# Integrated water resources assessment and management in a small watershed – a geomorphic approach

P. Rajendra Prasad, N. L. K. Reddy, N. V. B. S. S. Prasad and D. Nooka Raju


## ABSTRACT

Depleting water resources and increasing human demands on the available fresh water resources suggest the need and scope for integrated water resources assessment and management. Narava basin, a small watershed spread over 105 $km^2$ with a khondalitic suite of rocks and gneisses of Archaean age in the north coastal region of Andhra Pradesh, India was studied to propose effective water resources assessment and management strategies. The watershed, with an undulating topography and gentle to steep slopes, is drained by a dendritic to sub-dendritic drainage system. The watershed receives an annual average rainfall of 980 mm. With increasing agricultural activity, monsoon failures, and indiscriminate developmental activities, groundwater during the last two decades has become the main trusted source for irrigation and drinking. A hydrogeomorphological approach integrating remote sensing applications, geoelectrical investigations and hydrological studies was proposed to delineate and study the groundwater potential and recharge dynamics in the Narava watershed. Linking the remote sensing data, morphometric characteristics, topographic analysis, land use/cover assessment and groundwater conditions, hydrogeomorphic maps were prepared. Synergizing the lineament densities with layer parameters, aquifer yields, groundwater occurrence and dynamics, groundwater potential zones were demarcated and classified. Merging the characteristics of groundwater potential, hydrogeomorphology and water balance, suitable water harvesting structures and management strategies are suggested.


**Key words** | groundwater potential zones, hydrogeomorphology, integrated water resources management, lineament density, small watershed, water balance

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## INTRODUCTION

In many developing nations, there has been a spurt in farming and industrial operations resulting in an indiscriminate development and over-exploitation of aquifers. Changing climatic conditions, land use/cover patterns, human interventions on the natural fluvial regime have induced adverse changes in monsoon behavior, spatiotemporal water availability and groundwater dynamics (CGWB 1995; Prasad 2008). Attempts have been made to address this problem adopting suitable approaches such as managed aquifer recharge (MAR) (Dillon 2009) and water harvesting structures (CPWD 2002). Although MAR has gained popularity in many developed nations, its application has not been adequately realized in developing nations like India.

In agrarian nations like India, water harvesting structures can lead to supplementing water for irrigation, inflows to surface storage systems and groundwater recharge (Singh *et al.* 2009). Construction of suitable harvesting structures as per IMSD (1995) guidelines can be considered as one of the viable solutions to maintain a balance between annual recharge and groundwater abstraction (CGWB 1995) in different geological terrains.

This scenario warrants a multidimensional scientific approach to assess the water resources and their distribution to propose sustained management strategies. Integration of hydrogeological, morphological data with geophysical signatures has evolved to be a simple and rapid approach for the

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assessment of groundwater conditions (Sree Devi *et al.* 2005). With this perspective, an attempt has been made to assess the seasonal availability of water resources, demarcate groundwater potential zones and suitable recharge sites and their geomorphic implications using a synergic approach.

## LOCATION AND PHYSIOGRAPHY

Narava, a small watershed, spread over an area of 105 km$^2$ is located between 17°42′30″–17°47′30″ N latitude and 83°04′30″–83°12′30″ E longitude (Figure 1). The area is covered in Survey of India toposheets 65 O/1, O/2 and O/3. The Narava watershed is studded with undulating topography. The Narava hills form a part of the eastern ghat hill range and are located on the eastern flank of the watershed. These hills rise to a maximum height of 380 m MSL, while the rest of the region gently slopes towards the central part of the basin. The lowest elevation recorded is 10 m MSL at Chintala Agraharam located close to the Meghadrigedda reservoir.

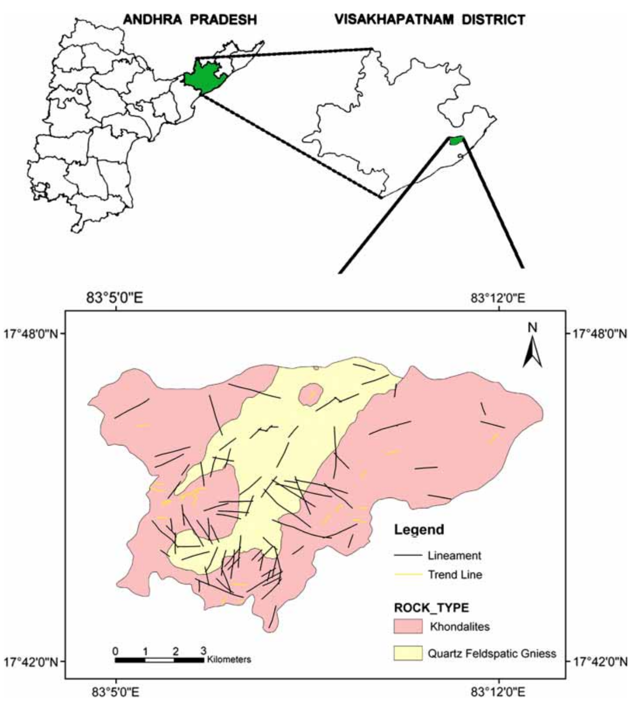


**Figure 1** | Location, geology and lineament map of Narava watershed.

## GEOLOGY

The area forms a part of the eastern ghat tectonic complex which is a major physiographic province and a principal Precambrian metamorphic unit of peninsular India. The prominent geological formations in the area belong to Archaean and Quaternary age. The Archaean system includes mainly a khondalite suite of rocks, granite gneisses (leptynites), charnokites, granites, pegmatites and quartz veins (Figure 1). Mostly the quartz veins occur as intrusive bodies in the khondalite suite of rocks. The Quaternary system includes laterites and surficial deposits. The geological sequence of the formations in the area is given below (Table 1). The general strike direction of the khondalite formation is N 60° E with 40° to 90° dip due south and the strike of the formation shifts in the middle of the basin from N 60° E to N 90° E.

## CLIMATE AND RAINFALL

Climatologically, the area is classified as semiarid (Swamy 1981). The basin receives an annual average rainfall of 980 mm, of which more than 80% occurs during monsoon. The area, dominated by the southwest monsoon, experiences 54 rainy days on an average annually. Sarma (2003), while analysing the rainfall occurrence and its spatial and temporal dynamics, indicated that the annual rainfall in Visakhapatnam district, of which the study area is a part, can vary widely in a short span of time from a minimum of 678 mm (2009) to a maximum of 1,569 mm (2010). This, in turn, adversely influences the functional properties of the surface

**Table 1** | Geological sequence of the formations of Narava watershed

| System | Age | Stratigraphic unit |
|---|---|---|
| Quaternary | Recent | Surficial deposits (piedmont fans, colluvium red sediments and alluvium) |
| | Subrecent | Laterite /laterite gravel |
| Archaean | Precambrian | Granites |
| | | Charnokites |
| | | Granite gniesses (Leptynites) |
| | | Khondalite suite of rocks |

water bodies leading to severe drought conditions. The winter months (December–February) experience the most pleasant weather with temperatures between 18 and 28 °C, while summer months (April and May) are the hottest with average temperatures of 37 to 39 °C.

## DRAINAGE

The Narava Gedda, an ephemeral river, flows in a SW–NE direction in the upper reaches and shifts its course to NW–SE before it eventually discharges into Mehadhrigedda reservoir (Figure 2). The Mehadhrigedda reservoir, with a holding capacity of 29,538 $m^3$ (NRLD 2009) is one of the major drinking water storage reservoirs catering for more than 30% of the water needs of the city of Visakhapatnam. The Narava watershed has attained steady-state condition with a fourth order drainage network dominated by dendritic to sub-dendritic patterns. Based on the drainage and other basin characteristics, Sarma *et al.* (1982) developed a hypsometric curve for the Narava watershed and deduced its stage of maturity as 'monadnock'. The sudden changes in the river course from northeast to east indicate structural influence on the drainage system.

## METHODOLOGY

The methodology broadly adopted consists of morphometric analysis, remote sensing applications, geoelectrical investigations and hydrological studies including geohydrology and surface water reservoir estimates.

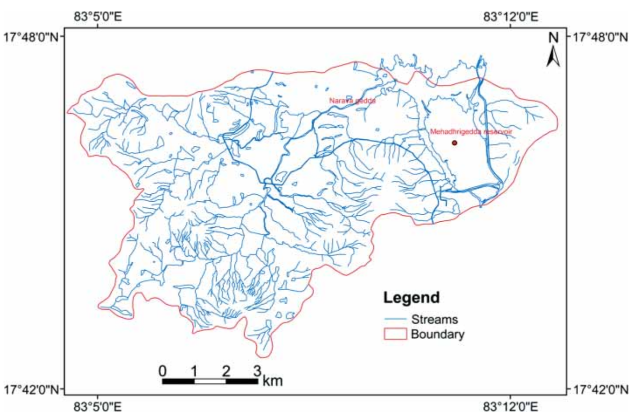


**Figure 2** | Drainage map of Narava watershed.

### Morphometric analysis

The morphometric analysis was mainly intended to understand the basin morphology and its measured and derived morphometric characteristics. Parameters such as stream order (Nu), stream length (Lu) were calculated, while bifurcation ratio (Rb), drainage density (Dd), stream frequency, elongation ratio (Re), circulatory ratio (Rc) and basin relief were derived. Thematic maps were derived from remote sensing data from IRS-LISS IV and CARTOSAT both captured in April 2005 and November 2005 and also 1:25,000 topographic maps published by Survey of India (SOI) in 1999. However, keeping in mind the constraints and discrepancies that can affect the morphometric characteristics extracted from maps of different scales (Sarachino *et al.* 2004) the remote sensing data have also been proportionately adjusted to 1:25,000. The morphometric characteristics were determined as per the definitions and methodology suggested by the British Geomorphological Research Group (Gardiner 1975).

### Remote sensing studies

Remote sensing data from IRS-LISS IV and CARTOSAT, which have a resolution of 5.8 and 2.5 m respectively, were used in the preparation of thematic maps. However, relevant information extracted from SOI topographic maps and ground truth was used for validation of the thematic maps. The hydrogeomorphology maps and groundwater potential maps were prepared giving weightages to geology, geomorphology, slope, land use, land cover, lineament density, sub-surface hydrogeology and surface infiltration characteristics. The geology and lineaments, drainage network and the hydrogeomorphology of Narava basin are presented in Figures 1–3 respectively.

### Geoelectrical studies

Resistivity sounding surveys were conducted at 51 locations using Schlumberger configuration (Zohdy 1974)

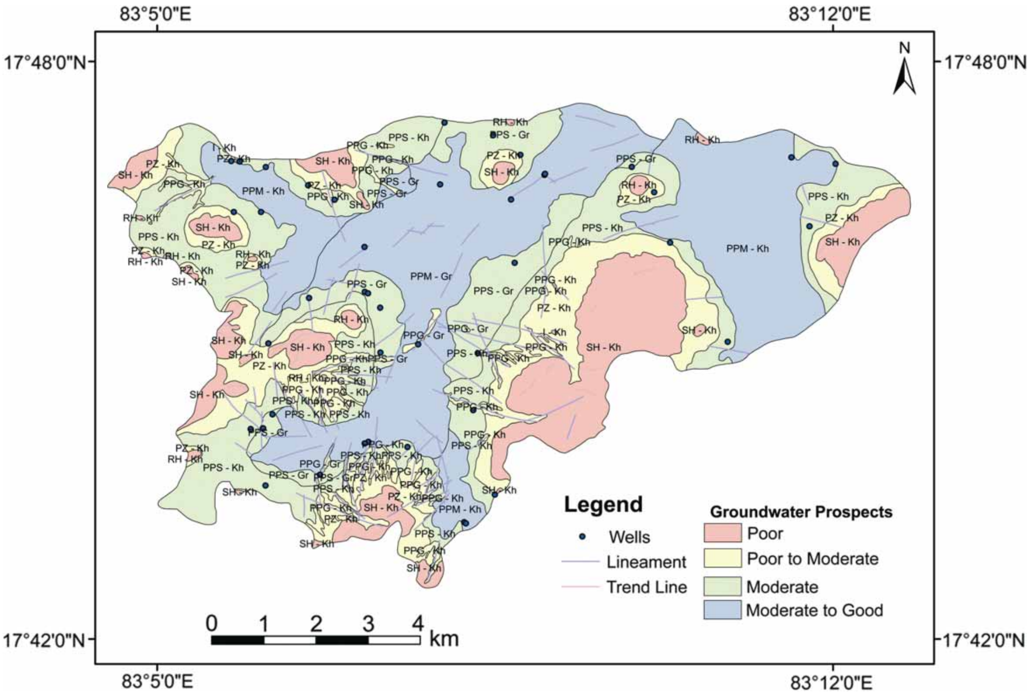


**Figure 3** | Hydrogeomorphology of Narava watershed.

up to a maximum AB/2 separation of 100 meters to delineate the subsurface layers, their thickness and resistivity characteristics. An automatic iterative technique developed by Prasad *et al.* (1983) was used to interpret the sounding data. The geophysical signatures of the sub-surface layers were translated into the geological layers.

### Hydrological studies

Hydrological studies included hydrogeological investigations and characterization of surface water bodies. The water level fluctuations and their seasonal variations were measured using water level indicators. The infiltration studies were carried out using double ring infiltrometer (Reddy 2005). The groundwater recharge was estimated using 'Groundwater Estimation Committee (GEC) 2009 norms specifically prescribed for Indian conditions by the Central Ground Water Board. The aquifer yields were determined using suitable pumping tests (Theis 1935; Papadopulos & Cooper 1967) depending on the nature of the aquifer, namely, confined or unconfined. The holding capacity of the surface water bodies was calculated using contour configuration generated from total station observations.

The data generated were integrated with the developing hydrogeomorphology maps, demarcating the groundwater potential zones and also to suggest suitable locations for the construction of rainwater and surface water harvesting and groundwater recharge structures.

## RESULTS AND DISCUSSION

### Drainage analysis

The data on measured and derived morphometric parameters are presented in Table 2. The stream order of the Narava basin, determined as per Strahler (1952), is of fourth order. The stream length ratio for different stream orders varies from 1.7 to 2.4 with an average of 2.0. The ratio for the fourth-order stream is as low as 1.75, indicating that the rock formations in the area drained by fourth-order streams have characteristically lower slope and

**Table 2** | Morphometric parameters of Narava watershed

| Sl. no | Parameter | Value |
|---|---|---|
| 1 | No. of first order streams | 217 |
| 2 | No. of second order streams | 46 |
| 3 | No. of third order streams | 9 |
| 4 | Total no. of streams | 273 |
| 5 | Stream length ratio | 1.7 to 2.4 (average 2.0) |
| 6 | Bifurcation ratio | 4.7 to 9.0 (average 6.2) |
| 7 | Dd | 1.42 $km/km^2$ |
| 8 | Stream frequency | 2.6 $/km^2$ |
| 9 | Elongation ratio | 0.784 |
| 10 | Circularity ratio | 0.7387 |
| 11 | Basin relief | 370 m |

higher permeability than those by the lower order streams. The bifurcation ratio (Rb) is observed to vary from 4.7 to 9.0 with a mean value of 6.2 indicating the prevalence of structural control on the development of drainage network. This also complies with the observations of Strahler (1957). The average Dd of 1.42 (Table 2) is indicative of a medium textured drainage. A medium textured drainage with medium to coarse grained soils can promote the accumulation of groundwater which is the case in the Narava basin. The stream frequency of 2.6 $km^2$ (Horton 1932) for the Narava watershed indicates moderate slope with medium permeability, runoff and infiltration. The elongation ratio of 0.784 supplemented by circularity ratio (Rc) (Schumm 1956) validates the above observation. At the same time a basin relief value of the order of 370 m supports the lower infiltration and higher runoff.

## Hydrogeomorphic classification

The hydrogeomorphic classification of the watershed, as derived from satellite images supplemented by field observations, is presented in Figure 3. Based on the characteristic morphological features and distinct differences in subsurface layer configuration with special reference to groundwater conditions, the hydrogeomorphic units have been classified. The characteristics of these units are described here.

### Pediplain with moderately weathered zone (PPM)

Moderately weathered pediplains are observed in the central, north western and north eastern parts of the basin. The zone covered with brown soil exhibits plain surface areas underlain by more than 30 m thick weathered rock formation. The highly weathered rock followed by fractured rock is characterized by increased discharges. Borewells drilled in this zone, up to a depth of 50 m, are observed to yield 5,000 to 8,000 liters per hour indicating moderate to good groundwater prospects.

### Pediplain with shallow weathered zone (PPS)

Pediplains associated with shallow weathered zones are observed in northern, central, north western and north eastern parts of the basin. The zones covered with brown soil exhibit smooth to irregular surfaces. The thicknesses of the underlying weathered zone vary between 15 and 20 m. Granite gneisses are prevalent in this zone. The combined thickness of the weathered and fractured zones varies from 5 to 40 m below the surface layer. The discharges from borewells located in this zone vary from 1,500 liters per hour to 5,000 liters per hour depending on the combined thickness of these layers. The groundwater prospects in this zone are treated as moderate.

### Pediplain with gullies (PPG)

The western, south western and eastern regions of the study area are covered by pediplains with gullies. This landform is erosional in character and acts mainly as a runoff zone. This area is observed to have poor to moderate groundwater prospects.

### Piedmont zone (PZ)

PZ is located in western, south western and eastern parts of the study area. This zone mainly consists of colluvium and gravel. Khondalite formations occur beneath the colluvium. Because of gentle to moderate slopes with a thin soil cover, the recharge reduces leading to increased runoff. The groundwater prospects in the zone are poor to moderate, which is comparable with the yield of the borewell drilled in the region.

### Structural hills, residual hills and inselbergs (I)

Structural hills are mostly located in the eastern, western and southern part of the area, whereas residual hills are observed in the northern and central parts of the basin. The groundwater prospects are very poor in these zones. Different hydrogeomorphic zones and the associated groundwater prospects are provided in Table 3.

### Land use, land cover classification

A detailed assessment of land use, land cover patterns was made integrating remote sensing data, toposheets and field observations (Table 4).

It is observed that variations in geology, soil cover and land use patterns, lineament geometry and infiltration rates have resulted in varying recharge conditions. Data on infiltration studies carried out in the region (Table 4(b)) indicate a wide variation ranging from 3.92 to 19.51 cm/hr. Assessment of the data indicate that agricultural land exhibits higher rates of infiltration preceded by clay and red soils. It should be mentioned here that the infiltration studies were carried out in the summer months when usually the temperatures reach 40 °C. Incidentally, the agricultural activity is clustered in sandy areas while other activities are confined to clay zones and red soils. Interestingly, the clay zone showed higher infiltration, which is mainly because of deep cracks developed in the layer due to high summer temperatures. The agricultural land being sandy in nature and frequently tilled exhibits high infiltration rates. Keeping this in mind, since almost 75% of the area is under agricultural use and subjected to irrigation, there has been significant groundwater recharge leading to better sustainability. In spite of the fact that a large area is covered by agricultural activity providing scope for good groundwater recharge, wide variations are observed in groundwater fluctuations. This validates wide variations in time lag in recharge, intensity and minimum amount of rainfall, that can trigger groundwater recharge and variations in hydrogeology mainly contributed by varying thickness of impervious kaoline layers and uneven overexploitation of groundwater (Rojstaczer 1988; Lee *et al.* 2006; Rajendra Prasad *et al.* 2009). Widespread heterogeneities in the hard rock terrain of the region can also be held responsible to some extent.

## Lineament studies

Lineament studies are significant in groundwater prospecting. The lineaments were identified by visual interpretation of LISS IV and CARTOSAT images. A number of major and minor lineaments identified from the satellite images are shown in Figure 1. The lineaments identified are of varying dimensions with different orientations. The lineaments observed in the study area may be the result of faulting and fracturing and hence it is inferred that these are zones of increased porosity and permeability within the hard rock. From geoelectrical surveys it is found that in areas where lineaments intersect, the thickness of the weathered

**Table 3** | Different hydrogeomorphic zones and associated groundwater prospects

| Hydrogeomorphic unit | Area of each unit ($km^2$) | Groundwater prospects | Coverage percentage | Development feasibility |
|---|---|---|---|---|
| Structural hill (SH) | 51.35 | Poor | 51 | Not suitable |
| Residual hill (RH) | 2.2 | | | |
| Piedmont zone | 11.1 | Poor to moderate | 12 | Moderately suitable for dug wells and low yield borewells (1,500–2,000 liters per hour) |
| Pediplain gully | 1.5 | | | |
| Pediplain shallow | 15.75 | Moderate | 15 | Suitable for dug wells and borewells |
| Pediplain moderate | 23.1 | Moderate to good | 22 | Suitable for dug cum bore wells and borewells |

**Table 4(a)** | Land use/cover classification of Narava watershed

| Land use/Land cover classification | Area in km$^2$ | Percentage |
|---|---|---|
| Built up land | 3.9375 | 3.75 |
| Agricultural land | 75.875 | 72.26 |
| Forest (degraded/open forest) | 9.375 | 8.92 |
| Waste lands | 8.00 | 7.61 |
| Mining land | 0.375 | 0.38 |
| Water bodies | 7.437 | 7.08 |

**Table 4(b)** | Classification of soil and infiltration characteristics

| Sl. no | Soil type | Land use | Location | Average infiltration rate cm/hr |
|---|---|---|---|---|
| 1. | Sandy | Agriculture | Pallavanipalem | 19.51 |
| 2. | Clay | Barren land | Gollalapalem | 7.09 |
| 3. | Sandy | Agriculture | Erukunaidupalem | 9.21 |
| 4. | Red soils | Oil palm field | Amrutapuram | 3.92 |
| 5. | Sandy | Agriculture | Paidawada | 8.63 |
| 6. | Clay | Barren land | Jagannadhapuram | 8.01 |
| 7. | Sandy | Mango garden | Pachikuravanipalem | 6.39 |
| 8. | Red sandy | Agriculture | Porlupalem | 8.05 |

zone is observed to be large indicating the scope for higher groundwater potential.

Based on the distribution and length of lineaments, a lineament density map was prepared. For this purpose the area is gridded equally with a grid size of $0.25 \times 0.25$ km and the length of the lineaments within the grid are used to determine the density in terms of km/km$^2$. The lineament density map thus generated is shown in Figure 4. A comparison of Figures 3 and 4 reflects a correlation between groundwater potential zones and lineament densities.

## Geoelectrical investigations

The geoelectrical sounding surveys conducted have reflected variations in aquifer thickness in different geomorphic units (Figure 5). The layer configurations obtained from vertical

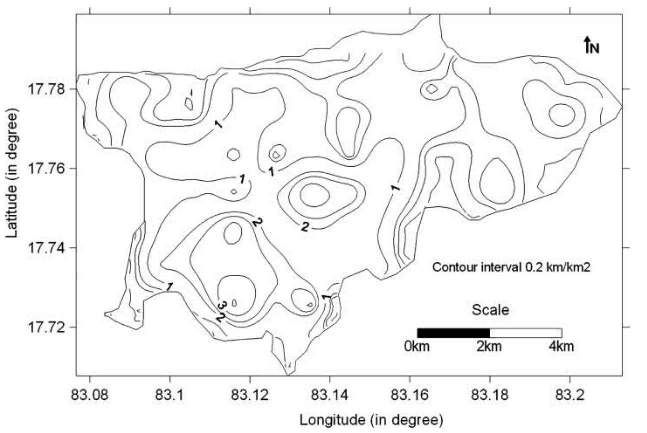


**Figure 4** | Lineament density map of Narava watershed.

electrical sounding (VES) data representing different units are shown in Figure 6. Further, the resistivity ranges, the thickness of various subsurface layers as obtained from the VES are also shown in Table 5. Characteristically, the PPM, PPS and PPG zones are observed to have weathered layers with thicknesses of 20–30, 15–20 and 10–15 m, respectively, indicating a proportionate relationship to groundwater potential. However, the PZs are observed to have very thin weathered layers indicating the prevalence of poor recharge and retention capacities. Comparable observations were also reported by Srinivasa *et al.* (2005), Dhakate *et al.* (2008) and Seethapathi *et al.* (2008).

## Groundwater potential zones

Attempts to synergize the data on slope characteristics, lineament density and weathered and fractured layer characteristics proved to be effective in depicting the groundwater potential zones. The groundwater potential zones of Narava basin prepared using these criteria are classified into five categories ranging from poor to good, namely, poor, moderate to poor, moderate, moderate to good and good based on the aquifer yield information (Table 6). The groundwater potential zones are validated on the basis of aquifer yields, characteristics of fractured and weathered layers, drainage, etc. (Sree Devi *et al.* 2001; Srivastava & Bhattacharya 2006; Adham *et al.* 2010; Ballukraya & Kalimuthu 2010). Poor groundwater potential zones occurring around the basin are characteristically associated with the presence of thin saturated zone and hard rock at shallow depth.

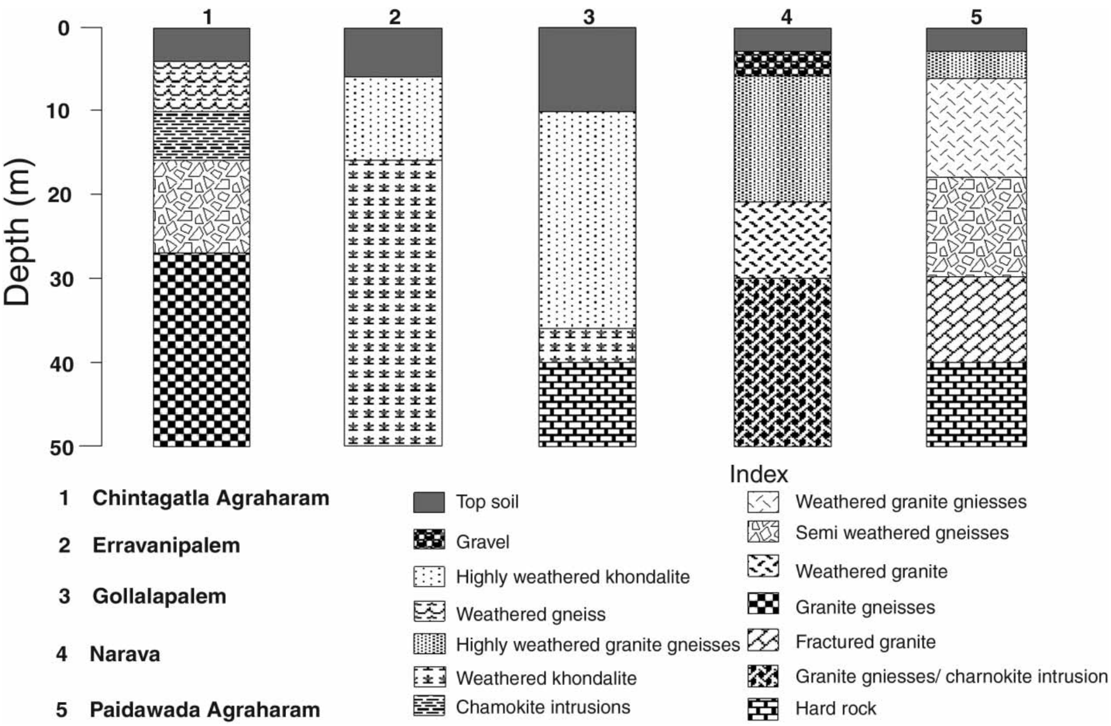


**Figure 5** | Subsurface lithology in the study area.

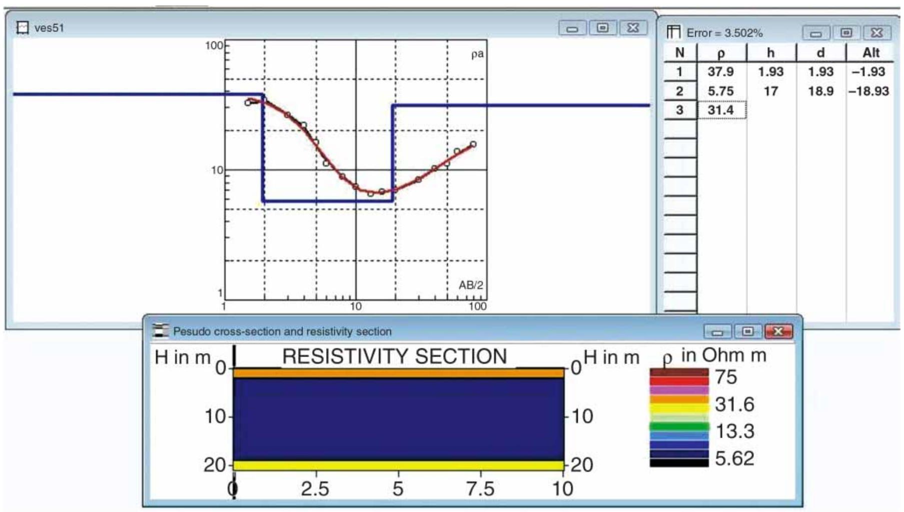


**Figure 6** | Vertical electrical sounding curve and the derived sub-surface layer characteristics in a typical granite gniess formation.

Pediplains with medium to low Dd (<2.0), low cumulative length of streams are observed to lead to moderate to high runoff and sparse vegetation cover. The fractured and weathered khondalite/granite gneiss is highly suitable to provide the necessary permeability and storage space. Lineaments with a density between 1.5 and 2.0 $km/km^2$ are considered to be suitable groundwater conduits.

**Table 5** | Resistivity ranges and layer thickness of subsurface lithologic units

| Sl. no | Subsurface lithological units | Resistivity Ω m | Thickness m |
|---|---|---|---|
| 1 | Top soil mixed with gravel | 2–95 | 0.7–2.9 |
| 2 | Highly weathered khondalite (kaolin) | 4–6 | 2–27 |
| 3 | Weathered and fractured khondalite/granite gneisses | 13–21 | 2–67 |
| 4 | Semi weathered khondalite/ granite gneisses | 25–44 | 9–22 |
| 5 | Hard rock | 41–99 | Infinite |

**Table 6** | Groundwater potential zones and associated weightages

| Property | Weight factor | Geomorphic feature/ Values | Descriptive level |
|---|---|---|---|
| Geomorphology | 5 | Pediplain moderately weathered | Good |
| | | Pediplain shallow weathered | Moderate to good |
| | | Pediment | Moderate |
| | | Denudation hills | Poor |
| | | Structural hills | Poor |
| | | Residual hill | Poor |
| Slope % | 4 | > 10 | Poor |
| | | 5–10 | Poor to moderate |
| | | 3–5 | Moderate |
| | | 1–3 | Moderate to good |
| | | 0–1 | Good |
| Lineament density | 3 | > 2 | Good |
| | | 1.5–2 | Moderate to good |
| | | 1–1.5 | Moderate |
| | | 0.5–1.0 | Poor to moderate |
| | | < 0.5 | Poor |
| Weathering thickness (m) | 3 | < 10 | Poor |
| | | 10–20 | Poor to moderate |
| | | 20–25 | Moderate |
| | | 25–30 | Moderate to good |
| | | > 30 | Good |

## Water balance approach

The climatic water balance was computed using the mean monthly precipitation, estimated runoff and calculated potential evapotranspiration (PET) as per Thornthwaite (1948); evaporation and the results are tabulated in Table 7. The availability and demand of water resources in the Narava watershed can be seen from this table. High intensity of rainfall resulted in a quick runoff in the month of June (Table 7). Even though the area receives an average annual rainfall of 980 mm, runoff characteristics lead to scarcity in summer months. The availability of the surface water is meagre resulting in lower evaporation rates. Water surplus was observed only during September, October and February in the basin while the rest of the period experiences a deficiency. As Narava Gedda is an ephemeral stream and no other reliable sources of water are supplemented by other sources, a scientific management strategy can effectively contribute to sustainability of the resource.

## Synergy between hydrogeomorphology, geohydrology and water balance

Areas characterized with slope <10 m/km are observed to have low hydraulic gradient and lower surface runoff and moderate infiltration leading to the possibility of groundwater accumulation. The lineaments present in the study area have provided surface manifestations supporting the structurally controlled linear features. The lineament density ranged from 0.5 to >2.0/km$^2$ in the basin. By integrating the information on slope, geology, lineament, hydrogeomorphology, lineament density, weathered zone thickness, geoelectrical and hydrogeological cross sections and by superposing these data, suitable groundwater harvesting sites and structures are proposed.

Geomorphological features such as structural and residual hills with high Dd (>2.0), bifurcation ratio and high cumulative length of first-, second- and third-order streams, and slope percentage exceeding 10, resulted in high runoff with low infiltration. The thickness of the weathered zone in these regions is also <3 m indicating low groundwater recharge. Such areas, covering an extent of 53.55 km$^2$, are classified as poor groundwater prospect

**Table 7** | Estimation of monthly water balance in Narava watershed

| Month | Monthly precipitation mm | Estimated runoff mm | Calculated PET mm | Calculated evaporation mm | Other losses mm (GW, SM, SD) |
|---|---|---|---|---|---|
| March-07 | 0 | 0 | 163.63 | 17.00 | – 180.63 |
| April-07 | 1.7 | 0 | 197.25 | 23.72 | – 219.26 |
| May-07 | 82 | 0 | 260.68 | 18.85 | – 197.53 |
| June-07 | 360.2 | 272 | 228.25 | 5.01 | – 145.06 |
| July-07 | 69.9 | 0 | 200.41 | 9.40 | – 139.91 |
| August-07 | 64.3 | 0 | 178.02 | 9.65 | – 123.36 |
| September-07 | 380.6 | 183.44 | 156.63 | 7.60 | 32.93 |
| October-07 | 354.2 | 171.76 | 132.41 | 9.49 | 40.54 |
| November-07 | 0.6 | 0 | 99.83 | 12.60 | – 111.83 |
| December-07 | 0 | 0 | 85.27 | 15.22 | – 100.48 |
| January-08 | 0 | 0 | 59.89 | 11.84 | – 71.73 |
| February-08 | 108.4 | 0 | 84.52 | 10.73 | 13.14 |
| Total | 1421.9 | 627.2 | 1846.79 | 151.10 | – 1203.183 |

PET – potential evapotranspiration, GW – groundwater, SM – soil moisture, SD – soil detention.

zones. High relief and steep slopes together with low permeable soil cover resulted in loss of a major portion of rainfall as quick surface runoff. Such areas, if provided with trenches, can retard the surface runoff leading to groundwater recharge.

The PZ and pediplain gully with a moderate to steep slope, containing colluvium and loamy sand soils, reduced the surface runoff and favoured infiltration. However, the water table in these zones is deep due to limited weathering. The well yields are also limited to 500 to 800 liters per hour. These zones formed mostly in the north western corner of the study area and are limited to an area of 12.6 $km^2$. The groundwater prospects are poor to moderate in these zones.

The geomorphic units with second- and third-order drainage supported with low to moderate slopes are major recharge zones in the foothills. These zones comprising unconsolidated materials such as sand and gravel, evolved to be the most effective infiltration zones in the area suitable for the development of rainwater harvesting structures.

## Water resources management strategy

Water resources management needs to be considered both from development and effective management perceptions. A comprehensive water resources development plan was generated by integrating all the thematic layers, groundwater prospect zones and the prevailing hydrogeological conditions. The development of groundwater for irrigation in the watershed is mainly through dug wells and borewells tapping the weathered residuum and fractured zones. Water conservation implies improving the availability of water through augmentation by means of storage of water in tanks, soil and groundwater zones. It emphasizes the need to modify the availability of water to meet the demands. In order to increase the recharge, tanks and percolation ponds may be provided with recharge pits to make them more effective in recharging the aquifer. Seven check dams and one percolation tank (Figure 7) were recommended within the legislative frame work provided by the Integrated Mission for Sustainable Development (IMSD 1995) and their locations are shown in Figure 7 (Girish *et al.* 2008; Chowdary *et al.* 2009; Singh *et al.* 2009). The check dams are recommended to regulate the surface water flow thereby increasing its influence over the command area and the groundwater levels. Percolation tanks are recommended across the streams to distribute the groundwater recharge over large areas and to have assured augmentation.

Most of the existing tanks became silted up and there is a need for desilting and bed cleaning. The promotion of

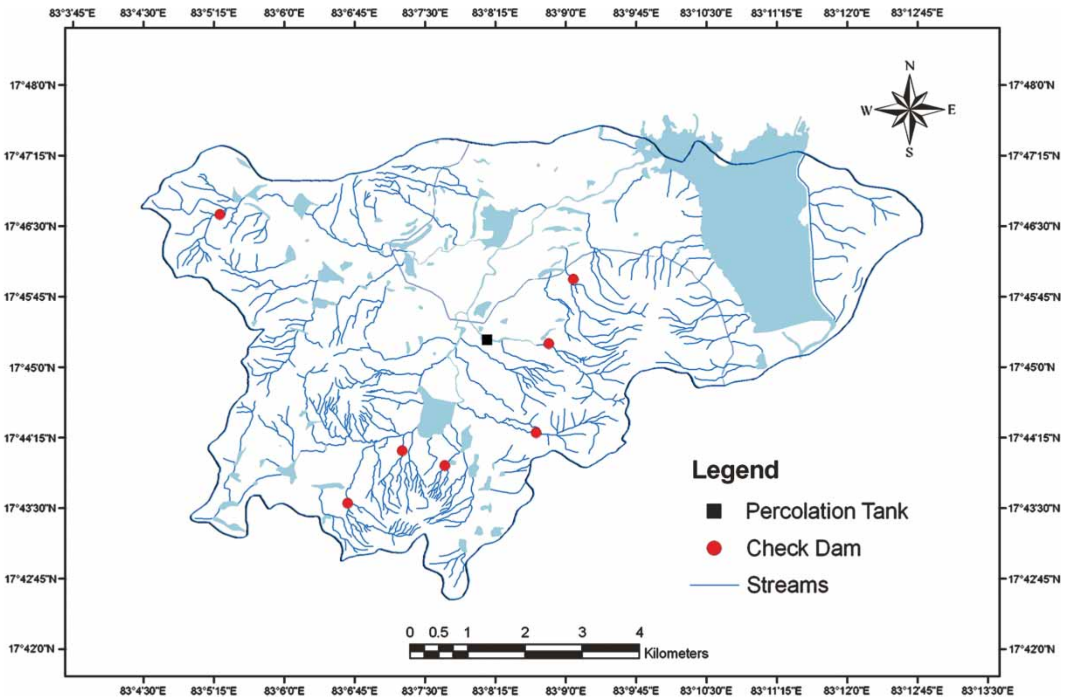


**Figure 7** | Integrated water resources development plan for Narava watershed.

participatory action in rehabilitating tanks for recharging is seen to go a long way in augmenting groundwater.

## CONCLUSION

Integration of results from morphometric analysis, lineament density studies, geo-electrical sections, hydrogeomorphological characteristics and water balance elements provide an effective approach for the delineation of potential sites for groundwater development and management and the optimum use of surface water resources. Thick weathered subsurface zones associated with low surface slopes and high lineament densities are observed to have good prospects while the areas characterized by thin weathered zones, higher slopes and low lineament densities have poor prospects for groundwater potential. Areas occupied by pediplains with moderate weathering are observed to be better conduits for groundwater resources. An integrated approach for the development and management of water resources in small watersheds will contribute to sustainability of the resources and the economic growth of the region.

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