A GIS based hydrogeomorphic approach for identification of site-specific artificial-recharge techniques in the Deccan Volcanic Province

M N Ravi Shankar and G Mohan*

Department of Earth Sciences, Indian Institute of Technology Bombay, Powai, Mumbai 400 076, India.
**e-mail: gmohan@iitb.ac.in*

The Deccan Volcanic Province (DVP) of India, as a whole, faces a severe shortage of water despite receiving a high annual rainfall, this is primarily due to excess runoff and lack of water conservation practices. In this study, an attempt is made to identify zones favourable for the application and adaptation of site-specific artificial-recharge techniques for augmentation of groundwater through a Geographical Information System (GIS) based hydrogeomorphic approach in the Bhatsa and Kalu river basins of Thane district, in western DVP. The criteria adopted for the GIS analysis were based on the hydrogeomorphological characteristics of both basins extracted from the IRS-1C LISS-III data supported by information on drainage pattern, DEM derived slope, lineament density, drainage density, and groundwater condition. The integrated study helps design a suitable groundwater management plan for a basaltic terrain.

1. Introduction

The groundwater scenario in India, which receives a substantial amount of annual rainfall, is not very encouraging primarily due to the imbalance between recharge and groundwater exploitation. A large amount of rain water is lost through runoff, a problem compounded by the lack of rainwater harvesting practices. Exploitation of subsurface water from deep aquifers, also depletes resources that have taken decades or centuries to accumulate and on which the current annual rainfall has no immediate effect. Few sustained efforts have been made to identify zones where artificial-recharge techniques can be implemented to conserve groundwater. The Deccan Volcanic Province (DVP) is one such region, which faces acute shortage of groundwater inspite of receiving a high annual rainfall (Raju 1998). Conventional hydrogeological studies would not suffice in studying the surficial parameters of a large area to identify suitable sites for artificial-recharge because there are many controlling parameters that must be independently derived and integrated. Modern remote sensing techniques facilitate demarcation of suitable areas for groundwater replenishment by taking into account the diversity of factors that control groundwater recharge. Remote sensing has emerged as a useful tool for watershed characterization, conservation, planning and management in recent times. In the present study, the objective is to identify site-specific mechanisms for augmenting groundwater recharge in the Bhatsa and Kalu river basins in the Thane district of Maharashtra, in western DVP (figure 1), using an integrated GIS approach (Ramaswamy and Anbazhagan 1997; Saraf and Choudhury 1998). The criteria and techniques of detecting site-specific mechanism for artificial-recharge were discussed by Ramaswamy and Anbazhagan (1997) with a case study from Ayyar basin; Saraf and Choudhury (1998) attempted an integrated approach to identify sites for groundwater recharge in a hard rock terrain through recharge basins or reservoirs.

Keywords. Artificial-recharge; DVP; GIS; hydrogeology.

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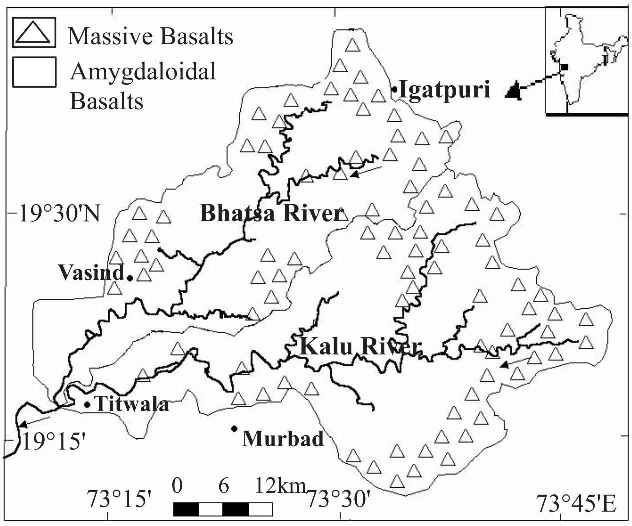


Figure 1. Map of the study area depicting the lithology in the Bhatsa and Kalu basins.

2. Status of artificial-recharge in Deccan traps

Groundwater augmentation involving the implementation of suitable artificial-recharge techniques is being practiced at a few places in the DVP. Studies on percolation tanks and their effect on groundwater have been carried out by the Central Ground Water Board (CGWB 1994); Rao (1975) and Thange (1990). Rao (1975) studied 30 percolation tanks in the Baramati region of Maharashtra in the DVP and calculated that a percolation tank of about 4 million cubic feet (Mcft) will eventually provide as much as 5 Mcft to the groundwater in a year under favourable conditions. A study by CGWB (1994) on the effectiveness of the 12 percolation tanks in Jerur sub-basin, Ahmednagar district showed that around 10% of stored water was lost as evaporation, 50% recharged the groundwater reservoir, and the remaining 40% was used partly for surface irrigation and partly stored for future use. Gandhi and Masoom (1990) reported the groundwater augmentation program in Aurangabad district where a series of *nalla* bunding (surface dam across rivulet) and terracing were done and three bore wells each of six inches diameter were drilled in the centre of the *nalla* bunds. The area around the wells were excavated and refilled with boulders and pebbles owing to which the water table level rose from 0.2 to 1 m in the wells in the vicinity of the project. Nilkalja and Masoom (1990) reported the effect of *bandharas* (sub-surface dams) in Jalna district where these were constructed across 2nd and 3rd order streams, resulting in a substantial increase in the water table levels (3 m in pre-monsoon and 8 m in post-monsoon with an increase in pumping hours). These *bhandaras*, which act as dykes, were used to impound moving groundwater in the storage space of the aquifer.

3. Study area

The study area encompasses the Bhatsa and Kalu river basins, which are the sub-basins of the Ulhas river in the Thane district, near Mumbai in western DVP (figure 1). The annual precipitation in this region is about 2500 mm and the post-monsoon availability of water is plentiful. However, owing to the higher slopes and scarps of the western limb of the Sahayadris (Western Ghats) flanking the eastern parts of both basins, the surface runoff is quite high. The top soil cover together with the underlying weathered rock forms the upper unconfined aquifer in the area. The rain water accumulates in the unconfined aquifers with gentle to moderately sloping grounds, then it flows downstream and ultimately to the Arabian Sea. The available water is sufficient during the early part of the winter season (till December); later, the water table declines rapidly, and by March, many of the shallow wells tapping the upper unconfined aquifers either become dry or do not adequately meet the requirement. Thus, although there is an abundance of surface water, there is still an acute shortage of water in summer. Hence, there is a need to identify regions where site-specific artificial-recharge methods can be adopted to augment water supply.

3.1 *Geology and geomorphology*

The study area comprises of volcanic rock with alternating layers of compact massive basalts and vesicular amygdaloidal basalts (figure 1). Most of the region is covered with soil with an average thickness of 3 m; hence, very few rock exposures are found and these are predominantly at road cuttings and along river banks. The typical soil type observed is the medium-black-cotton variety. There are, however, variations in the type of soil and several different varieties of soils, i.e., greyish black, brownish black, and reddish black soils are also observed. The region has an undulating topography with landforms typical of a basaltic province. The major geomorphic landforms demarcated are scarp slopes, hills and ridges, dyke ridges, and pedimented plains (figure 2a). The eastern boundaries of both Bhatsa and Kalu basins are marked by steep scarps, while the central and western parts of both basins are marked by gently undulating topography interspersed with hills and ridges. The average elevation in both basins is less than 200 m,

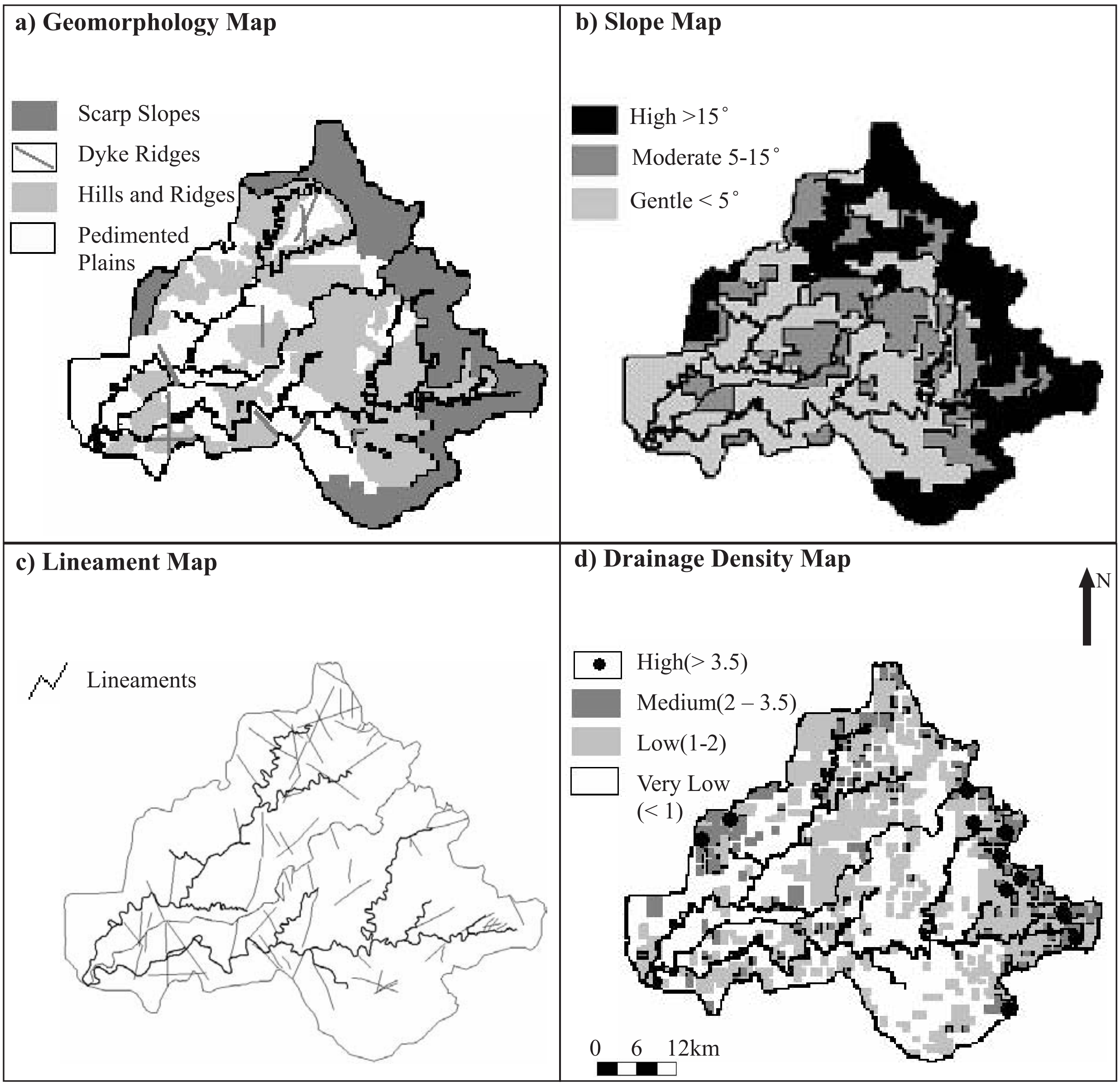


Figure 2**(a–d)**. Thematic maps of Bhatsa and Kalu basins prepared using conventional and remote sensing data: **(a)** Geomorphology map, **(b)** Slope map, **(c)** Lineament map, **(d)** Drainage density map.

with only the hills, ridges and scarps exhibiting higher elevations.

3.2 *Classified slope map*

Slope has a direct control on the runoff and therefore on infiltration. A Digital Elevation Model (DEM) derived slope model was generated for both Bhatsa and Kalu basins. The topographic maps were scanned and first geo-referenced to the specific coordinates and used to generate a DEM with 100 m resolution using Intergraph MGE Terrain Analyst and Modular GIS environment (MGE) Grid Analyst modules. The slope maps were then generated from the DEM and reclassified into three slope groups as gentle (0°–5°), moderate (5°–15°) and high (>15°) (figure 2b).

3.3 *Lineaments*

The IRS-1C and 1-D LISS-III data, which together covered the study region, for April 1997 and April 1998 were used to prepare the false colour composites. The lineaments map for the Bhatsa and Kalu basins was prepared using the topographic maps, satellite imageries and a field check to confirm the lineaments as geologic features of interest (figure 2c). The identified lineaments in both

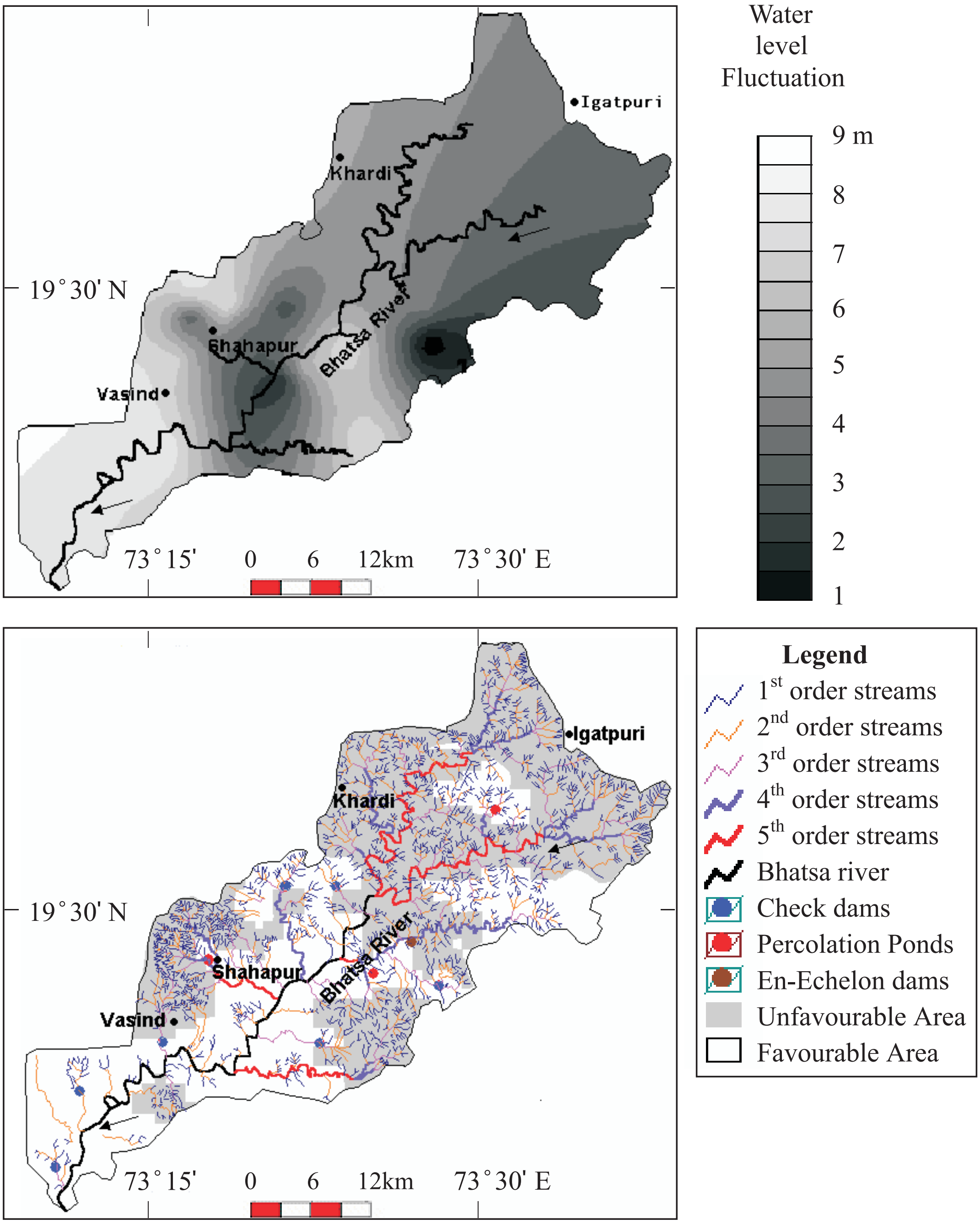
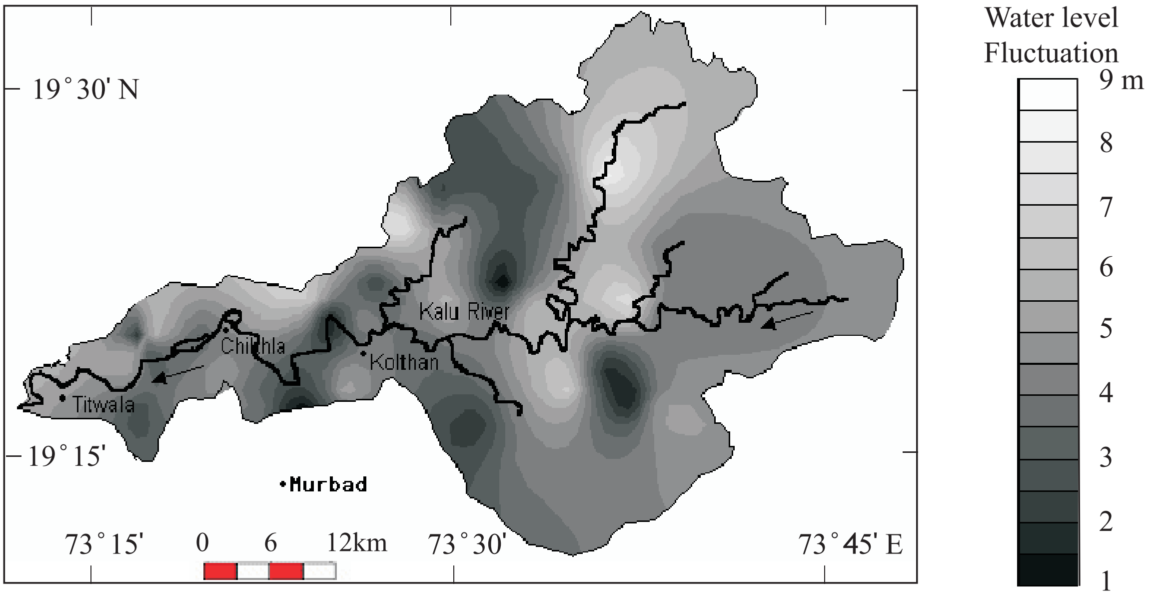


Figure 3. Water table fluctuation map of Bhatsa basin (top). Location map of sites recommended for artificial-recharge in Bhatsa basin (bottom).

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 of importance as the occurrence and movement of groundwater is controlled by these linear features. The lineament map was used for classifying the lineaments into four classes — high (>1.5), medium (1.0–1.5), low (0.5–1.0), and very low (0–0.5) based on the lineament density (km/km^2). A major portion (>85%) of both basins has low lineament density ($< 0.5\,km/km^2$).

3.4 *Drainage*

The major drainage in the study region comprises of the NE–SW and E–W flowing Bhatsa and Kalu rivers respectively and their tributaries (figures 3



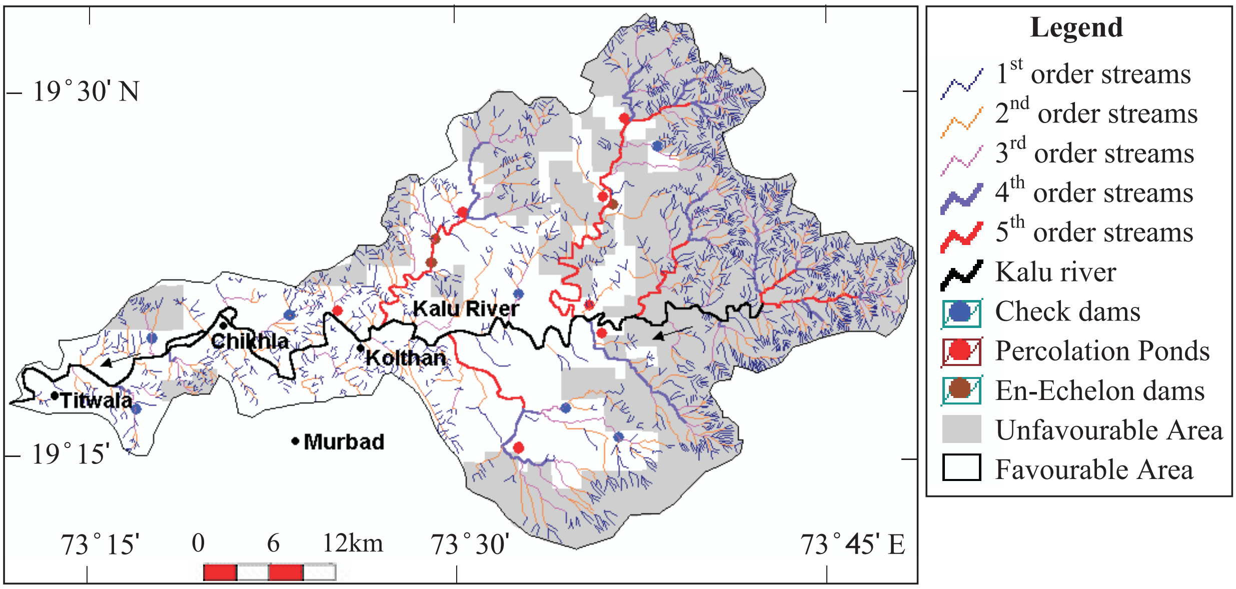


Figure 4. Water table fluctuation map of Kalu basin (top). Location map of sites recommended for artificial-recharge in Kalu basin (bottom).

and 4). The dominant drainage pattern observed is dendritic to sub-dendritic; rectangular drainage pattern is seen at a few places. The structural controls, especially on the Kalu river, are brought out by the sharp right angle turns and long linear stretches of the streams for a few kilometres. The lithological control results in the evolution of the dendritic and sub-dendritic pattern due to low infiltration. Both basins exhibit fine texture in the eastern part and medium-to-coarse texture in the central and western parts. Strahler's system of stream ordering (Strahler 1957) is used, in which the smallest finger-tip tributaries are designated as order 1 and when two 1st order channels join, a channel segment of order 2 is formed (and so on). The highest-order stream in a basin defines the order of that basin and both Kalu and Bhatsa are found to be 6th order basins.

3.5 *Classified drainage density map*

The study area was divided into square grids of 1 sq.km and the total lengths of all streams in each grid were calculated in order to determine the drainage density values in km/km^2. These values were regrouped to produce a drainage density map that was classified into four categories, i.e., high (>3.5), medium (2–3.5), low (1–2) and very low (0–1) for the Bhatsa and Kalu basins (figure 2d).

Table 1. *Area occupied by the classified land use/land cover categories in Bhatsa and Kalu basins.*

Classes	Bhatsa basin Sq. kms	Bhatsa basin Percentage	Kalu basin Sq. kms	Kalu basin Percentage
Dense vegetation	163	19	167	15
Sparse vegetation	146	17	111	10
Cultivated land	69	8	100	9
Barren land	447	52	668	60
Water bodies	34	4	67	6

A major portion (>50%) of the region has low drainage density ($<1\,km/km^2$).

3.6 *Classified land use/land cover map*

The supervised land use/land cover classified maps for both basins were prepared to quantify components of the water budget. Accordingly, five broad classes of land use/land cover were identified and demarcated in the region: dense vegetation, sparse vegetation, cultivated land, barren land, and water bodies. The area occupied by each class is shown in table 1. A major part (>50%) of both basins comprises of barren land; less than 10% land is cultivated.

3.7 *Water table fluctuation*

The pre- and post-monsoon groundwater fluctuation data of both basins were obtained from field measurements and also from Groundwater Survey and Development Agency (GSDA) for over 100 dug wells. The diameter and total depth of dug wells, which are mostly lined, averaged around 4 m and 8 m respectively. The post- and pre-monsoon fluctuation in the water table ranges from 2.2 m to 6.7 m for Bhatsa basin (figure 3) and 1 m to 8.3 m for Kalu basin (figure 4). The average pre- and post-monsoon water table level was 6 m and 2 m with an average water table fluctuation of 4 m. The minimum fluctuation in the water table was observed in the regions close to the Bhatsa and Kalu rivers in the central parts of the basins.

4. Artificial-recharge site selection

Several artificial-recharge methods like percolation ponding, recharge pitting, en echelon damming, flooding, induced recharging, and construction of a battery of wells are being practiced successfully all over the world (Karanth 1987; Muralidharan and Athavale 1998). Various other soil and water conservation methods, which are also commonly adopted, include contour trenching, terracing, *nalla*-bunding, and inter-basin transfer (Troch *et al* 1980). Selection of suitable sites for application of appropriate artificial-recharge techniques is critical for effective recharge and is dependent upon several parameters which are to be analyzed together in a GIS environment. A study by CGWB (1994) on percolation tanks showed that if the site of a percolation tank is properly selected and the tank designed appropriately, the groundwater recharge through the tanks can go up to 70% (Raju 1998). Many workers have adopted different criteria on the basis of the groundwater conditions in the area for integrating various geological and hydrogeological parameters to select suitable sites for recharge (Ramaswamy and Anbazhagan 1997; Saraf and Choudhury 1998; Pakhmode *et al* 2003). The parameters which play an important role in site selection are water table level fluctuation data, geological data (lineament density, depth to bedrock and soil cover), hydrogeomorphological data (drainage density, slope, landforms, land use/land cover).

The criteria for the choice of sites depends not only on the groundwater conditions, but also, and more importantly, on the suitability of the terrain for artificial-recharge. Artificial-recharge needs to be adopted not only to augment the groundwater in regions where it is insufficient, but also as an insurance against future droughts. In order to identify the regions where artificial-recharge techniques can be employed, a set of decision rules involving the hydrogeomorphic parameters controlling the groundwater flow need to be considered. The primary task is to identify regions of high, medium, low, and very low groundwater-potential zones (GWPZ) using a multiparametric integrated GIS approach (Krishnamurthy *et al* 1996; Ravi Shankar 2003) for evaluating the GWPZ using several thematic maps corresponding to the hydrogeomorphic parameters. The qualitative and quantitative GWPZ maps for Kalu and Bhatsa basins were prepared by Ravi Shankar (2003). The decision rules are derived from the hydrogeomorphic parameters corresponding to the medium-to-low groundwater-potential zones where adoption of artificial-recharge techniques is required. This would effectively exclude regions with very low groundwater-potential where artificial-recharge techniques cannot be employed and also the high groundwater-potential zones where artificial-recharge is not essential. The decision rules used to identify the sites suitable for artificial-recharge zones are listed in table 2, and the justification for the choice of each parameter is discussed below.

The pre- and post-monsoon groundwater fluctuation maps of both basins (figures 3 and 4) indicate that poor groundwater conditions resulting

Table 2. *Decision rules for selecting favourable sites for artificial-recharge.*

Set	Parameter	Value
Water table level data	Water table fluctuation	> 4 meters
Geological data	Lineament density	> 1.5 km/km^2
	Depth to bedrock	> 8 meters
	Soil cover	> 0.75 meters
Geomorphological data	Drainage density	< 2 km/km^2
	Land forms	Plains
	Land use/land cover	Barren land, cultivated land
	Slope	< 5°

from high water table fluctuation (greater than 6 m) are found mainly in the high-slope regions, which are unsuitable for artificial-recharge. On the other hand, in the most favourable zones, which have gentle slopes, the water table fluctuation is low (< 3 m), implying that these regions essentially do not require groundwater augmentation. As most wells are shallow, a fluctuation in water table higher than the average results in inadequate supply of water to meet the demands of the people. Hence, a water table fluctuation greater than 4 m, which is the average water table fluctuation in both basins, is taken as one of the criteria for consideration of sites for recharge. The adopted criteria encompass both the recharge and storage zones where appropriate techniques can be implemented. Another equally important criterion is the availability of storage space in the subsurface for augmenting the groundwater supply and storing it, so that water is available in the event of any eventuality like drought. Information about lithologs obtained from bore-wells predominantly in the plains, as well as field studies, indicate that the top soil and highly weathered zone has an average thickness of 5 m while the underlying moderately weathered zone has an average thickness of 10 m. Hence, the soil thickness and the depth-to-bed rock both satisfy the general criteria adopted in table 2. The fractured and weathered basalts are most suitable as they provide the necessary permeability and storage space. Lineaments facilitate movement of groundwater and the presence of moderate lineament density (1–1.5 km/km^2) is considered suitable. However, since the lineament density in both study basins is low and the soil and weathered zone is sufficiently thick to be considered suitable for artificial-recharge, the low lineament density zones are also included.

Pedimented plains which follow the steep slopes in the area are the most favourable geomorphological class because they check the velocity of surface runoff and thus provide more chance of water accumulation. Gentle slopes (< 5°) serve to build up the hydraulic gradient and are thus considered most suitable. Areas of steep slopes, basaltic plateaus, and scarps are all considered unfavourable. Moderate drainage density (2 km/km^2) is taken to be an optimum balance between runoff and infiltration.

The areas where the terrain is favourable for implementation of artificial-recharge methods is first demarcated using the hydrogeomorphic parameters given in table 2. The maps exhibiting the zones favourable and unfavourable for artificial-recharge are prepared for both basins. The drainage pattern map is then superimposed over the artificial-recharge zonation map and used to identify site-specific mechanism for artificial-recharge for both basins (figures 3 and 4).

5. Sensitivity analysis

A sensitivity analysis has been done for the Kalu river basin to demonstrate the robustness of the procedure adopted for demarcating the regions favourable/unfavourable for artificial-recharge. It is found that for minor variations in the hydrogeomorphic parameters there is very little change in the zones delineated for artificial-recharge. Hence, the hydrogeomorphic parameters were progressively varied by ±12% to demonstrate the limits up to which the identified sites for artificial-recharge remain unchanged. The artificial-recharge maps for the Kalu basin (figure 5) were prepared for −12% and +12% variation in the hydrogeomorphic parameters given in table 2. A positive variation of +12% results in decrease in the zone favourable for artificial-recharge and a negative variation of −12% increases the area favourable for artificial-recharge. Comparing figure 4 with figure 5 reveals that the suggested locations for artificial-recharge are not effected by the perturbations in the parameters. Thus, the procedure adopted for decision rules is indeed very robust and the identified locations for recharge structure are effected only for large variations >12% which is acceptable.

6. Recommended recharge structures

Artificial techniques for recharge would be effective provided they are chosen in accordance with the specific site conditions. In the present study, suitable recharge structures such as percolation ponds, check dams, and en echelon dams are recommended based on the drainage morphology in the areas demarcated as favourable for artificial-recharge for Bhatsa and Kalu basins (figures 3 and 4).

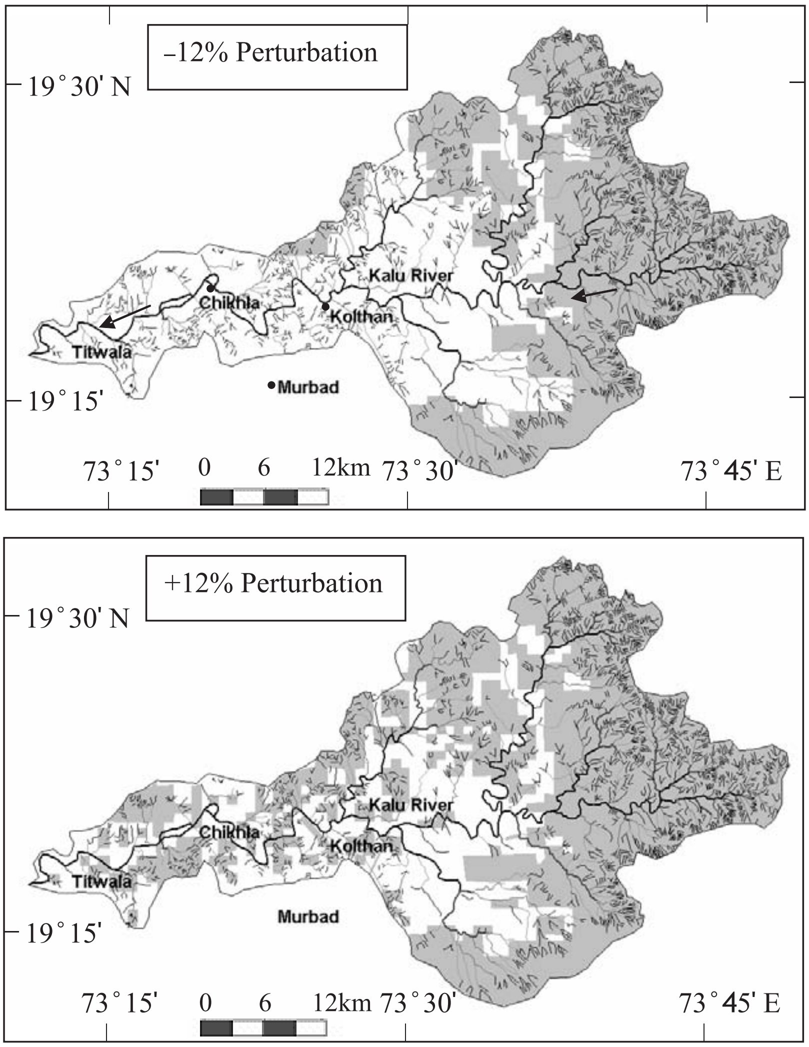


Figure 5. Maps showing the usable zone for artificial-recharge in Kalu basin for −12% (top) and +12% (bottom) perturbation in the hydrogeomorphic parameters given in table 2.

6.1 *Percolation ponds*

These structures are recommended in the favourable recharge–storage zones to ensure more recharge especially in the non-monsoon months. Similar types of percolation ponds are suggested wherever the highly favourable zone with suitable terrain conditions exist. Percolation ponds can perform efficiently only in areas where drainage pattern with catchment characteristics or closed watershed conditions are available within the favourable area. The drainage pattern map, which is superimposed over the artificial-recharge zonation map, enables the identification of sites that satisfy the above criteria for percolation ponding. The sites identified and recommended are in the low-potential zones with medium-to-high water table fluctuations. These points are located mostly near the 5th and 6th order streams as they supply water continuously throughout the year, which is a preferable criterion for the efficient performance of the ponds. Recharge through percolation ponding will be efficient in these sectors because of adequate runoff and a conductive medium as indicated by water level fluctuation, geology, and geomorphological evidences. Overall, nine sites have been identified in both basins; these serve as a guideline for identifying more such sites within the basins. These structures are economical and play a major role in augmenting the yield of wells.

6.2 *Check dams*

The check dams are small-scale structures built across lower order streams in order to prevent runoff and detain the water to enhance infiltration into the subsurface. Check dams are recommended at 14 locations across the 2nd and 3rd order streams in the runoff – recharge zones of the Bhatsa and Kalu basins, with low to moderate slopes. These regions exhibit high fluctuation in the water table and have low groundwater potential. It is expected that the check dams would prevent the water from flowing down to join the higher order streams and instead permit the water to spread out around the lower order streams and recharge the aquifer. Wherever possible these dams were located close to lineaments so that infiltration to the subsurface is enhanced.

6.3 *En echelon dams*

En echelon dams constructed across streams obstruct drainage, reduce the velocity of river flow, and thereby promote infiltration. In the study region, it is observed that rectilinear drainage is common not only in the 6th order streams, but also in the lower order streams. The long linear stretches of the river courses effectively lead to quick flow of water which gets little time for infiltration. In such cases, the most suitable recharge technique would be the construction of a series of en echelon dams which check the flow of water while allowing the water to flow with a reduced velocity, thus enabling it more time for infiltration. En echelon dams have been suggested at four places in the study region across streams which flow linearly for a considerable distance. Although there are a number of linear stretches of streams of lower order, they are not sufficiently wide and are also not perennial. Hence, the sites suggested are across the 5th order streams which are wide and the chances of flow of water in these streams throughout the year is high.

Similarly, other recharge structures can also be built wherever feasible in the demarcated favourable zones; especially in the moderate slopes in order to slow down the runoff and increase the infiltration. The artificial-recharge techniques which are recommended can also be implemented at several other sites in both basins (wherever a highly favourable zone with suitable terrain conditions exists) based on the guidelines on which the sites recommended were identified for specific techniques.

7. Conclusions

This study demonstrates application of remote sensing and GIS techniques in the identification of site-specific watershed management techniques to enhance the groundwater potential in an area. The conventional practice in water harvesting takes into consideration the availability of land, the suitability of a particular artificial-recharge technique depending on local conditions, and the area benefited. Hence, decisions regarding the location and type of recharge structure for water conservation can be made only after extensive ground study, which, for a large region would mean investing an enormous amount of time and money in identification of sites suitable for artificial-recharge. The role of GIS and remote sensing for groundwater-potential zonation and conservation is being fully realized only since the last decade. The current multiparametric approach using GIS and remote sensing is holistic in nature and will minimize the time and cost especially of identifying suitable site-specific recharge structures on a regional as well as local scale, thus enabling quick decision-making for water management.

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