	2.70	3.85
Rugri	2.88	2.55	3.26
Juludi	3.49	2.27	4.76

3.5.6 Muscle Problems

F^- contaminated water reacts grievously on muscle tissues to make the muscle pain and stiffness, and finally the muscle power is lost. Ultimately, a worker becomes a dependent person to his family. The proportions of patients of the muscular diseases from the five villages are given in Table 6.

3.5.7 Renal Impairment

Most of the excess F^- is excreted through thermal system of our body and thus the renal system is highly exposed to concentrations of F^- than other organs (Whitford 1994). Thus, it can cause renal impairment in which urine may be yellow–red in colour with much less in volume (Itai et al. 2010). It can also cause polyurea in which patients have tendency to frequent urination but the volume is less and polydipsia in which patients feel excessive thirst (RGNDWM 1993). In this study area, a few fluorosis patients are detected who are suffering from polyurea and polydipsia. However, in Bhul village 4.88% patients are found having been suffered from this disease followed by Juludi, Patamputra, Kharai and Rugri village (Table 7).

3.5.8 Neurological Problems

Excess ingestionof F^- canhamperthe nervous system of human body and the patients may face the problems of nervousness and depression, sometimes senselessness in fingers and toes (Choi et al. 2012). The gender-wise proportion of patients with neurological problems has been shown in Table 8.

Table 8 Percentage of fluorosis patients with neurological problems

Name of the villages	Total	Male	Female
Bhul	4.48	3.27	6.89
Kharai	1.03	0.00	2.33
Patamputra	3.79	2.70	5.77
Rugri	1.88	1.08	2.99
Juludi	3.49	2.27	4.76

Table 9 Percentage of fluorosis patients with allergy problems

Name of the villages	Total	Male	Female
Bhul	5.63	5.30	6.46
Kharai	2.11	0.00	4.65
Patamputra	5.56	1.92	4.76
Rugri	5.10	4.55	5.89
Juludi	5.41	4.45	5.70

3.5.9 Skin Allergy

After consuming F^- contaminated water, considerable numbers of individuals bear the symptom of skin allergy, which creates oval shaped skin eruptions with pinkish-red in colour and pain on the skin (RGNDWM 1993). These skin rashes are very painful and generally prevalent in women and children. This allergic fluorosis disease creates irritations and mental agony to the patients. The present study indicates that allergic patients are highest in Bhul village where 5.63% fluorosis patients are suffering from allergic problem. This is followed by Patamputra, Juludi, Rugri and Kharai village (Table 9).

3.5.10 Still Birth and Repeated Abortion

Excess intake of F contaminated drinking water has possible adverse effects on pregnancy outcome (Freni 1994). F is known to cause calcification in the foetal blood vessels or arteries which restrict the growth of the foetus. Repeated abortion and still birth have been reported in the study areas due to fluorosis. In Bhul village, nearly 2% fluorosis patients are suffering from the problems of still birth or repeated abortion but in Juludi village no woman of such problem has been found.

4 Conclusion

It is concluded that though the source of fluoride in groundwater is from naturally occurring fluoride bearing minerals like fluorspar, apatite and phosphorites, which are found in the different rock structures, some socio-economic factors also responsible for the onset of fluorosis. As most of the rural people of Purulia district use the groundwater-based tube wells drinking water, by drinking this fluoride contaminated water large numbers of people have been suffering from different types of fluorosis diseases like dental, skeletal and various types of non-skeletal fluorosis. People being economically backward and less educated with poor access to modern infrastructure, facilities and amenities, and suffering from malnutrition are mostly attacked by fluorosis disease. It also adversely affects the socio-economic condition of the family.

Some measures can be taken to reduce the problem like medical measures, interventions through the supply of fluoride free drinking water, and training and awareness programme. Regular fluoride testing of the tube wells should be done. The tube wells having high fluoride contamination should be red marked indicating unusable for drinking. The most important and urgent measure is to supply fluoride-free water to the fluorosis endemic villages. This could be achieved by finding out alternative sources of fluoride free water or by fetching water through pipe line from a distance. The defluoridation plants can also be installed or domestic fluoride filters can be provided if supply of safe water through pipeline is not possible.

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Primary Concept of Arsenic Toxicity: An Overview

Surjyo Jyoti Biswas, Monoj Patra, Santosh Kumar Giri, Sanjib Gorain, Dinesh Gope, Nimai Chandra Saha, and Bibhas Guha

Abstract Contamination of drinking groundwater with arsenic is a looming problem in several countries and has affected millions of people, distributed over some 20 countries, globally including people in West Bengal (India) and Bangladesh. Continued exposure to Arsenic ('As') leads to various disorders and malfunctioning of renal, reproductive, cardiovascular and respiratory system along with the lethal effects manifested on skin and epidermal cells. In the review, an effort was made to incorporate the findings of other investigators and to evaluate the relation among arsenic metabolism and the consequences of numerous chronic disease. Early indications/manifestations of arsenicosis is difficult because of the occurrence of non-specific symptoms in various water-borne ailments. It has emerged that orthodox drugs used for treating arsenicosis was highly unsatisfactory as they have their own toxic side effects. In such a scenario, insights to the biological and epidemiological meanings of arsenic metabolism can help in mitigating the risk of arsenic toxicity and provide a prospective means for disease prophecy, prevention and control.

Keywords Arsenicosis · Contamination · Groundwater · Risk assessment

Abbreviations

As	Arsenic
AsIII	Arsenite
AsV	Arsenate

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DMAV	Dimethylarsinic
DMAIII	Dimethyl arsinous
MMAV	Monomethyl arsonic
MMAIII	Monomethyl arsonous
ROS	Reactive oxygen species

1 Introduction

Arsenic is a naturally occurring metalloid that is extensively dispersed on the Earth's crust with the chemical symbol (As), atomic number (Z-33) and which is placed between phosphorus and antimony in group 15 of the periodic table. Arsenic exist in minerals, usually in amalgamation with sulphur iron and other metals, and also exist in its elemental form. This metalloid is found in groundwater as it percolates through rock and soils, air, food-grains and vegetables. It is also released into the environment by volcanic eruptions and indiscriminate mining. Arsenic in groundwater is a widespread and alarming problem that tends to be higher in drinking water drawn from ground sources, such as dug-well and tube-wells, than from surface water sources such as ponds, lakes or natural reservoirs. The maximum permissible content of inorganic arsenic in ground water as set by the U.S. Environmental Protection Agency (EPA) is 10 ppb in the USA. But the levels of arsenic in certain countries like India and Bangladesh have been measured at over 500 ppb (Naujokas et al. 2013).

Arsenic exist in environment in the form of trivalent arsenite (As^{3+}) or pentavalent arsenate (As^{5+}). As^{3+} form in particular is high in drinking water where the condition is anaerobic while the pentavalent form is predominant in aerobic conditions. The surge in cancer risk detected in several epidemiological investigations is mainly due to the occurrence of trivalent arsenic (arsenite) as its pentavalent form in water is quickly reduced when it enters a cell. The main reason for arsenite to enter a cell is because it is uncharged at pH 7 which is the normal physiological pH of the body while arsenate is negatively charged and impermeable to the cell membrane. Arsenite and arsenate, both the forms are genuine and established human carcinogens, but not a true animal carcinogen. In standard assays it was reported that only arsenite has the ability to cross transplacental barrier and thereby acts as a carcinogen and also as a co-carcinogen (National Research Council 2000; IARC 2004). It has been reported that arsenate is transported by the phosphate transporter while arsenite is transported by aqua-glycoporin 7 and 9 (Huang and Lee 1996; Liu et al 2002). Efforts till date by both Governmental and non-Governmental establishments in innumerable countries to provide As-free drinking water to highly contaminated zones remain exceptionally insufficient. Arsenic enters the human bodies of innocent populations not only through drinking water they consume but also through food and vegetables grown in contaminated soil. The current review attempt to describe the latest information on the toxicological aspects of arsenic based on the informations obtained from PubMed, Science Direct and Google Scholar databases. A search was made through permutation and combination of keywords such as arsenic, human and animal toxicity, biological activity, endocrine disruption, carcinogenicity, genotoxicity, immunological toxicity, neurogenic effects of arsenic, thyro-toxicity, cardiovascular, musculoskeletal, dermal toxicities, and antinuclear antibody. There were no language limitations as the articles were carefully studied for information on the various aspects of toxicity.

2 Routes of Exposure for Arsenic

The primary routes of entry of arsenic in the body are ingestion and inhalation. Though dermal exposure can happen in humans, it is not considered a primary route. In Europe and American alone 80% of arsenic ingestion is through consumption of meat, fish, and poultry. Various marine organism like fish, bivalve and algae contains arsenic as arseno-betaine and arseno-choline, which is also called as fish arsenic and both these forms have low toxicity levels in humans and are rapidly excreted through urine (ATSDR 2007). Recent studies revealed that a certain form of seaweed contains a high level of inorganic arsenic (Rose et al. 2007). Bedrock containing arsenic is primarily responsible to contaminate groundwater and this is a natural phenomenon which has been reported as leading cause of arsenic toxicity all over the world including Indo-Gangetic plain. Arsenic in drinking-water has caught attention since its discovery in the 1990s due to its wide occurrence in well-water in Bangladesh and parts of India (WHO 2001).

3 Metal Toxicities in Human and Experimental Animal

The detrimental effects of arsenic vary from individual to individual and by the body metabolism process. Soon after absorption, inorganic arsenic both arsenite and arsenate are methylated into MMA and DMA in the liver and are excreted through urine after passing through the kidneys along with unmethylated arsenic (Vahter 2002; De Loma et al 2018; Skröder et al. 2018). A relative proportion of metabolites in urine varies significantly within and among population groups. It has been reported by others that about 10–30% iAs (inorganic arsenic), 10 to 20% MMA and 60–80% DMA is excreted through urine (Hernandez and Marcos 2008; Huang et al. 2008; Gonzalez-Martinez et al. 2018). It was estimated that 50–70% of absorbed pentavalent arsenic (AsV) is rapidly reduced to trivalent arsenic (AsIII), a biotransformation reaction common in most species. In all experimental animals specifically rodents, DMA is the main metabolite excreted in urine. The proportion of methylation varies substantially between species, for example it has been reported that apes such as the marmoset monkey (Zaris) and chimpanzee do not methylate inorganic arsenic, on the other hand, the marmoset monkey accumulates arsenic in the liver (Zakharyan et al. 1996). The rat, has an effective methylation pattern of arsenic but the formed DMA gets collected in the red blood cells (Lu et al. 2007). Hence, rats have been shown to excrete lower levels of arsenic through urine. When human and rodents were exposed to DMA, it was found that about 5% of the dose is excreted through urine in the form of trimethylarsine oxide (TMAO) (Hughes et al. 2008). Similar studies conducted by other investigators found that when human subjects were exposed to quantified doses of inorganic arsenic their rate of excretion surges with the methylation effectiveness, moreover inter-individual variations were also noticed in the methylation of arsenic (Bailey et al. 2013). Recent studies on human subjects exposed to arsenic in northern Argentina have shown that they excrete low amounts of MMA, on the other hand, children showed a lesser grade of methylation of arsenic than adults (Concha et al. 1998; Vahter 2007).

4 Some Specific Aspects of Arsenic Toxicities

4.1 Genotoxicities

It has been stated by Dulout et al. (1996) that there was an surge in chromosomal aberrations in lymphocytes of people residing in north-western Argentina who consumed arsenic contaminated drinking water. Ghosh et al. (2006) conducted studies on 422 individuals from Haringhata and 24 Parganas (N) district of West Bengal, concluding that person showing skin-symptoms were more vulnerable to arsenic-induced toxicity and genotoxicity than those persons who do not show any symptoms of arsenic poisoning. Further, it has been stated that sodium arsenite treatment of rat ovarian cells results in DNA fragmentation (Akram et al. 2009). It was also revealed by other workers that children exposed to arsenic from early childhood had increased telomere length compared to children unexposed to arsenic (Chatterjee et al. 2018).

Arsenic is both genotoxic and carcinogenic to human and animals however it displayed tricky mutagenic potentials in bacterial systems. In bacterial system it induces DNA damage indirectly by inhibiting DNA repair mechanism. But the exact DNA repair inhibition mechanism could not be deciphered accurately (Samavarchi Tehrani et al. 2018). Rossman et al. (1977) had showed that arsenite supresses the post-replication repair pathway in *E. coli*. A similar study conducted by Lee-Chen et al. (1992) on UV irradiated Chinese hamster ovarian cells found that arsenite exerts its co-genotoxic consequence by preventing DNA repair mechanisms. By single cell gel (SCG) assay Hartmann and Speit (1996) noticed increased DNA damage in cells that were treated with sodium arsenite in various concentrations (from 200 to 1500 M) than the control culture. Similar experiments conducted by Schaumloffel and Gebel (1998), found that there was a significant induction of DNA damage when the cells were insulted with 0.01 M As (III). Further, when the frequency of micro-nucleated cells between people exposed to high concentration of arsenic in ground water (1312 g/L) was compared with low exposure to arsenic (16 g/L), it was found that there was a sudden elevation in the frequency of micronuclei in persons who drank high concentration of contaminated water when compared to lower groups Warner et al. (1994). Moreover, they were also assured that the incidence of micro nucleated bladder cells was certainly related with the urinary content and concentration of arsenic. It was also reported by the same group that frequencies of micronuclei containing acentric fragments and whole chromosomes also increased. Two cross sectional studies were conducted by Moore et al. (1997), in the states of Nevada and Chile to observe the association between arsenic ingestion and genetic damage in the urothelium and they concluded that amplified levels of arsenic in drinking water resulted in an increase in micro-nucleated cells in bladder.

4.2 Immunological Toxicities

It was earlier reported that low concentrations of iAs significantly repressed the action of macrophages and T lymphocytes (T cells), the two immune cell types involved in controlling infection and tumour development (Soto-Peña et al. 2006; Lemarie et al. 2006, 2008). As a carcinogenic environmental contaminant inorganic arsenic exerts immunosuppressive action on human T lymphocytes. A considerable reduction was found in interleukin-2 (IL2) secretion which is a cytokine and plays a pivotal role in immunology and also reduces T cell proliferation. It was revealed that in vivo, treatment of mice with iAs induced thymus atrophy caused by suppression of many genes which are involved in cell cycle advancement. Further, it also diminished in vitro proliferation of mitogen stimulated spleenocytes (Nohara et al. 2008; Soto-Peña and Vega 2008). Interleukin 2 (IL2) plays a big role in instigation of T-cells and progression through cell cycle. iAs-dependant inhibition of peripheral T cell proliferation was generally accompanied by repression of interleukin-2 (IL2) exudation (Lemarie et al. 2006, 2008), decreased adhesion of macrophages, reduced production of nitric oxide (NO) and dwindling chemotactic and phagocytotic indices (Sengupta and Bishayi 2002; Bishayi and Sengupta 2003, 2006). It was reported that people living in areas having groundwater arsenic contaminated by arsenic had increased antinuclear antibodies (ANA) compared to normal subjects (Belon et al. 2006). Several investigators have proved earlier that arsenic traverses the placental barrier, posing a threat to the normal development of the foetus (Rahman et al. 2009; Ferrario et al. 2009). A study in Bangladesh revealed that arsenic exposure during pregnancy was co-related with increased placental inflammatory reactions, diminished placental T cells, and altered cord blood cytokines. The findings of this study recommended unfavorable effects of arsenic on immunobiology that leads to weakened new-born function (Ferrario et al. 2009). Macrophages plays a vital role in immunological functions, it has been investigated that persons residing in ground water contaminated areas showed circularization of macrophages, diminished cellular adhesion, decreased phagocytic activity and expression of proteins such as CD54 compared to those living in arsenic free areas (Lemarie et al. 2006; Banerjee et al. 2009). Some also reported that the ratio of CD4/CD8 decreased when exposed to iAs, which could indicate immune suppression (Soto-Peña and Vega 2008). Arsenic also inhibit mitogen stimulated proliferation of SMC (Splenic mononuclear cells) and PBMC (Peripheral blood mononuclear cells) in broiler chickens. In some investigations with cat fish, it has been revealed that there was a general increase in the population of lymphocytes and a sudden decrease in IL4 when contaminated with arsenic (Ghosh et al. 2007a, b). This group also detected that arsenic inhibits humoral immunity by supressing primary and secondary antibody forming cells. Further, it was also stated that arsenic suppressed type IV hypersensitivity, (a delayed type of response to cutaneous sensitization) in mice, rats and chicken (Savabiesfahani et al. 1998, Patterson et al. 2004; Aggarwal et al. 2008).

4.3 Carcinogenicity

Investigators stated that dimethylarsinic acid (DMA V) administration to rats promoted for tumor development in various organs (Yamamoto 1995). Further, it was also observed that when mice were treated with arsenic at a concentration of 10 and 25 ppm in drinking water it resulted in formation of papilloma and carcinoma respectively and this was due to augmented proliferation of cells. Arsenic induces DNA damage, produces (ROS)/free radicals which modifies the expression of protein p21 and p53, which are regarded as tumour suppressors. Further, DMMTA (V) caused diminished protein expression of tumor suppressor along with enhanced damage of DNA and production of ROS (reactive oxygen species). Investigators reported a plausible association between incidence of prostate cancer and exposure to high concentrations of arsenic (Lin et al. 2013). But the link between exposure to low concentrations of arsenic and the onset of prostate cancer is unclear, and needs more epidemiological research. Investigation of pregnant mothers exposed to arsenic resulted in leukaemia which was reported by Heck et al. (2014). Recently, results of a 20-year retrospective cohort study on hepatocarcinogenesis involving 802 males and 301 females members belonging to 138 communities in Taiwan revealed significant increase in hepatocarcinogenesis in both genders after exposure to arsenic concentration above 0.64 mg/L. However, the same group also reported no significant changes which were lower than 0.64 mg/L (Baastrup et al. 2008). There are a few contradictory reports where investigators found no connection between occurence of bladder cancer even after exposure to low concentrations of arsenic and smoking (Meliker et al. 2010). Further confirmation in this area is needed as the group has incapacity to accurately measure smoking and correctly measure arsenic exposure levels. On the other hand, few groups also reported that ground water intake elevates bladder cancer incidence in a population-based study in New England (Zolot 2016). The reason for high rates of urinary bladder cancer might be attributed to hindrance/impediment of the detoxification process, thereby inhibiting repair mechanism of DNA and reduced essential nutrients levels.

4.4 Endocrine Effects

It was also reported that presence of arsenic in air was responsible for greater incidence in breast cancer (Khanjani et al 2017). Further, the same group has reported that emissions of arsenic, lead, and mercury were linked to the prevalence of estrogen receptor (ER)-positive breast cancer (Vu et al. 2019). The gonadal endocrine system plays a vital in regulating human reproductive behaviour. Investigation by earlier researchers showed that arsenic accumulates in the gonadal tissues and induces profound inhibitory effect on the development of the gonads (Zarooogian and Hoffman 1982; Shukla and Pandey 1985). Few other investigators reported that arsenic interacts with few sex hormones and causes inhibition of ovarian steroidogenesis, spermatogenesis and also impairs testicular function (Chattopadhyay et al. 1999, 2003; Zadorozhnaja et al. 2000; da Silva et al. 2017). Arsenic have also reported to have negative effects on semen quality and quantity in males (Kim and Kim 2015) in addition to inducing menarcheal age and abortions in females (Milton et al. 2005; Sen and Chaudhuri 2008). Chow et al. (2004) reported that after a 48 h exposure to 150 μg/L of AsIII transcription of ERα was repressed while AsIII did not compete with estradiol. Subsequent studies also revealed that AsIII caused immense toxicity in estrogen production by interfering with signalling pathways (Watson and Yager 2007). It was also known that AsIII had a high affinity to the sulfhydryl groups of proteins with the formation of stable cyclic thio-arsenite complexes thereby leading to glucocorticoid dysfunction and blocking of steroids from binding to glucocorticoids. Further studies on the thyroid hormone of fish revealed that 78 hours exposure to arsenic amplified thyroxine hormone levels in fish larvae. Sun et al. (2017) found that thyroxine levels in mice, rats increased by 18% on exposure to 50 mg/L AsIII for 10 days. Allen and Rana (2007) reported that treatment of rats with 40 mg per kg of AsIII enhanced the thyroxine content from 20.1 to 52.0 nmol/L. They concluded that rodents toughened their metabolism process by elevating thyroxine levels, resulting in more removal of arsenic from their bodies. This hypothesis was substantiated by another search which reported elevated levels of thyroxine stimulated arsenic excretion through urine in rats (Rana and Allen 2006). Other workers also observed that raised levels of thyroxine modulated rat immune systems, thereby lessening the unfavorable effects of contaminants by increasing the levels of thyroxine which in turn helps to decrease the body load of arsenic (Lam et al. 2005).

4.5 Neurogenic Effects

Arsenicals are known to harshly affect the nervous system. Long-lasting exposure to arsenicals is linked to developmental neurotoxicity, neurological complications and gradual weakening of cognitive progress, learning and reminiscence (Vahidnia et al. 2007; Tolins et al 2014). Astrocytes are macroglial cells in central nervous system (CNS) derived from progenitor cells in the neuroepithelium that help form the brain's physical structures. Astrocyes are involved in the exudation or absorption of neural transmitters and maintain the blood–brain barrier, populate the grey and white matter of the brain and spine in addition to maintaining the homeostasis of CNS (Abbot et al. 2006). Arsenicals saturate the blood–brain barrier and astrocytes are the first to counter them in the brain. Because of their strategical significant localization and high detoxification potential, astrocytes are the first line of defence against toxins which enters the brain (Dringen et al. 2016). Arsenic prevents alteration of pyruvate to acetyl coenzyme A thereby blocking the Krebs cycle and inducing neuropathy (Bjørklund et al 2020). The Agency for Toxic Substances and Disease Registry (2007) reported that Japanese kids who consumed arsenic-contaminated milk showed increased perceptive deficits, epilepsy and severe hearing loss.

4.6 Gastrointestinal Effects

Lee and Kissel (1995) stated that intake of 80 mg/kg of organic arsenicals lead to queasiness, abdominal ache, hyperactive bowel and diarrhoea and concluded that the gastrointestinal tract was the target for noxiousness following oral administration of MMA. Further investigations showed that feeding of MMA at a concentration of 72.4 mg/kg/day created pathophysiological situations in the large intestine and an upsurge in squamous metaplasia of the epithelial columnar absorptive cells in colon and rectum. Squamous metaplasia was described to exist in the colon of mice when chronically exposed to 67 mg MMA/kg per day (Gur et al. 1991; Arnold et al. 2003).Clinical manifestation of gastrointestinal irritation, like nausea, diarrhoea and occasional abdominal pain, were noticed/reported in all cases of chronic ground water arsenic contamination (Vantroyen et al. 2004; Belon et al. 2007). Chiocchetti et al. (2019a, b) described that exposure to arsenic III and V lead to production of ROS (reactive oxygen species) which thereby augmented the release of IL-8. ROS generated interfere with the proteins in tight junctions such as claudin, occluding and resulting in barrier function loss of the intestinal epithelium. Clinical investigation also established liver damage (Liu et al. 2002) and blood tests revealed elevated levels of hepatic enzymes after arsenic contamination (Belon et al. 2007; Khuda-Bukhsh et al. 2011). Histological observation of the livers of human exposed to ground water arsenic contamination revealed hepatic portal fibrosis (Mazumder 2005). Also chronic exposure to arsenic caused cirrhosis, a secondary effect of damage to the hepatic blood vessels.

4.7 Musculoskeletal Effects

Arsenic trioxide is often used to treat patients with cancer like promyelocytic leukaemia but clinical use of As_2O_3 has been restricted due to increased ill effects such as cardiotoxicity (Vinetha and Raghu 2019). Investigations on the muscle of tail of King prawn (*Penaeus latisulcatus*) revealed presence of arseno-betaine which is a water-soluble arsenic constituent. (Maher 1985; Francesconi and Edmonds 1987). It was also reported that As_2O_3 inhibits myogenic differentiation by inhibiting Akt-regulated signalling (Yen et al. 2010), inducing long-term muscle mitochondrial dysfunction and impaired metabolism (Ambrosio et al. 2014).

4.8 Cardiovascular Effects

High arsenic concentration in drinking water is associated with an increased prevalence of stroke. However, there are contradictory reports on the association between low concentration of arsenic in water and stroke. Ersbøll et al. (2018) conducted a study by taking into consideration 57,053 individuals from two major cities in Denmark. He found that 2195 individuals had incidence of stroke. The results proposed that the presence of arsenic even in small concentration in drinking water instigated high rate of stroke. Similar results were also revealed by another study conducted by the same group which concluded that there could be some association between the risk of myocardial infarction and low concentration of arsenic in drinking water (Milton et al. 2017; Monrad et al. 2017). Other investigators reported that chronic exposure to low-level iAs (inorganic arsenic) in drinking water was linked with amplified risk of coronary disease (James et al. 2015; Wade et al. 2015; Moon et al 2017). It is thus established that people with the highest concentration of arsenic in urine are more prone to cardiovascular disease compared to a population with low concentration of arsenic in urine.

4.9 Dermal Effects

There are several reports on the carcinogenicity of arsenic carried out in numerous countries such as Argentina, India, Taiwan, Bangladesh and Chile,where drinking water holds more than 150 ppb of arsenic (IARC 2012).

An investigation conducted by Haque et al. (2003) stated that ground water contaminated with high levels of arsenic induces skin cancer but this study was limited to few districts of West Bengal. Few external changes of chronic exposure observed through naked eyes includes pigment changes on the skin, hyperkeratosis, hyperpigmentation and patchy hyperpigmentation which may lead to malignancy. Mee's lines which crisscrosses the nails are effects of severe or long term exposure to arsenic (Sharma et al. 2016). Patchy hyperpigmentation is commonly visible in axillae, groin, nipples, temples and neck (Dastgiri et al. 2010). "Rain Drop syndrome" which is the appearance of dark brown patches present over the chest, back, and abdomen has often been visible in inhabitants who regularly consumed 400 μg/L or more arsenic in drinking water (ATSDR 2007).

4.10 Metabolic Effects

Sattar et al. (2016) investigated arsenic's influence on the disintegration of carbohydrates and the enzymes that participates in carbohydrate breakdown and glucose homeostasis. Once arsenic enters a mammalian body it is gathered in the liver, kidney and pancreas and shows detrimental effects on glucogenesis, gluconeogenesis by alterating and weakening the key enzymes involved in metabolism. Variation of hepatic glucose homeostasis has a major role in the pathobiology of diabetes. It is known fact that organisms have developed a complex system for the interaction of enzymes such as, Superoxide dismutase (SOD), Glutathione-s-tranferase (GST), catalase and myeloperoxidase. These enzymes are involved in the counteraction of both endogenous and exogenous oxidative stress. This array of Phase I and Phase II enzymes work stepwise to maintain a low ROS levels in the body (Wang et al. 1997; Banerjee et al. 2010). These investigators studied the effects of arsenic exposure on the human population from Murshidabad district and the concomitant levels of both enzymes. They reported that the activity of both enzymes was appreciably high in subjects exposed to arsenic compared to normal populations. They concluded that chronic arsenic exposure augmented the activity of serum catalase and myeloperoxidase due to which ROS activity increased thereby resulting in a huge amounts of DNA damage. Other investigators evaluated the association between arsenic exposure and antioxidant enzyme defence and oxidative stress in aquatic vertebrates i.e. *Salmo trutta*, and their investigation concluded that arsenic bioaccumulation induced lipid peroxidation and interfered with the antioxidant defence system (Greani et al. 2017).

4.11 Hematologic Effects of Arsenic

Severe or chronic arsenic intoxication leads to bone marrow depression which is manifested as pancytopenia initially. People suffering from arsenicosis often suffer from anaemia, eosinophila, leukopenia and thrombocytopenia. The above finding indicates that most studies were conducted on rural populations in India and Bangladesh who have low socioeconomic status. The anaemia varies from a normocytic or macrocytic condition with basophilic stippling being located on peripheral blood smears (Kyle and Pearse 1965; Selzer and Ancel 1983; Heck et al. 2008). It was reported by different agencies that chronic arsenic exposure or acute exposure to gaseous form of arsenic i.e. arsine gas causes intravascular haemolysis. (NRC 2000, 2001; IARC 2004).

5 Effects on Plants

Arsenic contamination hinder critical biochemical and metabolic progressions that results in plant death. A significant reduction in plant height was noticed with increasing arsenic loads in irrigation water (Majumder et al. 2019). Arsenic exposed seedlings of *Cicer arietinum* and *Oryza sativa* revealed remarkable stunted growth of roots and shoots (Malik et al. 2011; Vromman et al. 2013). Arsenic also suppresses the quantity of leaves, leaf surface area, and the fresh and dry mass of plants. Arsenic also induces chromatid and chromosomal aberrations in plants (Wu et al. 2010; Ghiani et al. 2014; Aksakal and Esin 2015) in addition to an increase in the occurrence of micro-nuclei in peripheral root tip cells of both *Zea mays* and *Vicia faba* (Duquesnoy et al. 2010).

6 Arsenic Mitigation and Management

Though arsenic calamity was reported in the early eighties true mitigation progressed slowly (Johnston et al. 2014) and hence the burden on public health remains very high. Flanagan et al. (2012) estimated that arsenic contamination alone could affect 19–20 thousand people annually in Bangladesh at >50 μg/L concentration levels. In a situation of very inadequate mitigation success, the challenge is to improve, enhance, develop and boost a sustainable and economic option that the public can adopt, install and maintain themselves. There are two main methods to eliminate arsenic from the water; one, to find an alternative source of arsenic free water and two,removal of arsenic from water through use of chemicals. It is known that water from deep wells with depths of more than 200 m is arsenic-free but what limits this process is the expense involved drawing it which most communities cannot afford. A few months after installation high amounts of metals like Mn and Fe often can cause intolerable taste and stains leading to discontinuation. Another option is the introduction of surface water bodies such as ponds and rivers after antimicrobial treatment which is also expensive and not feasible under certain climatic conditions (during rainy season). Rainwater harvesting can be implemented in areas known for arsenic contaminated ground water. A critical limitations to implementing rain water harvesting is the high installation cost and inequal rainfall over the year (Ahmed and Rahman 2003; Islam et al. 2011). Removal of arsenic by adsorption is considered a suitable option due to its simple operational procedure, less costs, sludge free operation, and regeneration and reusability of the adsorbents. Orthodox medicines such as di-mercapto succinic acid (DMSA), diethylene triamine pentaacetic acid (DTPA) and British Anti Lewisite (BAL) have been ineffective so far to treat patients suffering from arsenicosis, further they have a fluctuating efficacy and harmful side effects, hence there is a necessity for alternative agents which are cheap and can easily be procured by common masses (Chou et al. 2002; Belon et al. 2007; Biswas et al. 2019). People living in the ground water contaminated areas should be made aware to take nutritional diets with high amounts of folate, antioxidant and proteins. This natural silent calamity in the Indo-Gangetic plain especially in the region of Bengal and Bangladesh requires a sustainable solution.

7 Conclusion

Of all the heavy metal poisonings arsenic poisoning has received prominent attention especially in the Indo-Gangetic plain. Toxicity reports of arsenic are well documented and numerous molecular and cellular mechanisms have been proposed to explain arsenic's toxicological profile. To avoid risk it is recommended that people living in arsenic contaminated ground water areas undergo regular check-ups for arsenic levels in their blood and urine. Parents should educate their children to make them aware of arsenic-related toxicity and treatment strategies (which at times may not be effective due to the genetic makeup of individual, environmental factors and diet). The review summarizes the various aspects of arsenic toxicity is intended to serve as a reference to researchers involved in elucidating mechanism of toxicity and is intended to serve as a refrence for researchers involved in studying the mechanism of arsenic toxicity, provide results for the betterment of human-kind and conservation of biodiversity.

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Evaluation of Ground Water Quality by Use of Water Quality Index in the Vicinity of the Rajaji National Park Haridwar, Uttarakhand, India

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Abstract The research area is a heavy tourist occupied place due to the presence of various scared and adventures spots. The present study refers to the assessment of groundwater quality of five different sites demarcated in Haridwar district. Water samples were collected for three consecutive years (2017–2019) to test physicochemical parameters for tap water and hand pump water in the vicinity of a national park. The water quality index (WQI) was proposed on huge data set for the evaluation of quality status. The yearly index value was found 3.69, 3.72 and 4.32 respectively whereas, for all five sites index values were 3.62, 4.38, 4.24, 3.99 and 3.47 respectively, which indicated the groundwater quality was in very good condition (as WQI < 25). The observed values of major parameters were recorded under the permissible limits of governmental agencies, except the alkalinity (>200 mg/L) and hardness (200 mg/L). Therefore, it is suggested that the groundwater quality should be regularly monitored so that the risk of any contamination can be detected and treated before drinking and irrigation purposes.

Keywords Groundwater water quality index (WQI) · Haridwar · Pollution status · Water quality

1 Introduction

Water is the prominent blessing of mother earth for humans and other organism living on this planet (Chidambaram et al. 2010). More than 600 billion m^3 of water

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is consumed annually by Indians. Of that quantity, 245 billion m^3 are drawn as groundwater source. According to world bank, India is more dependent on groundwater than any other country which accounts for about one fourth part of world's demand. In India, more than 90% of groundwater is used for irrigation purpose. About 80% of residents of India depends on groundwater for both irrigation and drinking (Schneider 2018). But due to the untreated effluents from agricultural and industrial development, rapid urbanization, expanding population, wastewater runoff and poor sanitation, the quality and quantity of groundwater resources have drastically reduced (Anantha and Chandarkanta 2014; Matta et al. 2016a; Ray et al. 2017;). Therefore, the deterioration in groundwater quality has become major issue for arid and semi-arid regions (Carballo et al. 2016; Li et al. 2017). Many of the studies have been conducted on groundwater quality evaluation around the world (Joardar et al. 2008; Adhikary et al. 2010; Ketata et al. 2012; Prasad et al. 2014; Viswanath et al. 2015; Mora et al. 2017; Kumar et al. 2019).

It is one of the most significant compounds that significantly impact life. Groundwater is utilized for household and industrial water supply and furthermore for irrigation purposes in everywhere throughout the world. In the past few decades, there has been a huge increase in the demand for freshwater because of the rapid development of population and the quickened pace of industrialization. As indicated by the WHO organization, about 80% of the considerable number of diseases in people are caused by water.

Everybody required safe and clean water but in present era our freshwater resources becoming polluted day by day due to anthropogenic and natural reasons. Industrial effluent is also affecting groundwater quality (Matta et al. 2014). Increasing in chlorides, nitrates and heavy metals could be due to industrial effluents (Matta et al. 2015). A study revealed that heavy metal contamination in water poses a serious threat to human health (Waseem et al. 2014). Dissolved bicarbonates and carbonate, presence of microorganisms could be the threats for human health and animals, to keep groundwater safe from these impurities proper landfilling and more efficient treatment of industrial effluent is required (Matta et al. 2016b).

If we talk about the causes of water pollution, industrial effluents come among major sources of water pollution (Matta et al. 2018b). Different kind of industries effluent contains different types of contaminants at a different concentration which distract the cycle of life of living things in a different way. Like other industries, the sugar industry has a large share in term of effluent discharge, in study surrounding the sugar mills area groundwater has become polluted due to its effluent discharge (Matta et al. 2016a). This is observed that untreated domestic waste, commercial waste, tourism activity and other activity like washing clothes by using soaps are the anthropogenic source of surface water pollution in hilly areas (Matta and Kumar 2017a). The concentration of cations like calcium as Ca^{++} and magnesium as Mg^{2+} in groundwater could be due to dissolution of minerals from aquifers (Kamboj et al. 2017). The water quality in monsoon seasons is not good in comparison to winter and summer seasons (Matta et al. 2018a). The concentration of heavy metals such as Pb, Mn, Fe, Cu and Co in surface water could be due to the processing of ore and rocks weathering in concern area (Matta et al. 2018b). The huge gathering of humans (their activity like bathing and washing of clothes in the river water) at any religious activity at the bank of the river could lead to downstream water pollution (Matta et al. 2018c).

To get the overcome from such problems which spreading pollution in our environment could be easy by circulating awareness regarding such source of pollution among the public through scientific communication about health and hygiene, water hygiene and how to conserve the environment by a public meeting, hanging holdings etc. (Matta and Kumar 2017b). Depleting the quality of freshwater sources poses a significant threat to human health worldwide, the consequences of consuming poor-quality water leading to the degradation of human health (Matta et al. 2017a, 2018c). Therefore, before groundwater quality of any area become worse, continues monitoring and proper strategy has become utmost important. Thus, this paper integrates the analysis and spatial visualization of the collected water samples and at the same time uses the water quality index method to evaluate the groundwater quality.

2 Methods and Material

2.1 Research Area

The study area encompasses the Shivaliks, rich in biodiversity, center of attraction for nature lover and wildlife activist and near the foothills of Himalayas in the Uttarakhand state of India. Motichur, Chilla and Rajaji national park are three wildlife santuries and spread over the Haridwar and Dehradun district of Uttarakhand. The climate of the area is dry throughout the year but during monsoon season it becomes raging torrents. The selected sampling locations are dissected by the Ganges River (Fig. 1). The geocordinates of monitoring locations are given in Table 1.

2.2 Collection of Groundwater Samples and Anlysis

The groundwater samples were collected for three year of period (from January 2017 to June 2019) for physico-chemical anlysis. A Total of 90 water samples were taken bimonthly from hand pumps and taps located in selected monitoring locations. Water samples were preserved in an ice bucket by maintain its temperature upto 4 °C. The analysis was performed as per standard protocols recommended by the American Public health Association (APHA 2012). The water parameters like pH (hydrogen potential) and DO (dissolved oxygen) were monitored in-situ by the a multiparameter potable digital iinstrument of HACH (model: HQ40D) made from Germany. The chemical parameter such as BOD (biochemical oxygen demand), TS (total solids), TDS (total dissolved solids), TSS (total suspended solids), toal alkalinity, acidity and potassium were messured in the loboratory.

Fig. 1 Location map of the research area indicating monitoring locations

Table 1 Details of sampling sites at different locations with coordinates

S. No.	Sampling sites	Coordinates
1	Motichur Railway Station	29°58′51.1″N 78°10′38.8″E
2	Chilla Range	30°01′24.7″N 78°15′48.1″E
3	ShyampurKangri	29°52′00.6″N 78°11′06.7″E
4	Rajaji National Park, BHEL, Haridwar	29°58′10.6″N 78°06′25.8″E
5	Roshnabad	29°58′06.1″N 78°02′39.5″E

2.2.1 Water Quality Index (WQI)

As indicated by Tiwari and Mishra (1985) water quality index is an extremely helpful and compelling device to delineate the general water quality. To assess the suitability of the groundwater for drinking purposes, WQI is determined by the accompanying technique which is utilized in many research works (Ramachandramoorthy et al. 2010; Srivastava et al. 2011).

The WQI computation is expressed as follows:

$$\mathrm{WQI} = \mathrm{antilog} \sum_{i=1}^{n} w_i \log q_i \tag{1}$$

quality rating (q_i) is computed as follows:

$$q_i = \left\{ \frac{(V_a - V_i)}{(V_s - V_i)} \right\} \times 100 \quad (2)$$

V_a actual measured concentration of the ith parameter
V_i 7 for pH and 0 for other parameters
V_s water quality standard value of ith parameter.

For getting weight (w_i) values, the expression is followed as below:

$$W_i = \frac{k}{S_i} \quad (3)$$

where, k = proportionality constant and expressedas:

$$k = \frac{1}{\sum \frac{1}{S_i}} \quad (4)$$

3 Result and Discussion

The summary of physico-chemical determinants of groundwater at site 1 (Motichur Railway Station), site 2 (Chilla Range), site 3 (ShyampurKangri) site 4 (Rajaji National Park, BHEL, Haridwar), site 5 (Roshnabad) sampling locations are appended in Table 2.

3.1 pH

pH shows the hydrogen potential. The mean pH concentration is observed within the range prescribed by national agencies (Bureau of Indian Standards: BIS 2012 and Centeral Pollution Control Board: CPCB 2017) throughout the study period (Table 2). In the year 2017, the pH values were in range 7.06–7.25, where the maximum pH was recorded to be 7.25 at site-5. In the year 2018, the pH values were in the range of 7.45–8.05. The lowest value was measured at site 3, whereas the highest value was found to be 8.05 at site-5 and the year of 2019, the maximum pH concentration was recorded 7.54 at site-5 and the minimum concentration of pH was recorded 6.35 at site 4. According to standards, the limit of pH value for drinking water is specified as 6.5 to 8.5. pH is one of the most important parameter of the water quality in our aquatic system and the extent of pollution in the watershed areas (Kumar et al. 2011).

Table 2 Variation in hydro-chemical properties of groundwater for the year 2017

Sites	pH	D.O (mg/l)	B.O.D (mg/l)	T.S (mg/l)	TDS (mg/l)	TSS (mg/l)	Total alkalinity (mg/l)	Total hardness (mg/l)	Acidity (mg/l)	Potassium (mg/l)
Site-1	7.06	5.16	3.00	313.56	297.60	15.96	236.80	460.00	57.50	0.85
Site-2	7.25	4.76	1.20	319.54	308.20	12.14	231.00	380.00	57.50	0.66
Site-3	7.37	3.78	1.60	351.48	336.00	15.48	192.00	500.00	42.50	0.26
Site-4	7.35	6.10	2.30	650.00	387.50	262.50	320.00	260.00	30.00	0.77
Site-5	7.25	7.00	1.40	500.00	383.50	116.50	418.00	280.00	80.00	1.36
Mean	7.26	5.36	1.90	426.92	342.56	84.52	279.56	376.00	53.50	0.78
SD	0.12	1.24	0.74	145.93	41.66	108.86	90.35	106.21	18.76	0.40
CV	0.02	0.23	0.39	0.34	0.12	1.29	0.32	0.28	0.35	0.51
BIS	6.5–8.5	–	–	–	500	–	200	200	–	–
CPCB	6.5–8.5	>6	2	–	–	–	–	–	–	–

3.2 DO

In the year of 2017, the minimum values of DO was reported at monitoring location 5 (7 mg/l) and the maximum concentration of DO was 5.16 mg/l at site 1. In the year of 2018, DO values were in range 6.1–6.8 and the maximum values of DO was noticed 6.8 mg/l at site 1 whereas, the minimum values of DO was observed at site 5. The concentration of DO affects the groundwater quality substantially. It controls the ionic form of dissolved metals in water and confines bacterial metabolic process of dissolved organic matter in water (Rose and Long 1988). In the year of 2019, the minimum concentrations of DO were found 5.65 at site 2 and the maximum concentration of DO was found 6.55 at site 4.

3.3 BOD

In the year of 2017 BOD values were in range 1.2–3. The maximum and minimum values of BOD were 3 mg/l at site 1 and 1.2 mg/l at site 2. In the year of 2018, the minimum concentration of BOD was 1 mg/l at site 2 and the maximum level was 1.8 mg/l at site 5. Commonly, the maximum concentration of BOD affects the the human health. In the year 2019, the concentration of BOD was in the range of 0.4–1.25 mg/l (Table 3).

3.4 TS, TDS and TSS

Total solids represent the residue obtained after evaporation at 103–105 °C. In the year of 2017, 2018 and 2019 the concentration of TS was found in range 313.56–650 mg/l, 420–510 mg/l, 322.5–800 mg/l. TDS are naturally present in water or are the results of some anthropogenic activities like mining or some industrial treatment of wastewater. TDS in water mostly composed of many salts like, organic matter, calcium, potassium, sodium and other major particles (Hasan and Miah 2014; Bhadula et al. 2014). During this study, in the year 2017, 2018 and 2019 the values of TDS were found in a range 297.6–387.5 mg/l, 339–387.5 mg/l and 277–412 mg/l. TSS of > 1 μm restrict the light to penetrate into water and deposits in river bed in the form of sediments. In the year of 2017, 2018 and 2019 the concentration of TSS were found in range 12.14–261.5 mg/l, 46–131 mg/l and 31.5–388 mg/l (Table 4).

Table 3 Variation in hydro-chemical properties of groundwater for the year 2018

Sites	pH	D.O (mg/l)	B.O.D (mg/l)	T.S (mg/l)	TDS (mg/l)	TSS (mg/l)	Total alkalinity (mg/l)	Total hardness (mg/l)	Acidity (mg/l)	Potassium (mg/l)
Site-1	7.71	6.80	1.70	510.00	364.00	79.00	400.00	560.00	80.00	0.93
Site-2	7.68	6.50	1.00	420.00	355.00	64.50	375.00	360.00	90.00	1.12
Site-3	7.45	6.15	1.05	470.00	339.00	131.00	550.00	480.00	92.00	0.00
Site-4	7.62	5.75	1.30	440.50	387.50	46.00	650.00	260.00	45.00	1.00
Site-5	8.05	6.10	1.80	430.50	362.00	69.00	450.00	290.00	100.00	1.37
Mean	7.70	6.26	1.37	454.20	361.50	77.90	485.00	390.00	81.40	0.88
SD	0.22	0.40	0.37	36.34	17.54	32.00	114.02	127.28	21.56	0.52
CV	0.03	0.06	0.27	0.08	0.05	0.41	0.24	0.33	0.26	0.59
BIS	6.5–8.5	–	–	–	500	–	200	200	–	–
CPCB	6.5–8.5	>6	2	–	–	–	–	–	–	–

Table 4 Variation in hydro-chemical properties of groundwater for the year 2019

Sites	pH	D.O (mg/l)	B.O.D (mg/l)	T.S (mg/l)	TDS (mg/l)	TSS (mg/l)	Total alkalinity (mg/l)	Total hardness (mg/l)	Acidity (mg/l)	Potassium (mg/l)
Site-1	7.15	6.50	0.95	322.50	291.00	31.50	395.00	480.00	75.00	1.19
Site-2	7.40	5.65	0.40	394.00	342.50	51.50	400.00	280.00	32.50	0.68
Site-3	7.34	5.75	0.40	390.00	337.00	53.00	600.00	440.00	87.50	0.00
Site-4	6.35	6.55	1.25	657.50	277.00	380.50	650.00	300.00	32.50	0.95
Site-5	7.54	6.40	2.60	800.00	412.00	388.00	450.00	280.00	60.00	1.21
Mean	7.16	6.17	1.12	512.80	331.90	180.90	499.00	356.00	57.50	0.80
SD	0.47	0.43	0.90	205.44	53.01	185.85	118.34	96.33	24.81	0.50
CV	0.07	0.07	0.81	0.40	0.16	1.03	0.24	0.27	0.43	0.62
BIS	6.5–8.5	–	–	–	500	–	200	200	–	–
CPCB	6.5–8.5	>6	2	–	–	–	–	–	–	–

3.5 Total Alkalinity and Total Hardness

The results in the years 2017, 2018 and 2019 for the concentration of total hardness was found 260–500 mg/l, 260–60 mg/l and 280–480 mg/l and the total alkalinity of water was found 192–418 mg/l, 375–650 mg/l and 395–650 mg/l in the year of 2017, 2018 and 2019.

3.6 Acidity

Acidity is also one of the most important parameter to evaluate the quality of water. Dissolved CO_2 is the important and main factor which is responsible for acidity in unpolluted water. In the study area, the minimum and maximum values of acidity were found as (30–80 mg/l, 45–100 mg/l and 32–87.5 mg/l in the year of 2017, 2018 and 2019, respectively. In unsaturated zone, different natural procedures like nitrification, base-cation take-up by vegetation, natural corrosive generation in rotting vegetation and oxidation of decreased types of sulphur influence the groundwater creation, in this way expanding the acridity of permeating water (Reuss et al. 1987).

3.7 Potassium

Patassium comes into the water from weathering of transformative and igneous rocks. Evaporate deposits of sulfates and gypsum discharge includes an impressive measure of potassium into groundwater. Agricultural activities are major reason for potassium concentration into groundwater (Ramesh and Thirumangai 2014; Sayyed and Bhosle 2011). During the present study in the year 2017, the maximum concentration of potassium was found 1.36 mg/l at site 5 and the minimum concentration was found 0.26 mg/l at site 3. In the year 2018, the maximum values of potassium were found 1.37 mg/l at site 4 and the minimum value of potassium was 0.93 mg/l at site 1. In the year 2019, the values of potassium were found in the range of (0.68–1.205). The variation in correlation on variance is represented in Fig. 2.

3.8 WQI Interpretation

The calculation process of WQI for 3-year data and for each monitoring location is represented in Table 5. With due respect of calculated WQI, the excellent quality of groundwater samples (WQI < 25) during the study period is observed as 3.69, 3.72 and 4.32, respectively (Table 6). Similarly, the index value for each sampling site was observed under the excellent condition (Table 7). Khanna (2016) assessed the

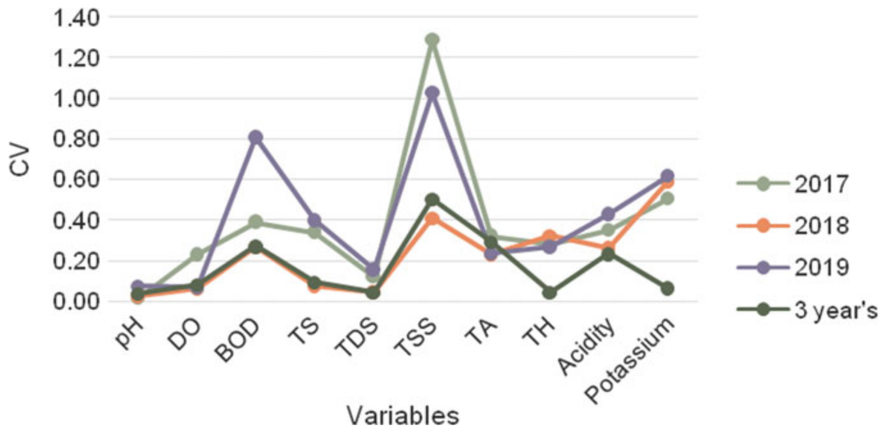

Fig. 2 Yearly variation in the correlation of variance (CV)

Table 5 Calculation process of WQI for each site and year

Parameters	Va	Vs	wi	qi	WQI
pH	7.61	6.5–8.5	0.15	40.67	3.47
DO	6.50	6.00	0.21	108.33	
BOD	1.93	2.00	0.63	96.50	
TDS	576.83	500.00	0.00	115.37	
Alkalinity	439.33	200.00	0.01	219.67	
Hardness	283.33	200.00	0.01	141.67	
$\sum w_i = 1$					

Table 6 WQI values for repective years

Year	2017	2018	2019
WQI	3.69	3.72	4.32
Quality	Excellent	Excellent	Excellent

Table 7 Groundwater quality on all 5 sites according to WQI throughout the study period

Sites	Site-1	Site-2	Site-3	Site-4	Site-5
WQI	3.62	4.38	4.24	3.99	3.47
Quality	Excellent	Excellent	Excellent	Excellent	Excellent

groundwater quality on the basis of WQI and reported the overall quality class in good condition and suitable for domestic use.

4 Conclusion

The applicability of quality index can be considered as important because the water resources are important for the development of a better society. On the basis of analytical results attained, water quality index is used to evaluate the groundwater quality of the research area. In this work, it is concluded that the proposed WQI is very informative for regular monitoring of groundwater quality. The applied WQI clearly categorized the quality class of water samples collected during the years 2017–2019. It is interpreted from the results that the water quality of selected monitoring stations is in excellent condition (WQI < 25) and found acceptable for drinking and domestic purposes throughout the study period but at the same time water samples were reported in alkaline and hard in nature. Therefore, long-term monitoring and assessment of groundwater quality are recommended to the study area.

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Assessment of Groundwater Resource Pollution in Kangsabati River Basin, Paschim Medinipur, West Bengal, India

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Abstract Assessment of the groundwater quality of the Kangsabati river basin confined with both agricultural and arid parts reside at Paschim Medinipur, West Bengal, India. Total 50 water samples were analyzed for studying the three different major seasons. Then the collected samples from the river basin were studied for electrical conductivity, TDS, pH, and major cations like sodium, calcium, potassium, magnesium as well as anions like carbonate, bicarbonate, chloride, nitrate and sulphate (followed by the American Public Health Association's protocol). The specified locations were selected to cover the whole study area and specific consideration was given to the region where contamination is expected. The usual groundwater contaminants were nitrate, chloride, TDS, Na and K elements. The results were assessed in relation to the drinking water quality standardized by the World Health Organization. To find out the precise distribution pattern of the concentration of different elements and targeted to differentiate the higher pollutants concentration, multiple statistical approaches also carried out, discussed, and presented in zone-based classification. Though the polluted areas in this are surveyed out but groundwater of Kangsabati river basin will be managed by applying the proper management practices.

Keywords Groundwater · Quality assessment · Kangsabati river basin · Physico-chemicals parameters · Pollution

1 Introduction

Groundwater is a fundamental wellspring of freshwater gracefully on the planet; it is the main inexhaustible water asset in dry locales (Famiglietti 2014). Therefore,

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sustainability of groundwater resources is thought to be significance in both fertile and semi-arid areas where water is a critical social and economical significance on global aspect. The variation of ions which are dissolved in groundwater is mostly run by the velocity, groundwater flow, salts' solubility, lithology, the phenomenon of geochemical reactions, local aquatic bodies and human activities (Ahmed et al. 2013).

The hydro-geochemical progression facilitate in getting near into the contributions of rock-water interface and anthropogenic pressure negatively effects on groundwater excellence in a specified areas. These chemical processes are vital factors for the spatial and seasonal differences in groundwater quality and quantity. Groundwater with chemicals developed by interrelate with geological formation minerals or combining between them totally different groundwater on flow methods within submerged point towards that will increase in matter absorption in the groundwater were caused mainly by erratic recharge, ruled by micro topographic environment(Zahid et al. 2008).

The groundwater in rural zones is powerless to the contaminants which are gotten from the agrarian synthetics(Spalding and Exner 1991). The significant issues inside the groundwater division of various zones are the ever-expanding new requests, declining water level bringing about a lacking inside the property of cylinder wells and low precipitation. The data of hydrochemistry is crucial to see the source of chemicals and their compositions of local groundwater (Kumar et al. 2006; Ravikumar et al. 2011).

Geochemical progressions are revealed the control of naturally occurred contaminants in the worldwide terrestrial habitats. Various scientific works have been done in India on groundwater quality have studied on behalf of the shallow aquifers chemistry within the different arid or fertile regions to the quality assurance mentioned by World Health Organization (WHO1993; Toda et al. 2002). However, during monsoon period, the riverine water bodies becomes coarse and intrudes towards land in summer, the low brackish water finds its approach through small channels and it mixed with low river bank by which deep groundwater becomes contaminated with undesirable particles (Kumar 2001). As a consequence, native aquatic ecosystem is extremely dependent directly or indirectly on water quality and biological diversity where such physicochemical parameters play a significant biological and physiological role in the particular aquatic environment (Kar et al. 2017). Along with, quality of the water is degraded by anthropogenic effects and natural as well as native climate, reluctantly irrigation practices and geological properties degradation also where as characteristic features by the chemical composition the groundwater determine its quality and utilization. Therefore, our present investigation endeavours the present status of ground water quality and illustrated the management policies within the Kangsabati river side in Paschim Medinipur, West Bengal, India.

2 Physiographic and Climatology of Study Area

The Kangsabati River enriched the Paschim Medinipur, Bankuraand Jhargram districts directly or indirectly(Kisku et al. 2017; Shit et al. 2014). However, sampling sites (three) in this river had been taken for the investigation from 2016 to 2018 where Site I, Site II and Site III consisting of the upper, middle and lower part respectively placed behind the town namely Midnapore of Paschim Medinipur (Site II) roofed by laterite soil. Whereas, Dherua (Site I) and Munibgar (Site III) covered with the fertile clay and alluvial soil in river bank that may facilitate to agriculture, fisheries and irrigation. Studied point for the physic-chemical analysis of that specified ones recorded by using handheld GPS (Table 1).The atmosphere of the entire examination locales becomes tropical sort with sweltering, dry summers (pre-monsoon period, March to June) having precipitations gathered in the monsoon (July to October) (Sen et al. 2004).Erosive nature of the scene at study regions becomes impact observably by spillover waters in rainy season changed soil attributes, pH, kept natural issue, ionic

Table 1 GPS location of different sampling places in three study sites at the Kangsabati river basin

Study area	GPS location of sampling points	
	Latitude (N)	Longitude (E)
Site I (Munibgar zone)	22°26′43.60″	87°5′28.93″
	22°29′36.49″	87°6′3.35″
	22°25′46.71″	87°6′28.98″
	22°28′26.91″	87°6′53.43″
	22°27′13.62″	87°6′25.73″
	22°30′46.46″	87°1′59.40″
	22°29′25.62″	87°4′16.06″
Site II (Midnapore zone)	22°23′48.71″	87°18′46.94″
	22°24′0.14″	87°18′33.61″
	22°23′24.85″	87°19′28.66″
	22°23′41.60″	87°20′1.76″
	22°23′48.82″	87°18′50.80″
	22°24′8.24″	87°18′7.40″
	22°24′21.15″	87°17′28.81″
Site III (Dherua zone)	22°23′58.41″	87°23′5.54″
	22°23′26.24″	87°23′42.69″
	22°23′44.30″	87°24′28.37″
	22°24′10.20″	87°24′59.01″
	22°23′42.09″	87°25′45.19″
	22°23′52.02″	87°26′43.12″
	22°24′53.48″	87°26′7.47″

focus, and cation-trade (Na^+, K^+, Ca^{2+}) and other fundamental physico-synthetic concoctions properties at the lower area of crevasses catchments.

3 Materials and Methods

The EC (electrical conductivity), pH, TDS (total dissolved solids), the +Ve ions like magnesium, calcium, potassium, sodium; −Ve ions like carbonate, chloride, bicarbonate, sulphate and nitrate are analyzed using the standard techniques by APHA (Apha 1995).The groundwater contaminants like chloride, nitrate, TDS, and so forth are assessed however out the examination destinations. Examining was done utilizing autoclaved polyethylene holders.

To understand and validation of the obtain data statistical analysis are done through ternary plot, Durov diagram and piper's trilinear diagram where the anions and cations are plotted in ternary plots. The peaks of the cation and anion plots are represented. Then the diamond plot is represented by the help of these two plots. The diamond plot is a matrix transformed graph represented by anions ($SO_4^{2-} + Cl^-$/total anions) and cations ($Na^+ + K^+$/total cations).

The piper's trilinear diagram plot had been generated through the following equation,

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} \cos\left(\frac{\pi}{2}\right) & \sin\left(\frac{\pi}{2}\right) & 0 \\ -2\sin\left(\frac{\pi}{2}\right) & 2\cos\left(\frac{\pi}{2}\right) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

4 Results and Discussion

Present investigation revealed that, understanding the groundwater quality is essential because domestic use, agriculture and aquatic habitat supported through the direct or indirect use of ground water as well as riverine water (Fig. 1). Real time survey data were analysed through different statistical tools to represent a significant co relation of physico-chemicals parameters which exceeding the concern limits in the some parts of the Kangsabati river side study areas (Table 2). Although, a details survey of groundwater degradation, was conducted during three major seasonal variations where in post monsoon the contamination result contribute higher range compared to others season (Fig. 2). Current study also explore that with the ternary plot, Site III showing the more threatened hydrobiological condition to the groundwater pollution where Site II and Site I shown lower range respectively. This statistical data analysis plot also showed the seasonal variations of different physico-chemical parameters values in the respective three study site at the Kangsabati river basin (Fig. 3a–c).

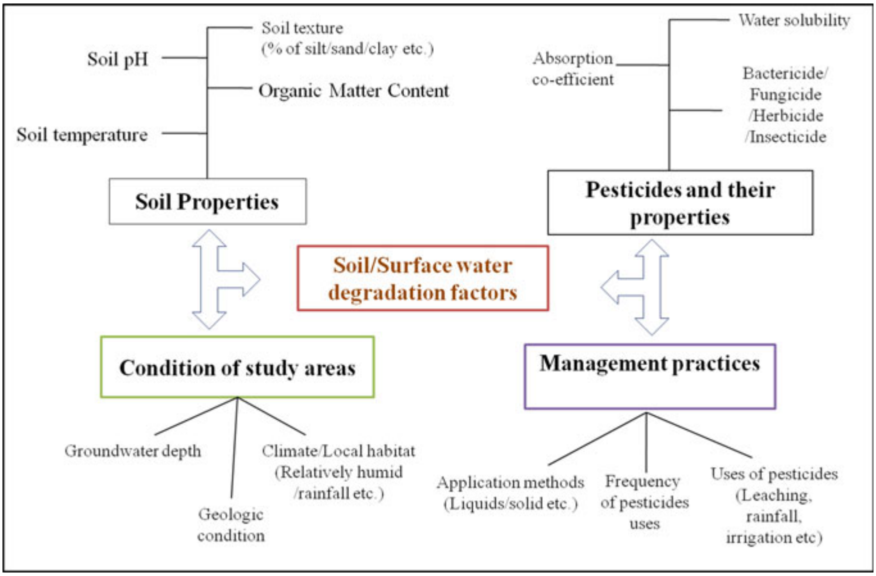

Fig. 1 Factors influencing groundwater pollution through pesticides usages

4.1 pH

Current investigation reports that, pH range of groundwater showed maximum 8.9 and minimum 6.2. Accordingly, Dherua and adjoin areas (SIII) of river bank belongs to lower measurable range of pH value where Munibgarh areas (SI) found basic or alkaline in nature. It indicates the nature of groundwater quality whether it is accepted for drinking or not (based on WHO guideline where required range is 6.5–8.5).

4.2 Ionic Chemistry

The dissimilarity of ionic concentration (both cation and anion) was highly correlated to the local untreated sewage discharge, heavy uses of pesticides in agriculture and rainfall fluctuation. The ionic concentration of Na^+ and Cl^- in groundwater could be gradually reduced by the boost of river water and rainfall in the infill layer of the study sites. Clearly Na^+ (normal centralization of 237 mg/l) rules in study region. In any case, study indicated the most elevated centralization of Na^+ (1.146 mg/l) while as the K is found in a least fixation (normal estimation of 21 mg/l) and Cl^- rules in the anionic science of the investigated area. In statistical analysis, fluctuation of certain amount of ionic concentration was calculated by Piper's trilinear diagram. Major parameters likeMg^{2+}, Na^+, Ca^{2+}, K^+, SO_4^{2-}, HCO_3^- and Cl^- in meq/l were assessed in groundwater of the Kangsabati river basin (Fig. 4a, b). The plot likewise

Table 2 Correlation of different physico-chemicals parameters occurs in the respective three study areas at Kangsabati river basin

	pH	TDS (mg/l)	TH (mg/l)	EC (µs/cm)	Na^+(mg/l)	K^+ (mg/l)	Ca^{2+} (mg/l)	Mg^{2+} (mg/l)	Cl^- (mg/l)	CO_3^- (mg/l)	HO_3^- (mg/l)	SO_4^{2-} (mg/l)	NO_3^- (mg/l)
pH		0.012667	2.94E−07	0.00033	0.011417	0.0074726	0.001988	9.13 E−05	0.012482	0.008317	0.023976	0.001754	0.01118
TDS (mg/l)	0.64545		0.00041306	1.66 E−07	5.80 E−12	1.43 E−07	9.40 E−05	0.00066964	2.96 E−10	5.48 E−06	2.18 E−05	5.38 E−08	7.71 E−11
TH (mg/l)	0.94673	0.81252		5.65 E−07	0.00031882	0.00014958	2.75 E−05	1.44 E−07	0.000408	0.001776	0.007264	1.39 E−05	0.000497
EC (µs/cm)	0.81994	0.95166	0.94047		4.50 E−08	3.16 E−08	1.13 E−06	2.05 E−06	6.21 E−08	7.76 E−05	0.000399	1.42 E−11	2.39 E−07
$Na^{+(}$mg/l)	0.65255	0.99138	0.82103	0.96124		7.76 E−10	2.78 E−05	0.00019363	4.90 E−15	2.80 E−05	6.75 E−05	4.84 E−09	6.69 E−12
K^+ (mg/l)	0.67985	0.95285	0.84359	0.9635	0.98044		4.98 E−07	1.77 E−05	4.70 E−11	0.000446	0.000801	5.15 E−09	6.84 E−08
Ca^{2+} (mg/l)	0.75042	0.85593	0.88386	0.93298	0.88359	0.94174		2.50 E−06	1.36 E−05	0.005636	0.010474	1.84 E−06	0.000218
Mg^{2+} (mg/l)	0.85665	0.79546	0.95278	0.9258	0.83626	0.89241	0.92326		0.000187	0.008008	0.017179	1.27 E−05	0.000529
Cl^- (mg/l)	0.64646	0.98336	0.81292	0.95907	0.99736	0.98777	0.89727	0.83725		7.17 E−05	0.000143	3.19 E−09	7.13 E−11
CO_3^- (mg/l)	0.67321	0.91215	0.75556	0.86069	0.88344	0.80989	0.69663	0.67557	0.86261		1.31 E−08	0.000202	1.21 E−05
HCO_3^- (mg/l)	0.59773	0.88845	0.68159	0.81372	0.86409	0.78869	0.65833	0.62357	0.84478	0.96852		0.000707	4.00 E−05
$SO4_2^-$(mg/l)	0.75613	0.96005	0.89678	0.98999	0.97339	0.97311	0.92717	0.89843	0.97519	0.83504	0.79341		4.66 E−08
NO_3^- (mg/l)	0.65397	0.98672	0.80619	0.94858	0.99118	0.9584	0.83276	0.80397	0.98689	0.89931	0.87601	0.96101	

Significance level 0.005%

Fig. 2 Field survey and groundwater quality assessment in respective study sites

shows that the greater part of the groundwater tests fall in the field of Na–Cl facies and some residual examples fall in Ca, Mg, SO_4 facies, it unmistakably demonstrates the change of groundwater into hard water in the investigation zone. The translation of hydrogeochemical investigation uncovers that the groundwater of this district is marginally alkaline in nature.

4.3 Total Dissolved Solids

The Total Dissolve Solid (TDS) values showed maximum 3424.2 mg/l and minimum 211.1 mg/l in range. Higher substance of TDS can be ascribed to the gathering of mud particles comprise with various bothersome substances in groundwater in contact with the spring body. Because of the alluvial locale, there can be some decrease and oxidation forms in water, in this manner it additionally causes advancement in TDS.

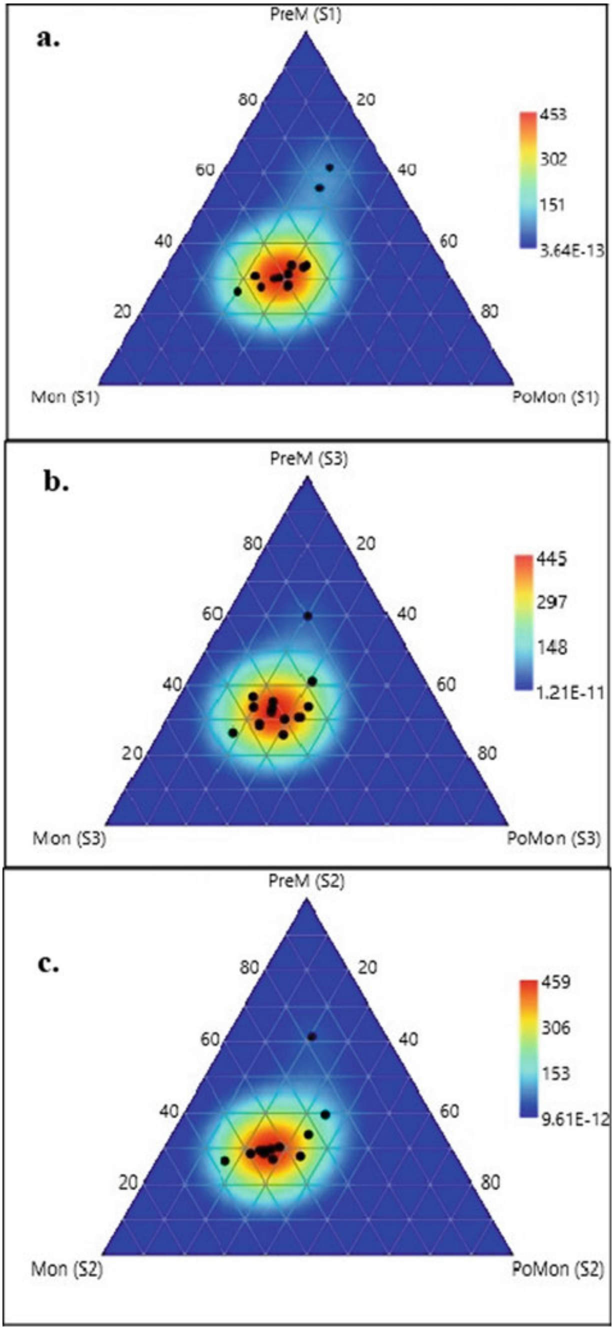

Fig. 3 a–c Ternary plot represent the seasonal variations of hydrological parameters at three different study sites (SI, SII and SIII) in Kangsabati river basin

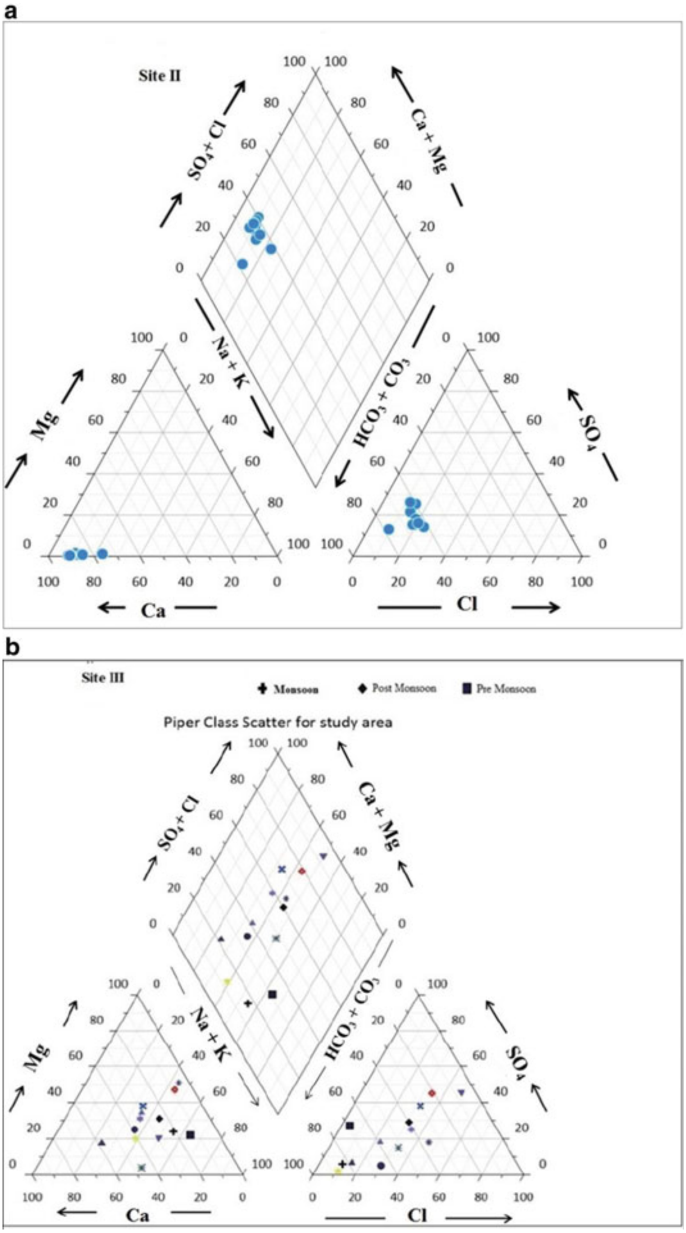

Fig. 4 **a**, **b** Piper class scatter plot of different ion distribution in Monsoon and Post-Monsoon period at SI study regions at Kangsabati river basin

4.4 Total Hardness

In this examination, the total hardness (TH) values go from 90 to 930 mg/l with a normal estimation of 253 mg/l where as the greatest allowable restriction of TH for drinking object is 500 mg/l and the most attractive breaking point is 100 mg/l.

4.5 Chloride

It was discovered that Chloride in drinking water begins from common sources, urban spill over containing salt, sewage and mechanical effluents, and saline interruption guided by WHO. The Chloride fixation in the investigation zone extending from 56 to 1.711 mg/l has been found in shallow groundwater where particle grouping of the examination zone goes over the passable furthest reaches of 600 mg/l in certain areas. In any case, no unfriendly wellbeing issue on human wellbeing have been accounted for from the admission of water containing a considerably higher substance of chloride from the whole examination zones.

4.6 Sulphate, Calcium and Magnesium Ion

SO_4^{2-} content changes essentially with continuous during the invasion of precipitation and groundwater. The convergence of SO_4^{2-} is probably going to respond with numerous human organs if the worth crosses the greatest furthest reaches of 400 mg/l which causes a Laxatives, laxatives, or aperients ailment on the human gastro digestive tract framework with the assistance of overabundance magnesium in groundwater. In any case, the SO_4^{2-} focus in groundwater of the investigation territory is inside the greatest passable breaking point. However, the varieties in focus may demonstrate the breaking of natural substances from dirt/water, leachable sulfate particle present in compost, and other human anthropogenic impacts. As needs be, a higher convergence of Ca^{2+} can cause stomach afflictions and is unwanted for residential utilizations causing encrustations and scaling. The chief wellsprings of Mg^{2+} in the common waters are magnesium-bearing minerals in rocks, and auxiliary sources are natural and mechanical wastages.

4.7 Irrigation Related to Water Quality

The productivity of examined region is effected by the Presence of extreme amount of suspend ion such as bicarbonate, sodium, and carbonate in irrigation water concern for plants and agricultural soil chemistry. Higher amount of Sodium concentration can affect on higher hardness of soil as well as a reduction in its permeability (Nag and Ghosh 2013).In this region establishment of several industries, uprising urbanisation and agriculture activities in river beds have depreciated the groundwater quality.

Contaminated water is described by a few anthropogenic contaminants and either doesn't manageable to human use, such as drinking water as well as experiences a checked move in its capacity to help its local natural surroundings (Austen et al. 2002; Swartjes 2011). Subsequently, the particular contaminants prompting groundwater contamination incorporate synthetic compounds and tangible changes, for example, raised temperature and staining (Otieno et al. 2012). The contamination of surface groundwater and wastewater which regularly polluted by such undesirable chemicals components into the agriculture field that transmit diseases and chemical components to the consumers (Ritter et al. 2002). Pungent smell, decolourisation, increased temperature, different contamination, pH changes, decreasing of oxygen level, and domestically used detergent that creates mass white foam like texture in river water, salt in ground water, eutrophication in surface water (Harrison 2015). However, present research also investigates the undesirable pesticide and fertilizer use due to gradual increases of reluctant agricultural activities increase nitrate (NO_3^-) and pesticide loading causes groundwater contamination higher at SIII study areas than others. Whereas NO_3^- leaching is a one of the common issue in most agricultural regions tends to increase possiblerisk of nitrate in groundwater of the Kangsabati River sites especially SIII. Accordingly, diagram of Durov analysis represented the geochemical evolution of the Site III areas groundwater at Kangsabati river basin where groundwater quality indicates a serious threat (Fig. 5). In this manner, springs' ecological impacts remember a decay for sea-going biodiversity, eutrophication of biological systems, and surface waters further diffuse nitrate contamination of groundwater. Although, heavy uses of pesticide to agriculture crops actually reaches the specific target pest but the rest amount go through the environment gratuitously, contaminating soil and groundwater where it becomes toxic or affect adversely to the non-target organism's presence in the aquatic environment.

5 Conclusion

Although, groundwater pollution remain considered as one of the burning issue in present day scenario where it effect directly or indirectly on both flora and fauna. The infinite varieties of environmental features within ponds, lakes, river and streams reflect the multiplicity of used chemicals and formulations seen heavy uses of among harmful elements (Fig. 6). These kinds of effects already noted and measured when chemical compound is accumulate in to soil or channelled within the riverine water bodies then transferred to aquatic environment, ultimately it threatened to all living biota among terrestrial as well aquatic. Therefore, targeted to protect and planned reduce the impact of such environmental threats its need to implement of some crucial management strategies as follows, (1) detect and prevent of contaminated soil, untreated runoff and sedimentation, (2) lowering the undesirable effects from

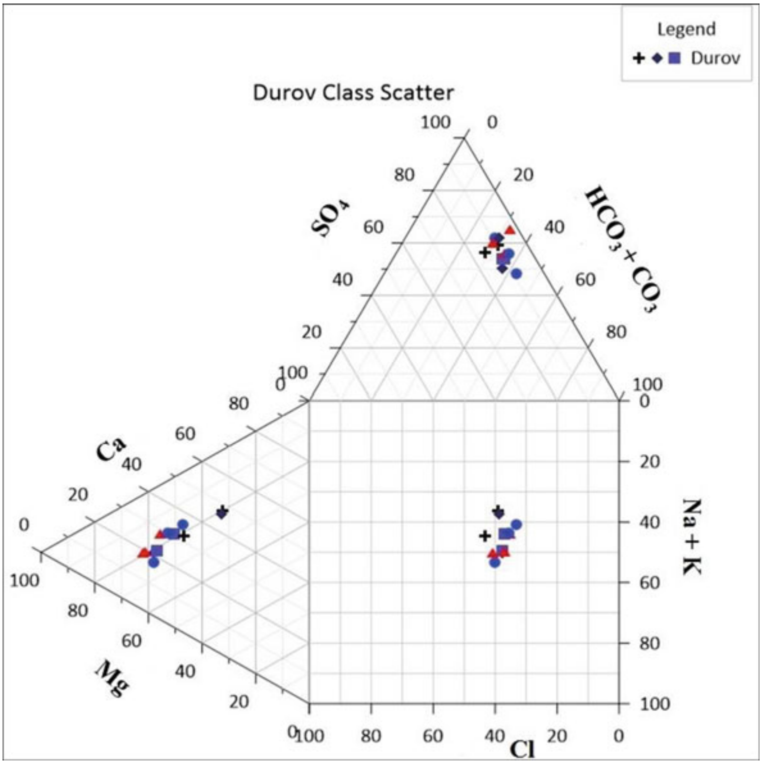

Fig. 5 Diagram of Durov showing the geochemical evolution of the Site III areas groundwater at Kangsabati river basin

chemicals use in agriculture purposes, (3) suitable plan for sewage disposal (4) maintain a standard guideline of physical and chemical water quality for agricultural water users, for riverine ecosystems and (5) concern and establishment of action lead to cost-effective water quality monitoring systems. Might be the groundwater of Kangsabati river basin areas will be managed and make pollution free by applying the short of best quality management practices from the present research design. Subsequently, such drive will definitely support and promote the localised humans and allied animals for superior life style in essential dependency to the ground water.

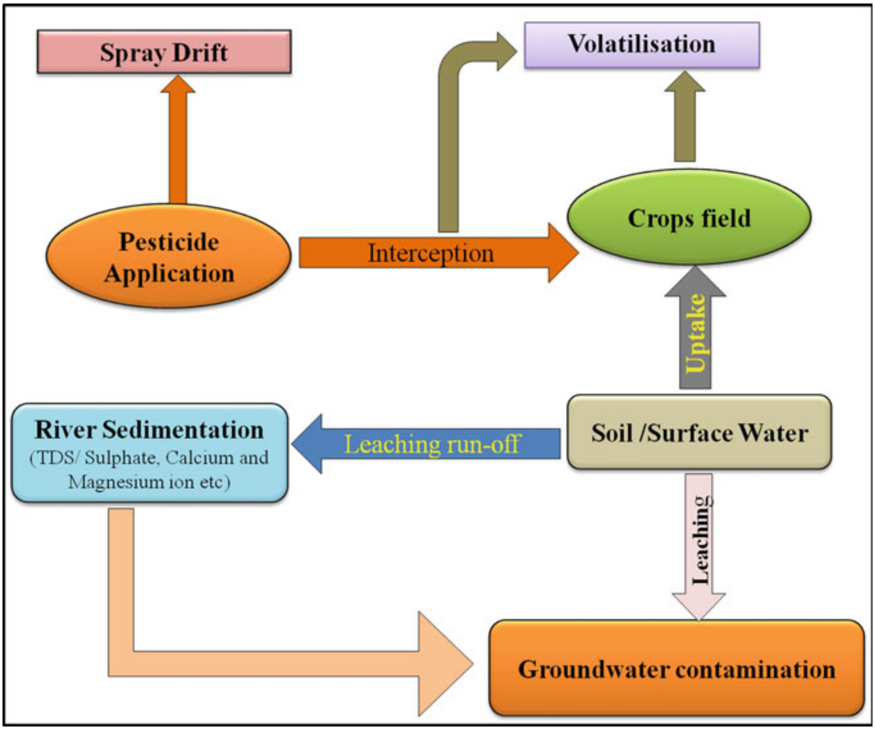

Fig. 6 Schematic pathway of pesticide applied to crop fields in the study area

Conflicts of Interest Authors declare no conflict of interest.

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Effect of Conventional Sand Mining Along Heavy Mineral Beach Placers and Its Environmental Impact

Samikshya Mohanty, Nimesh Kotadia, and Debashish Sengupta

Abstract The present study discusses the consequence of sand mining on erosion of coast and its impact on seawater intrusion along the eastern coast of Odisha, India. Unsystematic sand mining has a very severe influence on the environment and micro-ecology. The natural causes such as wind pattern, oceanic currents, and climatic factors also have significant impacts on coastal erosion along with sand mining. The sediments are removed from the nearshore region due to coastal erosion which consequently favors of the intrusion of saline water into freshwater zone. This study deals with satellite imagery to monitor illegal sand mining and coastal erosion. Thermal imagery of the study area has been proposed in consequent four years which are the results of the sand mining and several natural causes. Sea water intrusion is the source for contamination of groundwater. The high concentration of chloride and sodium ion in the groundwater is unfit for human consumption and also for industrial uses. Satellite imagery is used to observe the movement of heavy placer deposits and so that the beach nourishment could be made to prevent the movement of sand.

Keywords Radioactive heavy mineral · Thermal imagery · Sand mining · Sea water intrusion

1 Introduction

The significance of beach sands in terms of the economic resource is manifold viz. eco-tourism, valuable mineral resources, presence of plant species which have a symbiotic relationship with the traditional fishing communities, acting as a buffer against storm surges and the utility of quite of a lot of these plants for economic uses like medicines, perfumes apart from the plant leaves being used for a variety

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of applications. Quite a lot of these areas are of touristic interest due to the presence of prehistoric architectures and temples. Of-late the beach sands are being mined extensively for industrial applications. Erosion, transportation, and sedimentation processes have a major problem to terrestrial ecosystems resulting in the alteration of the water table and the soil loss in the catchment area apart loss of plant nutrients. Aquatic pollution is also affected by the changes in the nature of the ground water/surface availability (Gomoiu et al. 2016).

The eastern part of India which is adjacent to the Bay of Bengal is rich in heavy mineral placers deposits mainly Tamilnadu, Andhra Pradesh and Odisha coast. Beach sand mining is being extensively undertaken in various parts of the world including eastern India especially in Odisha, Andhra Pradesh and Tamilnadu in the eastern coastal part of India and Kerala along the western coast. The same is being actively pursued economic resources like ilmenite, garnet, zircon, rutile and sillimanite apart from monazites. The heavy mineral placer mining is undertaken by dredging which results in various associated impacts like the release of toxic heavy metals as well chemicals like polychlorinated biphenyl (PCB), enhancement of turbidity and its effect on the metabolic activity of aquatic species. It has also detrimental effects on marsh productivity from sedimentation, impact on species which prey on contaminated aquatic organisms (Sharma 2010). Due to the unsystematic and illegal mining, it has some adverse effect on the sea coast. Seacoast is eroded in a faster rate due to the mining rather than replenishment. There are negative environmental impacts such as salinization, seawater intrusion and ecological impacts due to the unsustainable exploitation of such resources. Several exploration and research institute has been involved in the exploration and evaluation of heavy mineral beach sands and inland placer deposits along the coastline of India in the last five decades. These deposits have been identified by carrying out traditional reconnaissance and detailed surveys (Jagannadha Rao et al. 2008). This approach though noble, is labour and cost intensive. Considering the vast length of the coastal belt, it becomes tedious to map the entire belt. Hence, with the help of high spectral and high spatial resolution satellite imagery, it is possible to reduce both costs as well as labour in mapping such heavy mineral placers deposits. In the present study, we have tried to demonstrate the use of sophisticated remote sensing techniques, such as thermal imagery in identifying areas where heavy minerals may be present in abundance.

The erosion of coast shifts the sediments to a specific distance resulting seawater intrusion beneath the freshwater zone. Seawater intrusion causes a major problem for coastal areas and happens due to various weather events, rising of sea level and erosion of coast and varying precipitation patterns (Isa et al. 2012).The intrusion of seawater takes place naturally caused by fluctuation of groundwater table resulting of coastal accretion and erosion and human activities which in turn monitoring hydraulic relation among fresh groundwater and seawater (Ghyben 1889; Gibbs 1970; Herzberg 1901; Gounari et al. 2014; Chandrasekharam and Ushakumari 1983).

The majority of the Indian coastal region experience severe erosional pattern resulting to intrusion of seawater that causes severe influences on the coastal environment, specifically groundwater contamination (Kumar et al. 2008; Chandrasekar et al. 2013; Vinayaraj et al. 2011). Coastal erosion as a result of longshore currents and sea waves resulting leakage flow of saltwater into groundwater, in that way affecting groundwater table (Kaliraj 2016; Hegde 2010; Hentry 2013). The process of watering or dewatering into groundwater table which is present below nearshore is regulating filtration of seawater, if the rate is higher along the coastline which leads to wearing away of particles that resulting seawater intrusion (Duncan1964; Selvakumar et al. 2016; Li et al. 2002; Horn 2006; Grant 1984).

2 Study Area

The study area comes under the Eastern Ghats Mobile Belt (EGMB) and it extends from the Rusikulya River up to 15 km in length towards south direction and 2 km in width (Fig. 1). The age of the rocks belonging to Eastern Ghats Mobile Belt varies from Archaean to Upper Proterozoic (Rickers et al. 2001; Sarkar and Paul 1998) (Fig. 2). This belt consists of several rock types such as charnockitic gneisses, khondalites, calc granulites and quartzite (Biswal et al. 2003). The formation of heavy minerals depends upon selective sorting on the coast due to the influence of waves and current. During this process lighter mineral for example feldspar, quartz and calcite are removed offshore leaving behind heavy minerals. For the present study, the study area is restricted to the berm region as it is least affected by diurnal tidal activities (Fig. 3). Moisture would increase in the sample as we move towards the shore line. So, the berm area is suitable to carry out remote sensing observations.

3 Materials and Methods

3.1 Thermal Imagery Principles

Remote sensing uses either a passive or an active source to acquire information of the earth's surface. Multispectral scanners function in specific portions of the electromagnetic spectrum to sense the radiation coming from the surface of the earth (Fig. 4). For 3–15 μm region of the EM spectrum, multi-spectral scanners sense energy emitted from the surface of the earth which is different than reflected energy. The instruments are referred toas thermal sensors. They utilize photo detectors to sense the emitted energy.

Figure 5 demonstrates the working principle of a thermal scanner system. The system operates in the following manner. (i) The thermal radiation is received from the ground at the rotating scanner mirror (ii) moves on to additional optics (iii) energy is focused on the thermal infra- red radiation detector (iv), which is enclosed by dewar filled with a liquid nitrogen coolant. Incoming radiation is converted into an electronic signal. (v) Signal is amplified by system electronics (vi) After A-to-D conversion signal is recorded digitally (Lillesand and Kiefer 1989).The thermal detector response

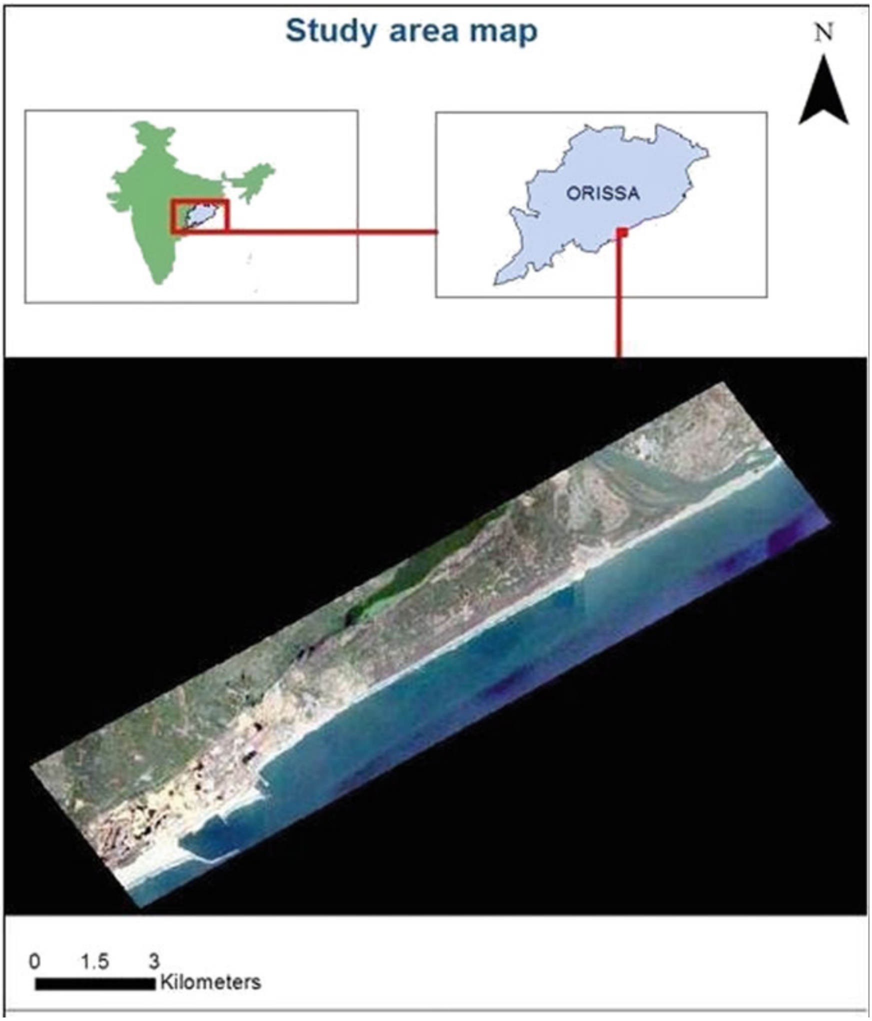

Fig. 1 Map showing google earth image of the study area containing heavy minerals

is pictorially represented on a line by line basis in a thermal scanner image. The data are recorded and current sensors achieve resolution of 0.1 °C.The usual convention while representing the relative radiant temperature in a thermogram is to have warmer earth surface features expressed in lighter tones, and cooler temperatures in darker tones. Atmospheric scattering is minimal since the wavelength of thermal radiation is longer than visible radiation. However, absorption plays a role of culprit and restricts the thermal sensing to two specific regions −3 to 5 and 8 to 14 μm.

This limitation restricts the resolution of thermal scanners to fairly coarse, relative to spatial resolution that can be achieved in reflected infrared and visible portion of

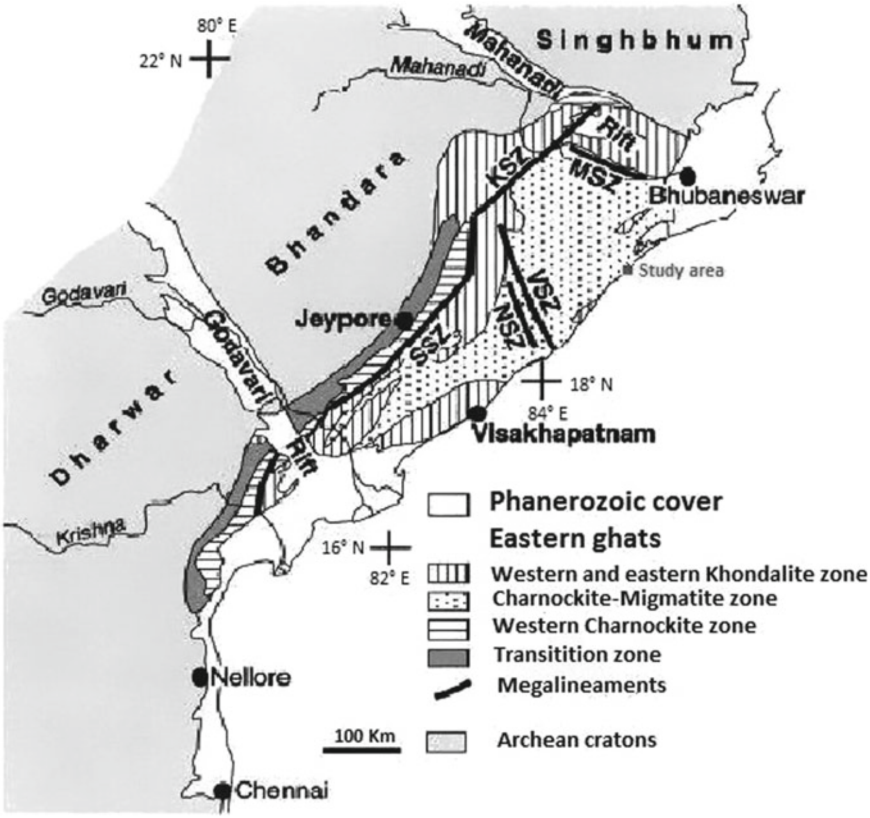

Fig. 2 Geological outline of the Eastern Ghats (EGMB) and adjacent regions [Simplified geological map of Ramakrishna et al. (1998) picturing the most important mega lineaments. (Modified after Dobmeier and Raith 2003)]

the EM spectrum. For this study, thermal imagery is used to identify the presence of REE bearing minerals along the coast of Orissa. Emissivity is defined as a factor that describes how efficiently an object radiates energy compared to a black body.

$$\varepsilon = \frac{\text{Radiant exitance of an object at a given temperature}}{\text{Radiant exitance of a black body at the same temperature}}$$

Radiant emittance has a unit of watts per square meter. Emissivity has the range between 0 and 1. Objects emit energy as a function of their temperature. This emitted energy is external manifestation the object's energy state. The radiant temperature is a measure of the emitted energy of an object. Thermal remote sensing measures what is known as the radiant temperature or brightness temperature or apparent temperature of an object. The kinetic temperature is an internal manifestation of the average translational energy of the molecules constituting a body. Kinetic temperature can

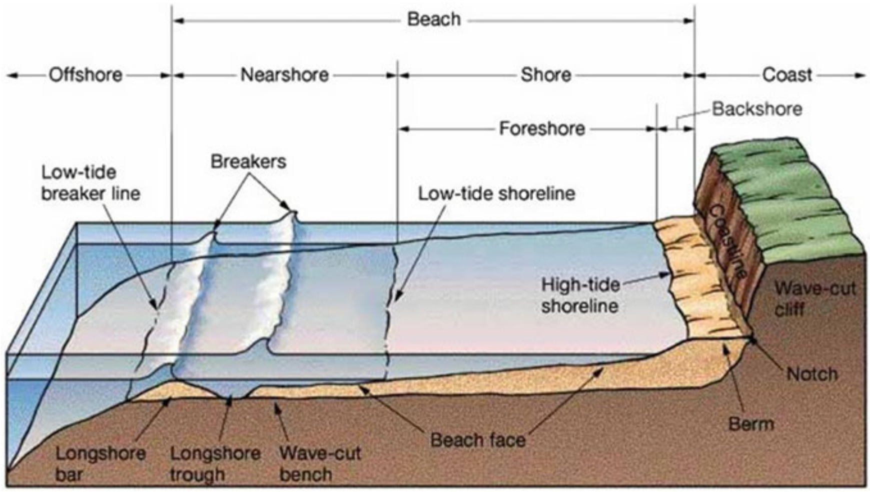

Fig. 3 Diagram showing different parts of the coastal area and the samples were collected from the Berm region which is beyond the high tide shore line. (Modified after Trujillo and Thurman)

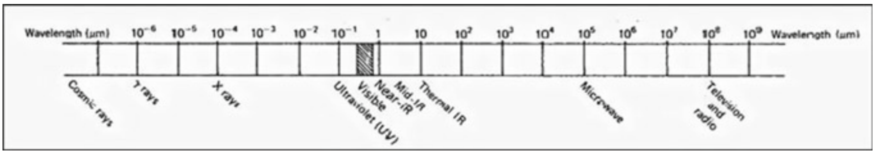

Fig. 4 Electromagnetic Spectrum (after Lillesand and Kiefer 1989)

be measured using a thermometer. There is strong co-relation between object's kinetic temperature and its radiant temperature.

The relation is expressed as follows

Trad = $\varepsilon^{1/4}$ Tkin.

The above equation shows that radiant temperature recorded by thermal scanner will always be less than the kinetic temperature of an object.

3.2 *Thermal Imagery of the Study Area*

Radioactive minerals emit radiation on account of decay process they go through due to their unstable nuclei. This radiation is in form of heat. However, due to dark texture of heavy sands it can also serve as a good absorber. These two processes can yield a thermal contrast of up to 4 °C between heavy sand and clean sand during particular time of the day, especially afternoon data or night time dataset. Normally, areas which contain radioactive minerals are composed of heavy sands which are darker in color.

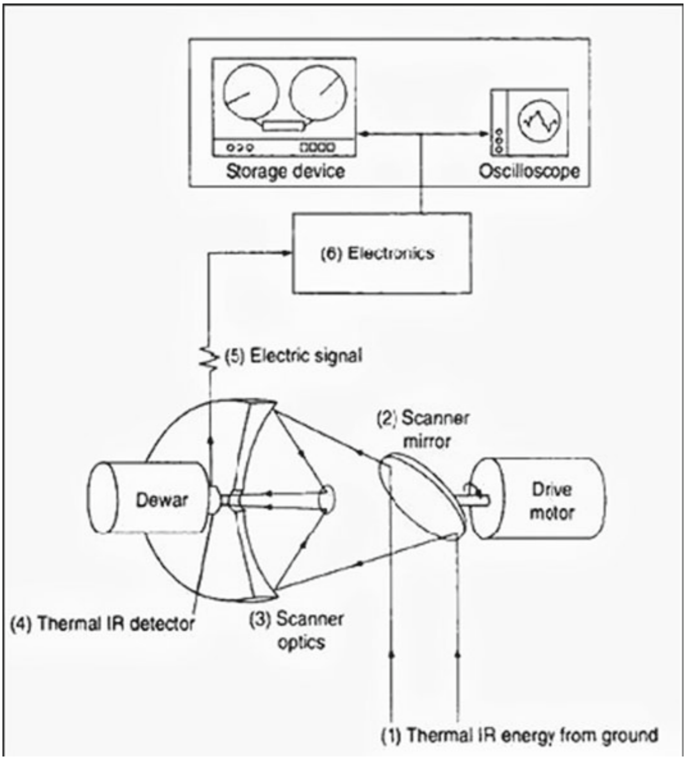

Fig. 5 Across track thermal scanner thematic (Lillesand and Kiefer 1989)

So as per the conjecture, areas which contain heavy minerals should show markedly dissimilar temperature values than areas which contain clean sands. Simply put forth, there should be thermal anomaly in beach areas where heavy minerals are present. Following are the relevant freely available thermal imagery datasets (Table 1).

Landsat 8 OLI/TIRS Level-2 'surface reflectance' data product is an on-demand product which is atmospherically corrected and converted to surface reflectance values. Product can be obtained from Earth Explorer website (https://earthexplorer.usgs.gov/). Also, analysis ready level-2 'Brightness temperature' data product

Table 1 Freely available thermal datasets

Product	Resolution	Spectral range
MODIS land surface temperature dataproduct (16 Bands)	1000 m	3.75–14.24 μm
ASTER L2 surface temperature V003 (5Bands)	90 m	8–12 μm
LANDSAT-8 TIRS (Band 10 and 11)	100 m (Resampled to 30 m)	10.60–11.19 and 11.50–12.51 μm

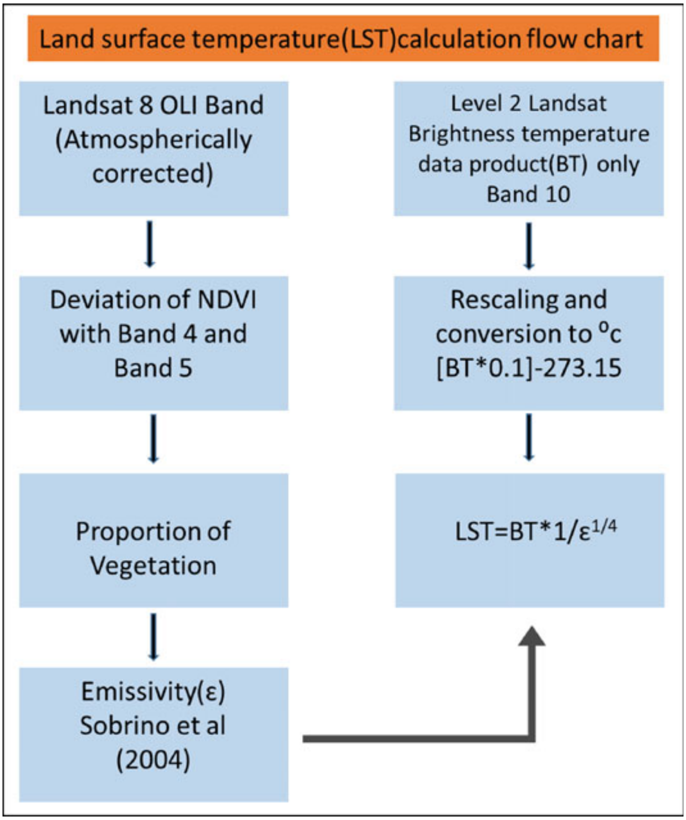

Fig. 6 Flow chart for LST (land surface temperature)

can be obtained from (https://espa.cr.usgs.gov/ordering/new/). Finally, LST can be estimated as depicted in the flow chart in Fig. 6.

4 Results

Radioactive minerals emit radiation due to the spontaneous decay process they undergo due to their unstable nuclei. The radiogenic decay products result in a thermal anomaly. However, due to the dark texture of heavy sands, it can also serve as a good absorber. These two processes can yield a thermal contrast of up to 4 °C between the heavy sands and clean sands during a particular time of the day, especially in the dataset obtained during the afternoon and night time. Normally, areas that contain radioactive minerals are composed of heavy sands which are darker in color. So as per conjecture, areas that contain heavy minerals should show markedly dissimilar temperature values when compared to areas which contain clean sands. Simply put forth, there should be a thermal anomaly in beach areas where heavy minerals are present. The radioactive placers deposits exhibit a positive thermal anomaly as shown in Fig. 7. Due to the erosion of coastal landforms due to several geomorphic agents, the sand size particles are produced which consecutively feed the beaches and dunes. The complex interaction between land and ocean interface shows the variability in the erosion rate of sedimentary landform. The combined action of waves, winds, currents and, changing water levels help to redistribute the sediments along the coast. The erosion of coast is also dominant as compared to the accretion process in this study area (Fig. 8). Jagatsingpur district is showing the highest erosional rate where as Bhadrak District is showing highest accretion process. The climatic factor, oceanic current, wind action, and rainfall play a major role in shifting the seacoast line.

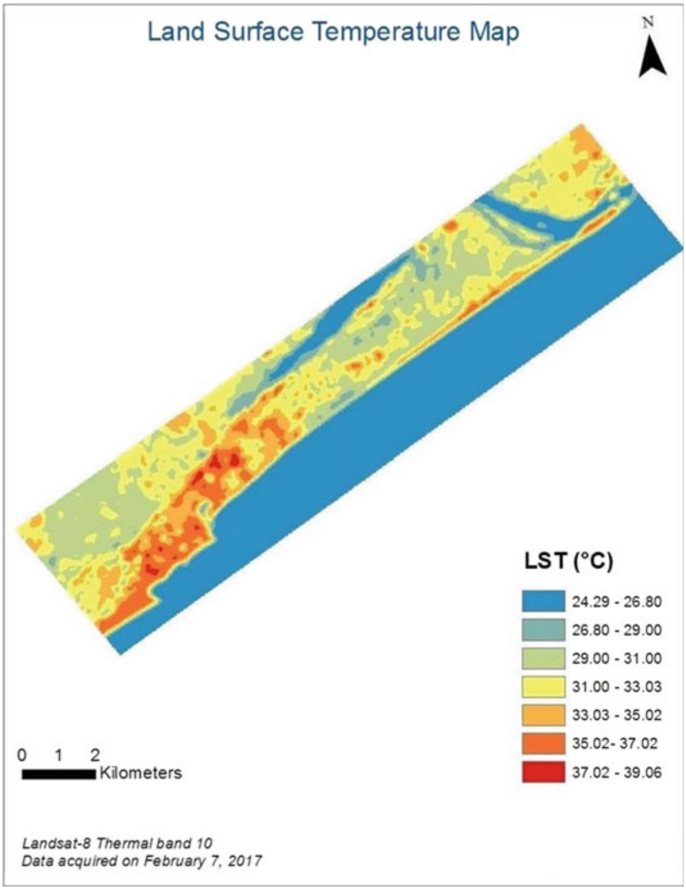

Fig. 7 Land surface temperature map showing the temperature variation in the study area based on thermal imagery mapping using Landsat data

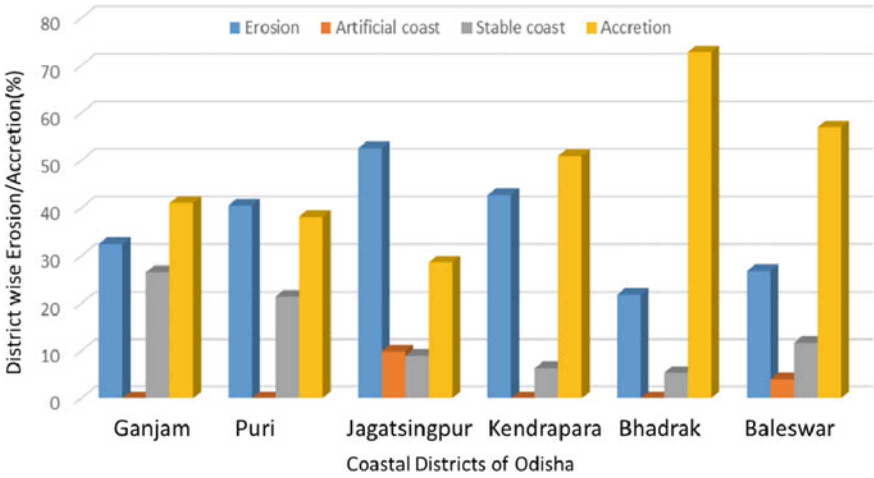

Fig. 8 A plot showing the erosion and accretion characteristics of different district in Odisha coast (modified after Ramesh 2011)

The climate of Odisha is tropical resulting in very high temperatures as this is lying South of the Tropic of Cancer. Rainfall is the primary source of water in Odisha which is estimated to be an average value of 1482 mm (Ramesh 2011). The Wind has a major role in the generation of oceanic currents along the coastal zones. Littoral drift is formed in the direction of flow of wind. Wind velocity plays important role in sediment transport by upwelling and downwelling of ocean currents. Southwest monsoon winds produce high waves striking the shore obliquely induces a littoral/longshore drift of sands along this coast which annually moves 1.5 million cubic meters of sand in the near shore regime in the eastern coast of India (Ramesh 2011).The wind speed may be strengthened resulting storms/cyclones when wind speed may reach around 117 kmh^{-1}. Cyclones are the center of low atmospheric pressure systems that form over oceans. The coast of Odisha is susceptible to multiple tropical cyclones and storm surges as summarized in Table 2. The sediment transport along the beach depends upon the direction of wind, tide, wind energy, and size of sediments. Sediment transportation by different geomorphic agents depends on sediment size. The stability of the shoreline depends upon the sediment budget.

5 Discussions

Because of erosion and accretion processes on coastline, coastal groundwater face potential vulnerability to seawater intrusion at various degrees which are affecting hydrodynamic factors for example variations in the net recharge rate and groundwater table. The eastern coastal zone present in the study area (Fig. 9) faces erosion and accretion in different areas caused by several natural as well as anthropogenic

Table 2 Extreme weather effects along Odisha and Andhra Pradesh (Eastern part of India)

Name of cyclone	Date/Year	Major area affected
Tropical cyclone Sidr, Wind Velocity ~215 km/hr	November 2007	Bangladesh, West Bengal and North-East India
Tropical cyclone Aila, Wind velocity ~120 km/hr	May 2009	Bangladesh and West Bengal
Phailin, Wind velocity ~215 km/hr	October 2013	Odisha (Gopalpur)
Hudhud, Wind velocity ~185 km/hr	October 2014	Andhra Pradesh and Odisha (Vishakhapatnam)
Extreme Precipitation, Total Rainfall ~171 mm (1st Aug–20th Aug 2018)	August 2018	Kerala, West coast of India
Titli, wind speed-126 km/hr	October 2018	Ganjam, Gajapati (Odisha)

activities that affects adverse influences on groundwater sources and contamination for a long-term scale. Figure 9 indicates a continuous shifting of temperature zone in the conjugative four years data which is associated with radiogenic placers deposits due to illegal mining and unsustainable exploitation.

The erosion along the coastal regions is generally controlled by seawater percolating towards the inland area (Kaliraj 2016). Among the 60.85 km^2 of the total coastal area, the area exposed by net erosion rate is about 20.94 km^2 in 41 different places, and the accretion at the rate of 6.45km^2 (Ramesh 2011). Erosion of coasts intensifies the spread of seepage flow of saltwater to inland, while salt content is mixed with freshwater by infiltration and diffusion process due to over pumping and population growth (Rajagobalan et al. 1983; Nazimuddin 1993). Groundwater which is present underneath the coastal areas found to be affected by seawater intrusion caused by dropping of the pressure of freshwater hydraulic head at the interface zone (Chang and Clement 2012; Basak and Vasudev 1983; Barlow and Reichard 2010; Bakker 2006; Post et al. 2007). The erosion of coast removes sediments thereby depleting recharge rate depth to groundwater table which ultimately intensify the seepage of saltwater towards inland areas (Reilly and Goodman 1987; Almasri 2008; Allouche et al. 2015; Kaliraj et al. 2016).

6 Conclusion

The quality of Groundwater is being deteriorated in quality due to seawater intrusion and other anthropogenic causes. This is mainly occurred due to coastal erosion and landward diffusion of seawater in populated region. Seawater intrusion mostly takes place along the coastal zone due to erosion and its direct effects on the groundwater table and recharge of surface water. The coastline aquifers are affected mainly by intrusion caused by the percolation of a enormous amount of saline water. It is strictly suggested that the groundwater resources in this area need to be protected

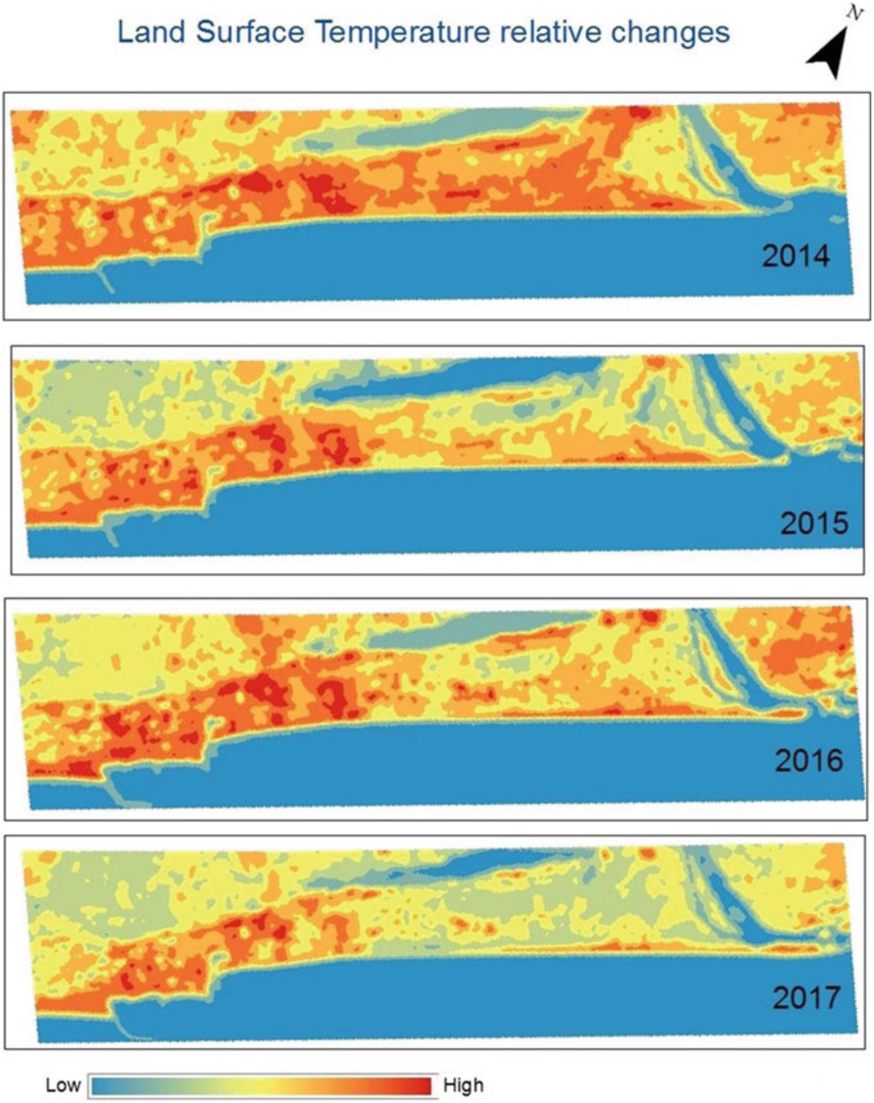

Fig. 9 Image exhibiting the variation of surface temperatures due to erosion of coast and movement of radioactive placer deposits associated with unsustainable mining and natural causes

from the intrusion of sea water through suitable management of the water bearing horizons in coastal zone. There is a need for monitoring the shoreline changes as a result of coastal erosion and accretion. Due to the geomorphic agents operating near the coastal area and illegal sand mining, the beach placer deposits are eroded in an unsystematic manner which is obtained from the analysis of thermal imagery and it has significant environmental impacts, such as sea water intrusion, saline changes etc.

In order to undertake reliable delineation of shoreline changes, the relevant data were examined and assessed in the light of present shoreline conditions. Recent changes in shorelines and the effects of human-induced alterations due to natural shoreline movements are reasonably quantified. Remedial measures like beach nourishment using suitable methodologies, including indigenous soil binding plants should be explored in a pro-active manner.

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Evaluation of Shallow Ground Water Quality: A Case Study for a Coal Mining Environment (East Bokaro Coalfield) of Damodar Valley, India

Mukesh Kumar Mahato and Ashwani Kumar Tiwari

Abstract Thirty shallow ground water (Dug well) samples were collected from a coal mining environment to assess the water quality status for drinking suitability. The pH, electrical conductivity, total dissolved solids, turbidity, total hardness, dissolved silica and total alkalinity in the ground water samples ranged from 6.91 to 8.44, 318 to 2408 μS/cm, 223 to 1710 mg/L, 0.3 to 7.9 NTU, 42 to 553 mg/L, 8.5 to 19 mg/L and 52 to 656 mg/L, respectively. The major anions such as F^-, Cl^-, NO_3^-, $SO_4^{2-}$and HCO_3^- ranged from 0.28 to 1.5 mg/L, 8.9 to 198 mg/L, 0.8 to 106.2 mg/L, 9.9 to 140.2 mg/L and 42.8 to 517.5 mg/L, respectively. The major cations such as Ca^{2+}, Mg^{2+}, K^+ and Na^+ were analyzed and found within the desirable limits, except for Mg^{2+} and Ca^{2+}. The overall study showed that the higher values found in some of the samples were mainly due to the higher values of total dissolved solids, HCO_3^-, total hardness, Mg^{2+} and total alkalinity. The other parameters are all within the maximum permissible limit of the Bureau of Indian Standards (BIS) and World Health Organization (WHO) drinking water standards. Moreover, the Water Quality Index (WQI) was calculated to provide a better understanding of the overall water quality for the coal mining environment. The WQI ranged from 44.6 to 127.4, which indicated good to very poor status of water quality.

Keywords Ground water · Major ions chemistry · Water quality index · Mining · East bokaro coalfield

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1 Introduction

Ground water is one of nature's most precious resource and inexhaustible gift. Groundwater is one of the most valuable assets and a reliable source of potable water for millions of rural and urban people (Kumar and Shah 2006). In recent years, rapid population growth, urbanization, mining and industrialization have created adverse quantitative and qualitative impacts on ground water. Access to secure drinking water in India has increased over a few decades. The increasing demands of safe water supply for domestic, agricultural and industrial purposes. An immediate requirement of safe water supplies is 30% (for urban) and 90% (for rural) population in India. Although still depends on untreated ground water supplies (Kumar et al. 2005). While, it is estimated that waterborne infectious diseases are more or less 21% of the communicable diseases in India (Bradon and Homman 1995). Moreover, it is possible to comprehend the change in water quality due to rock-water interaction (weathering) or any other anthropogenic influences (Todd 1980; Kelley 1940). The depletion rate of ground water levels in major cities and towns of the country is of urgent concern (Khurshid et al. 1997; Das et al. 1998; Sohani et al. 2001; Meenkumari and Hosmani 2003; Dhindsa et al. 2004; Ramashubramanian et al. 2004).

The ground water of the mining areas is affected by various aspects, such as physicochemical characterization of soil and soil erosion, rainfall, rock weathering, chemical reaction beneath the land surface, mining activity, agricultural waste and the role of micro-organism etc. (Abhishek et al. 2006). The component of wastes and mining effluents pollute the ground water quality by leaching. The high concentration of ions in water ultimately causes undesirable effects on human wellness. Ground water often consists of major ions such as, F^-, Cl^-, NO_3^- HCO_3^- SO_4^{2-}, Ca^{2+}, Mg^{2+}, Na^+ and K^+. Ground water chemistry strongly reflected the dominance of weathering of stone-forming minerals with secondary inputs from anthropogenic and atmospheric sources (Singh et al. 2013). Fluoride bearing rocks such as fluorspar, cryolite, fluorapatite, and hydroxylapatite are the principal sources of fluoride in ground water (Agarwal and Jagetia 1997). In the various coalfields, it has been observed that over the years, water resource conditions had been affected due to unplanned mining history and urban sprawl resulting in severe damage to the quality and water table (Ghosh and Ghosh 1991). Nevertheless, a qualitative analysis of individual parameters would not be able to offer a qualitative assessment of ground water. The Water Quality Index (WQI) is calculated as a rating methodology that incorporates the effect of different water quality parameters on the overall quality of the water (Rao 1997). The goal of this study is to assess the quality of groundwater and its suitability for drinking purposes on the basis of the WQI calculated.

2 Study Area (East Bokaro Coalfield)

The study area is third from the East in the chain of the coalfields of Damodar Valley and it is an important medium coking coal source situated in Bokaro district, Jharkhand. The area of study covers 237 km^2 and extends 65 km from east to west and 10–16 km from north to south (Mahato et al. 2016). The study area is drained by three major rivers viz. In the central part the Bokaro River, in the east the Konar River and in the south the Damodar River.The major part is occupied by Barakers, while the Barren Measures exposed mainly in the axial section. Rocks of the younger Raniganj and Panchet formations occupied in the western part and the youngest formations exposed in the large hills (Raja Rao 1987). The geological map shown in Fig. 1. The lithology of Barakar formation consists of coarse grained arcosic sandstone, fine grain laminated sandstone, gray shale, carbonaceous shale and seam of coal. The Barren Measures exposed in the central and western portions consists of Flaggy, fine-grained, micaceous sandy shale, ferruginous sandstone, and black shale with a siderite band comprise the crescent-shaped outcrops. The Panchet formation occupies the higher elevations on much of this coalfield in the west (Raja Rao 1987). The average temperature during the summer season and winter season is 30 °C and 20 °C, respectively. The maximum temperature rises up to 44 °C during the summer season. The annual average rainfall in the study area is about 1366 mm and maximum rainfall occurs during July–September.

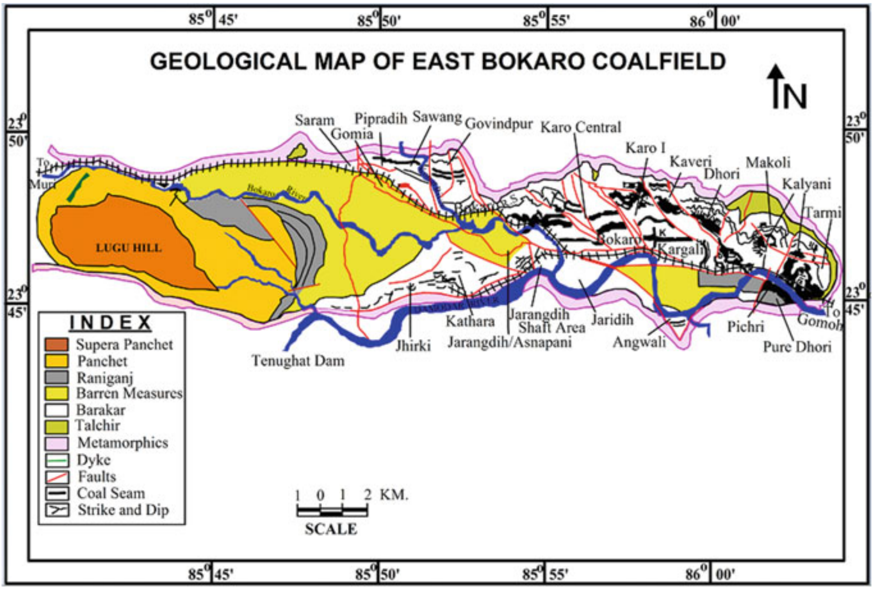

Fig. 1 Geological map of the study area (Mahato et al. 2016)

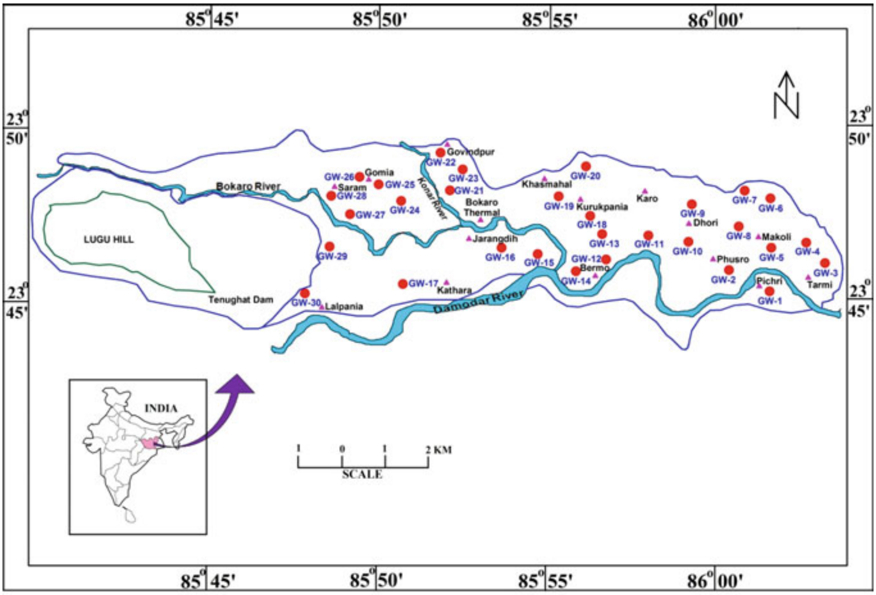

Fig. 2 Sampling sites of the study area

3 Material and Methods

3.1 Sample Collection

A systemic sampling was performed as per standard protocol (IS: 3025 1987) for the assessment of ground water quality. Representative thirty shallow ground water (Dug wells) samples were collected during May 2012 from East Bokaro coalfield area (Fig. 2). The samples were collected in pre-washed one liter polyethylene containers. Sample containers were washed with diluted hydrochloric acid and rinsed several times with deionized water. After that container was washed with sample water before collecting the samples. In the laboratory, 0.45 µm Millipore membrane filters were used to separate the suspended sediments from the sample.

3.2 Analytical Methods

Analysis of ground water samples was performed as per standard methods (APHA 1985) for the assessment of water quality parameters. pH and electrical conductivity were measured by using Benchtop pH and EC meter (CONSORT) and turbidity was analyzed by using a turbidity meter (EUTECH instruments TN-100). Dissolved silica was measured by molybdosilicate method, using UV–Visible Spectrophotometry (SHIMADZU, UV-2550) and the HCO_3^- concentration was measured byacid titration method. The major anions (F^-, Cl^-, NO_3^- and SO_4^{2-}) and major cations (Ca^{2+}, Mg^{2+}, Na^+ and K^+) were estimated by Ion chromatograph, DIONEX (DX 120). The overall precision %RSD was below 10% for all the samples.

3.3 Water Quality Index (WQI)

The water quality index is a mechanism for presenting a cumulatively derive a mathematical expression. WQI is defined as A rating technique which confers the composite influence of individual water quality parameters on the overall character of water (Yogedra and Puttaiah 2008). In the viewpoint of human usage WQI is computed. The criteria for the calculation of WQI have been taken for drinking purpose (BIS 2012). The weights for different water quality parameters are taken to be reciprocally proportional to the suggested standards for the corresponding parameters (Rao 1997; Mishra and Patel 2001; Naik and Purohit 2001; Rao et al. 2002).

The expression for weight calculation is made as follows:

$$W_i = k/S_i,$$

where, w_i is the unit weight for the ith parameter;

s_i the suggested standard for ith parameter and i = 1, 2, 3, …, 16; and k the constant of proportionality.

The computation takes the following steps:

(1) First, the calculation of the quality rating for each of the water quality parameters
(2) Second, a summation of these sub-indices in the overall index.

The individual quality rating is applied as follows:

$$q_i = 100v_i/s_i,$$

where, v_i is the measured value of the ith parameter in water sample under consideration and s_i the standard or acceptable limit for the ith parameter.

The WQI is then calculated as follows:

$$WQI = \sum_{i=1}^{n}(qiWi)/\sum_{i=1}^{n}Wi$$

4 Results and Discussions

4.1 Ground Water Quality Assessment

The results of the physico-chemical analysis of shallow ground water (dug wells) samples are illustrated in Table 1. The pH ranged between 6.91 and 8.44 with the maximum pH recorded in the Jaranjdih ground water sample. pH values were recorded slightly acidic to alkaline in nature in most of the water sample. The electrical conductivity(EC) varied from 318 to 2408 μS/cm and the maximum EC in the water sample of Phusro. The turbidity varied from 0.30 to 7.9 NTU with maximum turbidity 7.9 NTU was seen in the water sample of Jaridih Bazar. The total dissolved solid (TDS) varied from 223 to 1710 mg/L and maximum TDS 1710 mg/L measured in a ground water sample of Phusro. Which was beyond the desirable limit, i.e. 500 mg/L. The principal constituents of TDS are Ca^{2+}, Mg^{2+}, Na^{+}, HCO_3^{-}, Cl^{-} and SO_4^{2-}. The TDS level is <600 mg/L is generally recommended to be good, whereas TDS level is >1200 mg/L in drinking water becomes unsuitable (WHO 2011). The total alkalinity ranged between 52 and 656 mg/L with maximum alkalinity was recorded in the water sample of Kargali Bazar. The total alkalinity exceeds the permissible limits in almost all the cases, which is 200 mg/L as per the guideline provided by IS: 10500. The total hardness as $CaCO_3$ ranged between 42 and 553 mg/L and the maximum hardness observed at Govindpur. Hard water contains Ca^{2+} and Mg^{2+} ions due to the calcium carbonate equivalent of Ca^{2+} and Mg^{2+} ions present in water as expressed in mg/L. There is an indication that the death rates from cardiovascular disease are inversely and correlated with the hardness of the water. The guideline value for hardness at 300 mg/L ($CaCO_3$) is based on taste and household use consideration (IS: 10500). The dissolved silica varied from 8.5 to 19 mg/L. The HCO_3^{-} concentrations varied 42.8–517.5 mg/L with maximum HCO_3^{-} concentration was analyzed in the water sample of Kargali Bazar. The ground water containing 600 mg/L of HCO_3^{-} is considered fairly safe and good for irrigation and domestic purposes. The F^{-} ranged between 0.28 and 1.5 mg/L with an average concentration 0.63 mg/L was measured. The Cl^{-} content varied from 8.9 to 198 mg/L in the ground water sample. The Cl^{-} content was found too much below the permissible limits of 250 mg/L as laid by IS: 10500. The maximum chloride content was observed in the water sample of Saram Bazar. A high concentration of Cl^{-} in water gives an undesirable taste to water. The NO_3^{-} varied from 0.8 to 106.2 mg/L with average concentration 19.1 mg/L was estimated. The SO_4^{2-} ranged from 9.9 to 140.2 mg/L in the collected water samples, which is well within the BIS:10500 permissible limits. i.e.200 mg/L. A high concentration of SO_4^{2-} in association with Na^{+} or Mg^{2+} in the drinking water, might gives rise to gastrointestinal irritation.

The Na^{+} concentration ranged from 8.2 to 125.4 mg/L in the water sample of a mining environment. The desirable limit for Na^{+} is given as 200 mg/L as per WHO guidelines (WHO 2011). K^{+} is less common cation in the ground water and the K^{+} ranged between 1.3 and 57.9 mg/L in the water samples. The Mg^{+2} and Ca^{2+} concentration ranged from 2.3 to 74.4 mg/L and 7.0 to 284.1 mg/L, respectively in

Table 1 Comparison of ground water quality of the study area with WHO and Indian standards (BIS: 10500) for drinking water quality

Sl. No.	Parameters	Mean (N = 30)	Range (mg/L)	WHO (2011)		BIS (2012) IS:10500	
				Highest permissible	Max. desirable	Highest permissible	Max. desirable
1	pH	7.8	6.91–8.44	6.5–8.5	7.0–8.5	8.5–9.2	6.5–8.5
2	Electrical conductivity (EC)	800	318–2408	1500	750	–	–
3	Total dissolved solids (TDS)	568	223–1710	1000	500	2000	500
4	Turbidity	2.54	0.29–7.9	–	–	10	5
5	Total alkalinity as $CaCO_3$	317	52–656	–	–	–	200
6	Total hardness	166	42–553	500	100	600	300
7	Dissolved silica	12.8	8.5–19	–	–	–	–
8	Bicarbonate (HCO_3^-)	182.2	42.8–517.5	600	200	600	200
9	Fluoride (F^-)	0.63	0.28–1.5	1.5	0.6–0.9	1.5	1
10	Chloride (Cl^-)	70	8.9–198	600	200	1000	250
11	Nitrate (NO_3^-)	19.1	0.80–106.2	–	–	–	45
12	Sulphate (SO_4^{2-})	59.2	9.9–140.2	400	200	400	200
13	Sodium (Na^+)	49.5	8.2–125.4	200	–	–	–
14	Potassium (K^+)	7.4	1.3–57.9	–	–	–	–
15	Magnesium (Mg^{2+})	30.7	2.3–74.4	150	50	100	30
16	Calcium (Ca^{2+})	53.9	7–284	200	75	200	75

Note All units in mg/L, except pH, EC and Turbidity. The unit of EC ($\mu S\ cm^{-1}$) and Turbidity (NTU) the ground water samples. Ca^{2+} is one of the principal cation in ground water. The highest desirable limit for calcium is 75 mg/L and the maximum permissible level is to 200 mg/L. After Ca^{2+}, Mg^{2+} is the most important alkaline earth metal present in the ground water. It is one of the most important contributors to causes the hardness of water. The lower concentration of Mg^{2+} is not harmful, but higher concentration are laxative. As per BIS: 10500 guideline the maximum permissible limit of Mg^{2+} in drinking water is 30 mg/L. The overall analysis indicated that the higher values mainly due to the higher values of TDS, HCO_3^-, total hardness, Mg^{2+} and total alkalinity in some of the water samples. All the other parameters were found well within the permissible limit of IS: 10500 and WHO drinking water quality standards.

4.2 Major Ion Chemistry of Ground Water

All the analyzed major anions, In general the HCO_3^- contents was dominant (average 55%), Cl^- was the second dominant anion (average 21%). SO_4^{2-} and NO_3- were less dominant ions (average 18 and 6%), respectively, and F^- is the least dominant anion (average 0.2%) of the total anions. (Fig. 3a).The order of major anions loads as follows $HCO_3^- > Cl^- > SO_4^{2-} > NO_3^- > F^-$. Analyzed all major cations, Ca^{2+} concentration were the dominant ions (average 38%). Na^+ and Mg^{2+} ions were of secondary significance, (average 35% and 22%), respectively and K^+ was the least dominant cations (5%) of the total cations (Fig. 3b). The contribution of major cations in the order of $Ca^{2+} > Na^+ > Mg^{2+} > K^+$.

4.3 Calculated Water Quality Index

The analyzed ground water quality parameters were also used to calculate the Water Quality Index (WQI) for better understanding of the overall water quality. The BIS:10500 drinking water quality standards together with its corresponding status categories of WQI were provided in Tables 2 and 3 respectively (Rao 1997). The WQI in respect of individual sampling sites is provided in Table 4. The WQI ranged between 44.6 and 127.4. Which indicated Good to the very poor status of water quality. The highest WQI was calculated for the water sample of Phusro. This might be attributed due to the closeness of unscientific mining activities. WQI categories such as good (33%), poor (40%) and very poor (27%) were observed. More than half of the sampling sites fall in the poor to very poor category (Fig. 4).

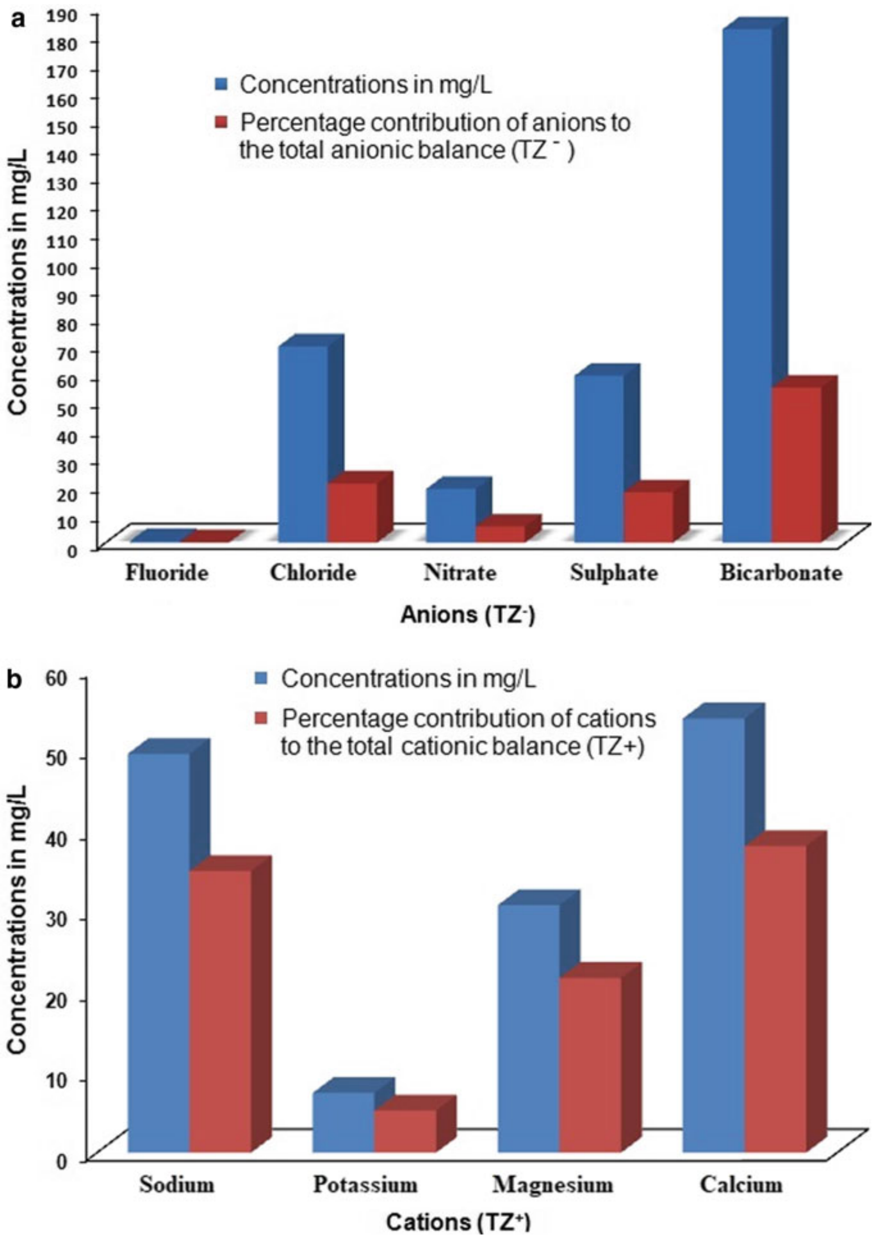

Fig. 3 **a** Percentage contribution of anions to the total anionic balance (TZ^-). **b** Percentage contribution of cations to the total cationic balance (TZ^+)

Table 2 Chemical parameters corresponding the IS: 10500

Parameters	Standards	$W_i = k/S_i$
pH	7.5	0.093465
Total dissolved solids	500	0.001402
Turbidity	5	0.140198
Alkalinity	200	0.003505
Total hardness	300	0.002337
Fluoride	1	0.700989
Chloride	250	0.002804
Nitrate	45	0.015578
Sulphate	200	0.003505
Bicarbonate	200	0.003505
Calcium	75	0.009347
Magnesium	30	0.023366
$\sum W_i = 1.00$		

Table 3 Status categories of WQI

WQI	Status
0–25	Very good
26–50	Good
51–75	Poor
>75	Very poor

5 Conclusions

The overall analysis indicated that the higher concentrations were observed may be due to the higher values of TDS, $HCO3^-$, total hardness, Mg^{2+} and total alkalinity in some of the ground water samples. This may be attributed to the natural weathering, mining and other anthropogenic activities. All the other parameters lie within the limits of BIS: 10500 and WHO standards. The analyzed data were also used to calculate the water quality index (WQI) for better understanding of the overall water quality. The WQI ranged from 44.6 to 127.4 for thirty samples and the water quality of the study area indicated good to very poor categories. About 40% of ground water samples were evaluated poor in quality and 27% of the samples are very poor quality. The ground water quality may improve through inflow of freshwater/rainwater or construct recharge pits for ground water recharge in the study area. The over all analysis suggested that some extents of treatment needs before its utilization and must be protected from the threats of ground water contamination.

Table 4 Water quality index for individual sites of ground water (dug wells) samples

Sl. No.	Sites	WQI	Descriptor category
GW-1	Pichri	52.9	Poor
GW-2	Phusro	127.4	Very poor
GW-3	Tarami	71.1	Poor
GW-4	Kari Pani	60.9	Poor
GW-5	Amlo	71.5	Poor
GW-6	Dhoi Khas	88.0	Very poor
GW-7	Sarubera	50.7	Good
GW-8	Makoli	53.1	Poor
GW-9	Subhas Nagar	76.1	Very poor
GW-10	Kargali, Bazar	75.5	Very poor
GW-11	Kargali	48.7	Good
GW-12	Bermo	56.1	Poor
GW-13	Sunday Bazar	53.0	Poor
GW-14	Jaridih Bazar	119.9	Very poor
GW-15	Jarangdih	59.6	Poor
GW-16	Asnapani	51.1	Poor
GW-17	Jhirki	55.8	Poor
GW-18	Kurukpania	82.0	Very poor
GW-19	Khas Mahal	78.5	Very poor
GW-20	Pilpilo ground	86.4	Very poor
GW-21	Lahariatanr	44.6	Good
GW-22	Govindpur	101.0	Very poor
GW-23	Kanjkiro	52.4	Poor
GW-24	Hazari	44.6	Good
GW-25	Swang 1-B	53.1	Poor
GW-26	Gomia	61.9	Poor
GW-27	Hosir	48.2	Good
GW-28	Saram Bazar	53.8	Poor
GW-29	Tulbul	47.1	Good
GW-30	Lalpania	52.7	Poor

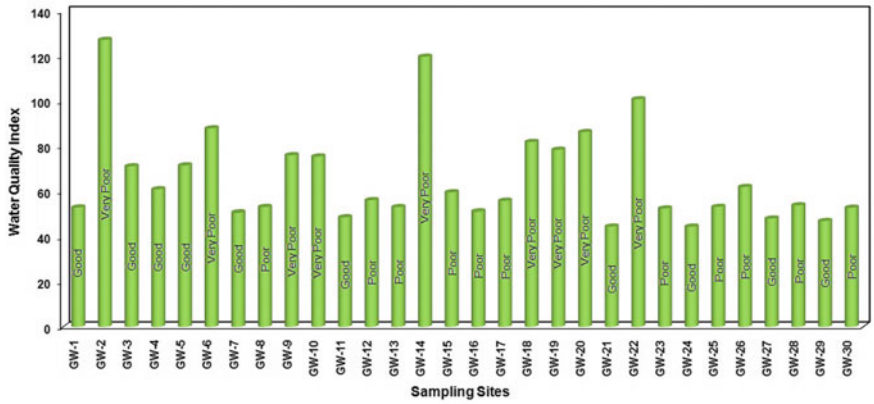

Fig. 4 WQI categories of samples

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Spatial and Temporal Categorization of Groundwater Quality for Domestic Use in Hisar District, Haryana, India

Reeta Rani and B. S. Chaudhary

Abstract Groundwater is being continuously stressed and contaminated due to human activities. The increased use of fertilizers, pesticides and other chemicals in the agriculture is leading to the deterioration in quality due to return flow. Groundwater quality analysis therefore becomes pre-requisite for the planning and analysis purpose for ensuring domestic supplies in an area. The present study deals with spatio-temporal analysis and monitoring of groundwater quality for domestic purpose in district Hisar of Haryana, India. Groundwater quality data of total of 87 observation wells of the study area for years 2000 and 2014 was used for this purpose. The analysis of various parameters of water quality such as Electrical Conductivity (EC), Hydrogen Ion Concentration (pH), Residual Sodium Carbonate (RSC), Sodium Adsorption Ratio (SAR) and Total Dissolved Solids (TDS) was carried out. To estimate the acceptable quality of water for domestic use, the area was divided into various categories of suitability as per various international and national standards. Spatial distribution maps of EC, pH, RSC, SAR and TDS were generated and integrated using GIS for demarcating different suitability zones of groundwater quality for domestic use. Integrated groundwater quality maps were prepared for the years 2000 and 2014. The study indicated that the maximum area of Hisar district was found in good to permissible category for year 2000 whereas in permissible to doubtful category for the year 2014 for drinking purpose. The present paper describes in detail the spatio-temporal characteristics of various suitability categories of groundwater for domestic use.

Keywords Domestic use · GIS · Groundwater quality · Hisar · India · Spatio-temporal analysis

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1 Introduction

Groundwater is an essential source of water use for various, purposes throughout the world. These include usage of groundwater for irrigation industrial and domestic purposes. There is continuous stress on fresh water resources due to exponential growth of population in developing countries coupled with industrialization and expansion of agriculture. According to WHO reports, nearly 80% of all the diseases in humans are caused by water contamination (Kavitha and Elangovan 2010). Groundwater availability and quality may be adversely affected by over drafting from aquifers. In some cases, the capacity of the aquifers to store water may be permanently lost due to over drafting. Maximum states in India employ water right process to manage the quantity of groundwater and also to mitigate the over exploitation (Cosgrove and Loucks 2015; Rani and Chaudhary 2015) which somehow helps in better management of aquifer health. On the basis of yield potential of aquifers, the state of Haryana can be divided into mainly three zones. First zone comprises of Bhiwani, Hisar, Jind, Mahendergarh and Sirsa districts having tube well yield of 50 m^3/h. Parts of Bhiwani, Gurgaon, Hisar, Karnal and Kurukshetra districts, covering an area of 7100 km^2 can yield between 50 and 150 m^3/h have been put into zone 2. The tube wells in parts of Ambala, Karnal, Kurukshetra, and Sonepat districts, having yield between 150–200 m^3/h and cover an area of 92,000 km^2 in the state are in zone 3. The parts of Bhiwani, Gurgaon and Mahendergarh districts have limited aquifer yield prospects as these are underlain by consolidated formations (Dhiman and Gupta 2011).

Groundwater aquifer conditions in Hisar are under unconfined, confined and semi-confined state. The groundwater conditions near surface are unconfined where water is tapped through dug wells for domestic purposes. The confined and semi-confined aquifer conditions exist in the alluvial formations, in which groundwater occurs under hydrostatic pressure and is tapped by shallow tube wells in the region. The rainfall is the main source of groundwater recharge which recharges aquifers annually during rainy season. The other indirect source of recharging of groundwater in the district is groundwater movement from other areas towards the district due to the difference in hydraulic gradient (Rani and Chaudhary 2015). Canals are also the source of recharging in some parts of the district. It has been observed during the field visits, while getting inputs from the local residents that the decline in the groundwater table results into decrease in groundwater quality in most of the area. In the present study, data from 87 observation well locations have been used to evaluate the values of groundwater quality parameters which uniformly represent the study area.

2 Materials and Methods

2.1 Study Area

The study area, which comprises of Hisar district, extends from 28° 53′ 45″ to 29º 49′ 15″ N latitudes and 75º 13′ 15″ to 76º 18′ 15″ E longitudes with an area of 4174 km^2. The district is bounded by Fatehabad district and Rajasthan state on the west whereas the Bhiwani, Jind and Rohtak districts on the south, north and east sides respectively. The location map of the study area is shown in Fig. 1. The area is nearly level with undetectable slopes. The sand dunes presents locally in and around the region are known as *tibbas* and have gentle slopes. The terrain gradient in the region is from NE to SW and then west (Haryana district Gazetteer, Hisar 2011; Rani

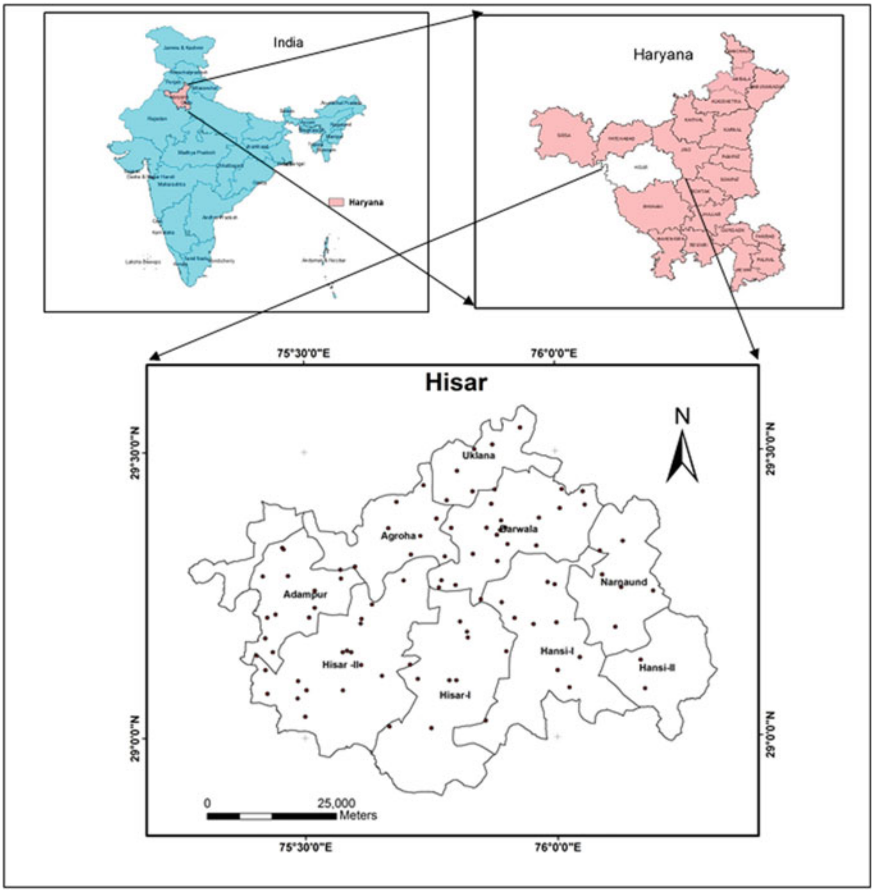

Fig. 1 Location map of Hisar District, Haryana

and Chaudhary 2015). The area comprises of three major geomorphological units. These are Aeolian plain, Chautang flood plain and Older alluvial plain which further have sand dunes, plains, old channels and basin as sub-units. Aeolian activities are dominant in west and south-west parts of district having presence of inter-dunal areas, sandy plains and sand dunes. The study area is a segment of the Indo-Gangetic alluvial plain and owes its occurrence synchronous with the upliftment of the Himalayas (Tandon et al. 2006). This depression has been filled up with the sediments carried from different channels and rivers of southern Aravali hills and northern Himalayas from Pleistocene to recent times (Tandon et al. 2006).

The Ghaggar, Drishdawati and Saraswati rivers have shifted their beds in Holocene times which are reflected as the relict channel beds in the alluvial plain. The area is covered by Aeolian deposits in the recent past with increasing aridity as a result of transportation of sand from nearby Rajasthan area. The Drishdawati and Saraswati rivers have receded leaving inter-locked alluvial fans which were later covered through Aeolian deposits, hence cause present day landscape occurrence (Valdia et al. 2016; Saini et al. 2019). The topography of the study area shows monotonous plains having sporadic presence of bars, depressions, heaps of sand, levees and relict channel courses. Geophysical and borehole data shows the variation in depth ranges of alluvium varies from 100 m to more than 400 m in the district (Haryana district Gazetteer, Hisar 2011).

2.2 Database and Methodology

The study area is covered by Survey of India Toposheet Nos.: H43P-7, 8, 10–12, 14–16 H43Q-03, 04, 08, H43V-09, 13 on 1:50,000 scale. Demarcation of district boundary, digital base map, and other collateral information has been extracted from these toposheets. Data of 87 observation well locations for the years 2000 and 2014 has been taken from Groundwater Cell, Department of Agriculture, Government of Haryana for groundwater quality parameters. The following standard equations have been used for calculating different water quality parameters like SAR, TDS, RSC, TH and PS from ionic concentrations (meq/l) of Na^{+}, HCO^{3-}, $CO_3{}^{2-}$, K^{+} and (Ca^{2+} + Mg^{2+}).

$$\mathrm{TDS} = 0.6 \times \mathrm{EC}$$

$$\mathrm{SAR} = \frac{\mathrm{Na}^{+}}{[(\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+})/2]^{1/2}}$$

$$\mathrm{RSC} = \left(\mathrm{CO}_3^{2-} + \mathrm{HCO}_3^{-}\right) - \left(\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}\right)$$

On the basis of different parameters, EC, pH, RSC, SAR and TDS; the acceptance of groundwater quality for domestic use was decided. Different standards for groundwater quality parameters enumerated as per BIS (1998) and WHO standards (2001, 2008) have been used in the present study and are given in the Table 1.

Table 1 Range of groundwater quality parameters used for drinking purpose

S. no.	Geochemical parameter	Parameter range	Classification
1	Electrical conductivity (EC) (μS/cm)	<250	Low salinity zone (LSZ)
		250–750	Medium salinity zone (MSZ)
		750–2250	High salinity zone (HSZ)
		2250–4000	Very high salinity zone
		>4000	VV high salinity zone (VVHSZ)
2	pH	<6.5	Acidic non-desirable
		6.5–8.5	Desirable
		>8.5	Alkaline non-desirable
3	Residual sodium carbonate (RSC in meq/l))	<1.25	Suitable
		1.25–2.50	Marginal
		2.5–3.0	Unsuitable
		>3.0	Bad
4	Total dissolved solids (TDS)	(<200)	Low salinity zone (LSZ)
		(200–500)	Medium salinity zone (MSZ)
		(500–1500)	High salinity zone (HSZ)
		(1500–3000)	Very high salinity zone (VHSZ)
		(>3000)	VV high salinity zone (VVHSZ)
5	Sodium adsorption ratio (SAR)	<10.0	Excellent
		10.0–18.0	Good
		18.0–26.0	Doubtful
		>26.0	Unsuitable

Interpolation technique of Inverse Distance Weightage (IDW) in Arc GIS Software was used in the present study. Three spatial interpolation techniques of Spline (Regularized and Tension), Inverse Distance Weightage (IDW) and Krigging were used to evaluate the absent values on the bases of remaining values.

However, Inverse Distance Weightage (IDW) was found better both in terms of accuracy and representation of spatial distribution (Goyal and Chaudhary 2010a, b; Goyal et al. 2010; Sethi et al. 2012; Srivastava et al. 2012; Selvam et al. 2013; Rani and Chaudhary 2015; Dhanasekarapandian et al. 2016; Kumari et al. 2018).

3 Results and Discussion

As per guide lines of WHO (2008) and BIS standards (1998), an EC range of 250–750 is suitable for drinking. The EC distribution map of the district (Fig. 2) reflects that the entire area falls under high to very–very high salinity category making it almost impossible to use for drinking purpose. The area wise distribution of EC has been

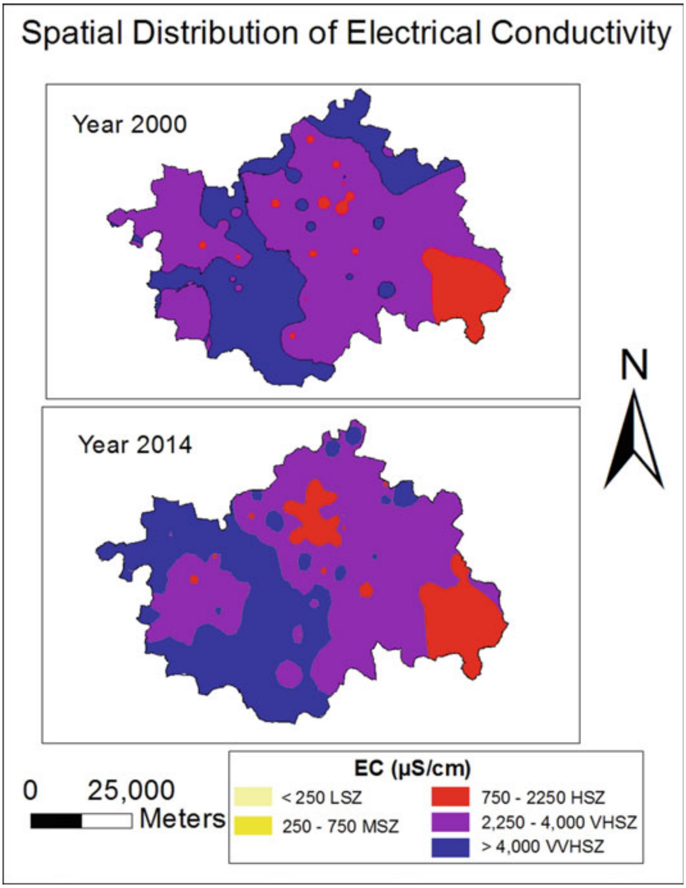

Fig. 2 Spatial distribution of EC in Hisar district in year 2000 and 2014

shown in Table 2. According to BIS standards, the pH value should be in the range of 6.5–8.5 so that it could be used for domestic purpose. The pH values in all observation wells present in district were found between 6.5 and 8.5 for year 2000 whereas for the year 2014, these were found between 7.3 and 9.0 (Fig. 3). May be the presence of high concentration of carbonates and bicarbonates could be causative factor for high pH values in this area. The area wise distribution of pH has been shown in Table 3. RSC of drinking water should be less than 1.25 according to various standards. Dominant portion of the study area i.e. 4149.15 km^2 in year 2000 and 4146.70 km^2 in year 2014, was found under this category and very small area under unsuitable category (Fig. 4). The area wise distribution of RSC has been shown in Table 4. SAR range of drinking water should be less than 10. The range of SAR in district was found in the range 0.1–25.58 and maximum area (3750.68 km^2 in year 2000 and 4173.37 km^2 in year 2014) is having less than 10 SAR range (Fig. 5). The area wise distribution of SAR has been shown in Table 5. According to various standards, the

Table 2 Area covered under different category of EC in Hisar district in year 2000 and 2014

S. no.	Class and range of EC (µs/cm)	Area (km^2)	
		2000	2014
1	Low salinity zone (LSZ) (<250)	–	–
2	Medium salinity zone (MSZ) (250–750)	–	–
3	High salinity zone (HSZ) (750–2250)	345.06	511.44
4	Very high salinity zone (VHSZ) (2250–4000)	2559.52	2154.46
5	VV high salinity zone (VVHSZ) (>4000)	1269.94	1508.62
Total		4174.52	4174.52

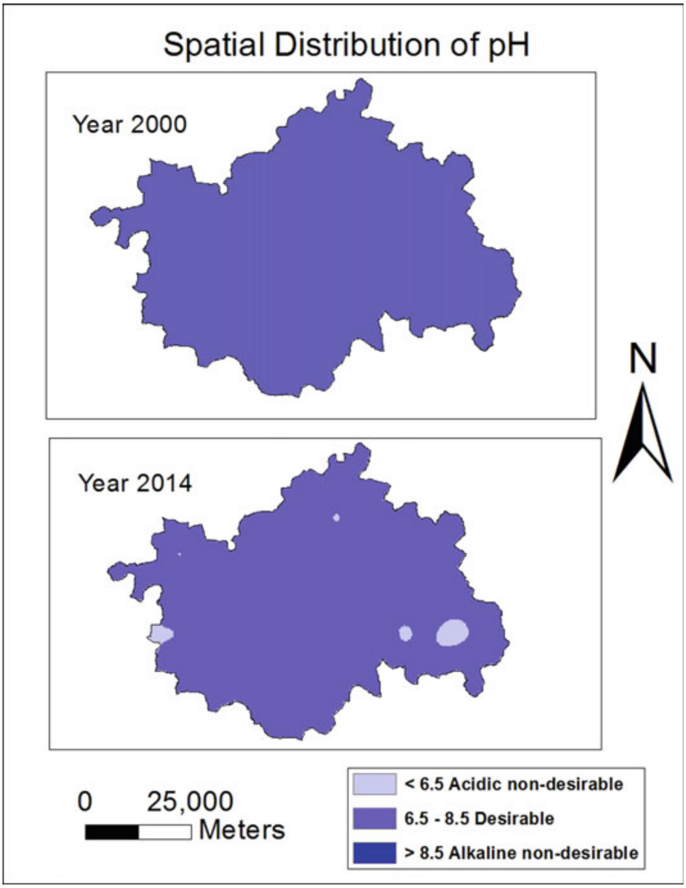

Fig. 3 Spatial distribution of pH in Hisar district in year 2000 and 2014

Table 3 Area covered under different category of pH in Hisar district in year 2000 and 2014

S. no.	Class and range of pH	Area (km^2)	
		2000	2014
1	Acidic non-desirable (<6.5)	–	78.45
2	Desirable (6.5–8.5)	4174.52	4096.07
3	Alkaline non-desirable (>8.5)	–	–
Total		4174.52	4174.52

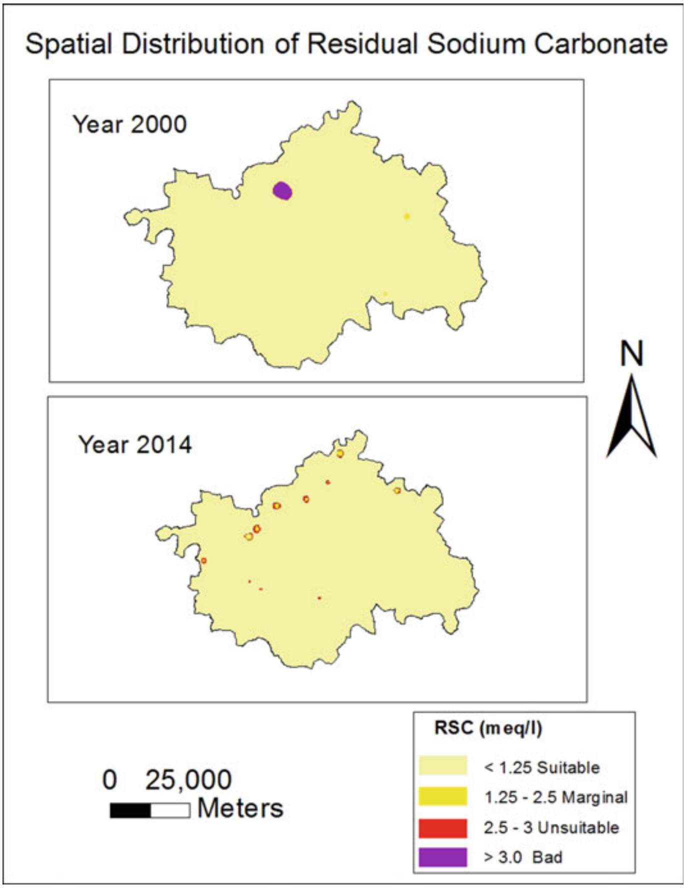

Fig. 4 Spatial distribution of RSC in Hisar district in year 2000 and 2014

values of TDS should be less than 500 for suitability of drinking water but in the district, only 1.3 km^2 area in year 2014 is covered under this category (Fig. 6). The area wise distribution of TDS has been shown in Table 6. Not much variation was observed in the values of pH, RSC and SAR and were found under good category

Table 4 Area covered under different category of RSC in year 2000 and 2014

S. no.	Class and range of RSC	Area (km^2)	
		2000	2014
1	Suitable (<1.25)	4149.15	4146.74
2	Marginal (1.25–2.5)	4.53	15.76
3	Unsuitable (2.5–3.0)	0.66	11.76
4	Bad (>3.0)	20.18	0.26
Total		4174.52	4174.52

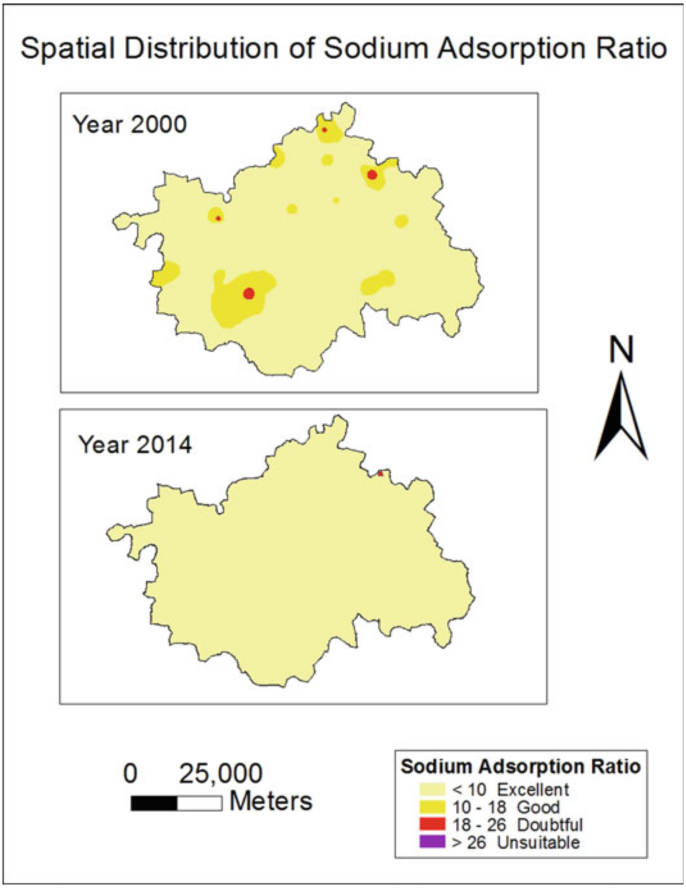

Fig. 5 Spatial distribution of SAR in Hisar district in year 2000 and 2014

Table 5 Area covered under different category of SAR in year 2000 and 2014

S. no.	Class and range of SAR	Area (km^2)	
		2000	2014
1	Excellent (<10)	3750.69	4173.37
2	Good (10–18)	407.23	1.15
3	Doubtful (18–26)	16.60	–
4	Unsuitable (>26)	–	–
Total		4174.52	4174.52

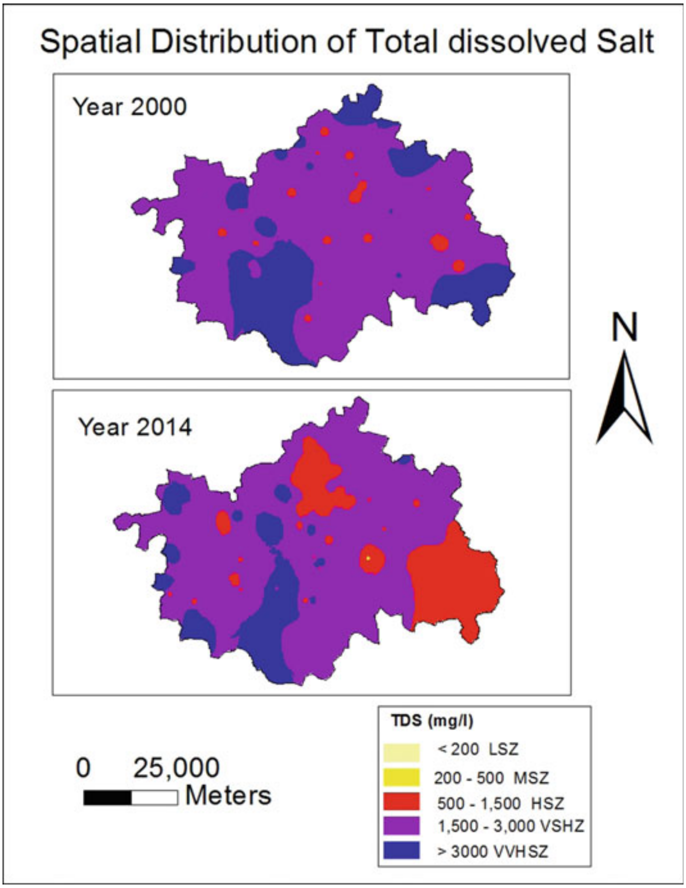

Fig. 6 Spatial distribution of SAR in Hisar district in year 2000 and 2014

Table 6 Area covered under different category of TDS in Hisar district in year 2000 and 2014

S. no.	Class and range of TDS (mg/l)	Area (km^2)	
		2000	2014
1	Low salinity zone (LSZ) (<200)	–	–
2	Medium salinity zone (MSZ) (200–500)	–	1.3
3	High salinity zone (HSZ) (500–1500)	78.29	876.93
4	Very high salinity zone (VHSZ) (1500–3000)	3127.78	2769.77
5	VV high salinity zone (VVHSZ) (>3000)	968.45	526.52
Total		4174.52	4174.52

in the district. But, it is not so in case of EC and TDS. Hence integration of all these parameters was considered for further analysis.

Different maps of EC, pH, RSC, SAR and TDS has been integrated to prepare integrated groundwater quality map for analyzing the suitability for drinking/domestic use in Hisar district, Haryana as shown in Figs. 7 and 8 for years 2000 and 2014. It was observed that maximum area of Hisar district falls in permissible category for domestic use in the year 2000. After comparison of these two maps, it was observed that area under good category has reduced to 55.18 km^2 in 2014 from 1159.71 km^2

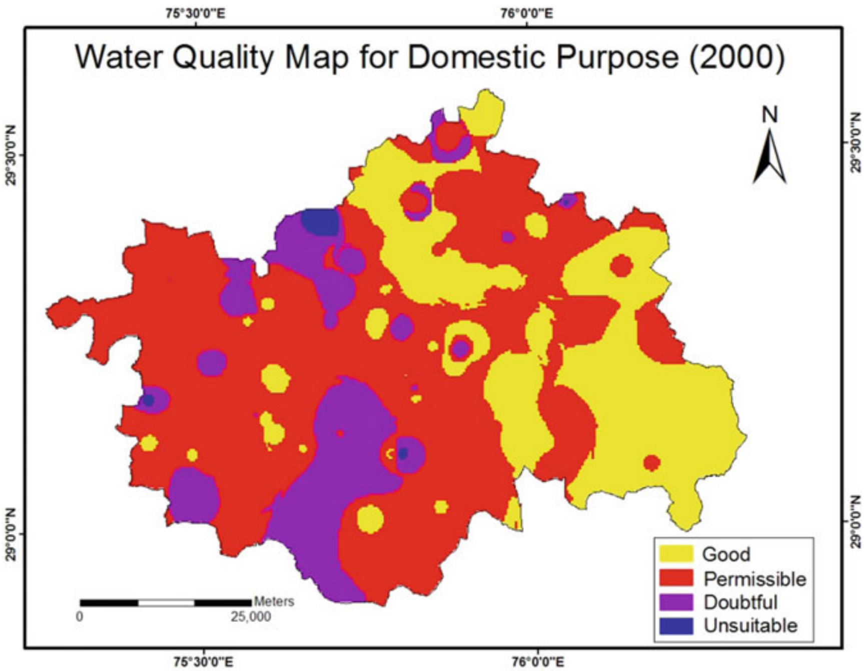

Fig. 7 Integrated groundwater quality map for Domestic use of Hisar district for year 2000

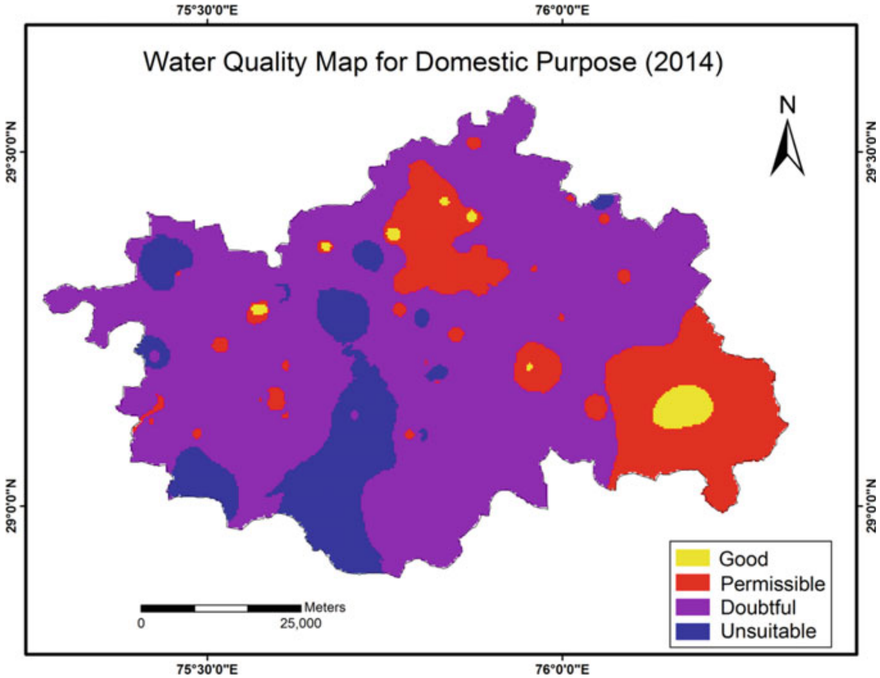

Fig. 8 Integrated water quality map for Domestic use of Hisar district for year 2014

in 2000. It is an alarming situation for Hisar district as groundwater quality of about 1100 km^2 area has changed within a period of 15 years in district. It was also observed that the area under permissible category has decreased by 1662.92 km^2. Moreover the area under doubtful category has increased by 2276.88 km^2. It has also been observed that there was an increase of 469.77 km^2 area under unsuitable category from 2000 to 2014. This reflects continuous deterioration in groundwater quality in the district. Table 7 shows the tabular representation of all these changes in area under various categories.

Table 7 Area covered under different category suitable for domestic/drinking purpose

Category	Area (km^2)	
	Year (2000)	Year (2014)
Good	1159.71	55.18
Permissible	2386.28	723.36
Doubtful	602.92	2879.8
Unsuitable	22.31	492.08

4 Conclusions

Analysis of spatial distribution of groundwater quality parameters was carried out using GIS. To ensure normal distribution the water quality parameters were log-normally transformed. An assessment of the quality of groundwater of Hisar district, Haryana was carried out for year 2000 and 2014 to examine the suitability of groundwater for domestic purpose. Different physio-chemical properties were compared with the international and national water quality standards set for domestic use. It was observed that only EC and TDS of groundwater of Hisar district falls in high to very–very high salinity class and all other parameters—SAR, PS and RSC falls in excellent to good class. Integrated water quality maps for year 2000 and 2014 showed that maximum area of Hisar district falls under good to permissible category for the year 2000 and permissible to doubtful for year 2014.

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Mapping Groundwater Level Fluctuation and Utilisation in Puruliya District, West Bengal

Devarupa Gupta and Priyank Pravin Patel

Abstract With India largely being an agrarian country, having a very significant rural population who are almost entirely dependent on agriculture or agro-based industries for their livelihoods, there has been a constant rise in the demand for water resources (both surface and groundwater) to enable the myriad economic practices. Groundwater extraction has thus continued unabated and only increased in amount and extent throughout the country, more so in its drier tracts, where scare surface water resources push people to obtain water from underground. Thus a substantial number of the rural and urban populations depend on this source to meet their daily requirements and therefore investigating the development and regulation of this vital resource is greatly required. In this study, we examine the groundwater development and extraction status in the mostly arid district of Puruliya, located in the eastern Indian state of West Bengal. We focus on the water table characteristics of this districts' individual blocks and its utilisation therein. The sources of groundwater are mainly located in the weathered, fragmented and jointed lithological entities that cover most of the district and within the narrow sediment filled valleys of the streams that course through this area. Both these source regions are tapped using mainly dug wells. However, during the harsh summers most of these shallower wells run dry causing a quite severe water scarcity. The fluctuation extents of the water table are also considerable, being located at around 6–8 mbgl during the pre-monsoon season and at about 2–4 mbgl during the post-monsoon season. We map these fluctuations seasonally and over time, and also detail the kinds of structures used to extract the groundwater. Overall, the district's southern and northern portions are poorer off in groundwater access than its central and western parts.

Keywords GIS · Groundwater · Puruliya · Seasonal fluctuation · Water table

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1 Introduction

The sustained availability of groundwater is a vital fillip to the socioeconomic development of a region (Okotto et al. 2015; Ward et al. 2016), as its proper utilisation can ensure adequate supply throughout the year for different purposes (Shah 2005; Olago 2019) and avoid marked depletion (Foster and Chilton 2003). It remains a vital resource in the Indian context, as 85% rural domestic purposes and 50% of urban household tasks are met through groundwater and 89% of the total groundwater is used for irrigation (Suhag 2016), and it is thus the sustaining resource behind most agricultural activities and agro-based industries in the nation (Shah 2009a,2009b; Zaveri et al. 2016). The demand for groundwater has surmounted even more due to changes in cropping and land utilisation patterns, especially in northern and western India (Kumar 2005; Tiwari et al. 2009; Chen et al. 2014), as a result of multi-cropping and the growing of high-yielding varieties of crops (Tiwari et al. 2009; Sharma 2016) that often guzzle greater water quantities (Chindarkar and Grafton 2019; Kayatz et al. 2019). Therefore proper monitoring and knowledge of groundwater levels in a region (Birkenholtz, 2008) is very important to keep it from becoming over-exploited (Fetter 2001; Bierkens and Wada 2019), discern its vulnerable areas (Adhikary and Dash 2017) and to also check pollution levels where required (Singh et al. 2005). While drilling and testing for water levels is often time consuming and expensive and not always feasible in all locales (Fetter 2001), preliminary assessments can be readily made using geographical information system (GIS) based methods and secondary remotely sensed and quantitative datasets available in the public domain (Rodell et al. 2009; Bhunia et al. 2012; Agarwal et al. 2013; Jasmin and Mallikarjuna 2013). Many studies have thus been based on using these methods and geospatial datasets of different types to gauge the suitability of locales for storing groundwater reserves (Sree Devi et al. 2001; Sankar 2002; Dhakate et al. 2008; Nag and Kundu 2016) or to delineate water table recharge zones, especially in groundwater scarce areas like hard rock terrains (Bhunia et al. 2012), by interpreting surface morphological features and lineaments (Nag 1999; Javed and Wani 2009; Murugesan et al. 2011; Nag and Ghosh 2013).

Purulia district in West Bengal is one of the noted drier districts of the country (Bhunia et al. 2019) and this region has experienced a number of droughts over the past century (Gupta et al. 2011). Thus it always remains in focus due the deficiencies faced in surface and groundwater availability (Ghosh 2019). While much recent work has been done on detecting potential groundwater zones in this region (e.g. Ghosh et al. 2016; Bera 2018; Das et al. 2018; Ghosh and Jana 2018; Maity and Mandal 2019), there is comparatively much less literature on the nature and spatial variation of groundwater status vulnerability (Mondal et al. 2019) and fluctuation overall, particularly in Puruliya district (e.g. Roy et al. 2015; Vishwajith et al. 2015a, b), and often only of select locales within it (e.g. Moyra 2015; Das 2018; Kundu and Nag 2018). Often groundwater fluctuation studies present only three simplistic scenarios of the mean pre-monsoon, monsoonal and post-monsoon groundwater level status for an area, using long to medium term datasets. There is however a pressing need to assess the rise and fall of the groundwater table in a region across each quarter (every three months) of the year and for the individual years over a medium to long term period to ascertain how and where changes occur in the groundwater table. This has been comparatively less addressed in the literature and thus represents a small research gap. These quarterly changes can then be linked to the nature of the agricultural cycle in the region and its climatic regime (Haldar and Saha 2015) and the implementation of various groundwater harvesting and irrigation measures (Chowdhury and Behera 2018; Banerjee et al. 2019), with comparison of respective quarterly figures across the years eliciting whether there are changes in the status quo of the groundwater table in that region over time. Furthermore, rather than presenting a holistic figure for an entire district, more detailed assessments are required for the changing status in each block, for better analysis. This paper thus uses the available depth to groundwater table information for a large number of stations in Puruliya district, distributed across the different blocks, to ascertain the medium term fluctuations in the groundwater level, across each of the seasons or cropping periods. Based on the above context, we aim to (1) Assess the block-wise extents of fluctuation in groundwater levels (utilization and replenishment) and (2) Document the various irrigation implements and groundwater extraction status in Puruliya district.

2 Methodology

This work is primarily based on secondary data, as follows:

1. Groundwater information and station-wise data accrued from the Central Groundwater Board (CGWB), Eastern Region, Kolkata.
   The groundwater information used in the work was from 2005 to 2013. This data pertained to the position of the groundwater table below the surface as recorded four times a year. The assessment periods were as follows:
   - After completion of *rabi* Crop—post-winter level (during January/February).
   - During the pre-monsoon stage (in May)—where the water table dropped to its greatest depth from the surface.
   - During the monsoon (August)—where the water table was nearest to the surface.
   - In the post monsoon stage (November).
     Using the above four primary variables, the following secondary parameters were tabulated for each year for each of the sampled locations:
   - Change in depth from pre-monsoon depth to monsoon level of same year = rise due to recharge.
   - Change in depth from monsoon to post-monsoon level of same year = drop due to utilisation during *kharif* crop.
   - Change in depth from post-monsoon to post-winter level of next year = drop due to utilisation during *rabi* crop.

- Change in depth from monsoon level to post-winter level of next year = drop due to total utilisation from *kharif* and *rabi* crops.
- Change in depth from post-winter level of next year to pre-monsoon level of next year = further drop during dry period.
- Change in depth from monsoon level of this year to pre-monsoon level of next year = cumulative decrease in groundwater depth due to total abstraction or utilisation.

2. District and ward-level administrative and groundwater data, maps and reports from Puruliya Municipality and from the Census.
3. The SRTM (Shuttle Radar Topographic Mission) DEM (Digital Elevation Model) dataset for deriving elevation attributes and information from the Geological Survey of India on the area's lithological aspects were used to prepare the relevant maps.
4. Collating published reports and prepared maps on the groundwater utilisation status in this district.

Data obtained from the Central Groundwater Board was processed to obtain the change in groundwater level during various periods in a year. The isopleth maps representing the depth to groundwater surface were prepared using GIS softwares like Mapinfo Professional GIS and ArcGIS and the groundwater level data for a total of 74 sites was tabulated, enumerated and mapped. The changes in the water table was thus analysed across the years. Cartograms were used to quantitatively represent the above spatial distribution of the groundwater fluctuations. Finally, representative 3D surfaces for the various information were created using Surfer software.

3 Study Area

3.1 Location

Puruliya is situated in south-western West Bengal, (22°43′ N–23°42′ N and 85°49′ E–86°49′ E), falling in parts of Survey of India toposheets nos. 73E, 73I and 73 J. The district covers an area of about 6,259 km^2 and is divided into 20 blocks (CGWB 2006a) (Fig. 1).

3.2 Physiography, Geomorphology and Drainage

The district can broadly be classified into various physiographic units—denudational hills and isolated hillocks, pediments, dissected plateau and highlands, undulating and gently sloping uplands and valleys (GSI 2000; DST–GoWB 2000). The district has moderate overall altitude and relative relief, with rolling landscape alongside

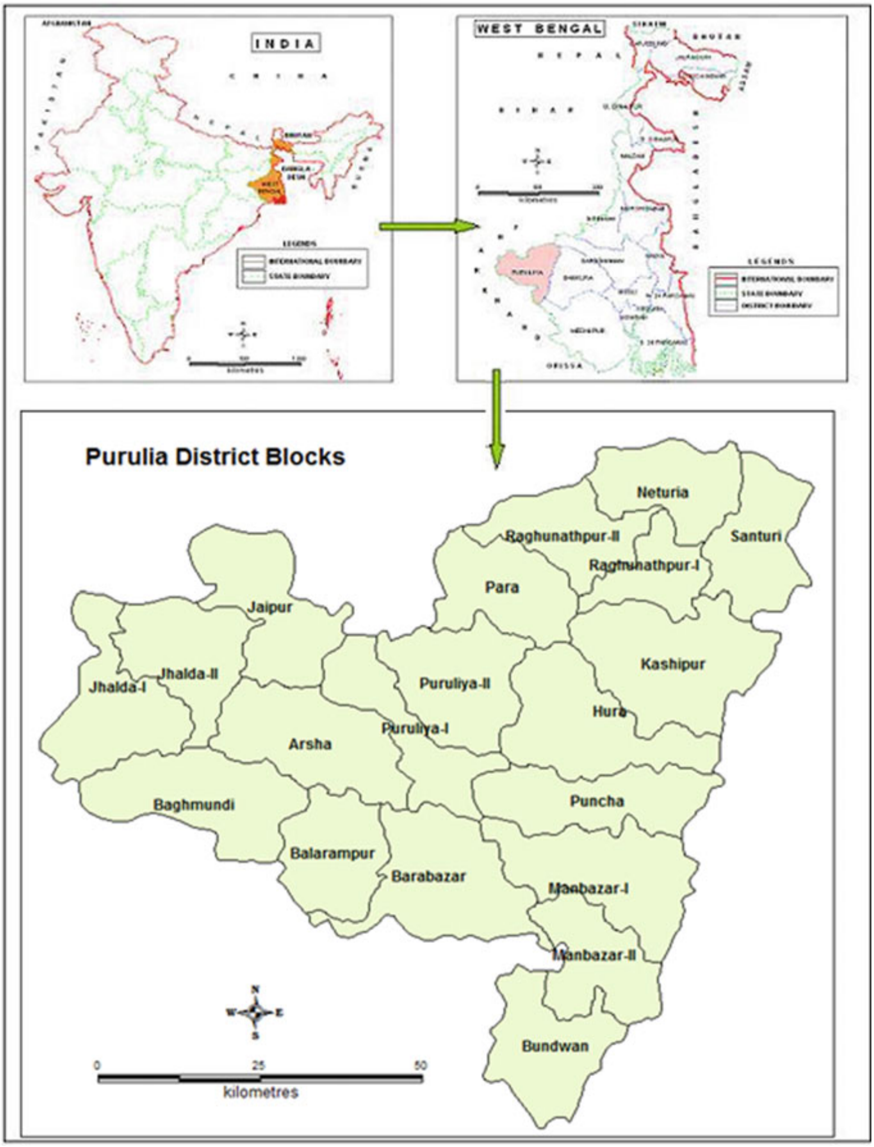

Fig. 1 Location Map of Study Area. *Source* Prepared from Census of India Administrative Atlas

hilly and rugged terrain, which are generally associated with fringe areas of the Chotonagpur Plateau (Patel and Sarkar 2010; Sarkar and Patel 2011, 2012, 2016). The elevation ranges between 150 and 300 m (Fig. 2), with the master slopes being towards the east and southeast. Altitude increases west and southwards, as denoted by abruptly rising hills having dense vegetation. The district has two broad physiographic entities:

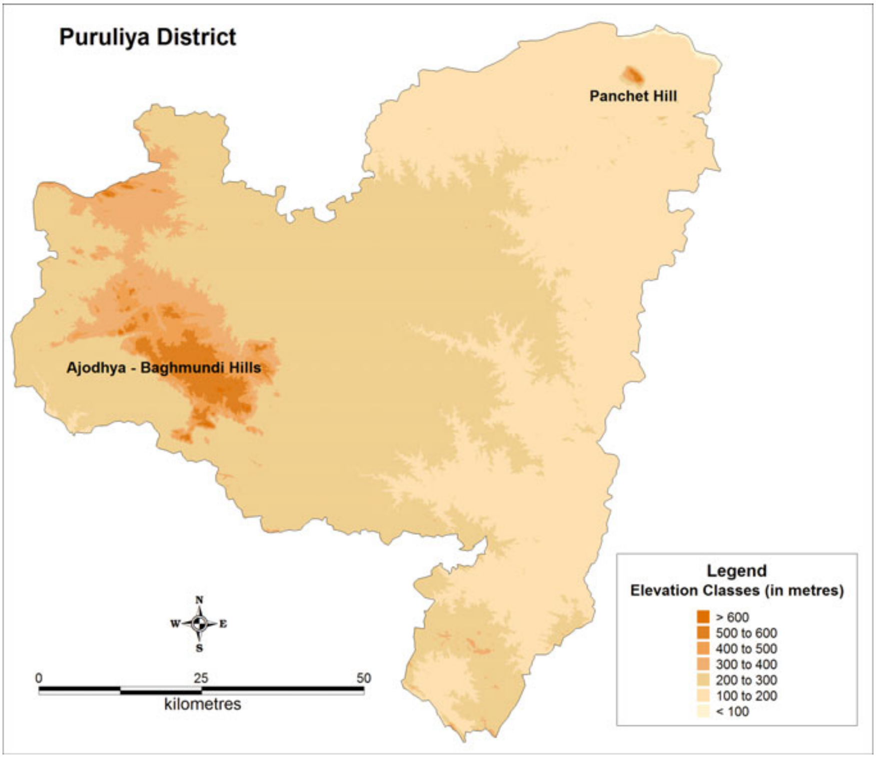

Fig. 2 Elevation map of the study area. *Source* Prepared from USGS SRTM & GSI datasets

the hilly terrain in the western and the southern part, where Ayodhya, Gorga Buru, Raika Pahar and Churni Pahar are the important hills and the undulating plain with isolated mounds and hills in the northern and eastern part which consists of 70% of the district area. The two highest peaks, Gorga Buru (677 m) and Karma Hills (663 m) are in the Baghmundi scarp. In the eastern–southeastern portion, slopes range from 10–20 m/km while for the middle section, this is >10 m/km, forming a basin. Westwards, slope values are higher, ranging from 20 to 80 m/km. The rivers Kasai, Damodar and Subarnarekha are the main perennial rivers of the district. The Kasai is the most important river in Puruliya, which is joined by its major tributary Kumari, in the southern part of the district.

3.3 Geology

The district is mostly covered by metamorphic Precambrian rocks, except minor portions in its north-eastern section, where Gondwana deposits are present (Fig. 3). Recent alluvial and colluvial deposits that are mostly unconsolidated occupy the

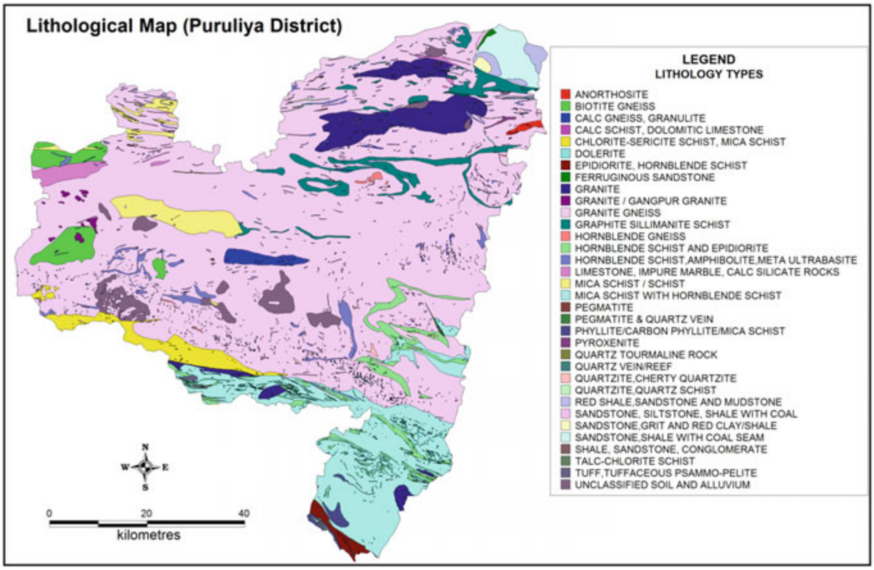

Fig. 3 Lithological Map of Puruliya District. *Source* Prepared from GSI datasets

narrow valleys carved by streams (Nag 2009). Most of the exposed rocks are granitoids. The entire district may broadly be divided into two geological formations, namely- the Archaean formation of granite and gneiss and the Gondwana formation of sedimentaries. The Achaeans are the oldest and the most extensive rock formation in the district. They comprise of granitic rocks, meta-sedimentaries, calc-granulites and meta-basics. The older schistose rocks include phyllite, quartz-schist and quartzite. The granitic rocks include grey banded biotite, granite gneiss, pink granite and porphyritic granite gneiss. The rock formations have numerous joints, being fractured and these also house numerous lineament swarms (GSI 2000). The SPSZ (South Puruliya Shear Zone), trends quite E-W, forming along the northern juxtaposition of the Singhbhum Group with the Chhotanagpur Gneissic Complex that traverses just south of Balarampur and this feature is indicative of brittle-ductile deformations (Bhattacharya 1989; Dasgupta 2004). Quite a few previous studies have analysed the impact of these lineaments on the local groundwater potentialities (Acharya et al. 2012; Acharya and Nag 2013; Nag 2005, 2013).

3.4 Hydrogeology

According to CGWB Reports (2004, 2006a), groundwater in the district occurs mainly in:

1. **Weathered Mantle**—This varies in thickness, upto a maximum thickness of 25 m. Groundwater is mostly extracted through dug/open wells as it manifests in water table condition.
2. **Saprolitic Zone**—At 10–30 mbgl, with an average thickness of 4 m, this zone has water in semi-confined condition.
3. **Fractured Zones of Hard Rock**—Fractures at relatively shallower depths of 50–60 m are exploited through borewells (handpump fitted) and their yields range from <1 to 2.77 lps. Where there is the presence of deeper fractures (at depths of 100–110 m), these yield around 3 lps at Manbazar. In the Gondwana sediments, drilling down to 103 m reveals the existence of fractures between 24–36 mbgl, which are capable of yielding 3.3–5.5 lps (CGWB 2006a).
4. **Narrow zone of unconsolidated sediments along the river valleys**—These are of limited thickness and fall within 5–13 mbgl, with an areal extent not exceeding 1–2 km across river valleys. Open wells and shallow tube wells are mostly in operation, yielding up to 20m^3/hr at economic drawdown for a considerable period of pumping (CGWB 2006a, 2006b).

3.5 Soil Cover

Soils in the district are in general of the residual type, having formed as a result of the weathering of the Archaean granitods and schists. Laterite and red soils prevail in the uplands while in the valleys reddish clay loams or white to reddish clays are common. Many textural classes can be noted- stiff clay of white or reddish hues and red-brown or sandy loams. A product of the rolling topographical facets, the soil cover is mostly thin and contains gravels or in some places even plinthite, being generally acidic, with fertility levels thereby being low.

3.6 Climate

Hot summers and cold winters characterize the climatic regime. The average annual rainfall is 1363 mm (IMD 2006).The hottest month is May (mean daily maximum and minimum being 40.3 °C and 27.2 °C, respectively). Conversely, January is the coldest month with corresponding values of 25.5 °C and 12.8 °C. The soil temperature class is “hyperthermic”. Puruliya district belongs to the agro-ecological sub-region 12.3 (AESR), which is described as being part of the Chhotonagpur plateau (NBSS&LUP 2000). Dry, hot winds blow in the summer through the district with a velocity of 5–6 kms/hr.

3.7 Land Cover and Land Use and Cropping Sequence

There are a number of protected/reserved forests, most notably towards the south-western (Matha P.F. around the Ajodhya Hills in Baghmundi Block) and western part of the district (Ratamjuri R.F.). The forested areas are generally of higher elevation and steeper slopes, often containing a number of rock exposures on which fractures are clearly visible. Cultivation in the district is predominantly mono-cropped (Fig. 4) and about 73% of all tilled plots (mostly sowing rain-dependent *aman* paddy in fragmented fields) belong to marginal and smallholder farmers. The net cropped proportion of the district is 50% while only 17% is multi-cropped. Farming is thus mainly of the subsistence type. On the whole the undulating surface has been broken up into an almost interminable sequence of *aals* which divide up the many field plots. The height of the *aals* varies from about 50 cm to almost a metre in some places, reflective of the steep rise in the local terrain. The field plots in such a landscape are generally aligned along the small nalas and streams or *bahals*, as is seen elsewhere in the region (e.g. Patel and Dasgupta 2009; Patel and Mondal 2019) in such similarly undulating terrain. Where depressions have formed, local groundwater may rise to the surface or rain water may accumulate and create ponds. A large proportion of the land in each block remains as current fallow, primarily due to the fact that these are all mono-cropped land due to poor irrigation facility year round. In a semi-arid

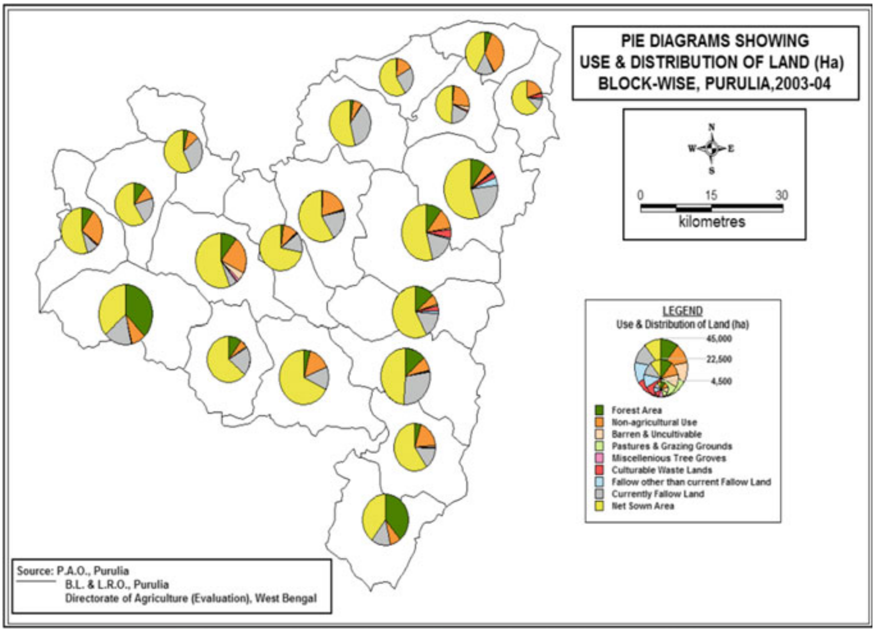

Fig. 4 Block-wise composition of land use and land cover units

region like Puruliya, where monsoonal rainfall is limited, increasing groundwater based irrigation is therefore very important.

4 Groundwater Extraction Modes (Specifically for Irrigation)

The three types of groundwater harvesting structures seen in the area (MoWR GoI 2001) are:

i. **Dug well**: The most common and of different dimensions, holed-out or sunk in the ground, being primarily kuchcha, dug/bore or of masonry architecture. These are private entities (i.e. belong to the farmers themselves) and are the overwhelming majority type present—almost 95% (Tables 1 and 2).
ii. **Shallow tubewell**: Based on boreholes for tapping shallower porous zones, not exceeding 60–70 m. Usually are operative for 6–8 h drawing 100–300 cubic metre/day, about 2–3 times more than possible via a dug well.

Table 1 Source-wise irrigation in Puruliya district

Source of irrigation	Culturable command area		Irrigation potential		Actual area irrigated	
	Number	Area (ha)	Number	Area (ha)	Number	Area (ha)
Dugwell	13,322	4998.58	13,322	10,114.96	12,796	4025.91
Shallow	2	4.80	2	4.80	2	4.00
Surface Flow	21,286	94,311.65	21,286	104,004.17	19,467	59,428.49
Surface Lift	313	8054.20	313	11,855.72	311	3444.00
Total	**34,923**	**107,369.23**	**34,923**	**125,979.65**	**32,576**	**66,902.40**

Source Official website of Puruliya District (www.puruliya.gov.in—accessed 10.12.2013)

Table 2 Season-wise actual area irrigated by source in Puruliya district

Source of irrigation	Season-wise actual area irrigated					
	Kharif	Rabi	Boro	Perennial	Others	Total
Dugwell	983.56	2767.90	15.25	83.02	191.43	4025.91
Shallow	0.40	1.20	0.40	1.20	1.20	4.00
Surface Flow	47,376.63	9936.11	2571.23	143.53	1972.22	59,428.49
Surface Lift	1721.49	1469.53	132.10	19.84	233.14	3444.00
Total	**50,082.08**	**14,174.74**	**2741.06**	**247.59**	**2397.99**	**66,902.40**

Source Official website of Puruliya District (www.puruliya.gov.in—ccessed 10.12.2013)

iii. **Deep tubewell**: Constructed under public schemes, these traverse till 100 m or more depth and draw 100–200 cubic metres/hour. They function primarily during the irrigation season, based on electricity availability, with outputs about 15 times more than shallow tube wells.

5 Groundwater Fluctuations and Utilization Structures

The data obtained from the 74 CGWB stations across the district (Fig. 5) were plotted against the respective locations of their stations and the required computations were performed. The generated water table depth maps are presented.

The water table in general varied from 6–8 mbgl in the pre-monsoon and from 2–4 mbgl in the post-monsoon (CGWB 2006a). The most north–eastern and southern portions had water table depths at more than 8 mbgl. Overall, this depth fluctuation is from 3–4 mbgl. Greater variations occur in the Gondwana and schistic rocks with lesser variability within granitic zones (CGWB 2006a). Longer duration water table

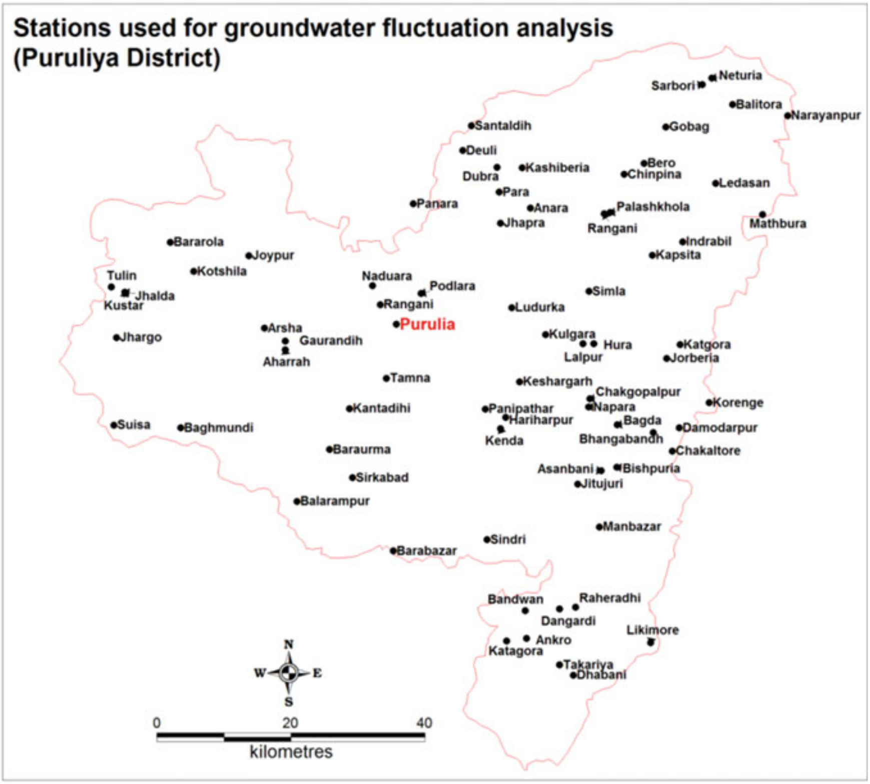

Fig. 5 Groundwater level measuring stations in Puruliya District

attitudes, as was previously projected by the CGWB from its 11 stations, revealed three trends, viz. pre-monsoon falling to post-monsoon rising; pre-monsoon falling to post-monsoon falling and pre-monsoon rising to post-monsoon rising (CSME 1997).

Figure 6 shows the average depth of groundwater according to different seasons in Puruliya for over time period from 2005–2013, as per the data availability. The pattern shows that the water table remains high in the monsoon period and in the post monsoon period and is lower for the summer months. Figure 7 shows the change in the water table over the years during the period of monsoon from a three dimensional view. The cross sectional view of the level of groundwater according to different seasons in the district and the average recharge and discharge of groundwater level due to extraction of water show marked fluctuations in some locations (Fig. 8). Due to unavailability of data continuously for all the stations across the district the right side of the diagram remains a little distorted. The average rise of the water table due

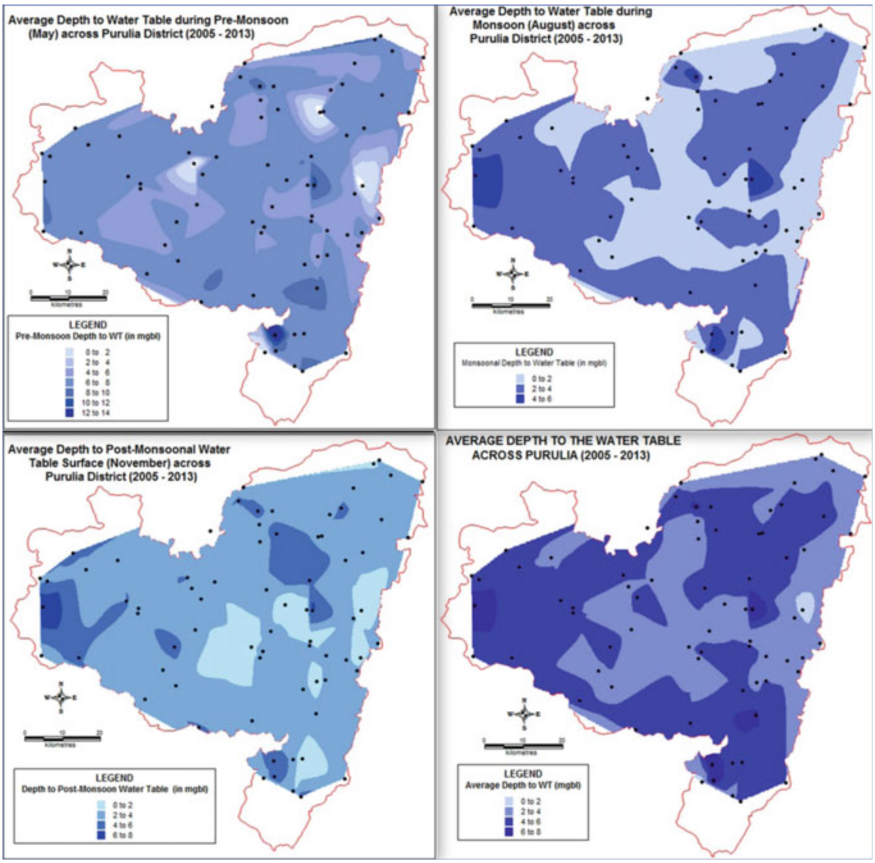

Fig. 6 Average depth to water table in different periods and overall

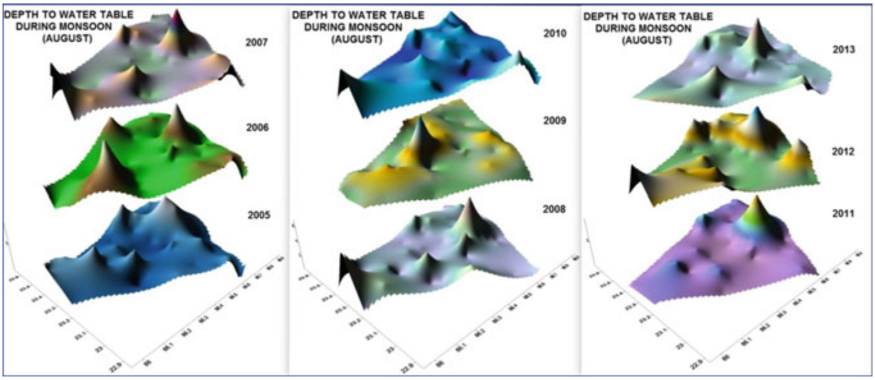

Fig. 7 Average depth to water table changes year-wise

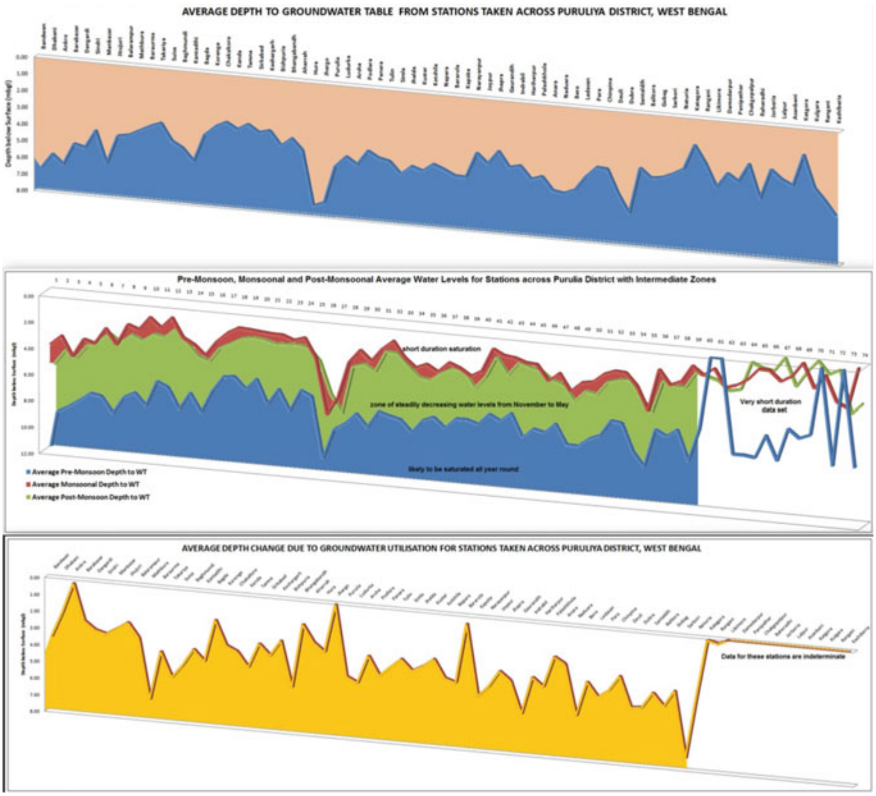

Fig. 8 Average depth to groundwater tables, average depth of water in different seasons and change in average depth of groundwater table due to utilization across Puruliya district (2005–2013)

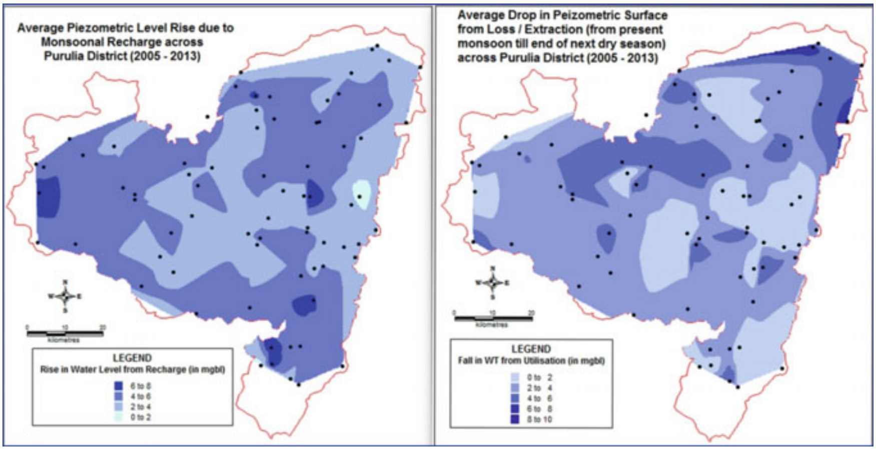

Fig. 9 Average water table rise due to monsoonal recharge and average drop in water table due to utilization across Puruliya district (2005–2013)

to monsoonal recharge and the drop in the surface from loss and extraction of water across different stations in Puruliya for the time period of 2005–2013 has also been shown (Fig. 9).

The pre-monsoon water level ranged from 4.32 to 11.68 mbgl and during the post-monsoon this was 2.07–5.60 mbgl in groundwater monitoring wells during 2006. Seasonal fluctuation marked variations in the water level. The maximum rise of 9.01 mbgl is recorded in Hura block. A decadal rising trend (1997–2006) for pre and post monsoon was recorded in an earlier study on Arsha, Bagmundi, Barabazar, Bandwan, Jhalda I&II and Puncha blocks (CGWB 2006a). The rest of the blocks experience rise as well as fall during the pre and post monsoons. The regional fluctuations are generally restricted to 2.0 mbgl.

For analysis of the most notable way in which the groundwater in the district is utilized and plays a role in the above fluctuations, we have used data about the minor irrigation structures and examined this aspect in much more detail (Figs. 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22). Since more recent data on this aspect is yet not fully available in all required details at the village level, we have had to, perforce use older data from former such reports for this purpose. As per the Minor Irrigation Census 2001, the number of dug wells constructed was 4218 in the district and this was the most important means of groundwater extraction. There was hardly any great increase in dug wells from the 1990 to 2001. The western and the central blocks had the highest number of dug wells. The initial years of the 1990 decade saw greater numbers of dug wells being constructed but then their numbers declined markedly towards the end of the decade. Only three blocks show an adequate and high number of dug wells being made, the rest lag far behind. The overwhelming majority of dug wells constructed are of *pucca* type. It is only in a few blocks in the western portion of the district that a portion of them are of the *kaacha* type. Individual

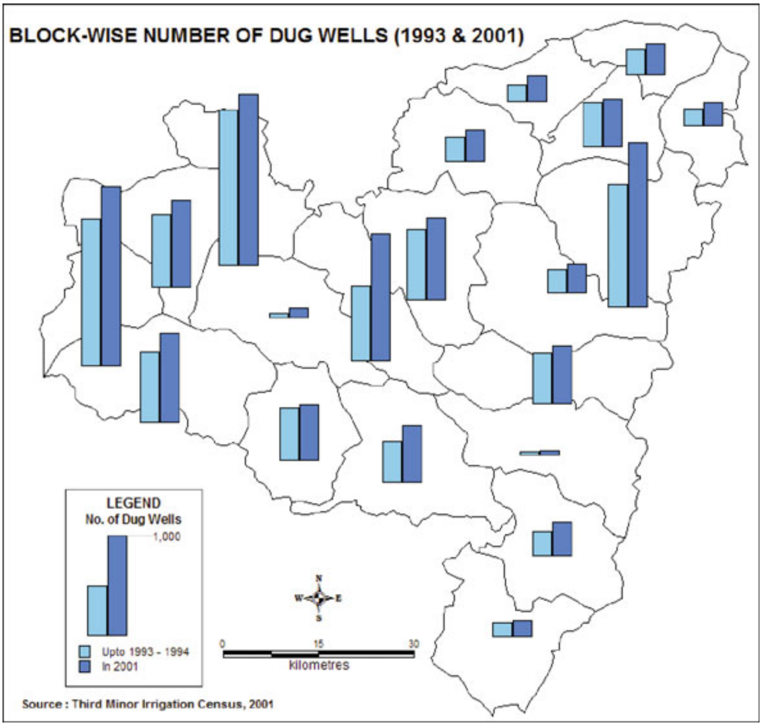

Fig. 10 Dugwell numbers (1993 and 2001)

farmers, followed by government agencies and then some panchayats own the most number of dug wells, respectively. The majority of the owners belong to the general or other social status type. *Kharif* followed by *rabi* crops are the two types most benefited by the creation of dug wells and supply of water to the fields during the non-rainy months. A large majority of dug wells are operated either manually or through manual power and the open-channel means of water distribution into the fields is the most prevalent one. The western blocks of the district utilize a greater portion of groundwater resources than the eastern side.

6 Conclusion

The state of groundwater utility (as per the data) was shown to be limited and not fully explored. To augment the existing structures in place, more extraction structures could be erected and this should be replenished with surface recharge measures. The feasibility of a particular groundwater structure will depend on the local hydrogeological setup and the amount of water required for varied usage. Shallow tube wells and dug wells are mainly suitable for private usage as it involves the farmer's

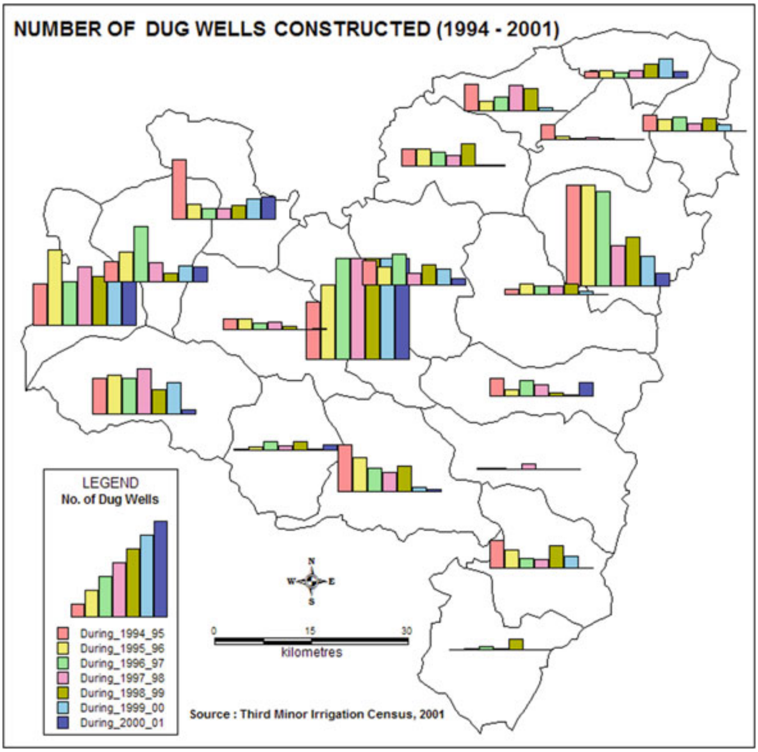

Fig. 11 Dugwell changes from 1995 to 2001

participation in a cooperative manner and also requires less expenditure on maintenance. Groundwater development through medium duty deep tube wells may be done but these involve a high cost for construction and maintenance and could thus be looked after by the concerned government department. Based on the above aspects and facts, some possible measures might be feasibly considered (proposal adapted from CSME 1997). Initially, sites requiring water harvesting structures on a priority basis are Baghmundi, Puncha, Jhalida-II and Banduan. After this, the same can be done at Kashipur, Raghunathpur-II and Manbazar-II areas. Finally, places like Puruliya-II, Arsha and Jaipur may be considered for the same. The locations in which these dug wells can be constructed can be determined using lineament intersection zones in combination with other morphological variables. Falling water-level trends are also apparent in most of the region especially during the post-monsoon phase (CGWB 2006a), particularly in blocks like Banduan, Baghmundi, Jhalda-II, Puncha, Manbazar-II, Raghunathpur-II and Kashipur blocks. Groundwater draft regulations are thus paramount.

Groundwater is possibly the most important ambient resource in Puruliya district as its proper utilisation holds the key to irrigate and bring under more-than-one crop status a larger portion of the cultivable area. There needs to be a judicious choice

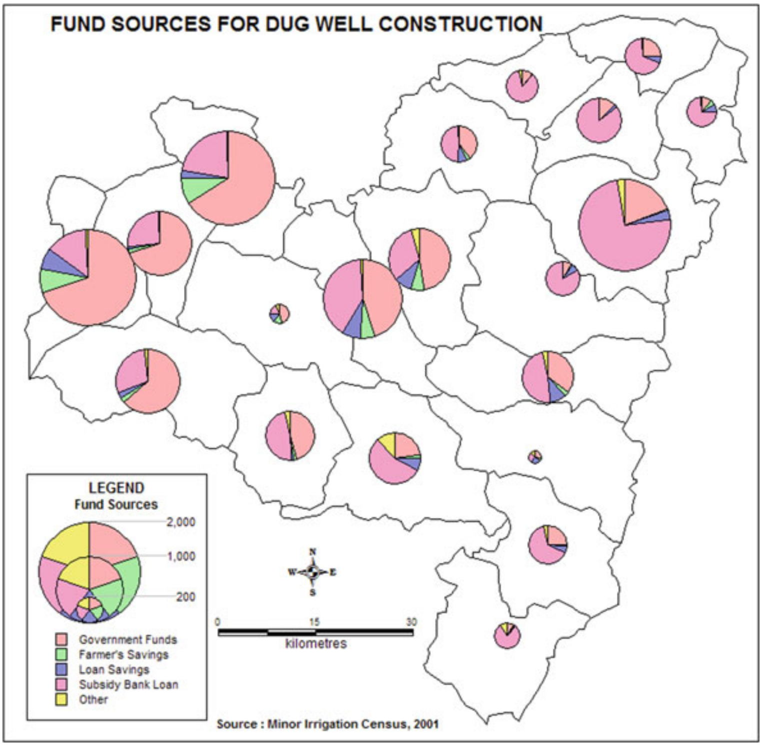

Fig. 12 Dugwell construction fund sources

of locations where the new groundwater harvesting structures can be set up and furthermore the provision of electricity is required throughout the district in order that deep tube wells can be operated in order to make it worthwhile for the farmers using them. The present utilisation status shows that there is an unequal level of development of groundwater extraction among the various blocks. The northern and southern reaches of the district are seemingly poorer off than the central and western parts.

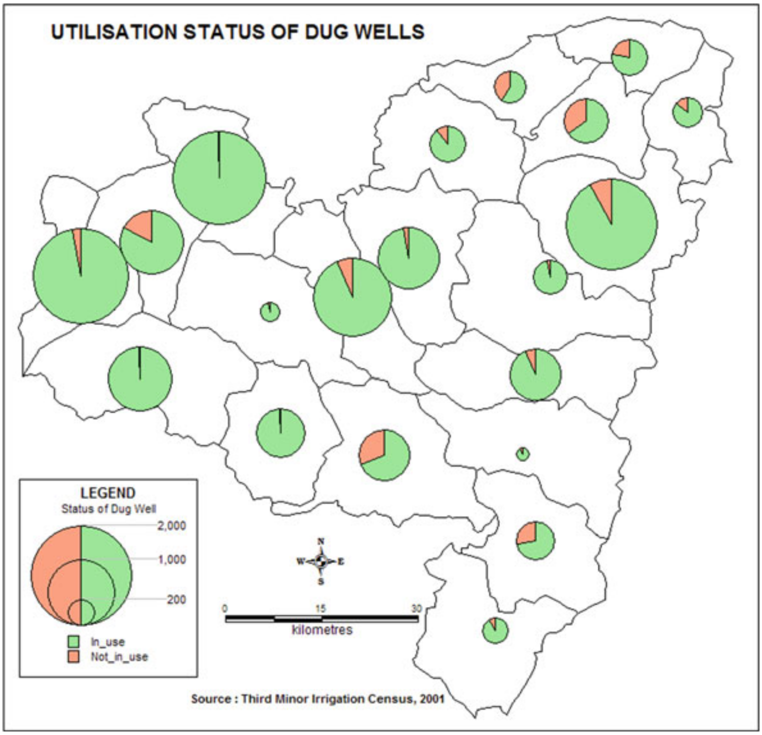

Fig. 13 Dugwell utilization status

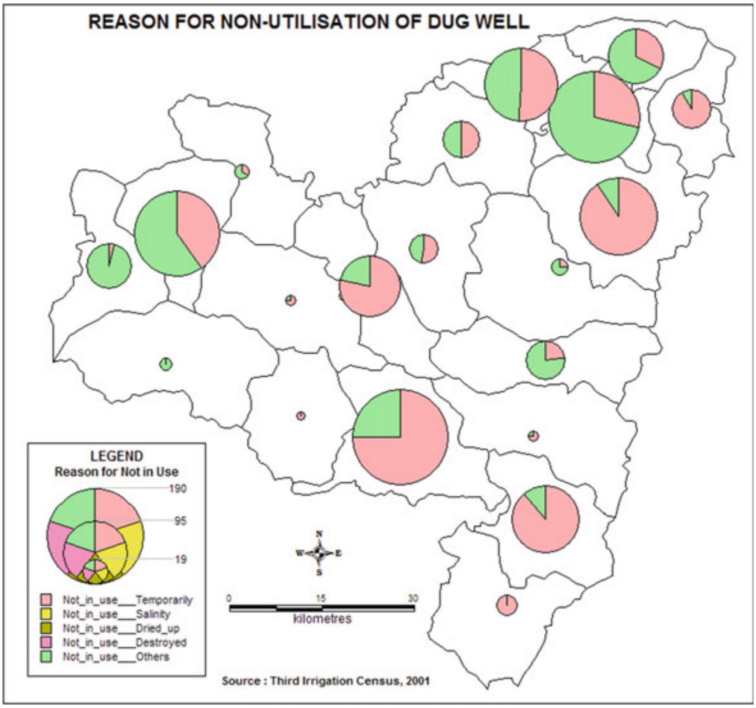

Fig. 14 Dugwell non-utilization status reason

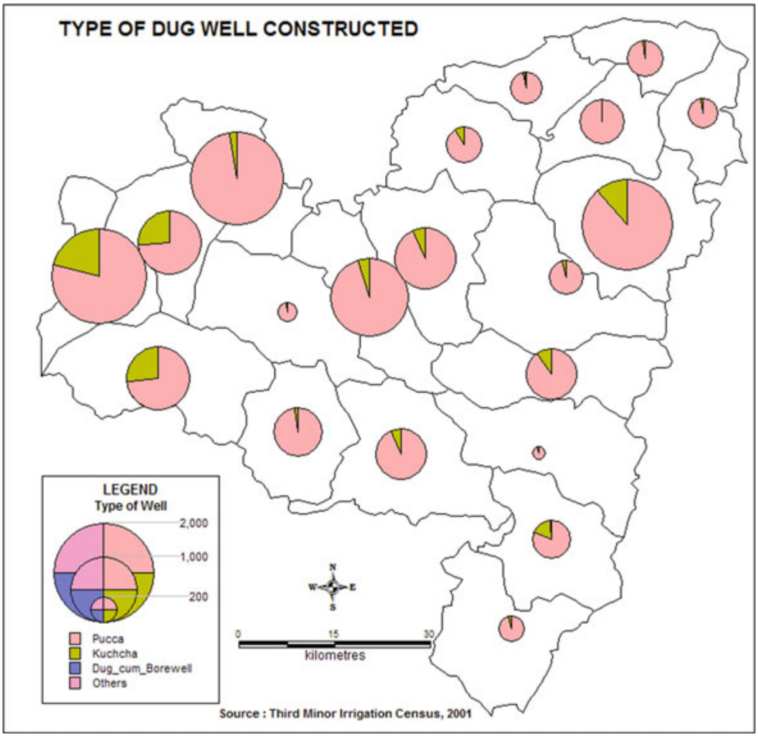

Fig. 15 Type of Dugwell construction

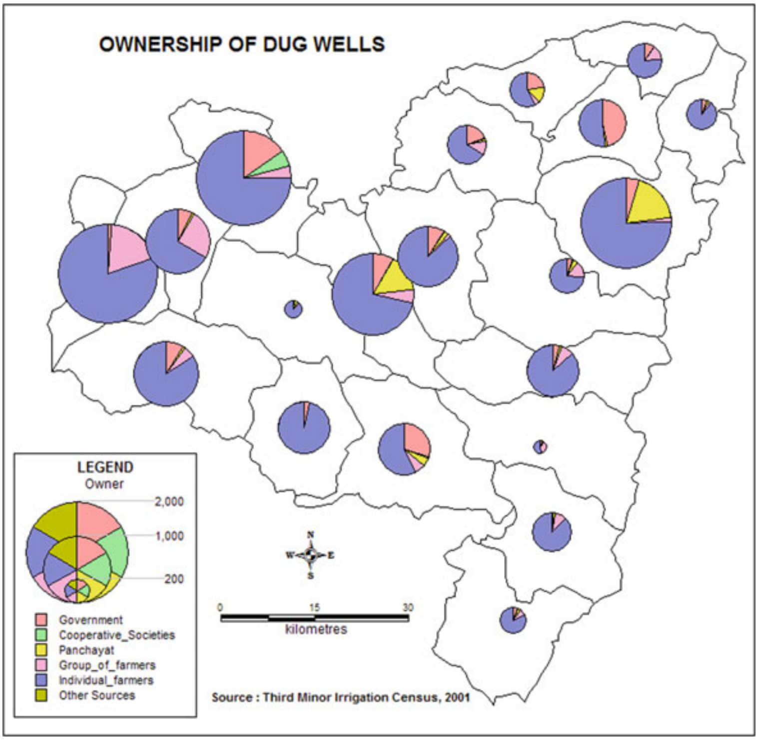

Fig. 16 Dugwell ownership

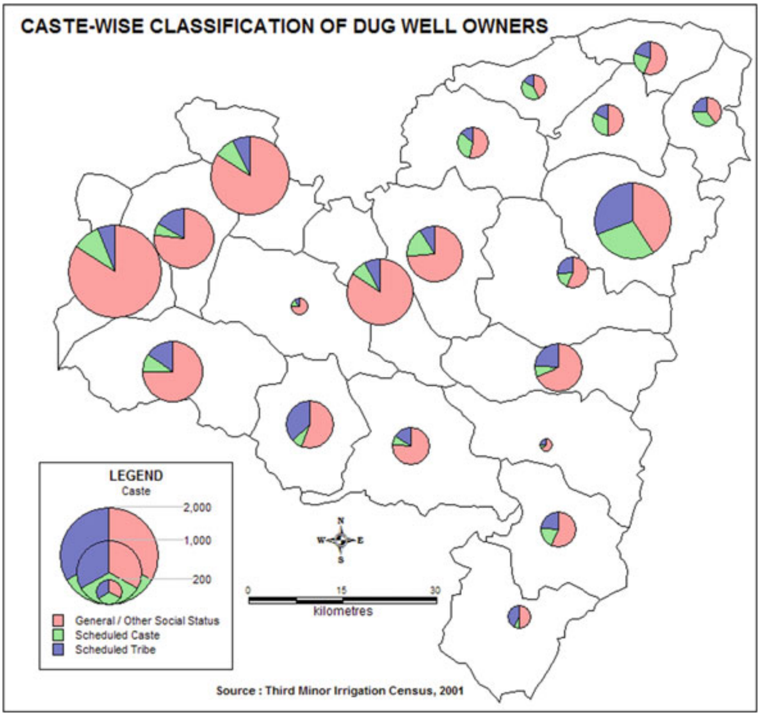

Fig. 17 Dugwell ownership category by caste

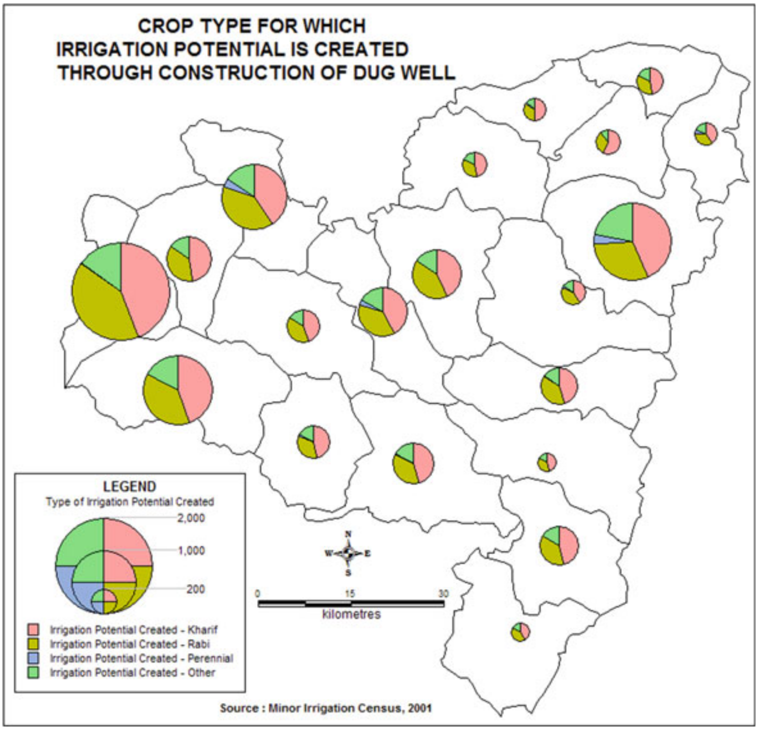

Fig. 18 Dugwell based crop potential

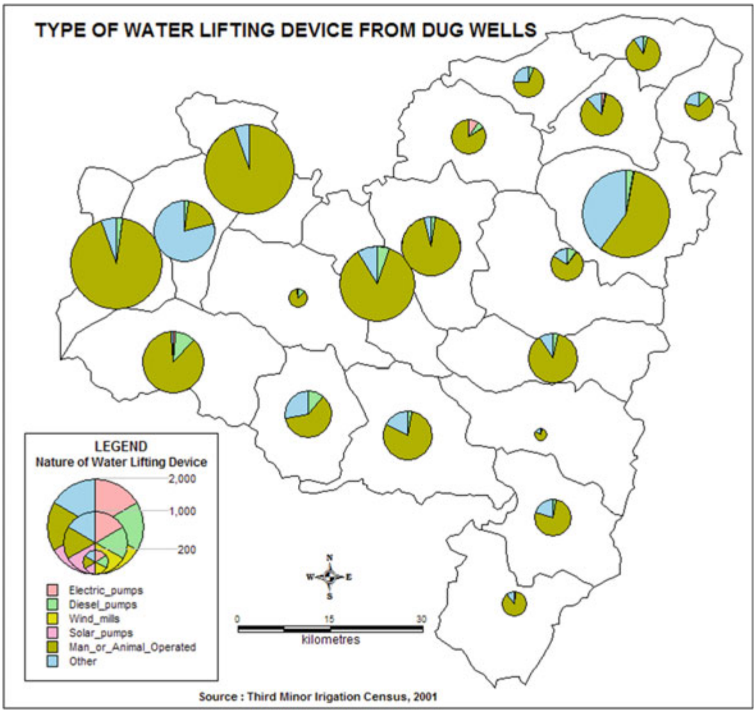

Fig. 19 Dugwell water extraction

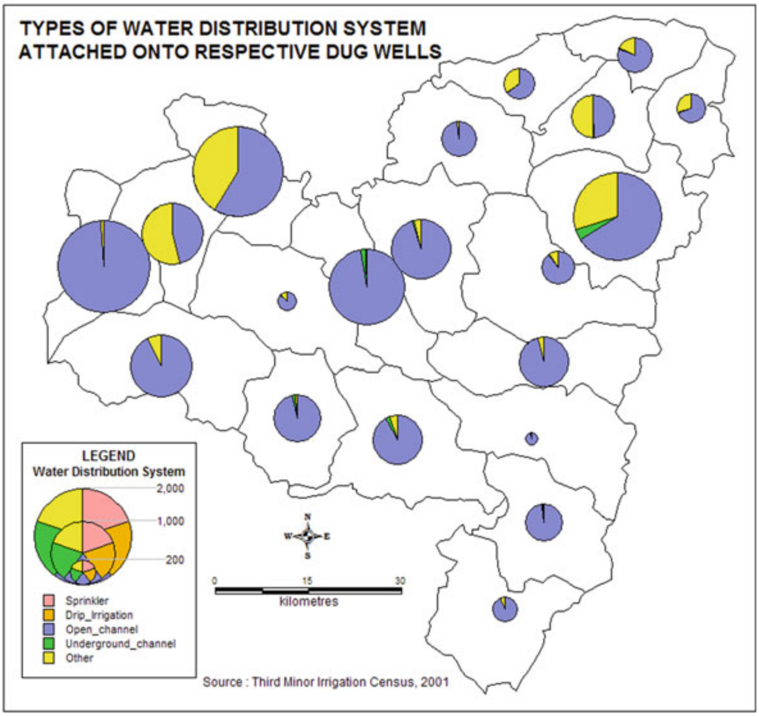

Fig. 20 Dugwell water distribution

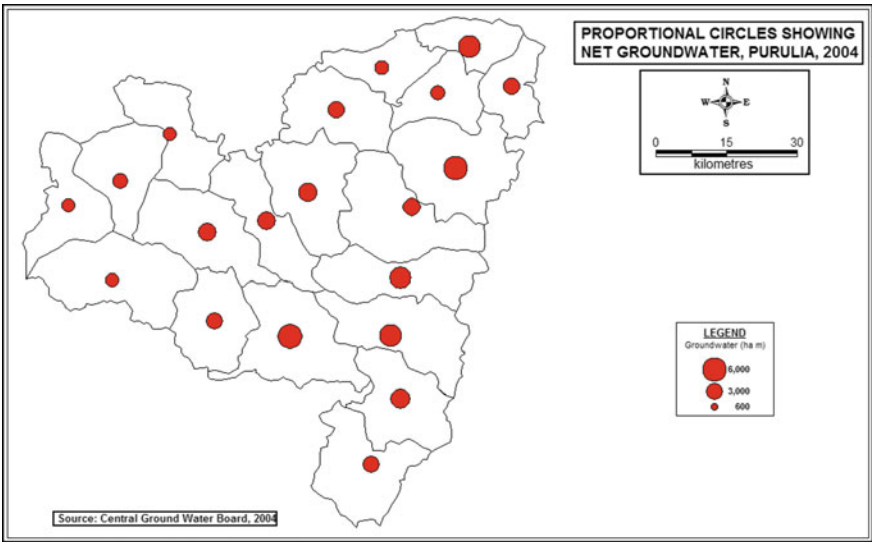

Fig. 21 Block-wise Amount of Groundwater Extracted

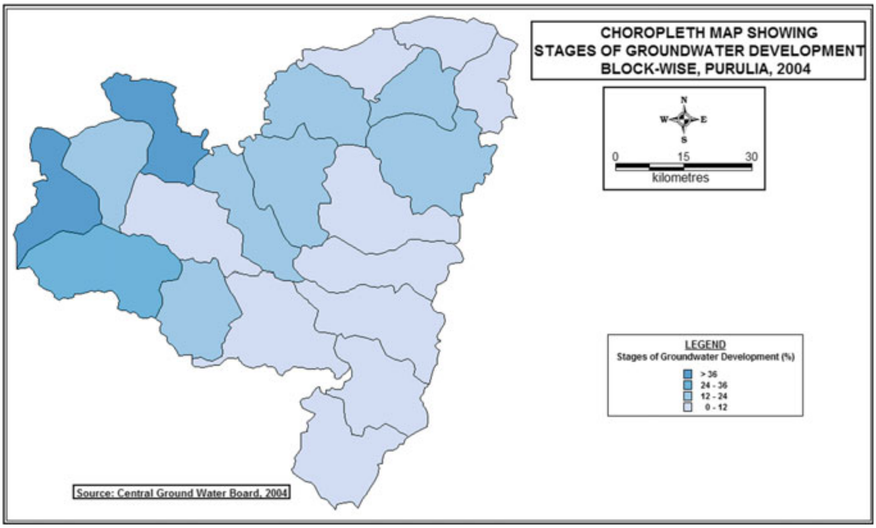

Fig. 22 Block-wise Groundwater Development Status

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Mapping Groundwater Recharge Potential Zones Using GIS Approaches and Trend of Water Table Fluctuation in Birbhum District, West Bengal, India

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Abstract Constant population expansion, continuous monsoon failure and over-exploitation put tremendous pressure on groundwater resources leading to its gradual reduction. In Birbhum district,demand for groundwater resources has increased tremendouslydue to continuous population expansions and extensive agriculture practices. In this context, our present research work is carried out in the perspective of delineation of potential groundwater recharge zones (GRPZ) in Birbhum district. Three different models namely knowledge-driven method (KDM), multi-influencing factor technique (MIF) and analytical hierarchy process (AHP) are implemented in the present study. Ten different factors that influence the groundwater recharge i.e., geology, geomorphology, rainfall, aquifer material, drainage density, soil type, lineament and fault density, slope, elevation and landuse/landcover are integrated into ArcGIS environment to derive the potential groundwater recharge zone (PGWR) zone. The model outputs are validated with success rate curve (SRC), prediction rate curve (PRC) and water-table fluctuation (WTF) data of 181 monitoring wells. The SRC implemented shows a prediction rate of 82.14%, 79.85% and 75.07% for MIF, KDM and AHP respectively suggesting the superiority of MIF techniques in comparison to other modelling. The Wilcoxon-signed rank test and results of map comparison show a significant difference (at a 5% significance level) in prediction among the models. The time series model used to investigate the WTF trend for past 23 years shows a significant declining trend water-table depth. Construction of various recharge structures at an appropriate location is suggested which must be

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preceded with details field investigations. The outcomes of the study can be useful resource for the policymakers, planners, government officials and leaders for the implementation of groundwater recharge projects in the future.

Keywords Analytical hierarchy process · Knowledge-driven method · Multi-influencing factor technique · Multiplicative model · Potential groundwater recharge zone · Water-table fluctuation

1 Introduction

The groundwater is one of the most valuable water resources and accounts for approximately 26% of total freshwater resource (FAO 2003; Todd and Mays 2005). Groundwater is water stored in the saturated zone in the sub-surface aquifer which gets recharged by infiltration rainwater and/or snowmelt water (Banks and Robins 2002). In hard rock terrain groundwater occurs in fracture and weathered zones at a limited extent (Saraf and Choudhary 1998).

In India, overexploitation, continuous failure of monsoon, rapid urbanisation and increasing demand causes tremendous pressure on groundwater resource eventually decreasing the water availability per capita day by day (Tiwari et al. 2009). About 1122 BCM (billion cubic meter) of water resource is available in India as utilizable water resources where renewable groundwater accounts for 432 BCM and surface water accounts for about 690 BCM (MOWR 1999; Singh et al. 2016). In West Bengal, the utilizable groundwater resources and surface water resources are estimated about 17.6 BCM and 132.9 BCM respectively (IWD 1987; CGWB 2001). The continuous trend of groundwater resource depletion and groundwater level decline has forced researchers, scientist, and planners all around the globe to understand and execute the groundwater replenishment artificially (Samadder et al. 2012). In such a scenario, the application of artificial recharge (AR) or managed aquifer-recharge (MAR) for sub-surface water storage has been a need of the hour (Bhuiyan 2015). Artificial groundwater recharge (AGR) is the properly planned methods to augment groundwater storage at times of water surplusto fulfil demand in times of extraction.

The groundwater exploration employing traditional approach such as geophysical, hydrogeological, geological method is expensive, laborious and extremely time-consuming (Nag 2005; Jha et al. 2010; Nampak et al. 2014; Adhikary et al. 2015; Razandi et al. 2015; Satheeshkumar et al. 2016; Selvam et al. 2015; Thapa et al. 2018a, b). Remote sensing and Geographic Information System (GIS) has provided time and cost-effective approaches of groundwater related studies (Jha and Chowdary 2007; Rahmati et al. 2014; Kazakis and Voudouris 2015; Thapa et al. 2018b). Geology, hydrogeology, rainfall, LULC etc. influences the groundwater recharge in an area (Zaidi et al. 2015; Senanayake et al. 2015).

Researcher all around the globe has carried out numerous studies implementing remote sensing and GIS to demarcate the suitable site for groundwater recharge

(Senanayake et al. 2015; Vijay Prabhu et al. 2016). Techniques such as knowledge-driven approach (Yeh et al. 2009; Kaliraj et al. 2013; Deepa et al. 2016; Selvarani et al. 2016; Thapa et al. 2017a, b), Boolean Logic (Ghayoumian et al. 2007; Zaidi et al. 2015), Multiple influencing factors (MIF) techniques (Shaban et al. 2006; Magesh et al. 2012; Thapa et al. 2017c, d). Analytical Hierarchal Process (AHP) method (Chowdhury et al. 2010; Mahmoud et al. 2015; Chezgi et al. 2016) have been implemented to carryout groundwater related studies.

The population of the Birbhum district has increased drastically (Statistical Handbook 2012) during the period 1951–2011 which eventually increases the groundwater resource demand. Introduction of high yielding varieties during agricultural practice put intense pressure on groundwater resource leading to over-exploitation of groundwater resource to extend beyond the naturally replenishable limit (Singh et al. 2016). There is an urgent need to adopt AGR to encounter the increasing water demand, water table decline, continuous failure of monsoon and widespread over-exploitation of the groundwater resource. In Birbhum district studies related to water quality and irrigation suitability, fluoride contamination etc. has been done but studies related to the identification of recharge sites has never been carried out making the present study consequential. Present study deals with PGWR zonation in Birbhum district and the achieve the objectives three different techniques were adopted i.e., knowledge-driven method (KDM), analytical hierarchy process (AHP) and multi-influencing factor (MIF) technique. The PGWR generated were validated with the reported data from a field investigation in order to compare the superiority of the model output. Wilcoxon-signed rank test and map comparison are applied to understand the difference in prediction among the models applied in the study. This research work also addresses the trend of water-table fluctuation (WTF) in the Birbhum district and suggestion of suitable recharge structures in the study area.

2 Study Area

The study area falls within 23° 32′ 30″ and 24°35′ 0″ N latitude and 88°01′ 40″ and 87° 05′ 25″ E longitude in West Bengal encompassing an area of 4545 km^2 (Fig. 1). Ajoy River demarcates the southern boundary of the district with Burdwan district. On the western and northern side, it shares its boundary with the state of Jharkhand. The study area shares its boundary with Murshidabad and Burdwan district of West Bengal on the eastern part. Approximately, 330 thousand hectares area is occupied by the net cropped area out of which 229 thousand hectares area is occupied by irrigated area and about 16 thousand hectors are occupied by the forest area. Major portion of the study area is used as cultivation land.

During summer seasons, the study area experience declining of water-table depth and thereby reduction in water storage. In addition, intensive irrigation using groundwater along with reduction in the trend of practising of storing pond water makes the population and entire study area more vulnerable to crop failure (Debnath and Mondal 2013, Thapa et al. 2018c, d). The water quality scenario in several regions of

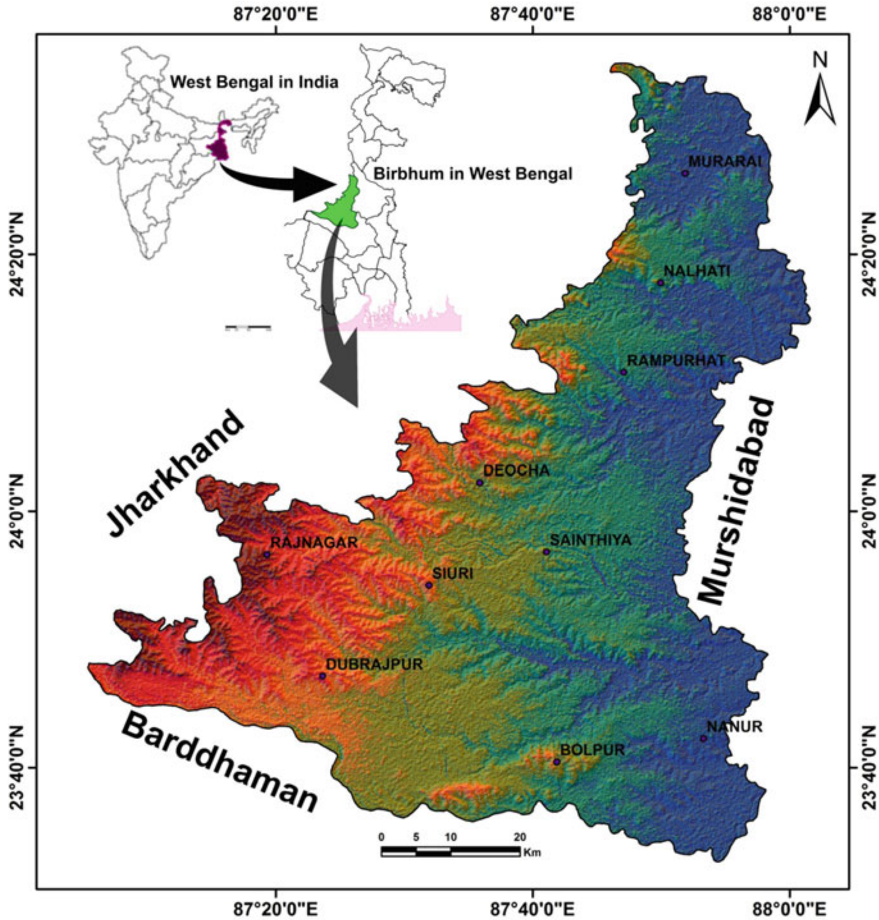

Fig. 1 Location map of the study area

the study is below the permissible limit of drinking water (Thapa et al. 2017d, 2018e). The subsurface disposition of aquifers of Birbhum district reported by CGWB (1985) is represented in Fig. 2. Table 1 represents the stratigraphic succession of the Birbhum district.

The groundwater scenario in the study area is represented in Table 2.

There is a huge gap between the actual irrigation practised in the study area in comparison to its actual irrigation potential. There may be several reasons that might contribute to this gap such as low groundwater availability, insufficient surface and pond water sources, hiked power cost, low voltage etc. (Govt. of West Bengal 2017).

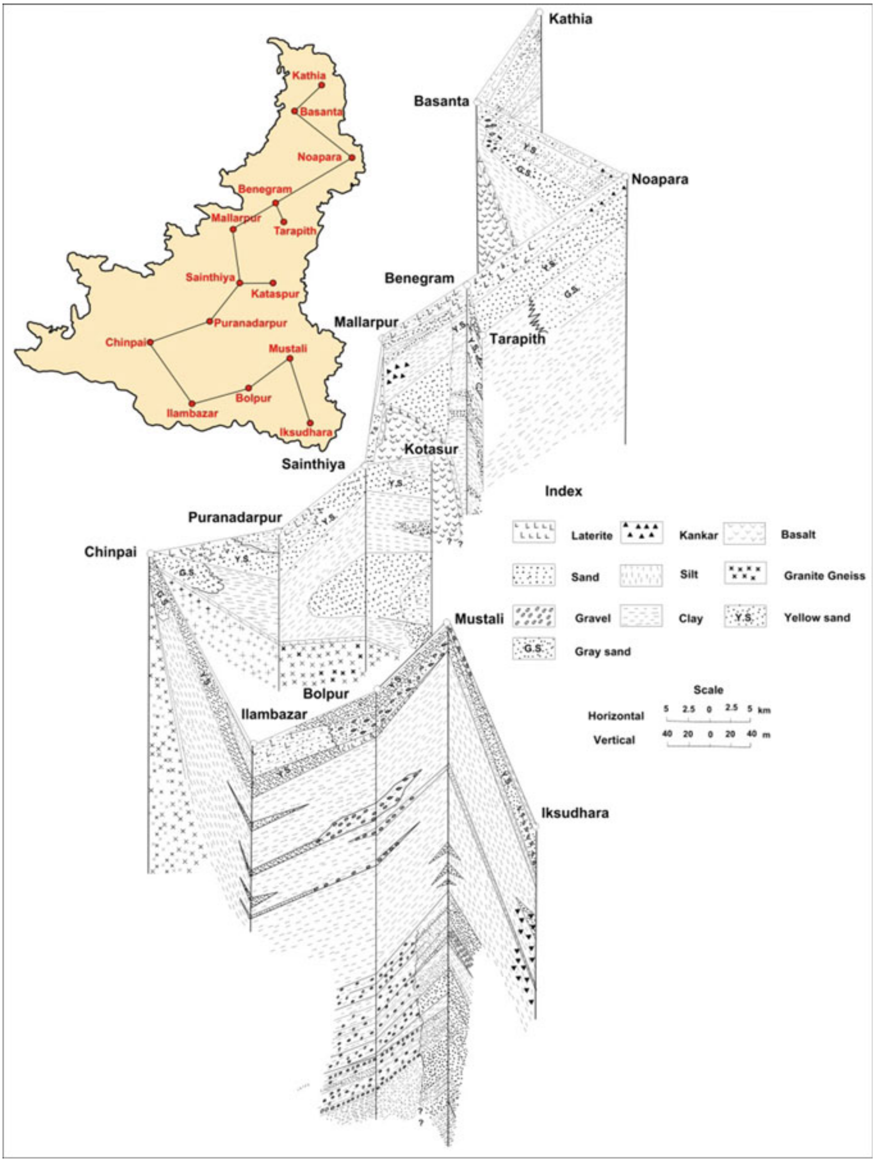

Fig. 2 Subsurface dispositions of aquifer within Birbhum district

3 Materials and Methods

The methodology followed to delineate the PGWR zones in the present study is represented in detail via the schematic diagram in Fig. 3 and the data used in the

Table 1 The stratigraphic succession of the study area

Litho-stratigraphy	Lithology	Age
Quaternary deposit	Alluvium/clayey soil with iron nodule, sandy sludge of medium to course brownish to grayish sand, few lateritic materials with pebbles and boulders at the base	Quaternary
Tertiary deposit	Variegated colours, brownish ferruginous iron stains and yellowish limonitic at places, claystone with sand and silt layer at places, medium to course grained, arenaceous, friable and unconsolidated, clayey sandstone	Tertiary
Unconformity		
Rajmahal formation	Rajmahal volcanics (Porphyritic/vesicular/amygdular, grey, hard and compact basalt with network of siliceous veins and zeolites)	Early cretaceous
Unconformity		
Gondwana super group	Dubrajpur Formation consisting of medium to coarse-grained, moderately sorted, hard and compact, ferruginous, sandstone, Barakar Formation consisting of fine to coarse-grained feldspathic sandstone, carbonaceous sandstone/siltstone with angular clasts, conglomerate, siltstone, grey shale, carbonaceous shale and coal seams, Talchir Formation Diamictic conglomerate, greenish, buff coloured mottled sandstone, siltstone and rhythmite shale	Late triassic to carboniferous
Unconformity		
Metamorphics (basement rock)	Variants of granite and granite gneiss, pegmatite veins and metabasic	Precambrian

Source CGWB (1985)

present research is tabulated in Table 3. Three different models i.e., KDM, MIF and AHP are implemented to generate the PGWR zones.

Table 2 Details of existing groundwater scenario of the Birbhum District, West Bengal

S. no.	Block	Net GW availability in ham	Current annual gross GW daft for irrigation in ham	Current ground water draft for domestic and industrial uses (ham)	Gross ground water draft for all uses (ham)	Stage of Ground Water Development as %	Categorisation as per GEC-97	Annual allocation of GW for domestic and industrial water supply upto next 25 years in ham	Net annual GW availability for "future irrigation use" in ham	No. of GW structures feasible	Annual allocation (ideal potential)	Villages	Populations
					(4 + 5)	(6/3) * 100			3 − (4 + 9)	STW	2005–06	(2016–2017)	(2016–2017)
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	BOLPUR-SRINIKETAN	15,461.12	2472.5	392.52	2865.02	18.53	Safe	569	12,419.62	3881	299	160	230,670
2	DUBRAJPUR	12,977.95	1518.2	350.55	1868.75	14.4	Safe	513	10,946.75	3421	263	199	178,348
3	ILLAMBAZAR	9937.58	3539.6	312.11	3851.71	38.76	Safe	451	5946.98	1858	143	127	168,944
4	LABHPUR	12,731.54	3129.8	396.39	3526.19	27.7	Safe	577	9024.74	2820	217	160	202,291
5	MAYURESWAR-I	8507.65	1121.4	300.99	1422.39	16.72	Safe	438	6948.25	2171	167	108	162,734
6	MAYURESWAR-II	8030.53	1989	255.11	2244.11	27.94	Safe	369	5672.53	1773	136	125	130,006
7	MURARAI-I	3759.79	739.4	316.35	1055.75	28.08	Safe	459	2561.39	800	62	82	257,950
8	NALHATI-II	4187.18	1887.4	231.93	2119.33	50.61	Critical	338	1961.78	Nil	Nil	59	145,299
9	NANOOR	13,711.17	3648	434.64	4082.64	29.78	Critical	633	9430.17	Nil	Nil	133	231,766
10	RAMPURHAT-II	7517.61	1552.7	357.51	1910.21	25.41	Safe	519	5445.91	1702	131	141	229,573
11	SAINTHIA	15,066.43	2784	400.41	3184.41	21.14	Safe	580	11,702.43	3657	281	328	209,791
12	MURARAI-II	7171.26	1587.3	374.09	1961.39	40.33	Critical	544	5039.96	Nil	Nil	69	239,117
13	KHAYRASOLE	4488.42	1039.2	315.17	1354.37	30.17	Safe	459	2990.22	934	72	126	153,097
14	MAHAMMADBAZAR	7071.8	305.2	300.29	605.49	8.56	Safe	434	6332.6	1979	152	138	165,406

(continued)

Table 2 (continued)

S. no.	Block	Net GW availability in ham	Current annual gross GW daft for irrigation in ham	Current ground water draft for domestic and industrial uses (ham)	Gross ground water draft for all uses (ham)	Stage of Ground Water Development as %	Categorisation as per GEC-97	Annual allocation of GW for domestic and industrial water supply upto next 25 years in ham	Net annual GW availability for "future irrigation use" in ham	No. of GW structures feasible	Annual allocation (ideal potential)	Villages	Populations
					(4 + 5)	(6/3) * 100			3 − (4 + 9)	STW	2005–06	(2016–2017)	(2016–2017)
1	2	3	4	5	6	7	8	9	10	11	12	13	14
15	NALHATI-I	4204.98	1649.3	450.59	2099.89	49.94	Safe	656	1899.68	594	46	121	215,572 ara>
16	RAJNAGAR	2246.17	54.7	158.87	213.57	9.51	Safe	229	1962.47	613	47	86	80,927
17	RAMPURHAT-I	8311.57	676.1	346.79	1022.89	12.31	Safe	504	7131.47	2229	171	114	193,998
18	SURI-I	5506.48	212.7	199.89	412.59	7.49	Safe	291	5002.78	1563	120	118	131,225
19	SURI-II	1722.64	517.1	168.2	685.3	39.78	Safe	245	960.54	300	23	85	90,030
	Total	152,611.9	30,423.6	6062.4	36,486	23.91		8808	113,380.3	30,296	2330	2479	3,416,744

Source NABARD in BIRBHUM (https://birbhum.gov.in/plp2005-06.htm) and NRDWP reports (https://indiawater.gov.in/IMISReports/)

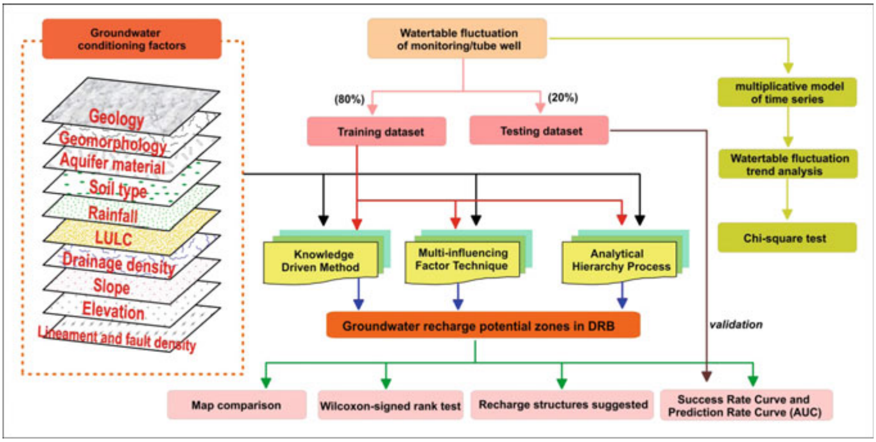

Fig. 3 Flow chart of the methodology adapted to delineate GRPZs in the study area

Table 3 List of data used in the present study along with their sources

Thematic layer	Data and source	Resolution and scale
Geology	District resource map, Geological Survey of India (GSI 2017)	1:250,000
Geomorphology	West Bengal Public Health Engineering Department (WBPHED 2017)	1:50,000
Aquifer material	West Bengal Public Health Engineering Department (WBPHED 2017)	1:50,000
Lineament and fault density	Bhuvan portal (NRSC 2017); Building Materials and Technology Promotion Council (BMTPC 2017)	1:50,000
Soil type	National Atlas and Thematic Mapping Organisation (NATMO 2009)	1:1,000,000
Rainfall	National Atlas and Thematic Mapping Organisation (NATMO 2009)	1:1,000,000
Land use/land cover	National Atlas and Thematic Mapping Organisation (NATMO 2009)	1:250,000
Elevation	CartoDEM, Bhuvan (NRSC 2017)	2.5 m
Drainage density	CartoDEM, Bhuvan (NRSC 2017)	2.5 m
Slope	CartoDEM, Bhuvan (NRSC 2017)	2.5 m
Water table variation	West Bengal Public Health Engineering Department (WBPHED 2017)	1:50,000

3.1 Model Used

3.1.1 Weighted Overlay Analysis (WOA)

In groundwater related studies, WOA method is widely accepted approach and has been implemented by several researchers for weights and ranks assignments to input parameters (Krishnamurthy et al. 2000; Shaban et al. 2006; Dinesan et al. 2015; Thapa et al. 2017a; Kaur et al. 2018a). The weights and ranks assigned based on a heuristic approach to each input parameters based on WOA are represented in Supplementary Table S1. The PGWR zones in the study area using WOA is generated using the following Eq. (1)

$$\mathrm{PGWR} = \sum_{\mathrm{i}}^{\mathrm{n}} \left(\mathrm{R_x} \times \mathrm{W_y}\right) \quad (1)$$

where

PGWR = potential groundwater recharge zonation,
R = rank allotted to the factor class,
W = weight allotted to the sub-class of the factor,
xth = represents the factor maps and
yth = is the factor class.

3.1.2 Multi-influencing Factor (MIF) Technique

MIF is an efficient, uncomplicated, and very efficient technique that is used in various aspect of groundwater related assessments and investigation (Riad et al. 2011a, b; Yeh et al. 2016). The interrelationship among all the input parameters is established based on literature review for allotment of weights and ranks to each input parameters. The statistical commutation followed and schematic interrelationship among input parameters is represented in Fig. 4.

Table 4 represents the allotted weights and ranks where factors having 'minor' effects on others are assigned a weightage of '0.5' and factors having 'major' effects on others are assigned a weightage of '1' (Magesh et al. 2012; Senanayake et al. 2015; Yeh et al. 2016) (Table 4). Based on a heuristic approach ranks to sub-classes are allotted. The proposed score of each parameter is calculated using the following Eq. (2):

$$\text{Proposed Score} = \left[\frac{(Ma + Mi)}{\sum(Ma + Mi)}\right] \times 100 \quad (2)$$

where

'Ma' = major effect and

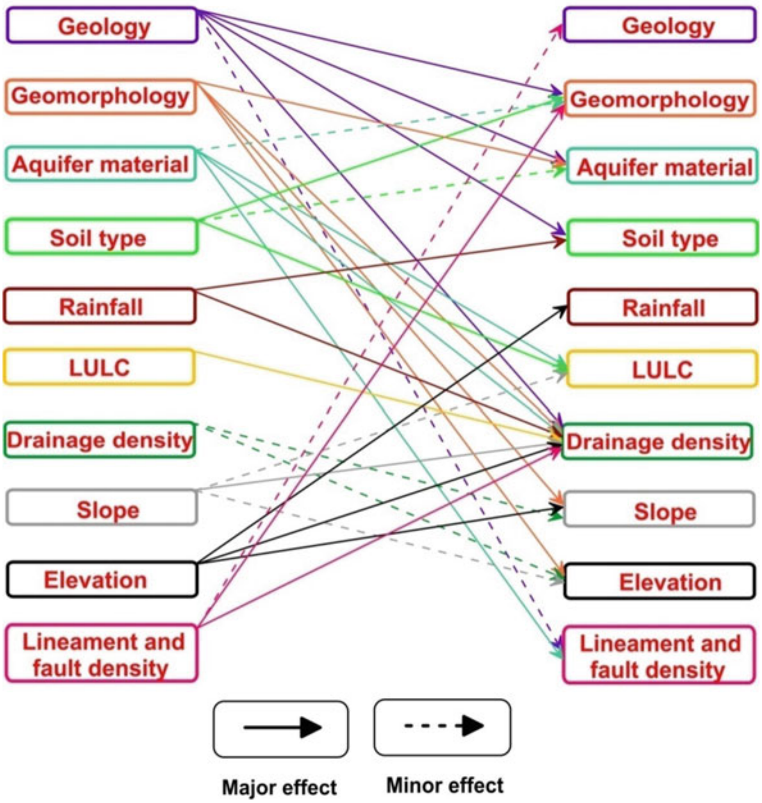

Fig. 4 Interrelation among all input parameters for assigning weightage through the MIF technique

'Mi' = minor effect.

The details of weight and ranks assigned using MIF technique is represented in Supplementary Table S2 and the PGWR zones in the study area using MIF is generated using the following Eq. (3)

$$PGWR = \sum_{i}^{n} (R_A \times W_B) \quad (3)$$

where

PGWR = Potential groundwater recharge zonation.
R = rank allotted to the factor class,
W = weight allotted to the sub-class of the factor,
A = factor maps and
B = factor class.

Table 4 Assigning of weights and ranks using MIF technique

S. no.	Factor	Major effect (A)	Minor effect (B)	Proposed relative rates (A + B)	Proposed score of each influencing factor
1	Geology	4	0.5	4.5	17
2	Geomorphology	4	0	4	15
3	Rainfall	2	0	2	8
4	Aquifer material	3	0.5	3.5	13
5	Drainage density	0	1	1	4
6	Soil type	2	0.5	2.5	10
7	Lineament and fault density	2	0.5	2.5	10
8	Slope	1	1	2	8
9	Elevation	3	0	3	12
10	LULC	1	0	1	4
Total		22	4	26	100

3.1.3 Analytical Hierarchy Process (AHP)

This is commonly used method in various groundwater related studies (Moustafa 2015; Baghbani et al. 2016). AHP involves decomposition, comparative judgment and assigning a normalized weight (Malczewski 1999). Saaty's numerical scale ranges from 1 to 9 where, a score of '9' indicates extremely importance of one parameter over other and a score of '1' implies equal importance of both parameters (Saaty 1996, 1999, 2004; Agarwal et al. 2013). The structure of the matrix used is expressed in Eq. (4)

$$A = \left(a_{ij}\right)_{n \times n} \tag{4}$$

where square matrix $A = (a_{ij})$ of order n with the constraints that $a_{ij} = 1/a_{ji}$, for $i \neq j$, and $a_{ji} = 1$, all I and 'n' are the elements to be compared.

For calculation of the consistency index of a matrix the following equation is used

$$CI = (\lambda_{max} - n)/(n - 1) \tag{5}$$

where

CI = Consistency index,
n = number of criterion/element and
λ_{max} = maximum Eigen value.

The λ_{max} determined from the priority matrix by multiplying on the right of the matrix of judgments by the eigenvector. It is important to note that when the mean of $\lambda_{max} < n$, it indicates an calculation error. The consistency ratio (CR) is the rescaled version of CI and is determined as represented in Eq. (6):

$$CR = CI/RI \tag{6}$$

where

RI = random matrix represented in the upper row.

When the CR value generated (using Eq. 6) < 0.1, the weights assigned to factors are accepted whereas when CR > 0.1 the weights assigned are rejected as it indicates inconsistency and a revision in the scale of preference is required (Saaty 2008). The final PGWR zones are generated using the following Eq. (7)

$$PGWR = \sum_{i}^{n} W_j \times W_{ij} \tag{7}$$

where

'n' = number of criterion/factors,
W_j = weight value of causative factor j and
W_{ij} = weight value of class a in causative factor j.

Weight and ranks assigned using AHP is represented in Supplementary Table S3. The eigenvector values of pair-wise comparison matrix and CR of PGWR are represented in Table 5.

3.2 Model Comparison

Three different models have been applied in the present study to generate the PGWR zones and the resultant zonations are compared among themselves to understand the difference in predictions. All the model output are reclassified into four classes very high, high, moderate and low represented by number 4, 3, 2 and 1 respectively. The maps are subtracted among each other and when models compared show no difference in prediction, it is represented by '0', when there is a difference of one class between the two models compared; it is represented by '1'. Similarly, '−2' or '2' and 3 or '−3' represents a difference of two and three venerability zones respectively.

3.3 Wilcoxon-Signed Rank Test

This is applied to investigate significant statistical differences among the models applied at 5% ($\alpha = 0.05$) significance level. Wilcoxon-signed rank test assumes that

Table 5 Pair-wise comparison matrix of potential groundwater recharges zonation influencing factors

Input parameters	Geology	Geomorphology	Aquifer material	Soil type	Elevation	Slope	Drainage density	Fault and lineament density	Rainfall	LULC	Normalised weights
Geology	1										0.26
Geomorphology	0.5	1									0.18
Aquifer material	0.33	0.5	1								0.15
Soil type	0.25	0.33	0.33	1							0.07
Elevation	0.33	0.5	0.5	2	1						0.09
Slope	0.2	0.25	0.25	0.5	0.5	1					0.03
Drainage density	0.17	0.25	0.25	0.5	0.33	2	1				0.04
Fault and lineament density	0.17	0.25	0.25	0.33	0.33	2	0.5	1			0.04
Rainfall	0.33	0.33	0.33	2	1	4	4	4	1		0.11
LULC	0.17	0.25	0.25	0.33	0.33	0.5	0.5	0.5	0.17	1	0.03

Principle Eigen value (PEV) = 10.55, Consistency ratio (CR) = 0.09

there is no difference in prediction between the models and the calculated p-value in the null hypothesis and z value are used to reject or accept the null hypothesis.

3.4 Measurement of Seasonal Fluctuation of Water-Table

Water-table is a very crucial parameter which indicates the water resource condition of the region. To get an insight into the trend and seasonal fluctuation of water-table (Y) depth multiplicative model of time series was implemented. The water-table information of 23 years i.e., from April 1996 to January 2018 was used to understand the water-table change with respect to time (India-WRIS 2019).

In this model, The predicted water-table depth (Y_t) is measured using the following equation

$$Y_t = T_t S_t C_t I_t \tag{8}$$

where, Y_t represents the predicted water-table, S_t represents the seasonal components, short term trend is represented by T_t, C_t is the cyclical components and I_t is the irregular components.

Firstly, the trend component (T_t) is derived from the averaged depth to water-table data using a simple linear regression as follows:

$$T_t = A_1 + A_2 t \quad (\forall t = 1, 2, 3, 4 \ldots n) \tag{9}$$

where, A_1 and A_2 represent the coefficient of intercepts and time respectively.

De-seasonlisation (S_t) of depth to water-table data was performed by dividing the water-table data with the trend factor to get rid of the irregular and cyclic variation of water-table depth. The ratio of Y_t to $\widehat{T_t}$ represents the seasonal variation along a part of irregular fluctuation and the average of all the values in each season take cares of the irregular component (I_t).

The final prediction of water-table variation ($\widehat{Y_t}$) is computed using the calculated value of $\widehat{S_t}$ and $\widehat{T_t}$ as follows:

$$\widehat{Y_t} = \widehat{T_t} + \widehat{S_t} \tag{10}$$

Pearson's chi-squared test was implemented to check the the goodness of fit of the model implemented as follows:

$$\text{Chi-square} = \sum_{i=0}^{n} \frac{(O_i - E_i)^2}{E_i} \tag{11}$$

where, O_i is the observed frequency and E_i is the expected frequencies.

4 Results and Discussion

4.1 Potential Groundwater Recharge Zone (PGWR)

The details of inputs parameters used in the present study are represented in Fig. 5a–j and supplementary Table S4. With the implementation of three different models, the final model generated an output of PGWR zones are generated and represented in Fig. 6a–c. The detail area calculation of PGWR zones with respect to various models applied are represented in Table 6.

In the case of KDM, the final output results are categorised into the following classes: very high, high, moderate and low accounting for 713.35 km^2 (15.69%),

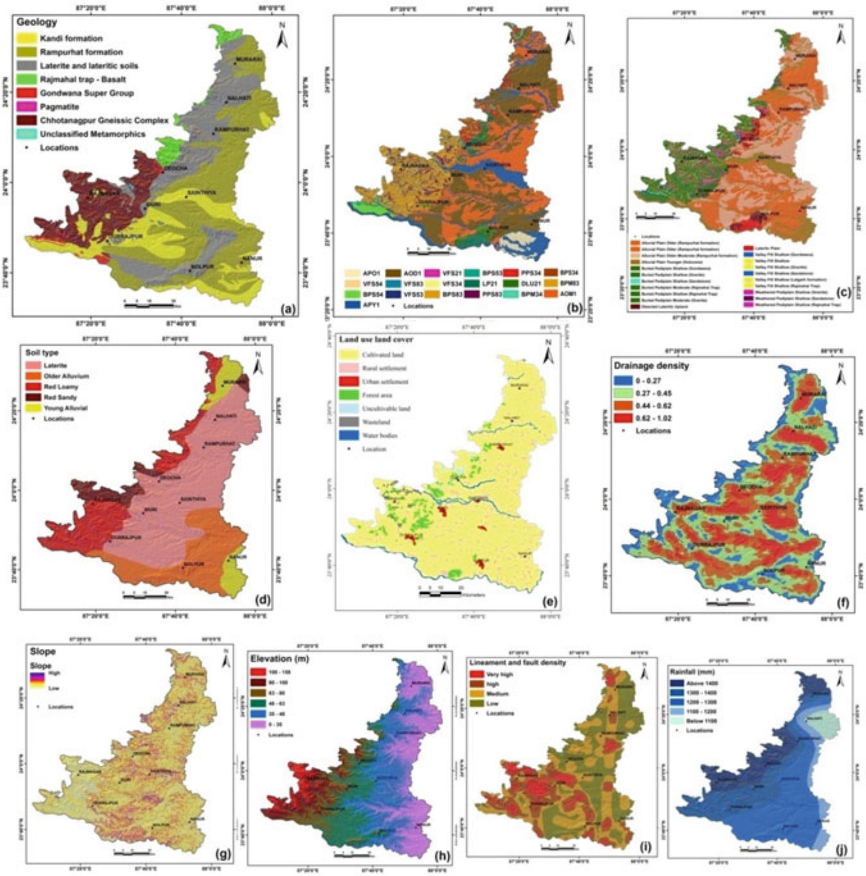

Fig. 5 Thematic inputs of Birbhum district **a** Geology, **b** Geomorphology, **c** aquifer **d** soil type **e** Land use/land cover **f** Drainage density **g** Slope, **h** Elevation, **i** Lineament and fault density and **j** Rainfall

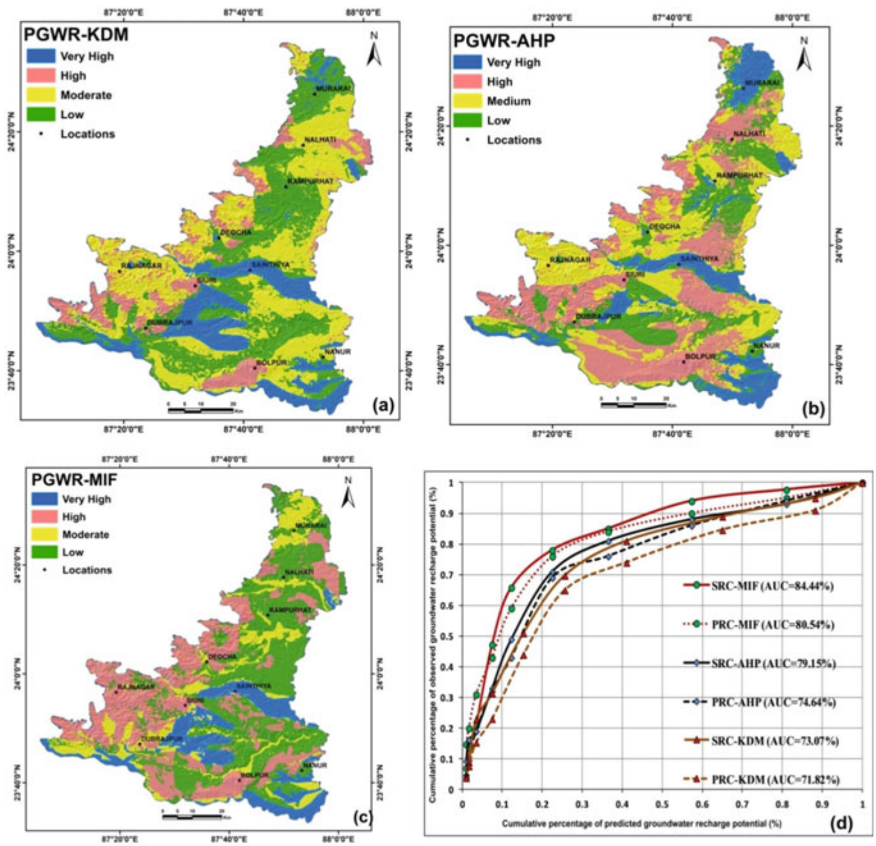

Fig. 6 The potential groundwater recharge zonation (PGWR) of Birbhum district **a** KDM technique. **b** AHP technique. **c** MIF technique. **d** Success and prediction rate curves of three different models applied

Table 6 Areal coverage (km^2) of potential groundwater recharge zonation based on different models applied

Models applied	Very high (km^2)	High (km^2)	Moderate (km^2)	Low (km^2)
KDM	713.35	555.88	1785.17	1491.14
AHP	612.4	1513.41	1385.57	1033.79
MIF	611.3	1395.32	707.08	1831.48

555.88 km^2 (12.22%), 1785.17 km^2 (39.25%) and 1491.14 km^2 (32.80%) area respectively (Fig. 6a). In the AHP model, the PGWR zonation map shows that very high zone accounting for 612.4 km^2 (13.47%), high zone accounting for 1513.41 km^2 (33.30%), moderate zone accounts for 1385.57 km^2 (30.48%) and low zone account for 1033.79 km^2 (22.74%) (Fig. 6b). In the MIF technique, very high, high, moderate

Table 7 Details results of all the possible map comparison combinations of models applied

Models comparison	−3	−2	−1	0	1	2	3
AHP-KDM	0	0.45	15.84	68.65	12.12	2.93	0
AHP-MIF	0	3.54	7.13	81.55	8.61	2.28	0
MIF-KDM	0	0	10.3	75.34	12.19	2.17	0

and low regions cover an area of 611.3 (13.45%), 1395.32 (30.70%) 707.08 (15.57%) and 1831.48 (40.29%) respectively (Fig. 6c).

4.2 Model Comparison

The PGWR zones obtained are compared among each other to understand the variation in the prediction and the details table representing all the possible comparison combinations are represented in Table 7. The model comparison indicates a similarity of about 65% among all models applied. With a similarity of 81.55% in prediction MIF and AHP shows the highest resemblance followed by 74.65% similarity between KDM and MIF whereas the maximum prediction difference among all the combination was seen between AHP versus KDM with about 68.65% prediction similarity of the two models.

4.3 Wilcoxon-Signed Rank Test

This is applied to understand the significant statistical differences in model's prediction at 5% ($\alpha = 0.05$) significance level (Sahin et al. 2017; Merghadi et al. 2018; Kaur et al. 2019). The z-value and *p*-value > 0.05 do not exceed the critical values indicating a significant difference in prediction (Bui et al. 2016). The z-value and *p*-value indicates a significant difference between AHP-KDM and AHP-MIF in prediction at 5% ($\alpha = 0.05$) significance level (Table 8).

Table 8 Pairwise comparison of the three models using Wilcoxon signed rank test

S. no.	No. pair wise comparison	z value	*p* value	Significance
1	AHP-KDM	−2.864[a]	0.013	Yes
2	AHP-MIF	−2.433[a]	0.024	Yes
3	MIF-KDM	−2.086[a]	0.039	Yes

Where [a] is based on positive ranks.

4.4 Validation of Models

The final models generated PGWR zones are validated using the WTF data of the study area. The WTF information is gathered from CGWB reported data for last 4 year (April 2013 to January 2017) where, the measurement of the water table is carried out quarterly (CGWB 2014, 2016a, b, 2017). Areas having greater WTF are generally a more suitable site for groundwater recharge in comparison to an area having lower fluctuation in groundwater level (Healy and Cook 2002). Success rate curve (SRC) and prediction rate curve (PRC) is implemented as a validating method and it very widely accepted method (Chung and Fabbri 1999, 2003; Kaur et al. 2017, 2018b; Thapa et al., 2017e). A total of 181 tube well data is used to measure the WTF. The WTF data is divided into two parts i.e., training dataset (145 points) comprising 80% of the total data is used to calculate SRC and testing dataset (23 points) consisting of remaining 20% data is used to calculate the PRC. The SRC shows a prediction rate of 84.44%, 79.15% and 73.07% for MIF, AHP and KDM and respectively and the PRC indicates a prediction rate of 80.54%, 74.64% and 71.82% for MIF, AHP and KDM and respectively (Fig. 6d). Among all the three models applied MIF has the highest success and prediction rate indicating its superiority above other models.

The water table levels reported from the monitoring wells (CGWB 2014, 2016a, b, 2017) were used to calculate the WTF and compared with the PGWR zonation derived from MIF technique. The distributions of the monitoring well are more or less uniform within the study area (Fig. 7). In Fig. 7 the number in the maps indicates corresponding well number.

About 27 monitoring wells (Well no. 1–27) fall with the very high GWRP zone and the detail WTF of each well is represented in Fig. 8a. In the very high GWRP zone the WTF varies from 6.36 to 19.5 m. Highest WTF is observed in Khyakura (Illambazar) and Raj Nagar (Bolpur) areas with 19.5 m and 18.55 m respectively. In high GWRP zone a total of 64 monitoring wells (well no. 28–91),ranging WTF from 2.83 to 21.14 m (Fig. 8b). In high GWRP zone some monitoring wells show very limited or low WTF throughout the year which might be due to the existence of localised aquifer condition (Mondal et al. 2014; Thapa et al. 2017d, 2018d). Similar observations has been reported by Rajaveni et al. (2017). The highest WTF value in the study area is observed in Mollarpur (Murarai-I) with a fluctuation of 21.14 m followed by Nalhati (Sehalai) area with the WTF value of 19.41 m.

Out of 181 monitoring wells, 57 monitoring wells (Well no. 92–148) fall on moderate GWRP zone (Fig. 8c). The WTF in moderate GWRP zone ranges from 3.13 to 8.9 m but majority of well show WTF within 6 m. In low GWRP zone the WTF of 33 monitoring wells (Well no. 149–181) ranges from 1.13 to 8.37 m, except 3 monitoring well shaving WTF within 5 m (Fig. 8d). The study area belongs to agricultural dominated region where, agricultural system mostly depends on groundwater. Overexploitation of groundwater resource can further intensify higher WTF in the region (Bouwer 2000; Scanlon et al. 2008; Thapa et al. 2017d).

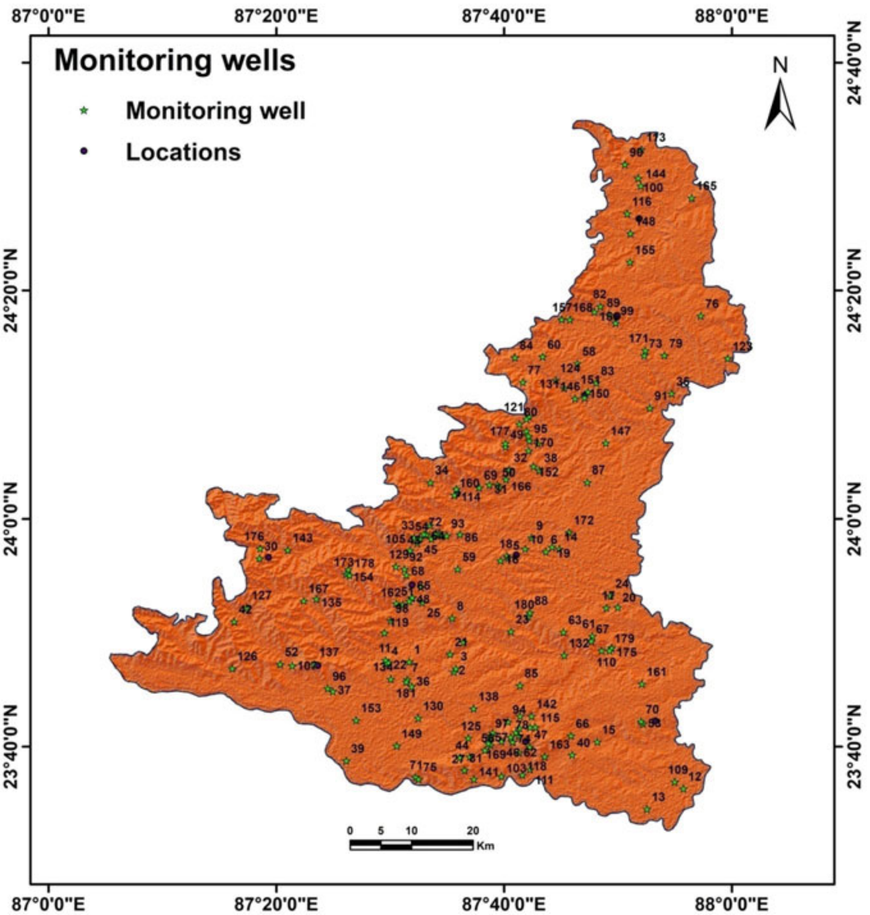

Fig. 7 Locations of the monitoring wells used for measuring water-table depth

4.5 Measurement of Seasonal Fluctuation

The long term WTF analysis can give useful information on groundwater recharge scenario, land use pattern and climate change (Turker et al. 2013). The WTF is important information in groundwater-related studies (Rajaveni et al. 2017). The multiplicative model of time series applied for shows that the $\widehat{S_t}$ value as 0.72, 0.87, 1.10 and 1.33 for the month of January, April, August and November respectively and the trend expression is $\widehat{T_t} = 3.84 + 0.04t$ (Supplementary Table S5) and Pearson's Chi-Squared test indicates significant ($\alpha = 0.05$) with a p-value of 0.31 which implies an increasing trend in the WTF in the study area with respect to time.

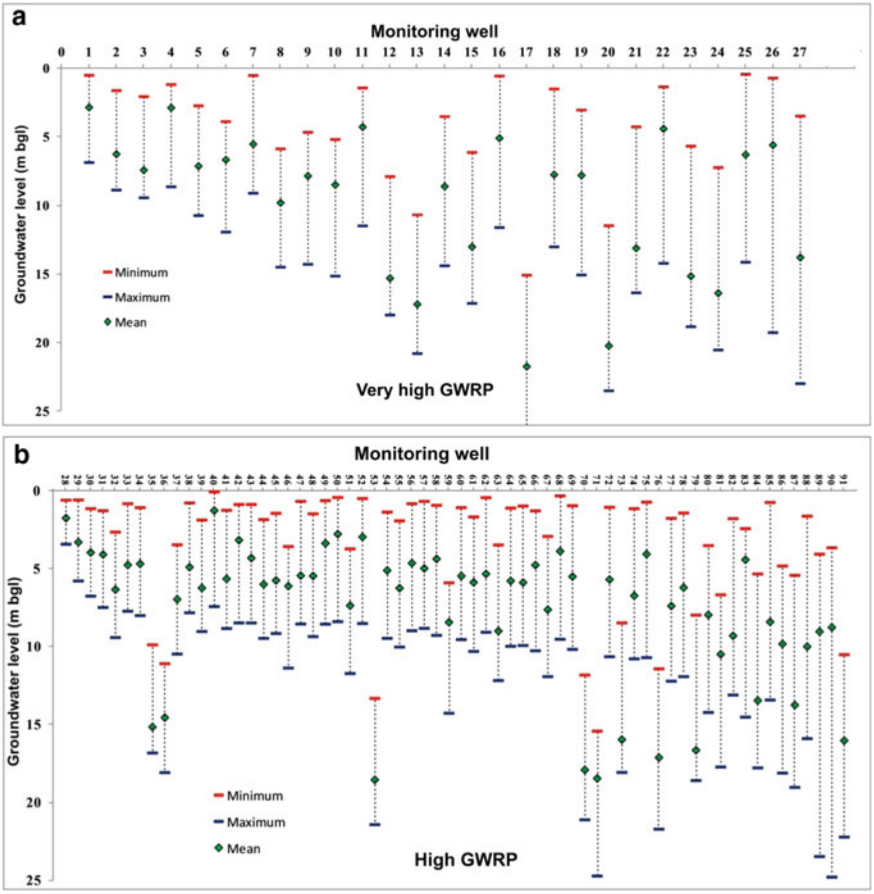

Fig. 8 **a** Fluctuation of the water-table level in monitoring wells in very high GWRP. **b** Fluctuation of the water-table level in monitoring wells in high GWRP. **c** Fluctuation of the water-table level in monitoring wells in moderate GWRP. **d** Fluctuation of the water-table level in monitoring wells in low GWRP

4.6 Proposed Recharge Sites

The study area has a good drainage network which can be a good source of groundwater recharge. Regions facing water scarcity scenario having an unfavourable hydrogeological condition such as poor/limited recharge conditions, declining water-table need more attention. Based on the aquifer materials, its characteristics, depth of water-table etc. suitable recharge sites and structures within the study area are demarcated. The locations suggested are tentative and a detail ground survey will be needed before fixing up the project. In the study area rainfall, surface runoff, overland flow, base flows area major source of groundwater recharge. To harvest the available overland flow we have identified four different recharge structures i.e., check dams, recharge

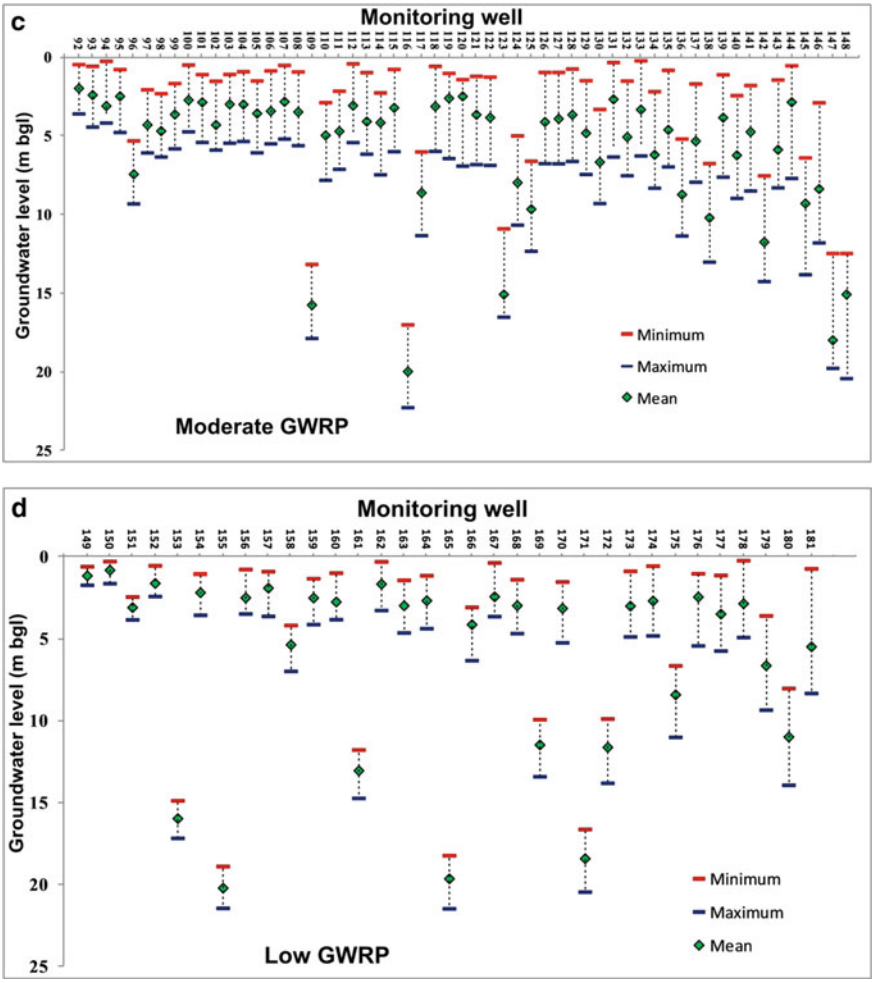

Fig. 8 (continued)

pits, recharge wells and desilting of wells. To harvest the overland flow, check dams are identified in the 1st and 2nd order streams in initial stages. Recharge wells/invert well are identified to harvest the overland flows in all geomorphic forms having impervious strata between the aquifer and source whereas those areas where there is scope for harvesting the surface runoff water, recharge pits are suggested. Silting up of the tanks resulting due to sediment deposition with due course of time can greatly reduce the efficiency of groundwater recharge. In order to facilitate better groundwater recharge small tanks may be desilted periodically. The details of all the recharge structure suggested are represented in Fig. 9.

In Rajnagar, Siuri, Deocha and Debrajpur areas with weathered zones in hard rock formations recharge pits will improve the sustainability of groundwater resource.

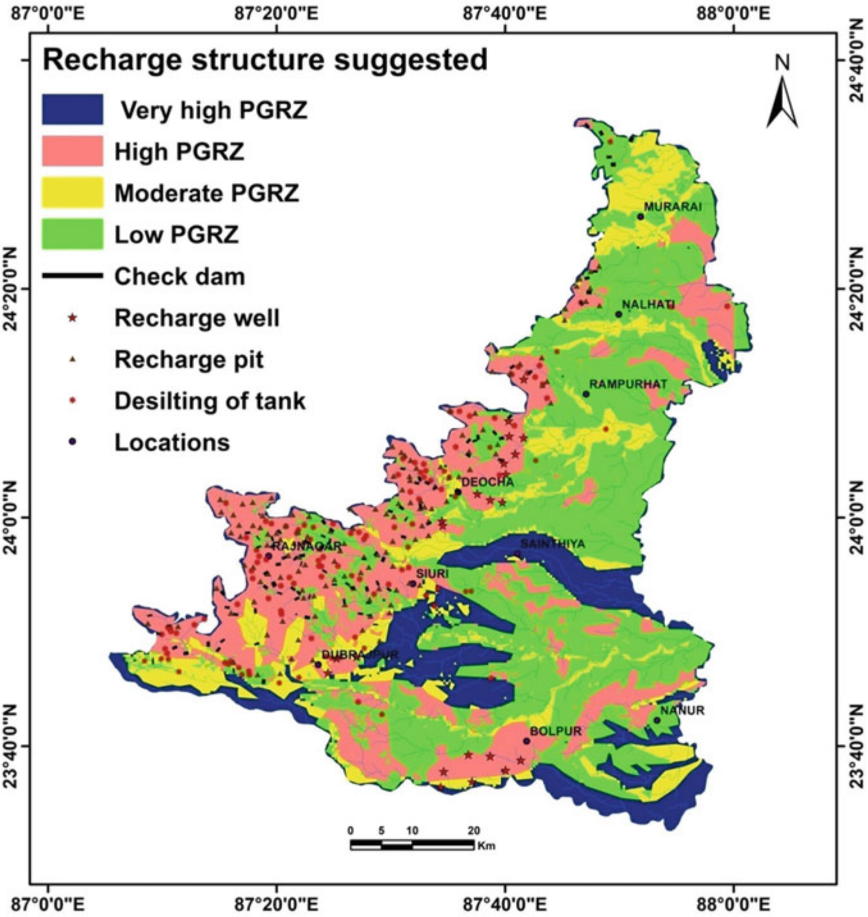

Fig. 9 Suggested recharge structures suggested in the study area

Presence of high drainage network in Deocha, Debrajpur and Rajnagar areas makes these region suitable sites for construction of check dams. In some areas of bolpur, recharge well can be an good option for groundwater recharge due to favourable underlain aquifer material and high water table fluctuation precailing in this areas. In areas such as Rampurhat, Nalhati, Murarai etc underlain by shallow weathered pediplain, the scope of recharge structure such as recharge pits and recharge wells are very limited due to the presence of hard rock formation conducting groundwater movement. Areas underlain by younger alluvium plain such as part of Sainthiya, Nalhati etc. there is no requirement of recharge structure as portable water is available at shallow depth and depth to water table is very less. In areas such as Rampurhat with older alluvium plain recharge well can be suitable.

5 Conclusions

In the present study integration of remote sensing and GIS techniques via modelling approach to assess the PGWR zones has proved to be an effective and useful tool. The output derived from the three different models were categorised as very high, high, moderate and low zones. Map comparison technique along with Wilcoxon-signed rank test shows a significant difference in prediction among the models applied. the final PRGW zones were validated with WTF data of 181 monitoring wells for a period of 4 years implementing SRC and PRC and the results show the superiority of MIF technique among other models. A significant decreasing trend in-depth to water-table is observed in trend analysis study of WTF. The Wilcoxon-signed rank test and results of map comparison show significant difference among model in prediction. The gradual depletion of groundwater depletion needs to be checked immediately. Hence, construction of recharge structure at appropriate sites will play a important part towards management of groundwater resource within the study area in the long run.

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Spatio-Temporal Dynamics of Groundwater Resources of National Capital Region, Delhi

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Abstract The rapid industrialization and urbanization of the National Capital Region (NCR) of Delhi is likely to have its impact on the groundwater resources. In this context, the article is an attempt to present a glimpse of spatio-temporal variations in dynamic groundwater resources of NCR Delhi. The groundwater resources data for years 2004, 2009, 2011 and 2013 were analyzed to observe spatio-temporal variations in net groundwater availability and the irrigation, domestic and industrial groundwater draft. Further, in order to have a better insight into the temporal and spatial variations, we attempted normalization by estimating "unit area draft". The unit area draft is a ratio of total draft corresponding to particular land use to the area under the given land use category. This article presents these analyses for NCR sub regions of Delhi, Haryana, Uttar Pradesh and Rajasthan. The vulnerable stretches in each sub-regions of NCR have been identified on the basis of the temporal variation in attributes of the groundwater system. It has been observed that the status of groundwater system has changed from the years 2004 to 2009 and further from 2011 to 2013. The study will help planners and environmental managers in formulating suitable policies in light of the facts highlighted in the article.

Keywords Dynamic groundwater resources · Groundwater abstraction · Groundwater recharge · Groundwater resource estimation · National capital region Delhi

1 Introduction

The groundwater crisis in north western India is a global focus (van Dijk et al. 2019; Shekhar 2006a). Most of the studies have either taken a regional view or adopted

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local area specific approach. In this article a macro level attempt has been made by taking the study area as the National Capital Region (NCR) of Delhi, which is witnessing rapid urbaization and industriliazation. The scientific studies on the groundwater crisis have mostly focussed on the water level scenarios. The artcile here attempts to take a holistic view by factoring the dyanmaic groundwater resources. This autmatically considers the recharge and groundwater extraction together. The NCR of Delhi, an emerging hotspot of groundwater crisis lies between 75.4° E–78.47° E and 26.7° N–30° N and comprises around 53,817 km^2 of area (Fig. 1).

The NCR is an extension of Delhi under inter-state regional planning and development under the NCRPB Act, 1985 to promote balanced development (NCRPB 1987). It consists sub-regions of four states i.e. Haryana, Uttar Pradesh, Rajasthan and the National Capita Territory (NCT) of Delhi whose details are given in Table 1. Ganga and Yamuna are two major rivers which flow approximately in north–south direction (Fig. 1). It is one of the most populated regions of India and attracts migration from all over the country. The population density and linked land uses show spatial variations in the region. The philosophy of creating NCR was based on the principle of decentralization of industrial and urban agglomerations to the satellite town in close vicinity of Delhi, having a good connectivity to Delhi. This has accelerated industrialization and urbanization in the NCR. With limited availability of surface water resources, the dependency on groundwater system for various uses is obvious. As, the surface and groundwater of the region are in dynamic equilibrium

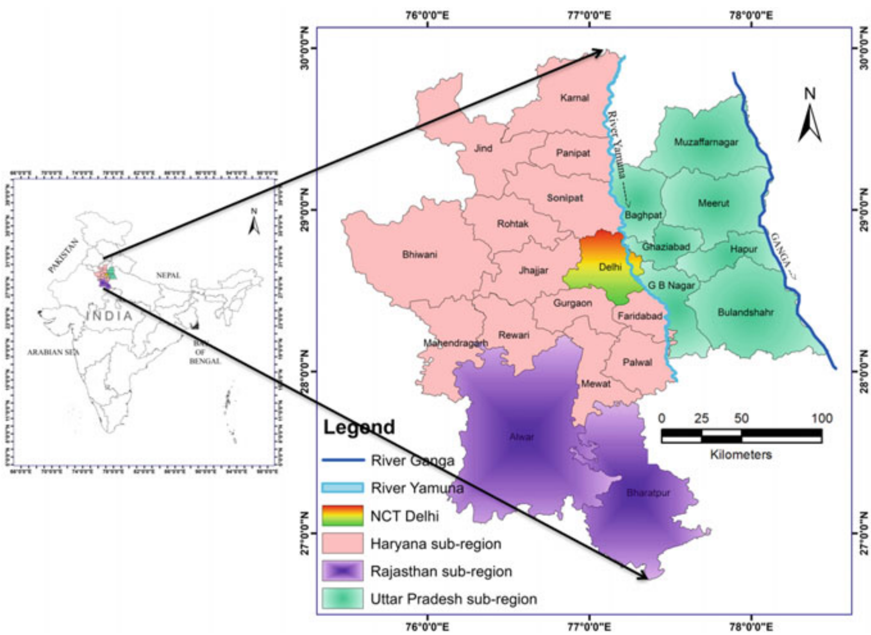

Fig. 1 Location map of NCR, Delhi (available at https://ncrpb.nic.in/)

Table 1 Constituent districts in NCR Delhi (NCRPB 1987)

Sub-region	Districts	Area (km^2)
NCT Delhi	Whole NCT Delhi	1483
Haryana (thirteen districts)	Faridabad, Palwal, Gurgaon, Mewat, Rewari, Jhajjar, Mahendragarh, Bhiwani, Rohtak, Sonipat, Panipat, Jind, and Kanal	25,327
Uttar Pradesh (seven districts)	Gautam Budh Nagar, Bulandshahr, Ghaziabad, Hapur, Baghpat, Meerut, and Muzaffarnagar	13,560
Rajasthan (two districts)	Alwar and Bharatpur	13,447

where any possible changes in one affect the other (Shekhar and Prasad 2009; Bawa et al. 2014; Kumar et al. 2019), the fast changes in land use is likely to leave its distinct footprints on the water resources.

The parts of NCR Delhi has been reported to have water scarcity and water quality issues (Shekhar et al. 2005; Kumar et al. 2006; Shekhar 2006a; Chatterjee et al. 2009; Kumar et al. 2009; Adhikary et al. 2010; Shekhar and Sarkar 2013, 2015; Saha et al. 2016; Sarkar et al. 2016, 2017; Adhikary and Dash 2017; Ali et al. 2016, 2019). The future lies in prudent management of the available water resources (Rao et al. 2007; Shekhar and Rao 2010; Shekhar et al. 2015; Soni et al. 2018). In this context this article aims to assess, spatio-temporal variations in dynamic groundwater resources of NCR Delhi incorporating variations in net groundwater availability, irrigation draft, domestic and industrial draft from groundwater. On the basis of temporal variation in attributes of groundwater system, the vulnerable stretches in each sub-regions of NCR would be identified for formulation of suitable policies.

2 Hydrogeology

NCR Delhi is a part of Indo-Gangetic plain which is mainly covered by Quaternary alluviums and Delhi Supergroup rocks of Pre-Cambrian age. The Quaternary alluvium is further classified into older and younger alluviums which are dominated by various grade of sand along with clay, silt and gravels (Chatterjee et al. 2009; Sarkar et al. 2016). The alluvium of NCR is potential source of groundwater which makes unconfined, semi-confined to the confined type of aquifer system (Shekhar 2006b; Shekhar and Prasad 2009; Kumar et al. 2017). The hard rock terrain of Delhi Supergroup is mainly exposed in Alwar, parts of Bharatpur, Gurgaon, Rewari, and southern parts of Delhi (CGWB 2015, 2016). These rocks mainly comprise of quartzite, phyllite, and mica schist. These weathered and jointed hard rock terrain make poor to moderate potential aquifers (NCRPB 1987). The hard rocks also act as basement of alluvium aquifers and are exposed as Delhi ridge in Delhi sub region (Shekhar and Sarkar 2013; Shekhar et al. 2015; Kumar et al. 2018).

3 Dynamic Groundwater Availability and Utilization

The groundwater is extensively used for domestic, industrial and agricultural purposes in Delhi NCR. The dynamic groundwater resource is referred to that part of the groundwater resources which is recharged or replenished annually (Chatterjee et al. 2009; Shekhar and Prasad 2009; Shekhar et al 2015). The dynamic groundwater resources were estimated using GEC (1997) approach by Central Ground Water Board (CGWB) for the assessment year 2004, 2009, 2011, and 2013. The net groundwater availability (dynamic groundwater resources minus natural discharge, refer Shekhar et al. 2015) and groundwater draft (abstraction) segregated for the domestic and industrial use and agricultural practices were estimated and are given in Table 2.

A look at Table 2 reveals a drastic reduction in the domestic and industrial groundwater abstraction of Gurgaon district in year 2013. This is mainly attributed to the adoption of conjunctive use principal in water supply where canal and groundwater together are supplied for drinking and industrial uses. Similarly in Rewari district of Haryana the domestic and industrial draft has increased by about ten times in year 2013 compared to the earlier assessment years indicating over-reliance on groundwater. The decrease in domestic and industrial groundwater abstraction of Rohtak district of Haryana is also attributed to shift from groundwater based supply to canal-based supply. The exponential increase in domestic and industrial groundwater abstraction in Meerut district of Uttar Pradesh in year 2013 is accounted by accelerated urbanization and overreliance on groundwater. Further, the data of Table 2 is discussed.

3.1 The Spatio-Temporal Variations in the Net Annual Recharge

The groundwater in NCR gets recharge through rainfall; canal seepage, water bodies, and irrigation return flow. In this study, the volume of net annual recharge to the groundwater has been separately studied for each sub-regions of Delhi NCR. The data for the sub-regions of NCR is shown by the bar graphs (Fig. 2).

It was observed that the temporal trends of the Haryana and Uttar Pradesh sub-regions are opposite to each other. The net recharge in Uttar Pradesh subregions shows a declining trend while the Haryana sub-region shows an increasing trend. Delhi and Rajasthan sub-regions have not shown any appreciable change in volume of groundwater recharges with time.

Table 2 Availability of recharge and extraction of groundwater from different sectors for the assessment year 2004, 2009, 2011 and 2013 in NCR Delhi

Year	Net GW availability (HaM)[a]				Domestic + Industrial draft (HaM)[a]				Irrigation draft (HaM)[a]				Net Sown area[b, c] (km^2)
	2004	2009	2011	2013	2004	2009	2011	2013	2004	2009	2011	2013	
Haryana sub-region													
Faridabad	55,074	20,228	19,564	17,141	1002	2232	2232	2232	26,811	14,118	12,691	14,777	1430
Gurgaon	43,117	23,261	24,048	23,827	11,315	18,150	18,152	3688	51,157	35,777	36,266	28,062	980
Jhajjar	35,646	42,718	41,238	42,462	156	192	291	295	30,873	40,751	40,768	35,002	1670
Sonipat	44,958	77,426	76,998	80,195	2931	3913	4630	2361	48,179	90,622	102,617	86,500	1470
Bhiwani	57,823	55,138	61,857	62,121	755	756	758	1742	59,307	43,068	70,596	103,397	3940
Jind	69,954	81,714	84,792	102,178	1950	3510	3717	3989	46,820	77,363	91,079	111,148	2570
Karnal	87,850	85,905	82,231	71,946	1245	1244	1244	1853	119,235	118,899	120,647	85,311	2000
Mahendragarh	18,214	21,437	22,480	25,630	388	388	421	551	19,141	22,453	22,506	21,607	1460
Mewat	N.F	21,623	22,364	21,814	N.F	1173	1190	1180	N.F	13,280	17,586	15,016	1740
Palwal	N.F	44,771	42,907	46,124	N.F	999	999	999	N.F	45,892	40,597	46,095	1070
Panipat	32,942	30,865	31,087	33,281	496	495	496	894	50,939	50,961	50,148	53,347	960
Rewari	26,065	27,999	28,392	30,962	301	116	116	1164	31,090	31,255	31,999	27,175	1290
Rohtak	25,313	45,017	43,771	47,795	0	2297	100	99	16,790	28,446	30,488	33,285	1430
Uttar Pradesh sub-region													
Baghpat	49,629	37,839	45,369	51,531	2412	2245	2199	2307	46,336	41,880	42,401	47,274	1091
G B Nagar	59,913	44,501	45,820	41,163	1582	1778	2772	1938	29,211	38,206	39,872	40,431	1165
Ghaziabad	98,164	82,474	30,016	29,233	3808	6899	7109	4802	66,685	56,040	24,457	26,449	[d]1499
Hapur	N.F	N.F	40,039	38,904	N.F	N.F	2670	2997	N.F	N.F	32,979	39,068	–
Meerut	120,668	105,298	115,160	114,865	3950	3729	3381	7997	74,405	66,349	77,433	77,846	2185.94

(continued)

Table 2 (continued)

Year	Net GW availability (HaM)[a]				Domestic + Industrial draft (HaM)[a]				Irrigation draft (HaM)[a]				Net Sown area[b, c] (km^2)
	2004	2009	2011	2013	2004	2009	2011	2013	2004	2009	2011	2013	
Muzaffarnagar	172,226	134,100	98,139	94,377	9792	7055	4718	3846	131,715	140,834	60,527	58,207	3273
Bulandshahr	148,011	145,091	151,866	134,035	5133	5791	5953	6228	91,898	106,148	118,443	115,312	2987
Rajasthan sub-region													
Alwar	79,036	79,482	73,169	85,504	6410	9204	9566	12,665	107,981	123,183	121,552	136,205	5071
Bharatpur	45,363	45,351	44,936	45,701	4097	6206	6378	6855	41,218	44,651	45,839	47,429	3964
Delhi	28,156	28,714	28,712	30,648	27,944	25,594	25,191	25,013	20,002	14,025	14,025	13,764	425.28

Sources
[a]CGWB (2006, 2011, 2014, 2017)
[b]https://cgwb.gov.in/District-GW-Brochures.html
[c]BHUVAN
[d]Includes Net sown area for Ghaziabad and Hapur
HaM hectare meters; *N.F* district not formed

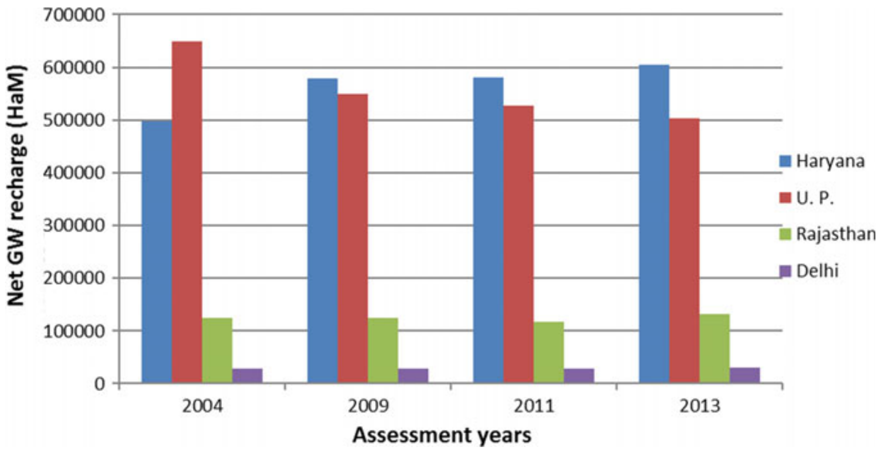

Fig. 2 The trend analysis of net annual groundwater recharge in sub-regions of NCR, Delhi

3.2 The Spatio-Temporal Variations in the Agriculture Draft

The agriculture sector is the major consumer of water. The groundwater demand for agricultural use in different sub-regions of NCR is presented in Fig. 3. The data shows that the total annual agriculture demand of groundwater in Uttar Pradesh and Delhi is now declining whereas the scenario is opposite in Haryana and Rajasthan sub-regions (Fig. 3).

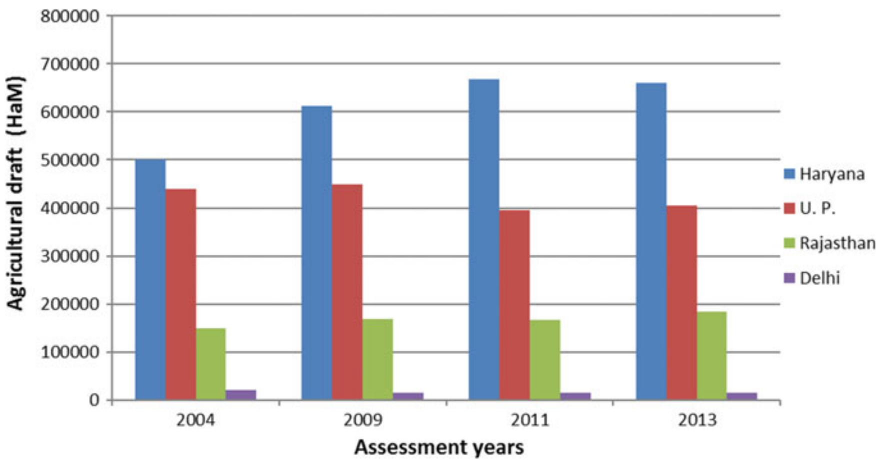

Fig. 3 Trend of annual agriculture draft in all four sub-regions of NCR, Delhi

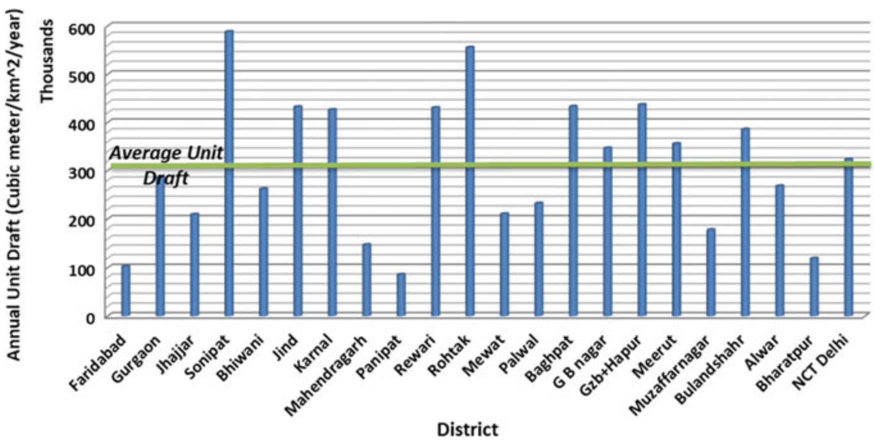

Fig. 4 Unit agriculture draft of year 2014 for NCR, Delhi

For better spatial comparison, draft per unit agriculture land is calculated by using the net sown area for each district (Table 2). Figure 4 shows the intensity of groundwater utilization in the agricultural fields of NCR, Delhi.

The NCR regions have an average annual unit draft of 3, 10,123 m^3/km^2. The calculated unit draft shows that districts such as Sonipat, Jind, Karnal, Rewari, Rohtak, Bagpat, Ghaziabad, Hapur, Meerut, Bulandshahr and NCT Delhi are exploiting groundwater much more than the average draft of the NCR region (Fig. 4). These districts are putting heavy stress on the groundwater resource. Thus, these regions need special focussed attention for the proper management of the groundwater resources.

3.3 *The Spatio-Temporal Variations in the Domestic and Industrial Draft*

The sum of annual, domestic and industrial draft for all four sub-regions is plotted in Fig. 5. The combined groundwater draft of domestic and industrial sectors shows a rising trend for the Uttar Pradesh (U.P.) and Rajasthan, however, a declining trend can be observed in Haryana and Delhi sub-regions (Fig. 5).

Further a decadal per capita comparision was attempted. The annual per-person groundwater draft was calculated using population census of India for the year 2001 and 2011 and the groundwater draft of domestic and industrial sector of nearest assessment year, that is 2004 and 2014. On account of district reorganization between 2001 and 2011 the comparsion was difficult. Thus data for Hapur, Palwal and Mewat has been clubbed together with their parent districts namely Ghazibad, Faridabad and Gurgaon respectively as the data were not available for year 2001. The result is shown as Fig. 6.

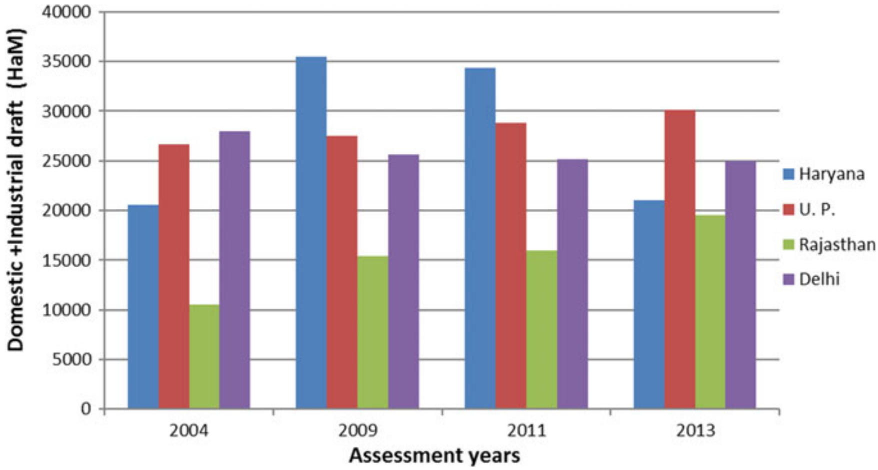

Fig. 5 Trend of annual domestic and industrial draft in all four sub-regions of NCR, Delhi

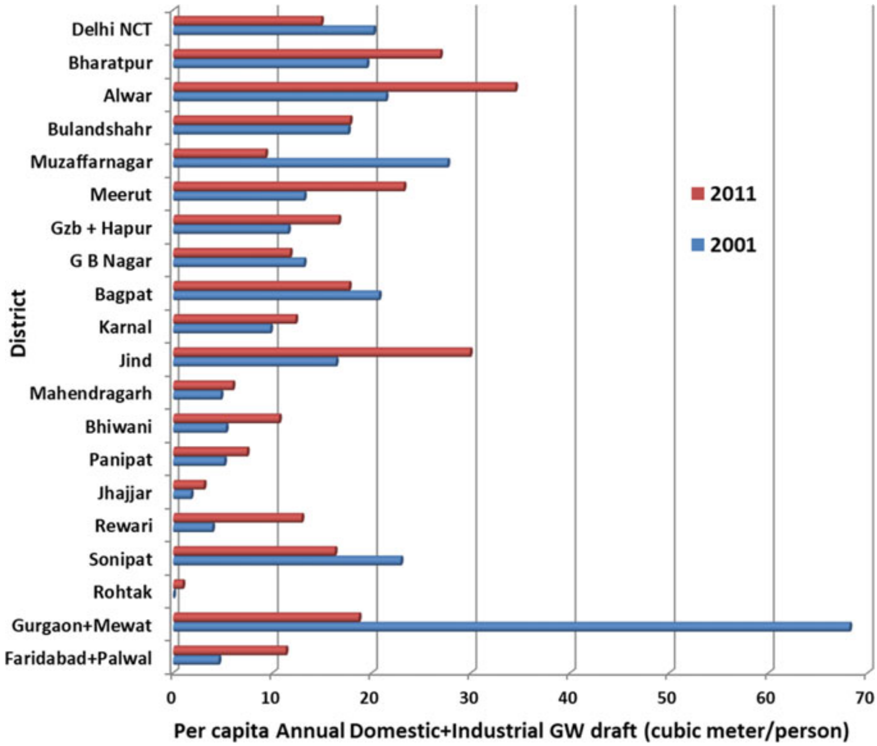

Fig. 6 Decadal change in per capita groundwater draft in domestic and industrial sector in NCR

The spatio-temporal varaiations in per capita annual domestic and industrial draft is interesting. The prominent parts of NCR like NCT Delhi, Gurgaon and Gautam Budh Nagar have shown decline in the percapital groundwater abstraction. Similarly, Muzaffarnagar, Baghpat and Sonipat have also shown similar decline. However, in other districts of NCR the percapita abstraction has increased over decade 2001–2011. It needs to be assessed how some parts responded positively to aggressive groundwater regulation and remedial measures, while others did not.

4 Conclusions

The NCR region shows distinct spatial and temporal variation in the dynamic groundwater resources. The overall stage of groundwater development of the NCR, Delhi is about 107% which makes the region in the category of over-exploitation. A deeper insight confirms that in the majority of the Delhi NCR sub-region the groundwater resources are overexploited. However, some districts are still in safe zones like Mewat, Rohtak, Meerut and Muzaffarnagar. While Jhajjar and Mahendragarh districts have about 90% stage of groundwater development. On the other hand, a good number of the districts have overexploited their groundwater resources. The heterogeneity in hydrogeology, land uses, water use efficiency and efficacy of regulation measures are reflected in the observed spatio-temporal variation of the dynamic groundwater resources. As the region is demarcated for gradual urbanization and industrialization, it is desired that advance planning may be initiated for sustainable management of the groundwater resources. The potential aquifers like flood plain of rivers may be protected for future water supply. In the canal command areas, after urbanization and industrialization conjunctive use of canal and groundwater may be adopted for water supply. The new development should recycle and reuse their water resources. These initiatives will ease the stress on the groundwater system. The ultimate aim should be development of satellite towns of Delhi which are self-reliant smart cities.

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Groundwater Hydrology in Arid Rewari District of Haryana: Assessment, Development and Management Options

Omvir Singh and Rekha Sharma

Abstract Groundwater has come up as a remarkable resource of water supply. Its more and more need in agriculture, industries and domestic sectors makes it as an asset of vital concern. Accordingly, this investigation has attempted to assess the dynamic groundwater resources of arid Rewari district at block level in Haryana. The investigation rests on secondary data sources pertaining to levels of groundwater, rainfall, area under irrigation, groundwater structures, net irrigation demand of crops, technical stipulations of surface water bodies (river, canal, drain etc.) and water management structures. The yearly renewable groundwater resources of the district have been observed to be about 715 million cubic meters, while the yearly groundwater extraction has been to the tune of 965 million cubic meters, thereby leaving a deficit of 250 million cubic meters. This large deficit in groundwater resources of the district can be attributed to over-utilization of the resource in four blocks out of five. These findings indicate towards the design of speedy groundwater management plans in the district such as artificial recharge on large scale through rain water harvesting, regulation on development of groundwater in over-exploited and risky areas, development of groundwater sanctuaries, power tariff on withdrawal of groundwater, judicious use of water etc. These measures will certainly bridge the gap between groundwater availability and demand in the district.

Keywords Draft · Groundwater · Management · Recharge · Water budgeting · Rewari district

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1 Introduction

Groundwater has come up as a remarkable resource of water supply. Its more and more need in agriculture, industrial and domestic sectors makes it as an asset of vital concern (Moreaux and Reynaud 2006). Worldwide calculations reveal that about 4430 km^3 of groundwater resources are withdrawn yearly, of which 70% are utilized for cultivation of crops, 25% in industries and remaining 5% in households (Kinzelbach et al. 2003). The yearly groundwater withdrawals for the planet earth are more or less 750–800 km^3, which has been found nearly 16% of the total withdrawals (Shah et al. 2000). Globally, the share of groundwater to agriculture sector is far less than the surface water. However, it has a special leverage like consistency, immediately obtainable, limited expenditure and mass production, which exceeds the quantitative access than surface water (Srinivasan and Kulkarni 2014). Rural economy has been revamped worldwide by speedy growth of groundwater irrigation, leading the way to substantial increase in food production and achieving food security, drinking water supply, industrialization, urbanization, drought mitigation, social and economic development (Singh and Singh 2002; Scott and Shah 2004; Rokade et al. 2004, 2007). Extensive withdrawals of groundwater have surpassed the natural renewals, thus causing significant reduction in its levels (Zektser et al. 2005; Steward and Allen 2016; Singh and Kasana 2017).

Groundwater could be a noteworthy source of water in numerous areas of India, particularly in parched areas (Tiwari et al. 2009). Since the second half of twentieth century in India, the extent and rate of groundwater removal have expanded by leaps and bounds, with an increment in number of tube wells from 12 million in 1990 to greater than 20 million in 2010 (Singh et al 2020). This development has brought about the over-utilization of groundwater assets, which is clear from the reality that "over-utilized or dark blocks" have expanded to the tune of 1071 in 2011 (CGWB 2012). The significance of groundwater assets in India can be understood by the reality that it accounts for about 53% of the overall water system potential, and around 50% of the total area under irrigation, 50% municipal water supplies and about 85% of drinking water need in countryside (Chadha 2002; Sharma et al. 2004; Shah 2007; Scott and Sharma 2009). Groundwater consumption at such a large scale have led to over-utilization of this valuable resource in various zones of India, thus resulting a decline levels of groundwater (Rodell et al. 2009). A drop in levels of groundwater by 0.66% every year could diminish gross food grain harvest of India roughly by 25% or even greater in future (Seckler et al. 1998; Gupta and Deshpande 2004).

The overdevelopment and detrimental impacts of irrigated agriculture on groundwater resource in Indo-Gangetic plain have been widely recognized (Bandyopadhyay 1987; Pant 1987; Ghose and Phadtare 1990; Singh 2000; Hira et al. 2004; Ambast et al. 2006, Dash et al. 2019). Intensive abstraction has caused widespread and serious groundwater levels decline (to the tune of 1–2 m/year) in parts of southern Rajasthan, north Gujrat, Saurashtra, the Kolar district of Karnataka, the Madurai and Coimbatore districts of Tamil Nadu, the whole Rayalaseema territory of Andhra Pradesh, and parts of western Uttar Pradesh, Haryana and Punjab (Singh and Singh 2002; Aggarwal et al. 2009a, b; Chatterjee et al. 2009; Chatterjee and Purohit 2009; Chawla et al. 2010; Singh et al. 2015, 2020). The levels of groundwater have declined by 5–15 m in the preceding 20 years, which has resulted in a drop of centrifugal pumps to deeper pits. Also, it has stimulated the farmers to change the centrifugal pumps with submersible one, leading to a monetary burden and a warning towards groundwater sustainability (Goyal 2010; Goyal et al. 2010). As groundwater levels fall then its abstraction becomes more difficult and expensive and eventually wells may dry up. This inclination toward overdevelopment of groundwater assets is established in the fast spread of pumping technologies, resource characteristics, demographic changes and governmental policies (Shah et al. 2003). Nationwide, a continuous growth rate of over 12% in diesel and electric pump sets have been observed (Dadlani 1990). Moreover, declining groundwater levels and use of economically available groundwater pools could have major social and economic outcome (Llamas and Santos 2005).

Recently, moving to increasingly productive harvests have additionally encouraged the groundwater demand. Conventional canal irrigation system has been generally ousted by increasingly guaranteed groundwater irrigation (Shah et al. 1998; Ambust et al. 2006). Over the years, an excessive withdrawal of groundwater than its recharge has influenced the ecology causing a recurring variation in the levels of groundwater (Balukraya 2000). In addition, a quick industrial expansion, urbanization and an increment in agricultural harvests have prompted the groundwater deficiencies. A growing difference between water demand and supply causes a risk to poverty reduction programmes, ecological viability and upcoming economic development (Kumar et al. 2002; Sethi et al. 2008).

In Haryana, groundwater is the key resource for supplemental irrigation and over 60% of the cultivated area is dependent on it (Amrita 2017). The share of tube wells irrigated area to gross irrigated area has escalated from 38.9 to 61.2% between 1975 and 1976 and 2011 and 2012 (Singh et al. 2020). Food grain production has increased from 2.59 million tones to more than 13.4 million tones because of major shifts in cropping pattern. Farmers have disowned customary crops needing less water and diverted to paddy, lured by periodic price enhancements. The rice and wheat cultivated area has recorded a growth of 550% (six-fold) and 241% (three-fold) respectively, in the state between 1966 and 2012 (Singh and Amrita 2015). This expansion has prompted an unusual increment in evapotranspiration requirement, which has been chiefly fulfilled by tube wells. This has resulted in a rise in their number from 0.02 to 0.73 million between 1966 and 2012, causing an excessive utilization of groundwater assets in most parts of the state. Moreover, the state is in a detrimental situation with respect to amount of water. Normally, the state gets 545 mm of rainfall every year, while the ecological need is about 1500 mm (Singh and Amrita 2015). Apart from this, an increasing population, climate change, utilization propelled growth, unrecyclable exploitation and faulty management practices are expanding the difference between supply and demand of water (Singh and Sharma 2010). Widespread aquifer depletion and water scarcity are vital symptoms of an imminent crisis. The scarcity of water particularly during crop growth stages is well pronounced, having a substantial impact on the agriculture of Haryana (Singh and Singh 2002). For the existing cropping scheme and a gross harvested area of about 6.2 million ha, the gross annual irrigation water requirement of Haryana has been estimated at 46 BCM (Singh and Amrita 2017).

Groundwater has declined at an alarming rate in parts of Rewari district. Some of the representative declining groundwater hydrographs for the district has been demonstrated in Fig. 1. By and large levels of groundwater trend are declining at the rate of 11.0–97.0 and 14.5–110.2 cm/year in the time between pre-monsoon (ahead of monsoon) and post-monsoon season (thereafter of monsoon), respectively during 1991–2008. The only exception being the Jatusana and Nahar blocks during the post-monsoon season (Table 1). A constant lowering in groundwater levels is thus a key environmental concern for the district as it has triggered the failure of shallow tube wells. Moreover, declining groundwater levels will also lead to a decline in its accessibility.

Keeping in view of the above preamble, this investigation has been attempted (1) to assess the block-wise availability and development of groundwater resources, and (2) to calculate the gap in supply and demand of groundwater resources in Rewari district of Haryana. The over-utilization of the resource in district has given rise to its progressive lowering, thereby seriously affecting the availability for drinking, agricultural and other purposes.

2 Materials and Methods

2.1 Environmental Setting

Rewari district extends between 27° 46′ to 28° 28′ N latitudes and 76° 15′ to 76° 51′ E longitudes. The total geographical area of the district is about 1509 km^2. Administratively, the district has been bisected into five blocks viz. Bawal, Khol, Nahar, Jatusana, and Rewari (Fig. 2). In general, topography of the district comprises of the alluvial plains of Yamuna River basin, dating back to Quaternary age. The district has extensive alluvial and sandy areas with scattered ridges of Aravalli hills, which are at times protected with blown sand. Alluvium chiefly comprises of very fine to coarse sand, gravel, clay silt and with kanker formations in differing ratios. On the whole, the district is flat and sandy except in its eastern parts. The topography differs from 232 m in north to 262 m above mean sea level in south, while major slope is towards the north. The ranges of Aravalli hills contain valuable mineral deposits and natural meadows. Due to arid climate, soils of the district are calcareous, medium textured and light coloured. The organic content of the soils ranges up to 40%. The obtainable phosphorus in soils is around 21.5 kg/hectare. Apart from this, soils in the district suffers from moderate salinity and alkalinity hazard.

Sahibi and Krishnawati are the major rivers of the district. Sahibi rises from Mewat hills in Jaipur-Alwar region of the Rajasthan state and lasts for a very short time.

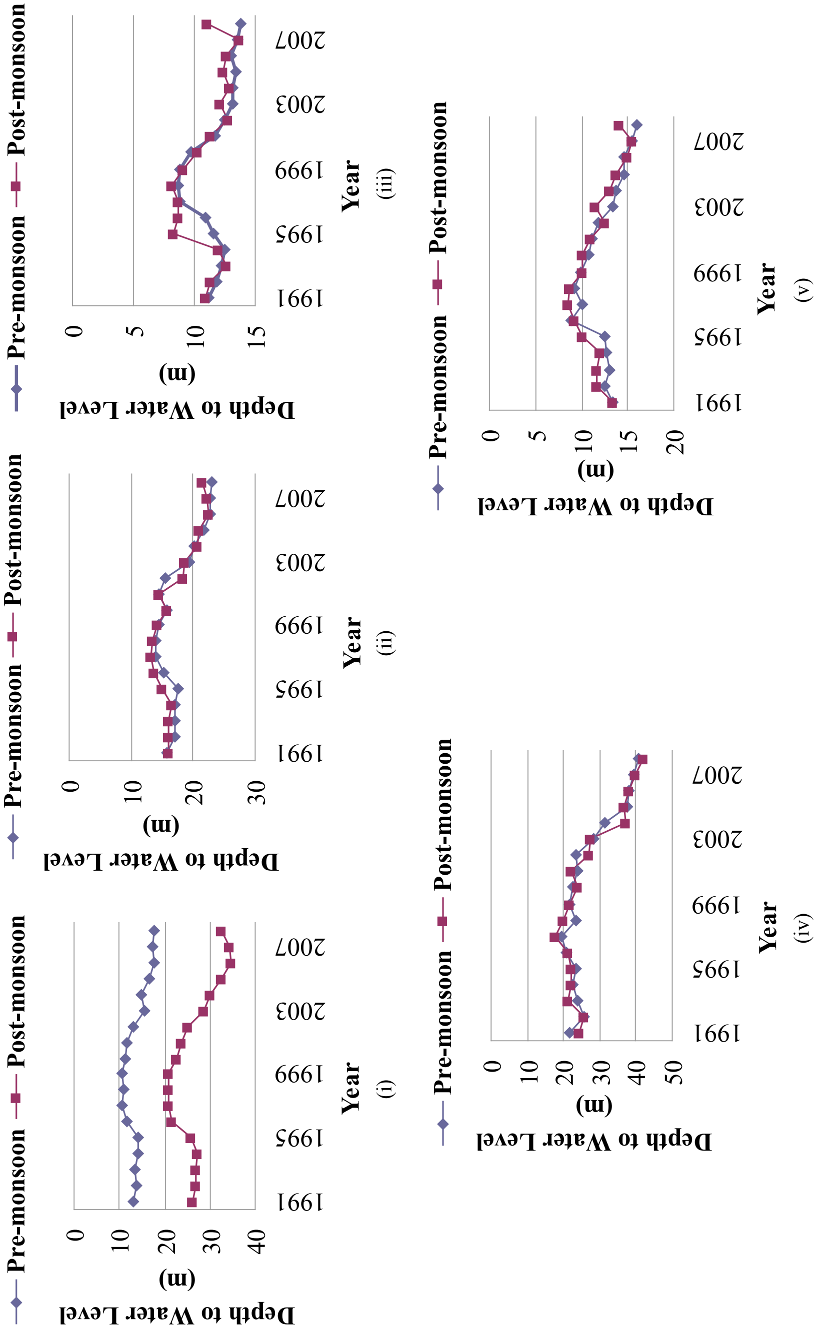

Fig. 1 Hydrographs of **a** Rewari, **b** Bawal, **c** Jatusana, **d** Khol and **e** Nahar block in Rewari district of Haryana. *Source* Groundwater Cell, Department of Agriculture, Narnaul

Table 1 Average trends in level of groundwater in Rewari district of Haryana during 1991–2008

Block	Trend pre-monsoon (May) (cm/year)	Significant decline (yes/no)	Trend post-monsoon (November) (cm/year)	Significant decline[a] (yes/no)
Rewari	−20.6	Yes	−14.5	Yes
Bawal	−39.8	Yes	−34.3	Yes
Jatusana	−14.7	Yes	−0.5	No
Khol	−97.0	Yes	−110.2	Yes
Nahar	−1.0	Yes	−7.7	No

[a]Significant decline is more than 10 cm/year

Annually, moderate to heavy floods are generated by Sahibi River in parts of the district and therefore, contributes to groundwater reservoirs. The Krishnawati River more or less forms the border between Mahendragarh and Rewari districts of the state. This is a partially sighted river and its water fall victim to sandy soils. Also, there are several other minor nalas which fetch rain water from the hills during rainy season.

The climate of district is labelled as hot and arid with excessive evapotranspiration and cold winter except in monsoon season when humid air from the sea invade into the district (Raju et al. 2013). The summer season begins from mid-March and continues to last week of June, which is accompanied by south west monsoon lasting up to September. The September and October months shape the post-monsoon season. The winter season begins late in November and stays up to initial week of March. The mean lowest and highest temperature ranges from 5.6 to 41 °C during January and June months, respectively. The usual monsoon and yearly rainfall are about 489 mm and 553 mm, respectively, which is not uniform and spans over just 23 days in a year. Around 85% of the annual total rainfall takes place during south west monsoon and remaining 15% falls during non-monsoon months due to western disturbances and thunderstorms. By and large, rainfall increments from south west to north east in the district.

Nearly all the land of district is suitable for cultivation. Therefore, agriculture forms the backbone of economy of the district. The gross irrigated area is about 1430 km^2 and mostly irrigated by tube wells. The principal groundwater reservoirs of Rewari district pertain to unconsolidated alluvial accumulation of quaternary age. Besides, a small quantity of groundwater also exists in hard rocks, which flow through cracks, joints and fractures. Jawaharlal Nehru canal system constitutes the man-made drainage network of distributaries and minors providing surface water.

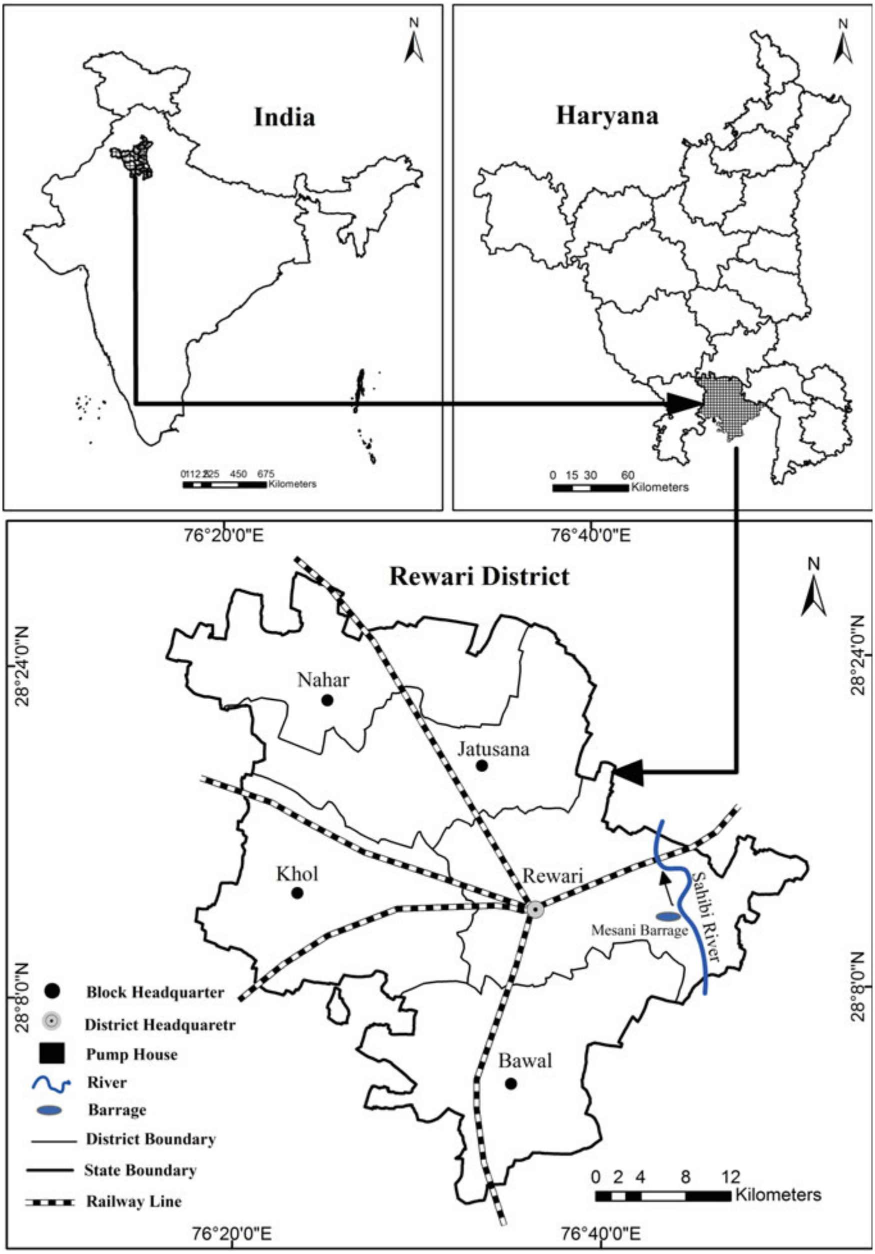

Fig. 2 Location of Rewari district in Haryana

2.2 Data Used

The assessment and development of groundwater resources of Rewari district has been done on block-level. The assessments are based on levels of groundwater, rainfall, area under irrigation, groundwater structures, net irrigation demand of crops, technical stipulations of surface water bodies (river, canal, drain etc.) and water management structures. The major sources of database are secondary and have been collected during the year 2011–12. The data sources include Central Ground Water Board, (Chandigarh), District Revenue Officer, (Rewari), Department of Irrigation, (Rewari), Department of Agriculture, (Rewari), Census of India, (New Delhi), District Statistical Handbook, (Rewari), Ground Water Cell, (Narnaul, District Mahendergarh), Chaudhary Charan Singh Haryana Agricultural University, (Regional Station, Bawal), Directorate of Economics and Statistics, (Chandigarh), Department of Soil and Water Conservation, (Rewari) and personal communications with officials of these departments.

2.3 Estimation of Groundwater Recharge Components

2.3.1 Groundwater Recharge from Rainfall

Rainfall contributes towards surface runoff, groundwater recharge, deep percolation and other losses in Rewari district. The rainfall pattern in the district is erratic and non-uniformly distributed. The predominant rainy season (monsoon) in the district extends from July to September. The usual yearly rainfall in the district is 553 mm and about 85% of yearly rainfall results during monsoon season. The remaining yearly rainfall pours as winter or thunderstorm rains during pre and post-monsoon season. The rainfall statistics employed for recharge assessments have been gathered from five meteorological stations located at various block headquarters in the district. The lowest normal yearly rainfall has been recorded at Khol (298 mm) whereas highest yearly rainfall has been recorded at Rewari (619 mm) (Table 2). For the computation of rainfall recharge, 50% of the total rainfall has been taken as effective rainfall. The amount of rainfall recharge has been computed by multiplying the 50% amount of rainfall (m) with the area (m) of the respective blocks (Mathur and Jain 1981; Gaur 2001).

2.3.2 Groundwater Recharge from Canal Seepage

Rewari district is marked with a widespread system of canal drainage network (Table 2; Fig. 3). Infiltrations through the network of canals and drains are considered significant contributors to groundwater regime of the district. Recharge from canal seepage (R_s) depends on cross-section and size of the canal, depth of flow, properties

Table 2 Sources of groundwater recharge in Rewari district of Haryana

Block	Rainfall (mm)	Canals and drains	Irrigation (km^2)	Groundwater level fluctuation (m)	Water conservation structures (Number of schemes implemented)
Rewari	619.4	Nayagaon, Jeetpur, Dhoki, Bhagwanpur budhana, Khatauli, Nikhri, Mundia khera, Jatuwas, Kamalpur	292.4	−0.82	244
Bawal	593.8	Rattanpur, Akbarpur, Bharawas, Bharawas sub minor, Bolni, Kheri Motla, Jalalpur, Mangleshwar, Bishanpur, Sanjarpur, Bidawas, Hassanpur, Jhabua, Pranpura, Tankri, Keshopur, Khandora, Kishanpur, Raliawas	259.5	−0.54	248
Jatusana	527.8	Sumakhera, Sumakhera minor, Bhurthal, Sheikhpur, Musepur, Rasoli, Balawas, Jamalpur, Ladhuwas	304.0	−0.88	140

(continued)

Table 2 (continued)

Block	Rainfall (mm)	Canals and drains	Irrigation (km^2)	Groundwater level fluctuation (m)	Water conservation structures (Number of schemes implemented)
Khol	298.4	Deewana distributary, Rajpura, Gangoli, Buroli, Bas, Nangla, Nangla minor, Siha, Khaleta, Zainabad, Bohka, Jaula, Mandola, Khol, Basduda, Rajiaka, Laduwas	292.0	1.54	449
Nahar	490.8	Jakhala, Mundra, Dhania, Kosli, Shadipur, Saidpur	331.5	−0.59	50

Source Compiled by authors

of soils in the bed, sites and location and level of drains on either side of the canal. Mathematically, it is represented as:

$$R_S = WP \times WA \times NCR \times SF \quad (1)$$

where, R_S = Recharge from canal seepage, WP = Total wetted perimeter, WA = Wetted Area, NCR = Number of canals running days (94 days for kharif and 92 days for rabi season) and SF = Seepage factor. Season wise discharges have been computed from daily canal water release. Daily seepage rate for unlined canals in normal soil (sandy loam) has been considered as 0.2 mcm/day/10^6 m^2 of wetted perimeter of canal and for lined canals is 0.06 mcm/day/10^6 m^2 of wetted perimeter of canal (CGWB 2005; Chatterjee et al. 2009; Chatterjee and Purohit 2009; Kumar et al. 2002).

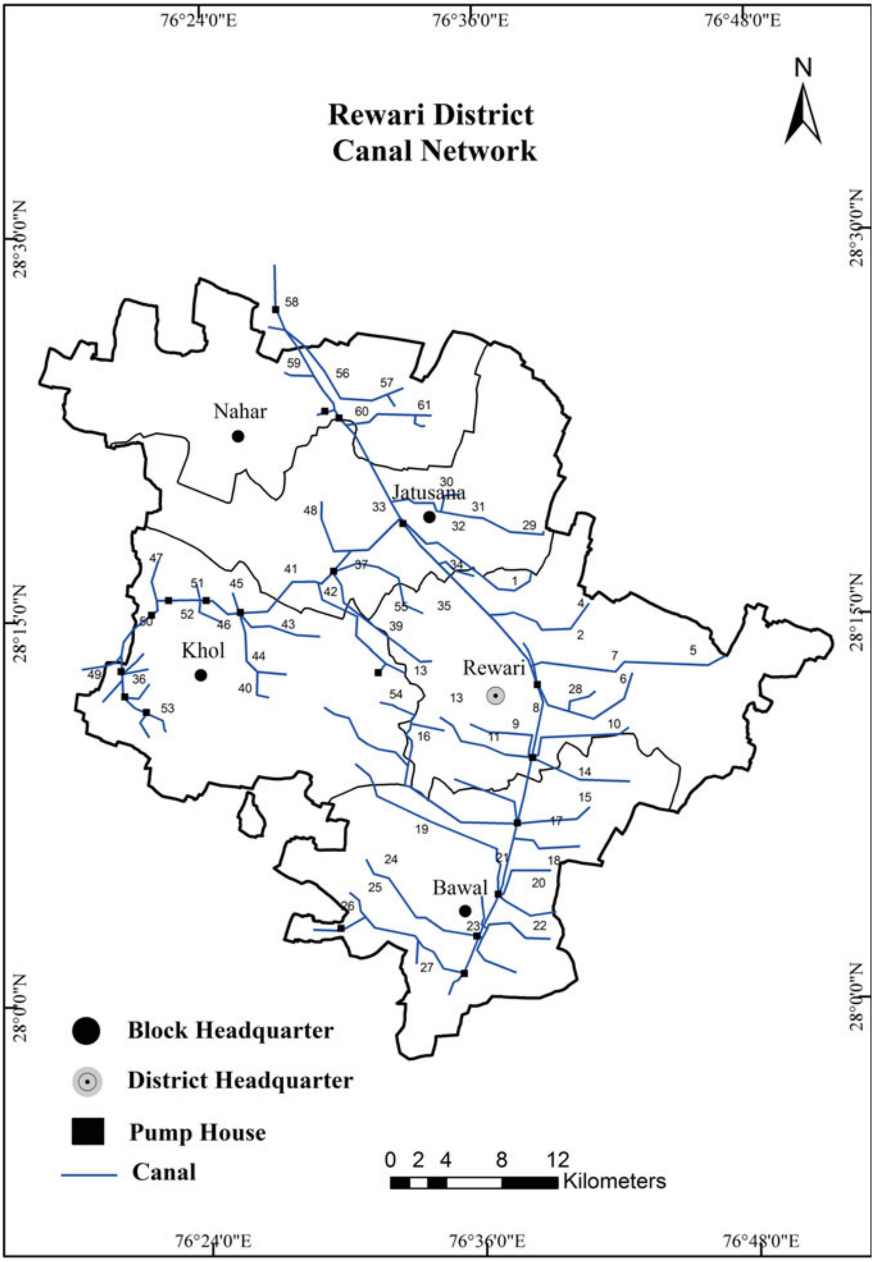

Fig. 3 Distribution of canal channels under different blocks in Rewari district of Haryana

2.3.3 Groundwater Recharge Due to Fluctuations in Level of Groundwater

Groundwater levels fluctuate yearly more or less in all wells of the district. The yearly increase in groundwater levels takes place on account of seepage from rainfall and narrowly by infiltration of water from surface storage tanks. Groundwater levels generally begin to increase in July and go on till October. The groundwater levels rise period generally resembles with the period of monsoon months. Groundwater levels normally fall during dry months till the end of June. In order to assess the character of groundwater level fluctuations in its recharge the specific yield, the mean groundwater level rise and the area of the aquifer have been mathematically calculated as:

$$R = A \times Y \times NS \tag{2}$$

where, R = Recharge, A = Area of aquifer (km^2), Y = Specific yield of the hydrogeological unit and NS = Fluctuations in level of groundwater in pre and post-monsoon periods.

Based on Groundwater Resources Estimation Committee (GWREC 1997), specific yield for district has been assumed as 6% because the district largely constitutes a part of the alluvial plains of Yamuna River basin. Moreover, 75% recharge due to groundwater fluctuations is accounted during kharif season while remaining 25% recharge for the rabi season.

2.3.4 Groundwater Recharge by Influent Seepage from Irrigated Fields

Agriculture is the backbone of Rewari district economy and it is fully supported by irrigation. Both water intensive crops and less water requiring crops are grown. Depending on prevailing hydrological conditions in the district, the proportion of recharge from influent seepage has been fixed at 10% (Mathur and Jain 1981). Therefore, with a total depth of irrigation water as 0.10 m, and the total irrigated area of each block, the recharge from irrigated fields is calculated as:

$$\begin{aligned}\text{Recharge from irrigated fields} = {} & \text{Fixed proportion of recharge}(\%) \\ & \times \text{Depth of irrigation} \\ & \times \text{Total irrigated area of block} \times 100\end{aligned} \tag{3}$$

2.3.5 Groundwater Recharge by Percolation from Water Conservation Structures

The district has a rich heritage of various water conservation structures such as tanks, ponds, percolation tanks, embankments, water harvesting structures which have been constructed by the residents in ancient times. Although, many of these structures are out of use due to faulty upkeep. However, water collected in these structures in rainy season contributes to the groundwater through infiltrations. All over, a record of 780 such structures have been compiled (Table 2) and greatest number of them have been found in Khol, Rewari and Bawal blocks of the district. Gross storage from these structures has been calculated by multiplying the number of water conservation structures with their storage capacity. Out of the total gross storage 75% storage has been taken as kharif recharge, while remaining 25% has been taken as rabi recharge.

2.4 Estimation of Groundwater Draft Components

2.4.1 Groundwater Draft Due to Domestic Use

Water demand for public is taken as 1001 per capita per day (lpcd) (CGWB 2005). Domestic water demand has been assessed by taking 2001 population as base population and a growth rate of 2.4% has been considered to determine the population for the period 2004–08. Total domestic draft has been estimated by multiplying the total population of each block with the unit draft and also by the days in a year (365). Further, out of the gross domestic draft 40% draft has been considered as kharif draft and 60% as rabi draft (Gaur 2001).

2.4.2 Groundwater Draft Due to Diesel and Electric Operated Tube Wells

The groundwater draft (ha-m) has been estimated by multiplying the unit tube well withdrawal with the number of tube wells in each block (GWREC 1997; Gaur 2001). The unit draft for dug well without pump, dug well and deep well fitted with pump and dug well and deep well fitted with electric motor have been considered as 0.003 mcm, 0.008 mcm and 0.009 mcm, respectively. Out of gross yearly draft 25% draft is taken as kharif draft and 75% as rabi draft (Gaur 2001).

2.4.3 Estimation of Crop Water Requirement

The key crops grown in Rewari district are jowar, bajra, sugarcane, cotton and paddy in kharif season and wheat, oilseeds, barley and gram in rabi season. Month wise crop coefficient and crop growth days for different crops have been used as proposed

Table 3 Crop growing days and crop coefficient under different crops

Crop	Growing days	Crop coefficient
Paddy	143	1.100
Bajra	73	0.714
Jowar	102	0.714
Sugarcane	320	0.900
Cotton	175	0.776
Wheat	145	0.632
Gram	135	0.638
Barley	145	0.632
Oilseeds	136	0.760

by Jalota and Arora (2002). The evapotranspiration has been estimated as:

$$ET = K \times E_p \quad (4)$$

where, ET = Evapotranspiration, k = Crop coefficient, andE_p = Pan evaporation.

Further, crop-wise evapotranspiration has been estimated using area and growing period (days) under each crop. Number of growing days for different crops and their cumulative coefficients has been presented in Table 3.

2.4.4 Groundwater Budgeting

The groundwater budget for different blocks of the district has been considered as the difference between net annual groundwater recharge available, and the net annual groundwater draft.

$$\text{Groundwater balance} = \text{Net annual recharge} - \text{Net annual draft} \quad (5)$$

Block-wise assessment of the shortage/surplus of groundwater resources have been acquired by calculating the deviation between the existing water resources i.e. rainfall, canal water, groundwater, seepage from irrigated fields and water bodies and domestic, diesel and electricity driven tube wells and evapotranspiration demand for kharif and rabi seasons.

2.4.5 Groundwater Development

Levels of groundwater development has been calculated as the proportion of yearly groundwater withdrawal to net yearly groundwater accessibility. The level of groundwater development has been computed as:

Table 4 Criteria for groundwater development and exploitation categories

Stage of groundwater development (%)	Categorization
Up to 65	White area
65–85	Grey area
85–100	Dark area
More than 100	Over-exploited area

$$\text{Groundwater development } (\%) = \frac{\text{Net annual draft}}{\text{Net annual recharge}} \times 100 \quad (6)$$

The stage of groundwater development and its utilization status has been categorized by following the classification as outlined in Table 4. Safe areas have likely possibilities for groundwater development. However, in semi-critical areas prudent groundwater development is advocated. In unsafe and over-utilized areas, there should be rigorous monitoring, while future groundwater development needs to be connected with water management measures (GWREC 1997).

3 Results and Discussion

3.1 Groundwater Recharge Pattern

The average groundwater recharge pattern of Rewari district during 2004–08 has been exhibited in Table 5. The annual available groundwater resource for irrigation in the Rewari district has been found to be 713.80 mcm, out of which 521.45 mcm (73%) during kharif season and 192.36 mcm (27%) during *rabi* season. The average depth of the available groundwater has been 472 mm, out of which rainfall, canal seepage, water conservation structure, water table and seepage from irrigated fields contributed about 54.3, 35.7, 2.0, 5.9 and 2.1%, respectively. The contribution of rainfall recharge in each block of Rewari district has been observed to be more than 40%, while about 60 and 54% of the total recharge in Khol and Bawal block has been contributed by canal seepage (Fig. 4). It has been revealed from the analysis that groundwater accessibility has been in descending order in blocks of Bawal (750 mm), Rewari (526 mm), Jatusana (372 mm), Khol (363 mm) and Nahar (322 mm). The greatest yearly average groundwater availability has been observed in Bawal block (235.01 mcm), while the least has been observed in Nahar block (86.29 mcm). The highest yearly accessibility of groundwater in Bawal block may be ascribed to a splendid system of canals in contrast to other blocks. Moreover, an adequate quantity of rainfall falling over the surface of Bawal block during the study period contributed to maximum availability of groundwater. Further, the analysis has revealed that tube well density and cropping intensity has been least in this block (16.2 tube wells/km^2 and 136%, respectively). Also, it has been contemplated that availability of rainwater has been highest in Rewari block during the study period. The

Table 5 Groundwater recharge patterns in Rewari district of Haryana (mcm)

Block	Recharge during kharif season (monsoon)					Recharge during rabi season (non-monsoon)					Annual recharge (sum total of 1–10)
	Rainfall	Return flow from irrigation	Canal seepage	Fluctuation in water table	Water conservation structures	Rainfall	Return flow from irrigation	Canal seepage	Fluctuation in water table	Water conservation structures	
	1	2	3	4	5	6	7	8	9	10	11
Rewari	88.94	0.52	23.89	11.94	2.76	10.82	2.41	23.38	3.98	0.92	169.57
Bawal	83.84	0.47	63.86	7.64	2.13	9.18	2.12	62.50	2.55	0.71	235.01
Jatusana	75.54	0.51	6.63	12.49	1.17	8.08	2.53	6.49	4.16	0.39	117.98
Khol	37.78	0.58	32.07	−7.81	4.37	5.38	2.34	31.39	−2.60	1.46	104.95
Nahar	61.11	1.10	2.30	7.11	0.51	7.16	2.21	2.25	2.37	0.17	86.29
Total	347.20	3.18	128.75	31.37	10.94	40.63	11.62	126.01	10.46	3.65	713.80

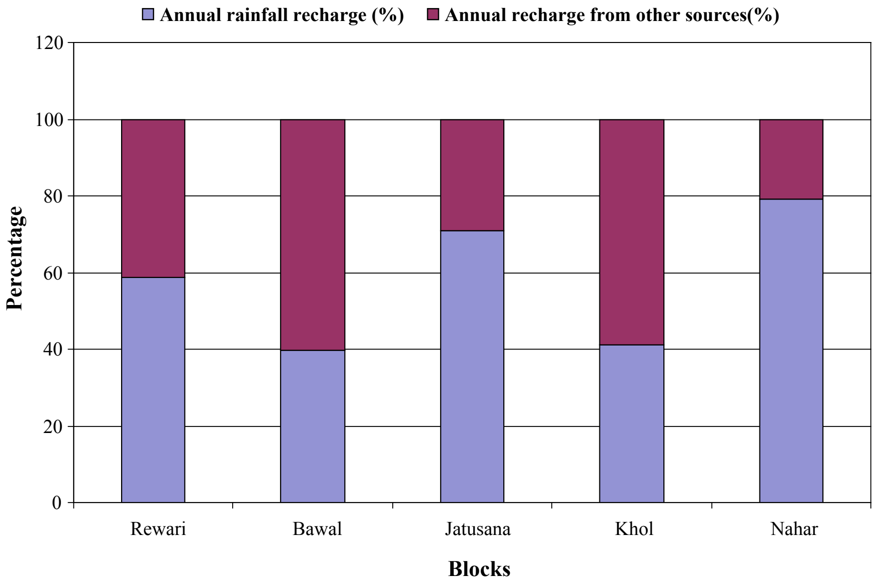

Fig. 4 Share of groundwater recharge through various sources in Rewari district of Haryana

average yearly effective rainfall has been computed as 257 mm. The average canal water availability in the district has ranged from 17–403 mm in different blocks. Bawal block received maximum canal water supply during the study period. The greatest depth to groundwater renewal from surface structures has been witnessed in Khol block due to construction of enough water bodies. Moreover, Khol block has witnessed negative groundwater recharge and the same is accredited to scarce rainfall experienced over the block. Khol block has experienced only 298 mm of average rainfall in comparison to 619 and 594 mm average rainfall received by Rewari and Bawal blocks, respectively. The maximum seepage from irrigated fields has been observed in Nahar block followed by Jatusana block. The highest recharge due to seepage from irrigated fields in these blocks is attributed to maximum irrigated area during the study period 2004–08. However, contribution from water conservation structures (2.0%) and seepage from irrigated fields (2.1%) has been found to be rather less significant.

3.2 Groundwater Withdrawal Pattern

Groundwater is largely extracted for agricultural usage in the district. The average annual groundwater draft in Rewari district has been observed to be 963.23 mcm out of which 388.37 mcm (40%) has been during kharif season and 574.85 mcm (60%) during the rabi season. Table 6 indicates the groundwater draft scenario of Rewari

Table 6 Annual groundwater draft pattern in Rewari district of Haryana (mcm)

Block	Draft during kharif season			Draft during rabi season			Annual groundwater draft (sum total of 1–6)
	Annual domestic draft	Annual tube well draft	Annual evapotranspiration	Annual domestic draft	Annual tube well draft	Annual evapotranspiration	
	1	2	3	4	5	6	7
Rewari	2.03	14.54	108.80	3.04	43.61	79.10	251.12
Bawal	1.66	9.54	45.73	2.49	28.61	70.53	158.56
Jatusana	1.50	13.35	42.99	2.26	40.04	82.77	182.91
Khol	1.92	11.43	49.94	2.88	34.28	77.28	177.72
Nahar	1.58	10.85	72.54	2.37	32.55	73.05	192.94
Total	8.69	59.70	320.00	13.03	179.09	382.73	963.23

district. The analysis has revealed that Rewari block has the maximum crop water requirement, whereas Bawal block has the minimum. The average seasonal crop water requirement of the district has been estimated to be 213 mm for kharif season and 254 mm for the rabi season. Maximum crop water demand has been 338 mm in kharif season for the Rewari block whereas minimum crop water requirement of 136 mm has been estimated for Jatusana block. Similarly, for the rabi season the maximum crop water requirement of 273 mm and minimum crop water requirement of 225 mm has been observed in Nahar and Bawal blocks, respectively. Bajra and cotton are the crops which require maximum amount of water during kharif season, whereas water requirement of wheat and oilseeds is maximum during the rabi season. It has been also observed that crop water demand has almost been fulfilled by rainfall during the kharif season. However, irrigation is applied as a supplemental during the dry spells. To accomplish the water demand of crop during the rabi season, groundwater and canal water is the lone source of irrigation for agriculturists in this area. The domestic water requirement has been observed to be highest in the Rewari block (5.07 mcm) and least in the Jatusana block (3.77 mcm). These results of domestic water requirement are well in agreement with the corresponding population of the blocks. The volume of water withdrawal from the ground storage by tube wells has been observed to be maximum from Rewari block (58.15 mcm) and least from Bawal block (38.15 mcm). Again, it is primarily attributed to tube well density in the block. The block-wise tube well density statistics demonstrated that tube well density is more in Rewari block. Hence, groundwater withdrawal has been observed to be highest in the block. Block-wise dispersal of yearly groundwater recharge and draft per hectare in Rewari district of Haryana has been presented in Fig. 5.

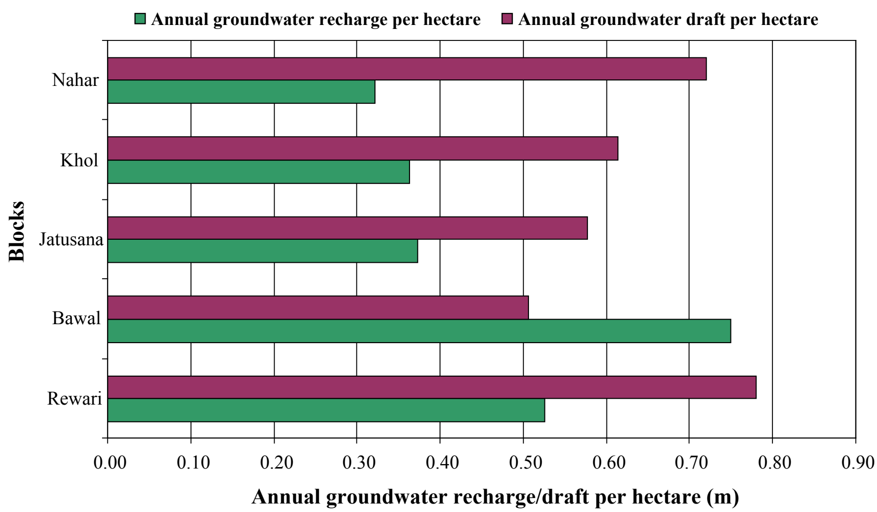

Fig. 5 Block-wise yearly groundwater recharge per hectare vs. yearly groundwater withdrawal per hectare in Rewari district of Haryana

3.3 Groundwater Budgeting

Block-wise disparity in groundwater availability and demand has been presented in Fig. 6. Negative signs in the figure indicate the water deficit whereas positive signs indicate water surplus for draft. Table 7 shows that the yearly groundwater demand has exceeded the average yearly available water in the district by 249.43 mcm. A deficit of about 382.49 mcm water has been observed during the rabi season, whereas a surplus of about 133.16 mcm water has been experienced during the kharif season. The availability of surplus water during kharif season is attributed to short duration crops of jawar and bajra. The average groundwater development during the study period in Rewari district has been observed as 135%. These findings advocate that

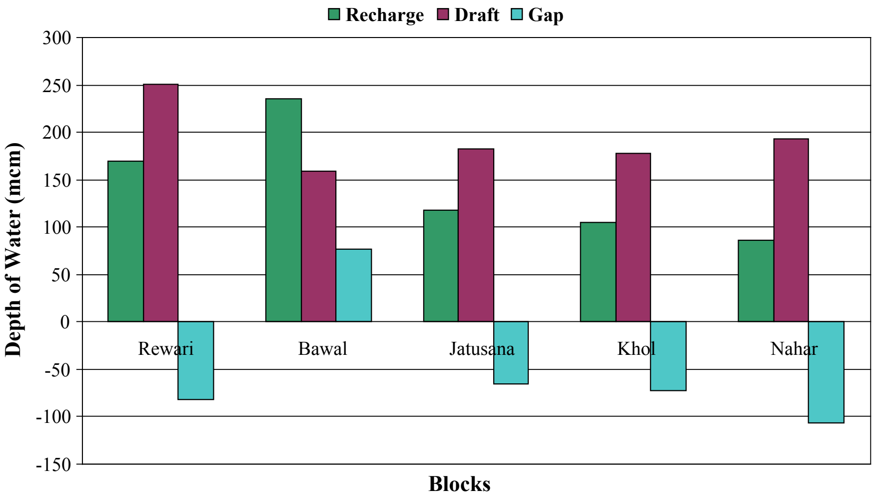

Fig. 6 Block-wise variation in supply and demand of groundwater in Rewari district of Haryana

Table 7 Yearly replenishable groundwater resource and level of groundwater development in Rewari district of Haryana

Block	Annual replenishable groundwater resource (mcm)	Yearly groundwater withdrawal (mcm)	Yearly gap in groundwater (mcm)	Level of groundwater development (%)	Categorization
Rewari	169.57	251.12	−81.55	148	Over-exploited
Bawal	235.01	158.55	76.46	67	Grey
Jatusana	117.98	182.91	−64.93	155	Over-exploited
Khol	104.95	177.72	−72.6	169	Over-exploited
Nahar	86.29	192.94	−106.65	224	Over-exploited
Total	713.80	963.23	−249.43	135	Over-exploited

further development of the resource is not possible by installing tube wells. Each and every block of the district is over-exploited excluding the Bawal block. It has been ranked as grey block with respect to the development of groundwater. This ranking of Bawal block is credited to better net yearly recharge and reasonably low withdrawal of groundwater. The groundwater resources assessment of Rewari district portrays the average standing of groundwater exploitation condition. However, there could be disparities in the standing of the groundwater regime within the district, which needs micro level investigations before any long-term groundwater management plan is launched in the susceptible areas.

4 Groundwater Management

It is evident from the groundwater development trends of the Rewari district that it has over-exploited its groundwater resources. Moreover, on account of quick changes both in population composition and pattern of land use in the district, the groundwater resources will deplete further. Heavy duty submersible pumps have been installed haphazardly without rendering any thought to the capacity of aquifers. If precautionary measures have not been put into practice to justify the demand with groundwater accessibility, the district will be devoid of groundwater in near future. Additionally, sustainable development of groundwater resources in the district has not been taken up as yet on behalf of the policy makers as the issue merits. Therefore, an urgent and appropriate groundwater resource development and management plan for the district is urgently required to eliminate the prevailing imbalances of water resources. Implementation of following conservation and management practices will certainly help in augmentation of depleting groundwater resources of the district. Unhampered implementation of following conservation and management practices will certainly help in augmentation of depleting groundwater resources of the district.

4.1 Rainwater Detention and Artificial Renewal to Groundwater

Rainwater detention and artificial renewal of groundwater has been welcomed worldwide as a remedial and practical measures for increasing groundwater availability and for capturing the falling trends of groundwater levels. Water supply in Rewari district, where rainfall is irregular and restricted within 2–3 months of the year can be increased by improved water detention and artificial renewal structures. Rainwater detention and artificial repletion of rainfall can enhance surface water resources, thereby resulting an increase in the quantity of groundwater resources (Sikdar et al. 1994). These technological interventions have shown excellent results regarding an increment in the availability of groundwater resources. Not only this, these interventions have checked the falling rate of groundwater levels and moderation of surplus runoff. The application of these techniques will further improve soil moisture, recharge of aquifers and irrigation potential of the district. Implementation of these techniques in the state of Haryana have shown an increment in the levels of groundwater to the tune of 0.25–0.70 m (Jha 2007). Moreover, construction of small water reservoirs (percolation tanks and shallow tanks) at suitable locations will increase the availability of surface water resources in the district, resulting an enrichment in groundwater reserves at the lower reaches.

4.2 Reduction in Transportation Losses

A large quantity of groundwater is lost in transportation process through seepage from surface water courses and field channels (canals, drains, distributaries, minors etc.). Therefore, to enhance the quantity of groundwater in different blocks of the district lining of irrigation network must be undertaken selectively with economic consideration for minimizing the percolation losses. However, water courses which contribute very little to groundwater should be lined for efficient conveyance and distribution of water. Lining of about 50% upper trunk length of the water course would give the best returns for lining on any part of the canal system.

4.3 Abatement During Application Losses

Flood and furrow irrigation are the key modes of irrigation in Rewari district. The applications of these irrigation techniques enhance the water loss through percolation and evaporation. Therefore, micro irrigation systems (sprinkler and drip) need to be replaced for meeting the water requirements of different crops. These irrigation techniques will provide uniform wetting and efficient water use. The replacement of flood and furrow irrigation with micro irrigation techniques will result in the saving of about 40% water (Ajula 1997). Moreover, the application of minor irrigation techniques will result in significant increase in crop yield.

4.4 Allotment of Water Resources

The allotment of water is a compromise between the need and amount of available water resources. The water in a canal command area is distributed owing to water availability and irrigation requirement of crops. The irrigation network in a canal command area is planned to support the Full Supply Designed Discharge (FSD) to guarantee the demand and supply. If a canal runs at FSD during a month, then the canal sufficiency factor is 1. The sufficiency factor of canals is fixed both for kharif and rabi seasons for various months to guarantee the maximum allotment of water for the crops. However, the sufficiency factor allotted once should not hold good forever. Shifting cropping pattern and enhanced use of groundwater are continuously changed both year by year and season by season. Therefore, sufficiency factor calls for a revision periodically.

4.5 Judicious Use of Water

Judicious use of water refers to the multipurpose use of waters in an integrated way, so that returns may be more than the gross output, whenever an individual opening is applied one by one. To increase the availability of groundwater resources in the district, several schemes with respect to judicious use of water should include, for example (1) enhancement of canal water by siphoning the groundwater through lifting tube wells along the canal systems (2) storage of rain water in open water bodies for usage in combination with canal and groundwater (3) application of good quality groundwater in rotation with canal water and vice-versa. By adopting conjunctive use water techniques maximum returns can be achieved without degrading the water resources of the region.

4.6 Treatment of Waste Water

There is a great potential for reuse and recycling of waste water from domestic and industrial sectors of the district. It has been observed that thousand liters of sewerage water is produced every day in different towns. An additional potential of water will be available for reuse if the generated waste water is treated and recycled. Adoption of this practice will thereby reduce the pressure on aquifers.

4.7 Pricing and Higher Power Tariff on Withdrawal of Groundwater

Since water is available without any financial liabilities in the district. Therefore, undue advantage of non-pricing of water is being taken by the effluent farmers and societies. Pricing of groundwater to commensurate, with demand can play a very important role in increasing water use efficacy in the district. Furthermore, rate of groundwater withdrawal is also intimately related to the power tariff. A major part of electricity delivered to the agriculture sector is used to pump groundwater for irrigation. Presently, power is supplied to rural areas at highly subsidized rates rather than based on actual power consumption. The highly subsidized rate, combined with efficient and reliable power supplies encourages the indiscriminate withdrawal of groundwater and sale of water in informal water markets. The higher tariff rates of energy would work as a limit for farmers to cultivate water demanding crops. Higher energy tariff rates will perform like an environmental tax, which the agriculturalists of the district have to reimburse for groundwater extraction. Moreover, separate feeders for domestic and agricultural sector will check the further exploitation of groundwater resource. This experience has paid good dividends in the effective controlling of the electricity consumption and thereby reducing groundwater withdrawal in Gujrat (Jha 2007).

4.8 Development of Groundwater Sanctuaries

Environmentally least affected landform in the Rewari district is Aravalli hills. Blessed with equitable biota these hills are well-known for their green belts. Moreover, these hills are also the potential recharge zones for aquifers. Therefore, these hills need to be protected as groundwater sanctuaries in the district.

4.9 Groundwater Augmentation Through Changes in Cropping Patterns

Changes in cropping pattern aimed at higher return of investment may lead to increased exploitation of groundwater resource in the district. Therefore, stable scientific innovations are necessary to solve this issue. The cultivation of such crops which have low water requirements with high market values need to be replaced. Moreover, shifting in the sowing time of crops may also augment the groundwater resource in different blocks of the district.

5 Conclusions

The present research concludes that Rewari district is slowly and steadily moving towards over-exploitation of groundwater assets. Moreover, on account of quick changes both in population composition and pattern of land use in the district, the groundwater resources will deplete further. Heavy duty submersible pumps have been installed haphazardly without rendering any thought to the capacity of aquifers. If precautionary measures have not been put into practice to justify the demand with groundwater accessibility, then the district will be devoid of groundwater in near future. Additionally, sustainable development of groundwater resources in the district has not been taken up as yet on behalf of the policy makers as the issue merits. Denying the farmers with their ownership rights to groundwater, imposing an environmental tax on its extraction, separation of agricultural and domestic feeders for supplying power in villages, location specific recharge structures to replenish fast depleting water resource would provide the district with a buffer. A regular evaluation of groundwater assets should be prime concern of water resource managers and policy makers. Groundwater controlling measures should be forced seriously in over-utilized groundwater areas. Aravalli hills, which is working as a revival zone in the district need to be ensured as groundwater sanctuaries. Moreover, check dams need to be raised at the outlet of streams and hydrogeologically sensitive areas to harvest the rainwater. Improved irrigation practices (sprinkler and drips) should be mimicked in order to minimize pressure on water resources. Indigenous village ponds need to be brought back into practice with community endeavor to guarantee the renewal of groundwater resources. Better water management at the individual level is the need of hour. Cropping pattern in the district should be replaced with low water consumption crops. Remarkably, mass consciousness and deployment of individuals with respect to different dimensions of groundwater management is the greatest prerequisite in the district. Finally, we must keep in our mind that the Nature can satisfy human need but not the greed.

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Environmental Tracers and Isotopic Techniques: Tools for Sustainable Water Management

Pankaj Kumar Gupta and Manik Goel

Abstract Isotopes, trace element and noble gases are regularly applied to quantify subsurface flow paths, sources, residence times and reactive processes in the geochemistry. Analysis of complex system necessitates use of isotopic techniques for more accurate resolution of the fluid transport and solute transformation. In this book chapter, a state of art of review has been discussed to understand the use of isotopic techniques and environmental tracers in water flow and solute movements. A detail discussion has been presented in this chapter to highlights applicability of the stable isotopes, noble gases as environmental tracers in water flow and contaminant transport study. This chapter will be helpful in designing experiments and field scale observation stations for investigation of groundwater pollution loading and implementation of management plan.

Keywords GC MS techniques · Groundwater pollution · Isotopic analysis · Monitoring

1 Introduction

The term 'isotope' is used for an element having the same number of protons but different numbers of neutrons as that of another element, for example dual hydrogen (^{1}H,^{2}H) or triple oxygen (^{18}O–^{17}O–^{16}O) in case of the water stable isotopes, consequently causing the water molecules of different atomic masses. Stable isotopes do not decay with time in contrast to radioactive isotopes. Stable isotopes are utilized reliably as an artificial or environmental tracer within the hydrologic sciences to study subsurface water flow paths, contaminant fate, residence times and biogeochemical processes (Bowen et al. 2019). Use of stable isotopes in subsurface research have

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gained more popularity due to—(1) its capability to capture finer temporal resolution and larger scales variations in subsurface processes, (2) smaller volume of samples requirements, (3) cheaper cost of analysis (Stumpp et al. 2018). Analytical technological advancement, for example new laser technologies reduces the cost of sample analysis relative to isotope ratio mass spectrometry, made possible to measure isotope dynamics with soil–water system.

In general, conservative tracer like sodium chloride (NaCl) has been used in past to trace water flow and solute transport parameters. However, competitive and concentration dependent absorption behavior of Cl^- has been reported in many research and thus conservative nature of Cl^- has been questioned in recent studies. Hence, high-precision measurements of water flow and solute transport parameters using isotope techniques than traditional tracer analysis help for a better understanding of biogeochemical processes (Pierchala et al. 2019). Naturally occurring isotopes of H, O, N, C, S and Cl are of particular interest for environmental scientists and biogeochemists. Isotope fractionation, that causes a shifting of isotopic composition of molecules during subsurface reactive processes/phase change due to difference in rate kinetics, diffusion and other physical properties. The major driver of these fractionation is the phase changes between vapor–liquid-solid phase water which is generally controlled by variation in subsurface conditions, for example seasonality of influx parameters like precipitation, evaporation and so on (Stumpp et al. 2018). Many of the fractionation processes are used to trace water, pollutant fate, nutrient cycling, and transforming processes in the atmosphere–plant–soil–groundwater continuum.

In subsurface research, ^{2}H and ^{18}O has been widely used to investigate infiltration and recharge (Böhnke et al. 2002), hydrodynamics of soil–water system (Barbieri et al. 2005), groundwater discharge (Luo et al. 2017), source, fate and chemical evolution of pollutants (Allen 2004; Tirumalesh et al. 2007; Kumar et al. 2019). For understanding the recharge sources and processes in subsurface, certain groundwater isotopes values can be compared with long-term average amount weighted isotope values for precipitation (Lapworth et al. 2015). During the journey of water molecules through the different phase of hydrological cycle, numerous isotopic molecular species with different isotopic combinations of hydrogen (^{1}H and ^{2}H or D) and oxygen (^{18}O and ^{16}O) in them are differentially allottedbetween solid, liquid, and vapour phases, imparting distinguishable isotopic signature to all the three phases (Bouchaou et al. 2005; Šanda et al. 2009; Adhikary et al. 2014; Bowen et al. 2019). One oxygen atom (any one of the three stable isotopes ^{16}O, ^{17}O, and ^{18}O) and two hydrogen atoms (any two of the two stable isotopes; 1H and D) combined to form a water molecule. Thus, nine probable arrangements of these three isotopes of oxygen and two isotopes of hydrogen are possible and the four most abundant isotopic molecules of water. Four major international standard references commonly used in case of the stable isotopes of water are VSMOW (Vienna Standard Mean Ocean Water), SLAP (Standard Light Antarctic Precipitation), SMOW (Standard Mean Ocean Water), and GISP (Greenland Ice Sheet Precipitation) (Gröning et al. 1999). One can refer article by Gröning et al. (1999) for more details about international standard reference materials.

Similarly, two stable isotopes of N i.e. ^{14}N and ^{15}N have been widely used to investigate (de-) nitrification processes, nutrient cycling, nitrate flow in subsurface (Kendall and Aravena 2000). Some of the study, combined N-isotopes (^{14}N and ^{15}N) with O-isotopes (^{16}O,^{17}O,^{18}O) for obtaining in-depth information about sources and cycling of Nitrate–N, (de-)nitrification processes than just N-isotopes alone (Czerwieniec and Tomaszek 2007). Nitrogen is recycled in an endless loop between the soil, atmosphere, and the biosphere. Thus, the fractionation of N-isotopes helps to understand different sources, processes and flow of N-cycling in soil–water system. For example, an inverse correlation of the ^{15}N and nitrate concentration indicates increasing denitrification with depth. Similarly, the variation in values of the $\delta^{15}N$ in different sources of N (fertilizer, animal waste etc.) helps to identify source zone and flow path of Nitrate–N in subsurface. These unique properties of dual nitrate stable isotope (O and N) help in tracking the contribution of nitrate from different sources (wastewater, fertilizer, atmospheric deposition) and different attenuating processes in subsurface (Kaushal et al. 2011; Zhang et al. 2014).

The stable isotopes of C (^{12}C and ^{13}C) have been reported very seminal to understand eco-hydrological processes and carbon pool in subsurface in earlier studies (Bowling et al. 2008). Variations in stable isotopic composition of root, steam, leaf tissues along with subsurface carbon pool and fluxes are used extensively to examine biogeochemical and ecohydrological processes (Cernusak et al. 2009a; Brüggemann et al. 2011). Temporal changes in metabolic processes and carbon allocation during pollutants degradationalong the transport pathways couldintensely affect the relationship between subsurface conditions and $\delta^{13}C$. For examples, variation in $\delta^{13}C$ can clearly indicate biogenic interferences in estimation of CO_2 generated due to degradation of hydrocarbons in subsurface. Root zone geochemical processes and factors affecting such processes can easily determine by C isotopic composition for better understanding of interaction in pollutant-soil–water-plant-atmosphere continuum. Generally, the combined analysis of the stable isotopes of C (^{12}C and ^{13}C) and or O (^{18}O) and ^{15}N was used in previous studies to understand ecohydrological responses and nutrient, contaminant movement in subsurface (Cernusak et al. 2009b; Brüggemann et al. 2011). Likewise, dual C and stable isotope of Chlorine (^{37}Cl) were also used to investigate fate and transport processes in soil–water system (Wiegert et al. 2012) (Table 1).

Spatial variation in indigenous topography and soil texture variations necessitates a large number of observation locations to evaluate groundwater recharge, water movement in subsurface. Which relay on measurement of hydro-meteorological parameters thus significantly increases the cost of study to assess it accurately? Furthermore, such analysis is more problematic and difficult to detect small changes in dry climatic regions (Allison et al. 1994). Thus, water isotopes have been extensively used to investigate groundwater recharge processes in the past (Stumpp et al. 2018). One can easily distinguish the dominating subsurface processes with isotopic methods, for example, whether net evaporation or recharge happens in an area of soil profile (DePaolo et al. 2004; Cendón et al. 2010). Additionally, moisture flow patterns and transport heterogeneities dominated by advection, dispersion, and diffusion can be identifying by comparing isotopic data with space and time (David et al. 2015;

Table 1 Summery of the stable isotopes used as tracer in subsurface research

Compounds	Stable isotopes	International standards
O	^{18}O, ^{17}O, ^{16}O	Standard MeanOcean Water (SMOW), Vienna Standard Mean OceanWater (VSMOW), Standard Light Antarctic Precipitation (SLAP), Greenland Ice Sheet Precipitation (GISP)
H	^{1}H,^{2}H or D	
N	^{14}N, ^{15}N	[a]IAEA-N1 (δ15N = 0.4 ± 0.07‰) and IAEA-N2 (δ 15N = 20.3 ± 0.09‰), Atmospheric Air Internal Laboratory Standards: Acetanilide; peptone and Merck-KNO_3
Cl	^{37}Cl, ^{35}Cl	[b, c]Standard Mean Ocean Chlorine (SMOC)

[a]Deutsch et al. (2006), [b]Xiao et al. (2002), [c]Choi et al. (2011)

Stumpp et al. 2018; Joshi et al. 2018). Analysis of stable water isotopes is sensitive monitoring tool to predict precisely water dynamics in the complex (un)-saturated zone of peatland/wetlands, and water scare regions (Beyer et al. 2016; Stumpp et al. 2018).

2 Environmental Tracers

The groundwater investigation has been an important issue during last two decades due to unsustainable abstraction, deteriorating water quality and emerging pollution threats to potable resources. Environmental tracers have become a common tool to understand groundwater flow processes, water budget, origins, chemical reaction processes, recharge sources and zones of deep aquifers and retention time (young and old waters) including validation or calibration of flow and transport models using groundwater age. These techniques are based on measurement of environmental tracers like: radon, chlorofluorocarbons (CFCs), sulphur hexafluoride (SF6), noble gases, stable isotopes and environmental tritium.

2.1 Radon

It is a naturally occurring radioactive element created during the uranium decay chain as Ur-238 (half life: 4.5 billion years)—Ra-226 (half life: 1600 years)—Rn-222 gas has time to leak into the air (half-life: 3.8 days)—Pb-210 (half life: 22 years)—Pb-206 (stable). It is a colourless, odourless, chemically inert gas that is fairly soluble in water. It is being used in the laboratory scale experiments for finding the residence time and velocity of water flowing through the artificial aquifer systems (Hoehn et al. 1992). Naturally occurring radon is a brilliant tracer for identify and quantify the areas of substantial groundwater discharge owing to its short half-life, ease in measurement, high profusion, and conservative nature in subsurface water as compared to the surface water. It is quite popular in quantifying the submarine groundwater discharge (SGD) in costal areas. In general, SGD studies helps to located ideal sites for construction of subsurface barrier and plan for the sustainable groundwater exploration of coastal aquifers keeping the seawater interface well within the safe limits. Relationship between ^{222}Rn and EC in water was used to find SGD (Prakash et al. 2018). Measurement of ground water samples for ^{222}Rn is generally carried out using a RAD-7 (radon-in-air monitor) deploying RAD H_2O technique with closed loop aeration concept. Radon-in-air water technique (RAD H2O) comprise of three constituents, (1) the RAD-7 or radon monitor, (2) the water vial with an aerator and (3) the tube of desiccant, supported by the retort stand. The extraction efficiency for the vial of 250 mL capacity should be 95% following the Wat-250 protocol.^{222}Rn activities are stated in kBq m^{-3} (disintegration per hour per m^3) with 2 r-uncertainties. At the end of the run (generally half an hour after the start of run), the RAD-7 produces a summary, displaying the average radon reading, a cumulative spectrum of the four cycles counted, and a bar chart. The radon level is calculated automatically by the RAD-7.

2.2 *Chlorofluorocarbons (CFCs) and Sulphur Hexafluoride (SF_6)*

Evaluation of groundwater residence time is a key component in planning any sustainable water management plan. The two trace gases, sulphur hexafluoride (SF_6), and Chlorofluorocarbons (CFCs) building-up in the atmosphere since past century due to various anthropogenic organic compounds (ranging from aerosol propellants to refrigerants)provides a suitable way of dating waters up to ~60 years (Aeschbach-Hertig et al. 2000). The input functions for these gases are not area-specific as with tritium because they can mix with the surrounding air efficiently. CFCs proved to be more sensitive toward modern water than tritium where modern and old water mix owing to its lower detectable limits. Apart from acting as tracers of modern water, CFCs and SF_6 are capable enough to found actual recharge ages when environmental contaminations are significant. Gases CFC-11 (CCl_3F), CFC-12 (CCl_2F_2) and CFC-113 ($C_2Cl_3F_3$) have comparatively extended residence times in the atmosphere (44, 180 and 85 years, respectively), and they can undergo equilibration with surface waters as a function of temperature. Both gases are generally evaluated using GC-ECD (electron capture detector) based on gas chromatography succeeding cryogenic pre-concentration. The detectable limit for CFC sand SF_6 concentration in water is limited to 0.01 pmol/L and 0.1 fmol/L respectively. Analysis of both SF_6 and CFCs must ideally be calibrated with bulk air deposited at an atmospheric monitoring station, preferably one of the AGAGE network.

The sensitivity of these dating methods depends on the rate of change of the concentration of these gases in atmosphere with time, and thus the capability to date very young water will reduce with time.

2.3 Noble Gases

Element found in the group 18 of periodic table referred as 'Noble gases' are highly unreactive in nature except in special circumstances. The six naturally occurring noble gases are helium (He), neon (Ne), argon (Ar), krypton (Kr), xenon (Xe), and the radioactive radon (Rn). Their concentration have being regularly examined in groundwater, rocks, sea water, and ice cores to address assorted complex problems in environmental sciences such as marine biological production, firn temperature and thicknesses, groundwater temperatures, air-sea gas exchange, and surface exposure ages. The inert nature of noble gases make them an ideal tracer to study groundwater ages so that various complexities can be avoided that would be otherwise appear while dealing with the isotope data. The solubility of these gases in water varies with the average temperature. This makes it possible to evaluate the recharge temperature of recent and paleo groundwater using the noble gases dating (Loosli et al. 2000). Closed equilibrium (CE) and the partial re-equilibrium model (PR) can be used to interpret the noble gas temperature data.

2.4 Stable Isotopes

Isotopes having infinite life and are difficult to decay are termed as stable isotopes. Water stable isotopes (δ_{18}O and δ^2H) are used in tracing physical phenomenon that water molecules undergo between evaporation from the ocean and arrival in the aquifer via recharge by rainfall and are considered influential tool to trace the movement and also origin of water throughout the hydrological cycle. As water molecules travel through hydrological cycle, various isotopic molecular species, with different isotopic combinations of hydrogen (D or ^{2}H and ^{1}H) and oxygen (^{16}O and ^{18}O) in them are differentially divided between solid, vapor, and liquid phases, conveying discrete isotopic signature to all the three assorted phases. Recharge source and process could be understood more clearly by comparing the groundwater isotope values with long-term average amount weighted isotope values for precipitation (Lapworth et al.2015). An H2O molecule is composed different combination of one oxygen atom (any one of the three stable isotopes ^{16}O, ^{17}O, and ^{18}O) and of two hydrogen atoms (any two of the two stable isotopes; 1H and D). Thus, total nine probable combinations of these three isotopes of oxygen and two isotopes of hydrogen are possible and the four most abundant isotopic molecules of water are given in 4 commonly used international standard reference materials, namely, SMOW (Standard mean ocean water), VSMOW (Vienna standard mean ocean water), SLAP (Standard Light Antarctic Precipitation) and GISP (Greenland Ice Sheet Precipitation). The values of measured abundance ratios (^{2}H/^{1}H and ^{18}O/^{16}O) in SMOW and VSMOW are given in Table 2 while SLAP and GISP are given in Table 3.

Stable isotopes (δ^{18}O, δD) are analysed on DI-IRMSand CF-IRMS with the minimum error limit within ±0.1‰ for δ^{18}O and ± 1‰ for δD. The isotopic

Table 2 Measured abundance ratios in international standard reference material

Isotopes	Standard	Abundance ratio	Reference
$^2H/^1H$	SMOW	0.000158 OR [158 (±2) × 10^{-6}]	Krishan (2015)
$^{18}O/^{16}O$	SMOW	0.0019934 OR [1993.4 (±2.5) × 10^{-6}]	
$^2H/^1H$	VSMOW	0.00015575 OR [155.75 (±0.45) × 10^{-6}]	
$^{18}O/^{16}O$	VSMOW	0.0020052 OR [2005.2 (±0.05) × 10^{-6}]	

Table 3 The oxygen and hydrogen isotopic compositions of SLAP and GISP

Standard Light Antarctic Precipitation (SLAP)	Greenland Ice Sheet Precipitation (GISP)	Reference
δ^{18} OSLAP = -55.50% VSMOW	δ^{18} OGISP = −24.76% VSMOW	Krishan (2015)
δ DSLAP = − 428.0% VSMOW	δ DGISP = −189.50% VSMOW	

analyses (δD and $\delta^{18}O$) of collected groundwater samples are performed by equilibrating water samples with Carbon dioxide and hydrogen, known as standard equilibration method. The samples are investigated using CF-IRMS (Continuous Flow Isotope Ratio Mass Spectrometer) to measure isotopes of oxygen ($_{18}O/_{16}O$) and DI-IRMS (Dual Inlet Isotope Ratio Mass Spectrometer) to measure isotropic ratio of D/H. δD and $\delta^{18}O$ values are calculated using a triple point calibration equation with Vienna standard mean ocean water (V-SMOW), Greenland ice sheet precipitation (GISP) and Standard light Antarctic precipitation (SLAP) standards. Table 4 presented summary of studies performed to investigate ecohydrological processes and groundwater resources using environmental tracers and isotopic techniques.

3 Conclusive Remarks

The isotopic systematics of natural soils, minerals, pore fluids, and groundwater are helpful in characterization of processes like water flow and pollutant transport through subsurface.The chlorofluorocarbons (CFCs), noble gases, sulphur hexafluoride (SF6),and stable isotope ratios of oxygen-18 (^{18}O) to oxygen-16 (^{16}O) and of deuterium (^2H) to hydrogen (^1H) of water have been used as natural tracers. The dispersion and attenuation of the seasonal isotope signal with increasing soil depth permits the investigation of vertical water and solute movement in subsurface under varying environmental conditions. Now a days technique are available for estimating isotope dynamics at increasingly larger scales or finer temporal resolutions within soils. Conventional isotope ratio mass spectrometry of past has been replaced by new laser technique that is cheaper and require smaller sample volumes for stable isotope analysis. Real-time observations using anisotopic monitoring system allowed effective modification of the remediation strategy with time.

Table 4 Major isotropic studies conducted for the groundwater pollution control and monitoring

Sr. No	References	Isotopes used	Study location	Collection methodology	Conclusive remarks
1	Datta et al. (1996)	^{18}O and Fluoride concentration	Laboratory scale experiment	Anion chromatography is used to identify fluoride ion concentration while VG Isogas Mass-Spectrometer 60 2D is used to measure ^{18}O concentration by equilibrating 2 ml water at 25 °C with a tank CO_2 gas using standard procedures	Lateral mixing of groundwater and leaching of fluoride from the soil are characterising using integrating concentration of both ^{18}O and fluoride
2	Broers (2004)	Tritium–helium	Observation wells of the Drenthe and Noord-Brabant regional networks, Netherlands	The monitoring wells for the regional network are tested for tritium at two different depths of about 9 and 24 m. The detection limits used are 5 TU (Tritium Units) (1 TU = 1 ^{3}H atom per 10^{18}H atoms of H) for the 1983 data and 0.6–1.6 TU for the 1992 data	Spatial variation of groundwater age is simulated at the characteristic depths of the Dutch monitoring networks, disregarding mixing and dispersion

(continued)

Table 4 (continued)

Sr. No	References	Isotopes used	Study location	Collection methodology	Conclusive remarks
3	Dulaiova and Burnett (2006)	^{222}Rn and ^{224}Ra	Chao Phraya Estuary, Gulf of Thailand	Discrete sampling is used for Radium through installation of CTD profiler while Radon is measured using continuous sampling only	The isotropic ratio of $^{224}Ra/^{222}Rn$ is used to quantify the radon air–water gas exchange. The water to air radon fluxes estimated experimentally comes in line with the theoretically calibrated model

(continued)

Table 4 (continued)

Sr. No	References	Isotopes used	Study location	Collection methodology	Conclusive remarks
4	Peterson et al. (2008)	Radium (^{224}Ra, ^{223}Ra, and ^{226}Ra) along with Radon (^{222}Rn) isotopes	Yellow river delta, China	Columns containing Mn-acrylic fibres are used to quantitatively sorbs the radium from samples. They are also analysed by gamma spectrometer for ^{222}Rn	24-h time series with multiple isotopic concentrations having finer resolution is used to measure submarine groundwater discharge (SGD). The results are showing similarity to the average values reported by seepage meters positioned in the same area

(continued)

Table 4 (continued)

Sr. No	References	Isotopes used	Study location	Collection methodology	Conclusive remarks
5	Kaushal et al. (2011)	$\delta^{15}N$, and$\delta^{18}O$ of Nitrite (NO_3^-)	Baltimore LTER site, USA	Samplings are performed biweekly up to 7 moths (June to December 2005). The samples are stored in frozen conditions and are analysed for stable isotopes of nitrite following the denitrifier method at the USGS Stable Isotope Laboratory in Menlo Park	Non-point source nitrogen is determined by linking isotopic source identification techniques with additional traditional routine monitoring and chemical analysis

(continued)

Table 4 (continued)

Sr. No	References	Isotopes used	Study location	Collection methodology	Conclusive remarks
6	Widory et al. (2013)	$\delta^{15}N$, $\delta^{18}O$ of NO_3 and $\delta^{11}B$	The study is conducted for the Alsace aquifer located in between the German, French and Swiss borders	Cation-exchange resin columns are used to find the concentration of stable isotopes of nitrite ($\delta^{15}N$ and $\delta^{18}O$) by $AgNO_3$ method. $\delta^{11}B$ values are determined by measuring the $Cs_2BO_2^+$ ion concentration using thermal ionisation mass spectrometer	The study considered four distinct cases: (1) natural denitrification, (2) natural soil NO_3, (3) multiple sources of NO_3 pollution and (4) single source of NO_3 pollution This work demonstrates that in maximum conditions the multi-isotope approach strongly helps restrain the source(s) and processes prompting the NO_3 budget in surface and ground water

(continued)

Table 4 (continued)

Sr. No	References	Isotopes used	Study location	Collection methodology	Conclusive remarks
7	Jona-Lasinio et al. (2015)	$\delta^{15}N$	Caprolace, Fogliano, and Sabaudialakes, Rome (Italy)	Each sampling sites are deployed with three replicatealgalspecimensfor48hat50–60cmwaterdepthinplasticcages.Theisotopicdissimilarity is evaluated as the alterations in the isotopic signature of each individual algal specimen after 48 h of submersion and the isotopic signature of its own fragment divided before arrangement	The study established the use of Bayesian statistical modelling for addressing the potentially confounding environmental effects on the ecological indication based on isotopic outputs returned by transplanted green macro algae could be addressed

(continued)

Table 4 (continued)

Sr. No	References	Isotopes used	Study location	Collection methodology	Conclusive remarks
8	Ta et al. (2016)	Stable isotopes (N,O) of NO_3^-	Tropical deltaic region of the Red River (Vietnam)	The surface water samples are collected and filtered in situ with Whitman GF/F filters, high-density polyethylene bottles with slightly acidic environment and directly transferred to the Environmental Isotope Laboratory of the University of Yamanashi, Japan. Bacterial Denitrification method is used for $\delta^{15}N$ and $\delta^{18}O$ values of nitrate coupled with isotope ratio mass spectrometer	The dual isotropic approach concludes that the Nitrite in river is due to anthropogenic activity only which leads to intense OM degradation

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Integrated Watershed Conservation and Management of Koshalya-Jhajhara Watershed, North India

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Abstract Remote Sensing and GIS collectively play an essential role in watershed studies. Koshalya & Jhajhara (K-J), two tributaries of Ghaggar River have been chosen for study of watershed conservation and management. To achieve the objectives morphometric analysis, Land Use/Land Cover (LU/LC) mapping, Soil erosion risk assessment and Ground Water Potential Zone (GPZ) mapping have been done using Geographic Information System (GIS). Aster DEM (30 m) has been used for morphometric analysis and to generate drainage density and slope map of the area. LU/LC mapping and monitoring has been done by using Landsat (7 ETM$^+$ and 8) data for the time window 1999–2000 to 2015–2016. A considerable change from 7.12 to 24.84 km^2 is detected under built-up land. The soil loss in watershed has been evaluated by collective use of Revised Universal Soil Loss Equation (RUSLE) and GIS. The result indicates that only 6.54% of watershed area comes under moderate-high to high soil erosion category. After integration of various thematic layers, GPZ map of the watershed has been prepared by applying Analytical Hierarch Process (AHP) approach. It is observed that only 4.91 and 5.83 km^2 area fall under good and very good category and dominant portion of K-J watershed falls under the poor and very poor category of ground water availability. The study indicates dominant conversion from agricultural and forest land to urban land. The watershed is suffering with increasing problems of deforestation, erosion and other land-use conversion issues. Surface water resource action plan map has been prepared which depicts fifteen sites for percolation tanks and fourteen sites for check dams. The suggested measures will lead to better management of land and water resources for the watershed.

Keywords Check dams · Land use/land cover · Conservation and management · Groundwater potential zone · K-J watershed · Percolation tanks · RUSLE

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1 Introduction

A watershed is a natural geohydrological unit, which have a common outlet or represents an area from which surface runoff is through a common outlet. It is synonym with drainage basin or catchment area. Watershed contains many smaller watersheds also called sub-watersheds. Watershed is an ideal unit for checking land degradation, water, and silt losses and thereby improving the environment as the problems of the watershed in upper and lower reaches are interdependent. To obtain optimal benefits from these resources, the watershed should be treated as a single unit, especially for soil and water conservation, flood management, control of siltation and sedimentation and to enhance the productivity of the land. The modern techniques of RS and GIS are being successfully used for land and water resource planning and management at global level. RS and GIS plays an important role in mapping and monitoring the natural resources due to synoptic view, temporal dimension and analysis capabilities. Chaudhary et al. (1996) studied the GIS applications to identify potential areas for groundwater prospecting using satellite data and aerial photographs in the Sohna area of Gurgaon, District, Haryana. Two sub-watersheds Mb2v and Mb2w of Dangri river catchment area, the main tributary of Ghaggar River in Haryana have been studied for watershed management plans (HARSAC 1997). Goyal and Chaudhary (2010) concluded that GIS is very useful for devising groundwater management plans needed to arrest the declining trend of groundwater in Kaithal district, Haryana, India which has observed more than 30 m decline from 1974 to 2010. Although many researchers did a tremendous efforts in watershed conservation and management using RS and GIS like: Sharma et al. (2001); Arya et al. (2002); Vuppala et al (2004); Saxena and Prasad (2008); Tefera and Sterk (2010); Sarma and Saikia (2012); Singh et al (2014); Nagaraja and Ekambaram (2015).

The present study has been carried out to study various morphometric parameters of K-J watershed and to suggest suitable land and water resources management plans for the area. The location map of the area is shown in Fig. 1. The objectives of the present study are morphometric analysis, land use/land cover monitoring, groundwater potential zonation, soil erosion risk zonation and to suggest suitable action plan for prudent use of land and water resources of the area.

2 Materials and Methods

2.1 Study Area

2.1.1 General Description

The K-J watershed is catchment area of two tributaries (Koshalya and Jhajhara) of Ghaggar River in northern India. It falls in parts of Panchkula and Solan districts of Haryana and Himachal Pradesh respectively. The Solan district comprises of five

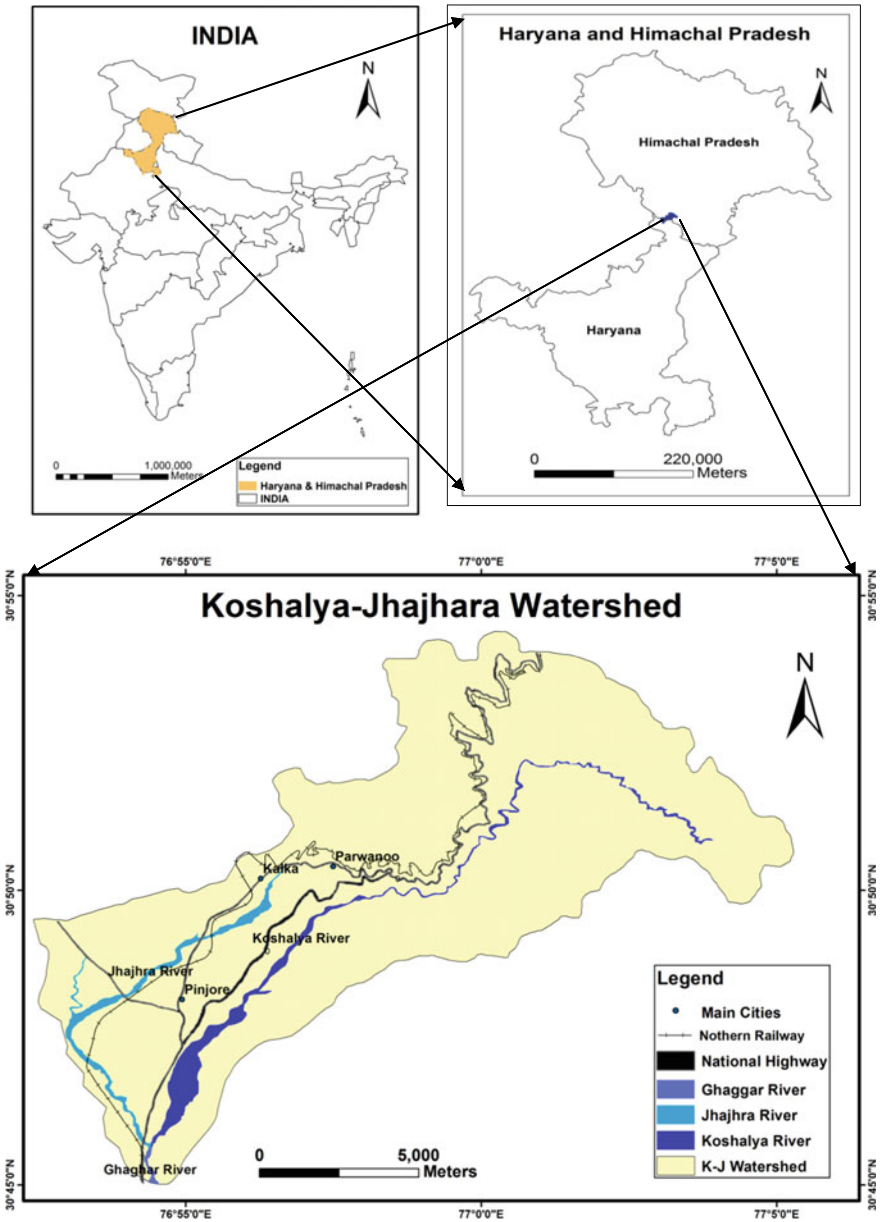

Fig. 1 Location Map of K-J Watershed

blocks viz. Nalagarh, Dharampur, Kandaghat, Solan and Kunihar whereas Panchkula district comprises of four blocks viz Pinjore, Barwala, Raipur Rani and Morni in Haryana. The K-J watershed covers an area of 134 km^2 of Dharampur and Pinjore blocks of Solan and Panchkula districts respectively.

2.1.2 Geology

Geologically, the watershed inhabited in Lesser Himalaya and Pre-Siwalik in North Eastern (NE) part and Siwalik range in South Western (SW) part. Subathu, Kasauli and Dagshai formation inhabited in Lesser Himalaya (Khan and Prasad 1998; Kumar 2017). Singh and Tandon (2010) have demarcated many geological thrusts in the area like Barsar Thrust, Jhajhara Thrust and Koshalya Thrust. There are also two faults Surajpur fault and Pinjore Garden Fault (PGF) in the region. The Himalayan Frontal Thrust (HFT) is the major thrust passing through the watershed. Figure 2 shows the Geological map of watershed and in Table 1 contains lithological description of watershed.

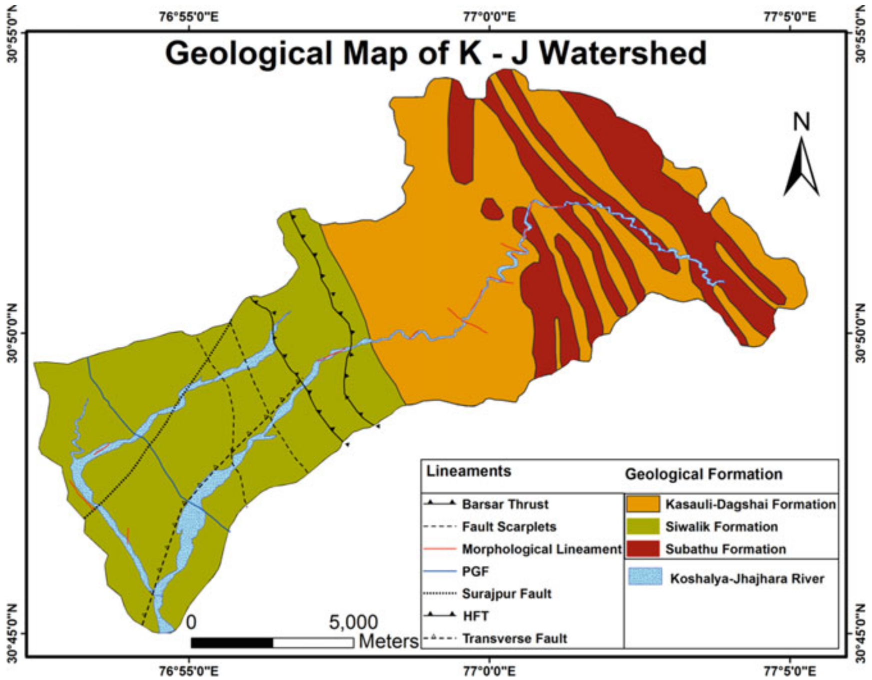

Fig. 2 Geological map of watershed (after Khan and Prasad 1998)

Table 1 General lithological description of K-J watershed

Parameter	Formations	Lithology
Geology	Siwalik formation	Conglomerate, sandstone, red clay
	Subathu formation	Shale, green mudstone
	Kasauli-Dagshai formation	Coarse grain sandstone, greyish green shale

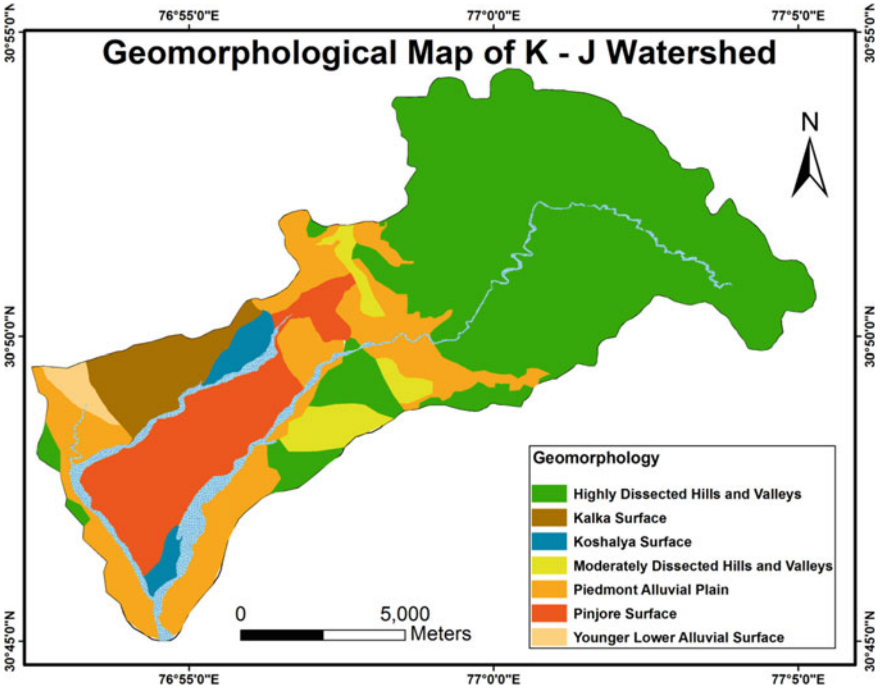

Fig. 3 Geomorphological map of watershed (after Malik and Nakata 2003)

2.1.3 Geomorphology

According to Malik and Nakata (2003), when one moves from south to north, the watershed splits into two crucial geomorphological units: Intermontane Valley (Doon) and moderately and Highly Dissected Hills. Figure 3 shows various geomorphic units of K-J watershed.

2.1.4 Moderately and Highly Dissected Hills

The dominant geomorphic features present in this unit are erosional features, fault, lofty mountain series, ridges and valleys having variation in elevation from 600 to

1800 m above MSL. There are non-perennial streams flowing through the watershed. Both Koshalya and Jhajhara tributaries originates from these mountain ranges. Koshalya River runs toward the south-west and at Kalka, it enters in Haryana (Nakata 1989; Malik and Nakata 2003; Singh and Tandon 2010).

The northern parts of watershed exhibit high altitude hill ranges, whereas south-western part is covered with low altitude denuded hill ranges of Siwalik. The narrow and deep valleys are trending in NW–SE direction having sharp slopes. The terrain of region is moderate to highly dissected with sharp slopes (Kumar 2017; Chaudhary and Kumar 2018a, b). Most of khads/streams/rivers keep base flow for the major period of the year. The density of drainage is high in the hilly region and having fine drainage texture as compared to the doon part of watershed (Bhatia 2013; Chaudhary and Kumar 2018a, b). Due to this more erosion occurs in the hilly portion (Kumar 2017).

2.1.5 Intermontane Valley

Pinjaur Dun is a piggyback basin (Ori and Frined 1984; Burbank and Reynolds 1988) and K-J watershed situated in the south-eastern side of it. According to Nakata (1972), Pinjore Dun having a thicker alluvial fill having age of Late Pleistocene to Holocene and overlaying the Lower and Middle Siwalik (Malik and Nakata 2003). The Barsar thrust separates Pinjaur Dun from Lower Siwalik. Pinjaur Dun or Intermontane basin bounded by Siwaliks in southern side and tertiary sub-Himalayan towards northern side (Singh and Tandon 2008). Kalka Surface, Koshalya Surface, Pinjaur Surface are three major surfaces present in the dun part and formed by boulders, cobble, mud beds and pebbles. The Kalka surface is situated towards the N-E of Jhajhara River and Pinjaur surface bounded by right and left banks of Koshalya and Jhajhara Rivers respectively. The Koshalya surface are situated near left side of Koshalya River and in SW part of the study area beside the Pinjore-Baddi national highway, a portion of the younger lower alluvial surface also exists (Singh and Tandon 2008).

2.2 Data Used and Methodology

The SOI Toposheet Nos. H43L01 and H43K13 covers the watershed area on scale 1:50,000. Landsat 7 ETM$^+$ and 8 data of Oct 1999, Feb 2000, Oct 2015 and Feb 2016 have been downloaded from USGS website. ASTER DEM (30 m) was downloaded from website of National Remote Sensing Centre (NRSC), Government of India organization and relief aspects were calculated by using this data. Ancillary data of 17 years of rainfall have been taken from Indian Meteorological Department (IMD) website. Watershed boundary was extracted from SOI toposheets and also from Aster DEM based on catchment area characteristics. The K-J watershed subdivided in 19 sub-watersheds based on the catchment area of drainage and different valleys of these basins. Arc GIS software have been used for detailed morphometric analysis in the present study.

Landsat 7 ETM^+ and 8 data have been used to prepare LU/LC maps of the study area. For preparation of LU/LC map, ancillary data and other published relevant material were used as reference data. SOI digital topographical maps on scale of 1:50,000 were used for planning of ground data collection and identification of basic features. GCPs were selected which were scattered uniformly throughout the area for georeferencing. Various LU/LC categories were identified based on standard image interpretation techniques using keys elements like; association, pattern, shape, size, texture and tone etc. and unsupervised classification was carried out. The built-up area gave doubtful signatures in the supervised/unsupervised classification and hence on-screen digitization was carried out for better accuracy (Chaudhary and Kumar 2017).

Soil Texture maps were collected from HARSAC and National Bureau of Soil Survey (NBSS) and the soil risk map was prepared by using RUSLE. The values of erodibility factor K were taken from literature. LS factor is calculated using DEM and C & P factors have been generated from the LU/LC map of the area. Using the raster calculator all the factors have been merged and final soil risk map of the watershed has been prepared.

For GPZ mapping, the drainage map has been updated with the help of satellite data. By using spatial analyst tool the drainage density of watershed has been calculated. The satellite images and other ancillary data used for geomorphological map generation. Geological map prepared by using map of Khan and Prasad (1998) as supportive information. With the help of conversion tool all shape files of various layers were converted into raster format for additional analysis. After that depending upon their impact on groundwater bearing properties, all thematic layers have been assigned weights and ranks after that AHP approach and raster calculator used to generate final GPZ map (Kumar 2017; Chaudhary and Kumar 2018a, b). Figure 4 shows the detailed flow chart of the methodology.

3 Results and Discussion

3.1 LU/LC Mapping

Land use may be defined as a part of land used by man for various purposes such as settlements, agriculture or industry. Land cover refers to the natural material present on Earth surface e.g. vegetation, water bodies, rocks/soils and others resulting due to land transformations. Although land use is generally inferred based on the cover, yet both the terms land use and land cover being closely related are interchangeable (Chaudhary 2003; Kumar 2017). Chaudhary et al (2008) has discussed influence of human activities on natural resources in Gurgaon districts.

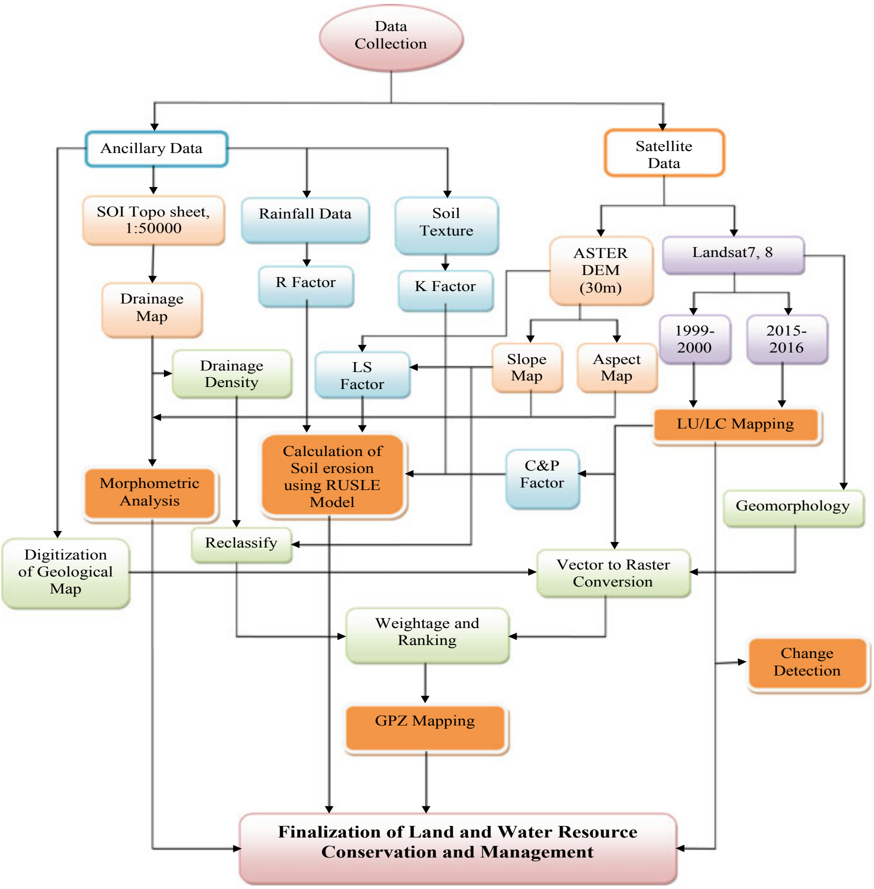

Fig. 4 Flow chart of methodology

3.1.1 LU/LC Mapping (1999–2000)

LU/LC map for the year 1999–2000 shows that about 109.35 km^2 area of watershed falls under forest category which is 81.04% of total area and it is further divided into three categories i.e. dense forest 85.54 km^2, open forest 3.90 km^2 and scrub forest 19.91 km^2 (Chaudhary and Kumar 2017, 2018a, b). The LU/LC map for the year 1999–2000 is shown in Fig. 5 whereas the area covered under different categories of LU/LC is shown in Table 2.

3.1.2 LU/LC Mapping (2015–2016)

The LU/LC map of 2015–16 indicates that 96.78 km^2 area of watershed is covered under forest category (Fig. 6), whereas agricultural land covers an area of 7.35 km^2

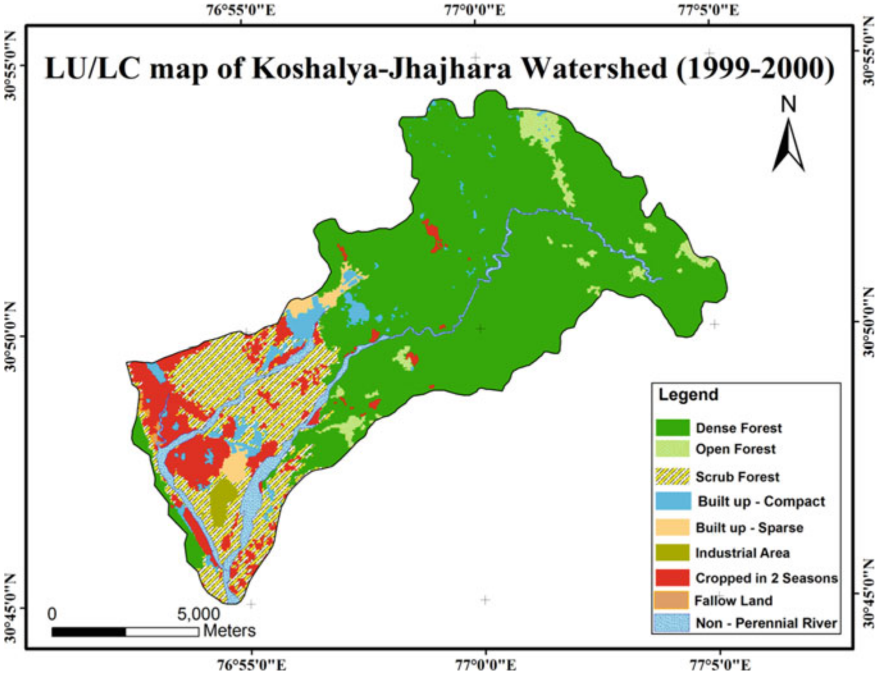

Fig. 5 LU/LC map of Watershed (1999–2000) after Chaudhary and Kumar (2017)

Table 2 Area under various LU/LC categories and Change (1999–2000 and 2015–16)

LU/LC distribution and change detection					
Sr. No.	L-II	L-III	Area (km^2) 1999–2000	Area (km^2) 2015–2016	Area of change (km^2)
1	Forest	Dense forest	85.54	82.45	−3.09
		Open forest	3.90	4.52	0.62
		Scrub forest	19.91	9.81	−10.10
2	Built-up	Industrial	1.02	1.02	0.00
		Built-up sparse	1.87	9.02	7.15
		Built-up compact	4.23	14.80	10.57
3	Agricultural Land	Cropped in 2 seasons	12.37	7.35	−5.02
		Fallow land	0.24	0.00	−0.24
4	Water bodies	River	5.83	5.94	0.11
	Total area		134.92	134.92	

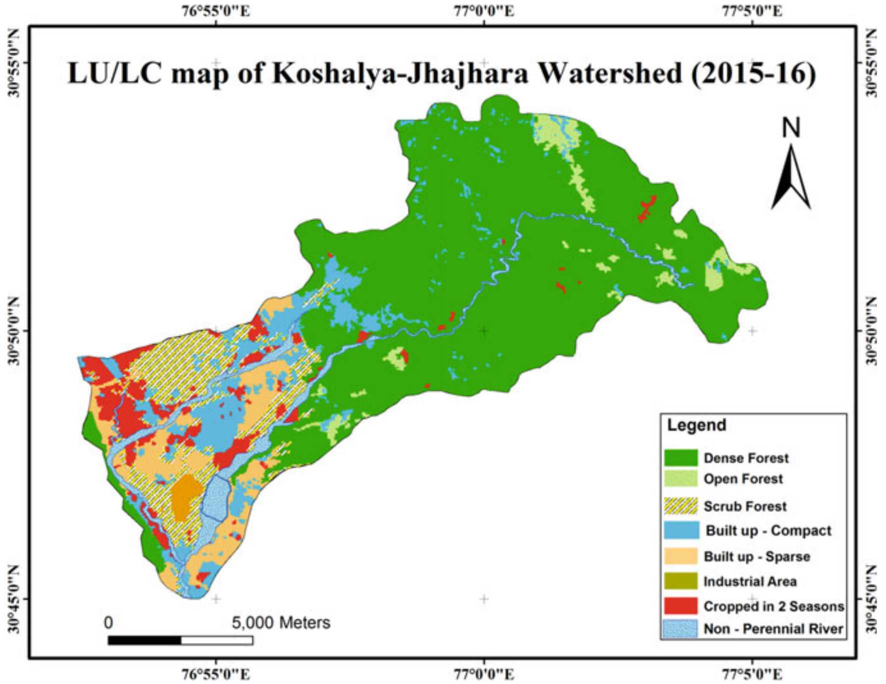

Fig. 6 LU/LC map of Watershed (2015–16) after Chaudhary and Kumar (2017)

(Chaudhary and Kumar 2017). The area under various categories of LU/LC is given in Table 2.

3.2 *Change Detection Mapping*

There is an alarming decrease in the area under agriculture and forests as inferred from LU/LC map (Fig. 7). The area under agriculture has reduced from 12.37 to 7.35 km^2 over the study period. Similarly, the area under forest has reduced from 109.35 to 96.78 km^2. This is because of increase which was observed in urbanization/real estate business seen in the study area during field visits. There is 17.72 km^2 growth in built-up land in these fifteen years. Further a decrease of 10.10 km^2 of the area under scrub forest was also observed. The area covered under forest has also decreased from 85.54 to 82.45 km^2 during this period.

The most conspicuous increase has been observed under built-up compact which has increased from 4.23 to 14.80 km^2 during these 15 years which indicates an increase of 10.57 km^2 (Fig. 8). There is an increase of 7.15 km^2 in the built-up sparse category over 15 years. The area under cropped in 2 seasons has decreased by 5.02 km^2 over 15 years. The area under Non-Perennial River category has increased

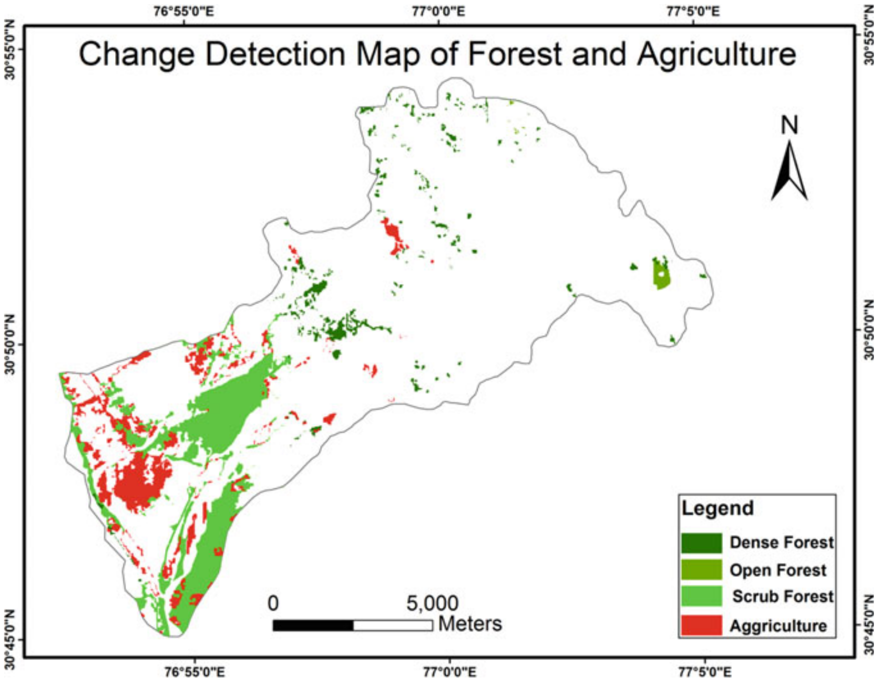

Fig. 7 Change detection map of forest and agriculture (2000–2016) after Chaudhary and Kumar (2017)

from 5.83 km^2 in 1999–2000 to 5.94 km^2 in 2015–2016 which shows the effect of erosion along the banks/bank cutting. It is clearly observed by comparing these two maps that the forest and agriculture land is being increasingly converted into built-up land during these fifteen years.

3.3 Morphometric Analysis of K-J Watershed

Morphometric analysis aims at quantitative description and analysis of landforms. Figure 9 shows the drainage map of watershed. The elevation range in watershed is from 399 to 1810 m MSL which indicates a rugged topography. Using GIS software the all three parameters: Linear, Areal and Relief aspects have been calculated for morphometric analysis. Total number of streams in the watershed is 991 out of which the highest order is 5th having 7 streams whereas 58, 124, 259, 543 are of 4th, 3rd, 2nd and first order respectively. The Koshalya-Jhajhara Watershed is having dendritic pattern of 5th order and is less elongated in shape. Higher stream orders indicate the chances of flood in the streams flowing through this watershed (Kumar and Chaudhary 2016).

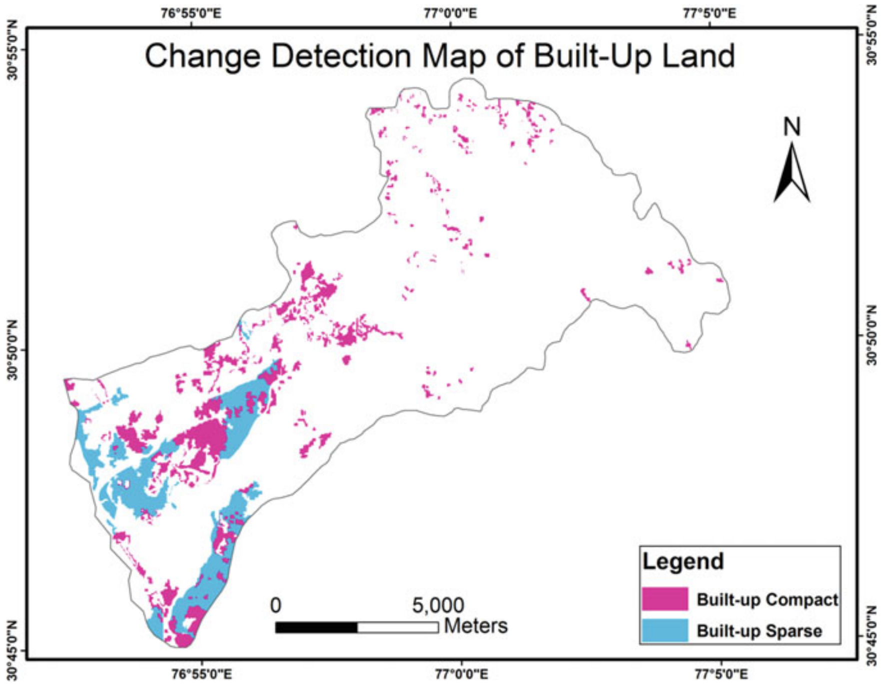

Fig. 8 Change detection map of built-up land in watershed (2000–2016) (Chaudhary and Kumar 2017)

3.4 Soil Erosion Estimation and Prioritization

Chaudhary and Kumar (2018a, b) have prepared soil erosion risk map for the watershed. All factors involved in RUSLE have been put to raster calculator to prepare the final soil erosion risk map. The map so generated is shown in Fig. 10. The area of watershed falling under various erosion categories is shown in Table 3. The map indicates that the Northern part of watershed is not having more erosion risk. The dun parts and river banks are found prone to high soil erosion risk.

3.5 GPZ Mapping

The groundwater potential zones were derived through ArcGIS 9.2 using Raster Calculator (Spatial Analysis tool) and weighted overlay technique was used for overlaying various thematic layers. The highest rank 5 is assigned to feature with maximum groundwater possibility in it. The lowest rank 1 was assigned to the features with minimum groundwater possibility. Table 4 gives the category wise explanation

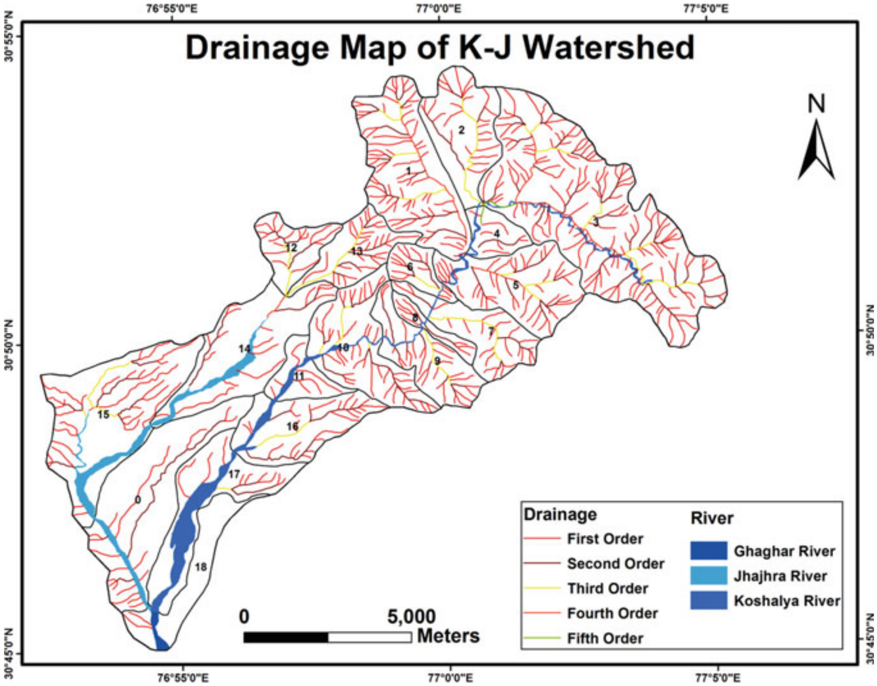

Fig. 9 Drainage map of watershed after (Kumar and Chaudhary 2016)

of ranks and weightages. After assigning rank and weight to all parameters and final GPZ map is generated and is shown in Fig. 11 (Chaudhary and Kumar 2018a, b).

According to Kumar (2017), moderately and highly dissected hills are in the poor and very poor category of groundwater capacity respectively, younger lower alluvial surface and piedmont alluvial plain are in the moderate category, Kalka and Pinjore surfaces are in good category and Koshalya surface is in the very good category of groundwater potentiality (Chaudhary and Kumar 2018a, b).

Chaudhary and Kumar (2018a, b) used an integrated approach of RS and GIS for generation of GPZ map of watershed by. It was found that dominant segment of watershed i.e. 37.87 and 61.83 km^2 area covered by very poor and poor category of availability of groundwater, respectively and it is observed that only 4.91 and 5.83 km^2 area is under good and very good category of groundwater availability, respectively. An area of 24.48 km^2 is covered by moderate category (Kumar 2017).

As per guidelines of Integrated Mission for Sustainable Development (IMSD 1995) developed by NRSA, Hyderabad a surface water resource action plan map depicting fourteen sites for check dams construction and fifteen sites for percolation tanks construction have been proposed. These were by taking into consideration drainage order, terrain, slope, soil texture and site conditions. Thorough geotechnical investigations should be done on these sites before implementation and actual construction. Proposed water harvesting structures map is shown in Fig. 12.

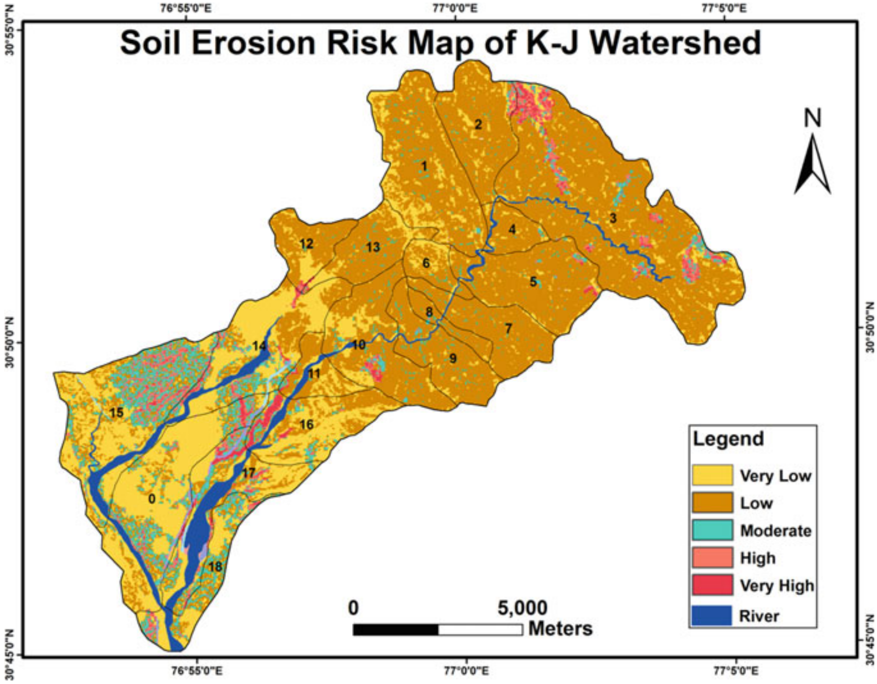

Fig. 10 Soil erosion risk map of watershed

Table 3 Area used various soil erosion categories

Soil erosion classes	Soil loss (tons/ha/year)	Area (km^2)	Area (%)
Very low	0–10	49.76	36.88
Low	0–11	65.65	48.66
Moderate	25–50	10.68	7.92
Moderate high	50–100	6.56	4.86
High	100–200	2.26	1.68
Total area		134.92	100

4 Conclusions

Morphometric analysis indicates that Koshalya-Jhajhara watershed is of fifth-order and contains the dendritic drainage pattern meaning thereby lack of structural control and textural homogeneity. Drainage density of the watershed is 3.05 km^{-1} which indicates impermeable surface. The measure of the drainage texture is more than 8 which exhibits extremely fine drainage texture. Circularity and Elongation ratios are 0.03 and 0.62 indicating dendritic stage and less elongated watershed. The slope and aspect map indicates that watershed have sharp slope areas. The characteristics

Table 4 Weightage and ranks of various parameters for GPZ, Chaudhary and Kumar (2018a, b)

Parameter	Classes	Groundwater prospect	Weight (%)	Rank
Geomorphology	Koshalya surface	Very good	40	5
	Pinjore surface	Good		4
	Kalka surface	Good		4
	Piedmont alluvial plain	Moderate		3
	Younger lower alluvial surface	Moderate		3
	Moderately dissected hills and valleys	Poor		1
	Highly dissected hills and valleys	Very poor		1
Slope (degree)	0–8	Very good	20	5
	8–16	Good		4
	16–25	Moderate		3
	25–34	Poor		1
	34–56.58	Very poor		1
Drainage density (km/km^2)	0–2	Very good	15	5
	2–3	Good		4
	3–4	Moderate		3
	4–5	Poor		2
	5–7	Very poor		1
Land use/landcover	Agriculture land	Very good	15	5
	Scrub forest	Good		3
	Open forest	Moderate		3
	Dense forest	Poor		1
	Built-up land	Very poor		1
Geology	Siwalik formation	Moderate	10	4
	Subathu formation	Moderate		3
	Kasauli-Dagshai formation	Good		3

of the water network, including the stream bifurcation and the discharge density, directly contribute to the increase in the water discharge. The LU/LC study of the watershed indicates a decrease of 10.10 km^2 of the area under scrub forest from 1999–200 to 2015–16. The area under dense forest has also decreased from 85.54 to 82.45 km^2 over this period. The most conspicuous increase has been observed under Built-up—Compact which has increased from 4.23 to 14.80 km^2 meaning thereby an increase of 10.57 km^2. There is also an increase of 7.15 km^2 in the built-up—sparse category over this period. This indicates a very fast rate of conversion to built-up category and may result in a threat to the ecosystem of the watershed. The area under

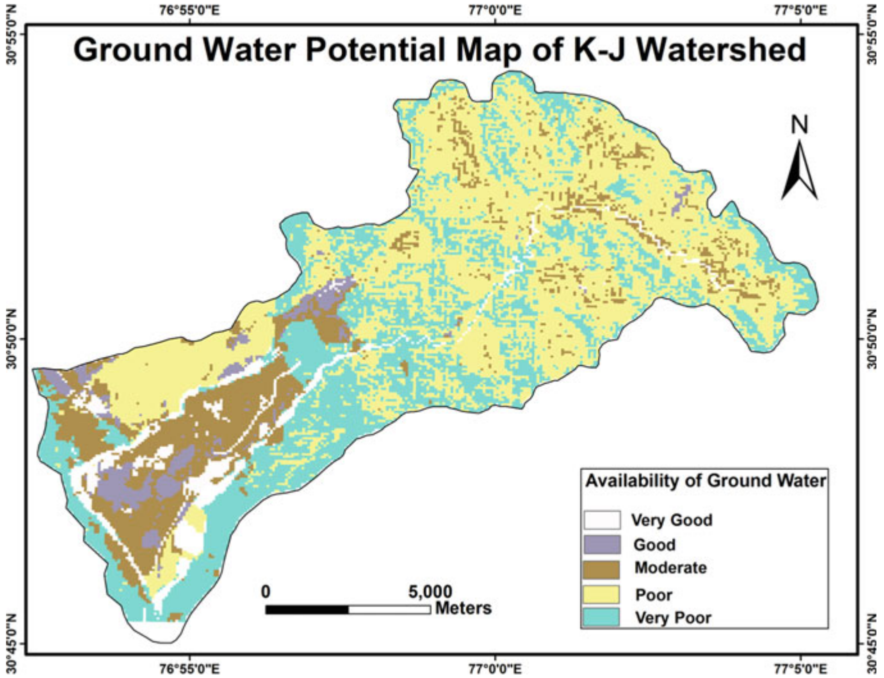

Fig. 11 GPZ map of watershed after Chaudhary and Kumar (2018a, b)

non-perennial River has increased from 5.83 to 5.94 km^2 which shows the erosion along the banks/bank cutting. GPZ map reflects good to the very good potential zone of groundwater in south-western part of watershed. An area of 99.70 km^2 which constitutes 74% of the total area of the watershed falls under poor to the very poor category of groundwater availability. These are the areas covered by higher hills and steep slopes. The soil erosion risk map reflects that the majority of the area of the watershed falls under very low to low category of soil erosion and amounts to 85.56% of the total watershed area. An area of 10.68 km^2 falls under the moderate category. An area of 8.82 km^2 which is 6.53% of the entire area of the watershed falls under moderate-high to the high category of soil erosion. Twenty nine water harvesting sites suggested in the area will help in sustainable water resources management in the area.

5 Recommendations

- Gully plugging and afforestation activities are recommended in the areas where soil erosion is very high.

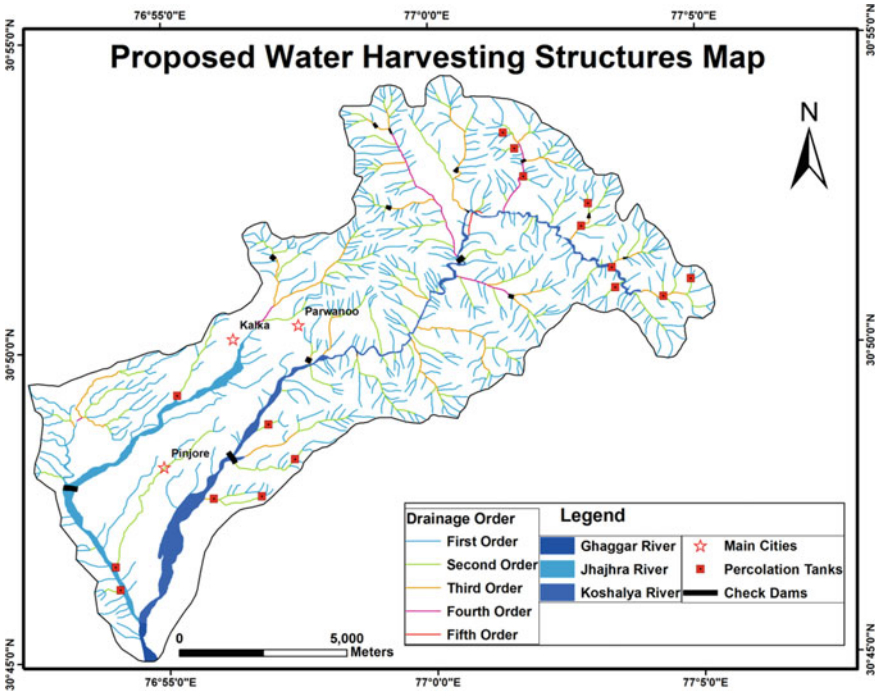

Fig. 12 Proposed water harvesting structures map for K-J watershed

- Maximum vegetal cover in the lean periods in the form of crops or forest should be provided in the plain areas to reduce soil erosion.
- Most of the areas in the watershed under first-order stream are facing problems of soil erosion and need to be arrested through gully plugging.
- There is a strong need to discourage fast conversion of forest and agriculture land to the built-up land otherwise it will disturb the ecosystem of entire watershed.
- There is a need to focus on afforestation/reforestation programs in southern and south-western sub-watersheds which have less forest cover.
- There is a strong need to take necessary steps to recharge the groundwater in the area. Groundwater recharge structures like infiltration well, recharge pits, subsurface dykes, check dams, percolation tanks etc. should be constructed for induced groundwater recharge.
- Rooftop rainwater harvesting structures should be encouraged in the entire watershed for sustainable water resources planning.

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Water Resources Management for Irrigated Agriculture in Perspective of Geospatial Techniques

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Abstract Uttar Pradesh is well known for its rice–wheat cropping system whenever it comes to agricultural sector. Being one of the highest producers of wheat and the second highest in terms of rice production, the state needs to be cautious about the usage of both of the quantity and quality of water as irrigation. The adversity of variability in climate has afflicted both the crop production as well as overall crop health. Crop irrigation water mainly comes from both the groundwater and surface water sources. Both the sources bear strong relation with the rainfall variability. The state has already begun to sense the over-exploitation of its groundwater resources. Even the surface water resources are under the threat of either insufficient rainfall to replenish them or they are unfit for use due to the quality issues. Besides, the anticipated climate change is further projected to alter the spatio-temporal pattern of rainfall enhancing the variability. Thus, there is a dire need to manage the water resources to make the irrigation facility more effective and thus pulling up the crop health. The groundwater deficits or its poor quality often get reflected through the vegetation health thriving on this resource. This study uses this key association between the groundwater and vegetation condition to venture into the issues related to water resources management with the help of varied indices in geo-spatial techniques. Moderate Resolution Imaging Spectroradiometer (MODIS) derived Enhanced Vegetation Index (EVI) has been used to monitor the seasonal vegetation status (crop yield) in correspondence with rainfall and groundwater fluctuations for the period of 1998 to 2017. Thereby, this study is an attempt to assess the spatial and temporal pattern of crop health in response to groundwater availability based on remote sensing approach. The study will help the farmers, irrigation engineers, agriculturalists and Government officials to take necessary steps for proper management of the water resources successfully.

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1 Introduction

Keeping in view the water-consumption in sectors like agriculture, industry, domestic requirements etc., it is the agriculture sector that is responsible for the highest consumption of the fresh water resources. In India, it accounts for about 80% consumption of the total water consumption of all other sectors put together (Mall 2013). Since, the work on 'Planetary Boundaries' by Rockström (2009) the critical stage of water resources has also become a compelling issue that may soon be a 'Planetary Boundary' crossing which the humanity would enter the state of 'no return'. Therefore, there is an urgent call not only in the nation but also internationally to recognize and sustain both the minor and major stages of resources-exploitation. The water management and conservation front is confronting on an everyday basis an exigent upsurge of challenges as consequences of the scaling demands for water due to increasing population, intense agriculture, rising industrial growth compounded by unplanned development of both the surface and groundwater resources as well as other related mis-handled caveats (Bates et al. 2008; Sharma and Gosain 2010; Moors et al. 2011; Bondre 2011; Taylor et al. 2013; Suweis et al. 2013; CGWB 2014). Numerous remote sensing and geographical system based studies have been conducted in the past that were impact and identification as well as assessment themed and focused upon ground water depletion, waterlogged land, crop and vegetation response, agricultural droughts etc. (Mondal 2012; Chinnasamy et al. 2012; Waikar and Nilawar 2014; Dutta et al. 2013, 2015; Kundu et al. 2016; Mandal et al. 2016; Dash et al. 2016; Lakshmi and Reddy 2018; Kamble et al. 2019; Senthilkumar et al. 2019; Adhikary et al. 2019). Even the spatio-temporal analysis of irrigated land expanding over vast land masses is especially popular while being undertaken in conjugation of satellite products like MODIS, AVHRR, IRS LISS III-IV (Thenkabail et al. 2009; Heller et al. 2012; Ambika et al. 2016).

In the Northern India the Ganga river basin cradles a huge expanse of agricultural land which is almost as huge as the great alluvial basin of river itself is. And the state of Uttar Pradesh (UP) falls in the very heart of the basin of the mighty River Ganga in these northern parts of the country. The per capita average annual water availability of the state is falling low day by day. Since the State lies in the Ganga Basin; the projected estimates of per capita average annual water availability for the basin could be reasonably appreciated as far as the water availability in the state is concerned. The later is to fall by 29% from its 2010 estimate of 1061.74 m^3 per capita by 2050, which isn't a far future (CWC 2013; EnviStats, India 2018). With such an insufficient stage of water resources to arrive soon, UP is rightly identified as one of the water risk hotspots of India (Sharma et al. 2018). UP is known as an 'agricultural state' of India dominated by the rice–wheat cropping systems. The state holds a good reputation of being the largest state having a share of wheat area (34% of whole India, 9.96 million hectare (Mha)) and of having the third largest share of rice area (13% of whole India, 5.98 Mha) (DES 2014) in the country. The water intensive crop like rice is under serious threat in longer term as far as its production sustainability given the irrigation support is the concern. 60% of the rice production is dependent on the irrigation facility and the rest 40% largely depends on rainfall (Sharma et al. 2018). Out of this 60% irrigation water major extraction is done from the groundwater resources. In this process not only that the groundwater table is falling down but mismanaged groundwater irrigation have left to sodification and has affected the crop cultivation (Kaushal et al. 1985; Srivastava et al. 2015, 2017; Minhas et al. 2019). Given the plausible condition of compromised irrigation to rice cultivation in near future even the following wheat cultivation may fall short of its optimum irrigation requirements. Already this year's rice production is estimated to be down by 4% from that of last year's (SkyMet 2019). Consequently, with the climate being highly variable such a scenario of diminishing per capita average annual water availability indicates towards severe imminent water scarcity befalling the State. Agriculture sector is a voracious consumer of fresh water resources; broadly 80% of the fresh water is used to irrigate the crops in India. It is already time that measures are taken to go economical in its use and to strike a good balance in the tradeoffs between water conserved to water consumed per unit crop harvested. Major management steps are in dire need to be acted upon to instill the 'resource-sustainability' in call of the manner in which the rice–wheat cropping systems are presently as discussed by Fishman et al. (2015a, b) and Bhatt et al. (2016). In the further sections to come the discussions unfold gravity of imprudent irrigation regimes popular in the Indian '*Rice–Wheat Cropping*' systems.

2 The Rice–Wheat Cropping System

The *rice–wheat cropping system* practiced across the whole belt of Indo-Gangetic Plain (IGP) wherein, it is mostly grown with an approximate 1500 mm (400 mm) water-requirement for rice (wheat) along with an additional 50 mm spent during seedling to transplanting stage in case of rice (Timsina and Conor 2001). Tuninetti et al. (2015) argue that the food production largely (>90%) depends on green water. Thus when the irrigation allows crop production rather more water-efficient, there lays the ray of hope to conserve water as requirement falls down. It is also discussed that to save water in Rice–Wheat fields not only adjustments with the weather conditions is necessary but scientifically prudent soil and water management too is required (Humphreys et al. 2005). It is therefore, the notion of water productivity comes into picture, which is a part of the ecosystem approach to manage water (Molden et al. 2007). In broadest sense the '*water productivity*' refers to the net return or socioeconomic and environmental benefits per unit water used (Molden et al. 2007, 2010). Thus when the opinions of Humphreys et al. (2005) are placed side by side with that of Molden et al. (2007) it becomes evident that to save water in rice–wheat fields the water management could be done by raising water productivity. Raising water productivity is accomplished by either raising yield or by lowering the water use (Humphreys et al. 2005). Nevertheless, higher net returns in yield do not always get translated into higher water productivity (Molden et al. 2010). For the time being if the second way of raising water productivity is considered in here, lowering of the water use i.e. by saving water in the rice–wheat fields could well be explored for the cropping pattern of Uttar Pradesh, the centrally located state in IGP. True water saving is achieved through two ways reducing the non-beneficial evaporative water-losses from the rice–wheat fields; one through reducing evaporation from soil and second reducing evaporation from free water lying on the field. There have been several methods that have been tried to achieve the objective of saving some of the water from the irrigational supply. Among such methods the saturated soil condition was found in many cases to have resulted in equal yields to that of those from a continuous flooding condition. Yields went falling when irrigation pattern moved beyond saturated soil conditions say to alternate wetting and drying conditions, especially for rice (Humphreys et al. 2005).

As per Humphreys et al. (2005) sandy loam soils have been found to be able to save 60 mm of water without causing much difference in the yields. Puddling is largely recommended by most in the case of rice crop to avoid the weed spread, to level fields and for transplanting. As all these are the initial stages of crop water-requirement, it serves two purposes; one, the necessary soil moisture for the wheat crop is maintained through the water that percolated during the puddling during rice cropping and second, the required rice-yield is achieved through cutting down the water supply two weeks before the harvest while saving some water too. Wheat is sown after the harvest of rice-crop; the roots of rice crop generally do not grow beyond top 20 cm of soil wherein the wheat crop roots grow deep up to 200 cm (Humphreys et al. 2005). Thus percolation losses during rice-season can be utilized for wheat crop season and can serve *available water capacity*. Since 2000 raised bed practice to grow crop has gained considerable popularity among the farmers of IGP. In the *Furrow Irrigated Raised Bed* (FIRB) planting system the crops are grown on the ridges or in the beds prepared in the field. FIRB cropping system has been quite a help in saving water in areas/regions where the ground water levels were found falling. In case of wheat crop it worked as increment in crop-productivity through intercropping of high value vegetable crops with wheat crop utilizing the same irrigational-water supply. Apart from fulfilling the major purpose of saving the irrigational-water this planting system allows the mechanical weed control as well as improves fertilizer application (Naresh et al. 2012). Fishman et al. (2015a, b) explained the role of agricultural water-use efficiency in saving groundwater in Indian state of agricultural practices, reveals that the laser land leveling technology for rice and sprinkler for wheat helps conserving water better than others.

Apart from such regimes of irrigational water supply in to the rice–wheat cropping systems which whether or not take any care of water conservation another issue is that of the water received during monsoon seasons. For there lies a very strong relation between irrigational water demand of the crop with that of the rainfall pattern of any particular region (Mahmood et al. 2012; Debaeke et al. 2017; Ali et al. 2017). The increasing climate variability in terms of rising temperatures and uncertain rainfall along with increment both in intensity and frequency of extreme weather events has become challenging aspect when the concern is crop water demand (Kukal and Irmak 2018).

Indian scenario of the rice–wheat cropping system has become less profitable a business as the availability of resources like water, energy, labour as well as capital has diminished (Bhatt et al. 2016). Hence, crop specific tillage, crop diversification with oilseed crops, optimized sowing dates, endeavours to improve the soil health (both site specific and in general), efforts to enhance the nutrient use efficiency, assigning greater importance to mulching processes and above all well-informed and well-managed irrigation strategies are the avenues that are being explored and tested in regular communication with the farmers to arrive at some sustainable solution to feed the next generation of 1.35 billion by 2025 (Reddy 2009; Karim et al. 2014; Singh et al. 2016, 2017; Srinivasarao et al. 2017; Panwar et al. 2018; Jalota et al. 2018).

3 The Prevailing Climate Variability Across Uttar Pradesh

Uttar Pradesh has been recently reported to experience *climatic-shift* from a *dry sub-humid* to *semi-arid climate*. This implies that the state would sooner be under the hold of drier climatic conditions (Raju et al. 2013). A non-parametric time-series analysis of 42 years' (1971–2013) of temperature and rainfall for various agro-climatic zones of UP showed significant increasing trend of about 0.02 °C/year in annual mean temperature and also increasing trend of annual number of days of temperature extremes (>40 °C) across the state. The state also has witnessed increasing minimum and maximum temperature trends of 0.03 and 0.01 °C/year, respectively during the same period. The temperature extremes (especially the heat waves) were marked by rising trend, which is supported by several studies (Dash and Mamgain 2011; Kothwale et al. 2010). The annual rainfall for the whole state shows the increasing trend whereas, monsoon rainfall (rice growing season) characterized by non-significant positive trend and winter rainfall (wheat growing season) significant negative trend. An in-depth analysis of the rainfall pattern of the recent last three decades brings forth the fact that whereas, the annual rainfall is marked by positive trend, the annual number of rainy days had undergone negative trend across the state (Mall et al. 2016). It was found that some zones were marked by significant decrease and some didn't show any trend in rainy days at all. However rainfall extremes across the state for most of the agro-climatic zones under the range of >50 mm but <100 mm didn't show any significant trend. Since 2000 the country has witnessed six El Niño years i.e. 2002, 2004, 2006, 2009, 2012 and 2013 (Bhatla et al. 2015). Out of which 2002, 2004, 2009 and 2012 resulted in severe drought conditions for whole of the country as well as Uttar Pradesh too witnessed the impacts of these droughts. An analysis was conducted as IMD criteria w.r.t the thresholds for a region to be assessed in terms of drought-affected or not affected using long term (1971–2013) rainfall data across various agro-climatic zones of the state, the South Western Semi-arid Zone and the Western Plain Zones were found to have been the worst regional drought hits in recent times (Shewale and Kumar 2005).

The study of temperature (maximum and minimum) and rainfall during projected period of 2041–2060 also revealed that the present trends might be continued in future also. Rainfall was in specific marked by increase in amount but increase in intense extreme rainfall events and decreasing rainy days has been noticed (Mall et al. 2018).

An assessment of the availability of water resources in the context of state's future requirements while particularly taking into account the multiplying demands for water, the expected impacts of climate change and variability could be of critical use for the state to implement various goals of sustainable development of water resources (Mall 2013; Bhatt and Mall 2015). Therefore, to attend to issues of high climate variability, decreasing *per capita water availability* and the rising food-demand, Uttar Pradesh, as a state must look into working plans to confront the daunting threats emerging due to utter carelessness in use of water in the agriculture sector (Mall et al. 2016).

4 The State-of-the-Art Water Resources in Uttar Pradesh

With the formulation of 12th Five Year Plan of India, the agendas set to be achieved by 2017 meeting the food demands of all kinds, the agricultural water use would increase anyway. In this regards, the state targets to reach productivity up to 3.4 t/ha from 1.7 t/ha at present with the existing irrigation facility. Out of total exploitable water resources of the state of 161 BCM of surface water only 117 BCM surface water is left future-use after what has already been utilized (UPSWP 2009). According to recent estimates of ground water resources, out of state's total annual replenishable ground water resources of 77 BCM, 74% has already been withdrawn holding up a very grim situation of ground water development and leaving the state only with meager amount to fulfill its future irrigation demands in the case of *business-as-usual scenario* (CGWB 2014).

4.1 The Water Use for Rice and Wheat Agriculture in United States of America (USA), China and India

Even when irrigated agriculture helps securing a 4-times greater yield than the *rainfed* one, nevertheless, it is largely acclaimed (by definition) that irrigated agriculture consumes more water as is done by the *rainfed* agriculture (McLaughlin and Kinzelbach 2015). Making the situations worse, the impending changes in the climate are projected to affect the water resources and thus eventually the productivity of the agricultural systems on varied spatial-scales with responses both in terms benefit and loss. Hence, the agricultural systems are projected to fall short of the available water volume and thus with the rising water scarcity the inefficient water allocation would cost the society very high (Sauer et al. 2010).

A general and a cursory look at the above sub-head raises a genuine inquisitiveness that whether the comparison of water-use by the rice and wheat crops in China and USA with that of India is at all a subject of comparison or not? Yes, it is unquestionably apparent that there are lot of differences regarding the climatic and crop-varietal factors among USA, China and India. Even then India spends far too much of water to grow a tonne of rice or wheat or even in terms of liters of water evapotranspired on every kilogram of rice or wheat produced (for its prevailing climate and crop varieties used differ totally from the rest of the two countries) (Kapur et al. 2009; Lal 2011). Nevertheless, another very basic and instantaneous inquisitiveness arises by looking at the country's urgent need to conserve its fast depleting resource of water, and that is, shouldn't the real requirement of the crop-water be looked into for the possible profligacy in water-use, in case of any? Therefore, against the backdrop of such a scarce scenario of water resource, even to uphold the present yields of rice and wheat of the state, the water use in the rice–wheat production would soar high (Fig. 1 and Table 1).

Based on the report estimates, the water used/consumed to grow these crops were found as follows (Kapur et al. 2009; Lal 2011):

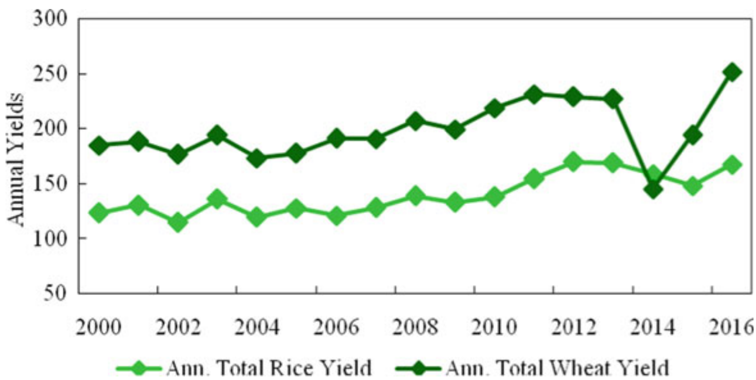

Fig. 1 Comparative overview of water use for rice and wheat in agriculture with the recent trend in rice and wheat yields across UP

Table 1 Comparative irrigational water-use in rice and wheat cultivation

Authors	Rice			Wheat		
	India	USA	China	India	USA	China
Lal (2011) (Liters evaporated per kilogram)	3700	1920	1370	2560	1390	1280
Kapur et al. (2009) (m^3 per tonne)	4113	1840	1906	1654	849	690

- To grow one-hectare wheat and rice, water consumed as per Lal (2011), the state spends 5632 and 5920 m^3 of water.
- To grow one-hectare wheat and rice, average amount of water used as per Kapur et al. (2009), the state forgoes 3638.8 and 6580.8 m^3 of water.

The standards reported as above have yielded two different estimates of the water-used to achieve the present day per hectare yields (mentioned earlier) of the state's two major crops. However, both the estimates seem to be highly profligate in terms of water use when compared with that of average water uses for the same crops grown in USA and China, the two of the leading global economies. Though it is to be remembered that the demands for the rice–wheat produce is considerably higher in India when compared to that in USA and China. The reason in demand is that these countries have larger stress on the animal-produce than on rice–wheat based produce. Still, increasing the water use efficiency while irrigating these crop-fields can save the country an enormous amount of water. A frugal approach towards agricultural water use may hold prospects to robustly enhance the water resource sustainability.

4.1.1 Groundwater Contribution in Relation to the Rice and Wheat Crop Yields

Central Ground Water Board (CGWB), Ministry of Water Resource reported that the net annual groundwater availability and total annual groundwater draft of the state are at 71.58 BCM and 52.76 BCM respectively. Thus the state's groundwater development stands at 50–100% Stage of Development (EnviStat 2018). 48.35 BCM of the annual groundwater draft is consumed to suffice for the irrigation demands of the State. The district level annual groundwater table records for both the *Kharif* and *Rabi* crop-seasons were closely studied to extract information regarding the relation between rise and fall of seasonal water table with yields of the major crops of the lately mentioned crop-seasons *i.e.* rice and wheat. In *Kharif* Season only 19.7% districts of U.P. recorded low water table conditions over the period between the recent dry year (2002) and wet year (2013). Whereas, in *rabi* season 71.8% of the districts recorded low water table conditions over the period of recharge as mentioned lately. The above two results culminated in inferring that it was *Rabi* period in which the water table fell deeper due to its poor recharge over the period of 12 years (2003–2014) since its stage of development in 2002. The rice and wheat yields of 2013 were higher than those of 2002 which is an obvious reason behind the drop of water table by the end of two cropping seasons in 2013; the water table fell to 6.13 and 6.66 mbgl from 5.81 and 5.73 mbgl in 2002 for *kharif* and *rabi* seasons respectively (Fig. 2).

Therefore, the inference highlights the fact that there is more need for better irrigation management in the State during the *rabi* season than that in the *kharif* season as far as the groundwater availability is concerned. A decadal look at the water table and corresponding yields of the *kharif* and *rabi* seasons for the rice and wheat since 2000 indicated that (Table 2, Figs. 2 and 3):

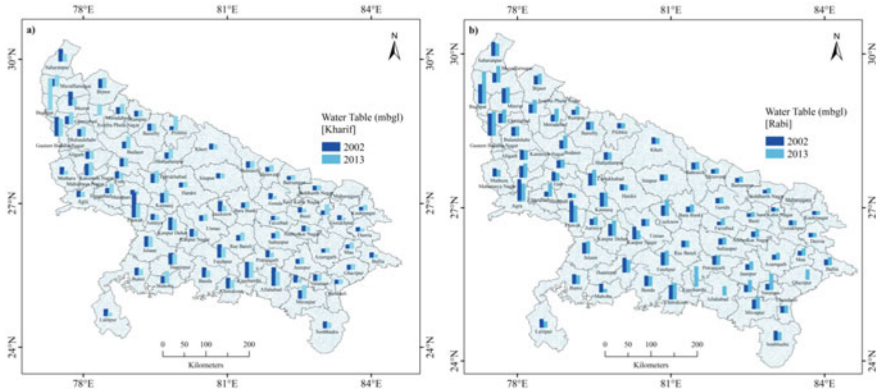

Fig. 2 **a** *Kharif* and **b** *Rabi* season water table for dry and wet year (2002 and 2013)

Table 2 Decadal overview of groundwater table of Uttar Pradesh in relation to rice and wheat yields

Decade	Avg. ann. rice yield	*Kharif* WT/mbgl	Avg. ann. wheat yield	*Rabi* WT/mbgl
I (2000–2010)	131.67	5.88	191.01	6.39
II (2011–2017)	161.94	6.66	213.00	5.89

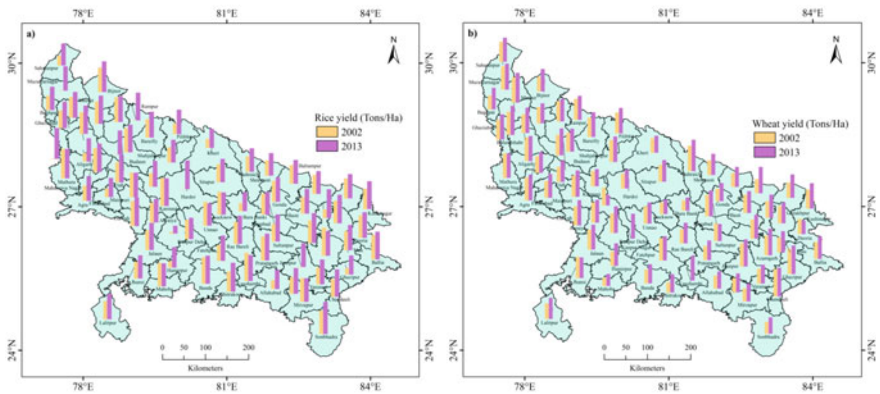

Fig. 3 **a** Rice and **b** wheat yield for dry and wet year (2002 and 2013)

- With the increment in the rice yield of the second decade the *kharif* season water table fell lower by 0.78 mbgl than that in the first decade in U.P.
- However, in the case of wheat yield though the crop was marked by increment only but rather than observing decrement in water table levels the State underwent a rise of 0.5 mbgl from that in the first decade.

That means in the second decade though to raise the *kharif* and *rabi* crop yields the State drafted more water for irrigation to meet the requirements yet there might have been causes that promoted the recharge of the rabi season water table. The causes can be clued to better rainfall in the decade secured by better water conservation practises through retention structures to raise the water table levels. However, even in 2013, which was a wet year, the districts e.g. Aligarh, Mathura, Mahamaya Nagar, Agra, Firozabad and Mainpuri had witnessed very low rainfall and thus rainfall excess cannot be always held responsible for water table rise. Nonetheless, the rainfall deficit of 2002 was very significant for more than three fourth of the State received low to very low rainfall and thereby, districts even witnessed drop in their water table levels (Figs. 4 and 5).

Earlier, however, efforts have been made to conserve water (increasing the water productivity) from the agricultural fields by developing improved varieties and region specific agronomic practices (especially for rice as it is a water-intensive crop). This approach in turn shifted to raising the water use efficiency and now finally research is focused on pulling up the water productivity (ratio of agricultural benefits to water use) for the crops (Sharma et al. 2015). Rest to get an in-depth understanding of methods (e.g. rather than flooding the fields the soil for rice cultivation can just be kept saturated by alternate drying and wetting regimes, mulching etc.) and technologies (e.g. Dry-seeded rice technology, soil moisture monitoring etc.) that can be adopted to frugally use the water in agriculture-sector (Singh et al. 2010; Sharma et al. 2015).

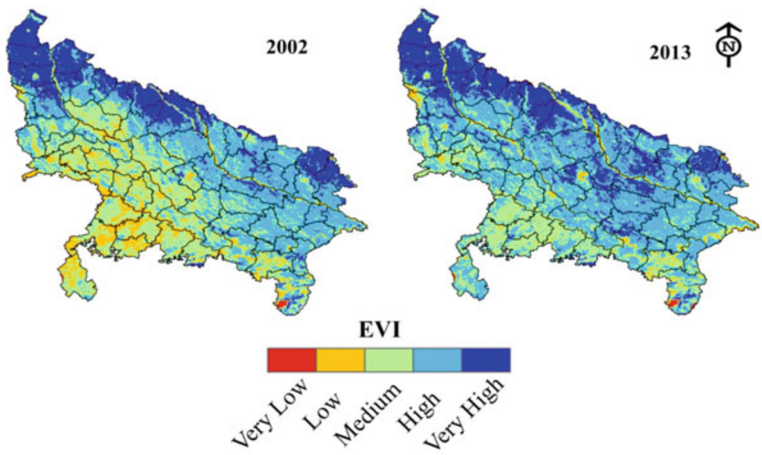

Fig. 4 Spatial pattern of EVI

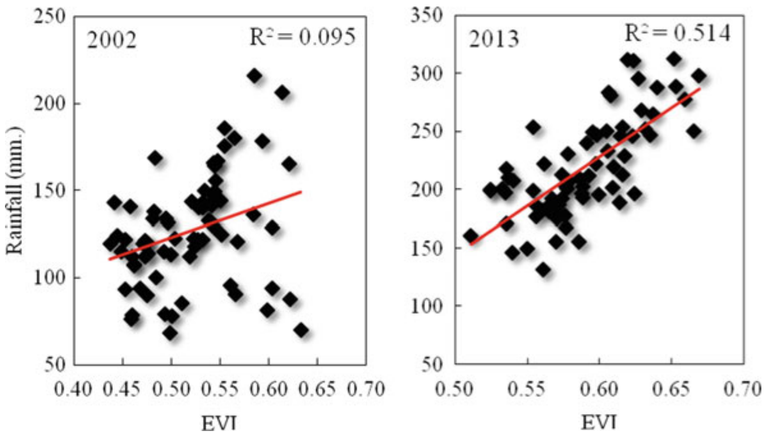

Fig. 5 Correlation between rainfall with EVI

5 Interrelation of Rainfall, EVI and Groundwater

In hot sub-humid and semi-arid situations, water table profundity is accounted for to be a significant factor affecting the vegetation spread and this biological system can be characterized as groundwater-subordinate vegetation (Benyon et al. 2006; Jin et al. 2011; Lv et al. 2013). In any case, unique vegetation (crop) types react differently to varieties in water table profundity. However, rainfall information from 1998 to 2017, demonstrated maximum = 215 mm; minimum = 68 mm rain in dry year (2002) whereas maximum = 312 mm; minimum = 131 mm were in wet year (2013). In addition, EVI information for the 72 districts of U.P. had a less in dry year (maximum = 0.63; minimum = 0.43) and high in wet year (Fig. 4). All of the 72 districts amongst rainfall and EVI was measurably critical ($p < 0.05$; n = 72). The normal individual connection was $r^2 = 0.095$ for dry and 0.514 in wet year (Fig. 5). We found a noticeable association among rainfall and EVI, demonstrating that on a yearly and at the scene scale, higher yearly rainfall likewise infers efficiency in bigger biological system. The highest EVI found in Saharanapur (0.67) district while lowest EVI observed in Gautam Buddha Nagar (0.50) in dry and wet years.

6 Conclusion

Uttar Pradesh is characterized by the presence of sandy loam soil in combination to alluvial, clay, clay loam, silty clay etc. Sandy loam can do well to maintain rice-yields even when the water supply is seized two weeks before the harvest of the crop. Thus if the rice cropping is taken up in a scientifically judicious manner, keeping the account of soil properties (e.g. soil type and infiltration rate), the state on the whole can successfully avoid the unwanted loss of irrigational water supply from the rice-fields as is discussed by Sauer et al. (2010) regarding irrigation methods to be acquired as per the soil and crop type and also as per two major exogenous conditions *i.e.* biophysical and socio-economic conditions.

The geospatial techniques can be very relevant in terms of their being real time to comprehend the complex interrelationship among ground water, rainfall and crop health. For example, EVI competently allows decision makers to visualize as well as assess the spatio-temporal pattern of the later mention interrelationship. The present study dwelt on the similar understanding and usage of the geospatial products at hand.

Recently, these days wheat-cropping systems are being designed to save water. They can be adopted by more farmers in areas/regions where the ground water levels were found declining so that water could be conserved as much as possible. Apparently, FIRB technique seems to save no quantitative amount of water but it does help conserving water in terms of almost the same amount of irrigation resulting in the harvest of two different crops within the same time span. A close inspection of water used in and water required by the rice–wheat cropping system can help the stakeholders take precautions to avoid profligate irrigation. Despite, all this technological assistance to conserve water from the irrigated agricultural sector (the largest user of freshwater), the water doesn't really get conserved. Fishman et al. (2015a, b) have strongly argued the fact that even when the water is saved through the use of water saving technologies it gets lost due to increase in agricultural area under irrigation. Nonetheless, the highly subsidized and poorly regulated water supply for agricultural use in India stands as a big hindrance reducing the efficiency of technological support to save water. In this perspective the suggestion of Fishman et al. (2015a, b) to help the water polices realize their potential fully they must not only be technology based but also incentive based too. Apart from that in regions where ground water resource is fast diminishing water supply should be assigned less subsidy. Pricing water for agricultural usage in India may raise considerable difficulties for most of the farmers as their monthly incomes are not that sufficient. Thus though not fully subsidized yet upon less subsidy water could be saved a great deal from the Indian rice–wheat fields.

Therefore, at the face of adversities the water resources are facing due to the changing climate, the actions taken up to stand the hardships of climate change with mere technological improvements won't be enough. Rather 'redefining not only of the lifestyles but also of the humanity's development goals' would eventually be required (Kapur et al. 2009). A prudently *frugal irrigation structure* may go far in subtle ways to back up humanity's development goals as well as lifestyles getting them aligned in securing *resource-sustainability*. Also, in the United Nations (UN) "2030 Agenda for Sustainable Development" in 2015 one of the Sustainable Development Goals (SDGs) i.e. Goal 6.4 is altogether aimed at achieving substantial increase in all sector pervading water-use efficiency and ensuring sustainable extraction and supply of freshwater to solve water scarcity related issues that too by 2030 (Giordano et al. 2017). Such goals require an in-depth inspection of water use and misuse even in sectors that are reputed to consume more for its time their consumptions get strictly monitored.

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Climate Change Impacts on Hydrology of a Small Watershed in a River Valley Project Catchment of Southern India

Uday Mandal, Dipaka R. Sena, Gopal Kumar, Sridhar Patra, and Shamla Rasid

Abstract The Kundhichira watershed is a sub-watershed of the Kabini river basin in Kerala. To simulate hydrological responses of the watershed, for observed as well as for the projected climate, hydrological model, Soil and Water Assessment Tool (SWAT) was used. The ASTER data derived DEM (30 m resolution) was processed to delineate stream network and ground verified by Google Earth provided digitized stream network. The land use map was prepared using Landsat-7 satellite imageries *i.e.* Enhanced Thematic Mapper (ETM+) and soil database was created from Govt. of India All India Soil and Land Use Survey (AISLUS) report. The model was calibrated and validated using sequential uncertainty fitting (SUFI 2) procedure through SWAT-CUP for the period 2003 to 2006 and 2007 to 2009, respectively with monthly observed runoff data. The modeling efficiencies (ME) during calibration and validation were 0.799 0.822 respectively. Monthly projections for the IPCC 3 SRES Scenario for 2020, 2050, and 2080 representing intermediate emissions (A2a) were used to simulate hydrological responses for future climatic change conditions. A substantial rise in temperature over the scenario and subtle change in rainfall may result in higher surface runoff rates (12.4% increases in 2080) and decreased base flow (7.4% decrease in 2050). The water yield may increase by 7% in 2020. The groundwater recharge components may increase by more than 90%. The crop yield in the face of increased temperature may reduce due to increased GDD (Growing

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Degree Days) negatively impacting the biomass yield as reflected in reduced evapotranspiration component (as low as 9.7% in 2050). The Climatic Net Primary Production of the study watershed is poised to have a limitation shift from precipitation to temperature.

Keywords A2a scenario · Climate change · Climatic net primary production · SUFI2 · SWAT · SWAT-CUP

1 Introduction

The effectiveness of land management in watershed mode has been acknowledged and widely adopted in India. Monitoring of watershed for hydrological responses of various interventions is though an essential and continuous process but has been largely ignored particularly for smaller watersheds. For making watershed programme robust, inclusive, and sustainable it is necessary to generate and consider the hydrological responses for future climate for which use of simulation model seems the only practical option. Soil and Water Assessment Tool (SWAT) model (Arnold et al. 1995, 1998) has been proved an effective and efficient tool to predict the impact of land use changes on water, sediment, and agricultural chemical yields in large complex watershed. The SWAT have been used for assessing water resource and environmental conditions and capable to assess the impacts of climatic change on hydrological fluxes and water availability (Neitsch et al. 2005; Arnold and Fohrer 2005; Dash et al. 2020). Being a continuous time model, i.e. a long-term yield model with the capability of scenario generation, it provides wider range of options to equip the policy makers.

Given the history of SWAT application in India, the database of application to smaller watersheds is scanty compared to those for larger watersheds due to lack of runoff and sediment observation stations required for calibration and validation of the said model (Adhikary et al. 2019). However, the policy requirement are heavily dependent on information on small watersheds (operational size of 500–5000 ha). Therefore, in the present study, geographical information system (GIS) based hydrological modelling, SWAT was used to simulate the hydrological fluxes of a small river valley catchment Kundhichira (area 60.40 km^2) located in the Kabini river basin. Attempt has been made to assess the attendant effect of climate change under three SRES scenarios (i.e. A2a 2020, 2050, and 2080) at 2.5 min grid size (Hijmans et al. 2005) with CO_2 concentration of 414 ppm, 522 ppm, and 682 ppm, respectively (Boomiraj et al. 2009).

2 Description of the Study Area

The Kundhichira watershed (River Valley Project code Ka4b) is located in between 76°11′ to 76°16′ E longitude and 11°39′ to 11°46′ N Latitude in Sulthan Bathery, Waynard District of Kerala State, India. The watershed is highly undulated in nature and elevation varies from 733 to 1050 m (above mean sea-level). The Kundhichira watershed (approximate area 60.40 km^2) is one of the sub-watersheds of the Kabini river basin (approximate area 7000 km^2). The Kundhichira watershed covers approximately 0.86% only of the Kabini River basin. The location of the Kundhichira watershed is shown in Fig. 1. The climate of the area is humid with annual average rainfall of 2066 mm (Table 1). The climatic Net Primary Production (NPP) is precipitation limited which suggests that the precipitation variation largely influences the biomass in the area occupied with largely dense to mix forested ecosystem. The watershed under study has also a significant representation from commercial plantations, such as coffee and rubber along with paddy based production system.

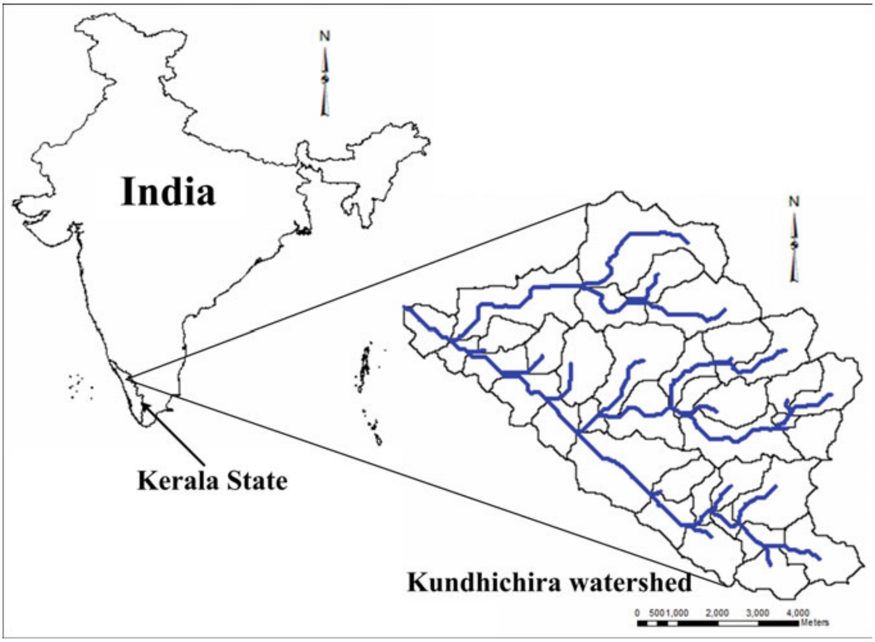


Fig. 1 Map showing the study area location of Kundhichira watershed

Table 1 General climatic information of the area (generated using New_LocClim: Local Climate Estimator, FAO 2005)

Parameters	Kundhichira watershed
Longitude	76.183° N
Latitude	11.71° E
Altitude	740 m
Annual rainfall	2066 mm
Radiation index of dryness	0.659
Budyko evaporation	1479 mm/year
Budyko runoff	1279 mm/year
Budyko evaporation	53.6%
Budyko runoff	46.4%
Aridity	Humid
Aridity index	1.74
Moisture index	74%
Precipitation deficit	−1171 mm/year
Climatic net primary production	Precipitation limited

3 Materials and Methods

The hydrological simulation for observed as well as climate change projections using SWAT model requires data on terrain, land use, soil and weather at various sub-basins. The ArcSWAT interface in ArcGIS was used to create a SWAT input layers using various dataset including DEM map, land use/land cover, soil class, and climatic variables information.

3.1 Preparation of DEM

ASTER GDEM[1] of 30 m spatial resolution was accessed, processed for the given outlet and clipped for the area of interest. Instead of DEM derived stream network, stream burn option was used to exactly focus on the intended outlet for steam network generation process based on flow direction, flow accumulation as intermediate process using pre-digitized streams from high resolution earth observation imageries (Google Earth Pro) (Fig. 2). The delineated watershed area (Fig. 2) was found 6040 ha.

[1] ASTER GDEM is a product of METI and NASA.

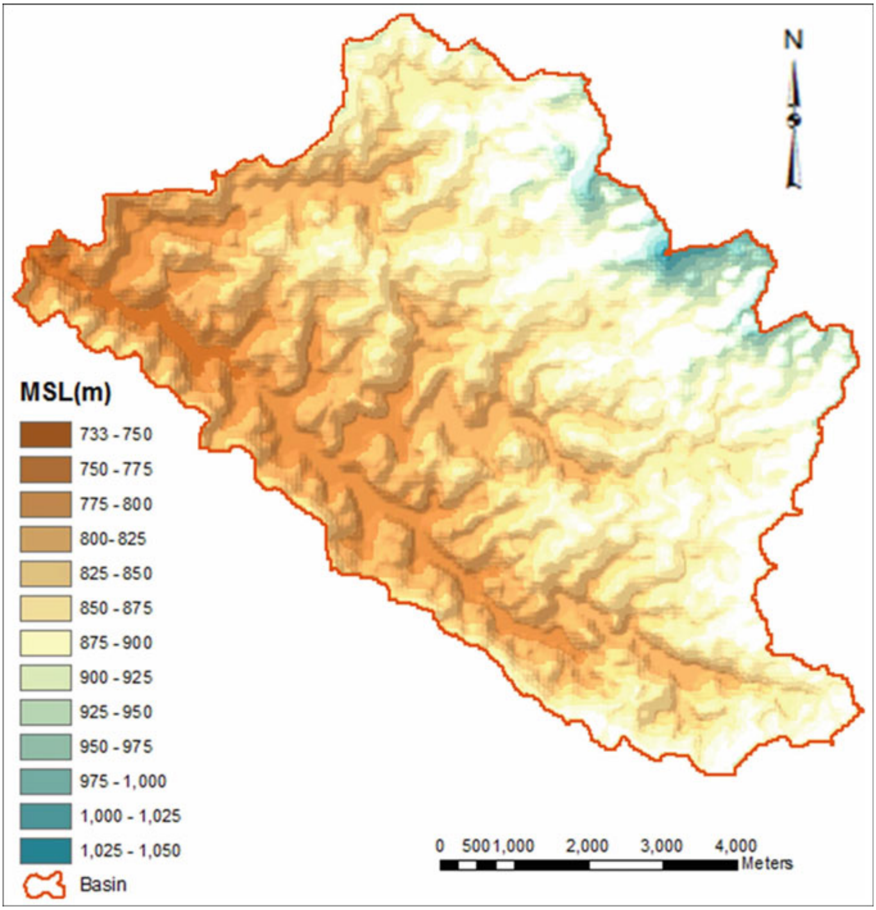


Fig. 2 Elevation profile of the study area generated from ASTER 30 data

3.2 Land Use Data

The land use map of Kundhichira (RVP, Kerala) watershed was prepared using LANDSAT data. The major crops database for the study area was collected from the published RVP reports (Anonymous 2009). Landsat-7 ETM+ data merged with Google earth image were used for classification, representing comparable land-use patterns. The acreage of various crops were computed using relative membership of reflectance values to a particular crop signature, the date of image capture (Google Earth and Landsat TM data) and map provided by the implementing agency (Anonymous 2009) (Fig. 3).

About 38.05% of the total area is under high value cash crops (Coffee and rubber) and 7.37% area is under paddy crop of the study watershed. Forest land (51.35%) is

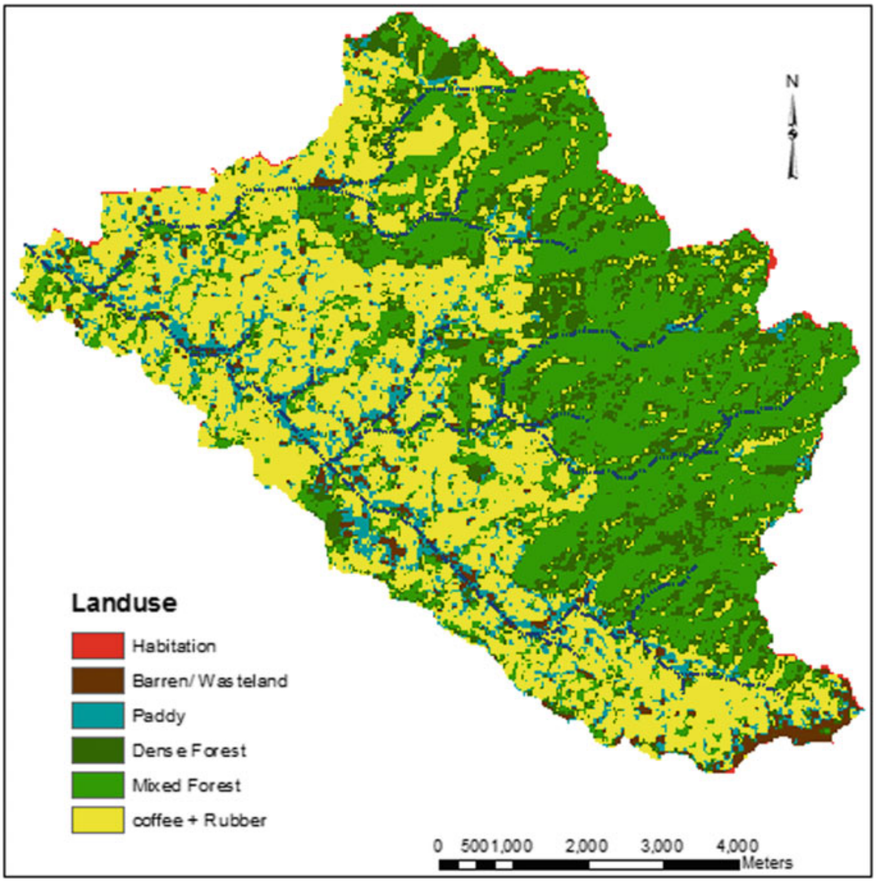


Fig. 3 Land use map of the Kundhichira watershed

the single major land use of the study area. The extent of barren/degraded lands is about 2.79% (Table 2).

Table 2 Land use classes of Kundhichira watershed

Land use	% area
Habitation	0.44
Barren/wasteland	2.79
Paddy	7.37
Dense forest	17.19
Mixed forest	34.16
Coffee + rubber + mixed plantation	38.05

3.3 Soil Database

The spatial soil database was prepared based on all India soil and land use survey report, Agri. 834/91 and used for the simulation. The digitized data of individual soil classes are then merged to three major classes (Fig. 4) as reported by the Soil Conservation authority in their report (Anonymous 2009). Alluvial and colluvium are the major soil of the watershed representing an area of 4100 ha, red and brown soils occupying an area of 1904 ha.

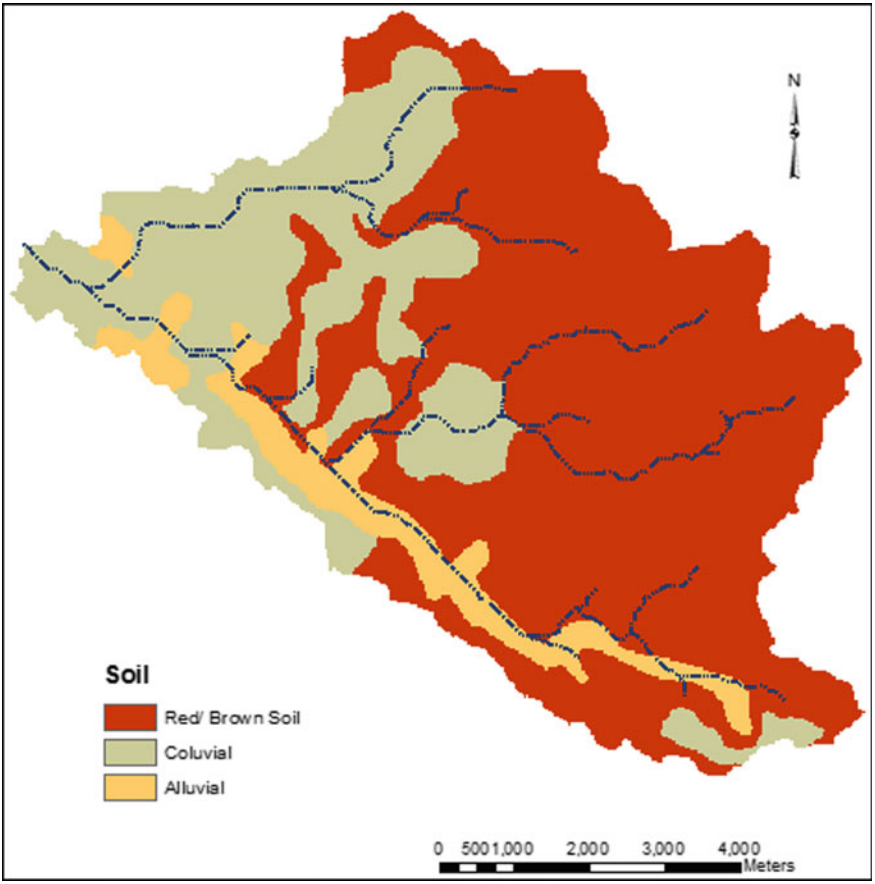


Fig. 4 Soil map of Kundhichira watershed

3.4 Climatic Data

The daily precipitation, maximum and minimum temperature, solar radiation, wind speed, and relative humidity needed for simulation of hydrological behaviour by SWAT were arranged from various sources including the inbuilt weather generator which are capable of predicting daily values of all these variables based on the long term weather statistics of existing data provided. However, a minimum data set of daily rainfall and temperature is required for better predictability of the model as these datasets are the key to the climatic projections applications (Singh and Gosain 2011). The daily rainfall record for the watershed was available from 2003 to 2009, which was concurrently monitored at Koleri silt monitoring station along with the runoff and silt observation. The all other climatic data were generated through the weather generator using long-term database maintained by FAO (2005) (New_LocClim v1.1 Local Climate Estimator).

3.5 Climate Change Scenario

Interpolated climate layer for global land areas (Hiljmans 2005) were downloaded from IPCC3 (https://www.worldclim.org/futdown.htm) at spatial resolution of 2.5 arc minutes of A2a scenario for the year 2020, 2050 and 2080. The data were appropriately processed using DIVA-GIS v7.5 (Hijmans 2011) interface to collate the grid database on precipitation and temperature. A2a scenario is characterized by continuous population rise along with regionally oriented economic development and hypothesized to be characteristic to Indian development (Boomiraj et al. 2009; Kumar et al. 2010). The data from regionally validated RCM (HadCM3/A2a) model were used for climate change impact study for which the change in atmospheric CO_2 concentration, maximum and minimum temperature, rainfall were identified. The projected CO_2 concentrations were 414, 522 and 682 ppm for the year 2020, 2050 and 2080, respectively. The climate change scenarios were put into the model through separate mathematical function for different agro-ecological zones under study.

3.6 Crop Database

The default crop database provided in SWAT model was used with some modifications based on available literatures and field data. The management files in each HRUs or sub-basin is defined as per the average date of scheduling which covers date of sowing, fertilization, and harvest as per the actual data obtained from the farmers within study area. Heat units were used as per the crop (paddy) physiological needs collected from various published literatures (Parthasarathi et al. 2013; Jasti et al.

2017). For perennial or annual crops like coffee, rubber and mixed plantation crops, heat units were adopted as per the information collected from expert consultation and published literatures (Kumar 2011) keeping all other parameters as default as defined by SWAT database.

3.7 Observed Runoff Database

The watershed was monitored daily from 2003 to 2009 for runoff and sediment yield were collected from the Directorate of soil conservation Kabini Project, Kalpetta, Wayanad, Kerala. The monthly average value of runoff was used for model calibration and validation. The analysis resented in the study is limited to observed runoff data.

3.8 Model Simulation

The database developed for the study watershed was used for setting up the SWAT model. Model calibration and validation was carried out using the monthly average observed runoff data from year 2003 to 2009.

3.8.1 Model Setup

Model setup was carried out with ArcSWAT extension (SWAT 2005) in ArcGIS environment. Sub-basins were delineated using ASTER DEM data. The grid files encompassing land use, soils, and slope were intersected to create HRUs based on percentage threshold value assigned 15, 10, and 5, respectively. The model was setup with 37 sub-basins and 335 HRUs (Fig. 5).

3.8.2 Model Calibration and Validation

To establish the model effectiveness to simulate hydrological responses to climatic variations, the model was subject to rigorous calibration with observed rainfall and runoff pairs on a monthly time scale. SWAT-CUP ver 2009 was used to calibrate and validate the model using Sequential uncertainty fitting (SUFI 2) (Abbaspour 2012). Runoff data from 2003 to 2006 was used to calibrate the model using the parameters based on sensitivity analysis carried out in SWAT-CUP environment.

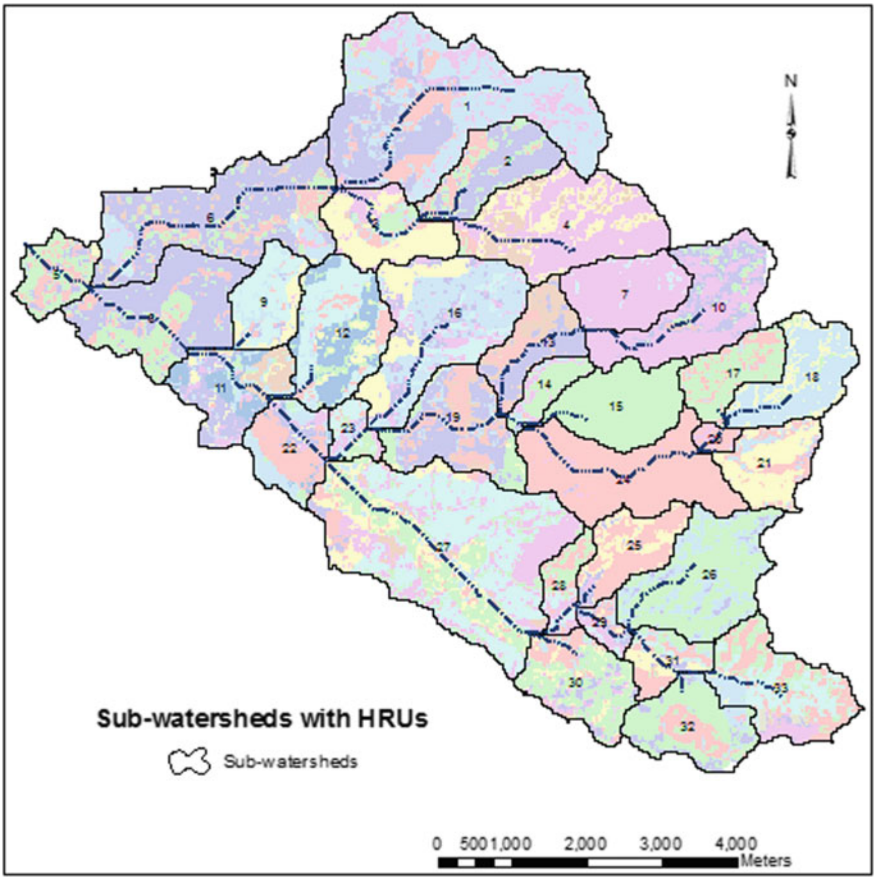


Fig. 5 HRU discretisation of the Kundhichira watershed

4 Results and Discussions

A total number of 1500 simulations with 11 parameters were carried out using monthly average runoff data during 2003 to 2006. Calibrated parameters are presented in Table 3. The model efficiency of 0.799 was achieved which exhibits a better simulation capability of the SWAT model. The R^2 value which represents the trend conformity of the model was 0.805 (Figs. 6 and 7). The d-factor (average distance between upper and lower bounds of 95 ppu band) value (0.17) is very less indicated the less parameter uncertainty. The p-factor value is 0.37 indicate the small parameter uncertainty associated with the monthly stream flow simulation uncertainty. Model validation was carried out using the observed monthly average runoff data during 2007 to 2009. The validation result is shown in Figs. 8 and 9. Though

Table 3 Parameters used for calibration and their value

Sl. No.	Parameter name	Fitted value	Min value	Max value
1	r__CN2.mgt	0.4654	0.30	0.60
2	r__SOL_AWC().sol	0.1557	0.10	0.30
3	r__SOL_BD().sol	−0.0016	−0.01	0.01
4	r__SOL_K().sol	0.6470	0.00	1.00
5	v__ALPHA_BF.gw	0.0659	0.04	0.07
6	v__ALPHA_BNK.rte	0.0051	0.00	0.10
7	v__ESCO.bsn	0.0804	0.00	0.10
8	v__GW_DELAY.gw	17.04	15	25
9	v__Gw_revap.gw	573.4	400	600
10	v__Gwqmn.gw	1612.8	1500	2000
11	v__Revapmn.gw	0.0494	0.00	0.10

Note r-means the existing parameter value is multiplied by (1 + a given value) and the v-means the existing parameter value is to be replaced by the given value

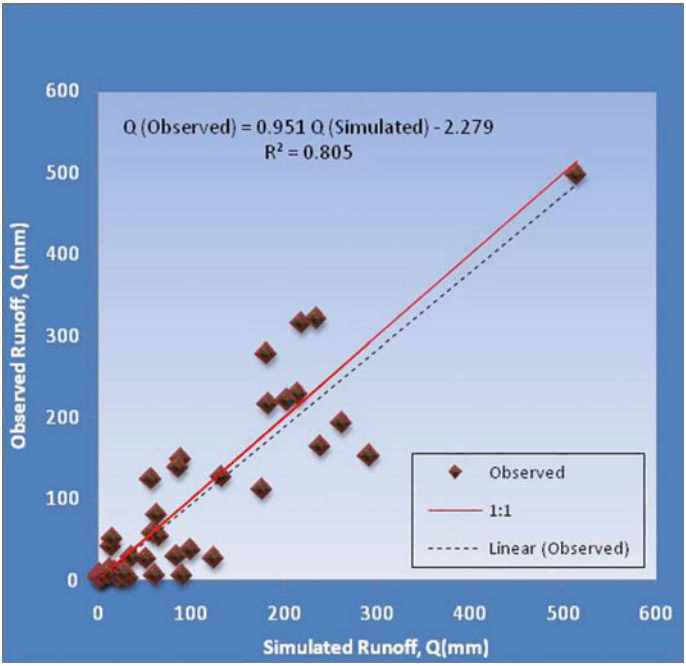


Fig. 6 Calibration of model output with their observed counterparts

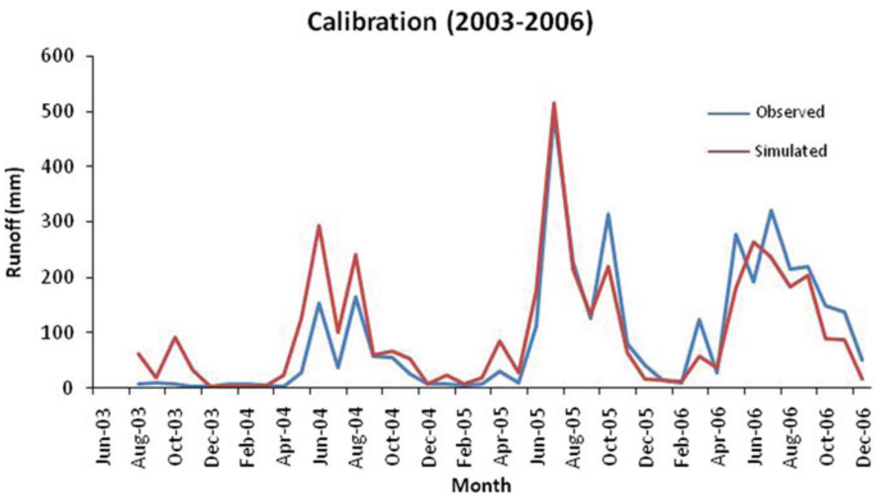


Fig. 7 Calibration of model time-series simulation and their observed time-series

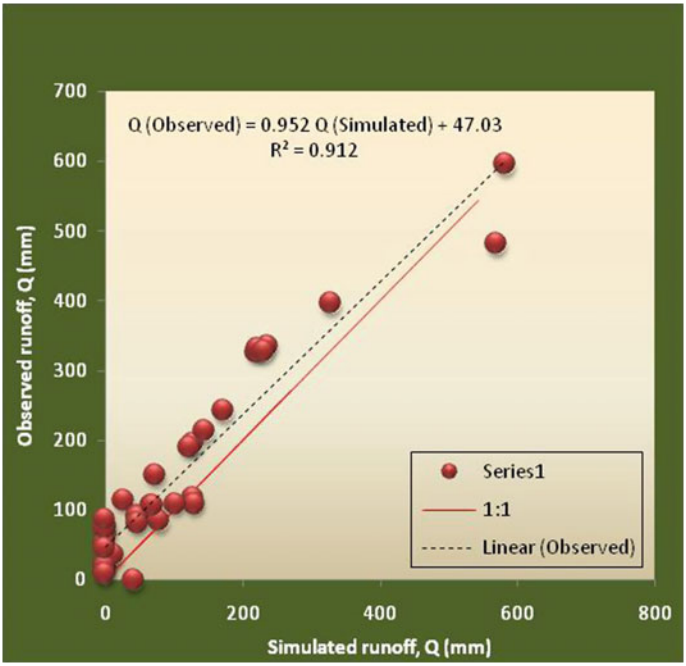


Fig. 8 Validation of model output with their observed counterparts

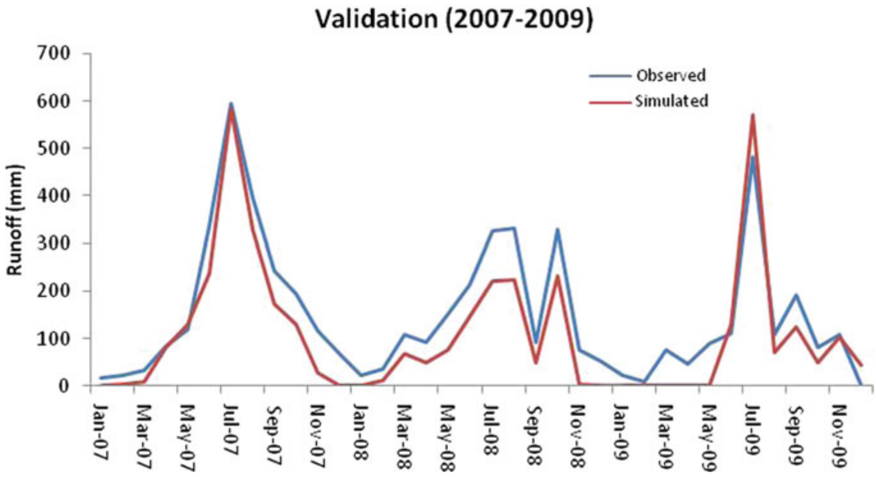


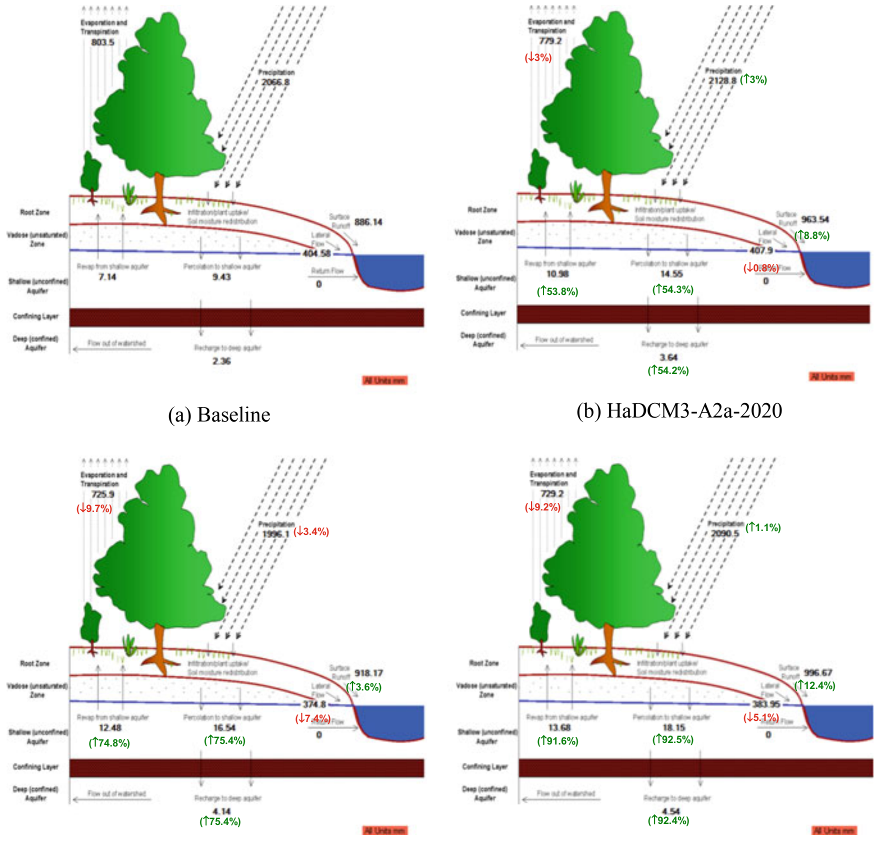
Fig. 9 Validation of model time-series simulation and their observed time-series

the observed data set for the said period is scanty, the trend conformity is well represented with R^2 value of 0.912 and model efficiency of 0.822 which demonstrate that the model predicted closely the observed values of stream flow. Result suggested that calibrated and validated hydrological model, SWAT is capable of producing climate change impacts on hydrology of the study watershed. Similar to the calibration stage, the model validation also shows that the model underestimates (positive PBIAS value) the observed runoff.

Scenario generation for the future climatic condition and land use change scenario is one of the most important applications of hydrological modelling. Thus the decision maker can take decision based on analysis of potential impact under futuristic scenarios (Singh and Gosain 2011). The present section describes the potential climate change implications imposed on the model on various hydrological fluxes of the study watershed.

4.1 Analysis of Climatic Scenario

In the present study, a various climate change scenarios were simulated and its impact on the hydrological characteristics of the basin were analysed. The aim of the simulation is to elucidate the effect of change of temperature and rainfall on hydrological fluxes assuming same land use pattern across the scenarios. The baseline period (Fig. 10) suggests that surface runoff (886.14 mm) and base flow (404.58 mm) are quite large corresponding to recharge components which is very less (9.43 mm shallow recharge and 2.36 mm deep aquifer recharge). This is a usual feature of the study area given the morphology, which is mountainous and groundwater recharge



(a) Baseline (b) HaDCM3-A2a-2020

(c) HaDCM3-A2a-2050 (b) HaDCM3-A2a-2080

Fig. 10 Pictorial water balance account of the study watershed in three SRES scenario (HaDCM3—A2a—2020/2050/2080)

in those areas is relatively less as comparison to surface runoff. The colluvial and red soils also have weak infiltration capacity leading to higher surface runoff. However dense vegetation (forest and plantations) improve retention of water in immediate subsurface (interflow) that appear as lateral flow.

Based on the simulation results (Figs. 10 and 11) a subtle change in the rainfall (3.4% decreases in 2050 to 3% increase in 2020) over the scenarios and a substantial increase in mean temperature (0.7 °C in 2020 and 2.4 °C in 2080) were indicated. Higher temperature rise will culminate into increased GDD (growing degree days) in all the crops. Increase in GDD will have a substantial effect on biomass as well as economic yield of plantation crops (Coffee and Rubber) and mixed forests (Kumar 2011), which has a substantial presence in the study area. This is reflected in lower ET rates over all the scenarios (3% in decrease in 2020 to 9.7% decrease in 2050).

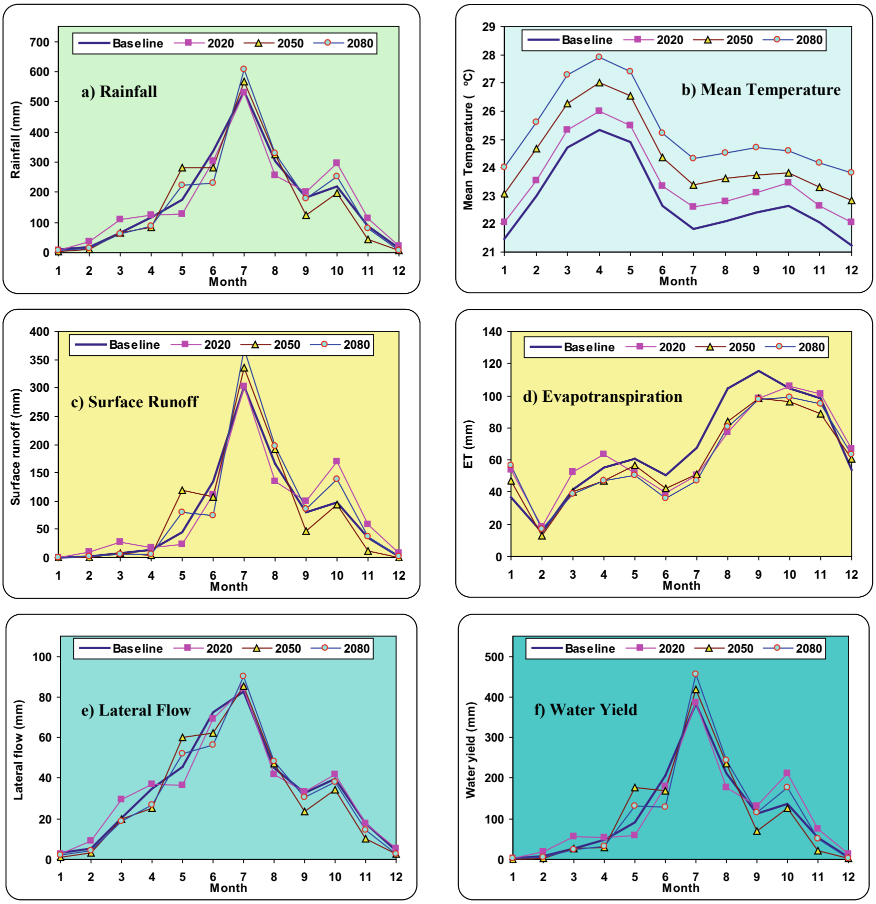


Fig. 11 Figures showing monthly variation of hydrological fluxes due to change in rainfall and temperatures in projected climate change scenario (CO_2 concentration assumed as 380 ppm, 414 ppm, 522 ppm and 682 ppm in baseline, 2020, 2050, and 2080, respectively)

Across the projected scenario, the climatic net primary production of the study area would be temperature limited which is at present precipitation limited. Moreover the shift of the peak ET rates towards right (by a month from of the annual) suggests that the maturity stages of the crops or the vegetations are likely to be delayed, which may be offset by the higher rate of GDD accumulation. The hydrological water availability during late monsoon (September to October) may result in increased surface runoff (3.6% in 2050 to 12.4% in 2080) while lowering base flow (0.8% in 2020 to 7.4% in 2050). The shallow aquifer evaporation may increase by 91.68% due to less water availability in the vadose zone. A rise in mean temperature may increase the evaporation component of the ET. The overall water yield over the tested scenario will register an increase from 0.2% in 2050 to 7.0% in 2080.

5 Conclusions

A GIS based hydrological modelling framework was used to assess the impacts of climate change on the hydrological regime of a small river valley watershed part of Kabini river basin catchments. The developed model was satisfactorily calibrated and validated with high model efficiency of 0.799 and 0.822, respectively and found to be effective in representing watershed hydrology. A substantial rise in temperature and subtle change in rainfall resulted in higher surface runoff rates (12.4% increases in 2080) and decreased base flow (7.4% decrease in 2050). The water yield increased by 7% in 2020. The groundwater recharge component is computed to increase by more than 90% due to least water extracting activities in vadose zone. This is because increase in mean temperature will result in decreased growing degree days (GDD) affecting the biomass yield which is reflected in reduced evapotranspiration component (up to 9.7% decrease in 2050). The Climatic Net Primary Production of the study watershed will have a limitation shift from precipitation to temperature.

Hydrological cycle must not be interpreted independently as several weather parameters are interwoven to it. Seasonal distribution of SWAT output shows increase in rainfall, which is more likely to affect surface runoff than any other hydrologic component as soils are more likely to be wet. Despite increase in projected temperature, ET may not increase because of the higher near surface humidity created by predominant woody perennials may restrict evaporation. The effect of CO_2 is difficult to corroborate due to lack of the information on interaction of CO_2 with other attendant climatic parameters. Since the study watershed is developed for various soil conservation activities, the interventions are required to offset the elevated temperature effect. Favorable ground water scenario, if suitably manipulated, may be used for better crop production. Additional soil and water conservation measures are required for control and productive utilization increased surface runoff/water yield.

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An Economic Analysis on Groundwater in India

Suman Chakraborty, Arpita Chaudhury, and Riddhima Panda

Abstract The country India is one of the highest groundwater extracted country in the world. We generally use 25% out of all groundwater extracted countries, which is ahead of the US and China. The high level demand or need for groundwater implies the necessity of capability to fulfil that demand in an equitable and sustainable way. In-sufficiency of water resource is likely to deteriorate, compared to growth rate of population in near future period in our nation. To address the issue of healthy water scarcity, masses need to be conscious about water storage, water reuse and common practices to reduce water pollution. Proper valuation and pricing of groundwater is an essential tool to protect the groundwater in India. Dynamic decision on price of ground water involves to pricing the value of the vital resource ground water. Enormous extraction of the resource can shrink surface water flows and declining the quantity of water available for other uses. Strategic externality depends on behaviour of extractors of groundwater. We have got a significant relationship between irrigation intensity and cropping intensity. Yield of paddy significantly depends on water productivity. The food grain production can be increased by improved water productivity. Increased food grain supply can fulfil the domestic demand and contribute on G.D.P (i.e.,Gross Domestic Product) of the nation. So that if we wish to gift healthy Nation to our future generation we have to think how to maintain the healthy groundwater.

Keywords Cropping intensity index · Externality · Groundwater · Irrigation intensity index

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1 Introduction

In the present era issues of groundwater is as the cloud in the blue and shining sky. In this era sustainable development is a most vital topic but we are not so much worried about the most vital resource that is groundwater resource. The resource is also the vital economic resource of any nation. So to present a healthy nation to our future generation we have to think how to maintain the healthy groundwater. It is our key objective to take care about the flow of groundwater. The availability of groundwater and the present condition of groundwater is in an alarming condition in India, i.e.; if we don't take care about it our future generation will be suffered badly. One of the most vital resource groundwater is astonishingly undervalued and underappreciated in our country (Berry and Bonen 1974).

Groundwater is continuing to use as a dependable resource for a several of purposes, such as industrial, domestic and irrigation. According to Burke, generally use of high quality groundwater for harvesting (irrigation) offsets other uses. Aquifers are degraded by industrial waste, disposal of human beings, pesticides etc. (FAO (2003) Groundwater management).

The high level demand or need for groundwater implies the necessity of capability to fulfil that demand in an equitable and sustainable way. But the economic worth of ground water is not understood and the power conflict regarding ground water till date looms as a huge problem. It can be said that, India is a groundwater related country. We generally use 25% out of all groundwater extracted countries, ahead of the US and China (Hindustan Times Mar 11, 2019, 19:36 IST).

The value of a resource is defined in terms of quantity of other resources/money, in modern societies, currency is typically the unit used for this exchange. Sometimes the value or worth of groundwater might be higher than or a lesser amount than the market price of an economy. Most environmental resources, including groundwater, are prime examples of 'non-market' resources. While there is a market for the groundwater abstracted (e.g. public supply), there is no market for many of the other benefits of groundwater. It is a well-established fact that the access to good quality reliable irrigation is important as it not only reduces risks faced by the rain fed agriculture; it also declines the cost and enhances the production (Dhawan 1988). Another significant fact is the equity in access to groundwater under the influence of surface water, which is the most vital factor of production and limited. In India, since the land distribution is biased in favour of big farmers, there is a natural inequality in ownership as well as access to groundwater. The utility of ground water depends on fundamentally on cost of producing obtaining the water and its value in the uses to which it is ultimately put. The cost of producing ground water involves cost of extractions, delivery and opportunity cost of using the water right away rather than leaving it in storage for future use. Huge extraction of the resource groundwater for harvesting has led to extensive over abstraction of groundwater which is untenable in the long period (A Sarkar 2011). We have shown a significant relationship in between irrigation intensity and cropping intensity by simple regression model. In this chapter we have analysed the economic impact of ground water on Indian economy and the related issues and also we have recommended few alternative strategies to balance the ecology or ecosystem.

In the Circumstances Our Major Objectives Are as Follows:

(1) To find out the present condition of groundwater.
(2) To analyse the economic impact, economic valuation and also the pricing methods of groundwater.
(3) To examine a significant relationship between irrigation intensity and cropping intensity.

2 Methodology

To accomplish the concerned objectives of our study secondary data were collected. The necessary secondary data has been collected from published sources such as, books and journals, articles, RBI reports, government reports, websites, economy survey government of India, socio-economic survey report of India. We have also used the different farm efficiency index such as, cropping intensity index, irrigation intensity index we have also used water productivity concept and the important statistical techniques to analyze and interpret the data. The various tools such as mean, frequency distribution, regression analysis have been used.

(1) Irrigation Intensity (I.I) = [{Total (Gross) Irrigated Area/Net Irrigated Area Sown}* 100] and,
(2) Intensity of Cropping (C.I) = [{Gross Cropped Area/Net Area Sown}* 100] (Directorate of Economics and Statistics Department of Agriculture, Cooperation & Farmers Welfare Ministry of Agriculture & Farmers Welfare Government of India).
(3) To examine the factor relationship regression analysis is used wherever it is necessary. Regression analysis is the most important way to estimate the exact relationship between dependent variable and explanatory variable.

Now, an equation of the linear regression line can be written as, $Y = (a + bX)$; here ***Y*** is the dependent variable and ***X*** is the explanatory variable. 'b' and 'a' are the slope and the intercept of the regression line respectively. The adjusted R^2 and F of the estimated regression equation of this model are such that the relevant regression model is fitted to the data set.

(4) Water Productivity: The concept of water productivity started gaining importance since the realization of increasing threshold being faced by countries and regions on account of its available water resource, particularly with respect to the huge allocation towards agriculture sector.

The water productivity will be analyzed from three broad perspectives such as

Physical water productivity = (crop output per unit of total consumptive water used (TCWU)), Irrigation water productivity = (crop output per unit of irrigation water applied by farmers) and.

Economic water productivity = (value of crop output produced per unit of TCWU as well as irrigation water applied) (Gulati, Mohan, Manchanda, Ray, and Amarasinghe; NABARD-ICRIER 2018).

The chapter is based on following subsections. Subsection first, analyses the availability and extraction of groundwater in India. Subsection second, explains the level of water fluctuations of groundwater of wells in India. Subsection third, analyses the valuation or pricing methods of groundwater in India. Subsection fourth, explains the economic impact of groundwater of India. Subsection fifth, analyses the relation between intensity of cropping and intensity of irrigation. Subsection sixth, makes summary and conclusion of the chapter.

3 The Availability and Extraction of Groundwater in India

Groundwater is still a vital source of life in many parts where surface supply water is scarce or expensive (Patel and Krishnan 2009). The problem of Groundwater has provoked more because of uneven distribution of surface water supply around the year and in between the years.

We Indians are thinking about modern cashless economy but we are not so much worried about availability and extraction of groundwater. We have to think about use of groundwater for extraction of groundwater for the betterment of India and also for our next generation. According to the statistics of groundwater we have got in India the availability of surface water is higher than groundwater. It is observed that 89% of groundwater is using for purpose of irrigation, followed by domestic use (9%) and industrial use (2%) (W and R Statistics, April 2015, C. W. C; PRS). 50% and 85% of water requirements of urban and rural for domestic purpose are also fulfilled by ground water respectively (Central Water Commission; PRS and Suhag, 2016, The status of ground water: Extraction exceeds recharge).

It is seen that the water accessibility of India as natural flow in rivers is 1,869 (B.C.M) Billion Cubic Metres/year (April 2015, C.W.C; PRS). The usable water resources of the nation have been estimated as 1,123 B.C.M/year due to inequality of distribution of the resource in various river basins. It is seen that, contributions of surface water and groundwater are 690 B.C.M per annum and 433 B.C.M per annum out of the entire accessibility of water resource respectively (Central Water Commission; PRS.). It is clearly observed that the availability of ground water is least compared to other sources of water in India (Table 1).

Table 1 Water resources in India

Items	BCM/Year
Availability of water per annum	1869
Groundwater	433
Surface water	690
Usable water	1123

Sources Water and related statistics, April 2015, Central Water Commission; PRS

3.1 Level of Water Fluctuations of Groundwater of Wells in India

This subsection of the chapter can be analysed in two ways. Firstly we can discuss level of water fluctuation in November 2016 compared to November 2015 and then we can go for a comparison of depth to level of water of November 2016 with the decadal (2006–2015) mean of November.

Level of water Fluctuation in November 2016 Compared To November 2015:

The level of water fluctuations of november 2016 compared to november 2015 depict that out of 14,291 wells, 6322 (44%) are showing rise and 7807 (55%) are showing fall in terms of level of water. Rest of 162 (1%) stations are remaining same in terms of level of water. It is seen that 31% wells (4491) are showing rise in the level of water in the range of level of under 2 m (metres). It is clearly observed that, 8% wells (1065) illustrate rise in level of water in the range of 2–4 m range and 5% wells (766) represent rise in level of water of greater than 4 m (metres) range. 55% wells are depicting decrease in level of water, out of which 41% wells (5885) are representing decrease in level of water in the range of under 2 m (metres). 9% wells (1263) are illustrating decrease in level of water in the range of 2–4 m (metres) 0.5% wells (659) are depicting decrease in level of water of greater than 4 m (metres) range. Majority of the wells are illustrating rise/decline falls in the range of 0–2 m (metres) (Fig. 1) (C.G.B. Ministry of W. R. Govt of India, November 2016).

A Comparative Scenario of Depth To Level of water of November 2016 With Decadal Mean of November (2006–2015):It indicates that, out of 14,884 wells analyzed, 6043 (about 41%) of wells are depicting rise in level of water, out of which 31% wells are illustrating rise of less than 2 m (metres). It is seen that 6% wells are representing increase in level of water in the range of 2–4 m (metres) and 4% wells are illustrating increase in level of water in the range of greater than 4 m (metres). 8818 (59%) wells are illustrating decrease in level of water, out of which 43% wells are depicting decline in water in the range of 0–2 m (metres). It is also seen that, 10% wells are illustrating decline in level of water in the range of 2–4 m (metres) and rest of 6% wells are in more than 4 m (metres) range (Table 2 and Fig. 2) (C.G.B Ministry of W.R Govt of India, November, 2016).

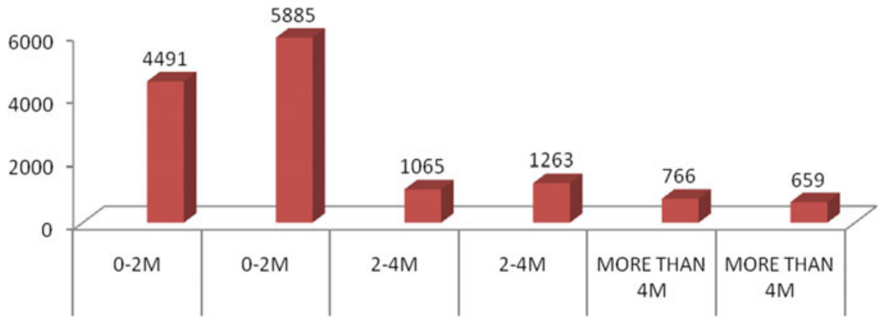

Fig. 1 Annual fluctuation and frequency distribution of different ranges from November 2016–November 2015 in India. *Sources* Central Ground Water Board Ministry of Water Resources Government of India November (2016)

4 Valuation or Pricing Methods of Groundwater in India

At present emerging and developing economies are encountering grave problems to provide supply safe drinking water to its citizens. (Hernández 2013).

The economic value of groundwater is increasing day by day due to high level of pollution of surface water, high level of population growth. So that economic value should be analysed properly and we have to think in future economic or socio economic impact of groundwater in India. The economic value of groundwater resource can be judged by its usability.

Total economic value can be segregated in two major components such as, use and non-use value. Use value is associated with physical interaction or dealings. It may be direct or derived. The term direct use represents direct physical interaction with the resource or extractive use of the particular resource where as the term indirect use shows derived value from the resource. Non-use value deals with satisfaction level of the particular resource or existence value or inheritance/bequest value.

Ground water can be pricing by many methods. Here we have shown the method of the dynamic price of ground water.

4.1 The Dynamic Price of Ground Water

A dynamic decision on price of ground water involves the optimal time rate of use (exploitation) of a natural resource. Optimization of time rate of natural resources is a complex dynamic decision to be made which involves balancing the marginal benefit (Additional benefit due to use of one extra unit of the product) and marginal costs (Additional cost due to use of one extra unit of the product).According to National Research Council, we can state that the marginal cost of extraction can be segregated in three types. These are,

Table 2 Fluctuation and frequency distribution of different ranges from November 2016 to Decadal Mean November (2006–2015)

No. of wells analysed	Rise						Falls						Rise		Falls	
14884	0–2M		2–4M		More than 4M		0–2M		2–4M		More than 4M					
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
	4590	31	907	6	546	4	6417	43	1468	10	933	6	6043	41	8818	59

Sources Same as above

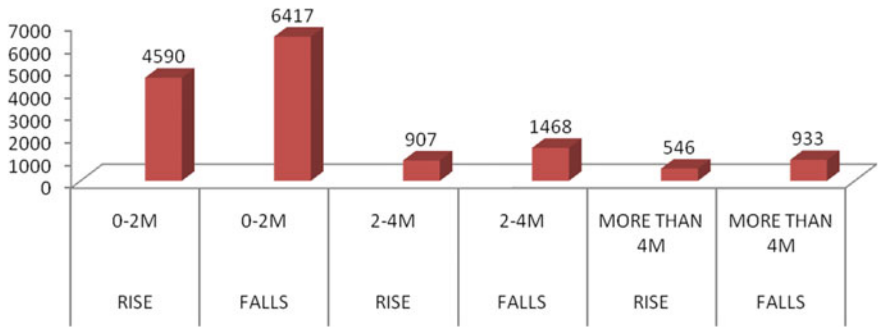

Fig. 2 Fluctuation and frequency distribution of different ranges from November 2016 to decadal mean November (2006–2015)

(1) Marginal pumping and distribution cost C(S).
(2) Opportunity cost of current extraction.
(3) Dynamic cost of pumping water includes usual cost of extraction and distribution along with opportunity cost as well as the cost of driving up future pumping cost.

Let us assume, a single owner "A" owns a confined aquifer, with no recharge, that is a finite exhaustible resource like mineral deposit. Now, 'W' is the stock of water left in aquifer after 't' periods of extraction or pullout. 'E' denotes the amount of water extracted or eroded by the firm in 't' periods. Again, let, P is the price of extracted water sold per unit and 'C' is the unit cost of pumping and distributing 'W' gallons of water. Thus the total cost can be written as (E*C) at 't' periods. The major goal of a private water supply company is to maximize the present value of extraction which requires the marginal gains of extraction should be equal to the rising costs of removal, and marginal benefit will be P, the price per unit of extracted water sold for (National Research Council 1997).

Now, $P = C + C^*$.

Where, 'C*' is the dynamic cost at period t. The dynamic cost of water raises as the ground water is exhausted. Increasing scarcity of water is reflected by increase in dynamic term C*.

If we deflate the price (P) by the base year price level (p*), we will be getting the real price.

Then the above Equation can be written as,

$$P/p* \;=\; (C/p*) + (C*/p*)$$

Here, (C*/p*) is the dynamic cost at period 't' in real term. The dynamic cost of water raises as the ground water is exhausted. Balancing marginal price and marginal extraction cost yields, (C/p*) rises while 'W' declines with continuous extraction. Increasing scarcity of water is reflected by increase in dynamic term (C*/p*).

If recharge of groundwater is considered, it will change the details of the model, but not its fundamental concept. In real term if the water stock is unchanged when aquifer enters a steady state, then price of water is constant and equal to stable extraction and dynamic costs (C/p*) + (C*/p*) (assuming energy and other costs remain stable). (C*/p*) is equal to zero, if aquifer discharges naturally to the stream, and then groundwater is not scarce. The term (C*/p*) also denotes the rental value of the ground water stock at real term. It is the value that the market places on additional groundwater resources which depends on objective of society. Magnitude of C* depends on various things. C* depends on the stock of water. If other things remain constant, as the stock go up, C* goes down and vice versa. Contamination or infectivity events can decline usable water supply that will drive up the dynamic water price, C*.Cases where contamination makes ground water inappropriate for some purpose, say, drinking, but leaves it acceptable for another purpose, say, irrigation, can bring changes in dynamic prices as the stock relative to the second demand will rise (National Research Council 1997).

4.2 Economic Impact of Groundwater of India

Socio-economic impacts of groundwater depend on future water demand and supply of groundwater (mbda.gov.au). The high salinity levels of the region and high costs of drilling lead to enhance price of ground water. The agricultural product which is directly or indirectly related to the groundwater would be higher cost oriented product. Input cost of agriculture can push the price level in the economy. i.e.; Agflation (Inflation in Agriculture produce) can be occurred.

According to minor irrigation census of 2001, there is an improvement in the ground water irrigation mediums in the country in the form of wells and tube wells. This has depicted in 60% reduction in the share of surface water (Shankar Vijay 2011).

Social cost will increase due to lack of healthy groundwater. The total stock of aquifer will be declined due to extraction of an extra unit of groundwater. So that, marginal costs of all extractors can be increased in future. It may create two consequences for both the extractor and all other users. Low level stock can increase the depth to groundwater and also the energy cost (costs for pumping) of all related users. This higher costs lead to negative externalities. Again low level stock reduces future availability and withdrawal (extraction) alternatives for all users. Strategic externality which is related to the pumping cost externality depends on behaviour of extractors of groundwater (Negri 1989).The economic impact can be analysed by using a regression analysis between water productivity and yield of paddy of selected countries. Here we have chosen four countries such as, China, India, Indonesia, and Bangladesh to establish a regression model.

The current limelight of water productivity has evolved to include the advantages and costs of water used for harvesting in global and aquatic ecosystems (Molden et al. 2007). In the broadest sense, it reflects the objectives of achieving more socio

Table 3 Overall water productivity and yield of paddy of selected countries in 2014–15

Country	Water productivity	Yield of paddy (t/ha)
China	14	6.8
Bangladesh	4	4.6
India	3	3.6
Indonesia	8	5.1

Source ADB, 2017, FAO aqua stat. And Agricultural Situation in India, VOL-LXXV, APRIL, 2018, NO-1. Directorate of Economics and Statistics Department of Agriculture, Cooperation & Farmers Welfare Ministry of Agriculture & Farmers Welfare Government of India; China—NBS (National Bureau of Statistics of China)

economic and ecological advantages at less cost of social and environmental for each unit of water consumed (Sharma et al. 2013). Improving water productivity in agriculture is the cornerstone of any water demand management in India (Sharma et al. 2018).

China has one of the highest values of water productivity and also for the amount of yield of paddy, followed by Indonesia (Table 3).India has one of the lowest values of water productivity and also for the amount of yield of paddy (Table 3).We have assumed Water Yield of Paddy (Y.P) as dependent variable and Water Productivity (WP) as independent variable (Table 3).

Regression equation concerning Water Productivity (W.P) and Yield of Paddy (Y.P) shows that the variation in Yield of Paddy (Y.P) is significantly explained by the Water Productivity (W.P) to the extent of 92%. It is also observed that coefficient of the variable Water Productivity (W.P) is significant at the level of 5%. The whole model is also satisfying at 5% level of significance (Table 4). Thus it can be said that, yield of paddy (Y.P) significantly depends on water productivity (W.P). Hence we can state that, the improved water productivity can enhance the food grain production. Improved food grain production can fulfil the domestic demand as well as contribute on G.D.P (i.e., Gross Domestic Product) of the economy.

The values in parenthesis are the "t" values.

Y.P—Yield of Paddy.

W.P—Water Productivity.

Table 4 Regression equation between Yield of Paddy (Y.P) and Water Productivity (W.P) in 2014–15

Regression equation	$AdjR^2$	F
$Y.P = 0.26W.P^{*} + 3.14$ (5.9) (8.4)	0.92	34.6*

* indicates significance at the level of 5%

5 Relationship in Between Cropping Intensity (C.I) and Irrigation Intensity (I.I)

Here, we have shown a regression analysis to examine the relation between Irrigation Intensity and Cropping Intensity of Indian economy for the year 2014–15.We have taken the relevant data from the states of our nation (India) to establish the relation. We have assumed Cropping Intensity as dependent variable and Irrigation Intensity as independent variable (Table 5).

Regression equation concerning Cropping Intensity (C.I) and Irrigation Intensity (I.I) shows that the variation in C.I is significantly explained by the I.I.to the extent of 35% and the coefficient of the variable I.I is significant at 1% level. The entire model is satisfying at 1% level of significance (Table 6).Thus Intensity of Cropping (C.I) significantly depends on Intensity of Irrigation (I.I).

The values in parenthesis are the "t" values.

C.I—Cropping Intensity.

I.I—Irrigation Intensity.

6 Summary and Conclusion

Excessive water use over the last decade has made an alarming situation for future generation as well as for our nation. It is seen that in the last decade (2001-'11) national per head or per capita accessibility of water has declined from 1,816 cubic metres to 1,544 cubic metres.This is a reduction of 15%. It is observed that, out of 14,884 wells analyzed, 41% of wells are depicting rise in level of water, out of which 31% wells are illustrating rise of less than 2 m. It is seen that 6% wells are representing increase in level of water in the range of 2–4 m and 4% wells are illustrating increase in level of water of more than 4 m range. 59% wells are illustrating decrease in level of water, out of which 43% wells are depicting decline in water in the range of 0–2 m. 10% wells are illustrating decrease in level of water in the range of 2–4 m and rest of 6% wells are in more than 4 m range (Table 2 and Fig. 2).

To address the issue of healthy water scarcity, masses require being aware about water storage, water reuse and common practices to reduce water pollution. One of the vital economical, feasible and facile method for water storage and reuse is rainwater harvesting. According to recommendation of M. S. Swaminathan in his ever green revolution rain fall water should be used in harvesting. Ground water can be charged a particular rate of price by installation of meter rather than a licensing system. Dynamic decision on price of ground water involves to pricing the value of the vital resource ground water. Another vital analysis is the marginal value of positive or negative externalities in the environment. Yield of Paddy significantly depends on Water Productivity. Thus it can be said that, the improved water productivity can increase the food grain production. Increased food grain supplies can fulfil the huge domestic demand and contribute on gross domestic product of the nation.

Table 5 State-wise cropping intensity and irrigation intensity in 2014–15

States	Irrigation intensity	Cropping intensity
Andhra Pradesh	132.76	123.3
Arunachal Pradesh	100.00	132.8
Assam	126.35	144.4
Bihar	176.36	145.4
Chhattisgarh	121.90	122.4
NCT of Delhi	131.82	161.5
Goa	100.00	122.0
Gujarat	142.07	124.0
Haryana	195.83	185.6
Himachal Pradesh	170.80	167.0
Jammu and Kashmir	152.27	155.3
Jharkhand	106.76	112.2
Karnataka	116.63	121.9
Kerala	113.53	128.5
Madhya Pradesh	107.48	155.1
Maharashtra	132.00	135.3
Manipur	100.00	100.0
Meghalaya	158.02	120.0
Mizoram	131.25	100.0
Nagaland	109.28	130.3
Odisha	117.95	115.6
Puducherry	169.23	168.3
Punjab	188.37	190.8
Rajasthan	129.04	138.3
Sikkim	100.00	176.0
Tamil Nadu	124.50	124.4
Telangana	146.52	121.5
Tripura	146.84	189.3
Uttar Pradesh	145.70	157.5
Uttarakhand	164.24	156.7
West Bengal	183.75	185.0

Source M. Of and F.W. (i.e., Ministry of Agriculture and Farmers Welfare), Government of India and RBI report

Table 6 Regression equation between irrigation intensity and cropping intensity in 2014–15

Regression equation	$AdjR^2$	F
$C.I = 0.57 I.I^{**} + 63.9$ (4.2) (3.34)	0.35	17.43**

** indicates significance at the level of 1%

Regression equation concerning Cropping Intensity and Irrigation Intensity shows that the Cropping Intensity significantly (1% level) depends on Irrigation Intensity. The entire model is satisfied at 1% level of significance. Huge extraction of groundwater can harm our society. It can damage the ecosystem by reducing surface water flows by linkage effect (hydrologic linkages). It is also declining the quantity and quality of water available for other uses. The stock externality depends on its use value. It is the part of F.M.O.C(I.E., full marginal opportunity cost) of extracting groundwater (Reineltb, Brozović c and Whittena a. CSIRO E Sciences, Canberra, E. Q, Reesona, Australia; b. St. Univ: of N. Y, Fredonia, USA; c. Univ:of Illinois at Urbana-Champaign, USA; d. Fenner School of Env: and Society, ANU, Canberra, Australia).The averting expenditures method was applied via a mail survey of households in which water contained the unregulated volatile organic chemical, per chloro ethylene (Abdalla 1990). The existence of groundwater stock to use in combination with random (i.e., stochastic) surface water supplies may create a buffer value (Tsur, Graham-Tomasi 1991). In the case of risk averse extractors, a risk externality might arise because low level stock increases the income variability tied to random (i.e., stochastic) surface water supplies as low level stock of groundwater are less capable to buffer against supplies of random (i.e., stochastic) surface water (Provencher and Oscar 1993). So that healthy flow of groundwater is inevitable factor of our nation to achieve the sustainable development.

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