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**Note:** Prof. B. S. Chaudhary has been named as the Executive Editors I/C for “e-Journal of Geohydrology”.
Welcome to INC-IAH India  
(Indian Chapter of International Association of Hydrogeologists)

International Association of Hydrogeologists (IAH) was established in 1956 to promote cooperation, to advance the science of hydrogeology worldwide and to facilitate the international exchange of information on groundwater.

IAH’s membership includes about 4,000 members representing 135 countries. IAH has 43 country chapters, including the Indian National Committee (INC).

The Indian National Committee of IAH (INC-IAH) was established in 1984 and during its journey of the last 30 years sincere efforts have been made to enhance the activities and strengthen the INC-IAH. INC-IAH also provides a valuable forum for scientists and engineers working in the fields of hydrogeology and groundwater resource planning, management, and protection who have a broad interest in and an international perspective on groundwater resources and hydrogeological issues.

The current agenda of INC-IAH includes the following items:

1. To organise national seminar/conferences on current topics of national concern with the aim of interaction on topics such as sustainable development of groundwater in the country due to ongoing depletion of groundwater resources resulting from various factors like variability in rainfall and climate changes.

2. To communicate relevant recommendations/resolutions of the conferences to the decision makers in the government.

3. To commence publication of an online journal of Geohydrology (on Biannual basis) by publishing academic research papers carrying findings of frontline research endeavours with the aim of dissemination amongst INC IAH members.

4. To organise a ‘National Groundwater Lecture Series’ on emerging groundwater issues, in major cities of India by eminent experts.
5. To institute suitable awards in the field of groundwater research for incentivisation of groundwater professionals by an impartial selection process.

6. To publish an e-Newsletter of the INC IAH on regular basis (3 to 4 issues per year) with the objective of updating its members about forthcoming international/national conferences and meetings within and outside India and other groundwater related news.

The IAH (international organization) has the following major activities:

- Publish the Hydrogeology Journal (sent to members eight times per year), memoirs in the series International Contributions to Hydrogeology, a newsletter and other membership information.

- Promote international cooperation among hydrogeologists and those from other disciplines who have an interest in groundwater.

- Sponsor international meetings and symposia, including an annual Congress.

- Encourage the worldwide application of hydrogeological skills through educational and technological transfer programs.

- Cooperate with national and international scientific organizations that have interest in groundwater.

Please explore our site and feel free to contact any of the INC-IAH Executive if you have queries/questions.
Esteemed Groundwater community Colleagues,

I, on behalf of whole editorial team of “e-Journal of Geohydrology” of INC-IAH, take this opportunity to wish you all a very happy holiday season, Merry Christmas and Happy New Year 2021! The very purpose of INC-IAH for providing opportunities to the researchers in the field of groundwater to carry it to the world stage through this online journal could see the light of the day only due to continuous encouragement and boosting from the office bearers of INC of IAH. We all are aware about various issues and problems concerning stress on groundwater resources due to burgeoning population, increasing industrialization and urbanization. The groundwater quality is also under continuous stress due to increasing use of fertilizers, weedicides, insecticides, herbicides and other chemicals being used in agriculture in addition to the industrial effluents and poor inland drainage conditions in the alluvial tracts of India. The coastal zones are continuously facing the threat of saline water intrusion. The climate change is further going to accentuate the problems related to groundwater conservation and management. It therefore necessitates putting together integrated strategies with innovative solutions in consonance with “Think Globally, Act Locally” site-specific solutions. The adverse impact on agricultural production in the wake of climate change needs adaptive strategies and coping mechanism to be identified and shared with scientists, researchers, and the community at large to make it more effective. The present initiative will help in achieving core objectives of the INC-IAH new office bearer’s dream of initiating this journal so as to provide platform for wider outreach. The determination of the Vice-President, INC-IAH and Chief Editor of this e-journal, Prof. A. K. Sinha needs special mention as he could put us all together for this initiative.

The entire credit for arduous work for the second issue of the “e-Journal of Geohydrology” regarding correspondence, review, draft and final version goes to Executive Editor Prof. Madan Kumar Jha who put all out efforts in completing the task in a very efficient and timely manner. I am indeed thankful to the Patron, INC-IAH Sri G. C. Pati, Chairman CGWB; President, INC-IAH Prof. D. C. Singhal; executive body of INC–IAH and entire editorial team for putting together their best efforts for this initiative. We are grateful to various authors who have contributed their research papers and case studies for this journal without which it could not see the light of the day. I wish you all a very happy and prosperous New Year 2021 and happy reading of the new issue!

B. S. Chaudhary
<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Title and Authors</th>
<th>Page</th>
</tr>
</thead>
</table>
| 1      | GIS-Based Village Level Ground Water Resource Assessment System for Rajasthan  
         by Mahendra Mehta, Sandeep Kumar Swaroop and Sunil Kumar                       | 1-8  |
| 2      | Managing Deccan Basalt Aquifers: Understanding Aquifer Heterogeneity,  
         Iniquitous Access and Groundwater Competition  
         by Himanshu Kulkarni and Rahul Gokhale                                          | 9-23 |
| 3      | A Comparative Study of Electrical Resistivity Tomography versus Vertical  
         Electrical Sounding  
         by S.N. Rai and S. Thiagarajan                                                  | 24-34|
| 4      | Groundwater Resource Assessment of Akaki Wellfield of Addis Ababa, Ethiopia  
         by Brijesh Kumar Yadav and Negasi Haile Bihon                                  | 35-46|
| 5      | Application of Electrical Resistivity Tomography for Investigation of Shallow  
         Subsurface HFT Zone in and around Mohand, Uttarakhand, India  
         by M. Zubair, Anita Devi, M. Israil1, P. Yogeshwar and B. Tezkan                 | 47-55|
| 6      | Identification and Modelling of Seawater Intrusion in Coastal Aquifers of Puri  
         Inter Basin, Odisha by R. M. Das                                               | 56-71|
| 7      | Groundwater Quality Assessment for Drinking Purposes Using Analytic  
         Hierarchy Process (Case Study: Roorkee Town, India)  
         by Supriya Bajpai, D.C. Singhal and H. Joshi                                    | 72-81|
| 8      | Hydrogeochemical Evaluation of Groundwater of Bemetara District,  
         Chhattisgarh  
         by M. K. Sharma, Surjeet Singh, Pradeep Kumar, A. K. Patre, Mohit Kumar, Beena  
         Prasad, A. K. Shukla and P. C. Das                                              | 82-92|
| 9      | Groundwater Chemistry of Unconfined Aquifers of Odisha State: Delineation  
         of Poor Water Quality Zones and Groundwater Discharge Corridors Using GIS  
         by Sudarsan Sahu and P. K. Mohapatra                                            | 93-107|
GIS-Based Village Level Ground Water Resource Assessment System for Rajasthan

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Abstract

It is widely accepted that there is a need for better governance of the precious ground water resource for accurate assessment of severity of the problem, raising awareness among the stakeholders and engaging end users. The quantification of ground water resource is essential for planning, sustainable development and management of ground water resource. The methods available for the estimation of ground water recharge are directly from precipitation and can be broadly divided into three process (i) inflow, (ii) aquifer response and (iii) outflow methods, according to these, studies were conducted to evolve a mechanism for estimation of village-wise resources. Rajasthan Ground Water Department, under the European Union’s State Partnership Program has embarked in a visionary project wherein, village-wise assessment of ground water resources has been conducted in 2012 in backdrop of Aquifer mapping of Rajasthan. A maiden attempt has been made to estimate, basin-wise ground water resources, adopting aquifer, as a unit. An innovative, GIS-based Spatially Distributed Recharge Estimation technique has been evolved; using Geo Spatial tools following the GEC norms. The geo-spatial tools inbuilt in to the standard GIS have been used for spatial interpolations of parameters and for various computations.

Keywords: Aquifer Mapping, GEC-1997, Spatially Distributed Recharge Estimation, Village-wise Resources

Background

Ground water development in India has been on an accelerated pace, ever since the country entered stage of green revolution. The growth in ground water exploitation led to steep fall in water table in several parts of the Country and Rajasthan has been the worst sufferer. As a result, ground water has become unsustainable with several adverse effects.

At present, our understanding of ground water availability and quality is constrained by insufficient data, in respect of lateral and vertical extent of aquifer and also the properties controlling the storage and transmission of ground water. Groundwater resource estimation is an integral part of planning, development and management of water resources.

It is widely accepted that there is a need for accurate assessment of severity of the problem, raising awareness among the stakeholders and engaging end users for better governance of this precious resource. The quantification of ground water resource is essential for planning, sustainable development and management of ground water resource. Estimating the rate of aquifer replenishment is probably the most difficult of all measures, in evaluation of ground water resources. The methods available for the estimation of ground water recharge, directly from precipitation, can be broadly divided into three process (i) inflow, (ii) aquifer response and (iii) outflow methods, according to these, studies were conducted to evolve a mechanism for estimation of village-wise resources (CGWB 1997). Village-wise assessment of ground water resources has been conducted in 2012 in backdrop of Aquifer mapping.
Ground Water Scenario in Rajasthan

Ground water scarcity in Rajasthan State is well known. In the state, 90% rural water supply and over 60% irrigation is through ground water (CGWB 2009). The extraction of ground water far exceeds the natural recharge, resulting in continuous declining water levels, failure of wells, higher energy consumption and marked deterioration in ground water quality. The contrasting situation of water logging has also been observed in canal command areas. Conjunctive use of groundwater & canal water is the need of the hour to avoid land degradation by water logging hazards and soil salinity/alkalinity (CGWB 2009). The stage of ground water development and categorization of assessment units based on the 2009 estimation is given in Fig. 1a and 1b, respectively.

![Fig. 1a Stage of GW Development (CGWB-2009).](image1)

![Fig. 1b Categorization of Assessment Units (CGWB-2009).](image2)

Major area of the Rajasthan State is having Stage of Development (SOD) more than 100%, (marked in red shades) and at places it goes up to 400%, in some parts of Jaipur and Jodhpur districts. Ground water resource has two components, namely, the dynamic resource in the zone of water-table fluctuation, which reflects seasonal recharge and discharge of aquifers and the static resource below this zone, which remains perennially saturated. However, wherever SOD is more than 100%, it signifies that resources are being exploited beyond annual recharging capacity.

Participatory Management of Ground Water

The need for involving Panchayats and local institutions in management of ground water resources has been emphasized by the National Commission for Integrated Water Resources Development (MoWR-1997) as well as Expert Group on Ground Water Management and Ownership of the Planning Commission (Planning Commission -2007). Given the vastness of the problem related to over-exploitation of ground water, a command and control system have little chance of success. Hence, there is no alternative but to involve local level institutions and end users themselves in the task of management of ground water.

Rajasthan Ground Water Department, under the European Union’s State Partnership Program has embarked in a visionary project. This was conceptualized by the technical assistance team of European Union. The objective of this project was computerization of vast archive of data available with the Central and State departments, dealing with ground water and bringing them into a user friendly GIS interactive environment. This laid the foundation for development of basin wise 36 unique GIS thematic layers. Adoption of systematic and complex overlay analysis, keeping the guidelines GEC 1997 in view, village level estimation of ground water resources was carried out. This assessment has facilitated farmers and other stakeholders, to keep an eye on the available ground water resources and plan accordingly, their annual water consumption needs.

Approach and Methodology

To meet the objective of developing user friendly, village-wise ground water resources tool, it has been preferred for application of GIS based analysis and methodology for Ground Water Resource Assessment in different hydrogeological terrains. GIS can be effectively used to store and analyze the various maps and to
derive the various parameters for the estimation of Ground water resource. In this project an attempt has been made to establish the use of Geo Spatial Technologies to prepare various layers and to derive the parameters needed for Spatially Distributed Recharge Estimation, following the GEC norms. Further, geo-spatial technique based water table fluctuation method has been attempted for assessment of ground water resources. Different maps and their attributes were created in GIS database and estimation of spatially distributed resource parameters has been carried out, to estimate the ground water resource aquifer wise / basin wise.

After reviewing all the prevailing techniques vis a vis the data requirements, as well as suitability in different hydrogeological environments, water level fluctuation method was found to be most suitable for assessment of dynamic ground water resources; as water level fluctuation is the resultant of all inflows and out flows from the aquifer system. The suitability of this technique is further established, as the depth to water level in major part of the state is quite deep and rainfall is less therefore a reasonable amount of rainfall is lost into compensating soil moisture before recharging to ground water aquifer.

In order to use this technique for entire Rajasthan a sample basin namely Banganga has been chosen and attempt made to estimate, basin-wise ground water resources, adopting aquifer, as a unit. An innovative, GIS based Spatially Distributed Recharge Estimation technique has been evolved; using Geo Spatial tools following the GEC norms. The geo-spatial tools inbuilt into the standard GIS have been used for spatial interpolations of parameters and for various computations. Different maps and their attributes were created in GIS database to facilitate the estimation such as aquifer dispositions, isopachs, depth to bed rock etc. as given in Figs. 2, 3 and 4.

In line with the GEC-1997 recommendations, the methodology adopted is broadly lumped water balance approach, based on the water level fluctuation and saturated zone technique. Generally, in arid and desert climatic conditions, as prevalent in Rajasthan, the rates of evaporation are very high, rainfall is low to very low, leading to high soil moisture deficiency and hence, direct impact of vertical and in situ recharge, to ground water from rainfall is not significant. Major quantum of rainfall gets attenuated in saturating the soil moisture and hardly any amount is left for percolation and subsequently joining the ground water. The principal mechanism of ground water buildup is lateral flow except in areas with shallow water level. Hence the Rainfall Infiltration Method is not very accurate and at times misleading in such situations.

It is found that depth to water level fluctuation approach adopted in the Banganga Basin is more realistic and comparable to the field scenario and hence the methodology can be replicated to other parts of Rajasthan. Accordingly, the ground water resources of Rajasthan have been estimated.

Fig. 2 Aquifer Distribution Map of Banganga River basin, Rajasthan (GWDR-2013).
Fig. 3 Isopach map of Banganga River basin, Rajasthan (GWDR-2013).

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Ground Water Resources Estimation

Based on the learning and experience from the Banganga Basin aquifer wise dynamic ground water resource assessment in Rajasthan is carried out, by creation of GIS based seamless dataset as an integral part of the analysis and assessment. As envisaged, one time dynamic ground water resources has been computed for the base year 2010 using the water level fluctuation for pre- and post-monsoon groundwater levels. Attempt has been made to overcome the limitation inbuilt in the GEC-1997 methodology through a semi-automated process based approach, to minimize the computational and assumptive errors. Some of the inbuilt limitations such as uncertainty in the recharge estimates made using the WTF and rainfall infiltration methods depends mainly on the uncertainty in Sy and RIF, and also on site-specific applicability of other norms, such as seepage, return flow factors, unit ground water draft, etc. were attempted to be eliminated to certain extent by using aquifer-wise hydrogeological parameters for different formations.

Primary validation of water level and fluctuation data has been made to eliminate all erroneous data, outlier / inliers or non-representative data. The pre and post water level fluctuation, for the year 2010 was observed to vary between -15 to +64 m. The data was subjected to secondary validation, using GIS based statistical tools in spatial domain, using parametric methods to identified outlier or extremes in trends, after confirmation, the same has been filtered from the data base to represent the true field conditions. In the present exercise, the distributed approach for spatial interpolation of water level has been adopted through geo-statistical tools. Water levels and fluctuation has been computed on a regular grid of 250 m x 250 m, which has been integrated to arrive at fluctuation of individual aquifers units. The draft data was available as lump for the each block and hence same was distributed equally in the respective blocks.

Aquifer-Wise Ground Water Resources Estimation

The assessment of dynamic ground water resources has been carried out for all the 683 aquifer units (assessment units) which are parts of 19 Principal Aquifers identified in the state of Rajasthan (SWRPD-2010). The aquifer map of Rajasthan depicting the principal aquifers is given in Fig. 5. Various thematic layers used in the present study for the all the river basin includes aquifer disposition, aquifer wise isopach maps, water level fluctuation maps and an exclusive layer of specific yield values attached with the aquifer polygons. Complete distributed approach has been used for computing the ground water resources (static and dynamic) by overlaying a grid of size 2.5 km square to the entire area available for assessment. After the grid wise computation, the same have been integrated to arrive at basin wise and aquifer wise totals.

Various steps involved in the present approach includes delineation of aquifers within the basin boundary as a first step, and subsequently based on the lateral and vertical extent of the aquifer, as well as saturated thickness.
(vertical extent between deepest water level and lower boundary of the aquifer) the ground water resources have been assessed separately as dynamic resource, referring to the volume of water available within the zone of fluctuation; and static reserve, considering the lower bound of the aquifer, indicating the total thickness.

Further, since the GWD computes and reports groundwater draft on aquifer wise block wise, it is not possible to directly compare the draft to aquifer wise and basin wise resources. Therefore, an area weighted approach was used to re-compute the draft to GIS based aquifer polygons which were then used to deduct from total of resources to arrive at available groundwater balance.

The aquifer unit wise resources have been assimilated and summarized to represent the dynamic ground water resources aquifer-wise, and is given in Fig. 6. It is observed that out of the total resources of 20.7 BCM, about 12 BCM (57%) is contained in the alluvial aquifers, followed by aquifers made up of sedimentary rocks consisting of sandstone, and limestone’s. The total saline ground water resource in the Dynamic zone has been estimated as 1024 MCM. Whereas, static ground water resources has been estimated as 466.25 BCM (Fig. 7). About 63% of ground water resources is contained in the older and younger alluvial aquifer. The share of hard rock aquifers in static resources is meager. The saline ground water is limited to four basin namely Banas, Ghaghar, Luni and Outside basin, out of the seventeen basins. Nearly 50% of the total saline resources in the Dynamic zone are available in Outer basin underlain by Older Alluvial aquifer (GWRD-2013).

Fig. 5 Aquifer Map of Rajasthan.

(Geological Setting: web link [http://waterresources.rajasthan.gov.in/1geology.htm](http://waterresources.rajasthan.gov.in/1geology.htm))

Fig. 6 Aquifer-wise Dynamic Ground Water Resources of Rajasthan (GWDR-2013).

Fig. 7 Aquifer-wise Static Ground Water Resources of Rajasthan (GWDR-2013).
Village-wise Assessment

In the next step the aquifer wise resources have been apportioned village wise, taking into consideration the area of the village and major aquifer system. The village wise resources, so obtained has offered the basis for developing village wise ground water management plans, taking in to account the total demand / utilization and availability of ground water and future scope for augmentation. Thus, dynamic groundwater resource is essentially the exploitable quantity of groundwater, which is recharged annually. It is also termed as annually replenishable groundwater resource. Various thematic layers used in the present assessment includes, aquifer disposition, aquifer wise isopach maps, water level fluctuation maps and specific yield values attached with the aquifer polygons. In addition, the layers depicting the spatial variation of ground water draft is also considered. All these layers have been integrated in to GIS and geospatial tools, and used for onetime assessment of aquifer wise ground water resources. A flow chart of the process adopted is given in Fig. 8.

![Fig. 8 Village-wise GW resources assessment Flow Chart.](image)

Since ground water recharge is dynamic in nature and is highly dependent upon the spatial and temporal variations of inputs, including rainfall and outputs from the system in terms of withdrawal, exchange with surface water streams and water bodies etc. The manifestation of these inputs and outputs and their resultant is measured in terms of water level changes. Once the database is created, the frequency of assessment can be increased to seasonal and even for the intervening periods, however that would require rigorous planning and protocol for intensive spatial and temporal data collection.

Development of Web Application

Under the project, a bilingual Web GIS application has been developed subsequently by M/s Rolta India Ltd. and implemented (GWRD-2013). Apart from posting all the GIS thematic layers on the web for the convenience of all user groups, pre-defined queries with user friendly drop down menus, allow quick access to ground water related information. The developed website also provides a tool for assessment and planning of ground water resource utilization at village level and for distribution of the available resources for domestic, cattle, and agriculture purposes judiciously following State’s policies. Some of the outputs of Web GIS applications are given below:
Conclusions

In the prevailing system of ground water governance, there is total absence of direct involvement of users in the resources assessment process as well as there is constraint of micro level data and dissemination system, hence, the seriousness of the ground water situation sometimes does not effectively percolate down to the user level. Attempt has been made to evolve a process through which ground water resources are assessed at micro level adopting a simplified methodology, which can be implemented by the users and can be effectively used for local level ground water governance. The village wise seasonal assessment of ground water and water budgeting has been facilitated through developing a web based application for computation of dynamic resources for which the only time variant data will be seasonal water level, unless and otherwise the ground water withdrawal is from the static reserve. Necessary facility to re-compute the static reserve by redefining the saturated thickness of the aquifer has also been provided in the application. The methodology proposed in the present exercise involves quantitative estimation of rainfall over the area considered for budgeting, surface runoff and ground water recharge available in the area etc. and accounting of water requirement for domestic and irrigation purposes on real time basis. The application essentially requires periodic data / parameters such as rainfall, water level with a good density of wells and ground water withdrawal for dynamic assessment. If required, monthly accounting of rainfall, evaporation and net ground water recharge may be carried out.
References


Geological Setting; web link http://waterresources.rajasthan.gov.in/1geology.htm.


Managing Deccan Basalt Aquifers: Understanding Aquifer Heterogeneity, Iniquitous Access and Groundwater Competition

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Abstract

The performance of large-diameter dug wells from a single Deccan basalt aquifer, reflected through well-yields, is widely different. Variability in weathering and fracturing leads to high degree of heterogeneity even within a single basalt aquifer. Responses of a typical unconfined basalt aquifer to boundary conditions under homogeneous and heterogeneous scenarios show different results. The variability of heads in the aquifer is enhanced by heterogeneity, where wells are uniformly placed in the aquifer under three boundary conditions. Heterogeneity results in depleted water availability for some farmers, while others can continue pumping throughout the summer resulting in iniquitous access to groundwater. The iniquity breeds competition among the users that may result into potential conflict. Understanding aquifer heterogeneity is important in designing the management of groundwater, especially in Deccan basalt aquifers.

Keywords: Basalt, heterogeneity, well-yield, socio-economic conditions, boundary conditions, iniquity

Introduction

The Deccan Volcanic Province (DVP) encompasses more than half a million km\(^2\) of India’s central-west regions. The DVP also occupies great thickness – ranging from a few tens of metres to several hundreds of metres - with a variety of basalt types forming a sequence of basalt ‘lava flows’ with clearly defined sub-units within each flow. Groundwater resources form an important source of water supply in the region underlain by basalt lavas. The DVP, outcropping in 6 states includes 50000 villages, 392 small towns and 32 variously sized cities (Shah and Kulkarni 2015) making it a region of immense socio-economic importance. Groundwater in the Deccan basalt aquifers forms a significant source of rural and urban water supply, constituting the mainstay for agriculture, the presence of many large dams in the region notwithstanding. Groundwater extraction from the basalt aquifers has been on an increase during the last four to five decades. Growing groundwater usage has meant an increase in competition among various users of this precious resource. Understanding the hydrogeological aspects of the Deccan basalt aquifers, particularly their heterogeneity, becomes important in developing strategic approaches to managing these aquifers and addressing challenges of groundwater competition and conflict in the region (Kulkarni and Vijay Shankar 2014).

Deccan basalts have been recognized as low-permeability rocks since many decades now (Adyalkar and Mani 1971; Dhokarikar 1984; Singhal 1997; Singhal and Gupta 1998). The first comprehensive assessment of the heterogeneity of these basalts was provided by Deolankar (1980) and subsequently described in some detail by Lawrence (1985), Kulkarni et al. (2000) and Duraiswami et al. (2012). The alternate sequence of the vesicular – amygdaloidal basalts (VAB) with their horizontal sheet fractures and the compact basalts (CB) with their vertical fractures come together in a sequence of basalt lavas and give rise to various aquifers through such fracture geometries.
The Deccan basalts show a great variation in hydrogeological factors controlling the accumulation and movement of groundwater, in turn leading to a range of aquifer properties (Deolankar 1980). While values of transmissivity vary over nearly four orders of magnitude across the Deccan basalt region (Deolankar 1980; Kulkarni et al. 2000), even a single aquifer such as the Pabal aquifer in Maharashtra, shows an extremely heterogeneous nature with limited storage (Deolankar and Kulkarni 1985; Macdonald et al. 1995). Such aquifers are commonly used to meet both irrigation needs and village drinking water supplies in the region. The many dimensions of water, such as location, timing, quality and variability – uncertainty imply that the assumption of water as a homogeneous commodity is false (Llamas and Martinez-Santos 2005).

The heterogeneity within a single aquifer as well as in a sequence of aquifers is relevant in understanding the competition and conflict over groundwater in a region. Understanding heterogeneity itself requires mapping the fracture density and fracture continuity in various locations in order to study the variation in aquifer properties, mainly in aquifer transmissivity. The phreatic surface for the unconfined aquifer can be distinguished from the potentiometric surface of the underlying confined aquifer even in bore holes that are located less than 100 m apart (Kulkarni et al 2005). Well-yields also vary significantly across such aquifers due to fracture discontinuity (Versey and Singh 1982). However, while working in the field with hundreds of farmers, it is often difficult to conduct controlled experiments and research with such bore holes.

Aquifer heterogeneity has great social relevance because it determines the relative shares of water available to different well-users. Community support and enforcement of regulatory measures are sensitive to the heterogeneity of groundwater users’ profiles (Foster et al 2007). A high degree of aquifer heterogeneity results in highly variable water availability to farmers in villages underlain by basalt aquifers. Some farmers own perennially high yielding wells while others are able to obtain only a limited quantity of water from their wells during a few months of the year. Understanding aquifer heterogeneity holds value in the practice of and the policy on groundwater management, especially in light of the need to ensure efficient and equitable supply of groundwater in India’s policy regime where aquifer mapping is expected to lead to improved groundwater management (Planning Commission, Government of India 2012).

This paper provides an insight as to how decrypting aquifer heterogeneity is not only important in improving the hydrogeological understanding of the Deccan Basalt, but also in the social paradigm of understanding competition around groundwater resources. In effect, such understanding becomes relevant in developing a national agenda on groundwater management and governance for the Deccan basalt region.

Methodology

There are two components to the methodology behind this paper. First, developing a conceptual model around aquifer heterogeneity based on pumping test data of large-diameter dug wells tapping a typical shallow unconfined Deccan basalt aquifer. Second, a simple exercise of simulation modeling using MODFLOW for understanding the social inequity arising from aquifer heterogeneity that leads to an unequal arena of competition. These two elements are described in detail in the following sections, along with the literature background to the conceptualization framework for these two steps.

While the purpose of this study and the results have wider implications, the conceptualization of the model is based on data from a shallow unconfined basalt aquifer from Pabal village in Shirur taluka of Pune district of Maharashtra state. Pabal village is 65 km northeast of Pune city. It is a largely rural setting spread over nearly 40 km² with a population of about 3500. The long-term annual average rainfall is 550 mm. Pabal village is also a typically drought-prone village that falls in the rain-shadow region of Western Maharashtra.

Conceptualizing heterogeneity in Deccan basalt aquifers

Comparable petrographic characteristics and similar hydrodynamic and redox conditions are helping organise complex groundwater occurrences in Europe into simplified patterns of aquifer typologies (Wendland et al. 2008). A groundwater typology can be defined by a region’s hydrogeological settings, aquifer scales and its socio-economic aspects (Kulkarni et al. 2015). Hence, the typology of groundwater decides the quantity and quality of water stored in an aquifer and the changes therein as a consequence of groundwater recharge and extraction. Natural factors such as climate (mainly rainfall, in a monsoonal setting such as India) and human fluxes (the great demand for groundwater in India) together determine the status of groundwater in the aquifer at any point in time. India’s great geological diversity has led to a variety of hydrogeological conditions not only across the country, but even within a single village or watershed. Six broad hydrogeological settings are captured in India’s groundwater typology (COMMAN 2005; Vijay Shankar et al. 2011). The volcanic systems constituting 16% of the total area of India and called the Deccan Volcanic Province (DVP) is one such hydrogeological setting. The DVP consists of multiple layers of solidified flood basalt that together are more than 2,000 m thick and cover an area of 500,000 km², representing a total volume of 512,000 km³ (Subbarao and
Aquifer heterogeneity and iniquity in groundwater access

The transition in patterns of usage and the degree of extraction from Deccan basalt aquifers is well-documented, with the major impact of over-extraction from such aquifers being a long-term fall in the water levels across the aquifer (Macdonald et al, 1995). Further, a typical unconfined Deccan basalt aquifer is usually quite local – of the order of a couple of square kilometres in its extent – and often with a recharge boundary corresponding either to the basin or watershed boundary or to the contact between two basalt types as described in Fig. 1. Hence, it can be said to be bounded typically by a constant head boundary on one or two sides and a no flow boundary (when groundwater pumping almost forecloses its natural discharge to streams) on two sides. These features may also lead to differentiation in the resultant pumped heads across the aquifer which, in turn, would lead to iniquity in groundwater access over different periods of time.

Variable well-behaviour represented by variable well-yields results in inequitable access to groundwater by different users (farmers in this case) even in the ever-evolving competition for improved access to groundwater. While we use the data from a single aquifer as a basis to investigate and illustrate the fact that aquifer heterogeneity is one of the primary causes of inequitable access to groundwater, the conceptual model developed here is based on a much wider spectrum of data from across the Deccan basaltic region of Maharashtra, India.

Sixty pumping tests on large-diameter dug wells were conducted in a basalt aquifer in Pabal village. These data constitute the main basis for the results in the following section. The results of these pumping tests were also compared with pumping test data and results from other regions of Maharashtra underlain by basalt rocks and similar aquifer conditions – mainly the type A groundwater system after Kulkarni et al. (2000). Pumping test data, especially on sample wells with full penetration of the aquifer and with similar pre-conditions to pumping, revealed varying responses in the drawdown at each of the wells. Figure 2 illustrates representative patterns of these variable responses through generalized drawdown hydrographs. On pumping each well under similar conditions – pumping rate, initial static water levels – the responses of pumped wells in the form of the
time-drawdown graphs were different. Broadly, the responses could be grouped into four categories (corresponding to the four portions of the aquifer depicted in Fig. 2).

Fig. 1 Conceptual depiction of a typical shallow unconfined basalt aquifer illustrating fracture geometry across the aquifer extent and thickness.
Table 1 Description of A, B, C and D sections of a typical unconfined basalt aquifer

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>VAB</strong></td>
<td>Sheet joints concentrated only in the upper section, with fewer sheet joints in the middle and lower sections</td>
<td>The entire section of the aquifer is fractured with sheet joints developed along the entire section of the VAB</td>
<td>Reduced frequency of sheet joints, but with hydraulic continuity with VAB in portions B and D</td>
<td>Sheet joints in the upper and lower parts of the VAB; the middle sections have fewer sheet joints</td>
</tr>
<tr>
<td><strong>Upper portion of CB</strong></td>
<td>Largely vertical joints, some of which extend upward into the VAB</td>
<td>Block fractures including close-spaced open vertical fractures some of which extend into the overlying VAB</td>
<td>Reduced frequency of sub-vertical fractures, a fewer of the fractures extending upward into the VAB</td>
<td>Largely sub-vertical fractures with a few extending upward into the VAB</td>
</tr>
<tr>
<td><strong>Groundwater storage</strong></td>
<td>Overall moderate storage, with dominant storage in the upper and lower portions of the aquifer; moderate to low storage in the middle portions</td>
<td>Storage throughout the thickness of the aquifer, with greater storage in the VAB than in the underlying CB</td>
<td>Low storage in the entire section</td>
<td>Moderate storage with greater storage in the lower portions of the aquifer at the contact of VAB and the underlying CB</td>
</tr>
<tr>
<td><strong>Groundwater transmission</strong></td>
<td>Good transmission when aquifer fully saturated but reduced transmission as water levels decline</td>
<td>Good transmission throughout the year</td>
<td>Limited transmission during the course of the year</td>
<td>Moderate transmission, which drops a little as water levels decline into the lower parts but still reasonably good in the lower portions of the aquifer</td>
</tr>
<tr>
<td><strong>Well-yield</strong></td>
<td>Reasonable well-yield that declines as water levels drop</td>
<td>High well-yield</td>
<td>Low well-yield</td>
<td>Moderate well-yield</td>
</tr>
</tbody>
</table>

![Fig. 2 Typology of time drawdown curves generalized from pumping tests on wells in a single basalt aquifer.](image)

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Indian National Chapter
1. Wells that showed rapid drawdowns were located in portions of the basalt aquifer with low transmissivity and storativity—corresponding to portion C of the aquifer in Fig. 1.

2. Wells that showed delayed but near steady responses in drawdowns, indicating moderate transmissivity portions of the basalt aquifer and possibly better storativity than in portions represented by (1) above—corresponding to portion D of the aquifer in Fig. 1.

3. Wells that showed steady, progressive drawdowns indicating aquifer dewatering under conditions of moderate to high transmissivity and relatively low storativity—corresponding to portion A in Fig. 1.

4. Wells that tapped the high transmissivity and storativity portions of the basalt aquifers in order to sustain limited drawdowns approaching near steady state in wells tapping such portions of the aquifer—corresponding to portion B of the aquifer in Fig. 1.

Heterogeneity can be simply described as different properties at different locations within an aquifer (Dillon et al. 2009). The heterogeneity of a single basalt aquifer is represented by variable ‘T’ values derived from pumping test data yielding time-drawdown plots such as the set depicted in Fig. 2. These graphs have been generalized from time-drawdown graphs of pumping tests conducted on the basis of pumping test analyses of data from the 60 large-diameter dug wells tapping the Pabal aquifer. What was also common in these cases was the variety of time-drawdown curves for dug wells tapping the same aquifer. Incidentally, the values of ‘S’ are also quite variable in the different portions of the aquifer. These values—presented in Table 2 in generalized ‘order of magnitude form’—are often representative of wells in different basalt aquifers. Hence, these values not only represent differential well-performance and variable well-yields but also represent parts of the aquifer that show varied response to recharge and discharge characteristics. While, the values presented in the table are derived only from the single basalt aquifer in Pabal village (located in Shirur taluka from Pune district of Maharashtra), they are also representative of those from single unconfined aquifers in similar hydrogeological settings in other parts of the Deccan Volcanic Province (Kulkarni et al. 2000; Badrayani et al. 2009).

**Table 2** Summarized typology of aquifer storage and transmission with corresponding well-behavior

<table>
<thead>
<tr>
<th>Graph type (representing wells)</th>
<th>Transmissivity (m²/day)</th>
<th>Storativity (fraction)</th>
<th>Response to pumping</th>
<th>Response to rainfall-recharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$10^0$</td>
<td>$10^{-3}$</td>
<td>Rapid drawdown and seasonal yield</td>
<td>Fills up rapidly in response to recharge</td>
</tr>
<tr>
<td>2</td>
<td>$10^0$ to $10^1$</td>
<td>$10^{-1}$</td>
<td>Slow drawdown, moderate yield and perennial</td>
<td>Gradual filling up on recharge</td>
</tr>
<tr>
<td>3</td>
<td>$10^1$ to $10^2$</td>
<td>$10^{-2}$</td>
<td>Moderate rate of drawdown but high yield but seasonal</td>
<td>Fills up rapidly in response to recharge</td>
</tr>
<tr>
<td>4</td>
<td>$10^2$ to $10^3$</td>
<td>$10^{-1}$</td>
<td>Slow drawdown, high perennial yield</td>
<td>Fills up moderately quickly in response to recharge</td>
</tr>
</tbody>
</table>

The distribution of heads in a typical Deccan basalt aquifer, especially during and at the end of the groundwater irrigation season (usually between October and February when monsoonal recharge is negligible) results in differentiated well-yields. In the case of Pabal aquifer, for instance, a farmer with well-type 1 can only grow a post-monsoon subsistence crop on his seasonal well. On the other hand, a farmer with well-type 4 has the capacity to cultivate perennial crops, say even a crop like sugarcane that fetches him a higher return (Deolankar and Kulkarni 1985). Subsequently, it was also observed that farmers owning well-type 2 often limit their irrigation through crop choice and cropping area and can naturally reserve water for sale during the peak summer, especially to farmers who own well-types 1 and 3 during the summer. Well-type 2 owners also sell water through tankers to meet the summer drinking water demand of their neighbourhoods. While this narration seems straightforward as presented here, it can get quite complicated, often increasing the degree of iniquity that develops across wells and farmers, particularly during the summer months.

Deccan basalt aquifers are being pumped extensively for meeting domestic, irrigation and urban needs in Western and Central India. Most access to the aquifers is through private wells, commonly through individual investments. At the scale of a single basalt aquifer, which is often coterminous with its watershed boundaries, layered basalt aquifers present an arena of competition over smaller groundwater storages; further, being
heterogeneous in character, their ‘T’ and ‘S’ vary laterally and vertically (Kulkarni and Vijay Shankar 2014). The variation in ‘T’ is especially relevant in understanding the iniquity in access leading to intensification of the competition to sink more wells and deepen existing ones across different aquifers in the region. The next section presents a simple model to help understand how the heterogeneity, combined with basic boundary conditions, leads to varying situations in wells that tap a basalt aquifer being pumped for irrigation. The case is presented through a simple model that attempts to understand such heterogeneity in the context of well-drawdowns and consequently in the equity of access to groundwater.

**Modeling heterogeneity in the context of well-yields**

The complex hydrogeological setting within layers of weathered and fractured basalt lavas and even within a single unit of a sequence of basalt units gives rise to high variability in the storage and transmission of groundwater as described in the previous section. While many other factors like the locations and pumping rates of other wells within this highly variable aquifer setting also influence how productively and sustainably a well will yield water, the focus here is on the hydrogeological factors that are beyond human control. Among these are the aquifer’s inherent hydrogeological properties - hydraulic conductivity and storativity - and the head and flow conditions at the boundaries of the aquifer. For the purpose of this article, we employ simulation modeling using the MODFLOW groundwater flow model to make a basic conceptual assessment of the influence of hydraulic conductivity and three particular forms of boundary conditions on the degree and nature of iniquity that unfolds at the end of a typical irrigation season.

A tighter definition of the local aquifer hydraulic properties is required in groundwater modelling to verify the well-field design and operational strategies in projects like Aquifer Storage Transfer and Recovery (ASTR) (Pavelic et al. 2005). A set of scenarios is considered in the model presented here, conceptually representing simplified forms of a typical single aquifer system found in the case of unconfined Deccan basalt aquifers. The dimensions of all these models are fixed at 1.5 km x 1.5 km x 10 m. The modeled aquifer system consists of a single unconfined aquifer, about 10 m thick and is quite common across the DVP (Pakhmode et al. 2003; Kulkarni et al. 2005).

In order to keep the model scenarios simple, the (initial) spatial patterns of transmissivity used in the models have been obtained simply through respective patterns of hydraulic conductivity, while assuming the aquifer thickness constant over the lateral extent. This section of the paper and the ensuing model are thus presented in terms of hydraulic conductivity patterns that represent the distribution of transmissivity across the aquifer. Since we aim to investigate the influence of inherent natural factors affecting iniquity in well-productivities, this simplification also sharpens the hypothesis surrounding heterogeneity and iniquity in access.

With the focus on the influence of heterogeneity, we assume the storativity (specific-yield, in this case) to be constant throughout the aquifer with a constant value of a realistic 3.5%, based on various estimates from different parts of the Deccan Volcanic Province (Deolankar 1980; Macdonald et al. 1995; Kulkarni et al. 2000; Saha and Agrawal 2006).

While several combinations of head and flow boundary conditions are possible, three common conditions observed in Deccan basalt aquifers are considered here:

1. no-flow condition
2. constant head condition
3. a hybrid condition (of the above two)

The model first explores the influence of the three boundary conditions under a homogeneous case - constant hydraulic conductivity across the aquifer - before exploring the effects under the three boundary conditions under the heterogeneous case. Hence, there are six cases for investigation in the model. Further, to assess iniquity the model has to incorporate wells along with their location patterns. To this end, a uniformly-spaced grid of wells is considered. While wells are not uniformly spaced in the real world, we make this assumption to develop a first-cut representation to deal with heterogeneity as the primary control on iniquitous access. Further, the same pumping rate of 20 m³/day is assigned to all wells in the model for all the six cases, a value based on a near-uniform rate of pumping for all the wells observed in the real-world situation too. The irrigation season in the region, when such dug wells are pumped almost continuously, lasts between 90 and 150 days between the months of October and the following March, depending upon factors such as crop type, crop variety, electric supply and markets. In most regions underlain by the Deccan basalt aquifers, there is little or negligible precipitation during this season. Hence, model-regimes for simulation are considered 120 days long with no precipitation to simulate the period of peak groundwater extraction.
Modeling details

MODFLOW-2005 (Harbaugh 2005; Harbaugh et al. 2017), was used to simulate the illustrative models. The illustrative outputs presented in the following sections are based on a model with a grid of 75 x 75 x 1 cells, each cell having a dimension of 20m x 20m x 10m. For homogeneous cases, hydraulic conductivity is taken to be 10 m/day for all cells. For the heterogeneous case, hydraulic conductivities of cells are obtained by applying kriging to sample hydraulic conductivities (based on data generated from pumping tests in the field – mainly from Kulkarni et al. (2000)) at cells (15, 15): 20 m/day, (15, 45): 8 m/day, (45, 15): 4 m/day, and (45, 45): 2 m/day. The resulting heterogeneous hydraulic conductivity surface is shown in Fig. 3. Forty-nine wells, in a uniform grid of 7 x 7 are located, one in every cell whose <row, column> indices are obtained using the numbers 8, 18, 28, 38, 48, 58, and 68. The initial head condition is a flat water-table 2 m below ground level (bgl) (i.e., a starting head value of 8m). In the constant-head models, the head on the boundary is held constant at 8 m.

The primary object of investigation in this article is to understand iniquity in groundwater access through a simple model. While strict mathematical or statistical analysis is not the intent of this article, a measure of the model output is helpful in judging the fundamental level of natural iniquity in the access to groundwater to the multitude of users. Therefore, we define a simple measure, denoted SD, to represent unequal groundwater availability, as the standard deviation of well-heads at the end of the 120 days pumping period. That this measure is utility-oriented - considered important in this article from a practical standpoint – is derived from the fact that heads only from those cells which contain wells are used in calculating the measure rather than heads from all the model cells.

Results

Modeling results

In the no-flow boundary condition with homogeneous hydraulic conductivity, all the wells (pumping at the same rate) induce drawdowns of roughly the same magnitude. Hence, the heads at the end of 120 days of pumping show a uniform geometry. The shallow, bowl-like shape indicates the significance of finiteness of hydraulic conductivity which results into a transient condition of non-uniform water-table (Fig. 4a). On the other hand, under conditions of heterogeneity, i.e. variable hydraulic conductivity, the iniquity becomes clearly visible, with the heads in regions having low hydraulic conductivity being contrastingly low compared to those in other regions at the end of the 120 days of pumping (Fig. 4b).
The influence of, what may be referred to as an ‘active’ boundary condition is clearly visible in models with a constant-head boundary. As the head along the lateral aquifer boundaries is ‘actively’ maintained at a fixed level, the wells closer to the boundary do not experience as significant a drawdown as experienced by those toward the centre of the grid (Fig. 5a). In a heterogeneous aquifer, such a boundary condition already provides conditions for iniquity, while the variable hydraulic conductivity further enhances drawdown variations across different locations, thereby resulting in a higher variance of the heads at the end of 120 days of pumping (Fig. 5b). The drawdowns are clearly more enhanced in wells located in portions of the aquifer with low hydraulic conductivity despite the same boundary condition in both the cases.

In the case of a hybrid boundary condition – combination of no-flow and constant-head boundaries – the value of SD is similar to the purely constant-head (hence ‘active’) boundary condition case where SD is quite high compared to the no-flow case. This points to the ‘active’ boundary condition as a significant factor in variability across the wells tapping the aquifer; this presence being the only qualitative similarity between the constant-head and hybrid case and the only qualitative difference between these cases and the no-flow case. However, even here, the degree of variation is clearly greater in the heterogeneous condition (Fig. 6b) than in the homogeneous condition (Fig. 6a).

The values of SD in these six models of an unconfined basalt aquifer having different conductivity patterns and boundary conditions are presented in Table 3. While, the table values bring out the expected relative variability in heads across the well-locations, it is clearer when the box-plots of the final well-heads in the six models are compared (Fig. 7). The influence of boundary conditions and the hydraulic conductivity pattern is clearly revealed through the plots. Under all three boundary conditions, the model yields higher variability in well-heads at the end of 120 days under the condition of aquifer heterogeneity (than in the homogeneous case) leading to different wells having differential access to groundwater for the remaining period (summer) during the year.
Fig. 6 Surface of the water table in the unconfined basalt aquifer representing drawdowns at the end of the 120 days pumping period under hybrid conditions (combination of no-flow and constant head boundaries) with (a) homogeneous conditions and (b) heterogeneous conditions.

Table 3 Standard deviation values of heads at the end of 120 days of pumping under six different conditions modeled using various combinations of boundary conditions and heterogeneity

<table>
<thead>
<tr>
<th></th>
<th>Homogeneous (constant K)</th>
<th>Heterogeneous (variable K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No-flow</td>
<td>0.03</td>
<td>0.64</td>
</tr>
<tr>
<td>Constant-head</td>
<td>0.24</td>
<td>0.96</td>
</tr>
<tr>
<td>Hybrid</td>
<td>0.30</td>
<td>0.91</td>
</tr>
</tbody>
</table>

Fig. 7 Box-plots of well-heads in the six models at the end of 120 days of pumping (whiskers at 5 and 95 percentile).

We make an important note about the essential aspect of iniquity that we have examined here. It is apparent from the water table plots, that the cones of depression are almost always sharp and are essentially a transient feature of the water table. Thus, they may seem not to warrant attention when assessing iniquity over the seasonal time-scale, let alone devising a measure of iniquity like SD based on their head values. Given sufficient
days of zero pumping after the 120 days of consistent pumping, even such abrupt water table can recover to an equitable (reasonably flat) state. However, this time of zero pumping is something what no user in a competitive atmosphere would like to rely on. It is in this spirit that the measure SD is meaningful to the users, for it captures the ‘real-time’ iniquity experienced during competitive continued pumping; real-time individualistic considerations currently being the dominating ones for the users in the DVP even when using a common pool resource.

Discussion

Model results

1. **Baseline model**: The case having uniform hydraulic conductivity and no-flow boundary stands out as the baseline model to compare other models with. Model results show some variance in heads even under such conditions, owing to the finiteness of hydraulic conductivity. If not for this finiteness, it would have been a water-tank model exhibiting zero variance, hence no iniquity (the ideal situation for human use) and hence the term ‘baseline’.

2. **Influence of hydraulic conductivity pattern**: Standard deviation is considerably higher in cases with heterogeneity irrespective of the boundary condition. This underlines the importance of hydraulic conductivity in the resulting heads, hence in groundwater availability, in different parts of the aquifer. Modeling and analysis based on hydraulic conductivity patterns in specific real-world situations can provide insights for evolving such form of groundwater management that can address iniquity. It is important to note that the hydraulic conductivity sample values used here have been moderated for the purpose of illustrative simulation, lest the simulation would fail to easily converge. In the real-world case of basalt aquifers, there are locations within the aquifer that have hydraulic conductivity values as low as 0.1 m/day and others as high as 200 m/day (Macdonald, et al, 1995; Kulkarni et al, 2000). The iniquity implications are that with continued pumping, wells actually dry out in some pockets and yield sustainably in others even in the same aquifer and given the fact that an aquifer is a common pool resource.

3. **Influence of differing boundary conditions**:
   - Models with differing boundary conditions show considerable differences in the magnitude of iniquity. However, it may also be hypothesized that for aquifer systems with larger dimensions, so that most of the utility wells are located in the (lateral) interior of the aquifer extent, the overall iniquity experienced by the users may not be so strongly influenced by differences in boundary conditions. Nevertheless, exploring the influence of such conditions would be important - certainly for aquifers with smaller extents and/or having more boundary exposure relative to the area they encompass, a case which is not so uncommon in Deccan basalt aquifers.

   - It is the ‘active’ nature of boundary conditions that primarily causes different response in wells near the boundary compared to those further away from it. The assessment of the precise nature of this influence in various cases of boundary conditions, also including cases not considered here, like constant flow, controlled varying head, etc., is worth investigating vis-à-vis its impact on groundwater availability.

4. The current model considers a uniform grid of pumping wells. However, in reality, pumping wells would be non-uniformly located and may induce a further enhancement of the variability, which, in combination with heterogeneity, could lead to greater iniquity in access to groundwater by different well-users.

Implications of heterogeneity: complex competition and growing distress

Pumped heavily for irrigation in different pockets and increasingly being used for supplementing urban water supply as well as industrial requirements, Deccan basalt aquifers have witnessed a competition over limited but layered stocks of groundwater, often within the same type of users, mainly farmers. In such aquifers, digging wells and drilling vertical and horizontal bore holes are mechanisms that define competition in accessing a limited resource with uncertain well-yields. Sourcing water is viewed in India as a fundamental right of a landowner to dig or drill a well in his plot of land. Seldom is there any acknowledgement of the fact that water in her or his well may well have moved through the aquifer underneath the lands of not only several neighbouring farmers but also may have travelled from underneath lands covered by forests and by the village itself.
The competition is further compounded by nuanced impacts of aquifer heterogeneity creating differentiated access, yields and outcomes even within a single village (Kulkarni and Patil, 2017). Table 4 presents a comparison between the four types of wells tapping a heterogeneous basalt aquifer with respect to the nature of groundwater competition. Two of the possible three boundary conditions are used in the table. Incidentally, the boundary conditions could also be replaced by variations in aquifer storativity about which a broad description is already available in Kulkarni and Vijay Shankar (2013). What emerged as a consequence of this work is the similarity between varying boundary conditions and aquifer storativity, clearly highlighting the importance of understanding the variation in hydraulic conductivity as the primary criterion that governs the consequent inequity and variable competition.

In shallow unconfined basalt aquifers, the contrary dimensions of right to individual access through wells and the aquifer as a common pool resource are amplified due to the heterogeneity of the aquifer itself. More than 80% of the state of Maharashtra in Western India is underlain by the Deccan basalts. The number of wells in the state increased from half a million in 1960 to 2.5 million in 2010; while well-yields peaked at 125 m³/day/irrigation well, they dropped to less than 80 m³/day/irrigation well in 2010 (Macdonald et al. 1995; CGWB 2011; GSDA and CGWB 2014). What lies beneath the decreased well-yield story, however, is the intense competition that is as much a result of increased well-numbers as it is of the inherent heterogeneity of a basalt aquifer, a few important dimensions of which have been presented in the current work.

### Table 4 Variable arena of competition as a consequence of aquifer inhomogeneity

<table>
<thead>
<tr>
<th>Low to Moderate T (representing low hydraulic conductivity)</th>
<th>No flow boundary</th>
<th>Constant head boundary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well-type 1 Groundwater levels drop quickly in response to pumping and well-recuperation is slow. The condition is self-limiting in competition as growing well numbers or well-deepening do not significantly affect neighbouring wells. All wells in this category are seasonal wells and zones where such wells are located belong to farmers who can grow rain fed crops and must either drill deep to tap deeper aquifers or import water, depending upon their economic and social status.</td>
<td>Well-type 3 Rates of recuperation are slow but steady, implying sustained well-yields, often extending into the summer season. Farmers with such wells have access to high value water. Most users expand the size of their wells by creating large storage capacities for each dug well. Some farmers also resort to horizontal drilling along permeable zone to attempt imparting ‘induced permeabilities’ to enhance the flow of water into wells. However, the limited hydraulic conductivity imposes a virtual boundary to enhancing well-yield through competitive means.</td>
<td></td>
</tr>
<tr>
<td>High T (representing high hydraulic conductivity)</td>
<td>Well-type 2 These wells are better than wells in type 1. High yielding, but seasonal, these wells witness a very competitive arena wherein, larger pump-sets are used to compete with neighbouring farmers. Skimming off the limited water as quickly as possible defines the domain of high impact competition. Competition is defined by the capacity of a farmer to invest in high-powered pumps as the permeable portion of the aquifer brings water quickly to wells. Seasonally high yields also enable larger-land holders to apply available water during 6-8 months of the year for maximizing returns while small and marginal landholders are often unable to do so. Seasonal well-yields also mean that the small land holders cannot doubly crop their land subsequently for a second or third crop, leading to serious inequity even within this group of farmers.</td>
<td>Well-type 4 Rapid rates of groundwater flow through sustained availability imply complex and highly competitive arena with multiple levels of competition within the group. Growing well numbers, well-deepening, horizontal drilling and large pump capacities all come into play, also imposing some impact on the neighbouring wells belonging to the other three classes, especially to the farmers with well-type 3. Given that these are the most better-off farmers (even small land-holders may sell water to their neighbours at premium rates), competition may sometimes lead to fully blown conflict. Most significantly, wells in this category turn out to be the main culprits in aquifer-level groundwater exploitation that affects all four categories in the longer run. In such a scenario, competition itself is further restricted to farmers in well-type 4, limiting access to farmers is well-types 1 and 2 severely.</td>
</tr>
</tbody>
</table>
Conclusions

A single basalt aquifer is quite heterogeneous in nature. Not only do the large diameter wells in a single aquifer respond differently to similar pumping, but they also yield variable ‘T’ and ‘S’ values across the aquifer from pumping test data. This variability – significantly represented by aquifer heterogeneity – is quite important in understanding whether the well will be low or high yielding and also whether yields will be seasonal or perennial. Moreover, such heterogeneity, resulting out of variable hydraulic conductivity, also results in iniquity of water availability, to farmers who own each well. As well numbers grow, more farmers gain access to groundwater. However, access is variable and pumping during the irrigation season results in different drawdowns (and water availability) at the end of the season.

Modeling the heads in a typical unconfined basalt aquifer at the end of the irrigation season reveals the effects of boundary conditions and heterogeneity on access to water from wells located in different parts of the aquifer. Boundary conditions, especially a hybrid of constant head and no-flow conditions, influence the variability in heads in the aquifer at the end of the irrigation season even when the aquifer is considered to be homogeneous. Hence, pre-summer variability in water-levels is greatly increased by heterogeneity, even when a simplistic model of access is applied, where wells are uniformly placed in the aquifer. This results in some farmers experiencing depleted water availability in their wells while others still have water that can be pumped. The situation represents a potential arena for competitive access, a competition that is further enhanced when responses to the situation by four types of well-owners are considered.

Heterogeneity within a basalt aquifer is important not merely in understanding the variation in the yields of wells across the aquifer due to varying ‘T’ and ‘S’ values. Such heterogeneity, in fact, results in highly variable water availability to farmers in villages underlain by such aquifers as some farmers may own and use perennially high yielding wells while others may be able to obtain only a limited quantity of water from their wells and that too during a few months of the year. A few farmers may obtain some water over the whole year while many others may obtain good well-yields only over a few months. As land gets divided further and farmers sink more wells to dedicate a source to each farm, the heterogeneity of the aquifer further intensifies the competition around groundwater, making it a case of 'more wells but more iniquity' (Kulkarni and Vijay Shankar, 2015). This is because each well now taps a decreased share of the aquifer storage - due to the limited storage in a basalt aquifer – but the iniquity remains or grows as the share becomes more unequal than before.

While further work is required to simulate complex real-world conditions from different basalt aquifers, this paper is an initial attempt to link aquifer boundary conditions, heterogeneity and access to water as the primary factors leading to iniquity and competition in user access to groundwater in the shallow unconfined basalt aquifers of West-central India, especially in the context of a growing clamor for mapping and managing perhaps the most exploited aquifers in any country in the world.

Acknowledgements

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References


A Comparative Study of Electrical Resistivity Tomography versus Vertical Electrical Sounding

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Abstract

Geophysical electrical methods are most suitable among all geophysical methods for groundwater exploration because of good contrast between the electrical resistivity of water saturated geological formations/structures and their counter parts devoid of water. Geophysical Electrical surveys are conducted by many methods based on several types of electrode configuration. Among all the electrical resistivity methods, Vertical electrical soundings (VES) using four electrodes and relatively new Electrical resistivity tomography (ERT) using multiple electrodes are mostly used for delineation of groundwater resources which is essential for sustainable development of groundwater to achieve the preset objectives of management. ERT has advantage of providing 2D images of sub-surface geological formation/structures which have been used for identification of groundwater resources suitable for exploration as well as sites suitable for managing aquifer recharge below the entire stretch of survey line. On the other hand VES provides 1D resistivity model of litho units falling below the centre of the survey profile only. Even though, VES is being extensively used for groundwater exploration in India. The objective of this paper is to demonstrate the advantages of ERT over VES in delineation of accurate locations of water bearing zones and selection of sites suitable for managing aquifer recharge by revisiting case studies from hard rock terrains.


Introduction

Economy of rural India which hosts more than 70% of total population is mainly based on agriculture produce. Almost two third of the surface area of India is occupied by different types of hard rocks. Volcanic Basalts of Deccan traps alone occupy more than half a million square kilometer areas in central and western part of India. Most of the regions south of Deccan traps province (DVP) are mainly covered by granites and granitic gneisses. Occurrence and movement of groundwater in hard rock terrains is controlled by secondary porosity developed in form of weathered formations, faults, fractures, joints and shear zones. Delineation of exact locations of these water bearing geological formations/structures in hard rock terrains is a challenging task because of their finite areal extent and sporadic nature of distribution. Because of this, acute shortage of water supply in hard rock terrain is well known. Vertical Electrical Sounding (VES) survey with four electrodes configuration have been used since more than five decades for delineation of groundwater potential zones and is still practiced widely (Bose and Ramkrishna 1978 ; Rao et al. 1983; Muralidharan et al. 1994; Jha et al. 2008; Israil et al. 2006; Rai et al. 2011, 2012, 2013; Coker et al. 2012; Abdullah et al. 2015; Meindinyo et al. 2017; Choudhary et al. 2017). The greatest limitation of the VES technique with four electrodes configuration is that it provides only 1D model of the resistivity variation below the center of the profile and does not take into account lateral variations in the resistivity value on either sides of the center which could be due to the presence of water bearing geological formations/structures in hard rock terrains is a challenging task because of their finite areal extent and sporadic nature of distribution. Because of this, acute shortage of water supply in hard rock terrain is well known. Vertical Electrical Sounding (VES) survey with four electrodes configuration have been used since more than five decades for delineation of groundwater potential zones and is still practiced widely (Bose and Ramkrishna 1978 ; Rao et al. 1983; Muralidharan et al. 1994; Jha et al. 2008; Israil et al. 2006; Rai et al. 2011, 2012, 2013; Coker et al. 2012; Abdullah et al. 2015; Meindinyo et al. 2017; Choudhary et al. 2017). The greatest limitation of the VES technique with four electrodes configuration is that it provides only 1D model of the resistivity variation below the center of the profile and does not take into account lateral variations in the resistivity value on either sides of the center which could be due to the presence of water bearing geological formations/structures such as weathered zone, faults, fractures, joints, etc. Therefore, delineation of water bearing formations by 1D model is not always possible unless these formations/structures coincidently lie below the center of the profile. This may be useful in delineation of groundwater potential zones in sedimentary formations where water bearing formations run laterally from several tens of meters to several hundreds of meters in continuation such as in Indo-Gangetic plains. Therefore, a more appropriate model would be a 2D
model which provides information about the resistivity variations in the vertical as well as lateral direction below the entire spread of the survey profile. This problem overcame by the development of 2D electrical resistivity tomography (ERT) technique using multi electrode system of sub-surface imaging and effective data processing software based on the inversion techniques (Griffith et al. 1990; Griffiths and Barker 1993; Loke and Barker 1996; Loke 1997, 2000). Electrical geophysical methods including VES and ERT have been described in Rai (2017). Managing aquifer recharge is another important aspect of sustainable development of groundwater resources to achieve the preset objectives of it’s management (Rai and Singh 2005). Recharge structures in hard rock terrains should be located either in thick weathered formation or should be connected to underlying deeper aquifers through faults/fractures. Identification of such suitable sites for construction of recharging structures such as injection wells, large diameter dug well, ponds etc is only possible from the 2D resistivity model. The main advantages of the ERT are: (i) automated acquisition of large amount of data in less time and cost, (2) automatic modeling of the resistivity data without involvement of human error, and (3) imaging of the subsurface geological formations/structures in both horizontal and vertical directions along the entire spread of survey line. The ERT technique is being successfully used worldwide for delineation of groundwater potential zones as well as addressing other hydrogeological problems such as selection of suitable sites for waste disposal, identification of geothermal reservoirs, dewatering of mining area, etc. in complex hydrogeological environs. For examples, it was conducted over meta-sedimentary strata and meta-volcanic in the Harare greenstone belt in northeastern Zimbabwe (Owen et al. 2005), in Banting, Selangor in Malaysia (Hamezah et al. 2006), in Pagoh and Johor, Malaysia (Kadri and Nawawi, 2010) and in parts of Kubanni River Basin, Zaria, Nigeria (Anthony and John 2010) to decipher groundwater potential zones. Ratnakumari et al. (2012) and Thiagarajan et al. (2018) have carried out ERT in Chandrabhaga basin of drought prone Vidarba region for the delineation of groundwater resources. Rai et al. (2015) have carried out ERT survey in the Tawarja basin located in drought prone Marathiwa region of Maharashtra to delineate groundwater potential zones. Gupta et al. (2016) have conducted ERT survey to delineate groundwater potential zones in Mangaon of Raigad district falling under DVP. Singh et al. (2019) have conducted ERT for delineation of fracture zones for groundwater in premises of CSIR- CIMFR at Dhanbad. The ERT has been carried out the granitic terrain in and around Hyderabad city for the delineation of groundwater resources (Rai et al. 2013b, 2019a; Kumar et al. 2016). Several bore wells have been drilled at identified locations in Chandrabhaga basin and in granitic terrain of Hyderabad city, namely in the premises of CSIR-NGRI, CSIR-ICT and CSIR-CCMB. These bore wells are in use to meet the water supply demand. ERT survey has been conducted to delineate ground water zones for other purposes such as for exploitation of geothermal energy (Kumar et al. 2011), to prevent land slide in opencast mines (Rai et al. 2019b), to prevent mine collapse in underground mine (Krusnamurthy et al. 2009) and to study contamination of groundwater (Abdullah et al. 2011). A brief description about VES with four electrodes and multi-electrodes ERT is presented in the next section.

Vertical Electrical Soundings (VES)

In Vertical Electrical Soundings (VES), Schlumberger configuration of four electrodes is used. Field layout of the Schlumberger configuration is shown in Figure 1. DC current, I, is sent into ground from the outer two electrodes C1 and C2. The outer electrodes are called the current electrodes. The corresponding potential difference, ΔV is measured between the two inner electrodes P1 and P2 which are called potential electrodes. In this method the centre point of the profile remains at a fixed position O, but the spacing between the electrodes is increased after each measurement of apparent resistivity as per requirements (Rai 2017). Apparent resistivity, ρa for Schlumberger array is computed by using the following expression:

![Fig. 1 Field layout of Schlumberger configuration of four electrodes for VES.](image-url)
\[ \rho_a = k \frac{\Delta V}{l} \]  

(1)

in which the geometric factor, \( k \) is given as \( k = \frac{\pi}{2} \frac{L^2 - l^2}{l} \).

Here, \( L \) is the half distance between the outer current electrodes and \( l \) is the half distance between the potential electrodes. The measured apparent resistivity value is used for the inverse modeling to get resistivity variation of each subsurface formation with their corresponding depth below the centre of the configuration. Several computer programs are developed for computation of 1D resistivity. This resistivity model is interpreted in form of geological formations by assigning resistivity values to the respective geological formations which in term is used for identification of groundwater potential zones.

Fig. 2 Field layout of ERT units with four multi core cables.

**Electrical Resistivity Tomography (ERT)**

Electrical Resistivity Tomography (also called imaging) is carried out by using multi-electrodes resistivity imaging system. In this system many electrodes are connected with multi-core cables to form a multi-electrode setup where selection of any four (two for current injection and two for potential measurements) of those electrodes is possible. Figure 2 shows field setup of an ERT survey with four multi-core cables. In this example 16 electrodes are placed at equal spacing in each multi-core cable. Multi-core cables are connected to an electronic switching unit. The switching unit is connected to a resistivity meter and the resistivity meter is connected to a laptop. Computer based software together with the electronic switching unit is used to select automatically four relevant electrodes (two current electrodes and two potential electrodes) for each measurement. Provision is made for resistivity survey using different electrode configurations such as Wenner, Schlumberger, Dipole-Dipole, Pole-dipole, Pole-Pole, etc. (Lok 2000). In the present study, Wenner configuration is used for the measurement of apparent resistivity. Spacing between two consecutive electrodes remains the same in Wenner configuration. For this configuration, the geometric factor of Equation (1) is given by \( k = 2a \pi \) in which ‘\( a \)’ is the spacing between the two electrodes. These measured apparent resistivity values are used for inverse modeling to create 2D model of resistivity variation with depth below the entire spread of the survey profile.
To demonstrate the sequence of measurements to build up a pseudo section, a cable fitted with 16 electrodes as shown in Figure 3 is considered. In this example, the spacing between adjacent electrodes is considered as ‘\(a\)’ for the first sequence of measurements. The first step is to make all the possible measurements with an electrode spacing ‘\(a\)’. For the first measurement, electrodes 1, 2, 3 and 4 are used. Electrode 1 is used as the first current electrode \(C_1\), electrode 2 as the first potential electrode \(P_1\), electrode 3 as the second potential electrode \(P_2\) and electrode 4 as the second current electrode \(C_2\). For the second measurement, electrodes 2, 3, 4 and 5 are used for \(C_1\), \(P_1\), \(P_2\) and \(C_2\) respectively. This procedure is repeated until electrodes 13, 14, 15 and 16 are used for the last measurement with spacing of ‘\(a\)’. The total number of first sequence of measurements for spacing ‘\(a\)’ will be 13. The apparent resistivity, \(\rho_a\), for spacing ‘\(a\)’ is computed using the formula of resistivity for Wenner configuration, i.e. \(\rho_a = 2\pi a(\Delta V/I)\) in which \(I\) is the induced current and \(\Delta V\) the potential difference between potential electrodes. After completing the first sequence of measurements with spacing ‘\(a\)’, the second sequence of measurements with spacing ‘\(2a\)’ is made. For measurement of second step electrodes 1, 3, 5 and 7 are used for the first measurement. The electrodes are chosen so that the spacing between adjacent electrodes is ‘\(2a\)’. For the second measurement, electrodes 2, 4, 6 and 8 are used. This process is repeated until electrodes 10, 12, 14 and 16 are used for the last measurement with spacing ‘\(2a\)’. The same process is repeated for measurements with spacing 3\(a\), 4\(a\) and 5\(a\). For spacing 5\(a\) there is only one measurement. Thus, the total number of measurement is 35 for one time laying of a multi-core cable containing 16 electrodes instead of only one measurement by a conventional survey with four electrodes. On left side \(n = 1\) to 5 indicates the levels of subsurface imaging corresponding to electrode spacings from \(a\) to 5\(a\), respectively. The next step is to convert the measured apparent resistivity values to a 2D model with their resistivity values and thicknesses. This task is accomplished by inverse modeling using a computer program RES2DINV (Loke 1997). This program automatically creates a 2D model by dividing the subsurface into a rectangular box. To initiate inverse modeling, some values of resistivity will be assigned to the model blocks. Thereafter, the program calculates the apparent resistivity values of the model blocks and compares them to measured apparent resistivity values. The resistivity values of the model blocks are adjusted iteratively until the calculated apparent resistivity values of the model are in close agreement with the measured apparent resistivity values. The final output is a 2D model of resistivity variations representing different litho units. Finally, the resistivity values are interpreted in terms of geological formations on the basis of their known values of resistivity.

![Fig. 3 Scheme of measurement of apparent resistivity using ERT survey.](image-url)
Study Area

Chandrabhaga basin which is part of eastern fringe of Deccan traps is considered for the present case study because both VES and ERT surveys have been conducted at 45 and 56 sites, respectively for aquifer mapping (Rai et al. 2011, 2012, 2013a; Ratnakumari et al. 2012; Thiagarajan et al. 2018). This basin is falling under Nagpur District of drought prone Vidarbha region of Maharashtra state, India. It occupies about 500 km² areas between 78° 42′ to 79° longitudes and 21° 11′ to 21° 20′ north latitudes and encompassing 50 villages. The basin covers part of Katol taluk, Kalmeshwar taluk and part of rural Nagpur. It is bounded by Satpura ranges from west and hilly Bazargaon forest from south. Geographical map of the basin along with the sites of VES and ERT surveys is shown in Figure 4. The VES sites are shown by the blue circle while ERT sites are shown by red square along with their respective numbers assigned for the identification purpose. Unlike other hard rock terrains, Deccan traps are compilation of several layers of lava flows alternately separated by sedimentary formations. These sedimentary formations are geologically known as intertrappeans and are markers of the interval time of eruption of lava flows. Each lava flows consists of two units. The top unit is vesicular basalt which is followed by massive basalt unit at the bottom (Ghosh, et al, 2006; Limaye, 2010). Vesicular basalt unit together with overlying intertrappean forms good aquifers at middle and deeper levels. Top weathered mantle together with highly fractured basaltic layer forms unconfined aquifers at shallower depths and is the main source of water supply in dug wells. In the basin, the basaltic layers of Deccan traps are underlain by a layer of sedimentary formation which is known as infratrappean. This layer represents paleo ground surface which was covered by lava flows of a major volcanic eruption that took place 65 million years ago. In geological terms this period is known as K-T boundary. The infratrappeans are underlain by Gondwana formations of Godavari graben. Thickness of Deccan traps within the basin area is found to vary between 45 m to 80 m which is confirmed by drilling borewells at some places selected on the basis of VES and ERT surveys. The stratigraphy of this region given by Mehta et al. (1989) is presented in Table 1.

![Map of Chandrabhaga basin with VES and ERT sites marked by red square and blue circle, respectively with associated numbers (prepared by using SOI topsheet nos. 55K/15 and 55K/16).](image-url)
Table 1 Regional stratigraphy (after Mehta 1989)

<table>
<thead>
<tr>
<th>Age</th>
<th>Formation</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recent to Quaternary</td>
<td>Alluvium</td>
<td>Black cotton soil, silt and clay</td>
</tr>
<tr>
<td>Lower Eocene to upper</td>
<td>Deccan lava flows</td>
<td>Massive and vesicular units of basaltic Lava</td>
</tr>
<tr>
<td>Cretaceous</td>
<td></td>
<td>flows with intervening intertrappean sediments</td>
</tr>
<tr>
<td>Permian</td>
<td>Lameta beds</td>
<td>Thin sedimentary sequences</td>
</tr>
<tr>
<td>Permian to Carboniferous</td>
<td>Gondwana group</td>
<td>Medium to coarse grain sandstones with stratified</td>
</tr>
<tr>
<td></td>
<td></td>
<td>clay/shale</td>
</tr>
<tr>
<td>Archaeans</td>
<td>Granites</td>
<td>Granite gneisses, meta-sediments of Sausar and Sakoli series</td>
</tr>
</tbody>
</table>

Agricultural produce and orange orchids are the main sources of income to the local populace. Mostly large diameter dug wells penetrating approximately 5 to 12 m depths up to the bottom of weathered / fractured mantle are the primary source of water supply for irrigation. Most of the dug wells go dry from the beginning of summer season. Thus, water available in these dug wells is inadequate to meet the present demand of water supply. Therefore, VES and ERT surveys were conducted to explore groundwater at deeper level. Both VES and ERT surveys were conducted along two closely placed parallel profiles with the centers located very close to each other. The centre of the VES profile is at 78° 47' 47.5”, 21° 14’ 37.8” while the centre of the ERT profile is located at 78° 47' 49.7”, 21° 14’ 38.2”. Locations of VES and ERT are marked by S38 and P53, respectively in the map. Because of that results of 1D resistivity model obtained from VES and 2D resistivity model obtained from ERT are considered for the comparison in the next section to demonstrate the advantages of ERT over VES. The site under consideration falls within the administrative jurisdiction of Raulgaon of Katol Taluk and is located near western boundary of the basin.

Table 2 Resistivity values of different rock type in the study area (Source: CGWB website)

<table>
<thead>
<tr>
<th>Geological Formation</th>
<th>Resistivity in Ohm m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alluvial, Black cotton, bole bed (water saturated)</td>
<td>5-10</td>
</tr>
<tr>
<td>Alluvial, Black cotton (dry)</td>
<td>10-20</td>
</tr>
<tr>
<td>Weathered/fractured/vesicular basalt saturated with water</td>
<td>20-40</td>
</tr>
<tr>
<td>Moderately weathered/fractured/vesicular basalt with water</td>
<td>40-70</td>
</tr>
<tr>
<td>Massive basalt/dry fractured formation</td>
<td>&gt;70</td>
</tr>
<tr>
<td>Water saturated Gondwana sandstone</td>
<td>&lt; 50</td>
</tr>
<tr>
<td>Gondwana fractured/compact sandstone</td>
<td>&gt; 50</td>
</tr>
</tbody>
</table>

Results and Discussion

1D resistivity model

The 1D resistivity model for the VES site S38 is presented in Figure 5. This is computed by using RESIST program (Vander Velpen and Sporry 1993). The model provides resistivity values for each litho units falling below the centre of the profile and their respective thicknesses. These values are given in the inset of the figure in two columns marked as $\rho_h$ for resistivity values and $h_c$ for thicknesses of the respective litho units. The litho units are characterized with a range of resistivity values. The resistivity values for the different litho units of investigated region are given in Table 2. These values are used for the geological interpretation of litho units. The interpretation of resistivity model reveal 0.6 m thick top dry alluvial layer characterized with 33.9 Ohm-m resistivity values. This is followed by 6.4 m thick layer of massive basalt characterized with 120.8 Ohm–m resistivity value. Below it is a 2 m thick water saturated fracture zone with 78.3 Ohm-m resistivity value. This
water saturated fracture zone is underlain by a 27.3 m thick layer of massive basalt characterized with 190.7 Ohm-m resistivity value. The resistivity value of water saturated fracture zone is modified to a higher value because of its less thickness and under the influence of massive basalt layers of higher resistivity values present on its top and bottom. Below the layer of massive basalt is a 4.4 m thick layer of another water saturated fracture zone having 17.7 Ohm-m resistivity. This layer is underlain by 8.6 m thick layer of a massive basalt (200.2 ohm-m) followed by water saturated Gondwana formation characterized with 22.7 Ohm-m resistivity at 45.7 m depth.

At this site a bore well was drilled up to a depth penetrating 3 m below the traps. Groundwater at high pressure was struck in a fractured zone at 7 m depth as well as in the other fracture zone at 29 m depth which is in conformity with the presence of two water bearing fracture zones identified by the interpretation of 1D resistivity model. The last water bearing geological formation with 22.7 Ohm-m resistivity value at 45 m depth is found to be Gondwana sandstone. Thicknesses of litho units observed from the drilled bore well are presented in the third column under heading $h_n$ in the inset of the figure. A comparison of the computed thicknesses of different litho units with the observed thicknesses from bore well are found in close agreement. This validates our interpretation of VES data. It is worth to mention that the interpreted results of 1D resistivity model is about the litho units vertically falling below the centre of the survey profile. It does not provide any information about the litho units in lateral direction away from the center.

![Fig. 5 1D resistivity model for VES site S-38 (after Rai et al. 2011).](image1)

![Fig. 6 2D resistivity model computed from ERT data; GWZ represent groundwater zone (after Thiagarajan et al. 2018).](image2)
Two-dimensional model

Figure 6 presents a 2D resistivity model of the litho units below the entire stretch of the profile which is not the case with 1D resistivity model. The figure presents lateral as well vertical extent of geological formations/structures along with the coordinates of the center of the profile, color index representing range of variation in resistivity values of individual geological formations/structure, electrode spacing and computational error in the form of percentage of r.m.s. Location of each electrode is marked on top of the resistivity model by small vertical spikes at 10 m spacing along the profile. Length of the profile is 630 m. Vertical depth measured from the ground surface in meter is marked on the left side of the model. The 1st electrode is placed at starting point of the profile marked as 0 and 64th electrode is placed at 630 m distance. The depth of the investigation is limited up to 115 m. Direction of profile is marked by E for east and W for west. The 2D resistivity model presents the images of geological formations/structures starting from 2.50 m depth. Exposure of hard rock is visible up to 100 m from its western edge. Remaining part of the profile is covered by thin layer of soil/weathered formation. The model shows the presence of a layer of the massive basalt (> 100 Ohm-m) of varying thickness below the entire spread of the profile except in the centre of the profile where it is bisected into two parts by a fracture zone. This fracture zone connects the deeper water bearing formation (< 40 ohm-m) to the overlying soil between 320 m and 330 m. This zone of exposure between 320 m to 330 m is a suitable site for development of recharging structures such as ponds, large diameter dug well etc.

As stated above that the centers of both profiles are closely located at 320 m distance marked at the ERT profile where the location of the bore well is. Therefore, interpretation of the sub-surface geological setup at 320 m distance obtained from ERT is considered for comparison with that obtained from 1D model of VES data. At this point 2D model shows the presence of weathered formation (<40 Ohm-m) which is underlain by a thin layer of massive basalt (>70 Ohm-m). This weathered formation corresponds to the top layer of weathered formation (33.9 Ohm-m) of 1D model and the thin basalt layer correspond to the basalt layer of 1D model characterized with 120.8 Ohm-m. Below the massive basalt layer shows a thin layer of water saturated fracture zone which correspond to the 2 m thick layer of water saturated zone of 1D model. This water saturated fracture zone is underlain by thick layer of massive basalt (>100 Ohm-m) which is extended up to 40 m depth. This layer of massive basalt corresponds to a 23.7 m thick layer of massive basalt delineated in 1D model. This layer of massive basalt appearing in 2D model is underlain by a water saturated fracture zone followed by a layer of massive basalt and Gondwana formation in sequence. The same sequence of geological formations is also found in 1D model. It suggests that the results of 1D and 2D are in close agreement. However, in this case delineation of water bearing zones by VES survey becomes possible because incidentally it lies below the centre of the VES profile. If this centre would have been located somewhere in between western edge and up to 80 m distance, then delineation of the water bearing formation would have not been possible. On the other hand, for the same location of the centre of the ERT profile, it is possible to delineate a part of the water bearing formation. This is one advantage of the 2D resistivity model over 1D resistivity model. Because of the knowledge about the vertical and horizontal extents of water bearing formation from 2D model, drilling of another bore well at 210 m distance became possible. Presently both bore wells are being used by two farmers for irrigation. This was not possible by VES survey with four electrodes. By practicing roll along survey by ERT, one can do continuous sub-surface imaging for any length of the profile. The 2D resistivity model also shows the location of exposure of a fracture zone between 320 m to 330 m which is suitable for development of infrastructure such as injection well, dug well etc to manage recharging of deeper aquifers. This kind of information is not possible from 1D resistivity model.

Fig. 7 2D resistivity model for Wenner configuration (after Rai et al. 2013b).
Concluding Remarks

Comparison of the results of 1D and 2D resistivity models reveals several advantages of ERT over VES. 1D model can provide information about the sub-surface litho units only below the centre of the profile. Therefore, delineation of the target is possible only if it lies below the centers of profiles. Thus detection of targets away from the centre is not at all possible by VES survey. There is always possibility of human errors in the modeling and interpretation of 1D resistivity models. But on the other hand, ERT survey provides 2D images of subsurface in the entire spread of the profile. Therefore, there is no chance of missing any target present below the entire spread of the profile. Based on this knowledge, drilling of another bore well at 210 m distance became possible. 2D model can be also used for selection of sites suitable for development of recharge structures. In the present study such a suitable site is identified between 320 m to 330 m where a fracture zone is found to be hydraulically connected to the deeper aquifer. Such identification is not possible from 1D model.

Based on 2D resistivity model the presence of groundwater potential zones have been confirmed in a geological set up of hard rock terrain in which weathered formation is dipping downwards against the massive hard rock unit. One such example of geological setup is shown in 2D resistivity model of Figure 7 for granitic terrain in the campus of CSIR-National Geophysical Research Institute. In this case the depth of investigation is confined only up to 26 m because of the non-availability of space to increase the length of the profile. Availability of space as per the requirement of the survey is a common problem in cities. Only on the basis of the knowledge of such geological setup from 2D resistivity model a bore well was drilled near the contact zone on the side of weathered formation. Occurrences of groundwater potential zones have been confirmed at this site and some other investigated sites having similar geological setup (Rai et al. 2013b, 2019a). The bore well site in Figure 7 is marked by vertical red line. Presence of massive hard rock unit will restrict the lateral movement of groundwater beyond the interface with the dipping weathered formation. In such situation the ground water will percolate down to get stored in the contact zone. Groundwater collected in the contact zone further percolate down in to fractures, faults and joints within the granite units in case if these geological structures are connected to the contact zone. This is another major advantage of the ERT over VES. From the point of view of field operation also ERT has many advantages over VES. In ERT survey entire field operation such as selection of type of electrode configuration, spacing between electrodes etc are automatically controlled by computer program. The entire measurement of resistivity for any electrode configuration can be performed by one time layout of electrodes. Only operator has to change the mode of operation from one type of configuration to another type of configuration using program based command. This is not the case with VES. Positions of electrodes are changed for every reading and also for every form of electrode configuration. It requires more time and manpower. For example, Figure 8 presents 2D resistivity model for Schlumberger configuration using the same layout of electrodes positions used for the 2D resistivity model of Figure 7. For better resolution, the spacing between consecutive electrodes is reduced to 5 m. Comparison of 2D resistivity model of Figure 8 with that of Figure 7 shows that the Schlumberger configuration provides better resolution and more depth of investigation in comparison to Wenner configuration. However, surveying time for the Schlumberger configuration is more than double required for survey using Wenner configuration. That’s why Wenner configuration is preferred over Schlumberger configuration in ground water exploration to speed up survey in order to cover more areas in a given time. ERT survey using Schlumberger configuration is preferred for mineral exploration where high resolution of sub-subsurface image is required. 2D resistivity model of Figure 7 (or Figure 8) also suggest suitable site for recharging near contact zone between 85 to 90 m on the side of weathered formation. Depth of the recharge structure should be more than 3 m. Such details are possible only by ERT survey.
Acknowledgements

We express our sincere thanks to Dr. Dewashish Kumar and Mrs. Ratnakumari for their valuable contributions in completion of the present work.

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Groundwater Resource Assessment of Akaki Wellfield of Addis Ababa, Ethiopia

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Abstract

Groundwater utilization in Addis Ababa and its nearby area is increasing in the wake of growing urbanization and production of agricultural commodities. It is necessary to evaluate the availability of existing groundwater and its spatio-temporal behaviour for proper management of water resources of a region. This study focused on assessing groundwater of the Akaki wellfield by predicting spatial and temporal flow dynamics using transient flow modeling. The saturated zone of this area is made of Scoria, Scoracious basalt and fractured vesicular basalts types of aquifer media. The whole aquifer system in the area is multi-layered and numerous deep wells are screened randomly through these layers connecting them hydraulically. Thus, the whole aquifer system is simulated considering it as a single saturated zone of 550 m of thickness using MODFLOW. The model is designed by taking 45 rows, 40 columns with 387 active cells with a regular grid spacing of 268 m x 322 m for the entire study area of 87.3 km\(^2\). The model inputs are obtained based on the pumping test data, and hydraulic head analysis is done based on elevation of the existing groundwater table. Pumping tests show that the transmissivity of the entire saturated zone significantly varies, \(26.5 - 34400\) m\(^2\)/day, with storativity between 0.0001603 - 0.071. The model is calibrated using the possible distribution of hydraulic conductivity of the aquifer system. For the flow assessment, an overall well yield 85357 m\(^3\)/day is considered for the whole study area. Recharging flux to the study domain is computed as 7199.3 m\(^3\)/day. The model validation is performed based on the observed heads at all selected stress periods, and the range of correlation coefficient is observed as 0.88 - 0.99. The observed and calculated heads are matching well in general and fitting better in particular with progression of simulation period of 2015-2018. The results of this study can be used for predicting groundwater flow dynamics under the relevant input data and boundary conditions for management of groundwater resources.

Keywords: Akaki Wellfield, Groundwater Resource Assessment, MODFLOW, Ethiopia

Introduction

Managing groundwater resources of an area is crucial and even becoming more challenging due to industrialization and development advancements. Ethiopia has enormous groundwater resource potential and is unevenly distributed (Demlie et al. 2007). The country has no physical water shortage, but the production of water supplies in Ethiopia is at its nascent stage (Adeba et al. 2015). Addis Ababa water supply coverage area is rising steadily, currently reaching more than 75% and 85% in rural and urban areas, respectively. Out of the total water used in the city, about 76% comes from surface and remaining 24% is extracted from groundwater at present.

The Akaki wellfield is the largest source of the groundwater supplies and it serves the city for its domestic and industrial demands along with the agricultural water supply in nearby areas. Different geological, hydrological, and geophysical investigations were conducted in past for the Addis Ababa and its nearby areas and a declining trend is reported in groundwater resource of the area (Mengistu et al. 2019). The population of Addis Ababa and urban growth is rising alarmingly in recent years, and the continuous population increase has triggered the high community demand for potable water supply. Most of the groundwater supply to Addis Ababa city is covered from Akaki wellfield. While the coverage of water supply is increasing rapidly, the gap in water demand and supply is expanding (Demlie et al. 2019). Thus, estimation of groundwater flow pattern along with its associated natural recharge is essential for management of the groundwater resources of the well field in a long term.
The assessment of natural and artificial recharge to the aquifer is based on available data, local geographic, and geophysical conditions (Demlie, 2015). As direct measurement of groundwater recharge in the wellfield is complex and associated with many uncertainties, groundwater flow model can be used to predict the distribution of natural recharge at temporal and spatial scales. The emerging pattern and availability of groundwater with time (Yadav et al. 2014) and its movement needs to be evaluated for proper planning and sustainable usage of the wellfield site. Groundwater flow modeling is an important tool often used in managing the quantity and quality of groundwater. Through groundwater flow models, attempt is made to simulate the set of operations associated with a subsurface system using relevant approximations by solving governing equation (Kumar et al. 2011).

The main focus of this study is to assess the groundwater resources and its spatial and temporal variability using transient groundwater flow modeling and to provide groundwater balance under different extraction patterns of Akaki wellfield. The specific objectives of this study were 1) To evaluate the hydrological processes for assessment of groundwater resources in the study area, 2) To develop a transient groundwater model of the Akaki well field for predicting the ground flow pattern. 3) To identify the study area boundary and conceptualize the boundary conditions and calibrate the transient model of the wellfield. This analysis includes an overview of the target area's groundwater infrastructure, which can help in framing appropriate policies for groundwater extraction and its management.

**Study Area**

The Akaki catchment is situated in central Ethiopia, highland along the western edge of the main rift valley (MER) of Ethiopia (Demlie et al., 2007) (Fig.1). It is located approximately 22 km south-east of Addis Ababa, in the sub-city of Akaki-Kality, crossed by a railway and Addis Ababa-Debrezeiet road. The catchment of the study area located at the north-western Awash River basin between 8°46'–9° 14' N latitude and 38°34' –39° 04' E longitude (Lulu and Ababa, 2005). The total surface of the study catchment is 87.3 km², and the area of the wellfield is 16 km². Huge mountains and numerous volcanic rocks characterize the border of the watercourse. The elevation in the north of the Intoto Mountains ranges from 2060 m in the south of the Akaki well area to 3200 m from mean sea level (msl) (Ayenew et al. 2008).

Addis Ababa climatic condition is determined by weather circulation, and during the wet season from June to September, rainfall in the Akaki catchment area is received from the Intertropical Convergence Zone (ITCZ) movement toward the central part of the country. The climate of the study area is defined in wet and dry seasons. The rainy season lasts from late April to earlier November, and the dry season is extended from December to earlier April. Most of the precipitation occurs in the wet season during July and August, contributing about 80 percent of annual rainfall, and remaining 20 percent of rain falls during rest of the year.

The Akaki wellfield rainfall period can be classified in three parts; small rain that falls from mid-February to March, and medium rain occurs from April to half of June, and normal rain is received from mid-June to September, and the main rainfall occurs in July and August. The upper part of the study area is occupied by different activity projects of settlement. A mixed land use, and the industrial zone of the city of Addis Ababa is clustered around the Akaki River. Various quarries of building material are there nearby to the wellfield catchment. The Akaki Catchment land cover is divided into Savanna or forest cover, Grassland, Croplands and Uplands. The study area and its nearby regions is consisted of varied geological formations, and the country's oldest rock forms the basement and Precambrian period. Geologically, the study area is made of Nazareth series (Nn), Bishoftu Basalt (NQtb), Chilalo Formation (Nc), Alluvial and lacustrine deposits (Q), Alliteration (PNa) and Basalt Plateau (Qb).

**Methodology**

Groundwater abstraction data and water level data were collected from Addis Ababa Water and Sewerage Authority (AAWSA). Pumping test data in form of drawdown at discharge constant rate for different wells were also collected from the AAWSA. Meteorological data were collected from different stations which are from Intoto station, Addis Ababa Bole, Addis Ababa Observation, Debrezet (AF). Data related to Akaki station located in the surrounding of the study area, were also collected from the National Meteorology Agency (NMA) of Ethiopia. Akaki River discharge and geological map and cross-sections, soil and land use map of Awash basin were obtained from the Ministry of Water, Irrigation and Electricity of Ethiopia. The whole methodology adopted here is shown in the form of a flow chart (Fig. 2).

Groundwater model runs were made before performing calibration of the model under steady-state and transient state flow conditions. The aquifer parameters were obtained from the pumping test data sets and other
hydrogeological data. Pumping tests were performed in the Akaki well field of the study area for determining aquifer parameters viz Srotativity (S), Transmissivity (T).

Fig. 1 Location map of the study area.

The well-depth of the study area varied from 120m - 550m below ground level and the aquifer thickness is from 30 - 220 m. The diameter of borehole ranges from 12 - 22 inches, which is selected as control during the pumping test at constant discharge. The aquifer properties (S and T) determined using the Cooper – Jacob’s method as mentioned by Anderson and Woessner (2016). The recovery test started after stopping the pumping well when the water levels in the well and the surrounding piezometers started rising. The pumping tests data are used to evaluate aquifer parameters through constant pumping while observing the aquifer’s drawdown in the observation well (Kruseman and de Ridder, 1971). The aquifer parameters obtained from the pumping test analysis are the storage coefficient, transmissivity and hydraulic conductivity of the aquifer. These aquifer properties are then used as an initial input value for running the groundwater flow model.

For groundwater flow modelling using MODFLOW, the study area is subdivided into many small areas called cells, and a basic equation of groundwater flow is solved for each cell taking into account its water balance. MODFLOW is the a powerful tool for simulating groundwater flow and pollution transport modeling, incorporating the most powerful and intuitive interfaces (Khadri and Pande 2016). The governing equation for simulating groundwater flow is developed by integrating Darcy’s law and continuity equation for a single-phase flow having constant density in a continuous porous media. 3D form of the groundwater flow in transient state for heterogeneous and anisotropic condition is mentioned as

$$\frac{\partial}{\partial x} \left( k_x \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left( k_z \frac{\partial h}{\partial z} \right) - W = S_s \frac{\partial h}{\partial t}$$

(1)

Where \(k_x, k_y\), and \(k_z\) represents hydraulic conductivity along \(x, y,\) and \(z\) respectively, \(h\) represents the Hydraulic head, \(W\) is Flux per unit volume of sources and sink, \(S_s\) is Specific storage, and \(t\) is time.

A 3D model grid is used to represent a two-dimensional aerial flow through a single layer (Demlie et al., 2007). The architecture of the model is constructed by taking 45 rows and 40 columns with 399 active cells and 1401 inactive ones.
For the entire wellfield area of 87.3 km², a standard grid spacing of 268 m x 322 m of the wellfield is considered. The gridded boundary of the model is determined from the study area map, which is prepared by GIS and saved in JPG file format. The Map image is projected through UTM coordinates and imported into MODFLOW. A finite-difference grid superimposed over an area of 87.3 km² is built and constructed on the basis of a mathematical model simplified for describing the physical properties of the groundwater system. For this study, the $k_x$ value is taken as equal to $k_y$ value, and $k_z$ value is 0.1 of $k_x$ or $k_y$. The lower boundary of the study domain is a basement volcanic rock, where groundwater flow is negligible and hence it is considered as a no flow boundary. Existing wells of the study area are imported to the model by using ASCII Text file formats. The pumping rates are entered into the model, which is located in the grid. The positive rates are used for the injection wells, and the negative rates are for the pumping wells (Khadri and Pande, 2016). The head on observation wells are taken as input data for the MODFLOW package. The observation head data of wells are used here for the model calibration. The transient model simulation runs for four years (1462 days), are divided into ten stress periods, and daily time steps are considered for the total model simulation. The different time steps over the specified period of the model simulation are listed in Table 1.
Table 1 Time stress periods of the transient flow modelling

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Time(day)</th>
<th>Stress period</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>56</td>
<td>56</td>
</tr>
<tr>
<td>2</td>
<td>124</td>
<td>68</td>
</tr>
<tr>
<td>3</td>
<td>205</td>
<td>81</td>
</tr>
<tr>
<td>4</td>
<td>302</td>
<td>97</td>
</tr>
<tr>
<td>5</td>
<td>419</td>
<td>117</td>
</tr>
<tr>
<td>6</td>
<td>560</td>
<td>141</td>
</tr>
<tr>
<td>7</td>
<td>728</td>
<td>168</td>
</tr>
<tr>
<td>8</td>
<td>929</td>
<td>203</td>
</tr>
<tr>
<td>9</td>
<td>1171</td>
<td>242</td>
</tr>
<tr>
<td>10</td>
<td>1462</td>
<td>291</td>
</tr>
</tbody>
</table>

The steady-state model simulation of the Akaki well field is developed using an ASCII file format consisting of the well locations, and the aquifer parameters are imported to the model domain. Transient simulations require consideration of aquifer properties, initial conditions, the effects of hydrologic stresses, time, as well as space, and field observations used in model calibration. Sensitivity analysis is performed to establish the effect of uncertainty on the calibrated model. The sensitivity analysis is performed by changing the parameters K, specific yield ($S_y$), total porosity ($\eta_{total}$), effective porosity ($\eta_{eff}$), recharge/draft etc. It is found that 'K' is the most sensitive parameter for this model. The groundwater model is then run by using the calibrated model parameters for getting better results. The model validation is performed by comparing the computed water table level with field observed head throughout the stress periods. The water balance of Akaki wellfield is evaluated finally from the output of the transient state model. The components of the water balance like surface water recharge, groundwater storage, groundwater abstraction, general head, and constant heads were computed.

Results and Discussion

The yearly rainfall in the catchment varies with elevation, and in general, the annual rainfall is high in summer monsoon with mean monthly rainfall varying from 179.3 to 493.9 mm. The maximum temperature ranges from 24 to 27 °C, while the minimum temperature is recorded between 11 and 19 °C annually. The mean monthly wind speed in the study area varies from 1.3 to 1.6 m/s. The duration of sunshine hours affects the rate of evapotranspiration and the maximum sunshine time varies between 4.21 and 10.54 h/day, and the average relative humidity (RH) of Akaki wellfield is observed from 39.23 to 61.4%. The climatic variations are summarized in Table 2 and shown in Figs. 3, 4, and 5.

Table 2 Mean monthly variation of climatic data of the study area

<table>
<thead>
<tr>
<th>Climate</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainfall (mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temp (°C)</td>
<td>19.6</td>
<td>14.79</td>
<td>69.03</td>
<td>69.4</td>
<td>66.22</td>
<td>141.4</td>
<td>249.4</td>
<td>243.6</td>
<td>131.9</td>
<td>39.9</td>
<td>6.51</td>
<td>6.65</td>
</tr>
<tr>
<td>Sunshine (h/day)</td>
<td>8.53</td>
<td>9.73</td>
<td>8.35</td>
<td>8.4</td>
<td>8.44</td>
<td>6.84</td>
<td>5.4</td>
<td>5.5</td>
<td>7.4</td>
<td>9.2</td>
<td>9.7</td>
<td>9.7</td>
</tr>
<tr>
<td>Wind (m/s)</td>
<td>1.4</td>
<td>1.6</td>
<td>1.5</td>
<td>1.6</td>
<td>1.5</td>
<td>1.31</td>
<td>1.16</td>
<td>1.01</td>
<td>1.03</td>
<td>1.29</td>
<td>1.61</td>
<td>1.5</td>
</tr>
<tr>
<td>RH (%)</td>
<td>56.45</td>
<td>39.23</td>
<td>52.02</td>
<td>52.78</td>
<td>46.11</td>
<td>53.3</td>
<td>61.5</td>
<td>61.4</td>
<td>55.8</td>
<td>55.1</td>
<td>52.1</td>
<td>55.05</td>
</tr>
</tbody>
</table>
Fig. 3 Annual rainfall distribution of Akaki well field with its minimum and maximum values.

Fig. 4 Relationship between Rainfall, Maximum and Minimum temperatures of the study area.

Fig. 5 monthly rainfalls observed at Addis Ababa observation station.
The aquifer properties obtained from the pumping test (Fig. 6) show extremely high and low values of transmissivity. Hydraulic conductivity values are obtained from nearby wells shows existence of heterogeneity in the subsurface. Transmissivity varies from 92.41 to 2220 m²/day, and the storativity is observed between 0.0001603 - 0.071. Specific yield also varies significantly, having its value from 0.07 to 38.04. These aquifer properties are used as initial input values for the groundwater flow model setup. The steady-state condition is used for model calibration by assigning distributed hydraulic conductivity values in different zones (Table 3).

### Table 3 Hydraulic conductivity of different zones

<table>
<thead>
<tr>
<th>Zone</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>K (m/day)</td>
<td>5.2</td>
<td>3.7</td>
<td>12.3</td>
<td>4.5</td>
<td>20.5</td>
<td>15.5</td>
<td>5.3</td>
<td>4</td>
</tr>
</tbody>
</table>

Fig. 6 Scatter plots of the steady-state model.

Transient simulations require consideration of aquifer properties, initial conditions, the effects of hydrologic stresses, and time along with field observations for model calibration. Time stress of four years period is used for running the transient model. The transient model is calibrated by assigning distributed specific yield between 0.025 - 0.162 in different eight zones so that the calculated hydraulic heads becomes close to the observed head. The field data has more errors due to fewer observations well, and lack of availability of hydrogeological parameter data and inconsistency of groundwater level data recording. Due to these errors, the transient model calibration is affected adversely. The water table elevation contours in transient state calibration are shown in Fig. 7, and the transient model output simulated for groundwater level becomes closer to the observed values of the hydrograph heads, as shown in Figs. 8a-b.
Fig. 7 Groundwater table elevation for transient flow model.

Fig. 8a Observed and simulated groundwater heads of transient state model for pumping at well 2.

Fig. 8b Observed and simulated groundwater heads of transient state model for pumping at well 11.
The model validation is used here to check the computed head by comparing with field observed data throughout the selected stress periods. The model validation result is matching fairly well with the correlation coefficient of 0.888 (December 1, 2015), 0.918 (April 1, 2016) and 0.935 (October 1, 2016), 0.961 (June 1, 2017), 0.986 (March 31, 2018) and 0.994 (December 1, 2018). The model validation is shown using the scatter plots for different stress periods (Figs. 9, 10 and 11).

Fig. 9 Scatter plots for transient state on model on June 1, 2017.

Fig. 10 Scatter plots for transient state on model on March 31, 2017.

Fig. 11 Scatter plots for transient state model on December 1, 2018.

The components of the water balance are surface water recharge, groundwater storage, groundwater abstraction, general head, and constant heads (Figs. 12 and 13). In the transient state model simulation period, the maximum
recharge occurred during the wet season during the stress period 15 (0.141 mm/day) from July to September 2018, and minimum recharge happened in the dry season during the stress period 4 (i.e., 0.0009 mm/day).

**Fig. 12** Daily basis groundwater balance of Akaki aquifer system. Here R is recharge, GHB is groundwater outflow, W is a well abstraction, and S is the change of groundwater storage. Units are in m$^3$/day.
Fig. 13 Groundwater balance components of the study area under a) Recharge of the well, b) Groundwater storage (S), c) Well abstraction (W), and d) General head boundary (GHB).
Conclusions

The annual meteorological parameters of the study area vary significantly with season and space. The monthly rainfall amount of the catchment is having the coefficient of variability as 0.94. The mean monthly rainfall of the area is varying from 179.3 to 493.9 mm/month, the temperature ranges from 16 to 27 °C and the wind speed varies from 1.3 to 1.6 m/s. The maximum sunshine hours range from 4.21 to 10.54 h/day. These changes in hydrological parameters in short/long terms are thus affecting the groundwater resources of the wellfield due to changing groundwater extraction and recharge rates. The aquifer properties obtained from the pumping test show low values of transmissivity, and different values of hydraulic conductivity obtained from nearby wells indicate the heterogeneity of the subsurface. The pumping tests show variability in transmissivity from 26.5 to 34400 m²/day, and the storativity is observed between 0.0001603 and 0.07. In general, the groundwater level of the wellfield is rapidly declining due to more groundwater abstractions along with a decreasing amount of surface recharges. The groundwater level in the wellfield has declined from 48 to75 m bgl during the year July 2015 to June 2018, and the average daily groundwater abstraction is calculated as 4525.474 m³/day. Field observations are used in model calibration for running the model by taking the time stress of four years period. The model is calibrated by assigning distributed specific yield varying in between 0.025 - 0.162 in different zones of the aquifer system. A correlation coefficient of 0.888 - 0.994 shows the model capability of simulating the groundwater flow quite accurately. According to the water balance analysis, the average groundwater recharge, well abstraction, storage, general boundary, and constant boundary were estimated as 5199 m³/day, 6511 m³/day, 2639 m³/day, 1494 m³/day, and 2896 m³/day respectively. For a better understanding of the groundwater flow pattern and accurate assessment of the Akaki wellfield water resources, automatic level recorders are needed to be installed for continuous monitoring of the groundwater level.

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References


Application of Electrical Resistivity Tomography for Investigation of Shallow Subsurface HFT Zone in and around Mohand, Uttarakhand, India

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Abstract

Electrical Resistivity Tomography (ERT) data recorded in and around Himalayan Frontal Thrust (HFT) zone in Mohand area are interpreted in terms of subsurface resistivity variation at shallow depth. Seven ERT profiles were recorded along the Khajnawar Rao and Mohand Rao stream beds covering mainly the HFT zone in the region. Out of these, two were located on the Khajnawar Rao bed and the remaining five were located along the Mohand Rao. ERT data are first processed to eliminate spikes and noisy signals and subsequently inverted using RES2DINV, 2D inversion code, to obtain resistivity depth images for each profile. Depth of investigations was computed for each image to determine the zone of reliable resistivity depth images. To facilitate comparison, resistivity depth images are presented in the same scale range. The results indicate that the bedrock and unsaturated top formations are generally highly resistive (> 800 Ω·m), whereas, highly sheared fractured zone saturated with water represented by low resistivity values (50 Ω·m to 100 Ω·m). Saturated clayey and fine sand formation represented by a low resistivity range (10 Ω·m to 50 Ω·m). In essence, the resistivity variations recorded here in this study are properly correlated with geological formations like that of river born material, pebble-cobble, gravel, sandy loam and their water saturation in the region.

Keywords: Electrical Resistivity Tomography (ERT), 2D Inversion, Himalayan Frontal Thrust (HFT)

Introduction

Geophysical techniques can be used to solve a variety of problems related to soil characterization for foundation design of civil engineering structure, environmental (Ward 1990; Sudha et al. 2009) and hydrological related investigations (Israil et al. 2006). These methods are indirect, non-destructive, economical and less time consuming in comparison to excavation and borehole drilling. Large range of electrical resistivity values of earth’s subsurface formations material is an advantage for its use in the delineation and characterising of subsurface formations. The basic physical principle used in resistivity measurements is based on four-electrode device. Multi-electrodes resistivity imaging also known as Electrical Resistivity Tomography (ERT) is now routinely used in various field applications (Zubair et al. 2020; Szalai et al. 2020; Devi et al. 2017; Szokoli et al. 2017; Marescot et al. 2003). In the present investigation, ERT data recorded in an HFT zone in and around Mohand area are used to characterize the subsurface formation and its water saturation.

Geology and Geohydrology of the Study Area

The study area is located in and around Himalayan Frontal Thrust (HFT) zone near Mohand town in the vicinity of the Dehradun, Uttarakhand, India. The area extends from 77°47’ E to 78°01’ E longitudes and 30°09’ N to 30°18’ N latitudes (Fig. 1). HFT is the southern limit of Sub-Himalaya, which represents a zone of active deformation between the Sub-Himalaya in North and the Piedmont alluvial plain in the South. It transports sediments of the Siwalik group over the Indo-Gangetic Plain (IGP) in southward direction. HFT in Mohand, dips generally ranging between 20° to 30° towards north and in the narrow zone adjacent of the HFT, a dip reversal defines the Mohand anticline with a dip of 45° to 70° to the south on the forelimb of anticline (Thakur and Kumar 1995). Anticline structure is characterised by numerous closely spaced and laterally discontinuous
fold between the Mohand and Yamuna River (Rao et al. 1974; Karunakaran and Ranga Rao 1976; Raiverman et al. 1993; Powers et al. 1998).

Lithology outcropped in the Mohand include fluvial sediments (sandstones, shales and conglomerates) and Lower-to-Upper Siwaliks rocks (Karunakaran and Ranga Rao 1976). The structure of rocks visible in Mohand range is an antiform/anticline with varying geometry from east to west between the Mohand and the Yamuna River. Numerous, closely-spaced, symmetric and laterally-discontinuous folds were also reported within the southern limb near the HFT over time (Rao et al. 1974; Raiverman et al. 1993; Srivastava et al. 2016). The HFT in Mohand Range is also commonly depicted as a blind thrust (Raiverman et al. 1990; Yeats and Lillie 1991). However, later observations from a deep borehole near Mohand, shallow exploratory well and series of trenches shows that the HFT reaches the surface, covered by a thin deposit in the active streambeds (Senthil et al. 2006). Wesnousky et al. (1999) described the Schematic lithological composition of fluvial terrace deposits in the study area is shown in (Fig.2). Senthil et al. (2006) discussed the geological formation boundaries can be seen in a trench, ZT02, shown in (Fig. 3), located near ERT-2 in Khajnawar Rao. The oldest unit exposed is highly sheared Siwalik bedrock. The Siwalik bedrock is thrust over alluvial pebble-cobble gravels in clayey silt to sandy matrix. The boundary between Siwalik bedrock and alluvial deposits of the floodplain is abrupt and steep. Siwalik bedrock overriding young alluvial deposits along a low angle thrust fault that can be seen in a Khajnawar trench (Senthil et al. 2006).

Alluvial fans, hillocks, river terraces, and flood plains are the major geomorphic units in this region; the valley fills in the region have been described as ‘Dun gravels’ (Nossin 1971; Nakata 1972; Singh et al. 2001; Thakur and Pandey 2004; Thakur et al. 2007). Fan deposits in the region mainly consist of boulders, cobbles, and pebbles with a sandy and silty matrix (Nossin 1971; Thakur 1995). Additionally, there are numerous ephemeral Rao (stream) that originate in the Sub-Himalayan foothills and issue onto the Gangetic Plain. Khajnawar Rao and Mohand Rao streams are present in the study area. Streambeds are composed of rounded pebble and cobble gravels in a sand matrix. Several terraces are located 20 to 30 m above the modern stream level in Khajnawar Rao, Mohand Rao and other Rao along the Siwalik range front, south of the Dun Valley in Garhwal Himalaya. These terraces are interpreted to have been uplifted by displacement on the underlying HFT. The Khajnawar terrace sits upon a tight and overturned fold within the underlying Siwalik Group.

**Description of the ERT Data and 2D Inversion**

Seven ERT profile data were recorded from the study area. Out of these, two are located in Khajnawar Rao and the remaining five are located along in and around Mohand Rao. Data recording parameters, the number of electrodes used and inter-electrodes spacing are given in Table 1. All the data were first examined, spikes and outlier in data removed by visual inspection and subsequently, a damped least-squares constrained robust inversion option was used in 2D inversion code, RES2DINV (Loke 2018). Diagonal filter option was used to generate resistivity depth section along the entire profile length. Diagonal filter reduces the artefact in the inverted model by modifying the horizontal roughness (Loke 2018). To facilitate comparison all resistivity depth models are presented in the same scale range and colour, this has been done using MATLAB. Inverted resistivity depth images are for all ERT profiles are shown in (Figs. 4 to 10). In all images, the top surface shows the linear distance scale and direction along the profile. The geological and geo-hydrological interpretation of resistivity-depth models obtained from inversion of each ERT data has been discussed in the following section.
**Fig. 1** Study area showing the locations of Electrical Resistivity Tomography (ERT) profiles and major streams in Google map.

**Fig. 2** Schematic presentation of composition of fluvial strath terrace deposits in the study area (Wesnousky et al. 1999).
Fig. 3 Distribution of fluvial terrace deposits along the Khajnawar River in Mohand area. Bottom panel showing the trench log (Senthil et al. 2006) near ERT-2 location. Sheared Siwalik bedrock underlying quaternary gravel deposits near the fault trace, F1.
The first profile, ERT-1, lies in the South of HFT, in the Khajnawara Rao riverbed oriented in the S-N direction with origin (location of the first electrode) in the south. Electrical resistivity variation with depth along the profile is shown in (Fig. 4). Depth of investigation is marked by a dotted line. High resistivity (> 500 Ω-m) formation corresponds to near surface dry riverbed that includes gravels, pebbles and coarse sand material and this zone extended up to the depth of 8 m. The stream bed was dry at the time of acquisition. The profile region lies in the upper piedmont zone and is defined as a fan area with boulders, cobbles and pebbles and thus acting as an infiltration zone (Singh et al. 2012). Localised water saturated zones in the central region of the profile on the surface along the profile length from 80 m to 128 m with the resistivity range of 100-200 Ω-m can be seen. Below the depth of 16 m is the sandstone of the Middle Siwalik Subgroup represented by resistive zone (Wesnouksy et al. 1999).

The second profile, ERT-2, part of the profile is located in the Khajnawar Rao bed in the North and the southern part is in a flood plain. The trench site (ZT-02) (Fig. 3) is located near this profile (Senthil et al. 2006). Resistivity depth image along the profile section is shown in (Fig. 5). Southern zone (0 to 168 m) shows the high resistivity (410 Ω-m to 650 Ω-m) in South indicating Shiwalik bedrocks below the dry gravels and pebbles of the Khajnawar Rao River bed in the depth range of 9-45 m (Wesnouksy et al. 1999 ; Senthil et al. 2006). A thin layer, in the depth range of 0-9 m, of moderate resistivity in the range of 200-350 Ω-m in the south of profile is due to the older alluvial deposits of the surrounding floodplains. Further, a low resistivity of < 45 Ω-m in the North is due to water saturated gravel and sand formation in an active stream bed. Senthil et al. (2006) highly sheared Siwalik bedrocks are thrust over the older alluvial deposits of the surrounding floodplains and both these layers are overlain by the thin layer of river bed gravels, which can be seen in the trench log (Fig. 3). Beneath the active stream bed, resistivity values do not differentiate between saturated fractured and sheared Siwalik bed and older alluvium boundary (Fig. 3).
The third profile, ERT-3 is located in Mohand Rao bed, another stream in HFT zone. The profile is approximately oriented in the E-W direction with origin (location of the first electrode) in the east. Electrical resistivity variation with depth along the profile is shown in (Fig. 6). A dotted line marks depth of investigation. Highly resistive (> 500 Ω-m) formation corresponds to near surface dry river bed gravels, pebbles and coarse sand material, this zone extending up to the depth of 5 m. Below the top unsaturated/partially saturated layer, the fractured saturated sandstone of the Middle Siwalik Subgroup with the low resistivity in the range of 40 Ω-m to 120 Ω-m is present.

ERT-4, located in Mohand Rao bed, oriented in the S-N direction with origin (location of the first electrode) in the south. The profile is passing through the southern limb of the Mohand Anticline. Electrical resistivity variation with depth along the profile is shown in (Fig. 7). Southward dipping of bed can be seen in resistivity depth image with increasing depth toward the south (2 to 12 m) of older alluvium (Quaternary). This is interpreted as an electrical image of the southern limb of Mohand anticline, dipping southward. Highly resistive (> 500 Ω-m) formation corresponds to top surface partially saturated Mohand Rao river bed, which is composed of gravels, pebbles and coarse sand material. The older alluvium represented as moderate resistivity (> 250 Ω-m) zone in yellow colour. Below this zone, water saturated fractured sandstone of the Middle Siwalik Subgroup is appeared as low resistivity (40 Ω-m to 120 Ω-m) formation.

ERT-5 was recorded further north of ERT-4, along the uplifted terrace at a height of ~ 4 m. The profile is crossing another seasonal stream in the middle region from 200 m to 250 m on the surface scale; the stream can also be seen in (Fig. 1). The resistivity depth image for this profile is given in (Fig. 8). The area around the stream is represented by lower resistivity (10-40 Ω-m). This low resistivity zone is broadening and moving southward in deeper depth. This is an example of ground water movement through fracture zones in the area. The alluvial deposits at the top near surface as yellow colour are shown by high resistivity (> 100 Ω-m) in the depth range of 0-8 m.
The profile ERT-6 is located in the north of Mohand anticline. The bedding plane is dipping northward at a low angle. Resistivity depth image for this profile is shown in (Fig 9). Highly resistive (> 800 Ω-m) dry top layer with thickness increasing northward (2 m to 15 m) represent older dry alluvium (Quaternary). Below the top layer, water saturated fractured sandstone of the Middle Siwalik Subgroup, represented by the resistivity of 50-100 Ω-m is present. The very low resistivity (< 20 Ω-m) layer in the middle zone presented a high amount of water saturated clayey formation.

The resistivity depth image of ERT-7 is shown in (Fig. 10). The high resistivity (> 300 Ω-m) of top surface dry layer, older alluvium (Quaternary) in the depth range 0- 6 m is observed. The thickness of this layer varied from 2 to 6 m. Below this fractured saturated sandstone of the Middle Siwalik Subgroup can be seen as low resistivity (<130 Ω-m) formation. Beneath 4 m along the horizontal distance between 85 m to 95 m nearly vertical fault with the resistivity of 50 Ω-m can be seen in (Fig. 10).

<table>
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<th>Location</th>
<th>GPS Coordinate</th>
<th>Profile length</th>
<th>No. of Electrodes</th>
<th>Inter-electrode spacing</th>
<th>Array type</th>
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<td>N30 10.857 E77 52.046</td>
<td>188</td>
<td>48</td>
<td>4</td>
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<td>2</td>
<td>Pelo Khurd</td>
<td>N30 10.735 E77 52.838</td>
<td>N30 10.912 E77 52.865</td>
<td>329</td>
<td>48</td>
<td>7</td>
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<td>3</td>
<td>Mohand</td>
<td>N30 10.628 E77 54.253</td>
<td>N30 10.577 E77 54.297</td>
<td>118</td>
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<td>2</td>
</tr>
<tr>
<td>4</td>
<td>Mohand</td>
<td>N30 11.38 E77 54.765</td>
<td>N30 11.467 E77 54.827</td>
<td>188</td>
<td>48</td>
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</tr>
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<td>5</td>
<td>Mohand</td>
<td>N 30 12.640 E77 55.067</td>
<td>N 30 12.780 E77 55.237</td>
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<td>48</td>
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Conclusions

Electrical Resistivity Tomography (ERT) data are used for shallow subsurface investigations. Seven ERT profile data recorded in and along Khajnawar Rao and Mohand Rao streams are interpreted. ERT data are first transformed in terms of resistivity depth section along each profile. Resistivity values are used to delineate near surface formation characteristic and water saturation in the area. Resistivity values of different formation zones vary in a wide range; it is as less as 10 Ω·m saturated clay. Resistivity values of water saturated sand zone vary from 50 Ω·m to 100 Ω·m. It also increases with an increase in river born material, pebble-cobble and gravel. High resistivity (> 300 Ω·m) represents Siwalik bedrock or dry top near surface formation.

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References


Identification and Modelling of Seawater Intrusion in Coastal Aquifers of Puri Inter Basin, Odisha

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Abstract
The present study involves identification and flow modelling of seawater encroachment into coastal aquifers of an inter-basin falling in Puri district of Odisha state. The study involves development of a variable density groundwater flow model taking the maximum depth to water table and the lateral penetration of fresh water-seawater interface, as constraints. These state variables are computed invoking a variable density groundwater flow and transport model based upon SEAWAT 2000 Code. The model has been calibrated employing available data base and aquifers visualization gained through an innovative hydrogeological and groundwater quality study.

Keywords: Coastal Aquifers. Seawater Intrusion. Modelling. Puri Interbasin. Odisha

Introduction
The quality of groundwater in coastal aquifers of Puri region of Odisha in India is threatened by various human activities like irrigated agriculture, industrialization urbanization and tourism etc. which disturb the hydrodynamic equilibrium between the fresh water–saline water interface. Earlier hydrogeologic studies by workers like Desai et al. (1979) helped in ascertaining the extent of fresh-saline groundwater interface in Manglor – Chorward tract of coastal Saurashtra. The area of seawater ingress along the coastal tract of Kachchh and Saurashtra was identified by surface geophysical measurements (GWRDC, 1998). Raghav Rao et al. (1993) used a model for simulating salt water intrusion in coastal aquifers of Gujarat for a period of 5-years by finite difference approximation. Bhatt (1994) conducted extensive studies in saltwater intrusion in Kutch areas of Gujarat and was able to delineate the salt water- fresh water interface. He also gave his conclusions on the origin of the salinity of ground water in the coastal Kutch region as being due to residual salinity besides the seawater encroachment. Hydrogeological studies were also conducted during 1990-2000 for delineating seawater intrusion into coastal aquifer by analyzing borehole lithologs and geophysical investigations in the east coast of India by Bhattacharya et al. (2002, 2004). Keeping such studies in view, it seemed relevant to undertake the present study in the Puri area of Odisha state, an area affected by intense religious tourism and industrialization(GWS&I, 2002). Accordingly, it is essential to have adequate and precise details of the fresh / saline interface and changes therein as a prerequisite in preventing sea water intrusion through controlled abstraction within economical viability (Das,1991; GWS&I,2000,2001). The extent of intrusion depends on freshwater outflows to sea, climatic condition, hydrogeology of the area and the pattern of current ground water development.

Present Study
This study relates to an interbasin of coastal Odisha adjoining Bay of Bengal with a coastline of around 65 km. In this area, ground water is an important source of irrigation. The only source of drinking water supply to Puri city, falling in this interbasin, is from groundwater resources,P.K.Das et al.(2004), which have been put to considerable stress because of its strategic location in the coastal area. The region is prone to frequent flooding
and cyclones, G.K. Roy (2004), which adversely affect the agriculture, the main livelihood of the people of the area. Therefore, there is a need to develop groundwater resources in this region by carefully considering the relevant constraints involved due to the suspected seawater encroachment.

**Earlier Studies**

Although the first known reported case of saltwater intrusion (Braithwaite, 1855) dates back to 1855, attempts to understand the process began much later probably by Ghyben in 1888 and Herzberg during 1901 resulting in the well-known Ghyben-Herzberg equation. This simple equation Eq. (1) (assuming a sharp interface, hydrostatic pressure distribution, and stationary salt water) relates the depth of interface \( Z \) to the water table elevation \( h_f \) (Fig. 1.) as follows.

\[
Z = \frac{\rho_f}{\rho_s - \rho_f} h_f \tag{1}
\]

where, \( \rho_f \) = density of freshwater and \( \rho_s \) = density of saline water.

![Fig. 1 Hydrostatic equilibrium between Fresh ground water and Salinewater in a coastal aquifer as per Ghyben-Herzberg approximation.](image)

Hubbert (1940) followed by Luszczynski and Swarzenski (1966) generalized the Ghyben-Herzberg equation and proposed the following equation Eq. (2) which relates the freshwater head \( h_f \) and saltwater head \( h_s \) at a point on the interface to its elevation \( Z \) accounting for dynamics of saline water:

\[
Z = \frac{\rho_s}{(\rho_s - \rho_f)} h_s - \frac{\rho_f}{(\rho_s - \rho_f)} h_f \tag{2}
\]

Although initial studies aimed at understanding the process of saltwater intrusion visualized a sharp interface between the freshwater and seawater, in reality due to hydrodynamic dispersion the contact between freshwater and seawater takes the form of a transition zone across which the salt concentration (and hence density of water) varies from freshwater to that of seawater. In this zone, the diluted seawater (being lighter than original seawater) rises and moves seaward causing saltwater from the sea to flow towards the transition zone. This induces a cyclic flow of seawater from the floor of the sea to the transition zone and finally back to the sea. As a result of this circulation, the toe of the disperse interface is displaced towards the seaward side (Cooper et al., 1964). Relatively few studies are reported in respect of model assisted planning which ensures feasibility as well as optimality (Bear, 1979; Gupta, 1985; Guo and Langewin, 2002). The presence of transition zone makes the mathematical modeling of seawater intrusion a complex task, since it involves simulation of flow with variable density. If the width of this transition zone is small relative to the thickness of the aquifer, then it is assumed for the purpose of analysis that seawater and fresh water are immiscible fluids.
separated by a sharp interface instead of the dispersed interface. In view of the above, mathematical models postulated so far can be broadly classified into two groups viz. sharp interface and dispersed interface models. Further, groundwater studies in coastal areas may be on regional or local scale.

In dispersed interface (or miscible transport) models, the problem of seawater intrusion is posed as that of a variable density fluid flow accounting for the effects of dispersion. The models require the simultaneous solution of the coupled groundwater flow and advective-dispersive equations. For a variable density fluid, the groundwater flow equation Eq. (3) is given as under (Bear, 1979):

\[
\frac{\partial}{\partial x} \left( \frac{k_x r}{\mu} \frac{\partial p}{\partial x} \right) + \frac{\partial}{\partial y} \left( \frac{k_y r}{\mu} \frac{\partial p}{\partial y} \right) + \frac{\partial}{\partial z} \left[ \frac{k_z r}{\mu} \frac{\partial p}{\partial z} + \gamma \right] + W \gamma^* = S_x \frac{\partial c}{\partial t}
\]  

where \( x \) and \( y \) are the coordinates in the horizontal plane; \( z \) is the coordinate along the vertical direction; \( t \) is time; \( p \) is the fluid pressure; \( k_x, k_y, \) and \( k_z \) are the intrinsic permeabilities in the \( x-, y- \) and \( z- \) directions, respectively; \( \gamma \) is the specific weight of fluid; \( S_x \) is the specific storage of porous medium; \( \mu \) is the dynamic viscosity of fluid; \( \gamma^* \) is the specific weight of source or sink fluid; \( \phi \) is porosity; \( c \) is the solute concentration (defined as the mass of solute per unit volume of solvent); and \( W \) is the source / sink volume flux per unit volume of porous median (+ve for inflow).

The term \( \phi \frac{\partial \gamma}{\partial c} \frac{\partial c}{\partial t} \) on the right side of Eq. (3a), represents the rate of change in specific weight due to a change in concentration over time. Since the contribution of this term compared to other terms is small, it is mostly neglected. Thus, the flow equation is usually expressed as under:

\[
\frac{\partial}{\partial x} \left( \frac{k_x r}{\mu} \frac{\partial p}{\partial x} \right) + \frac{\partial}{\partial y} \left( \frac{k_y r}{\mu} \frac{\partial p}{\partial y} \right) + \frac{\partial}{\partial z} \left[ \frac{k_z r}{\mu} \frac{\partial p}{\partial z} \right] + W \gamma^* = S_x \frac{\partial c}{\partial t}
\]  

The advective – dispersive equation describing the transport of dissolved salt in Eq. (4) (assuming no chemical reactions and no interaction with the solid matrix) is as under (Bear, 1979).

\[
\frac{\partial}{\partial x} \left[ \phi \left( D_{xx} \frac{\partial c}{\partial x} + D_{xy} \frac{\partial c}{\partial y} + D_{xz} \frac{\partial c}{\partial z} \right) \right] + \frac{\partial}{\partial y} \left[ \phi \left( D_{yx} \frac{\partial c}{\partial x} + D_{yy} \frac{\partial c}{\partial y} + D_{yz} \frac{\partial c}{\partial z} \right) \right] + \frac{\partial}{\partial z} \left[ \phi \left( D_{zx} \frac{\partial c}{\partial x} + D_{zy} \frac{\partial c}{\partial y} + D_{zz} \frac{\partial c}{\partial z} \right) \right] - q_x \frac{\partial c}{\partial x} - q_y \frac{\partial c}{\partial y} - q_z \frac{\partial c}{\partial z} + W (c^* - c) = \frac{\partial c}{\partial t}
\]  

where \( q_x, q_y, \) and \( q_z \) are the Darcy velocities; \( c^* \) is the solute concentration in the source or sink fluid; and \( D_{xx}, D_{xy}, \) and \( D_{xz} \), etc., are coefficients of hydrodynamic dispersion.

The solution for the seawater intrusion problem, which involves the simultaneous solution of the coupled flow and transport equations, is numerically difficult. Yet, the advective component of transport equation dominates in most of the field problems. Solution of such an equation by conventional techniques viz., finite differences or finite elements is susceptible to numerical dispersion (Pinder and Gray, 1977; Huyakorn and Pinder, 1983). A more attractive strategy to overcome some of these difficulties is to apply the moving particle methods. Seawater intrusion models, using the moving particle methods, are largely based on the method of characteristics (MOC) proposed by Garder et al.in 1964. The SEAWAT code (Guo and Langevin, 2002) has been developed by combining the USGS MODFLOW and MT3DMS codes into a single program to simulate 3D variable density.
transient groundwater flow in porous media and has been used in a number of field studies by researchers for mathematical simulation of coastal aquifers (viz. Rao et al., 2004; Masterson, 2004; Wolfert et al., 2005; Larabi, 2008). A recent version of SEAWAT by Langevin and Guo (2006) combines variable density groundwater flow coupled with multi-species solute and heat transport. Sanford and Pope (2010) used SEAWAT to develop and calibrate a 3D model of the aquifer system of the Eastern Shore of Virginia, USA to reproduce historical water levels and forecast the potential for saltwater intrusion. Cobanera et al. (2012) employed SEAWAT to model the seawater intrusion mechanism in the Goksu Deltaic Plain along the Mediterranean coast of Turkey. Rasmussen et al. (2013) quantified the impact of sea level rise and changes in groundwater recharge for an island located in the Western Baltic Sea. SEAWAT was used to simulate the historical, present and future freshwater-sea water distribution in the area. Numerical experiments for a field-scale 2D cross section were performed by Motz and Sedighi (2013) to investigate saltwater intrusion and recirculation of seawater at a coastal boundary.

However, important issue not addressed adequately is that of long-term sustainability of the groundwater development in coastal aquifers. The present work attempts to address such issues in an interbasin area, including Puri city, in Odisha, with varying level of rigor.

**Study Area**

The Index map of the study area is shown in Fig. 2. The Study area is located between 85°32’5”E 86°5’36”E Longitude and 19°42’4”N to 20°19’34”N Latitude. It has geographical area of 1834 Square Km. The study area has river Daya flowing along its northwestern boundary whereas river Kushabhadra flows along the eastern boundary. The Bay of Bengal occurs towards southeast of the study area and Chilika lake is situated on the southwestern boundary. The area falls in the lower Mahanadi delta region. The study area comprises of ten blocks out of which 8 blocks belong to Puri District and two belong to Khurda District (Das 2013).

**Climate and Rainfall**

The area of study enjoys a subtropical, humid climate characterized by three distinct seasons: summer, winter and rainy. May is the hottest month with an average temperature of 33°Celsius whereas December is the coldest month with an average temperature of 24°Celsius. The maximum temperature goes up to 43°Celsius in summers whereas the minimum temperature recorded is 14°Celsius in Winter. The annual average rainfall of the study area is 1449.1 mm out of which around 89% rainfall occurs in monsoon i.e. from mid-June to October. Rest of the rainfall takes place during
Non-monsoon period i.e. from November to June. The relative humidity is generally high throughout the year. It varies from 69.92% in December to 87.00% in August. The mean monthly potential evapotranspiration value varies from 102.61 mm in December to 158 mm in May (calculated average of 1992-2001). The average wind velocity is 257.37 km/Day. The number of average sunshine hours is 5.82 with the maximum of 7.80 in April and minimum of 2.80 in July.

**Hydrogeology**

The unconsolidated sand and gravel layers of Tertiary and Quaternary age form the main aquifers in the area of study. The upper aquifer is generally unconfined in nature and ground water occurs under water table conditions up to 135 m depth below ground level (CGWB, 2004). Below this, there are semi confined and confined aquifers, the confining layers being mainly clay. The aquifers are extensive, interconnected and have prolific yield potential. The thickness of individual aquifer varies from 6 to 10 m whereas the cumulative thickness of aquifer zones varies from 15 to 79 m down to a depth of 250 m.

The sand and gravel layers, the potential aquifers, may be in the form of lenses or laterally interconnected and repetitive units, forming multi aquifer systems. The sandy aquifers having admixture of clays have low hydraulic conductivity. The deeper horizons are confined by extensive clay beds thickening towards the coast.

In the upstream areas, the aquifers occur as horizontal layers showing increasing dips towards the coast. The Tertiary and Quaternary formations occur mainly in the eastern and southern parts of the district. Laterite occurs as cappings on the Crystallines and Gondwanas.

For developing the subsurface geological picture of the study area, around 30 boreholes drilled by CGWB and GWS&I were analyzed to ascertain the extent and thickness of different strata. Besides, data of around 20 vertical electrical soundings were also used for the above purpose. Based on the analysis of the above data, a geological fence diagram of the study area was prepared as given in Fig. 3 (Das 2013).

![Geological fence diagram of the study area](image-url)
**Interpretation of Groundwater Quality Data**

While the salinity of groundwater may change due to seawater encroachment of coastal aquifer, an aquifer may also acquire high salinity due to following causes:

i) Inherent salinity enrichment through repetitive evaporative processes

ii) Salinity ingress through tides and creeks in the coastal areas

In the present study, available historical data of groundwater quality of 39 dug wells monitored by CGWB and Odisha State Groundwater survey and investigation (GWSI) department was interpreted for the period from 1990 to 2001. The data was not available for the later years.

Among the chemical attributes of the groundwater, the total dissolved solids (TDS) of the groundwater ranged from 119 to 2723 mg/lit whereas the chloride values ranged from 14 mg/lit in 1990 (at Brahmagiri, in the southwest corner of the study area) to 525 mg/lit at Algum (west-central part) in 1995. However, amongst the anions, carbonates are almost negligible due to the pH of the groundwater being generally below 8.3 except at few localities. The bicarbonate ion ranged from 73 mg/lit at Brahmagiri, Nimapara and Balakati in 1990 to 641 mg/lit at Algum in 1995.

**TDS maps**

The GIS based TDS contour maps for the shallow groundwater of the study area were prepared for understanding the nature of spatial variation of total dissolved solids for the pre-monsoon period from 1990 to 2001. These maps for 1990, 1995 and 2001 are presented in Fig. 4a, 4b and 4c respectively for ready reference. Fig. 4a (for year 1990) which included only 24 ground water sampling points indicates that maximum TDS of the ground water was observed to be around 2000 mg/lit (at Moradapada village) whereas the minimum TDS of around 200 mg/lit was observed near Brahmagiri area. Similarly, the spatial distribution of total dissolved solids (TDS) in the shallow groundwater of the study area for the year 1993, when a larger number of sampling locations were covered (Fig. 4b), indicated that the TDS ranged between 172 mg/lit at Ramchandi (in the extreme southeastern corner of the study area) and 1131 mg/lit at Algum (in the west-central part). At most other localities, the TDS of the groundwater was within 1000 mg/lit. The localities with low TDS (<400 mg/lit) shown by shades of green are quite widely spread within the area, especially in the east-central and northern part.

In contrast to the above, TDS contour maps for years 1990, 1995, and 2001 (Fig. 4a, 4b and 4c) are showing area around Algum having highly saline groundwater. The areas with relatively higher TDS (600-1000 mg/lit) are at Gopinathpur and around Madrang (towards east). However, during 2001 (Fig. 5c), new areas of high TDS (1800 mg/lit) are visible near the seashore at Mahapur (2929 mg/lit) and Moradpada (1691 mg/lit).

**Identification of seawater encroachment into aquifer(s)**

The foregoing discussion about the total dissolved solids in the shallow groundwater of the study area have brought out a reasonable understanding of the groundwater chemistry but has failed to indicate any incidence of abnormal salinity in the groundwater except at Algum village in the west central part of the area and a couple of localities near seashore.
Fig. 4a TDS Map for 1990.

Fig. 4b TDS Map for 1995.
Some CGWB reports attribute high salinity at Algum to use of fertilizers in irrigation. Yet, the TDS and chloride values at this location are also not abnormally high. Thus, it would be logical to consider other viable criteria for identifying the seawater intrusion, if any, in the area as the seashore is not far from the study area and Siara, Gopinathpur, Puri, Balighai and Ramchandi villages are situated close to the seashore.

In the light of above discussion, chloride-bicarbonate ratio has been used in the present work to identify seawater intrusion in the aquifers of the area, based on the approach given by Revelle (1941). If Cl/HCO₃ < 0.5, it may indicate that the water is unaffected by encroachment due to sea water. The higher ratio of over 0.5 is taken to indicate that groundwater is moderately affected due to seawater encroachment. A Cl/HCO₃ ratio > 6.6 may indicate that groundwater is strongly affected due to seawater intrusion. Further, the incidence of seawater encroachment should be supported by abnormally high TDS values (greater than 1500 mg/lit).

**Chloride-Bicarbonate Ratio maps**

Fig. 5 shows the bar diagrams indicating chloride-bicarbonate ratio at a few sampling wells during pre monsoon period of 1996. Besides, the Fig.6 and Fig.7 show the contours of chloride-bicarbonate ratio in the shallow groundwater of the area during 1990, and 1997 respectively (Such contour map could not be prepared for year 1996 due to lack of enough sampling points). It is seen from these maps that during early times of 1990, the groundwater was found to have high chloride-bicarbonate ratio (between 2.2 to 5) around Budhiabar-Rebana Nuagaon-Chandanpur near the coast, which seems to indicate slight onset of seawater encroachment. But this zone seems to have shrunk around Rebana Nuagaon-Budhiabar village during 1997. Further, the areas around Baliguari (northeast of Puri town) and Gopinathpur (in southwest corner) near the seashore also show Cl/HCO₃ ratio higher than 1.8 which indicates slight to moderate seawater intrusion. Yet, it may be noted that even areas far away from the coast around Mangalpur-Delang villages also seems to be affected by the encroachment. It is difficult to assign a specific reason for such encroachment but the seawater ingress due to tidal fluctuations along the local and regional rivers (viz., Daya and Kushabhadra rivers) may not be ruled out. The bar diagram for Cl/HCO₃ ratio for the year 1996 also seems to corroborate existence of groundwater contamination by seawater at Balipatna, Sakhigopal, Balighai and Delang villages (Fig. 5).

It may be noted that more recent groundwater quality data was not available for the above analysis.
Fig. 5 Chloride/Bicarbonate Values for Premonsoon 1996.

Fig. 6 \[ \frac{I^{-1}}{\left(\text{CO}_3^{2-} + \text{HCO}_3^{-}\right)} \] Ratio map for Pre-monsoon period 1990.
Fig. 7 \[
\frac{\text{Cl}^1}{(\text{CO}_3^{-2} + \text{HCO}_3^{-1})}
\] - Ratio map for pre-monsoon period 1997.
Table 1 Summary of groundwater quality data analysis

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Name of Well Hyd. Station</th>
<th>TDS(1997), Mg/lit</th>
<th>Cl&lt;sup&gt;−&lt;/sup&gt;/(HCO&lt;sub&gt;3&lt;/sub&gt;)&lt;sup&gt;−&lt;/sup&gt; 0.5-6.6</th>
<th>Cl&lt;sup&gt;−&lt;/sup&gt;/(CO&lt;sub&gt;3&lt;/sub&gt;&lt;sup&gt;2&lt;/sup&gt;+HCO&lt;sub&gt;3&lt;/sub&gt;)&gt;6.6</th>
<th>Remark (Origin)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Algum (Satyabadi)</td>
<td>1147</td>
<td>-</td>
<td>-</td>
<td>Fertilizers</td>
</tr>
<tr>
<td>2</td>
<td>Sakhigopal (Satyabadi)</td>
<td>427</td>
<td>Sakhigopal</td>
<td>-</td>
<td>SWI</td>
</tr>
<tr>
<td>3</td>
<td>Chandanpur (Puri)</td>
<td>510</td>
<td>Chandanpur (Puri)</td>
<td>Chandanpur</td>
<td>SWI</td>
</tr>
<tr>
<td>4</td>
<td>Rebana Nuagaon (Brahmagiri)</td>
<td>600</td>
<td>Rebana Nuagaon</td>
<td>Rebana Nuagaon</td>
<td>SWI</td>
</tr>
<tr>
<td>5</td>
<td>Baligur (Puri)</td>
<td>396</td>
<td>Baligur</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Mangalpur (Pipli)</td>
<td>283</td>
<td>Mangalpur</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Budhibar (Brahmagiri)</td>
<td>510</td>
<td>Budhibar</td>
<td>-</td>
<td>SWI</td>
</tr>
<tr>
<td>8</td>
<td>Gopinathpur (Brahmagiri)</td>
<td>750</td>
<td>Gopinathpur</td>
<td>-</td>
<td>SWI</td>
</tr>
<tr>
<td>9</td>
<td>Delang</td>
<td>551</td>
<td>Delang</td>
<td>-</td>
<td>SWI</td>
</tr>
<tr>
<td>10</td>
<td>Balipatna (Balipatna)</td>
<td>-</td>
<td>Balipatna</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Balikati (Balipatna)</td>
<td></td>
<td>Balikati</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: SWI = Seawater intrusion is suspected

Inferences from Analysis of Groundwater Quality

Table 1 presents a summary of the groundwater quality in the study area highlighting the possible source(s) of high salinity in the ground water. On the basis of the chemical analysis, following localities seem to be affected by slight to moderate seawater encroachment into the shallow coastal aquifer of the study area:

(i) Gopinathpur, Budhibar and Rebana Nuagaon in Brahmagiri block

(ii) Chandanpur and Baligur (Puri block)

(iii) Sakhigopal in Satyabadi block

(iv) Delang in Delang block

(v) Balipatna and Balakati villages in Balipatna block (Khurda district)

(vi) Majority of the above locations barring Delang (in Pipli block) and Balipatna block are located within a distance of about 3-4 km from the seashore. Yet, Algum in Satyabadi block seems to be having relatively high TDS of groundwater (1147 mg/lit in 1997 and 1811 mg/lit in 2001) but the Cl<sup>−</sup>/HCO<sub>3</sub><sup>−</sup> ratio is within permissible limits (<0.5). Therefore, the high salinity at this place seems to be due to a cause other than sea water encroachment (like use of excessive fertilizers during agricultural cultivation etc.). This is also corroborated by the sources of GWS&I (2002) and CGWB (2004).

(vii) Generally, majority of the groundwater monitoring wells affected by higher Cl<sup>−</sup>/HCO<sub>3</sub><sup>−</sup> ratio show the total dissolved solids to be well below the limit of 1500 mg/lit, the value above which there may be greater likelihood of ground water contamination by seawater. However a couple of locations (e.g., Delang, Balipatna and Mangalpur) being far off over 15 km from the seashore, also seem to be affected by seawater encroachment which may be explained due to these places being located close to the Daya river which is believed to be affected by sea water ingress during high tides.

Modelling of Seawater Intrusion

In the present study the seawater intrusion in coastal aquifer in the inter-basin of Puri District, India has been simulated employing an available model/package named as SEAWAT (Guo and Langevin, 2002). The aquifer system of the study area is conceptualized in accordance with the outcome of the hydrogeological analysis presented earlier.

Vertical Profile: The aquifer system in the study area is idealized as a set of eight horizontal layers (Table 2) with a cumulative thickness of 240 m. The uppermost layer is bounded on the top by ground surface. The lowermost layer is bounded on the bottom by an impervious medium.
Table 2 Vertical Discretization

<table>
<thead>
<tr>
<th>Layer no</th>
<th>Thickness (m)</th>
<th>Type of soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>Sandy clay</td>
</tr>
<tr>
<td>2</td>
<td>40</td>
<td>Medium sand</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>Sandy clay</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>Sand and gravel</td>
</tr>
<tr>
<td>5</td>
<td>20</td>
<td>Sandy clay</td>
</tr>
<tr>
<td>6</td>
<td>60</td>
<td>Sand and gravel</td>
</tr>
<tr>
<td>7</td>
<td>20</td>
<td>Clay</td>
</tr>
<tr>
<td>8</td>
<td>40</td>
<td>Coarse sand</td>
</tr>
</tbody>
</table>

Lateral Boundaries
The aquifer layers described above are assumed to be interfacing with the sea (Bay of Bengal)/Chilika lake towards its southern boundaries (Fig. 2).

The interface is assumed to extend over the entire thickness of the flow domain. Chilika lake is assumed to be hydraulically connected to the sea. As such, the head along this boundary is assumed to be to be the mean sea level. Whereas the concentration along the sea boundary is assumed to be 35,000 mg/lit, the concentration along the lake boundary is assumed as 10,000 mg/lit.

Along the western and eastern boundaries, the aquifer system is assumed to be interfacing with rivers Kuakhai, Daya and Kushbadra respectively. The interface is assumed to extend vertically up to the bottom of first layer. A water divide is assumed to exist below that. Accordingly, the aquifer heads and concentrations along these boundaries in the first layer are assigned in accordance with the available river stage/water quality data from Central Water Commission (CWC), Bhubaneswar and State Pollution Control Board Bhubaneswar.

Spatial and Temporal Discretization
A finite-difference grid is developed to adequately discretize the flow domain. The domain encompasses an area of 1634 km². The grid consists of 109 columns, 76 rows with 8284 regular cells in plan view. Each cell is 500 m x 500 m in the horizontal plane. Further, the domain is discretized vertically into 8 layers.

To align the grid along the principal directions in plan, it was oriented along and across the general coast line i.e. 15° from true North. The top and bottom elevations of the model are set at 15 m (AMSL) and -225 m (AMSL) respectively. The top and bottom elevations of each layer correspond to the average top and bottom elevations of the strata of the field as identified earlier.

Checks on Space and Time Steps: In solving the advective-dispersive transport equation, numerical error can be related to two dimensionless numbers viz. and Peclet number (Pe = Δx/α), where V = velocity, Δx = space step, Δt = time step and α = Dispersivity.

In the present study, the time steps are generated dynamically employing the “current” velocity fields. The limiting Co(Courant number = VΔt/Δx) has been conservatively taken as 0.75. Further, it is ensured that outputs are compulsorily produced at the discrete times at which the observed water table and concentration data are available.

Model Calibration
The model parameters are estimated employing a data base comprising of the spatial distribution of water table elevation and the salt concentration in the top layer at 40 discrete times spanning over a period of 10 years viz., January 1992 to Jan 2002. The calibration is conducted by a subjective minimization of the mismatch between the observed and model computed head/concentration fields (Das 2013).
Initial and Boundary Conditions

Initial conditions in respect of the head and concentration were assigned invoking the available data of January 1992. Boundary conditions are assigned in accordance with the conceptual model. The source/sink term is assumed to comprise of (i) pumpage (ii) rainfall recharge and (iii) evapotranspiration.

Transient Calibration

This calibration is based upon the observed water table elevation data from 25 observation wells; and observed salt concentration data from 32 observation points. These data span over a period of ten years viz. 1992 to 2002. While the water table data are available four times a year (January 1, April 1, August 1 and November 1); the concentration data are available only once a year (April 1). These discrete point data are employed to generate cell-wise water table heads at 40 discrete times, and cell-wise concentration values at 10 discrete times.

The objective of this calibration is to estimate the model parameters other than the hydraulic conductivities that are already estimated during steady state calibration. As such, the following layer-wise parameters are estimated during transient calibration (Das 2013): (i) Specific storage ($S_s$), (ii) Effective porosity ($\theta_e$) and (iii) Longitudinal dispersity ($\alpha$).

As per the local practices, other parameters viz. Specific yield, Infiltration factor and Extinction depth are assumed to be 0.06, 0.2 and 4 m. The calibration is conducted by minimizing the mismatch between the observed and model computed head and concentration fields in the first layer. The mismatch is quantified by the following statistics (SS & SSC).

\[
SS = \sum_{k=1}^{r_1} \sum_{i=1}^{n} (H_{ikc} - H_{iko})^2
\]

\[
SSC = \sum_{k=1}^{r_2} \sum_{i=1}^{n} (C_{ikc} - C_{iko})^2
\]

where $n =$ number of cells in first layer, $r_1 (=40)$, $r_2 (=10)$ number of discrete calibration times in respect of water-table and salt concentration, $h_{ikc} =$ computed head at $i^{th}$ cell at $k^{th}$ time, $h_{iko} =$ observed head at $i^{th}$ cell at $k^{th}$ time, $C_{ikc} =$ computed concentration at $i^{th}$ cell at $k^{th}$ time, $C_{iko} =$ observed concentration at $i^{th}$ cell at $k^{th}$ time.

In all the calibration is conducted over six runs. The first run corresponds to the parameter values derived from published data (CGWB 2004, Gelhar 1992). In subsequent runs, the parameter values were changed subjectively by visual inspection of the mis-match between simulated and observed heads/concentrations. Through such judicious trials, the mis-match parameters (SS and SSC) reduced from Run 1 to Run 3. Subsequent trials (Runs 4 to 6) did not yield any further improvement. (Table 3). It may be inferred that Run 3 leads to minimum SS and near-minimum SSC. As such, these parameter values were accepted.

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Calibration runs</th>
<th>SS (m$^2$)</th>
<th>SSC (mg/lit)$^2$</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Run 1</td>
<td>993</td>
<td>2709153</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Run 2</td>
<td>992</td>
<td>2547975</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Run 3</td>
<td>833</td>
<td>2558009</td>
<td>Calibrated parameters</td>
</tr>
<tr>
<td>4</td>
<td>Run 4</td>
<td>995</td>
<td>2709141</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Run 5</td>
<td>1014</td>
<td>2709141</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Run 6</td>
<td>1148</td>
<td>3145703</td>
<td></td>
</tr>
</tbody>
</table>

The corresponding reproduction of the head and concentration fields at a few typical advancing times is given in Figs. 8 and 9.

The calibration reported above is based upon assumption of ($d_e = 4$ m) and ($\beta = 0.2$). These assumptions were cross-checked by computing SS with $d_e$ varying in a range of 1.5 to 4 m; and $\beta$ in a range of 0.1 to 0.25. It was revealed that SS is minimal at the assumed values of $d_e$ and $\beta$ as in Eq. (5) and Eq. (6).
Fig. 8 Computed and Observed Water Table Contours (Time: 366 days; Jan. 1, 1993).

Fig. 9 Computed and Observed TDS Contours (116 days, April 1992).

**Computation of Extent of Seawater Intrusion**

The extent of sea-water intrusion at the end of simulation period (January 2002) along a reference vertical section XX normal to seashore is quantified by drawing contours of concentration in this section (Fig. 10). The figure displays a diffused seawater freshwater interface where in the salt concentration varies from 35000 to practically zero mg/lt.
Recalling that the assumed salt concentration in seawater is 35000 mg/lit, the contour of 17500 mg/lit represents the midway concentration in the diffused interface. It is a common practice to align the sharp interface along the contour of this “mid-way” concentration. As such, in the present study the contour of 17500 mg/lit is deemed to be position of sharp interface (Das 2013).

Conclusions

The above study has brought out the areas of seawater encroachment in the coastal areas of Puri and Khurda districts of Puri interbasin area of Odisha during the period between the years 1990 and 2001. The study revealed that the coastal parts of the Brahmagiri, Puri, Satyabdi and Delang Blocks in Puri District and Balipatna Block in Khurda district were severely affected by seawater encroachment, as reflected from high TDS values and increasing Chloride-Bicarbonate ratios in the groundwaters. Further, the seawater intrusion in the study area has been simulated by using SEAWAT software package. The calibrated model revealed that during the period between years 1990 and early 2002, the seawater interface had penetrated beneath the ground surface up to a lateral distance of around 3500m from the shore line. After the transient model calibration conducted over six runs, it was concluded that Run 3 displayed minimum mismatch between simulated and observed heads/concentrations. However, there is a strong need to optimize the most economic cropping pattern in the area in order to enable farmers of the area maximise their agricultural income.

Acknowledgements

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Groundwater Quality Assessment for Drinking Purposes Using Analytic Hierarchy Process (Case Study: Roorkee Town, India)

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Abstract

In the present paper groundwater quality of Roorkee town (Haridwar District) in the Uttarakhand State of India is assessed on the basis of numerical indexing using the Analytic Hierarchy Process which is a multi-criteria decision-making approach (MCDM). For this purpose, 22 groundwater samples from different locations were collected and physico-chemical analysis, heavy metal analysis and bacteriological analysis were performed to estimate the concentrations of the groundwater quality parameters. The study shows that though the physico-chemical quality of the groundwater is within the permissible limit for drinking water, the concentrations of few heavy metals (Hg, Al, B, Fe and Mn) are very high in most of the groundwater samples. The bacteriological analysis shows that faecal coliforms are also high at Saliar and Fish market. Ground Water Quality Index (GWQI) was calculated using seventeen groundwater quality parameters (Hg, As, Pb, Cr, Cd, Cu, Al, B, Zn, NO₃, Fe, Mn, Mg, Se, TH, TDS and TA) and a GWQI map has been prepared for pre-monsoon 2012. It is observed that the GWQI is higher towards north-western and south-eastern parts of the study area, showing a poor ground water quality for drinking purposes.

Keywords: Groundwater quality, Analytic hierarchy process, Data analysis, Roorkee town.

Introduction

Increasing urbanization and industrialization is resulting in rapid degradation of water quality of the cities around the world thus placing the groundwater resources unfit for drinking. In a number of studies all over the world, poor water quality has been a main reason for unsustainability of water resources. This necessitates the continuous monitoring of fresh water resources. Groundwater is one of our most important sources of water for drinking, agricultural and industrial purposes; however, the quality of groundwater varies as a result of physical, chemical, and ecological changes.

Use of poor quality drinking water may result in serious health hazards (Germolec et al. 1989). Water Quality Index is used to rank the quality of water numerically (Horton 1965) by combining multiple water quality parameters to estimate a dimensionless number that represents the water quality (Miller et al. 1986). Analytic Hierarchy Process (AHP) is a multi-criteria decision-making (MCDM) approach used to evaluate the quality of water and hence, estimate Water Quality Index (Melloul and Collin 1998; Tirkey et al. 2013; Jeihouni et al. 2014; Singhal et al. 2012). MCDM is a multi-criteria complex decision making approach used to solve problems in many engineering fields and determine the best criteria among the multiple conflicting criteria (Agarwal et al. 2013). The approach is widely used in ground water pollution potential assessment (Jhariya et al. 2019) and disaster management applications (Ustun and Barbarosoglu 2015). MCDM approach is also applied to evaluate the potential ground water zones (Kumar et al. 2014).

Roorkee town is situated on the right bank of Solani river and the groundwater serves as the main source of drinking water in the town and its suburbs. The topology of study area has a slope from north-west to south-east and the river follows this slope. The sewage irrigation practice in Saliar village (6 km north-west of Roorkee town) increases the possibility of transportation of sewage pollutant towards the town. The aim of this study is to evaluate the pollution hazard in the Roorkee and its suburbs and to point out the possible sources and reasons of ground water contamination. To evaluate the groundwater quality, Ground Water Quality Index (GWQI) is computed using AHP in terms of heavy metals and physicochemical parameters. Subsequently, GWQI is used to estimate Ground water Quality for drinking purpose.
Study Area

The Roorkee town and its suburbs (latitude 29° 50' to 29° 55' N and 77° 50' to 77° 50' E) are situated in northern parts of India in the foothills of Himalayas and right bank of the Solani River in the district Haridwar, Uttarakhand, India (Fig. 1). The Solani River flows from north-west to south-east direction. The surface topology of the study area has a slight slope towards south-east. The Upper Ganga Canal which is 230 km long flows through the centre of the town, divides the town into two parts: old Roorkee area, situated on the west bank of canal and IIT campus and cantonment area, situated on the east bank of canal. Malakur cut is a subsidiary drain flowing in the study area towards east.

Methodology

In the present paper, the AHP is used to assess groundwater quality and vulnerability. This is a MCDM approach introduced by (Saaty 1986) that is used in solving a large variety of engineering problems. The process is widely used in the assessment of the groundwater pollution potential by performing pair-wise comparisons to determine the relative importance of the multiple parameters. For analysing the groundwater quality, the groundwater samples were collected from 22 locations during pre-monsoon 2012 (Fig. 1). The bacteriological, physico-chemical and heavy metal analysis of the field data were performed. The chemical analysis of the groundwater samples indicates the high concentration of faecal coliforms at few locations (Saliar and Fish market) (Tables 1a, 1b). For estimating the GWQI of the study area, seventeen groundwater quality parameters (Pi) (Hg, As, Pb, Cr, Cd, Cu, Al, B, Zn, NO3, Fe, Mn, Mg, Se, TH, TDS and TA) (Tables 2a, 2b) and (Figs. 2a, 2b) are selected. Only those water quality parameters are considered that are important for human health according to the Central Ground Water Board (CGWB 2012). The groundwater quality parameters are classified
into five groups depending on the human health significance (Table 3). The parameters in Group I are considered the most important and the parameters in Group V are least important for human health. The pair-wise comparison is performed to determine the relative importance and the relative weights of the parameters in the comparison matrix. The AHP judgement matrix and parameter weights for estimating GWQI are computed in the following steps:

1. Pair-wise comparison is performed by the decision-maker by weighing the importance of the parameter. Depending upon the relative importance of the parameters a numerical weight $a_{ij}$ is assigned to the first parameter over the second parameter with the constraint $a_{ij}=1/a_{ji}$ and an AHP judgement matrix is prepared.

2. Eigen vector or the geometric mean of each criterion/parameter is estimated.

$$E_i = \prod_{j=1}^{N} \left(a_{ij}\right)^{1/N}$$  \hspace{1cm} (1)

3. The fuzzy weights of each parameter is calculated as follows:

$$W_i = \frac{E_i}{\sum_{i=1}^{N} E_i}$$ \hspace{1cm} (2)

4. Relative weights of each parameter $W_{r,i}$ is estimated by scaling each parameter weight with the maximum weight ($W_{max}$).

5. To transform the water quality concentration values to the rating values $Y_{ij}$, the field data $P_{ij}$ of $i^{th}$ row and $j^{th}$ parameters are normalized by their permissible limits ($P_{j,d}$) with respect to drinking water (BIS:10500, 2012) as $X_{ij}=P_{ij}/P_{j,d}$.

6. $X_{ij}$ is related corresponding to rating value $Y_{ij}$ using the function, $Y_{ij}=f(X_{ij})$ as follows:

- For good groundwater quality, $X_{ij} = 0\cdot1$, the corresponding rating value is approximately equal to 1.
- For acceptable groundwater quality, $X_{ij} = 1$, the corresponding rating value is approximately equal to 5.
- For unacceptable groundwater quality, $X_{ij} >= 3\cdot5$, the corresponding rating value is approximately equal to 10.

The parabolic function for rating values is estimated using the above $X_{ij}$ and $Y_{ij}$ values:

$$Y_{ij} = -0\cdot712X_{ij}^2 + 5\cdot228X_{ij} + 0\cdot484$$

7. Using the above rating equation the rating value of any $X_{ij}$ can be estimated and the relative rating value ($Y_{r,ij}$) is estimated by dividing the rating value by the maximum possible rating value ($Y_{max}=10$).

8. The GWQI is determined by follows:

$$GWQI_i = C/N \left[\sum_{j=1}^{N} (W_{r,j} \cdot Y_{r,ij})\right]$$  \hspace{1cm} (3)

where, $C$ is a constant and its value is chosen as 10.

The above mentioned method is used to determine the GWQI for the study area and the GWQI map is prepared (Fig. 3).

### Table 1a Bacteriological quality of groundwater (pre-monsoon 2012) (Mishra 2012)

<table>
<thead>
<tr>
<th>Location</th>
<th>10.0 ml</th>
<th>1.0 ml</th>
<th>0.1 ml</th>
<th>MPN/100 ml</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saliar</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>300</td>
</tr>
<tr>
<td>Rampur</td>
<td>0</td>
<td>0</td>
<td>0</td>
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</tr>
<tr>
<td>Sheikhpuri</td>
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<td>NIL</td>
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<td>3</td>
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<td>80</td>
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<td>50</td>
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<td>4</td>
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<td>IIT</td>
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</table>
Table 1b Faecal coliform data of groundwater (pre-monsoon 2012) (Mishra 2012)

<table>
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<tr>
<th>Location</th>
<th>10.0 ml</th>
<th>1.0 ml</th>
<th>0.1 ml</th>
<th>Fecal Coliform/100 ml</th>
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<td>1</td>
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<td>Rampur</td>
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<td>NIL</td>
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<td>Sheikhpuri</td>
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<td>0</td>
<td>NIL</td>
</tr>
<tr>
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<td>1</td>
<td>0</td>
<td>2</td>
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<td>NIL</td>
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<tr>
<td>Malakpur</td>
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<td>0</td>
<td>0</td>
<td>NIL</td>
</tr>
<tr>
<td>Adarshnagar</td>
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<td>0</td>
<td>0</td>
<td>NIL</td>
</tr>
<tr>
<td>Main market</td>
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<td>0</td>
<td>0</td>
<td>NIL</td>
</tr>
<tr>
<td>IIT</td>
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<td>0</td>
<td>0</td>
<td>NIL</td>
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</tbody>
</table>

Results and Discussion

GWQI map suggests that 16 out of 22 locations have GWQI higher than 2 and 7 locations have GWQI higher than 2.5 (Saliar, Rampur, Ramnagar, Salempur, Khanjarpur, Malakpur and IIT) suggesting that the groundwater is unfit for drinking purposes at these locations (Fig. 3). Northwestern parts (Saliar, Rampur, Ramnagar, Salempur and IIT) and eastern part (Khanjarpur and Malakpur) of the study area have lower water quality than other parts of the study area. The reason for poor groundwater quality in the northwestern parts and eastern parts might be due to the promotion of sewage irrigation in Saliar village, discharge of the industrial waste from the industries located in Ramnagar industrial area and a subsidiary drain flowing in the eastern part known as Malakpur Cut. Although the GWQI is used to estimate the pollution level in the study area, there is also a need to study the groundwater vulnerability in a more systematic manner by analyzing the effect of hydrogeological features on groundwater pollution.

Table 2a Groundwater quality data (Hg, As, Pb, Cr, Cd, Cu, Al, B) (Singhal et al. 2015)

<table>
<thead>
<tr>
<th>Location</th>
<th>Hg (mg/l)</th>
<th>As (mg/l)</th>
<th>Pb (mg/l)</th>
<th>Cr (mg/l)</th>
<th>Cd (mg/l)</th>
<th>Cu (mg/l)</th>
<th>Al (mg/l)</th>
<th>B (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ibrahimpur</td>
<td>0.0039</td>
<td>0.00091</td>
<td>0.0255</td>
<td>0.0042</td>
<td>35.2132</td>
<td>0.0088</td>
<td>0.0684</td>
<td>4.9618</td>
</tr>
<tr>
<td>Saliar</td>
<td>0.0065</td>
<td>0.0061</td>
<td>0.2578</td>
<td>0.0083</td>
<td>0.0409</td>
<td>0.0554</td>
<td>0.5971</td>
<td>3.0316</td>
</tr>
<tr>
<td>Rampur</td>
<td>0.00356</td>
<td>0.0089</td>
<td>0.1305</td>
<td>0.0049</td>
<td>0.4186</td>
<td>0.0659</td>
<td>0.1156</td>
<td>2.7544</td>
</tr>
<tr>
<td>Ramnagar</td>
<td>0.0026</td>
<td>0.0103</td>
<td>0.0229</td>
<td>0.0037</td>
<td>0.0685</td>
<td>0.037</td>
<td>0.1216</td>
<td>1.7259</td>
</tr>
<tr>
<td>Muttalapur</td>
<td>0.003</td>
<td>0.0018</td>
<td>0.0189</td>
<td>0.00463</td>
<td>0.02705</td>
<td>0.0168</td>
<td>0.093</td>
<td>1.941</td>
</tr>
<tr>
<td>Kashipuri</td>
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<td>0.0052</td>
<td>0.0128</td>
<td>0.0041</td>
<td>0.0076</td>
<td>0.01252</td>
<td>0.218</td>
<td>2.0921</td>
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<td>Azadnagar</td>
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<td>0.0019</td>
<td>0.0695</td>
<td>0.00409</td>
<td>0.00136</td>
<td>0.0169</td>
<td>0.1115</td>
<td>1.4228</td>
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<td>0.0033</td>
<td>0.0203</td>
<td>0.0097</td>
<td>0.0015</td>
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</tr>
<tr>
<td>Ganeshpur</td>
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<td>0.00257</td>
<td>0.00536</td>
<td>0.00515</td>
<td>0.0132</td>
<td>0.0756</td>
<td>0.0316</td>
<td>1.1771</td>
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<td>Salempur</td>
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<td>0.0039</td>
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<td>0.0269</td>
<td>0.01311</td>
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<td>1.5628</td>
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<tr>
<td>Padligujar</td>
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<td>0.0238</td>
<td>0.00278</td>
<td>0.0209</td>
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<tr>
<td>Rahimpur</td>
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<td>0.01359</td>
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<td>0.0027</td>
<td>0.00372</td>
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<tr>
<td>Mohanpura</td>
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<td>0.0005</td>
<td>0.03377</td>
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<td>0.012</td>
<td>0.0162</td>
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<td>0.0004</td>
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<td>Khanjarpur</td>
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<td>0.0082</td>
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<td>0.00934</td>
<td>0.0075</td>
<td>0.0204</td>
<td>0.1425</td>
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</table>
Conclusions

The groundwater quality has been evaluated for Roorkee town and its suburbs. The quality of the groundwater is poor at the places located towards the north-west and south-east of the study area (unfit for drinking purposes). The major source of drinking water in Roorkee town is groundwater. Therefore, there is a need for planning groundwater protection strategy for the area. The suggestions for putting restraints in operation and management of the groundwater for drinking and other purposes should be provided by the authorities. NGO’s, civic authorities and public awareness campaigns can play an important role in this context.

Table 2b Groundwater quality data (Zn, NO$_3$, Fe, Mn, Mg, Se, TH,TDS) (Singhal et al. 2015)

<table>
<thead>
<tr>
<th>Location</th>
<th>Zn (mg/l)</th>
<th>NO$_3$ (mg/l)</th>
<th>Fe (mg/l)</th>
<th>Mn (mg/l)</th>
<th>Mg (mg/l)</th>
<th>Se (mg/l)</th>
<th>TH (mg/l)</th>
<th>TDS (mg/l)</th>
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<tr>
<td>Ibrahimpur</td>
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<td>Group V</td>
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</tr>
<tr>
<td>Mercury (Hg)</td>
<td>Copper (Cu)</td>
<td>Iron (Fe)</td>
<td>Total dissolved solid (TDS)</td>
<td>Total alkalinity (TA)</td>
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<td>Lead (Pb)</td>
<td>Aluminium (Al)</td>
<td>Manganese (Mn)</td>
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<td>Arsenic (As)</td>
<td>Boron (B)</td>
<td>Magnesium (Mg)</td>
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<td>Cadmium (Cd)</td>
<td>Nitrate(NO₃)</td>
<td>Selenium (Se)</td>
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<td>Chromium (Cr)</td>
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</tr>
</tbody>
</table>

Table 3 Water quality parameters based on human health significance (Mishra 2012)
Fig. 2a Plots showing the concentration of groundwater quality parameters (Hg, As, Pb, Cr, Cd, Cu, Al and B).
Fig. 2b Plots showing the concentration of groundwater quality parameters (Zn, Nitrate, Fe, Mn, Mg, Se, TH and TDS).
Fig. 3 GWQI map for pre-monsoon 2012.

References


Hydrogeochemical Evaluation of Groundwater of Bemetara District, Chhattisgarh

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Abstract

Bemetara district comprises of rocks of the Meso to Neo-Proterozoic sequence, is represented by the Chhattisgarh Super Group, Raipur Group comprises Chandi formation, Tarenga formation, Hirri formation and Maniari formation. Maniari Formation is the youngest formation having both primary and secondary deposition of Gypsum. The primary deposition of Gypsum/Anhydrite is sedimentary in origin, deposited during intermediate exposure of marine beds, which due to evaporation have formed the Gypsum/Anhydrite. These primary depositions of Gypsum/Anhydrite drape the lamination of Maniari shale/dolomite. The gypsum karsts occurring in the Maniari formation of this province are more productive. Hydrogeochemical studies relevant to the water quality explain the relationship of water chemistry to aquifer lithology. Such relationship would help not only to explain the origin and distribution of dissolved constituents but also to elucidate the factors controlling the groundwater chemistry. The groundwater of Bemetara district is affected by sulphate contamination. Fifty eight representative groundwater samples were collected during the pre-monsoon (June 2019) and post-monsoon season (December 2019). The groundwater samples were analyzed for physico-chemical parameters and assessed for drinking water quality as per BIS (2012). The values of total dissolved solids (TDS) in the groundwater vary from 250 to 10440 mg/L and 289 to 3583 mg/L during pre- and post-monsoon seasons respectively. Very high concentration of sulphate was observed and about 55% of the samples fall within the acceptable limit of 200 ppm and 28% samples exceed the permissible limit 400 ppm during the pre-monsoon season. Hydro-chemical data processed to understand the geochemical processes controlling the chemical composition of groundwater using Scatter Plots and Gibbs Plot and it was observed that carbonate weathering is a major source of dissolved ions in the groundwater of the study area. Data plot of (Ca+Mg) vs HCO3+SO4 shows that the reverse ion exchange process controls the chemistry of groundwater of the region. The plot of Na vs Cl indicates contribution of silicate weathering through the release of Na. High relationship was observed between Ca and Mg with SO4 (R²≥0.5). It can be inferred from this discussion that the high concentration of sulphate in the groundwater of district Bemetara may be attributed to dissolution of gypsum veins present within Maniari shale formation existing in the study area.

Keywords: Groundwater . Maniari shale formation. Hydrogeochemical process . Bemetara . Scatter Plot

Introduction

Water is a unique natural resource which is of great importance for existence of all living creature including humans and it continuously cycles between land, ocean and atmosphere in different form. About 70% of the earth surface is covered with water and a limited portion represents as groundwater. Increasing world population and industrialization leads to more consumption of groundwater and ultimately more pressure on existing water resources. According to WHO, about 80% of all the diseases in human beings are caused by water. High rates of mortality due to water-borne diseases are well known in India. Access to safe drinking water remains an urgent necessity, as 30% of urban and 90% of rural households still depend completely on untreated surface or
Groundwater. Groundwater quality depends on important process like atmospheric precipitation, quality of recharge water and inland surface water. Moreover, the quality of groundwater is degraded due to disposal of industrial waste and mining activities (Rodell et al. 2009, Chopra and Gopal 2014). Water pollution changes the quality of water which results in threats for human health, economic development and social welfare (Milovanovic 2007). The evaluation of water quality is very important for development of water resource strategies for sustainable water use and to provide database for future planning.

Groundwater situation in different parts of India is diversified because of variation in geological, climatological and topographic set-up. Geo-environmental conditions have a marked influence on the groundwater quality. Hydrogeochemical studies relevant to the water quality explain the relationship of water chemistry to aquifer lithology. Such relationship would help not only to explain the origin and distribution of dissolved constituents but also to elucidate the factors controlling the groundwater chemistry. In India and various parts of the world, numerous studies have been carried out to assess the geochemical characteristics of groundwater (Graniet al. 1999; Umar and Ahmad 2000). Narany et al. (2014) studied the hydrogeochemical processes in groundwater using classic integrated geochemical methods and geostatistical techniques, in Amol-Babol Plain, Iran and reported that water rock interaction mechanisms, followed by cation exchange, and dissolution of carbonate and silicate minerals have influenced the groundwater chemistry in the study area. The hydrogeochemical characteristics of groundwater show a shift from low mineralized Ca-HCO₃, Ca-Na-HCO₃, and Ca-Cl water types to high mineralized Na-Cl water type.

Singh et al. (2012) investigate the chemical characterization of melt-water draining from Gangotri Glacier, Garhwal Himalaya, India and reported that weathering of rocks is the dominant mechanism controlling the hydrochemistry of drainage basin. Redwan and Moneim (2015) investigated the factors controlling hydrogeochemistry in the area of west of Thata, Sohag, Upper Egypt and observed that the dominance of Ca²⁺ + Mg²⁺ over Na⁺ + K⁺ and HCO₃⁻ + SO₄²⁻ over Cl⁻ suggesting silicate minerals dissolution and reverse ion-exchange reactions. Gu et al. (2017) studied the hydrogeochemical characteristics of groundwater in the karst region, southwest China and found that the chemical compositions of the groundwater of the study area are dominated by Ca²⁺, Mg²⁺, HCO₃⁻, SO₄²⁻, which have been derived largely from dissolution of carbonate rocks (limestone and dolomite).

Li et al. (2017) studied the long period change in water chemistry of large freshwater Reservoir Danjiangkou, China and reported that waters are controlled by carbonate weathering with the dominant ions of Ca²⁺ and HCO₃⁻. Xiao (2017) investigated the geochemical characteristics and controlling processes of groundwater in a typical long-term reclaimed water use area and reported that groundwater chemical compositions in both shallow and deep aquifers are still dominantly controlled by natural processes such as silicate weathering, minerals dissolution and cation exchange. Mattos et al. (2018) studied spatio-seasonal changes in the hydrogeochemistry of groundwater in a highland tropical zone of Brazil and reported that during the recharge period of the aquifers (rainy season), a relatively significant amount of the sulphate anion was mobilized to the groundwater, thus changing the hydrogeochemistry composition. The origin of this sulphate may be linked to either the weathering of evaporitic rocks or biogeochemical processes. Ibrahim et al. (2018) investigated the processes of water-rock interactions and their impacts upon the groundwater composition in Assiut area of Egypt and observed that dissolution and precipitation play the essential control on the groundwater composition in the Pleistocene aquifer around the Nile, while ion exchange is more effective in controlling the water composition in the Plio-Pleistocene and Eocene aquifers in Assiut area.

**Study Area**

The Bemetara district is one of the newly formed district of Chhattisgarh state, India and covers an area of 2854.81 km² (Fig. 1). It is bounded by latitude 21°22’ to 22°03’ N and longitude 81°07’ to 81°55’ E. The Minor Mineral is Low grade. Limestones, Sandstone, Quartzite, Soil, River sand are also found in huge quantity. Different types of soils are found in the District viz; Red Soil (Bhata) Entisols, Sandy loams (Matasi) Inceptisols, Dorsa (Alfisols), Black (Kanhar) vertisols and Alluvial Soil (Kachhar). The area has a tropical wet and dry climate, temperature remains moderate throughout the year, except from March to June, which can be extremely hot. In summer, the temperature can also go up to 50°C. The city receives about 1300 mm of rain, mostly in the monsoon season from late June to early October. Winters last from November to January and are mild, although lows can fall to 5°C.

Physiographically, the area in Bemetara District has almost flat topography. The general slope of the district is towards the northeast, in which direction, the major streams of the district flow. In District Bemetara, there are six rivers namely Shivnath, Kharun, Haff, Sakari, Surahi and Phonkriver. Geologically, the district comprises of rocks of the Meso to Neo-Proterozoic sequence, is represented by the Chhattisgarh Super-group, Raipur Group comprises Chandi formation, Tarenga formation, Hirri formation and Maniari formation (Fig. 2). Chandi Formation of grey and purple stromatolitic limestone with arenite/ferruginous sandstone intercalations (Deodongar member); Tarenga Formation of greenish grey and reddish brown shale with chert/porcellanite and
green clay interbands; Hirri Formation by grey, thinly to thickly bedded dolomite and argillaceous dolomite and Maniari Formation consists reddish brown and purple non-calcareous shale with gypsum interbands. Quaternary is represented by pebble beds, (Khamaria pebble bed). Mineral deposits of Bemetara district include Dolomite, Limestone, Ordinary stone, Sand and Soil, etc.

The Maniari Formation is the youngest formation of Raipur Group, Chhattisgarh Supergroup having both primary and secondary deposition of Gypsum. The primary deposition of Gypsum/Anhydrite is of sedimentary origin, deposited during intermediate exposure of marine beds, and due to evaporation has formed the Gypsum/Anhydrite. These primary depositions of Gypsum/Anhydrite drape the lamination of Maniari shale/dolomite and are less than 1 mm to 1 cm in thickness in general. However, Das et al. (1992) have reported maximum thickness over a meter in few sections. The primary Gypsum/Anhydrite laminations dissolved later on due to circulating water and are deposited along the fracture/joints and bedding formed secondary deposition of Gypsum, while the primary depositions are mainly amorphous, the secondary deposition shows euhedral to the well-developed crystal phase of Gypsum. Example of gypsum flower (twin crystal) can be seen along the Hanp River in Andhiyarkhor area. Geode and cavity filling crystals of gypsum and calcite are also found in the area.

![Map showing the location of sampling sites in the study area.](image)

**Material and Methods**

58 groundwater samples were collected from groundwater sources existing in district Bemetara viz; open wells, dugwells, borewells, and handpumps, during pre-monsoon (June 2019) and post-monsoon (Dec 2019), which are extensively being used for drinking water purpose and analyzed for physico-chemical parameters using Standard Methods (APHA, 2005). Before collecting samples handpump were pumped for 5 minute to remove stagnant water and plastic bottles rinsed with groundwater. In situ parameters were analyzed on site like pH and electrical conductivity. Other parameters like major cation and anion were analyzed using Metrohm Ion Chromatograph.
Results and Discussion

Hydrogeology of the study area

The Precambrian sedimentary province of the district includes Chhattisgarh Super Group of rocks of Upper Proterozoic age of marine origin. This province occupies whole district area. It mainly consists of arenaceous-argillaceous-calcareous rocks and is dominated by limestone/dolomite and calcarceous shale. The ground water in these formations occurs under water table, semi-confined and confined conditions. The weathered, cavernous and fractured part of the formation constitutes the aquifers in the area. These formations are the most potential in regards to ground water yield and development of the district. The weathered zone is restricted to upper 30 m depth and in exceptional cases it is observed extends down to 58 m depth. Most of the cavernous zones occur between 10 and 70 m depth and fractures are productive down to 150 to 200 m.

In this province, cavernous zones sometimes start just after soil horizon, particularly in the stratified calcareous rocks along the bedding. These caverns provide good channel for ground water movement when free from residual clays. But many a times the solution channels are filled with residual clay and cause hindrance to ground water movement. The gypsum karsts occurring in the Maniari formation of this province are more productive. Though gypsum is more soluble than calcite, their alternative assemblage with thinly laminated shale provides special condition where dissolution of gypsum laminae causes roof collapses to create larger openings. Artesian conditions are also reported from this province especially in gypsum karstic terrain. The formations are more productive where the gypsum karst developed significantly. However, all the formations in the district are productive. The contact zones between different formations in this province are generally found productive. The ground water development in this province is through dug wells and bore wells. The dug wells are generally restricted up to 20 m, whereas bore wells are 30 to 180 m deep.

Hydro-chemical characteristics of groundwater of the study area

Fifty eight groundwater samples during pre-monsoon (Jun 2019) and post-monsoon seasons (Dec 2019) were collected from the study area during the year 2019-20 from the abstraction sources extensively being used for drinking purpose. The hydro-chemical data for two sets of samples collected during pre- and post-monsoon season are given in Table 1.
The pH values in the groundwater of the study area mostly fall within the range 6.2 to 7.72 during pre-monsoon and 6.14 to 7.06 during the post-monsoon season. The pH values for most of the samples are alkaline in nature and fall within the limits prescribed by BIS (2012) and WHO (1996) for different uses including drinking.

In the study area, the values of total dissolved solids (TDS) in the groundwater varies from 250 to 10440 mg/L and 289 to 3583 mg/L during pre and post-monsoon seasons, respectively. About 55% samples in pre-monsoon season and 66% samples in post-monsoon season have total dissolved solids (TDS) above the acceptable limit but within the maximum permissible limit of 2000 mg/L. The spatial distribution map of TDS for pre-monsoon is shown in Fig. 4.

Table 1 Hydro-chemical characteristics of groundwater of the study area (Pre- and Post-monsoon 2019)

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Parameters</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Average</th>
<th>Permissible Limit, BIS (2012)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>pH</td>
<td>6.2 (6.14)</td>
<td>7.72 (7.22)</td>
<td>7.06 (6.7)</td>
<td>6.5 – 8.5</td>
</tr>
<tr>
<td>2</td>
<td>EC (µS/cm)</td>
<td>390 (452)</td>
<td>16312 (5598)</td>
<td>1808 (1569)</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>TDS (mg/L)</td>
<td>250 (289)</td>
<td>10440 (3583)</td>
<td>1157 (1004)</td>
<td>2000</td>
</tr>
<tr>
<td>4</td>
<td>Alkalinity (mg/L)</td>
<td>83 (52)</td>
<td>280 (415)</td>
<td>183 (210)</td>
<td>600</td>
</tr>
<tr>
<td>5</td>
<td>Hardness (mg/L)</td>
<td>119 (116)</td>
<td>3267 (2124)</td>
<td>657 (604)</td>
<td>600</td>
</tr>
<tr>
<td>6</td>
<td>Na (mg/L)</td>
<td>7 (8)</td>
<td>2694 (201)</td>
<td>103 (66)</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>K (mg/L)</td>
<td>0.67 (0.15)</td>
<td>53 (201)</td>
<td>11.4 (22.3)</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>Ca (mg/L)</td>
<td>26 (26)</td>
<td>569 (648)</td>
<td>167 (162)</td>
<td>200</td>
</tr>
<tr>
<td>9</td>
<td>Mg (mg/L)</td>
<td>11 (12)</td>
<td>488 (259)</td>
<td>58 (49)</td>
<td>100</td>
</tr>
<tr>
<td>10</td>
<td>HCO₃ (mg/L)</td>
<td>101 (62)</td>
<td>341 (506)</td>
<td>223 (256)</td>
<td>-</td>
</tr>
<tr>
<td>11</td>
<td>Cl (mg/L)</td>
<td>10 (12)</td>
<td>1080 (652)</td>
<td>92 (109)</td>
<td>1000</td>
</tr>
<tr>
<td>12</td>
<td>SO₄ (mg/L)</td>
<td>3 (4.5)</td>
<td>5734 (2002)</td>
<td>469 (283)</td>
<td>400</td>
</tr>
<tr>
<td>13</td>
<td>NO₃ (mg/L)</td>
<td>0 (0)</td>
<td>194 (569)</td>
<td>26 (53)</td>
<td>45</td>
</tr>
<tr>
<td>14</td>
<td>F (mg/L)</td>
<td>0.06 (0)</td>
<td>2.4 (1.04)</td>
<td>0.45 (0.42)</td>
<td>1.5</td>
</tr>
</tbody>
</table>

*Values in the parenthesis represent post-monsoon values of different parameters.

The presence of bivalent ions mainly calcium and magnesium along with their carbonates, sulphates and chloride are the main cause of hardness in the water. Total hardness value in the study area varies from 119 to 3267 mg/L during pre-monsoon and 116 to 2124 mg/L during the post-monsoon season. About 50% of the samples of the study area cross the acceptable limit of 200 mg/L but are within the permissible limit of 600 mg/L and 38% sample crosses the permissible limit 600 mg/L during the pre-monsoon season. During the post-monsoon season, about 67% samples are within the permissible limit and 28% samples crosses the permissible limit 600 mg/L because of the dilution. The spatial distribution maps of hardness are given in Fig.5 for pre-monsoon season. It is observed from the data of both the season, the northeastern part of the study area is highly contaminated and the value of hardness reaches up to 3000 ppm. In groundwater of the study area, the values of calcium range from 26 to 569 ppm during pre-monsoon and 26 to 648 ppm during the post-monsoon season. About 24% of the samples exceeds the maximum permissible limit of 200 mg/L during the pre-monsoon and 17% samples crosses the permissible limit during the post-monsoon season. The less number (7%) of samples crosses the 200 ppm limit in the post-monsoon season because of the dilution effect as compare to pre-monsoon season.

The values of magnesium vary from 11 to 488 mg/L during the pre-monsoon and 12 to 259 mg/L during the post-monsoon season. Only 12% samples exceeds maximum permissible limit 100 mg/L during the pre-monsoon and 7% exceed above 100 mg/L during the post-monsoon.

The concentration of chloride varies from 10 to 1080 ppm during the pre-monsoon and 12 to 652 ppm during the post-monsoon season. More than 90% samples of the study area fall within the acceptable limit of 250 ppm during both the seasons.
Sulphate content in the groundwater generally found as soluble salts of calcium, magnesium and sodium. During the pre-monsoon the concentration of sulphate varies from 3 to 5734 ppm and 4.5 to 2002 ppm during post-monsoon season. Bureau of Indian standard has prescribed 200 ppm as the acceptable limit and 400 ppm as permissible limit for sulphate in drinking water. In the study area, 55% of the samples fall within the acceptable limit of 200 ppm and 28% samples exceed the permissible limit 400 ppm during the pre-monsoon season while 67% samples fall within the acceptable limit of 200 ppm and 19% samples exceed the permissible limit 400 ppm during the post-monsoon. The spatial distribution of the sulphate in the study area is shown in the Fig.6 for pre-monsoon season. The northeastern area of the study area is highly contaminated as shown in the spatial distribution maps for both the seasons.

The nitrate content in the study area varies from 0 to 194 mg/L during pre-monsoon season and 0 to 569 mg/L during post-monsoon season. About 93% of the samples of the study area fall within the permissible limit of 45 mg/L and 7% of samples even cross the permissible limit during pre-monsoon season and about 67% of the samples of the study area fall within the permissible limit of 45 mg/L and 33% of samples even cross the permissible limit during post-monsoon season because of percolation of fertilizer contents and sewage waste into groundwater. The fluoride content in the groundwater of the study area varies from 0.06 to 2.4 mg/L during the pre-monsoon season and 0 to 1.04 mg/L during the post-monsoon season. Almost all the samples fall within the acceptable limit of 1.0 mg/L during both the seasons except one sample.

Hydrogeochemical evaluation of groundwater of the study area

Hydrogeochemical studies relevant to the water quality explain the relationship of water chemistry to aquifer lithology. Such relationship would help not only to explain the origin and distribution of dissolved constituents but also to elucidate the factors controlling the groundwater chemistry. Gibbs (1970) proposed a hypothesis to elucidate the major natural mechanisms controlling world water chemistry. Three mechanisms – atmospheric precipitation, rock dominance and the evaporation-crystallization process – are the major factors controlling the composition of dissolved salts of the world waters.

Fig. 4 Spatial distribution of TDS in groundwater of the study area (Pre-monsoon 2019).
Fig. 5 Spatial distribution of Hardness in groundwater of the study area (Pre-monsoon 2019).

Other second-order factors, such as relief, vegetation and composition of material in the basin dictate only minor deviations within the zones dominated by the three prime factors. Almost all collected groundwater samples from study area fall in rock dominance zone suggesting precipitation induced chemical weathering along with dissolution of rock forming minerals. Few samples are away from this zone reflecting the contribution of anthropogenic activity responsible for chemical composition of ground water of the study area (Fig. 7).

Scatter Plots between Ions

The scatter plot of (Ca+Mg) vs TZ$^+$ shows that all the points fall above 1:1 equiline (Fig. 8). The relatively high contribution of (Ca+Mg) to the total cations (TZ$^+$) and high (Ca+Mg)/(Na+K) ratio indicate that carbonate weathering is a major source of dissolved ions in the groundwater of the study area (Fig. 8).

The scatter plot of (Na+K) vs TZ$^+$ shows that all the point’s fall above 1:1 equiline with a low ratio indicating a relatively low contribution of dissolved ions from silicate weathering (Fig. 8). Na$^+$, K$^+$ and dissolved silica in the drainage basin are mainly derived from the weathering of silicate minerals, with clay minerals as by-products. The plot of (Ca+Mg) vs HCO$_3^-$ for most of the samples in the study area indicates an excess of Ca+Mg over HCO$_3^-$ suggesting an extra source of Ca and Mg. This requires that a portion of the (Ca+Mg) has to be balanced by other anions like SO$_4^{2-}$ and/or Cl. The plot of (Ca+Mg) vs HCO$_3^-$+SO$_4^{2-}$ is a major indicator to identify the ion exchange process activated in the study area. If ion exchange is the process, the points shift to right side of the plot due to excess of HCO$_3^-$+SO$_4^{2-}$. If reverse ions exchange is the process, points shift left due to excess Ca+Mg.
Fig. 6 Spatial distribution of Sulphate in groundwater of the study area (Pre-monsoon 2019).

Fig. 7 Gibbs plot for mechanism controlling the groundwater chemistry.

Plot of (Ca+Mg) vs HCO$_3^+$+SO$_4^{2-}$ shows that most of the plotted points clusters around the 1:1 equiline and fall in Ca+Mg indicating the reverse ion exchange process which may be due to the excess of Ca+Mg (Fig. 8). The
plot of Na vs Cl indicates most of the points lie below the 1:1 equiline reflecting contribution of silicate weathering through the release of Na (Fig. 8).

The plot of Ca, Mg, Na and K vs SO$_4$ were also made and these plots indicates strong relationship between Ca and Mg with SO$_4$ ($R^2 \geq 0.5$) (Fig. 9), which supports the source of sulphate concentration in the study may be compounds of calcium and magnesium, i.e., CaSO$_4$ and MgSO$_4$.

**Conclusions**

The Precambrian sedimentary province of the district includes Chhattisgarh Super Group of rocks of Upper Proterozoic age of marine origin. It mainly consists of arenaceous-argillaceous-calcareous rocks, and is dominated by limestone/dolomite and calcareous shale. The ground water in these formations occurs under water table, semi-confined and confined conditions. The weathered, cavernous and fractured part of the formation constitutes the aquifers in the area. These formations are the most potential in regards to ground water yield and development of the district. The gypsum karsts occurring in the Maniyari formation of this province are more productive. Though gypsum is more soluble than calcite, their alternative assemblage with thinly laminated shale provides special conditions where dissolution of gypsum laminae causes roof collapses to create larger openings. Artesian conditions are also reported from this province especially in gypsum karstic terrain. All the formations in the district are productive. The contact zones between different formations in this province are generally found productive.
Fig. 9 Relationship between Na, K, Ca and Mg with SO₄.

Geo-environmental conditions have a marked influence on the groundwater quality. Hydrogeochemical studies relevant to the water quality explain the relationship of water chemistry to aquifer lithology. Such relationship would help not only to explain the origin and distribution of dissolved constituents but also to elucidate the factors controlling the groundwater chemistry. The physico-chemical data of groundwater of the study area reveals that very high concentration of sulphate is observed. Further hydrogeochemical study indicates that carbonate weathering is a major source of dissolved ions and the reverse ion exchange process controls the chemistry of groundwater of the region. It can be inferred from this discussion that the high concentration of sulphate in the groundwater of district Bemetara may be attributed to dissolution of gypsum veins present within Maniyari shale formation existing in the study area.

Acknowledgement

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References


Groundwater Chemistry of Unconfined Aquifers of Odisha State: Delineation of Poor Water Quality Zones and Groundwater Discharge Corridors Using GIS

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Abstract

The work analyzes the patterns of quality parameters and hydrochemical facies of 1105 (n = 851 in hard-rock; n = 254 in alluvium) groundwater samples which were drawn from the phreatic aquifer in the state of Odisha, India. From the patterns in chemistry (various solutes and their ratios), the study tries to demarcate various quality zones (excellent, very good, good, and poor) and the groundwater flow zones (recharge-discharge corridors) in the state of Odisha in Geographic Information System (GIS) platform. The poor quality tracts fall in a major way in the central and western parts of the Mahanadi River Basin (MRB). In Mahanadi deltaic plain and the lower Rushikulya River basin, also such poor quality zones are observed. In and around Angul the poor quality groundwater in the shallow aquifer is linked with the mining and other related anthropogenic activities. The groundwater discharge corridors fall along the river lines, specifically in the western parts of MRB, where the tributaries of Mahanadi confluence. Other important groundwater discharge areas fall in the lower Rushikulya basin and the deltaic parts of Mahanadi. The hydrochemical facies types in the discharge corridors are rich in Na+ and Cl-.

Keywords: Phreatic aquifer, Odisha, India, groundwater quality, fluoride, patterns in chemistry, quality zones, recharge-discharge corridors.
Introduction

In view of the increase in our dependency on groundwater resources for needs in irrigation, domestic and industrial sectors, it has been very much crucial to map the available aquifers (in any river basin or geopolitical entity) in respect of their type, yield potential (qualitative and quantitative), water quality, and their recharge and discharge avenues. Besides, it has also been very imperative to monitor (both the quality and quantity) and conserve the groundwater resources. To monitor the groundwater quality and particularly to delineate the poor quality zones have been of paramount importance in the scenario of deteriorating groundwater quality and an increase in demand for drinking supply. For sustainable management of water resources, including that of groundwater, besides the knowledge of groundwater quality in the area, the information on groundwater recharge-discharge corridors are equally important.

The integrated techniques of remote sensing and Geographic Information System GIS have proved to be efficient tools in various reconnaissance hydrogeological studies (including groundwater exploration, mapping groundwater potential zones, and favorable recharge sites, etc.) for the sustainable development and management of aquifers, and groundwater resources (e.g., Krishnamurthy et al. 1996; Jaiswal et al. 2003; Sener et al. 2005; Jha and Peiffer 2006; Hoffmann and Sander 2007; Chowdhury et al. 2010; Mukherjee et al. 2012; Singh et al. 2013; Ndutuwoong and Yadav 2014; Sahoo et al. 2015; Badamasi et al. 2016; Hussein et al. 2017). Authors have also applied GIS techniques for processing and interpreting the groundwater quality data by integrating various thematic layers (Rao and Jugran 2003).

The present study, for the first time, uses the GIS techniques in the spatial analysis of a set of data pertaining to the groundwater chemistry in the shallow phreatic aquifer of Odisha State, India. The patterns in chemical quality of groundwater remain less haphazard and rather depict systematic variation between the ends of groundwater recharge and discharge, in relation to the spatial variations in the hydrogeology and geomorphology. Though the GIS techniques have earlier been applied elsewhere in preparing the groundwater quality zonation maps from the patterns in quality distribution (Brindha and Elango 2012; El-Hames et al. 2013), their applications in the demarcation of groundwater discharge corridors are still to be explored. In the present study, the patterns in various groundwater quality parameters have been utilized to demarcate the groundwater discharge corridors in the state of Odisha.

Study Area

The Odisha State, on the east coast of India, covers a geographical area of 1,55,707 km$^2$ (17°49’ to 22°34’ N latitudes and 81°24’ to 87°29’ E longitudes) with a coastline of 480 km long along the Bay of Bengal (Fig. 1). The state experiences a sub-tropical climate of hot and humid character. During summer (Mar-May), the temperature reaches up to ~45° C while in winter (Nov-Feb) it falls to ~3-12° C. The south-west monsoon (Jun-Oct) brings rain in the state. The mean annual rainfall is around 1502.66 mm (range: 1200-1700 mm), out of which ~85% is comes during the monsoon. The northern coastal parts of the state receive maximum rainfall up to 1500-1700 mm, whereas some rain-shadow areas in the western parts of the state receive up to 1200 mm of rainfall. Floods in the coastal districts and droughts in the inland areas are common phenomena.

The Mahanadi River, originating in the Maikal hill ranges in Chhattisgarh state in the west, forms the principal river system in the state. It receives all its tributaries such as Tel, Ong and Suktel in the western part of the basin and thereafter flows as a single treading river until it forms distributaries in the delta forming process at around Cuttack. The Mahanadi River Basin (MRB) is the largest river basin, covering ~48% of the state area (Fig. 2). Other major rivers in the state include the Brahmani, Baitarani, Rushikulya, Burhabalanga, Subarnarekh, Bansadhara, Nagavali, Bahuda, Kolab and Indravati (Fig. 2). Though, initially in the west and north of the state, the rivers flow southward and north/northeastward, the ultimate flow-direction remains towards east/southeast towards the Bay of Bengal. All the rivers are basically seasonal in nature and very minor flow occurs in them during the lean periods.

Physiographically, hills, mountains (including the Eastern Ghat Hill Range), rolling uplands, plateaus, valleys, etc. cover ~85% of the state area (max. elev.: 1640 m asl). The coastal plain (max. elev.: 50 m asl) in the east and the minor alluvial plains in the river valleys in the hinterland constitute the rest of the state area. Geological formations range between the oldest of Precambrian to Recent (Mahalik 1998; CGWB 2004). The consolidated Precambrian formations (granites and granite gneisses, khondalites, charnockites, anorthosites, gabbro, rocks of granulite facies, different types of schistose rocks, quartzite, marble, dolomite, silicified shales and sandstones, etc.) cover ~75% of the state area (Fig. 1). The semi-consolidated rocks (shale-sandstone sequence) of Gondwana Group (Palaeo-Mesozoic) occur in faulted basins in the Mahanadi-Brahmani rift-grabens. The semi-consolidated Tertiary formations (Baripada Beds) are represented by limited patches in the north-east of the state. The unconsolidated Quaternary formations (sand, silt and clay) occupy the coastal plain (deposited in deltaic, fluvio-deltaic and fluvial and marine environments) and the narrow-discontinued patches
of plains in the river valleys. Laterites occur as capping over the older crystalline formations more extensively in the adjoining parts of coastal alluvium in the eastern parts of the state.

![Fig. 1 The location map of the study area, the Odisha State.](image)

The map of Odisha illustrates the generalized geology (CGWB 2004) along with the major drainage and structural features. A major part of the state is covered by various granite types and their metamorphic derivatives. Alluvium covers the coastal parts and narrow tracts in the river valleys. The map also shows isohyets and the groundwater quality monitoring stations.

The weathered residuum (max. up to 30 m below ground) in the hard rock areas (consolidated and semi-consolidated formations) forms the shallow phreatic aquifer that holds water in an unconfined state. The fractures and joints at deeper levels hold water in semi-confined to confined conditions. Various regional as well as local faults/shear zones/lineaments and dykes have created suitable groundwater storage locations by inducing deformations in the rocks. Several faults/shear zones occur in the state including those associated with the Mahanadi rift-graben and the coastal depression that run in NE-SW, NS, NWW-SEE, and EW directions. In the coastal plains, the granular zones in the alluvium (at places even exceeding 300 m below ground) form the repositories of groundwater, existing in an unconfined state in the shallow phreatic aquifer and in semi-confined to confined state in the deeper aquifers.

The depths to water levels remain largely shallow that varied between 0.20-14.2 m (mean: 5.3 m) and 0.15-11.35 m (mean: 3.2 m) below ground level (bgl) during the pre- (Month: May) and post-monsoon (month: Nov) periods respectively in the year 2016 (Sahu 2018). Major parts of the state including the coastal parts and the river valleys with comparatively lower slope reflect shallow water levels (<5.0 m bgl). The rivers are effluent in nature where groundwater discharge contributes the flow in the rivers especially during the non-monsoon periods (Sahu 2018).

**Materials and Methods**

The Digital Elevation Models (DEM) of Shuttle Radar Tomographic Mission (SRTM) was used to prepare the drainage map for the state and to assess the topography and terrain. The False Color Composite (FCC) satellite imageries (IRS-1A, LISS-II) were used to study the major geomorphic units in the state. The Survey of India topographical sheets (scale: 1:250,000) were consulted as and when required.
The study uses the analytical results of 1105 groundwater samples which were collected from 1105 different locations in the state (Fig. 2) during the pre-monsoon period of the year 2015 (CGWB 2016). The locations are a set of dedicated network stations, known as National Hydrograph Network Stations (NHNS), monitored by the state office of the Central Ground Water Board (CGWB) both for the groundwater level and groundwater quality regime. The observation points are basically dug wells in the depth range of 5-15 m below ground level (bgl). The monitoring stations are distributed in different areas with varied geomorphic and hydrogeological conditions; 62% (n = 685) of the samples fall in the hard-rock terrain comprised of consolidated to semi-consolidated formations and the remaining 38% (n = 420) samples belong to mainly coastal alluvium.

Groundwater samples were collected in high-density polythene bottles of one-liter capacity each. Before collection, the water in dug well was agitated properly in order to get a representative groundwater sample. Before filling, the bottles were rinsed 2-3 times with the respective groundwater samples. The water samples were analyzed for quality in the regional chemical laboratory of CGWB at Bhubaneswar. The major cations (Ca$^{2+}$, Mg$^{2+}$, Na$^+$, K$^+$) and the major anions (HCO$_3^-$, Cl$^-$, SO$_4^{2-}$, CO$_3^{2-}$) were analyzed using the standard protocols adopted by the American Public Health Association (APHA 1995). Other than the major parameters, the samples were also analyzed for hydrogen potential (pH), electrical conductance (EC), total hardness (TH) and alkalinity of groundwater. The TDS values have been worked out from the EC values by taking a factor of 0.65 of EC. The fluoride (F$^-$) levels in the groundwater have been determined through Ion-Selective Electrode Method (Thermo Scientific).

The regional distribution patterns of various hydrochemical parameters including the major ions and their ratios have been studied across the state. Contour maps of various parameters have been prepared using the Inverse Distance Weighted (IDW) method. The interpolation technique estimates the missing values based on the values at nearby locations weighted only by distance from the interpolation location. The IDW method is based on the assumption that the value of an attribute $z$ at any unvisited point is a distance weighted mean of data points occurring within a neighborhood or window surrounding the unvisited point (Karydas et al. 2009).

The concentrations of the major ions in groundwater were also used to determine the hydrochemical facies types. The patterns in the groundwater quality parameters and the facies types were studied in order to understand their relation with groundwater flow system, drainage and geomorphology. Various quality parameters were used to prepare a quality zonation map of the Odisha State in GIS Platform. The quality and different ratio parameters were also used in the weighted overlay analysis in GIS to prepare a groundwater recharge-discharge zonation map to corroborate the hydrochemical facies distribution patterns.

**Results and Discussion**

**Groundwater chemistry: Shallow unconfined aquifer**

A box and whisker plot (Fig. 3) has been prepared to depict the range of major quality parameters in groundwater in the state of Odisha. Table 1 shows the statistical values (min., max., mean, std. dev.) of the
parameters along with the guideline values (WHO 2011; BIS 2012) for potability of groundwater for drinking and domestic purposes. Issues have been identified with some minor numbers of samples as far as the drinking suitability and domestic uses are concerned (Table 1). The groundwater in both the alluvial (predominantly coastal alluvium) and hard-rock terrains in the state is largely potable except the pockets of salinity and those with elevated concentrations of fluoride (F⁻). The long exposures and use of groundwater having high F⁻ in excess of the drinking limit of 1.5 mg/l (WHO 2011) results in fluorosis of dental (mottling of teeth), skeletal (bending of bone and spinal cord) as well as non-skeletal kind (ligament deformation).

![Fig. 3 Box and whisker plots showing the min., max., median, and lower and upper quartiles of the groundwater quality parameters (in mg/L). pH has been produced as inset.](image)

**Table 1** Statistical summary of measured parameters compared to WHO (2011) and Indian standards (BIS 2012) for drinking water

<table>
<thead>
<tr>
<th>Parameters (Ions in mg/L)</th>
<th>Min.</th>
<th>Max.</th>
<th>Mean</th>
<th>Std. dev.</th>
<th>WHO (2011)</th>
<th>BIS (2012)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>6.6</td>
<td>8.7</td>
<td>7.9</td>
<td>0.28</td>
<td>7.0-8.5</td>
<td>6.5-8.5</td>
</tr>
<tr>
<td>EC (in µS/cm)</td>
<td>40.0</td>
<td>6280.0</td>
<td>595.7</td>
<td>503.2</td>
<td>750.0</td>
<td>-</td>
</tr>
<tr>
<td>TDS</td>
<td>21.0</td>
<td>3511.0</td>
<td>316.3</td>
<td>278.6</td>
<td>500.0</td>
<td>500.0</td>
</tr>
<tr>
<td>TH</td>
<td>15.0</td>
<td>2052.0</td>
<td>186.4</td>
<td>160.8</td>
<td>500.0</td>
<td>300.0</td>
</tr>
<tr>
<td>Alkalinity</td>
<td>5.0</td>
<td>1130.0</td>
<td>135.9</td>
<td>93.8</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ca²⁺</td>
<td>4.0</td>
<td>480.0</td>
<td>38.1</td>
<td>35.3</td>
<td>75.0</td>
<td>75.0</td>
</tr>
<tr>
<td>Mg²⁺</td>
<td>0.0</td>
<td>284.0</td>
<td>22.2</td>
<td>24.7</td>
<td>30.0</td>
<td>30.0</td>
</tr>
<tr>
<td>Na⁺</td>
<td>0.0</td>
<td>860.0</td>
<td>44.9</td>
<td>61.0</td>
<td>200.0</td>
<td>-</td>
</tr>
<tr>
<td>K⁺</td>
<td>0.0</td>
<td>380.5</td>
<td>10.9</td>
<td>27.7</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CO₃²⁻</td>
<td>0.0</td>
<td>93.0</td>
<td>1.0</td>
<td>6.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>HCO₃⁻</td>
<td>6.0</td>
<td>1379.0</td>
<td>163.7</td>
<td>111.3</td>
<td>200.0</td>
<td>200.0</td>
</tr>
<tr>
<td>Cl⁻</td>
<td>4.0</td>
<td>1205.0</td>
<td>92.1</td>
<td>114.9</td>
<td>250.0</td>
<td>250.0</td>
</tr>
<tr>
<td>SO₄²⁻</td>
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<td>596.0</td>
<td>26.5</td>
<td>43.1</td>
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<td>200.0</td>
</tr>
<tr>
<td>F</td>
<td>0.0</td>
<td>4.0</td>
<td>0.5</td>
<td>0.46</td>
<td>0.6-1.5</td>
<td>1.0</td>
</tr>
</tbody>
</table>

The analytical results of solute chemistry for both the alluvial and the hard-rock terrains closely resemble (Fig. 4a-b) except the elevated EC levels in a few groundwater samples collected from the coastal alluvium. The unconfined aquifer in both the terrains in the Odisha hosts groundwater of alkaline nature with the pH values varying in the range of 6.6-8.7 (mean: 7.9 in alluvium and 8.0 in hard-rock terrains). The electrical conductance (EC) values vary widely between 40 and 6280 µS/cm (mean: 588 µS/cm). The worked-out TDS of groundwater fall in the range of 21-3511 mg/L (mean: 316 mg/L) with 98% of the sample populations registering TDS<1000 mg/L.
mg/L. The mean TDS reflects significant correlations with the mean contents of Na\(^+\) (R\(^2\) = 68\%), Cl\(^-\) (R\(^2\) = 83\%) and Mg\(^{2+}\) (R\(^2\) = 56\%) in the groundwater (Table 2). The groundwater samples register TH values varying between 15 and 2052 mg/L (mean: 188 mg/L). Water containing calcium/magnesium carbonates at concentrations below 60 mg/L is generally considered as soft; 60–120 mg/L, moderately hard; 120–180 mg/L, hard; and more than 180 mg/L, very hard (McGowan 2000). In major parts of the state the groundwater is moderately hard (n = 303), hard (n = 267) and very hard type (n = 442). Better correlation of TH with Ca\(^{2+}\) and Mg\(^{2+}\) ions (66 and 77\% respectively), as shown in Table 2, indicates the hardness of water is owing to the increased content of Ca\(^{2+}\) and Mg\(^{2+}\). The groundwater alkalinity (ability to neutralize the effect of more acidity without modifying pH) depicts a range of 5–1130 mg/L (Table 1).

### Table 2 Inter-elemental correlation matrix of dissolved ions (n = 1105)

<table>
<thead>
<tr>
<th></th>
<th>pH</th>
<th>EC</th>
<th>TD</th>
<th>TH</th>
<th>Alk</th>
<th>Ca</th>
<th>Mg(^{2+})</th>
<th>Na(^+)</th>
<th>K(^+)</th>
<th>CO(_3^2)</th>
<th>HC</th>
<th>Cl(^-)</th>
<th>SO(_4^2)</th>
<th>F(^-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
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<td></td>
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<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>TD</td>
<td>0.0</td>
<td>0.9</td>
<td>1.0</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TH</td>
<td>0.0</td>
<td>0.7</td>
<td>0.6</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alk</td>
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<td>0.5</td>
<td>0.4</td>
<td>0.3</td>
<td>1.00</td>
<td></td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>Ca(^{2+})</td>
<td>0.0</td>
<td>0.4</td>
<td>0.4</td>
<td>0.6</td>
<td>0.13</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Mg(^{2+})</td>
<td>0.0</td>
<td>0.6</td>
<td>0.5</td>
<td>0.7</td>
<td>0.34</td>
<td>0.1</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Na(^+)</td>
<td>0.0</td>
<td>0.6</td>
<td>0.6</td>
<td>0.1</td>
<td>0.37</td>
<td>0.0</td>
<td>0.20</td>
<td>1.00</td>
<td></td>
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</tr>
<tr>
<td>K(^+)</td>
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<td>0.1</td>
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<td>0.0</td>
<td>0.01</td>
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<td></td>
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</tr>
<tr>
<td>CO(_3^2)</td>
<td>0.1</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.11</td>
<td>0.0</td>
<td>0.06</td>
<td>0.02</td>
<td>0.00</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HC(_O_3^2)</td>
<td>0.1</td>
<td>0.5</td>
<td>0.4</td>
<td>0.3</td>
<td>0.99</td>
<td>0.1</td>
<td>0.33</td>
<td>0.37</td>
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<td>1.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cl(^-)</td>
<td>0.0</td>
<td>0.8</td>
<td>0.8</td>
<td>0.6</td>
<td>0.15</td>
<td>0.4</td>
<td>0.51</td>
<td>0.48</td>
<td>0.08</td>
<td>0.01</td>
<td>0.15</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SO(_4^2)</td>
<td>0.0</td>
<td>0.5</td>
<td>0.5</td>
<td>0.3</td>
<td>0.19</td>
<td>0.1</td>
<td>0.30</td>
<td>0.40</td>
<td>0.07</td>
<td>0.00</td>
<td>0.21</td>
<td>0.3</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>F(^-)</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.06</td>
<td>0.0</td>
<td>0.05</td>
<td>0.02</td>
<td>0.00</td>
<td>0.04</td>
<td>0.06</td>
<td>0.0</td>
<td>0.00</td>
<td>1.0</td>
</tr>
</tbody>
</table>

The mean cation chemistry in the groundwater samples falls in the order of Ca\(^{2+}\)>Na\(^+\)>Mg\(^{2+}\)>K\(^+\). The mean loadings of Na\(^+\) and Mg\(^{2+}\) are, however, very close to each other, standing at 32.1\% and 28.4\% respectively in alluvium (Fig. 4a.i), and at 30.0\% and 29.2\% (Fig. 4b.i) respectively in hard-rock terrain (combined mean of 29.6\% and 29.2\% respectively). The alkali earth metals (Ca\(^{2+}\)+Mg\(^{2+}\)) predominate in the groundwater of the phreatic aquifer. About 83.5\% (n = 923) of the groundwater samples show Ca\(^{2+}\)+Mg\(^{2+}\) loading beyond 50\% of the total cation concentration. Alternately saying, only ~16.5\% (n = 182) of the groundwater samples exhibit higher loading of alkali elements (Na\(^+\)+K\(^+\)). Among the alkali earth metals, it is the Ca\(^{2+}\) that contributes beyond 50\% of the content in ~64.4\% (n=712) of the groundwater samples. It signifies, the Mg\(^{2+}\), being even a lesser abundant element in the earth’s crust, predominates in a significant 35.6\% (n = 393) of the samples. Higher Mg\(^{2+}\) than the Ca\(^{2+}\) content may denote the supply of excess Mg\(^{2+}\) from weathering of dolomite and/or mafic minerals or precipitation of Ca\(^{2+}\). K\(^+\) is the least abundant ion in the groundwater of Odisha (Fig. 4a.i-b.i). It might be due to its tendency to be fixed by clay minerals and participate in the formation of secondary minerals (Matthes 1982).

![Fig. 4 Pie diagrams depicting the mean composition of ions (mg/L); (a) (i)-(ii) alluvial aquifer system, and (b) (i)-(ii) hard-rock aquifer systems.](image-url)

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Indian National Chapter
It can be observed that the alkaline earth metals (Ca$^{2+}$ + Mg$^{2+}$) exceed alkali metals (Na$^+$ + K$^+$), and weak acids (CO$_3^{2-}$ + HCO$_3^-$) greatly exceed strong acids (SO$_4^{2-}$ + Cl$^-$). The diagrams indicate no remarkable difference in groundwater quality in both the aquifer systems.

The general abundance of the anions in the shallow aquifer systems falls in the order of HCO$_3^-$>Cl$^-$>SO$_4^{2-}$>CO$_3^{2-}$ in both the alluvial and hard-rock areas in the state (Fig. 4a.ii-b.ii). As a percentage of total anions, the HCO$_3^-$ constitutes 4.91% (mean: 51%) in the entire sample population. Among the anions, though, the weak acids (HCO$_3^-$+CO$_3^{2-}$) remain predominant, those are restricted to only 55.9% (n=618) of the groundwater samples. The strong acids (SO$_4^{2-}$+Cl$^-$) gain control over in the remaining significant 44.1% (n=487) of the groundwater samples. Owing to negligible CO$_3^{2-}$ content in almost all the samples, HCO$_3^-$ is the predominant weak acid. The predominance of HCO$_3^-$ suggests intense chemical weathering of primary silicate minerals dominated by alkaline earths owing to high residence time of water in the aquifers (Rose 2002).

Among the strong acids (Cl$^-+$SO$_4^{2-}$), it is Cl$^-$ that controls the chemistry in ~98.4% (n = 1087) of the groundwater samples. Chloride is considered as a good indicator of the quality of groundwater and at times it is used as a tracer for groundwater contamination (Loizidou and Kapetanios 1993). Its concentration levels widely vary between 4-1205 mg/L. Chloride (Cl$^-$) in groundwater may have geogenic and/or anthropogenic sources. The mixing of seawater increases the concentration of Cl$^-$ in groundwater. Dissolution of salt deposits and weathering of halites and evaporites are considered as the major lithogenic source of Cl$^-$ in the groundwater (Tiwari and Singh 2014). The soluble salts emplaced in sediments by the evaporation of groundwater in discharge or shallow water level areas also raises the Cl$^-$ concentration in groundwater (Piper and Garrett 1953; Izbicki et al. 2006). Irrigation return flow, leachates from landfill, waste dumps, septic tanks, industrial and animal wastes are some of the possible anthropogenic sources of chloride in groundwater (Appelo and Postma 1996).

**Groundwater fluoride (F$^-$) contamination**

Groundwater fluoride contamination is a significant problem in the state of Odisha that affects several discontinuous patches more conspicuously in central and western parts of the state (Mahapatra 2007; CGWB 2010). Its enrichment takes place mainly through leaching and weathering of the Fluoride (F$^-$) bearing minerals like fluorite, topaz, muscovite, biotite, fluoro-apatite, cryolite, amphiboles etc present in the rocks and sediments, besides industrial and agricultural sources (Handa 1975; Bardsen et al. 1996; Appelo and Postma 1996; Brindha and Elango 2013). Various hydrogeochemical conditions in the aquifer, rock-water interaction and rate of recharge and discharge of groundwater play roles of fluoride levels in groundwater.

It is remarkable that the major numbers of source wells with F$^->1.0$ mg/L are located in the Hirakud Reservoir Canal Command area in the western parts of the state. The F$^-$ levels in groundwater in the tested samples from shallow aquifer vary between 0 and 4 mg/L (mean: 0.5 mg/L). The levels exceed the drinking limit of 1.5 mg/L at 49 locations in different pockets (falling in 14 districts) in the state (Fig. 4). Another 86 locations depict F$^-$
concentrations in the critical range of 1.0-1.5 mg/L, beyond the maximum desirable limit (BIS 2012) of 1.0 mg/L. Major such locations with F⁻ >1.0 mg/L are found in the western parts of the state, particularly in the Hirakud Canal Command area (Fig. 5).

The pH levels (mean: 8.0) in 97% of the samples (n=135) with F⁻>1.0 mg/L fall between 7.5-8.51 indicating the alkaline nature of groundwater. The TDS levels are <1000 mg/L (range: 71-911, mean: 341 mg/L) in 98% (n=132) of the samples. However, the overall correlations of F⁻ levels in the groundwater samples (n=135) with the pH, TDS and the Na⁺, Ca²⁺, Mg²⁺, and HCO₃⁻ ions remain very poor (Table 2).

**Hydrochemical facies**

The Piper trilinear diagrams (Piper 1944) prepared separately for the groundwater samples from the alluvial and hard-rock terrains depict the clear dominance of alkaline earths (Ca²⁺+Mg²⁺) over alkalis (Na⁺+K⁺) in a major number of samples (Fig. 6a-b) in both the cases. However, the weak acids (HCO₃⁻+CO₃²⁻) and the strong acids (SO₄²⁻+Cl⁻) seem to occupy nearly equal space in the groundwater chemistry with marginal dominance of the former. A major number of sample points falling in the fields of 1 and 5, indicating the predominance of Ca-Mg-HCO₃ followed by Ca-Mg-Cl-HCO₃ hydrochemical water types. A significant number of water samples are also plotted in the fields of 2, 3, and 6 (comprising ~14% of total groundwater samples) indicating the water types of Na-Cl, Ca-Mg-Cl, and Na-Ca-Mg-HCO₃-Cl respectively.

![Fig. 6 Piper (1944) Trilinear diagrams illustrating the chemical composition of water samples and the major hydrochemical water types in the shallow aquifer systems in (a) alluvial area, and (b) hard-rock area respectively in the state.](image)

The above plots show the predominance of alkaline earth metals (Ca²⁺+Mg²⁺) over alkali metals (Na⁺+K⁺), and that of weak acids (CO₃²⁻+HCO₃⁻) over strong acids (SO₄²⁻+Cl⁻).

**Patterns in groundwater chemistry**

**Hydrogen Ion potential (pH)**

The pH of water is an important parameter giving clues about its chemical quality. The water charged with CO₂, when dissolves CO₃²⁻ and HCO₃⁻ from the aquifer framework, its pH is raised (Cole and Prairie 2009). An increase in the content of CaCO₃ increases the pH of water, making it alkaline. The regional distribution of pH (Fig. 7a) shows some definite patterns following the aquifer lithology and geomorphic set-up. Where the interfluvies regions depict the pH levels <8.0, the areas with pH>8.0 fall in some specific linear stretches which in major cases coincide with the river valleys, canal command areas, and the coastal tract (Fig. 7a). These areas might be indicating higher soil moisture, groundwater recharge/discharge and higher mineralization. It has also been stated that the ion exchange processes that change the groundwater from Ca-type to Na-type, also causes in the carbonate content of water alongside the increase in the pH levels (Krainov et al. 2001).

**Carbonate (CO₃²⁻) and bicarbonate (HCO₃⁻)**

The anions HCO₃⁻+ CO₃²⁻ expressed as the percentage of total anions have been plotted in Fig. 7b. In general, the anions constitute more than 50% of the total anions in major parts of the state, falling in a major
way away from the narrow river valleys, floodplains, valley fills, and other low slope areas close to the hills, which in general act as the groundwater recharge areas. It implies the content of $\text{HCO}_3^- + \text{CO}_3^{2-}$ remains less than 50% of the anions in some stretches of the river channel corridors, parts of the coastal tract (including the Mahanadi delta) and high slope hills, which characterize the groundwater discharge zones. However, the canal command area of Hirakud Reservoir in the western parts of the state in Bargarh district depicts the carbonates and bicarbonates to constitute more than 50% of the anions. These patches are also characterized by a higher pH (>8.0) (Fig. 7a). Irrigation water with high pH and $\text{HCO}_3^-$ causes the dissolution of organic matter in soil and also promotes precipitation of calcite ($\text{CaCO}_3$) in the sub-soil zone (Al-Rawajfeh et al. 2005).

### Total dissolved solids (TDS)

The TDS values of groundwater fall in the range of 21-2390 mg/L (mean: 316 mg/L). Mineralization is low with the TDS values <250 mg/L along the higher elevation zones and drainage divides in the state (Fig. 7c). Low to moderate values of TDS (range: 250-1000 mg/L) occurs in the river valleys, valley-fills and parts of coastal tract, particularly in the Mahanadi deltaic area (Fig. 7c). Significant parts in the western catchment area (saucer-shaped) and the central parts of the MRB also depict such values. The mean TDS is relatively higher at 358 mg/L in the MRB (n=605), which is 267 mg/L (n=500) in the rest of the state area. The associated faults in the rift basin and the induced fractures/joints in the rocks might have created the storage and passageways for groundwater facilitating enhanced mineralization in MRB. The area with high pH values in the northern parts of the coastal tract (Fig. 7a) are not reflected in the corresponding TDS levels which commonly vary between 21-250 mg/L in major cases. It may be signifying the ingress of saline water and not the mineralization, as the reason behind high pH in the phreatic aquifer. Moderate to high TDS levels are observed in dispersed patches in the state with their higher incidence in the MRB and Rushikulya River basin. The clusters of such samples fall close to the river lines and the coastal tract where the groundwater reaches at its end of the flow path. Relatively high TDS indicates the maturity of groundwater and its long residence time in the aquifer system in a longer flow path.

![Fig. 7](image_url) The map of Odisha state showing the regional distribution of (a) pH, (b) ($\text{HCO}_3^- + \text{CO}_3^{2-}$) % of total anions, (c) TDS (mg/L), and (d) Cl^- % of total anions. It may be observed that the upper levels of pH and TDS more frequent in the MRB. The water in the MRB is relatively enriched with Mg^{2+}. The ($\text{HCO}_3^- + \text{CO}_3^{2-}$) % is more in the western parts of the MRB (refer text for details). Cl^- % in the MRB is relatively less (20-40%).
Chloride (Cl⁻)

Except for certain pockets, in major parts of the state, the Cl⁻ values remain within 100 mg/L. The Cl⁻ expressed as a percentage (Cl⁻ %) of total anions have been plotted in Fig. 7d. The figure shows relatively high and peak values coincide with Cl⁻ % with the areas with low bicarbonate (HCO₃⁻) and carbonate (CO₃²⁻) in groundwater. Interestingly, the high Cl⁻ pockets are observed in small linear patches which coincide with the major faults in the state (particularly the eastern and western ones, Fig. 1). This generally happens due to the upward rising of Cl⁻-rich groundwater along the fault plane (Kirk et al. 2009). It may be explaining the high Cl⁻ along the fault in the coastal tract (Fig. 1). However, in the hard-rock terrain, it seems, the groundwater recharge and accumulation of Cl⁻ along the fault/shear zones causes the salinity. Interestingly, Fig. 7d also indicates the Cl⁻% is less (20-40%) in major parts of MRB, which might be indicating the smart flushing process in the basin, which subdues the load of Cl⁻ into groundwater and rejuvenates the groundwater quality.

Ratio of Ca²⁺/Mg²⁺

The Ca²⁺/Mg²⁺ ratio (ions in mg/L) varies between 0.27-14.55 (mean: 1.50). Around 37% (n=30) of the samples shows Mg²⁺ enrichment (Ca²⁺:Mg²⁺ ratio <1.0). Majority of such values with the Ca²⁺:Mg²⁺ ratios of less than 1.0 fall in the MRB and in some other river basins like Brahmani, Baitarani and Rushikulya (Fig. 8a). This specific distribution pattern might be reflecting the groundwater flow rather than different original Ca²⁺:Mg²⁺ content in the aquifer material as the cause of Mg²⁺ enrichment in the shallow aquifer. It might also be indicating the intermediate to the terminal flow state, where the groundwater system is losing Ca²⁺. The river valley is the major discharge corridor in the state. The flow of groundwater from the recharge to discharge areas generally results in a gradual increase in TDS, and a decrease in the ratios of Ca²⁺/Mg²⁺, Ca²⁺/Na⁺ and SO₄²⁻/Cl⁻ (Chebotarev 1955; Ophori and Toth 1989).

The low Ca²⁺:Mg²⁺ ratio in the northern parts of the coastal tract might be indicating either precipitation of Ca²⁺ as CaCO₃ owing to alkaline (high pH) condition in the shallow aquifer or the influence of saline water ingress. Generally, the Mg²⁺ content of seawater remains high. The higher irrigation intensity in this part as well as in the Hirakud Canal Command area might also be playing role in the Mg²⁺ rich state of groundwater. In the NE and SW parts of the state, the groundwater shows Ca²⁺:Mg²⁺ ratio >1.0. This Ca²⁺ enrichment of groundwater may be purely lithogenic (silicate dissolution) as the host rock types comprise granites, granite gneiss, charnockites and khondalites containing abundant calcic feldspars.

Fig. 8 The map of Odisha state showing the regional distribution of the ratios of (a) Ca²⁺/Mg²⁺, (b) Ca²⁺+Mg²⁺/HCO₃⁻ and (c) Ca²⁺/Na⁺ (for details refer text).

Ratio of Ca²⁺+Mg²⁺/HCO₃⁻

A Ca²⁺+Mg²⁺/HCO₃⁻ ratio of less than 1.0 is also suggestive of fresh recharge or the meteoric nature of groundwater (Nazzal et al. 2014), which is being indicated by 23.5% (n=260) of the groundwater samples in the state. In the present study, the majority of samples (n=852) have a very high Ca²⁺+Mg²⁺/HCO₃⁻ ratio ranging between 1.0-17.8. The regional distribution pattern of the ratio shows a major part of the state is being covered within the ratio value up to 1.5 (Fig. 8b). Thus, the Ca²⁺+Mg²⁺/HCO₃⁻ ratio up to 1.5 might be suggesting fresh recharge from rainfall in the state. The ratio of <1.0 largely falls in the coastal tracts and in some river valleys like that of Rushikulya. The ratio values of >5.0 fall close to some river lines and deltaic parts of Mahanadi River.

Ratio of Ca²⁺/Na⁺

Fresh and immature groundwaters remain Ca²⁺ rich with Ca-HCO₃ facies types reflecting evapotranspiration and carbonate dissolution during recharge (Allen and Suchy 2001). The water types are generally associated with higher values of Ca²⁺/Na⁺ ratio. However, in due course of movement of water in the aquifer, Na⁺ is continuously released through cation exchange of Ca²⁺, the water is naturally evolved to intermediate varieties of Na-HCO₃ due to the mixing of other water types (Allen and Suchy 2001; Fetter 2001).
Thus, gradually, the ratio of Ca$^{2+}$/Na$^+$ decreases towards the end of the journey of water in the aquifer (Chebotarev 1955; Ophori and Toth 1989). In the present set of data, the Ca$^{2+}$/Na$^+$ ratio (ions in meq/L) varies between 0.06-78.0 (mean: 2.4), with the values exceeding unity in 63% (n=697) of the groundwater samples. Na$^+$ remains relatively higher in comparison to Ca$^{2+}$ in 37% (n=408) of the groundwater samples. The geographic distribution of the ratio points in the state of Odisha shows that the values less than 1.0 fall in the coastal tracks and the river basins of Rushikulya, Bansadhara and Brahmani (Fig. 8c). Such values also cluster in the central parts of MRB. The ratio values greater than 1.0 fall in the hilly tracts in the southwestern and northeastern parts of the state, and also in the downstream of Hirakud Reservoir in the canal command areas. The sodium enriched areas (Ca$^{2+}$/Na$^+<1.0$) might be representing the tail end of the groundwater flow system in the discharge corridors.

**Groundwater quality zones**

The overlay analysis of the patterns of distribution of major groundwater quality parameters helps in the delineation of quality zones (Raj and Shaji 2017). Four parameters, namely, the EC, F$^-$, TH and Cl$^-$, which largely control the quality of groundwater in the state, have been used to prepare a groundwater quality zonation map by using GIS for the state. The ranks and weightages to the parameters have been assigned suitably (produced in Table 3) based on their importance to affect the groundwater quality and as per the standards in other published literature (e.g., Raj and Shaji 2017). The broader groundwater quality zones are shown Fig. 9.

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Fig. 9 The groundwater quality zonation map of the Odisha State for the shallow phreatic aquifer. The poor quality zones are specifically observed in MRB (western parts) and lower Rushikulya basin.

Four zones of groundwater quality have been demarcated; (1) excellent, (2) very good, (3) good and (4) poor. As per the results, 59 and 25% of the state area fall in the excellent and very good groundwater quality zones (Fig. 9), while 11% and 5% of the area represent good and poor groundwater quality areas. The poor quality zones are specifically clustered in the western and central parts of the MRB, and in and around Angul in the Brahmani River basin. Such patches are also observed in the coastal tracts including the Mahanadi deltaic plain, and patches in the Rushikulya plain at its confluence with the sea, and a few patches surrounding the Chilika Lake. The poor quality of groundwater in the lower Rushikulya basin and the western parts of MRB (Hirakud canal command area) may be related to the irrigation and use of fertilizers in the agricultural field, whereas that in and around Angul, seems to be linked with the mining-related activities. In the Hirakud canal command area in the Barghar district in the western parts of the state elevated levels of F⁻ have been (Fig. 5) observed which have been linked to the large scale application of fertilizers and pesticides in the agricultural fields. In the Hirakud canal command area, however, the poor quality zones are reflected owing to the elevated levels of EC, Cl⁻ and TH. At the end stages of the groundwater flow system in the discharge areas, these parameters are generally found in increased levels in groundwater due to mineralization (Ophori and Toth 1989).

**Groundwater recharge-discharge zonation based on quality patterns**

A recharge-discharge zonation map of the Odisha State has been prepared in GIS based on the groundwater quality patterns (Fig. 10). The parameters (TDS, HCO₃⁻, Cl⁻, SO₄²⁻ and the ratios of Ca²⁺/Na⁺, Ca²⁺/Mg²⁺ and Ca²⁺+Mg²⁺/HCO₃⁻ used for the purpose has been produced in Table 4 along with the ranks and weightages considered during the weighted overlay analysis. The natural breaks in the patterns of distribution of the parameters have been taken into account while analysing for the groundwater recharge-discharge zones. As observed by Ophori and Toth (1989) the ratios of Ca²⁺/Na⁺ and Ca²⁺/Mg²⁺ generally goes on decreasing from the recharge to discharge area. While fresh and young water remains richer in HCO₃⁻, the old and matured water towards the discharge area becomes enriched in TDS, Cl⁻ and SO₄²⁻. A Ca²⁺+Mg²⁺/HCO₃⁻ ratio of less than 1.0 is also suggestive of fresh recharge or the meteoric nature of groundwater (Nazzal et al. 2014).

Fig. 10 Groundwater recharge-discharge zonation map depicting the major groundwater discharge boundaries.
The hydrochemical facies types predominated with the Na⁺ and Cl⁻ ions are superposed to assess the quality of the matured groundwater at the endpoints of the flow system (for details refer text).

The recharge-discharge zonation map (Fig. 10) shows three areas; groundwater recharge, midline, and discharge areas. The hydrochemical facies types predominated by Na⁺ and Cl⁻ (e.g., Na-Ca-Cl, Na-Mg-Cl, Na-Mg-Cl-HCO₃, Na-Ca-Cl-HCO₃, Na-Cl and Na-Cl-HCO₃, Ca-Na-Cl and Ca-Na-Cl-HCO₃, Mg-Na-Cl-HCO₃, etc.) in a major way fall in the discharge areas.

Table 4 Ranks and weightages of parameters to delineate groundwater recharge-discharge zones

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Conclusions

Groundwater in the State of Odisha is predominantly alkaline in nature (Mean pH: 7.9). Around 90% of the groundwater is moderately hard to very hard. Groundwater fluoride contamination in the shallow aquifer is observed in isolated patches with more incidences in the western and central parts of the state. The overall mineralization in the state is low (mean TDS: 316 mg/L), though it exceeds 1000 mg/L in small and dispersed patches in the state. The elevated TDS levels are observed in patches in the MRB (including the deltaic part) and the lower Rushikulya River basin. Such patches represent the tail end locations of the groundwater flow system in the shallow unconfined aquifer. Close to the groundwater discharge areas in parts of the MRB and coastal alluvium, the Ca²⁺/Mg²⁺ ratio also remains <1.0, suggesting maturity in groundwater quality and depletion in Ca²⁺ levels owing to its removal through either the precipitation of calcium carbonates (kankars) or through the ion exchange processes. The groundwater in the MRB and coastal tracts is also Na⁺ enriched as indicated by the geographic distribution of Ca²⁺/Na⁺ ratio.

The groundwater in the shallow phreatic aquifer of Odisha is largely potable. Considering the patterns of quality parameters such as EC, TH, Cl⁻, and fluoride (F⁻), the poor quality tracts falls in a major way in the MRB, more specifically in its central and western parts. Other significant patches fall in the Mahanadi deltaic plain and the Rushikulya River basin at its confluence zone with the sea. Another significant shallow aquifer zone with poor quality groundwater also exists in and around Angul and Talchir.

The significant groundwater discharge corridors exist in the western parts of MRB, where the tributaries of Mahanadi confluence. Such corridors lie along the river lines. Other important groundwater discharge areas fall in the lower Rushikulya basin and the deltaic parts of Mahanadi. The hydrochemical facies types rich in Na⁺ and Cl⁻ (e.g., Na-Ca-Cl, Na-Mg-Cl, Na-Mg-Cl-HCO₃, Na-Ca-Cl-HCO₃, Na-Cl and Na-Cl-HCO₃, Ca-Na-Cl and Ca-Na-Cl-HCO₃, Mg-Na-Cl-HCO₃, etc) mark the groundwater discharge corridors.
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