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ORIGINAL ARTICLE

M.N. Ravi Shankar
G. Mohan

Assessment of the groundwater potential and quality in Bhatsa and Kalu river basins of Thane district, western Deccan Volcanic Province of India

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M.N.R. Shankar · G. Mohan (✉)
Department of Earth Sciences, Indian Institute of Technology Bombay, Powai, 400076 Mumbai, India
E-mail: gmohan@iitb.ac.in
Tel.: +91-22-25767274
Fax: +91-22-25723480

Abstract Scarcity of groundwater necessitates the present study to evaluate groundwater potential and quality for designing suitable water management plans in the Bhatsa and Kalu river basins in the Thane district in the western Deccan volcanic province of India. A Geographical Information System platform is used to integrate and spatially analyse multiparametric data comprised of satellite, topographical, geological and hydrogeological information to generate several thematic maps, including groundwater potential zonation map. This study reveals that 70% of the area has medium to low groundwater potential, while only 10% has high potential. The static and dynamic groundwater potentials are estimated to be 10.7 and 4.8% of the annual rainfall. The groundwater quality in terms of hardness, total dissolved solids, salinity and chloride is suitable for domestic and irrigational purposes. A database is developed for sustainable water management program for the region and areas where suitable water conservation techniques need to be adopted are identified.

Keywords GIS · Groundwater · GWPZ · Quality · India

Introduction

The utility of remotely sensed data in extraction and demarcation of different lithological, structural and geomorphological features is well recognised (Jensen 1996; Walsh et al. 1998). The remote sensing systems provide synoptic coverage and accurate spatial information which enable economical utilisation over conventional methods of hydrogeological surveys. Rapid advances in the development of the Geographical Information System (GIS) which provides spatial data integration and tools for natural resource management have enabled integrating the data in an environment which has been proved to be an efficient and successful tool for groundwater studies (Meijerink 1996; Nour 1996; Krishnamurthy et al. 1996; Smith et al. 1997; Edet et al. 1998; Jaiswal et al. 2003; Rao and Jugran 2003). The utility and suitability of such integrated studies in delineating groundwater potential zones and identifying recharge sites in a hard rock terrain like the Deccan volcanic province (DVP) of India is demonstrated by Saraf and Choudhury (1998). The importance and the need for groundwater potential zonation, especially in DVP, stems from the chronic water scarcity in this region in spite of receiving a high annual rainfall of about 2,500 mm (Raju 1998). Groundwater potential zonation (GWPZ) enables identification of zones with varying groundwater potential, thus allowing suitable remedial action through a sustainable water management program. The present study attempts to evaluate the groundwater potential in a segment of western DVP using a multiparametric data set. The quality of groundwater is also assessed through geochemical analysis to determine suitability for domestic and irrigational purposes.

Study area

The area chosen for study encompasses the Bhatsa and Kalu river basins, the sub-basins of the Ulhas river. The Bhatsa and Kalu basins adjoin each other at about 50 km northeast of Mumbai in the Thane district of Maharashtra, India, western DVP. The study region encompasses an area of about 2,000 km^2 lying between longitudes 73°10′ –73°50′E and latitudes 19°10′–19°45′N and is covered by the Survey of India toposheets 47°E/ 3,6,7,10,11,12 and 15 on a 1:50,000 scale (Fig. 1). The basaltic terrain has an undulating topography with landforms typical of the DVP. The eastern boundaries of both basins are marked by the steep scarps of the Western Ghats, which run parallel to the west coast of India. The average elevation of both basins is less than 200 m, with only the hills and scarps exhibiting higher elevations.

Data

A multiparametric data set comprising satellite data and survey of India topographic sheets at 1:50,000 scale supported by field research was used. The satellite data (LISS-III) for both basins were obtained from the Indian remote sensing satellites, IRS 1C and 1D for April 1997 and April 1998. The geological field surveys were carried out to obtain information about the lithology, structure, geomorphology, land use and land cover and weathering patterns. These field studies were performed in segments of the Bhatsa and Kalu basins, previously identified through False Colour Composites (FCC) prepared using remote sensing data. The hydrogeological field surveys involved water-level measurements, well inventory and collection of water samples in the post- and pre-monsoon periods during 1999–2001. In addition, information pertaining to the hydrogeological parameters for both basins was obtained from the Groundwater Survey and Development Agency (GSDA) for the period 1991–2000.

Methodology

Digital image processing and analysis, including preprocessing, image enhancement, composite generation, georegistration was carried out with the satellite data. Several thematic maps were prepared based on the remote sensing data, toposheets and field observations, which were then integrated using Intergraph Geomedia Professional software. The assessment of the groundwater

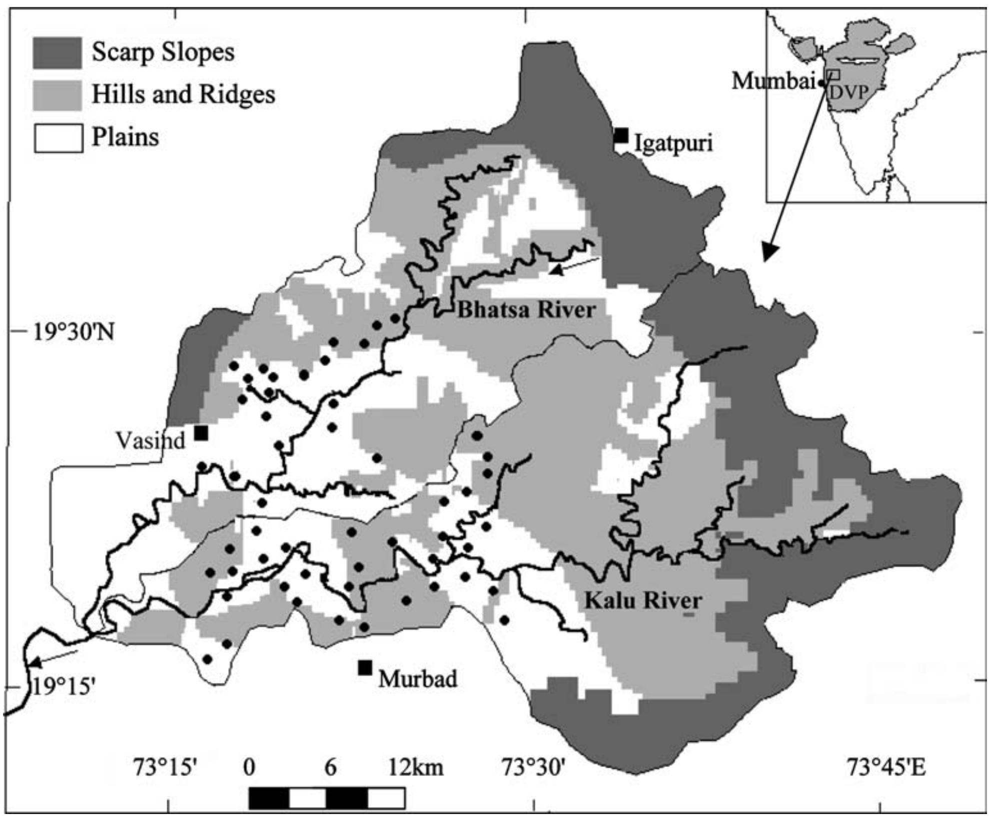

Fig. 1 Map of the study area depicting the Bhatsa and Kalu basins. *Inset map* shows the location within the Deccan Volcanic Province (*DVP*) in India

potential is based on a statistical analysis using the thematic maps. A schematic flow chart of the methodology is shown in Fig. 2. In the information value method, the weights assigned to individual thematic maps are based on a statistical analysis. The information value I_i for a variable, X_i, is calculated using the below expression

$$I_i = \log\left\{\frac{S_i/N_i}{S/N}\right\}, \quad (1)$$

where S_i = No. of pixels with favourable groundwater occurrence and presence of variable X_i,
N_i = No. of pixels with variable X_i,
S = Total no. of pixels with favourable groundwater occurrence,
N = Total no. of pixels in the study area.

The groundwater potential for any pixel (j) is calculated by the total information value (I_j),

$$I_j = \sum_{i=0}^{m} X_{ij} I_i, \quad (2)$$

where m = No. of variables,
$X_{ij}=0$, if X_i is not present for pixel j; and $X_{ij}=1$, if X_i is present.

This analysis involves one dependent variable (groundwater occurrence) and one independent variable (slope, geomorphic unit, etc.).

Thematic maps

Several thematic maps necessary for evaluating groundwater potential were prepared on the basis of information obtained from the toposheets, remote sensing data and field visits, and coordinated using GIS. The classification involves subdividing the information into several categories to enable zonation of potential into several classes. Thematic maps were prepared for lithology, landforms, slope, lineament density, drainage density and drainage frequency, water table fluctuation and land use/land cover.

Lithology

The basaltic flows encompassing the study area are comprised of alternate layers of compact massive basalts and amygdaloidal basalts (Fig. 3a). The massive basalts are mostly unweathered or weathered only surficially wherein a thin weathering rim is formed on the surface, while the core rock remains unaffected. However, at the lower reaches of the high hills, extensive jointing is seen in massive basalts at many places in the study area. The amygdaloidal basalts, which are fine-grained and light to dark grey in colour, both overlie and underlie the massive basalt layer. The amygdules which are composed of secondary minerals like zeolite, calcite and silica vary in size from 2 to 20 mm. Some open vesicles which are spheroidal, elliptical, pipe-like or irregular in shape were also found. These rocks in most places were found to be highly weathered with numerous joints with clayey infillings. The typical soil type observed in the study region is the medium black cotton variety. However, there are variations in the soils and several different varieties of soils, viz., greyish black, brownish black and reddish black soils were also observed.

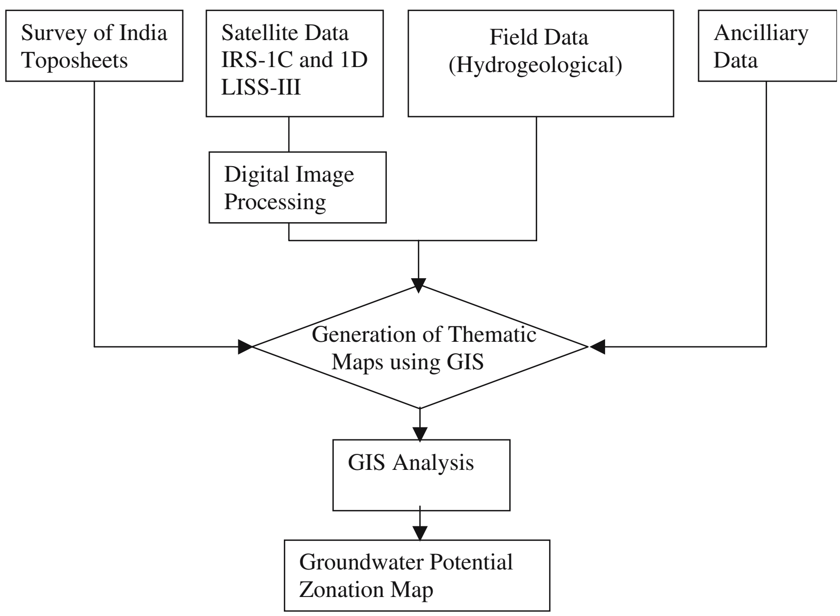

Fig. 2 Flow chart of the methodology adopted

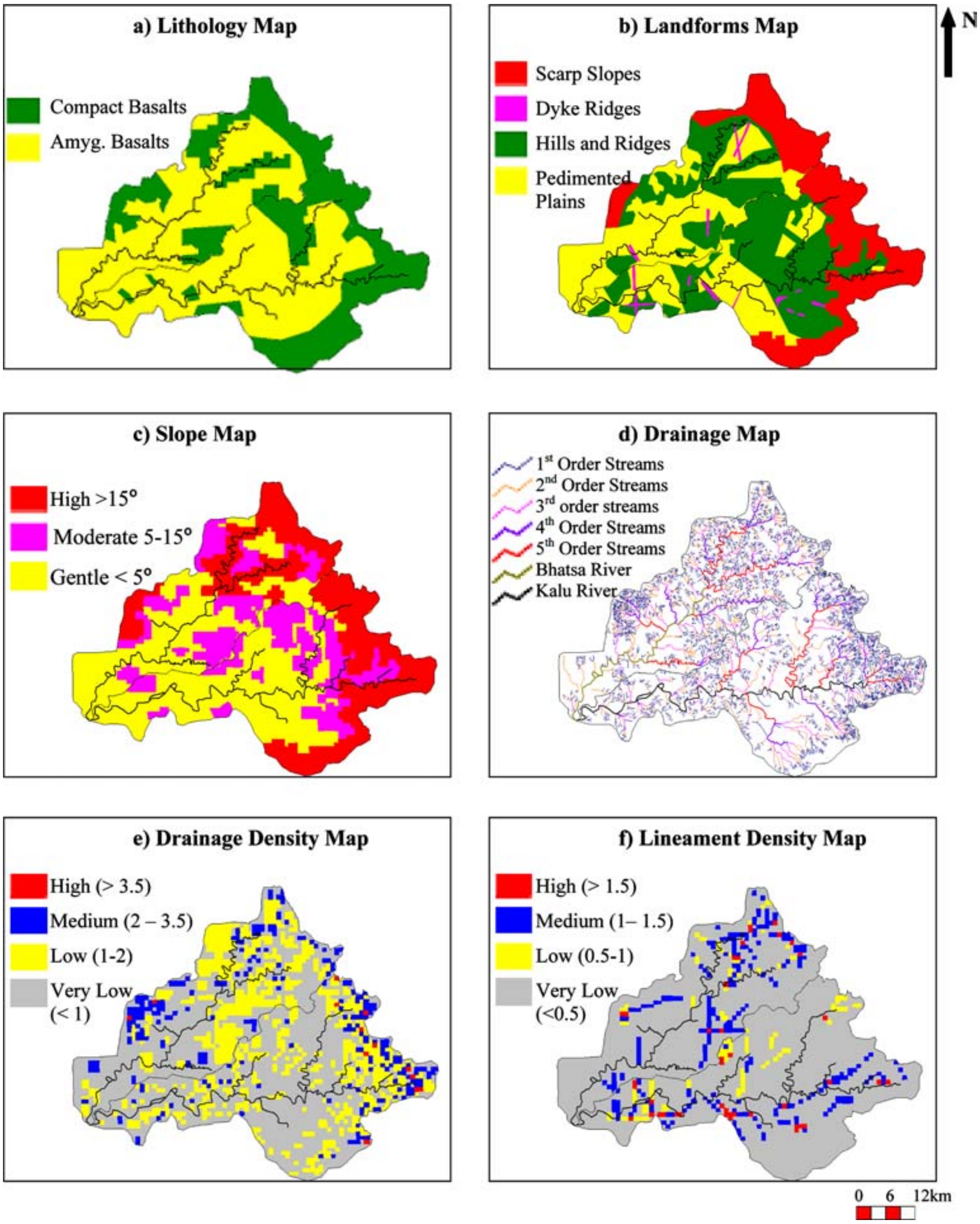

Fig. 3 **a**–**f** Thematic maps for Bhatsa and Kalu basins prepared using remote sensing and conventional data : **a** lithological map; **b** landforms map; **c** slope map; **d** drainage map; **e** drainage density map; **f** lineament density map

Geomorphology

Geomorphological landforms were identified and demarcated on the basis of Survey of India topographical maps on the scale 1:50,000 and other characteristic features into four broad classes—scarp slopes, dyke ridges, hills and ridges and pedimented plains (Fig. 3b). These landforms were studied through remote sensing data followed by field visits to confirm ground truth. In both basins, the eastern boundaries are marked by steep scarps (average elevation ≈1 km), while the central and western parts are marked by gently undulating topography interspersed with hills and ridges. The average elevation in both basins is less than 200 m, with only the hills and ridges and the scarps exhibiting higher elevations to about 800 m.

Slope

Slope is a critical parameter with a direct control on runoff and therefore on infiltration. The scanned topographic maps were first georeferenced to the specific coordinates for on-screen digitisation of the elevation contours at 100 m interval using the Intergraph MGE Terrain Analyst and MGE Grid Analyst modules. The digitised contours were converted from vector to raster (grid). A digital elevation model (DEM) with 100 m resolution was generated. The slope maps were then generated from the DEM and reclassified into three slope groups as gentle (< 5°), moderate (5–15°) and high (> 15°) as shown in Fig. 3c.

Drainage density

The NE–SW flowing Bhatsa river and the E–W flowing Kalu river and their tributaries form the major drainage. The drainage pattern is dominantly dendritic to sub-dendritic, but rectangular drainage patterns were observed at certain places (Fig. 3d). The study area was divided into grids of 1 km^2. The total lengths of all streams in each grid were calculated and used to determine the drainage density values in km/km^2. These values were regrouped to produce a drainage density map classified into four categories, viz., high, medium, low and very low as shown in Fig. 3e. Similarly, the drainage frequency was calculated using the same grids of 1 km^2 by counting the number of streams irrespective of their order in each grid.

Lineament density

The lineaments map was prepared using the topographic maps, imageries and a field check to confirm the lineaments as geologic features of interest. The identified lineaments in both the basins trend north–south, northeast–southwest, northwest–southeast and east–west. Several lineaments intersect one another and a few lineaments appear to be associated with the faulted segments of the rivers. The majority of the lineaments correspond to either dyke ridges or stream channels, which are important as the occurrence and movement of groundwater is controlled by these linear features. The lineament density map was classified into four classes—high, medium, low and very low based on the number of lineament per km^2. The classified lineament density maps of both basins are shown in Fig. 3f. In the Kalu basin, most of the lineaments are concentrated in the vicinity of the Kalu river. Several lineaments appear to influence the river course, indicating structural control. The Bhatsa basin shows a much higher density of lineaments, a majority of which occur away from the Bhatsa river, especially in the eastern part of the basin. A major portion (> 85%) of both basins is comprised of low lineament density.

Land use/land cover

Knowledge of land use and land cover is necessary to help quantify the water budget. Land use and land cover affect evapotranspiration, surface-water runoff, volume and timing and recharge of the groundwater system. Five broad classes of land use/land cover were identified and demarcated in the study region, namely, dense vegetation, sparse vegetation, cultivated land, barren land and water bodies. A major portion (> 50%) of both Bhatsa and Kalu basins is comprised of barren land with only about 10% of land being cultivated, 25–35% of the land being vegetated, and the rest consisting of water bodies.

Groundwater potential zonation

Groundwater potential zonation involves identifying and delineating the zones which are favourable for the occurrence of groundwater based on a multiparametric approach. The parameters used for GWPZ are the thematic maps prepared for lithology, land use/land cover, lineament density, drainage density, geomorphology, slope and water table fluctuation (Table 1). The GWPZ map of the Bhatsa and Kalu basins (Fig. 4) shows four distinct classes corresponding to high, medium, low and very low groundwater potential. The map reveals that, these GWPZ can be broadly correlated with three distinct hydrogeomorphological environments. The high potential zones encompass the pedimented plains around the major rivers and demarcate the areas where the terrain is most suitable for groundwater recharge and storage, and also indicate the availability of water in

Table 1 Parameters used in Geographical Information System integration

Parameters	Variables
Lithology	Massive Basalts
	Amygdaloidal Basalts
Slope	Gentle (0°–5°)
	Moderate (5°–15°)
	High (> 15°)
Geomorphology	Hills and ridges
	Scarp slopes
	Pedimented plains
Land use/land cover	Dense vegetation
	Water body
	Barren land
	Sparse vegetation
Lineament density (per km^2)	Very low (0–1)
	Low (1–2)
	Medium (2–3.5)
	High (> 3.5)
Drainage density (per km^2)	Very low (0–1)
	Low (1–2)
	Medium (2–3.5)
	High (> 3.5)
Water table fluctuation (m)	Low (0–5)
	High (> 5)

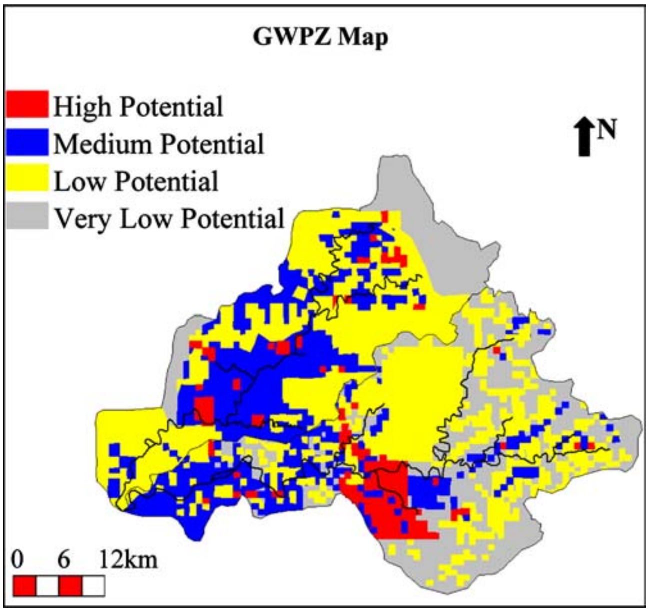

Fig. 4 Groundwater potential zonation map of Bhatsa and Kalu basins

the subsurface. The central and western parts comprising of gently sloping plains interspersed with hills and ridges constitute the predominantly medium to low potential zones which exhibit low drainage density and low water table fluctuations (<3 m). In Bhatsa basin, the low and medium potential zones in the lower Bhatsa, downstream of the Bhatsa reservoir, may benefit from the groundwater infiltration from the Bhatsa reservoir. The eastern segments of both basins are marked by scarp slopes which constitute the very low potential zones. A major portion ($>50\%$) of both basins exhibit low to very low groundwater potential.

Quantification of groundwater potential

It is possible to quantify the amount of groundwater reserves in the aquifer by estimating the static and dynamic groundwater potentials. The static groundwater potential is the equivalent depth of water column between the bottom of the aquifer and the lowest water table level measured. The lithologs from GSDA indicate that the thickness of the weathered zone averages 15 m and the depth to the deepest groundwater level averages about 6 m during summer, implying a static column of 9 m of available water. The static groundwater potential was estimated using the formula given by the Ministry of Irrigation (1984), which is expressed as

$$S_{wp} = S_t \times A_e \times S_y,$$

where S_{wp} is the static groundwater potential, S_t is the saturated thickness of aquifer below the zone of water-level fluctuation, A_e is the area of influence and S_y is the average specific yield.

Considering the total area encompassed by both the medium and high groundwater potential zones, which is 38 and 46% for the Bhatsa and Kalu basins, respectively, and the average S_y for basalts to be 3% based on the range of S_y given by GSDA, Ministry of Irrigation (1984) and Deolankar (1980), the S_{wp} for Bhatsa and Kalu basins works out to be 88 and 138 MCM, respectively, which is about 10.7% of the average annual rainfall in this area.

The dynamic groundwater potential (D_{wp}) is the exploitable groundwater available between the periods of maximum fluctuation in groundwater table levels. The pre- and post-monsoon fluctuation in water table averaged about 4 m. This value was used to determine D_{wp} using the expression given by Ministry of Irrigation (1984)

$$D_{wp} = W_f \times A_e \times S_y,$$

where D_{wp} is the Dynamic water potential, W_f is the pre- and post-monsoon fluctuation in groundwater table, and A_e and S_y are as given earlier.

The dynamic water potential for the Bhatsa and Kalu basins was calculated at 39.3 and 61.4 MCM, respectively, which is about 4.8% of the annual rainfall.

Hydrogeochemistry

Hydrogeochemical analysis enables assessment of the groundwater quality and its suitability for domestic and irrigational purposes. Water is an excellent solvent and tends to dissolve minerals. This process is influenced by several factors, including rock type, chemical weathering processes and anthropogenic factors. Regional groundwater typically contains seven major ions Ca^{+2}, Mg^{+2}, Na^{+1}, K^{+1}, Cl^{-1}, HCO_3^{-1} and SO_4^{-2}, and other elements in minor concentrations. The hydrogeochemistry of the water samples in both basins was analysed. Pre- and post-monsoon water samples were collected from 20 locations in Bhatsa basin and 31 locations in Kalu basin (Fig. 1) from various sources, including surface water (rivers, tributaries), groundwater from dug wells and bore wells. Chemical analysis was carried out as per the procedures stipulated by American Public Health Association (APHA 1998). The physical parameters considered were colour, odour and turbidity. Chemical parameters considered were the hydrogen ion concentration, specific conductance, total dissolved solids (TDS), total hardness and concentrations of all major cations and anions.

Groundwater quality analysis for drinking water

Quality of groundwater determines usability depending upon the specific standards for different purposes. Chemically, the water used for drinking should be soft, low in dissolved salts and free from poisonous constituents. The standards for drinking water are specified by the World Health Organisation (WHO 1971) on the basis of several factors, viz., taste and odour, pH, TDS, hardness and chloride content, among others. The water samples collected in the study area were, in general, colourless, odourless and free from turbidity, and the pH varied between 6 and 8 for both pre- and post-monsoon water samples.

Chemical analysis

Chemical analysis was carried out to determine the major ion concentrations. The maximum and minimum concentrations of ions in milliequivalents per litre denoted as epm (equivalent parts per million), in the pre- and post-monsoon groundwater samples is given in Table 2. Groundwater is of the calcium–magnesium–bicarbonate type as expected in a basaltic terrain.

Total dissolved solids

Total dissolved solids are the residue of a filtered water sample after evaporation. In natural waters, dissolved solids are primarily composed of carbonates, bicarbonates, chlorides, sulphate, phosphate, silica, calcium, magnesium, sodium and potassium. Caroll (1962) proposed four classes of water based on TDS values, of which water samples with TDS < 1,000 mg/l belong to the fresh water class. The TDS of water samples in both basins are less than 1,000 mg/l. The results fall within the fresh water class for both pre- and post-monsoon periods and satisfy the criteria of WHO (1971) for drinking water (Table 3).

Hardness

The presence of major ions, such as calcium, magnesium, bicarbonate, chloride and sulphate in water causes hardness and makes it unsuitable for drinking. Total hardness of the water samples from the Bhatsa and Kalu basins varies between 178–326 ppm, and 80–350 ppm, respectively, for post-monsoon water samples, and 218–326 ppm and 240–680 ppm, respectively, for pre-monsoon water samples. In general, the hardness of the water samples in both basins, with few exceptions, is found to be moderately hard to hard (Table 4), as per the classification of Sawyer and McCartly (1967), but within the hardness limits (< 600 ppm) specified by the ISI (1983) for drinking water.

Chloride concentration

Chloride ion is the predominant natural form of the element chlorine and is extremely stable in water. The

Table 2 Concentrations of major ions in groundwater samples

Ions	Bhatsa basin				Kalu basin			
	Post-monsoon (epm)		Pre-monsoon (epm)		Post-monsoon (epm)		Pre-monsoon (epm)	
	Min	Max	Min	Max	Min	Max	Min	Max
Na	0.27	1.09	0.07	1.17	0.34	2.93	0.06	0.91
K	0.02	0.12	0.0	0.12	0.0	0.96	0.01	0.50
Ca	1.14	3.5	1.08	2.99	0.80	4.80	0.80	4.05
Mg	1.0	5.1	2.22	5.09	0.20	3.25	3.02	8.85
HCO_3	2.78	6.23	1.38	6.45	1.25	5.54	1.93	4.83
Cl	0.02	1.00	0.28	1.25	0.14	3.70	0.51	3.63
SO_4	0.08	0.58	0.04	0.29	0.28	2.82	1.05	2.11

epm denotes equivalent parts per million

Table 3 Water quality based on total dissolved solids (TDS)

TDS in mg/l	Water quality	Bhatsa basin		Kalu basin	
		Post-monsoon	Pre-monsoon	Post-monsoon	Pre-monsoon
0–1,000	Fresh water	181–879	285–954	106–614	258–684
1,000–10,000	Brackish water				
10,000–100,000	Salty water				
> 100,000	Brine				

Table 4 Classification of water based on hardness

Hardness in ppm as $CaCO_3$	Water class	Bhatsa basin		Kalu basin	
		Post-monsoon	Pre-monsoon	Post-monsoon	Pre-monsoon
0–75 75–150 150–3,000 > 3,000	Soft Moderately hard Hard Very hard	178–326 (20)	218–326 (17)	80–140 (12) 160–350 (19)	241–683 (31)

Table 5 Sodium hazard classification

Class	SAR	Quality	Bhatsa basin		Kalu basin	
			Post-monsoon	Pre-monsoon	Post-monsoon	Pre-monsoon
S1 S2 S3 S4 and S5	10 10–18 18–26 > 26	Excellent Good Doubtful Unsuitable	0.19–0.72	0.04–0.79	0.35–2.31	0.04–0.72

range of chloride concentrations varies between 0.02–1.0 epm and 0.14–3.70 epm for post-monsoon water samples, and 0.28–1.25 epm and 0.51–3.63 epm for pre-monsoon water samples in Bhatsa and Kalu basins respectively. Chloride concentration is within the limits specified by WHO (1971) for drinking water.

Groundwater quality analysis for irrigation

Water quality, soil type and cropping patterns play an important role in successful irrigation. Important chemical constituents which affect the suitability of water for irrigation are total concentration of soluble salts, relative proportion of sodium to calcium and relative proportion of bicarbonate to calcium and magnesium. Water quality problems in irrigation include alkalinity and salinity of groundwater. The sodium hazard in irrigation water is expressed by the sodium absorption ratio (SAR) which is given by the relation (Karanth 1987)

$$SAR = \frac{Na}{\{(Ca + Mg)/2\}^{1/2}},$$

in which concentrations are expressed in epm. Low sodium water (S1) can be used for irrigation in almost all types of soils. Since both pre- and post-monsoon groundwater samples fall in the low sodium category (Table 5), there is no hazard of alkalinity (Richards 1954).

Salinity hazard

Salinity hazard is categorised into several classes on the basis of the specific conductance of the water samples (Table 6). The specific conductance (Ec) of water samples in the Bhatsa and Kalu basin vary between 450–1,500 $\mu\Omega^{-1}$/cm and 400–1,100 $\mu\Omega^{-1}$/cm, respectively, for pre-monsoon, and 280–1,400 $\mu\Omega^{-1}$/cm and 150–1,000 $\mu\Omega^{-1}$/cm, respectively, for post-monsoon. Most samples fall in the medium salinity hazard (C2) category and are suitable for irrigational purposes, with a few exceptions which fall in the C3 category (Table 6).

Conclusions

The GIS approach results in a groundwater potential map for both Bhatsa and Kalu basins to serve as a guide

Table 6 Salinity hazard classification

Class	Ec, $\mu\Omega^{-1}$/cm	Quality	Bhatsa basin		Kalu basin	
			Post-monsoon	Pre-monsoon	Post-monsoon	Pre-monsoon
C1 C2 C3 C4 and C5	100–250 250–750 750–2,250 > 2,250	Excellent Good Doubtful Unsuitable	283–639 (12) 765–1,374 (8)	445–732 (6) 756–1,491 (11)	166–234 (5) 256–746 (25) 960 (1)	403–720 (23) 756–1,098 (10)

The number of samples are given in brackets for groundwater exploration. The multiparametric information sets form a useful database for decision makers to use in planning and management of water resources for both domestic and irrigational purposes. The Bhatsa and Kalu basins exhibit similar hydrogeomorphological characteristics in terms of lithology, geomorphological units, drainage and lineament pattern, structural controls and groundwater fluctuation, and consequently show comparable groundwater potential. This study reveals that a major portion (≈70%) of the study area in both basins exhibits low to medium groundwater potential, which explains the scarcity of water during summer seasons. In such regions, the groundwater needs to be augmented through suitable watershed management techniques which can be implemented on the basis of the multiparametric database. The quality assessment of groundwater in the study region shows that all elements of water samples fall well within the desirable limits as given by the norms of WHO and Indian Standards Institution (ISI 1983). The groundwater is generally of "fresh water" and Ca–Mg–HCO_3 type, and is suitable for agricultural and drinking purposes. This study demonstrates the importance and utility of integrated studies for evaluation of ground water resources potential and quality in a basaltic terrain.

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