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

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

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

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

## 1   Introduction

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

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

## 2   Study Area

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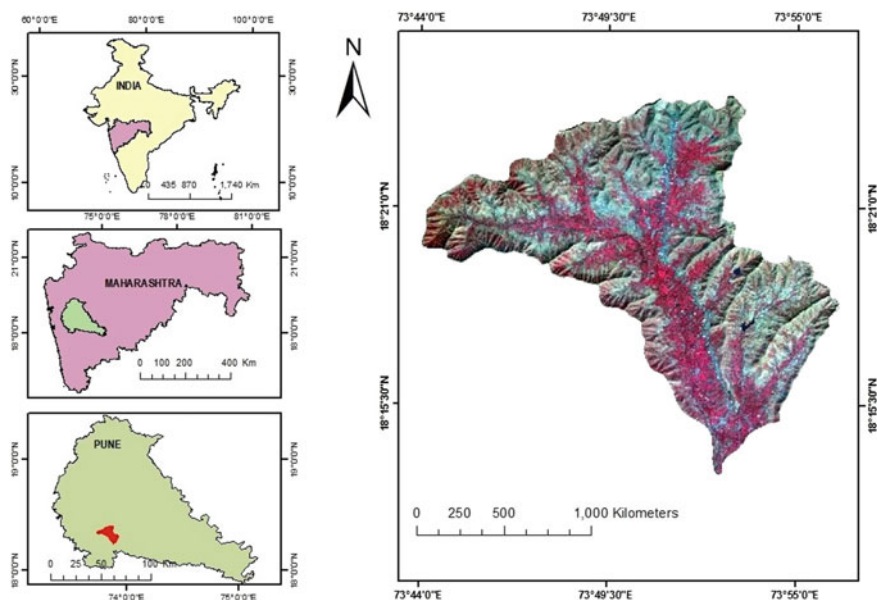
**Fig. 1** Index map of Shivganga basin, Maharashtra

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

## 3   Methodology

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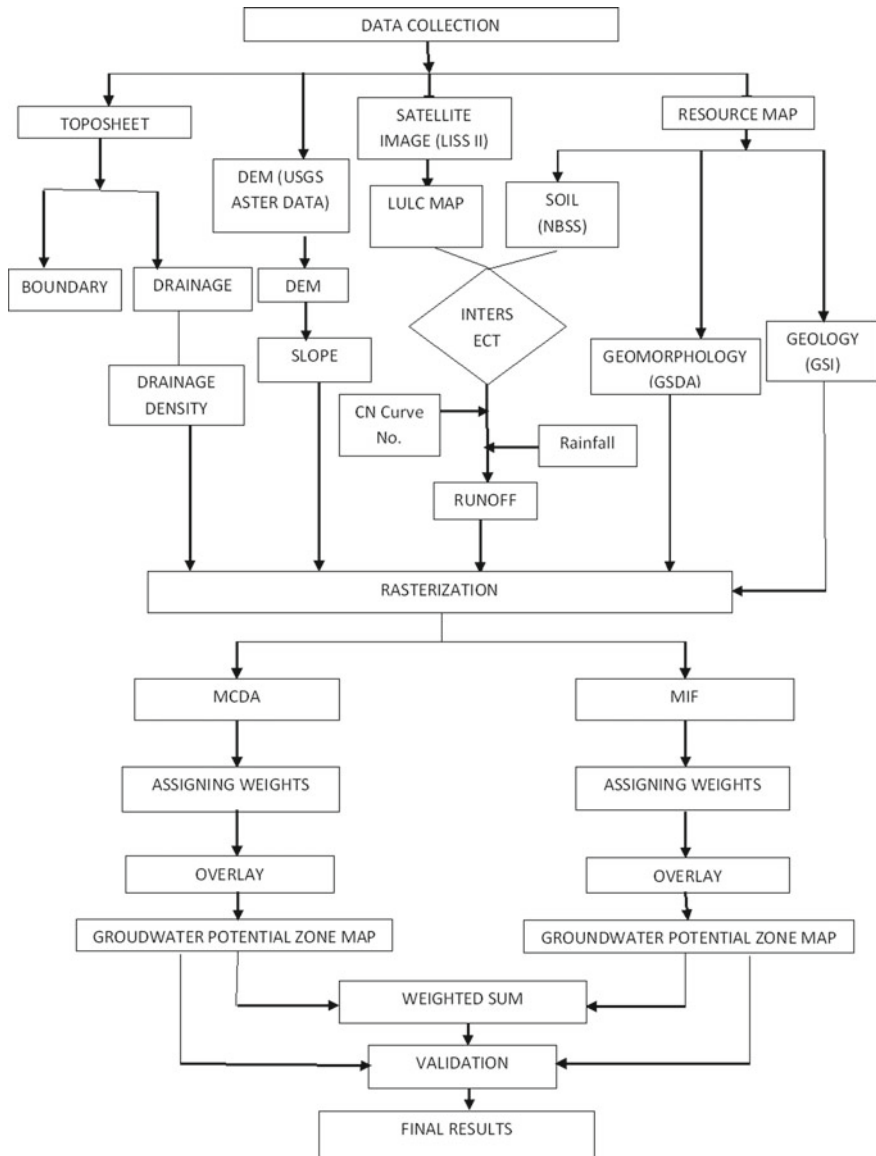
**Fig. 2** Methodology adopted to delineate GWPZs

The GWPZ in the study area was identified using two approaches and compared to find out the best fit method amongst them. In the first approach, as per significance of the theme and the domain experience, weight was assigned to each theme and ranks were allocated to each feature class of theme under consideration. In second approach, MIF technique was used to give weights, where weights were allocated

based on the reliance of the parameters on each other. The weights were allotted using MIF and weighted overlay analysis was performed on ArcGIS 9.3 platform. The results of weighted sum calculations, obtained by deploying MIF and MCDA methods were used to derive a final GWPZ output of the study area.

# 4   Results and Discussion

## 4.1   Slope

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

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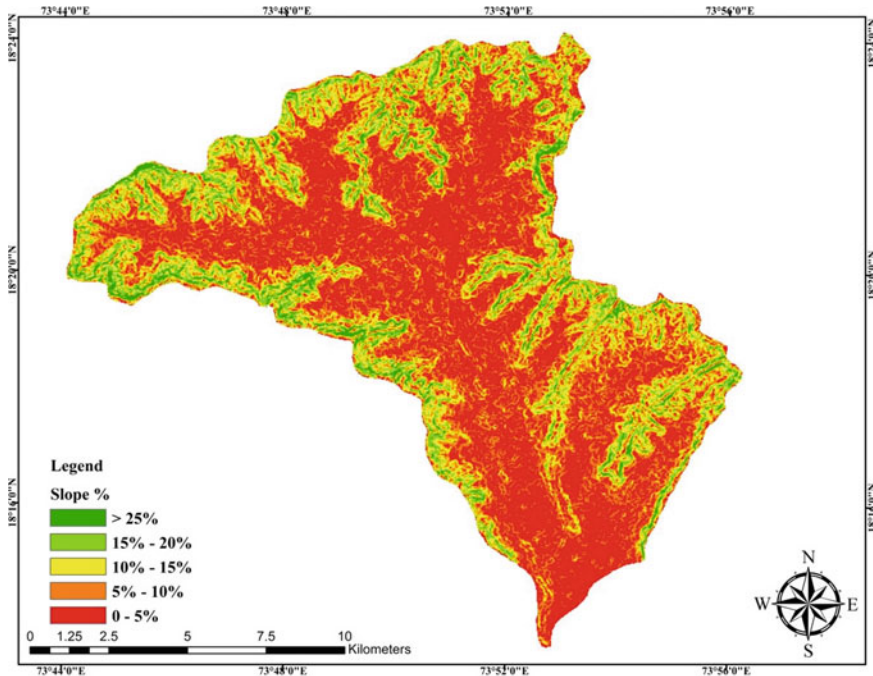


**Fig. 3**  Slope map of Shivganga basin

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

## *4.2  Geomorphology*

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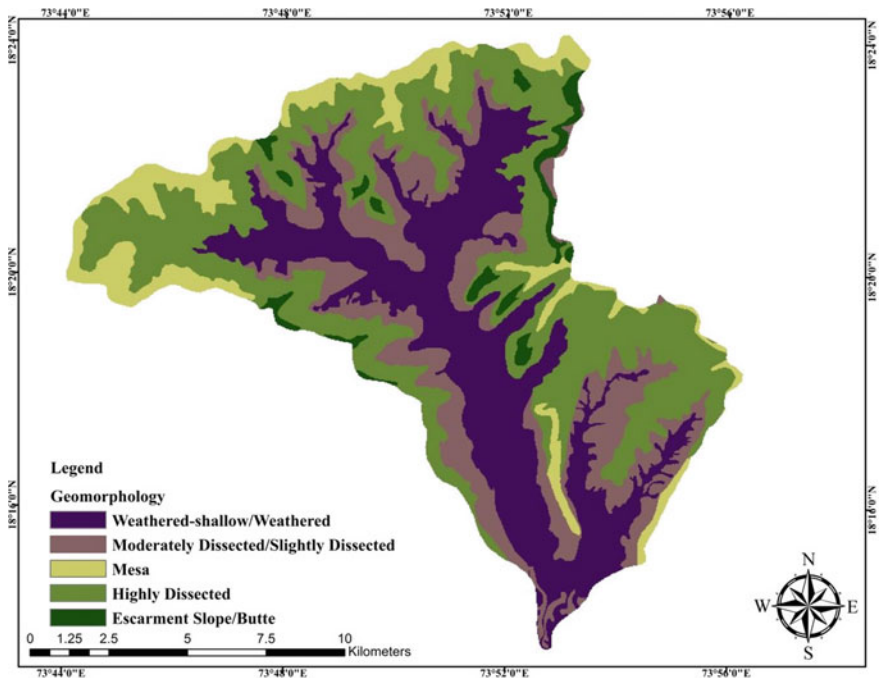


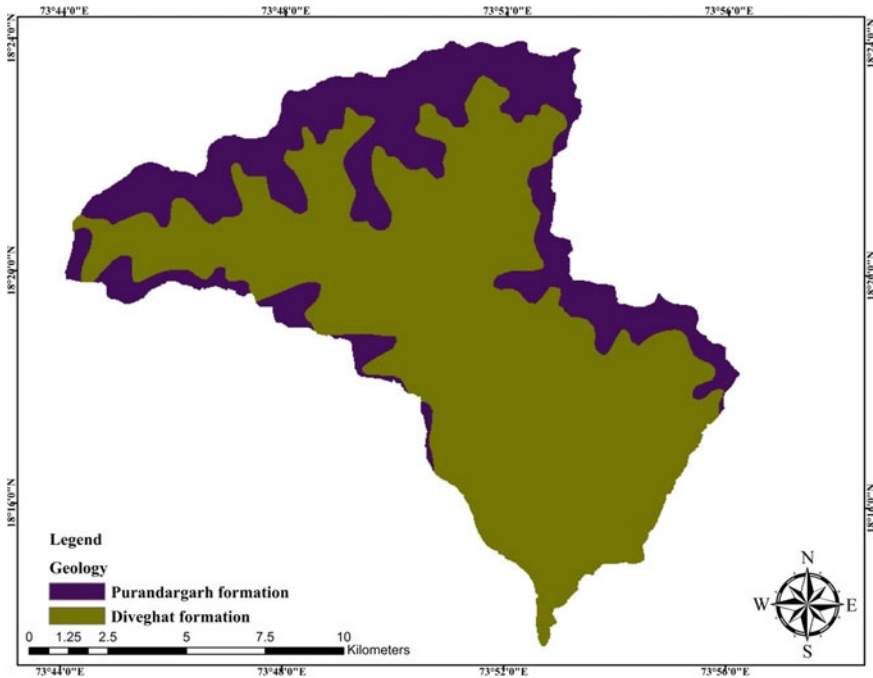**Fig. 4**  Geomorphological set-up of Shivganga area

**Fig. 5** Geological map of Shivganga basin

## 4.3 Geology

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

## 4.4 Land Use and Land Cover

The land utilization pattern is rapidly changing in the process of urbanization and as a result land initially being favourable for recharge is getting converted to impervious type. The southern part of the basin is experiencing haphazard urbanization and
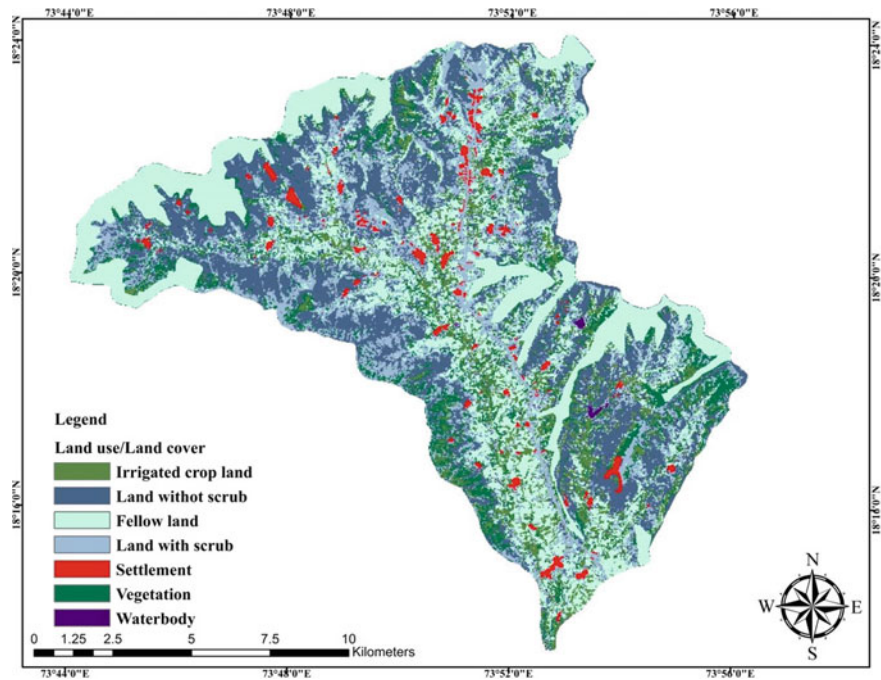
**Fig. 6** Land use land cover map of Shivganga basin

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

## 4.5 Drainage Density

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

The map depicts very low drainage density in the central part of the watershed that increases outward. The categorize of this parameter covers five classes namely
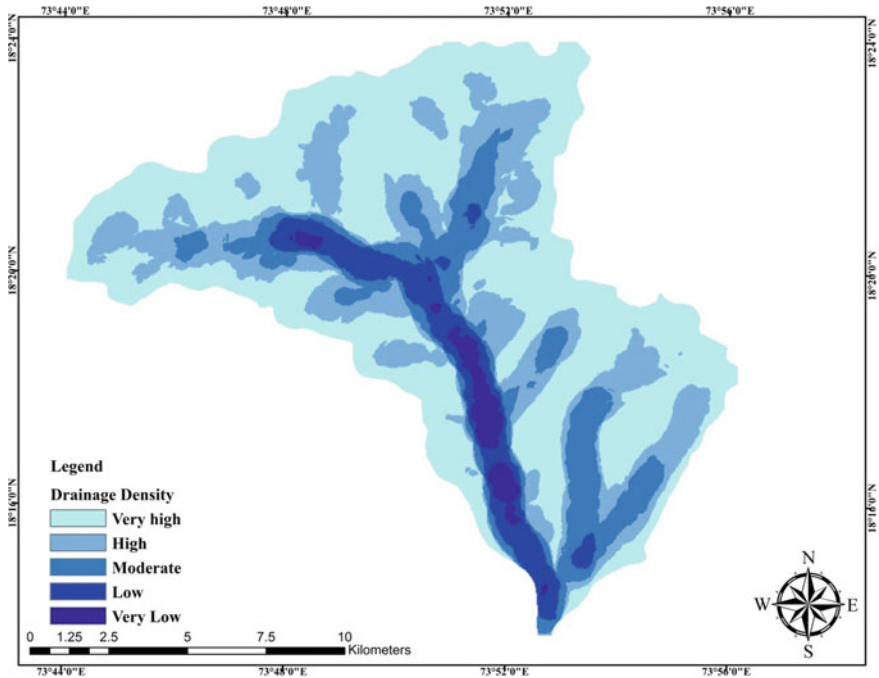
**Fig. 7** Drainage density map of Shivganga basin

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

## 4.6 Runoff

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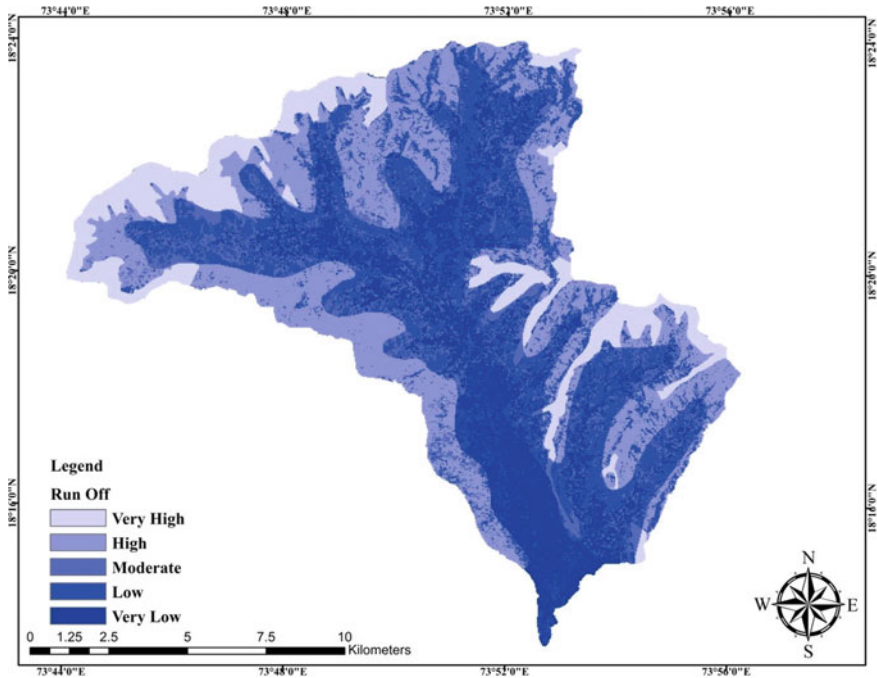
**Fig. 8** Runoff map of Shivganga basin

## 4.7 Soil

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

## 4.8 Multi Criteria Decision Analysis (MCDA)

The GIS facilitated MCDA technique primarily concerned in combining geographical data (map criteria) on the basis of value findings (expert opinion preferences) to organize them into a one unique guide of assessment, from which decision makers can make the final choice (Malczewski 2006). Therefore, MCDA has been conducted
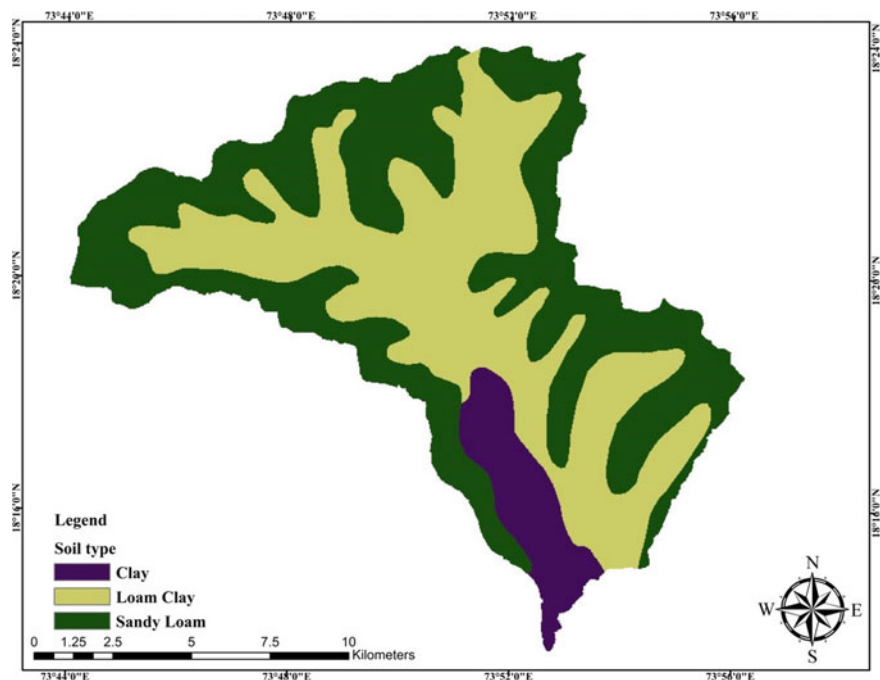
**Fig. 9** Soil types of Shivganga basin

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

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

### 4.9　Multi Influencing Factor

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

**Table 1** Categorization of factors influencing recharge potential in Shivganga basin

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

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

$$\frac{A + B}{\sum (A + B)} \times 100. (1)$$
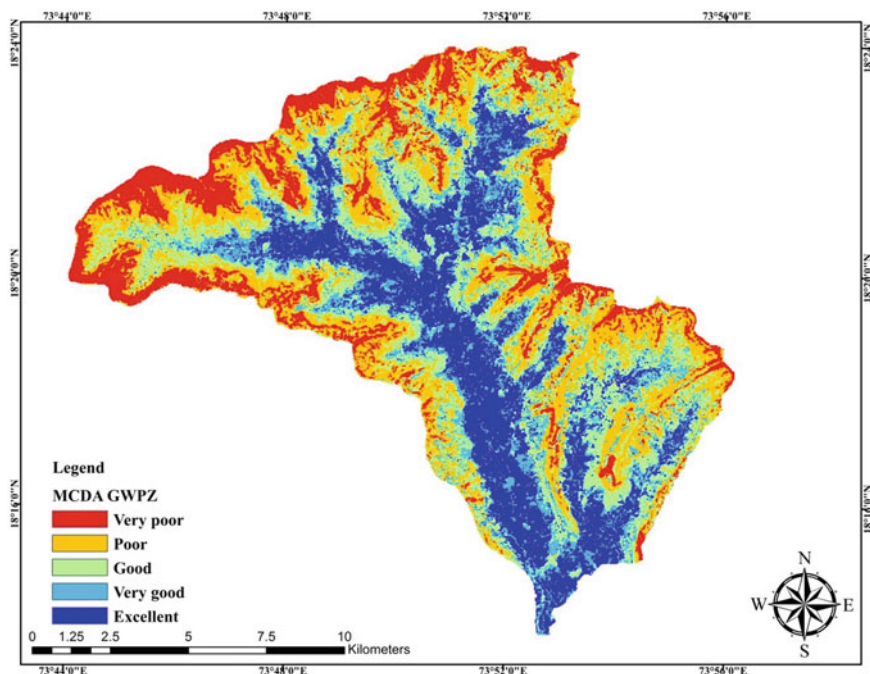
**Fig. 10** Groundwater potential map derived by MCDA

**Table 2** Statistics of MCDA groundwater potential map

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

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

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

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

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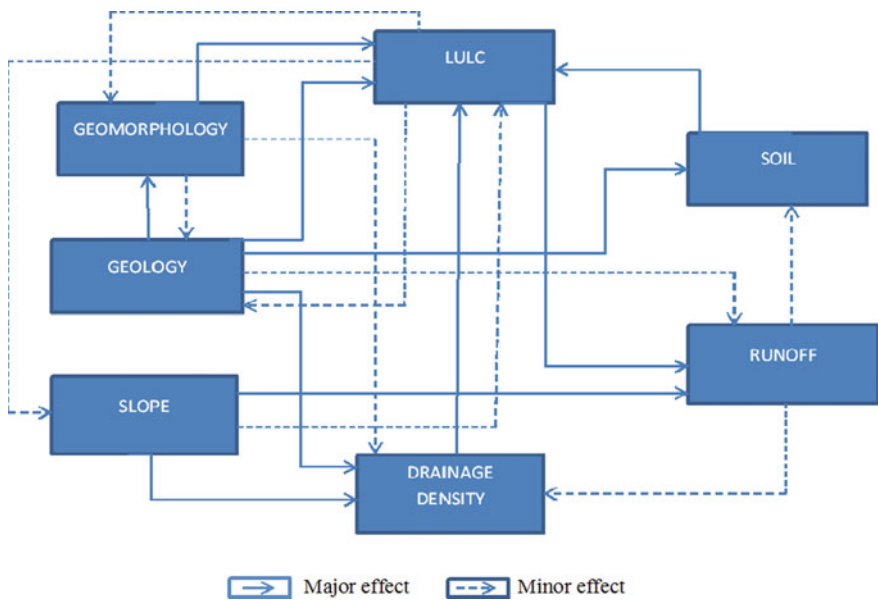


**Fig. 11** Interrelationship between the multi-influencing factors concerning the GWPZ (Magesh et al. 2012)

### 4.9.1　Weighted Sum

The weighted sum technique uses the several raster's for multiplying each other by their given weight and adding them together. The technique offers the capability to weight and group many inputs to make a combined analysis. Since two different techniques have been used to find out the potential zones of groundwater, weighted
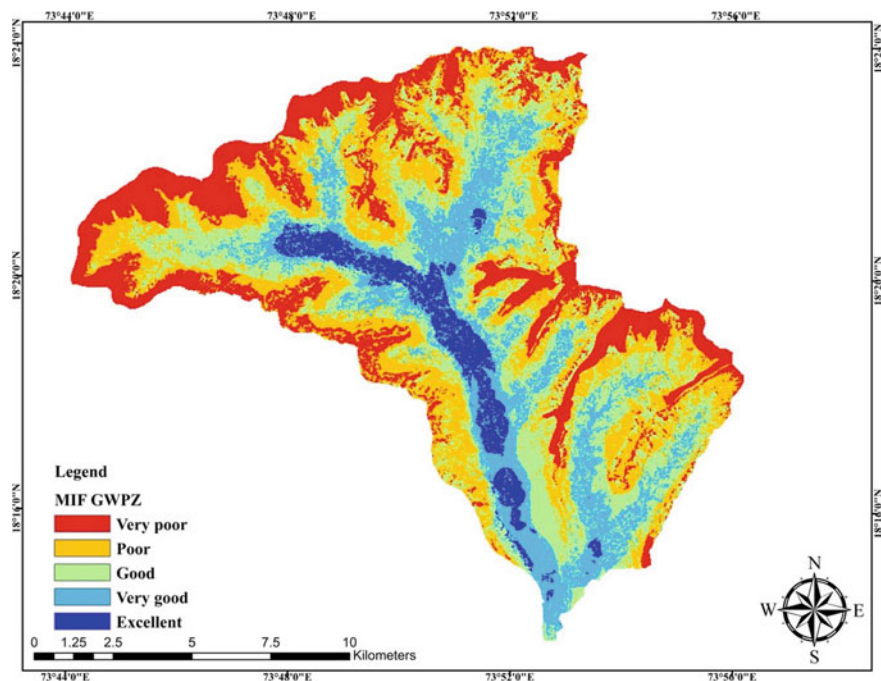
**Fig. 12** MIF groundwater potential map

**Table 4** Statistics of MIF groundwater potential map

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

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

### 4.9.2 Validation

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

**Table 5** Statistics of weighted sum groundwater potential map

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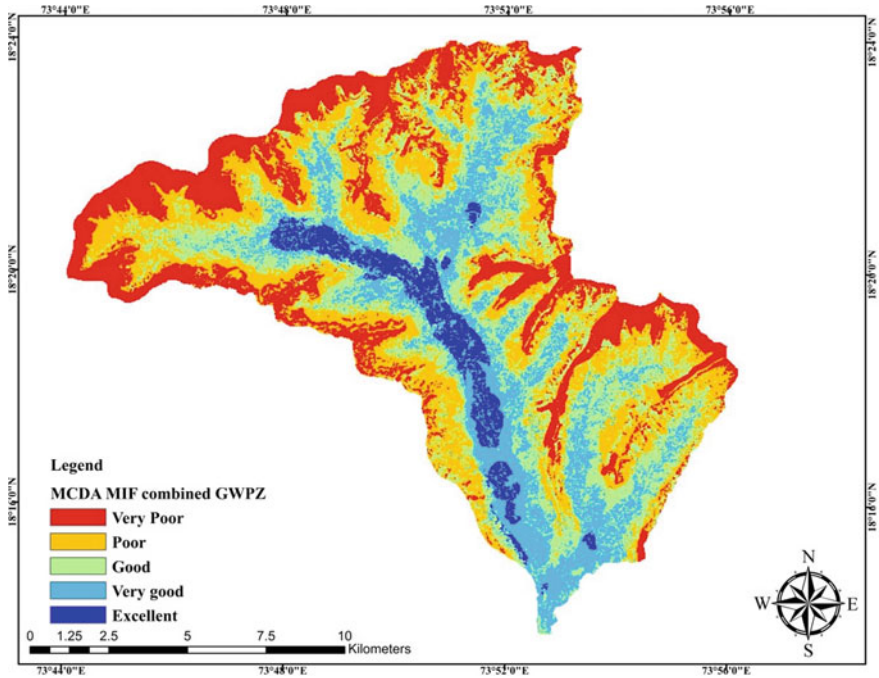


**Fig. 13** Weighted sum groundwater potential map

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

Validity of MCDA—GWPZ Map with Well Information

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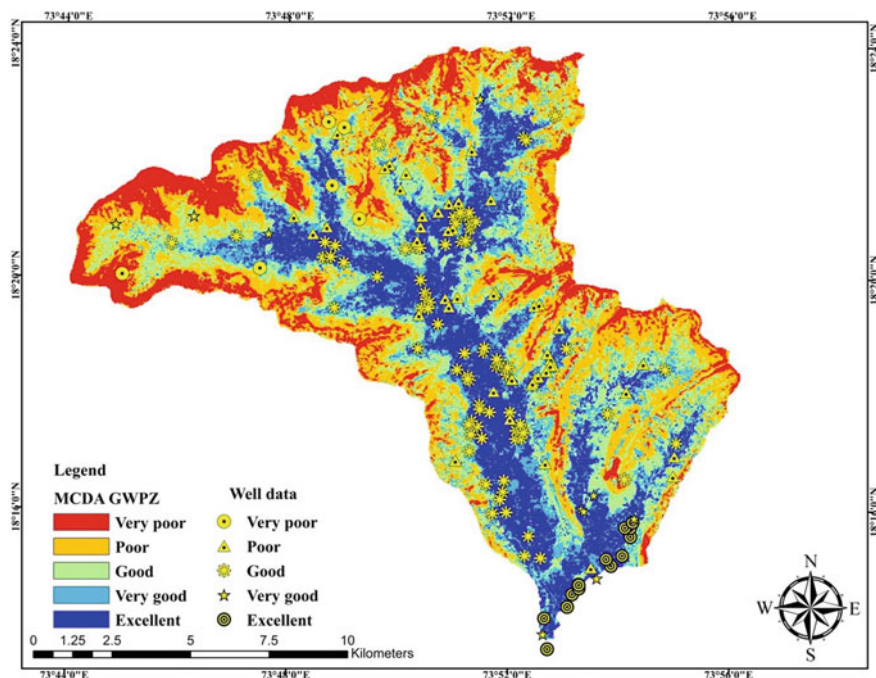
**Fig. 14** Validation with MCDA groundwater potential map

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

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

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

Validity of MIF- GWPZ Map with Well Information

The validation of MIF with GWPZ map shows 4% of the wells under 'very good' depth GWPZ, 45% of the wells under 'good' depth GWPZ and 50% of the wells in
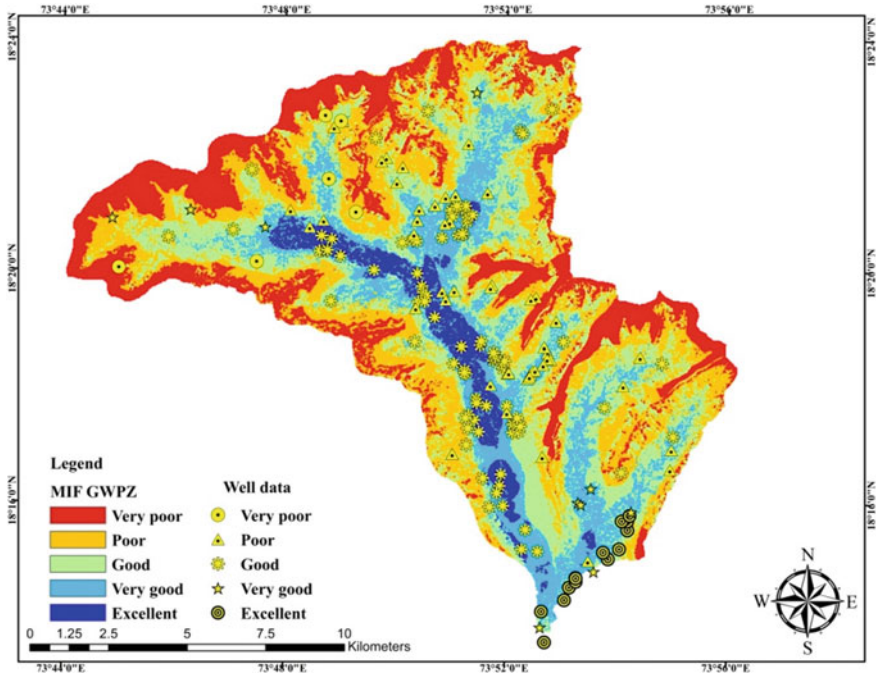
**Fig. 15** Validation of MIF-GWPZ map

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

Validity of Weighted Sum—GWPZ Map with Well Information

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

## 5 Conclusion

The present study identifies the GWPZ in Shivganga river basin representing semi-arid zone of Western Ghats applying MCDA, MIF and weighted sum technique. The thematic layers in raster format were generated using imageries, topographical
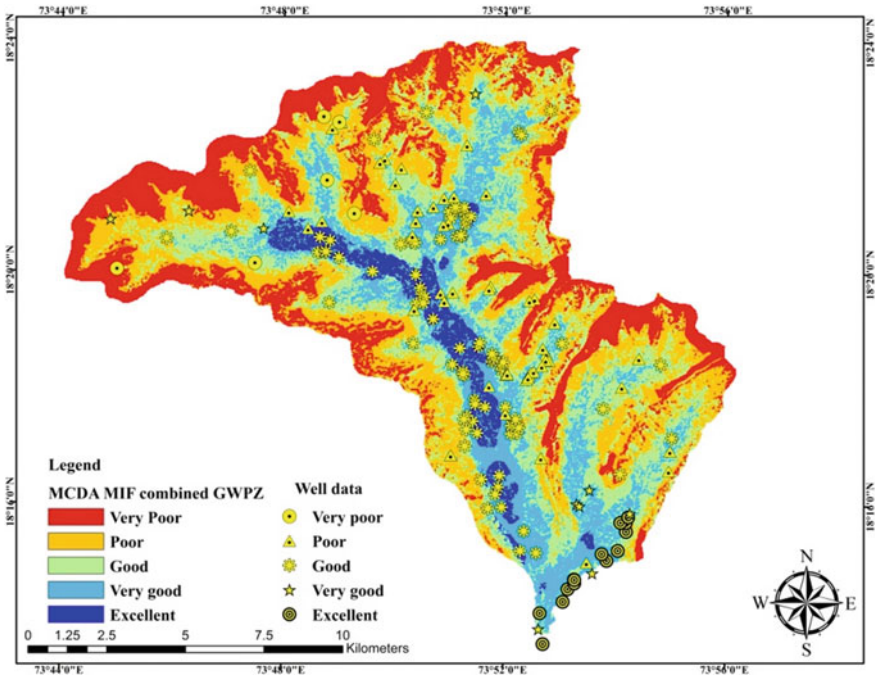
**Fig. 16** Validation with weighted sum groundwater potential map
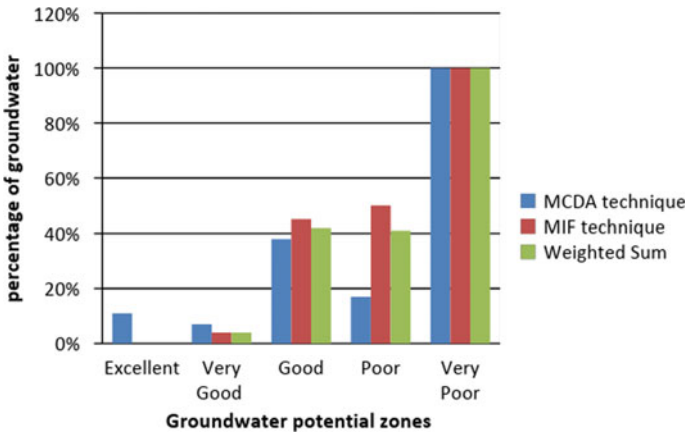


**Fig. 17** Groundwater potential zone with different techniques compared to ground validation

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

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

# References

Adhikary, P. P., Chandrasekharan, H., Chakraborty, D., & Kamble, K. (2010). Assessment of groundwater pollution in west Delhi, India using geostatistical approach. *Environmental Monitoring and Assessment, 167,* 599–615.

Adji, T. N., & Sejati, S. P. (2014). Identification of groundwater potential zones within an area with various geomorphological units by using several field parameters and a GIS approach in KulonProgo Regency, Java. *Indonesia. Arabian Journal Geoscience, 7*(1), 161–172.

Balamurugan, G., Seshan, K., & Bera, S. (2017). Frequency ratio model for groundwater potential mapping and its sustainable management in cold desert. *India. Journal King Saud University Science, 29*(3), 333–347.

Bali, R., Agarwal, K., Nawaz, A. S., Rastogi, S., & Krishna, K. (2012). Drainage morphometry of Himalayan Glacio-fluvial basin, India: hydrologic and neotectonic implications. *Environment Earth Science, 66*(4), 1163–1174.

Ballukraya, P., & Kalimuthu, R. (2010). Quantitative hydrogeological and geomorphological analyses for groundwater potential assessment in hard rock terrains. *Current Science, 98*(2), 253–259.

Bhattacharyya, T., Pal, D. K., Mandal, C., Chandran, C., Ray, S. K., et al. (2013). Soils of India: historical perspective, classification and recent advances. *Current Science, 104*(10), 1308–1323.

CGWB. (2011). *Dynamic groundwater resources of India.* Ministry of Water Resources, Government of India, New Delhi: Central Ground Water Board.

Chandio, I. A., Matori, A. N. B., WanYusof, K. B., Talpur, M. A. H., Balogun, A. L., & Lawal, D. U. (2013). GIS-based analytic hierarchy process as a multicriteria decision analysis instrument: A review. *Arabian Journal of Geosciences , 6*(8), 3059–3066.

Chenini, I., & Mammou, A. B. (2010). Groundwater recharge study in arid region: An approach using GIS techniques and numerical modeling. *Computer Geology Science, 36*(6), 801–817.

Chowdhury, A., Jha, M. K., Chowdary, V. M., & Mal, B. C. P. (2009). Integrated remote sensing and GIS based approach for accessing ground- water potential in West Medinipur district, West Bengal. *India. International Journal Remote Sensing, 30*(1), 231–250.

Deepa, S., Venkateswaran, S., Ayyandurai, R., Kannan, R., & Prabhu, M. J. (2016). Groundwater recharge potential zones mapping in upper Manimuktha sub basin Vellar River Tamil Nadu India using GIS and remote sensing techniques. *Model Earth System Environment, 2,* 137.

Doell, P., Schmied, H. M., Schuh, C., Portmann, F. T., & Eicker, A. (2014). Global-scale assessment of groundwater depletion and related groundwater abstractions: combining hydrological modeling with information from well observations and GRACE satellites. *Water Resources Research, 50*, 5698–5720.

Golkarian, A., & Rahmati, O. (2018). Use of a maximum entropy model to identify the key factors that influence groundwater availability on the Gonabad Plain. *Iranian Environment Earth Science, 77,* 369.

Gumma, M. K., & Pavelic, P. (2012). Mapping of groundwater potential zones across Ghana using remote sensing, geographic information systems, and spatial modeling. *Environmental Monitoring and Assessment, 185*(4), 3561–3579.

Horton, R. E. (1932). Drainage basin characteristics. *Transactions American Geophysics Union, 13,* 350–361.

Jasrotia, A. S., Bhagat, B. D., Kumar, A., & Kumar, R. (2013). Remote sensing and GIS approach for delineation of groundwater potential and groundwater quality zones of Western Doon Valley, Uttarakhand. *India. Journal of Indian Society Remote Sensing, 41*(2), 365–377.

Jenifer, M. A., & Jha, M. K. (2017). Comparison of analytic hierarchy process, catastrophe and entropy techniques for evaluating groundwater prospect of hard-rock aquifer systems. *Journal of Hydrology (Amst), 548,* 605–624.

Jha, M. K., Chowdary, V. M., Kulkarni, Y., & Mal, B. C. (2014). Rainwater harvesting planning using geospatial techniques and multicriteria decision analysis. *Resource Conservation Recycling, 83,* 96–111.

Kadam, A. K. (2018). Hydrological response-based watershed prioritization in semiarid, basaltic region of western India using frequency ratio, fuzzy logic and AHP method. *Environment Development and Sustainability, 21*(4), 1:25.

Kaliraj, S., Chandrasekar, N., & Magesh, N. S. (2014). Identification of potential groundwater recharge zones in Vaigai upper watershed, Tamil Nadu, using GIS-based analytical hierarchical process (AHP) technique. *Arabian Journal of Geosciences , 7*(4), 1385–1401.

Kumar, A., & Krishna, A. P. (2018). Assessment of groundwater potential zones in coal mining impacted hard-rock terrain of India by integrating geospatial and analytic hierarchy process (AHP) approach. *Geocarto International, 33*(2), 105–129.

Li, P., He, S., Yang, N., & Xiang, G. (2018). Groundwater quality assessment for domestic and agricultural purposes in Yan'an City, Northwest China: Implications to sustainable groundwater quality management on the Loess Plateau. *Environment Earth Science, 77*(23), 775.

Machiwal, D., Madan, K., Jha, M. K., Bimal, C., & Mal, B. C. (2011). Assessment of groundwater potential in a semi-arid region of India using remote sensing, GIS and MCDM techniques. *Water Resource Management, 25*(5), 1359–1386.

Magesh, N. S., Chandrasekar, N., & Soundranayagam, J. P. (2011). Morphometric evaluation of Papanasam and Manimuthar watersheds, parts of Western Ghats, Tirunelveli district, Tamil Nadu India: A GIS approach. *Environmental Earth Science, 64*(2), 373–381.

Magesh, N. S., Chandrasekar, N., & Soundranayagam, J. P. (2012). Delineation of groundwater potential zones in Theni district, Tamil Nadu, using remote sensing. *GIS and MIF Techniques. Geoscience Frontiers, 3*(2), 189–196.

Malczewski, J. (2006). GIS-based multicriteria decision analysis: A survey of the literature. *International Journal of Geographical Information Science, 20*(7), 703–726.

Malekmohammadi, B., Mehrian, M. R., & Jafari, H. R. (2012). Site selection for managed aquifer recharge using fuzzy rules: Integrating geographical information system (GIS) tools and multi-criteria decision making. *Hydrogeology Journal, 20*(7), 1393–1405.

Mishra, S., Tiwary, D., Ohri, A., & Agnihotri, A. K. (2019). Impact of municipal solid waste landfill leachate on groundwater quality in Varanasi. *India. Groundwater for Sustainable Development, 9*(10), 1002–1030.

Murthy, K. S. R. (2000). Groundwater potential in a semi-arid region of Andhra Pradesh-a geographical information system approach. *International Journal of Remote Sensing, 21*(9), 1867–1884.

Naghibi, S. A., Pourghasemi, H. R., Pourtaghi, Z. S., & Rezaei, A. (2015). Groundwater *qanat* potential mapping using frequency ratio and Shannon's entropy models in the Moghan watershed. *Iran. Earth Science India, 8*(1), 171–186.

Nampak, H., Pradhan, B., & Manap, M. A. (2014). Application of GIS based data driven evidential belief function model to predict groundwater potential zonation. *Journal of Hydrology, 513,* 283–300.

Patra, S., Mishra, P., & Mahapatra, S. C. (2017). Delineation of groundwater potential zone for sustainable development: A case study from Ganga Alluvial Plain covering Hooghly district of India using remote sensing, geographic information system and analytic hierarchy process. *Journal of Cleaner Production, 172,* 2485–2502.

Selvam, S., & Sivasubramanian, P. (2012). Groundwater potential zone identification using geoelectrical survey: A case study from Medak district, Andhra Pradesh, India. *International Journal of Geomatics and Geosciences, 3*(1), 55–62.

Senanayake, I. P., Dissanayake, D. M. D. O. K., Mayadunna, B. B., & Weerasekera, W. L. (2016). An approach to delineate groundwater recharge potential sites in Ambalantota. *Sri Lanka Using GIS Techniques. Geoscience Frontiers, 7*(1), 115–124.

Singhai, A., Das, S., Kadam, A. K., et al. (2019). GIS-based multi-criteria approach for identification of rainwater harvesting zones in upper Betwa sub-basin of Madhya Pradesh. *India, Environment Development Sustain, 21*(2), 777–797.

Thakur, J. K., Thakur, R. K., Ramanathan, A., Kumar, M., & Singh, S. K. (2011). Arsenic contamination of groundwater in Nepal—An overview. *Water, 3*(1), 1–20.

Thapa, R., Gupta, S., Guin, S., & Kaur, H. (2017). Assessment of groundwater potential zones using multi-influencing factor (MIF) and GIS: A case study from Birbhum district. *West Bengal. Applied Water Science, 7*(7), 4117–4131.

Umar, R., Ahmed, I., & Alam, F. (2009). Mapping groundwater vulnerable zones using modified DRASTIC approach of an alluvial aquifer in parts of central Ganga plain. *Western Uttar Pradesh. Journal Geology Society India, 73*(2), 93–201.

White, P. A., Hong, Y. S., Murray, D. L., Scott, D. M., & Thorpe, H. R. (2003). Evaluation of regional models of rainfall recharge to groundwater by comparison with lysimeter measurements, Canterbury. *New Zealand. Journal of Hydrology, 42*(1), 39–64.

Yeh, H. F., Cheng, Y. S., Lin, H. I., & Lee, C. H. (2016). Mapping groundwater recharge potential zone using a GIS approach in Hualian river. *Taiwan. Sustainable Environment Research, 26*(1), 33–43.