King Saud University

Journal of King Saud University – Science

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REVIEW

Frequency ratio model for groundwater potential mapping and its sustainable management in cold desert, India

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Abstract Groundwater potential mapping and its sustainable development are an important aspect in Leh valley due to an increase of tourists and the local population. In the present study, the groundwater potential zones were delineated by adopting a frequency ratio (FR) model. Land use and land cover, hydro geomorphology, slope, geology, lineament density, drainage density, spring well locations and ground water level were the thematic factors considered for groundwater potential zone mapping. There are 86 spring wells located in the study area, of which 60 wells were considered for success rate and remaining 26 wells considered for prediction rate in the FR model. The final groundwater potential map was classified into five zones as very high, high, moderate, low, and very low. The success and prediction rates of FR model were measured as 81.25% and 77.23% respectively. Water budget of the valley was also calculated on the basis of consumption, demand and supply of water by taking account of the floating population. There is a huge demand of water supply requirement during the tourist season from May to September months and deficiency of water in the area was calculated as 4,224,557 (in l). Finally, suitable sites for artificial recharge for sustainable groundwater management were identified. The sites were selected on the basis of depth of groundwater level, source of spring well locations and gradient from natural spring to selected recharge wells.

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Contents

1. Introduction

Over the last few decades, areas with varying demographics and economic reliance have been forced into the 'water crisis', which has to be topmost among the many crises staring us in the face. In fulfilling the water needs of the majority of the population in India, groundwater resources have the highest priority. Groundwater is less vulnerable than surface water sources to climate fluctuations in an undisturbed aquifer system and therefore, acts as a key buffer against drought and normal variations in rainfall. Reliable supply of groundwater lead input for increasing yields, reducing agricultural risk, stabilizing farm incomes and thus leading to higher levels of social and economic security (Moench, 2003). Groundwater exploration entails delineation and mapping of different lithological, structural and geomorphologic units (Solomon and Quiel, 2006). In fluvio-glacial regions particularly outwash plains, valley fills and buried outwash are indicators for source of groundwater potential (Thornbury, 1969). Groundwater obtained from fluvio-glacial region is utilized for domestic and industrial purposes in many cities among the world such as Champaign, Urbana, Illinois, Canton, Ohio (White et al., 1946), Schenectady, New York (Simpson, 1949) etc. In hard rock terrain, the task of groundwater potential mapping becomes a relatively more complex task involving complex decisions owing to lack of reliable data and the highly variable nature of the geological environment (Kellgren, 2002; Anbazhagan et al., 2011). Groundwater in hard rock aquifers is essentially restricted to fractured horizons as the movement of water is mostly through these fractures. Therefore, extensive hydro geological investigations are required to thoroughly understand groundwater conditions in hard rock region (Krishnamurthy et al., 2000; Solomon and Quiel, 2006; Balamurugan et al., 2008; Pradhan, 2009; Anbazhagan et al.,

2015) to delineate the groundwater potential zones (GWPZ) through remote sensing (RS) and Geographical information systems (GIS), which act as powerful tools and several studies have been carried out in different parts of the world (Evans and Myers, 1990; Saraf and Choudhury, 1998; Panagopoulus et al., 2005; Rai et al., 2005; Sener et al., 2005; Singh and Singh, 2009; Yan et al., 2010; Biswas et al., 2012; Hammouri et al., 2012; Kuria et al., 2012; Sharma and Kujur, 2012; Sudarsana, 2012; Anbazhagan and Jothibasu, 2014). The identification of GWPZ using remote sensing and GIS techniques involves interpretation of various themes such as vegetation, land use land cover, hydro geomorphology, drainage, lithology, subsurface lithology, structure, slope etc. which have been used in inferring the occurrence of groundwater (Hung et al., 2002; Xiuwan, 2002; Shaban et al., 2006). In hard rocks, which has low or absence of primary porosity, the intersections of secondary structural features are crucial for productive groundwater well (Kumanan and Ramasamy, 2003; Balamurugan et al., 2008). There are various statistical methods that were adopted for groundwater potential zone mapping such as frequency ratio (Davoodi et al., 2013; Manap et al., 2014; Pourtaghi and Pourghasemi, 2014; Naghibi et al., 2015), multi-criteria decision evaluation (Murthy and Mamo, 2009; Kumar et al., 2014; Rahmati et al., 2014; Machiwal and Singh, 2015; Razandi et al., 2015; Jothibasu and Anbazhagan, 2016), logistic regression model (Ozdemir, 2011; Pourtaghi and Pourghasemi, 2014), weights-of-evidence model (Ozdemir, 2011; Pourtaghi and Pourghasemi, 2014), random forest model (Rahmati et al., 2016; Naghibi et al., 2016; Zabihi et al., 2016; Naghibi and Pourghasemi, 2015), maximum entropy model (Rahmati et al., 2016), boosted regression tree (Naghibi et al., 2016; Naghibi and Pourghasemi, 2015), classification and regression tree (Naghibi et al., 2016), multivariate adaptive regression spline
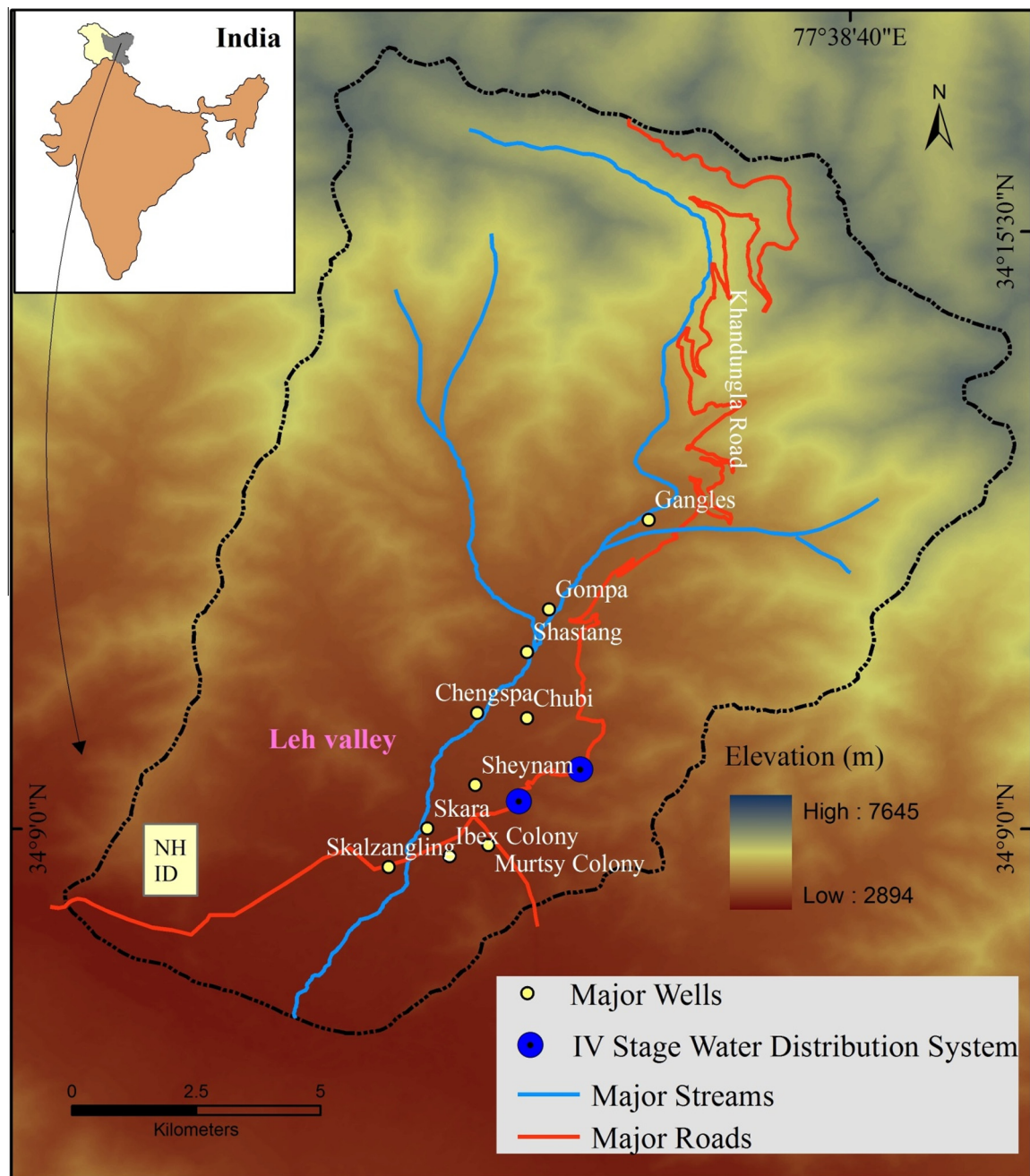
Figure 1 Base map of study area, Leh Valley, Jammu and Kashmir, India.

model (Zabihi et al., 2016), certainty factor model (Zabihi et al., 2016), evidential belief function (Pourghasemi and Beheshtirad, 2015; Naghibi and Pourghasemi, 2015), and generalized linear model (Naghibi and Pourghasemi, 2015). These statistical methods were used to carry out the GWPZ based on different influencing parameters, their interconnection and contribution to the groundwater movements and accumulations.

Artificial groundwater recharge is a process by which groundwater reservoir is augmented at a rate exceeding what is the case under natural conditions of replenishment (Bhattacharya, 2010). Augmentation of this natural infiltration

of water either from precipitation or surface or snow melting, into underground formations can be achieved by various methods such as water spreading, recharge through pits, shafts, injection wells, trenches, snow harvesting, check dams cum groundwater dams. Many research studies have been carried out on artificial recharge sites selection for aquifer replenishment in various parts of the world (Johnson and Sniegocki, 1967; Warner and Moreland, 1972; Ramasamy and Anbazhagan, 1997). In the last few decades, remote sensing and GIS techniques play an important role for identification of suitable sites for artificial recharge structures for sustainable groundwater resource management (Anbazhagan
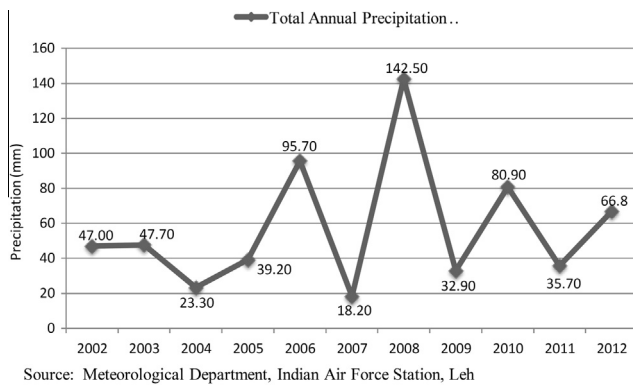
Figure 2   Annual rainfall of Leh area from 2002 to 2012.

Table 1   Details of source data.

Data and source	Resolution and scale	Thematic layers
IRS P6 LISS IV Satellite Image, date of acquisition on 29th July 2012. Procured from National Remote Sensing Centre (NRSC), India	5.8 m	Land use and land cover Hydro geomorphology Lineament
Aster DEM dated 17th Oct 2011, earthexplorer.usgs.gov	30 m	Slope Drainage
Geology map, (Geological survey of India, 2005)	1: 200,000	Geology
Public Health and Engineering (PHE), 2013	–	Groundwater level Wells location

et al., 2005; Jasrotia et al., 2007; Muthukrishnan and Manjunatha, 2008; Nagarajan and Singh, 2009; Hossein et al., 2014). The geological, subsurface geological, geomorphological, slope, drainage, structures and hydrogeological parameters were analyzed in the process of suitable site selection for artificial recharge.

The present study is focused on GWPZ mapping and its sustainability of Leh valley which has historically been a low precipitation area as < 100 mm per annum. In 1974, this area was opened for tourists and since then has seen a steady rise in visitor's number over the decades, especially during the last few years. As per the tourism and labor department information, the number of the tourist population in 1974 was 527 which has risen to 179,491 in 2011. As an inevitable consequence, the water demand has suddenly gone up and pressure on natural resources of the region, especially groundwater, has increased exponentially. In such a scenario, it becomes important to delineate the GWPZ in the area and identify the suitable sites for artificial groundwater recharge. In an attempt to achieve this target, the study has encompassed several objectives such as to develop groundwater potential zonation map, calculate the water budget and to identify the suitable sites for artificial groundwater recharge based on their relative properties with springs present in the study area. The study was carried out through an integrated Remote Sensing, GIS techniques, and field investigation. The frequency ratio (FR) method was adopted for GWPZ mapping.

2. Study area

The Leh district of the Ladakh region also known as "Cold Desert" is one of India's most elevated, coldest, mountainous and sensitive places and lies in the higher Himalayan range. Leh is situated in between 34°00′N to 34°20′N latitude and 77°32′E to 77°40′E longitude and at an altitude of 3524 m (11,562 ft). The study area situated at a distance of 434 km from Srinagar and 474 km from Manali. Leh and Srinagar are connected by National Highway (NH) of 1D. It is bounded by Pakistan in the northwest, Kargil in the west, China in the north and eastern part, and Lahaul Spiti of Himachal Pradesh in southeast (Fig. 1). According to the census of 2001, the local population was 117,232 which has gone up to 147,104 in 2011. This region is dominated by both arctic and desert climate and the main features of this "Cold Desert" are wide diurnal and seasonal fluctuations in temperature with −40 °C in winter and +30 °C in summers. The average annual rainfall in this region is less than 100 mm. However, the study area also received the highest rainfall of 142.50 mm in 2008 and the lowest rainfall of 18.20 mm in 2007 (Fig. 2). This study is mainly focused on the area from the lower reaches of the Leh valley starting near the Indus River and upward toward the Gyamtsa and Gangles sides on the upper portions of the valley. Agriculture is the main source of livelihood in the study area and wheat and barley are the main crops.

3. Materials and methodology

To carry out the GWPZ, various data sets were used in the study viz. satellite images, toposheets, field data and secondary data were collected from different Government departments (Table 1). High resolution Indian Resource Sat-2 satellite image acquired on 29th July 2012 by Linear Imaging Self Scanner IV (LISS IV) sensor with 5.8 m spatial resolution procured from NRSC, India was used to interpret the various groundwater influencing factors such as land use and land cover, hydro geomorphology, lineament and drainage. The ASTER satellite Digital Elevation Model (DEM) with 30 m resolution has been used for preparing slope map. Groundwater level data and rainfall data were obtained from Public Health and Engineering (PHE) and Airforce Stations present in the Leh region respectively. The average monthly water consumption pattern of residential and floating tourist population data was also collected from PHE for water budget analysis. Once all the relevant thematic maps were prepared from satellite data, the field visits was carried to check the accuracy of visual interpretation and also to map the locations of wells and springs. Primarily, determinations of influencing factors play a vital role in preparing the groundwater potential zone map. In various literatures that were referred, it was observed that many researchers have used the different influencing factors viz., slope gradient, slope aspect, altitude, curvature, stream power index, topographic wetness index, rainfall distribution, groundwater level, distance from water body, distance from fault, drainage density, lineament, lineament density, lithology, hydro geomorphology and land use and land cover features, were considered for GWPZ mapping on the basis of data availability, and characteristics of study area. However, in this study total eight major influencing factors namely land use and land cover, hydro geomorphologic features,
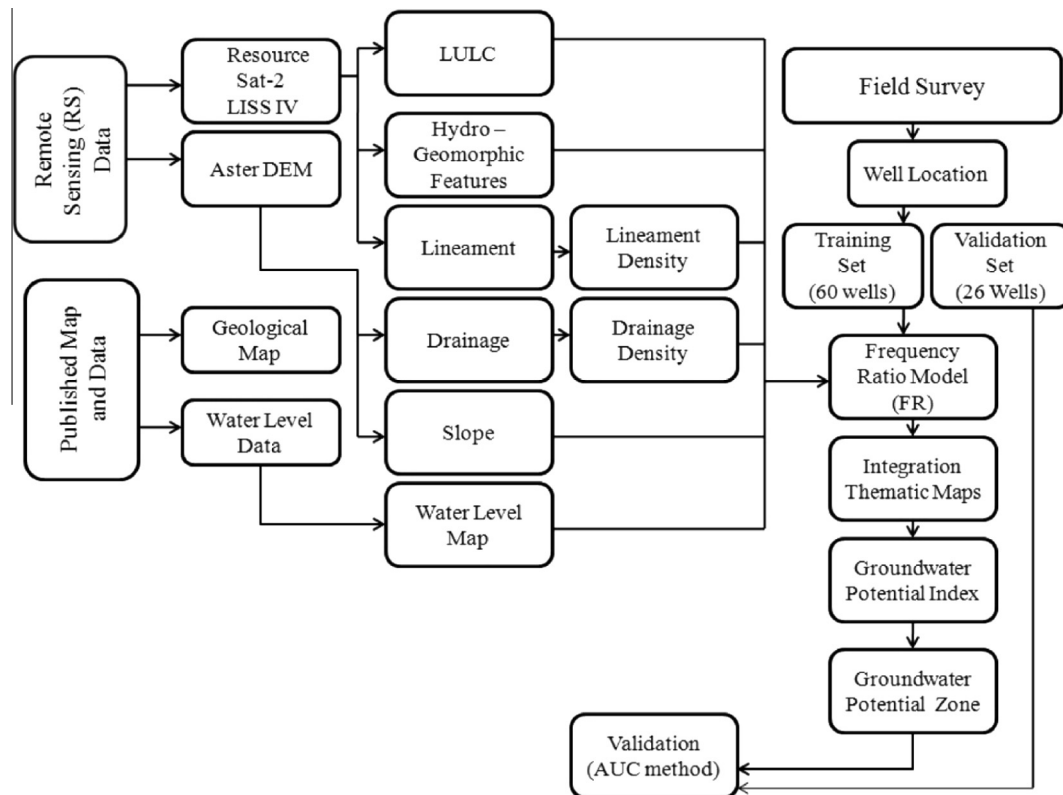
Figure 3 Flow chart shows materials and methodology adopted in the research study.

slope, geology, lineament, lineament density, drainage density, groundwater level were considered for preparing GWPZ map. The different thematic layers were generated in ArcGIS and stored in geodatabase. The accuracy of land use and land cover map was calculated from the Kappa index. All the thematic maps were converted from vector to raster format with $10 \text{ m} \times 10 \text{ m}$ grid cell for further integration analysis for GWPZ using FR model. After the identification of GWPZ, the validation was carried out by area under curve (AUC) method considering cumulative percentage of spring wells and percent of groundwater potentiality index value. The materials and methodology adopted in the present study are shown in Fig. 3.

3.1. Frequency ratio model

The FR is a bivariate statistical approach and used to determine probability of groundwater potential areas on the basis of relationships between dependent variable viz., spring wells and independent variables viz., groundwater influencing factors (Oh et al., 2011; Naghibi et al., 2016). FR is defined as;

$$FR = \frac{W/TW}{CP/TP} \qquad (1)$$

where, FR is frequency ratio of the class of factor, W is a number of pixels of spring well locations for each class of thematic maps; TW is a number of total pixels of spring well in the study area. CP is a number of pixels in each thematic class and TP is a total number of pixels in the study area. In the FR model,

FR value of each class in a thematic layer was considered as weight of that particular class in thematic parameters to determine groundwater potentiality.

The FR value was derived from each thematic layer on the basis of relationship with spring wells of training set data using Eq. (1). The accuracy of FR model was validated using receiver operating characteristic (ROC) curve in form of success rate curve and prediction rate curve were used (Nandi and Shakoor, 2009 and Zabihi et al., 2016). The area under curve (AUC) value indicates the prediction accuracy (Pradhan and Lee, 2010). In the present study, AUC were determined by using the training set of 60 spring wells for measuring the success rate curve and remaining 26 spring wells retained as test data set.

3.2. Thematic maps generation

3.2.1. Land use and land cover (lu)

Land use and land cover of any region play an important role in runoff, infiltration, and recharge of groundwater (Anbazhagan et al., 2005 and Bhattacharya, 2010). The land use and land cover of the study area were demarcated into five categories such as rocky terrain, mixed agricultural land, built up land, sandy area, and river bed by visual interpretation of Resourcesat2 LISS IV satellite image (Fig. 4a). The accuracy of land use and land cover map was calculated from Kappa index method (Gómez et al., 2008; Gómez and Montero, 2011; Ronny et al., 2015). In this process of accuracy measurements there are 139 sample locations (collected from field) of
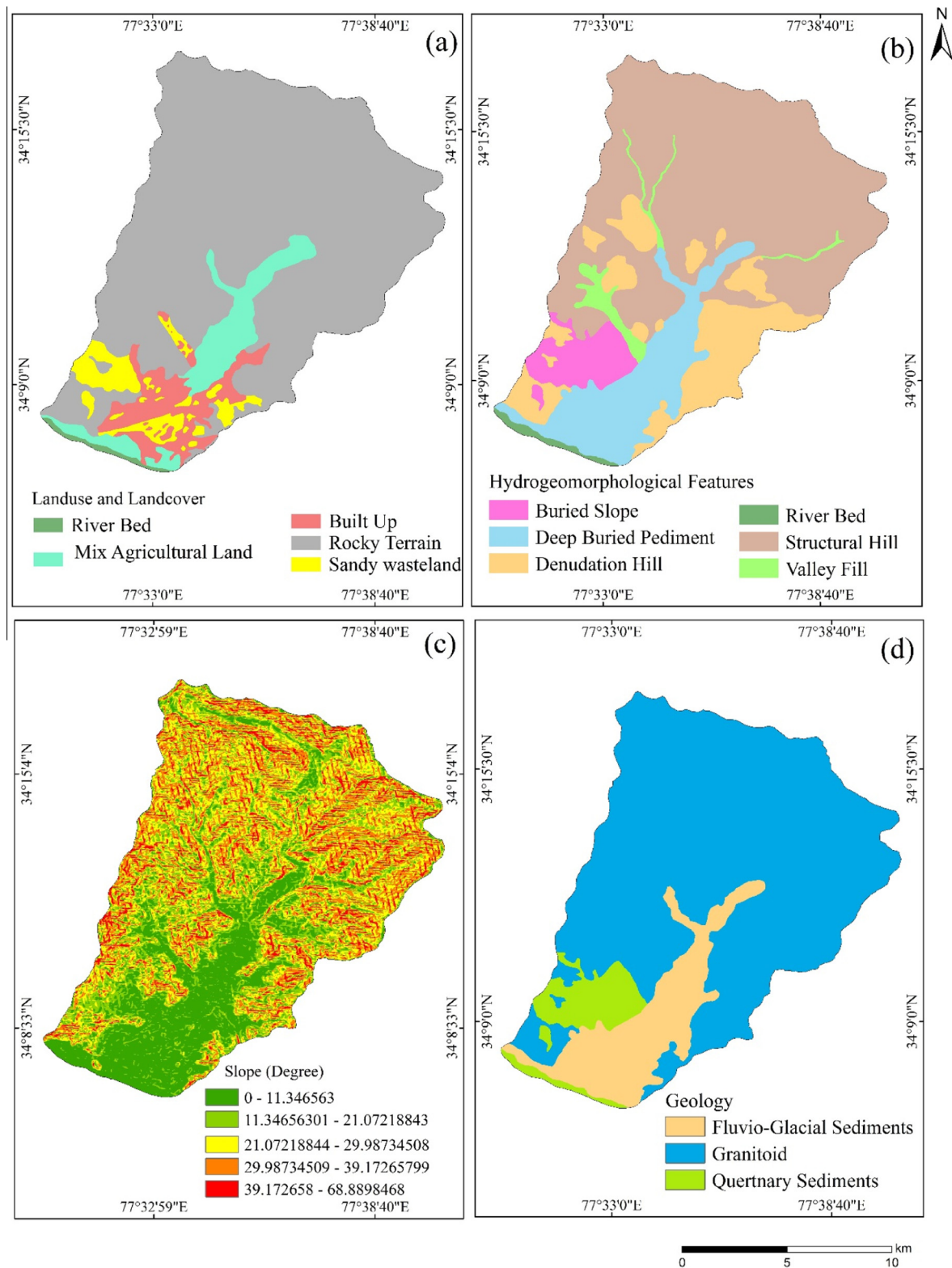
Figure 4 Thematic maps (a) land use and land cover, (b) hydro geomorphic features (c) slope, (d) geology, (e) lineament density, (f) drainage density, (g) groundwater level, (h) wells for training set and testing set.

different land use and land cover features and the land cover classified output was considered as input. Finally, accuracy of land use and land cover map was calculated as 88.7%.

3.2.2. Hydro geomorphological features (hg)

Hydro geomorphological features have an important role to play in percolation and recharging of groundwater into the
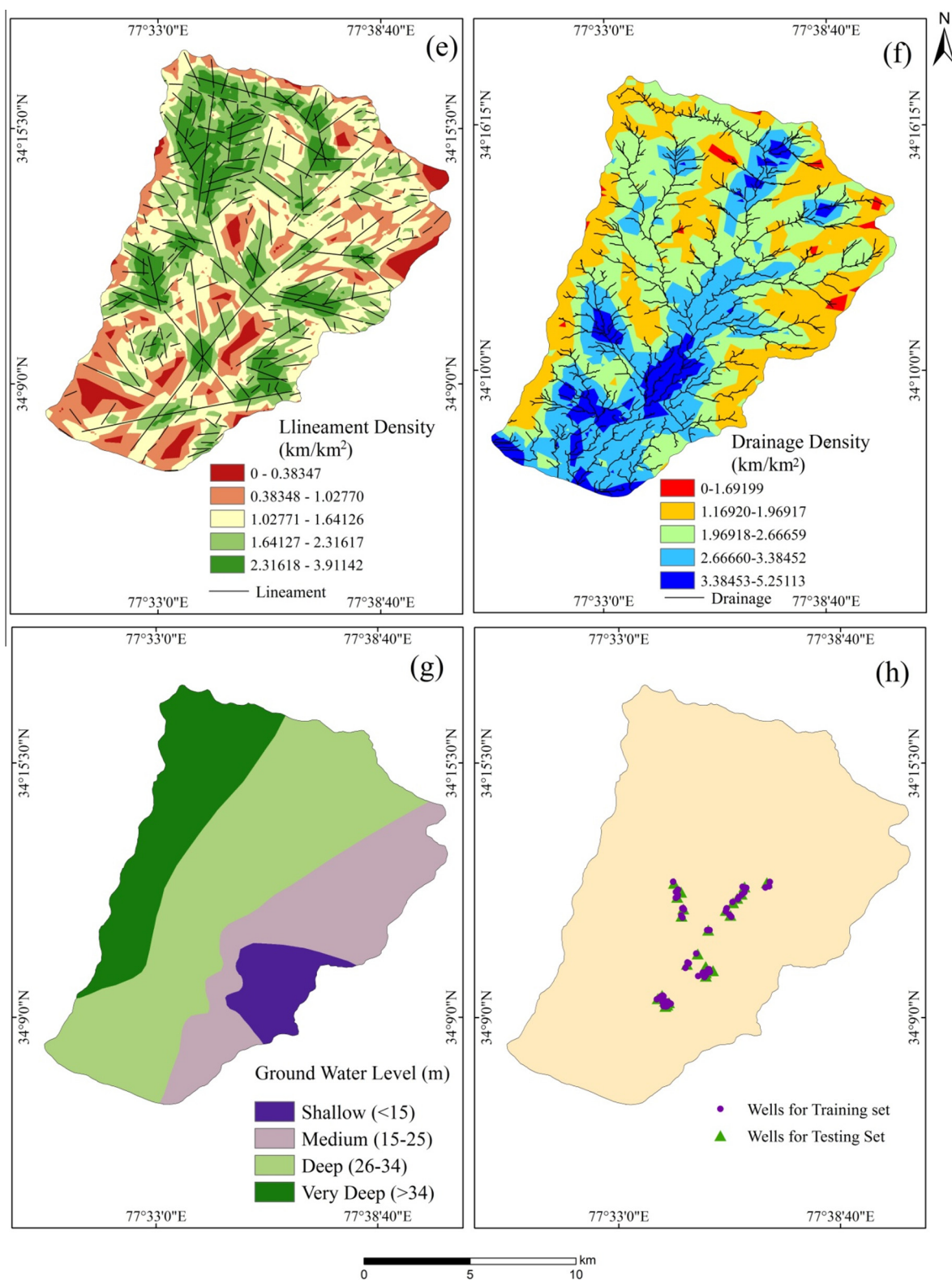
Fig. 4 (*continued*)

subsurface (Ramasamy and Anbazhagan, 1997; Balamurugan et al., 2008). On the basis of field data and satellite image (Resources at LISS IV), the hydro geomorphological features were interpreted. Six categories of features such as – deep buried pediment, river bed, valley fill, buried slope, denudation hill and structural hill were interpreted and mapped (Fig. 4b).

3.2.3. Slope (sl)

Slope defines the variation of elevation in a particular area which influences the runoff (Naghibi et al., 2016). Generally, in gentle slopes, the movement of water is slow which allows more percolation into the ground. On the other hand, there was steep slope increase runoff and decrease in the percolation and infiltration into the ground. Slope map was produced from ASTER DEM with 30 m resolution (Fig. 4c). The slope degree varies from 0° to 68.88° and classified into five classes viz., 0–11.34656°, 11.34657–21.07219°, 21.07220–29.98734°, 29.98735–39.17266°, and 39.17267–68.88984° on the basis of natural breaks classification method (Jenks, 1967).

3.2.4. Geology (ge)

The study area is geologically composed with granitoid, fluvio-glacial deposits, and quaternary sedimentary rocks (Fig. 4d). The different lithological units were demarcated and delineated on the basis of published geology map (GSI, 2005) and also necessary field checks were carried out. Unconsolidated sedimentary and fractured granitoid rocks were more favorable for groundwater movement and accumulation than massive rock.

3.2.5. Lineament density (ld)

Lineaments control the groundwater infiltration and act as a transmitting medium, especially in hard rock fractured aquifer terrain (Kumanan and Ramasamy, 2003 and Balamurugan et al., 2008). The lineaments were extracted from Resource sat LISS IV image by visual interpretation method on the basis of existence of fracture features, tonal contrast in images. Lineament density was prepared using Line Density tool in ArcGIS10 per km^2. The density map was classified as five categories using natural breaks method (Jenks, 1967) viz., 0–0.38347, 0.38348–1.02770, 1.02771–1.64126, 1.64127–2.31617, and 2.31618–3.91142. Fig. 4e shows the lineament density of the area overlaid with lineament feature.

3.2.6. Drainage Density (dd)

Drainage carries water from the mountain region from precipitation or glacial or snow melt to the plains. It plays a major role as the groundwater source in a given area. The drainage systems are controlled by structural features like faults and fractures in the area and hence forth drainage acts as transmitting medium for glacial melt water movement into the subsurface.

Drainage of study area was extracted from ASTER DEM data and verified with satellite image i.e. Resourcesat2 LISS IV. Drainage density per km^2 was calculated by line density tool in Arc GIS 10 and it was classified into five zones viz., < 1.16919, 1.16920–1.96917, 1.96918–2.66659, 2.66660–3.38452, and 3.38452–5.25113 using natural breaks method (Jenks, 1967) (Fig. 4f).

3.2.7. Groundwater Level (gl)

The groundwater data were collected from Public Health and Engineering (PHE) Department, Leh. The gl were measured from 17 observed wells. These data were used to plot the groundwater level contour map which was classified into four classes i.e. shallow (<15 m), medium (15–25 m), deep (26–34 m), and very deep (>34 m) (Fig. 4g). Generally, shallow groundwater levels indicate high groundwater potentiality whereas the deeper groundwater levels indicate less groundwater potential.

3.2.8. Spring wells

Based on the field visit and PHE data, the natural springs were identified in different parts of the study area. During the field visit, it was observed that in some locations, the PHE had constructed artificial wells for collecting the spring water as open or closed tanks for the drinking water purposes. At many places, the agricultural irrigation depends on the spring water source. The springs discharge water at different rates depending on the season and local climatic conditions, for example, in the winter season the area is covered by snow while in summer, the spring wells discharge water (ranging from 50 l/min to 200 l/min). There are total 86 spring well locations in the area and these wells are located at various altitudes ranging from 3300 m to 3900 m at the Leh valley (Fig. 4h). Among the spring wells, 70% (60 wells) were selected as training data set for GWPZ mapping using FR model and remaining 30% (26 wells) were selected as testing data set for validation of model on the basis of random dividing method (Lee et al., 2012).

3.3. Groundwater potential zone mapping

The groundwater potential zone (GWPZ) indicates the groundwater potentiality in quantitative form i.e. high GWPI indicates high groundwater potentiality whereas low GWPI indicates low groundwater potentiality. In this study the GWPI were derived by integration of all thematic data layer using raster calculator tool in Arc GIS 10 using Eq. (2):

$$GWPI_{FR} = \sum (lu_{FR} + hg_{FR} + sl_{FR} + ge_{FR} + ld_{FR} + dd_{FR} + gl_{FR}) \quad (2)$$

where, $GWPI_{FR}$ = Groundwater Potential Index using frequency ratio method.

lu_{FR} – frequency ratio of land use and land cover; hg_{FR} – frequency ratio of hydro geomorphic feature; sl_{FR} – frequency ratio of slope; ge_{FR} – frequency ratio of geology; ld_{FR} – frequency ratio of lineament density; dd_{FR} – frequency ratio of drainage density; gl_{FR} – frequency ratio of groundwater level.

4. Results and discussion

The various categories in each thematic map as well as their distributions are as follows; in land use and land cover category, the most part of the study area is covered by rocky terrain (80%), mix agricultural land (7.49%), built up land (6.85%), and sandy area (5.01). The hydro geomorphological features are an important input to the FR model. In this category, the structural hills cover a larger part of the study area (59.31%), whereas denudational hills cover 16.75% and the river bed occupied 0.87% of the area. Lithologically, maximum area was covered by granitoid rocks (74.48%) and the remaining area covered by recent sedimentary formations. In the study area, the groundwater level is varying from shallow to deep. However, most of the area falls in moderate to deep groundwater level ranging from 15 m to 34 m respectively. The steep and moderate slope categories cover totally

Table 2 Frequency ratio value of different thematic attributes for groundwater potential mapping.

Thematic maps	Attribute details	No of pixel in a class	% of pixel in a class	No of pixel of wells	% of pixel of wells	Frequency ratio
Land use and land cover	River bed	11,090	0.63	0	0.00	0.00
	Mixed agricultural land	130,864	7.49	54	90.00	12.02
	Built up land	119,714	6.85	4	6.67	0.97
	Rocky terrain	1,398,377	80.02	2	3.33	0.04
	Sandy wasteland	87,543	5.01	0	0.00	0.00
Hydro geomorphic features	Deep buried pediment	256,466	14.68	57	95.00	6.47
	River bed	15,216	0.87	0	0.00	0.00
	Valley fill	48,270	2.76	0	0.00	0.00
	Buried slope	98,298	5.62	0	0.00	0.00
	Denudation hill	292,883	16.76	0	0.00	0.00
	Structural hill	1,036,455	59.31	3	5.00	0.08
Slope	0–11.34656	408,257	23.36	47	78.33	3.35
	11.34657–21.07219	380,010	21.74	8	13.33	0.61
	21.07220–29.98734	452,615	25.90	4	6.67	0.26
	29.98735–39.17266	365,731	20.93	1	1.67	0.08
	39.17267–68.88984	140,975	8.07	0	0.00	0.00
Geology	Granitoid	1,377,608	78.83	3	5.00	0.06
	Fluvio-glacial deposits	256,466	14.68	57	95.00	6.47
	Quaternary sedimentary	113,514	6.50	0	0.00	0.00
Lineament density	0–0.38347	77,451	4.43	26	43.33	9.78
	0.38348–1.02770	342,828	19.62	10	16.67	0.85
	1.02771–1.64126	594,345	34.01	12	20.00	0.59
	1.64127–2.31617	483,111	27.64	11	18.33	0.66
	2.31618–3.91142	249,853	14.30	1	1.67	0.12
Drainage density	<1.16919	17,018	0.97	0	0.00	0.00
	1.16920–1.96917	496,013	28.38	0	0.00	0.00
	1.96918–2.66659	639,701	36.60	8	13.33	0.36
	2.66660–3.38452	464,859	26.60	23	38.33	1.44
	3.38452–5.25113	129,997	7.44	29	48.33	6.50
Groundwater level	Shallow	122,673	7.02	9	15.00	2.14
	Medium	428,857	24.54	21	35.00	1.43
	Deep	821,718	47.02	30	50.00	1.06
	Very deep	374,340	21.42	0	0.00	0.00

69.92% of the area and gentle slope covers 30.08%. In lineament density, the high lineament density covers 51.43% of the area which indicates that these lineaments are acting as a transmitting medium for groundwater. The high, medium and low classes of drainage density covered the area of about 9.19%, 19.48%, and 71.59% respectively. Structural features like faults and fractures controlled the drainage systems in the study area and these drainages act as a transmitting medium for glacial melted water movement into the subsurface.

FR values were estimated from each thematic layer on the basis of the relationship with spring wells. The relationship between hydro geomorphic features and groundwater potentiality shows deep buried pediment region having the high FR value of 6.47 than other features. The results also show the FR value of lineament density of 9.78. The FR value of the slope is found to be gradually decreasing with the increasing the degree of slope. Among the geological units fluvio-glacial deposits have highest FR value of 6.47 and indicated the high possibility of the presence of groundwater in this feature. The relationship with drainage density reveals that high FR value is concentrated among the high and very high density zones. The relation with groundwater level also shows the FR value is decreasing with the increasing of depth of the groundwater level. The FR value of different thematic layers and its classes are shown in Table 2. From the FR model the GWPZ mapping is prepared in the study area and the details are discussed in the following in sub headings.

4.1. FR Model for groundwater potential zone mapping

FR model provides values of GWPI ranging from 0.21999 to 46.72999. It was classified into five potential classes based on Jenks (1967) natural breaks classification method, i.e., very low, low, moderate, high and very high (Fig. 5) and each class is occupied in the study area 71.66%, 12.05%, 8.51%, 4.59%, 3.19% of total study area respectively (Table 3). The mean and standard deviation of this model are 6.99325 and 9.21219. It is notable that most of the high and very high potential zones are located in the central part of this study area due to the presence of high lineament density, high drainage density, lower slope, and porous nature of surface and subsurface which was composed of boulder, gravel, sand in deep buried pediment deposit (Agarwal and Garg, 2016; Kolawole et al., 2016; Liu et al., 2015; Kumar et al., 2014; Khodaei and Nassery, 2013; Nag
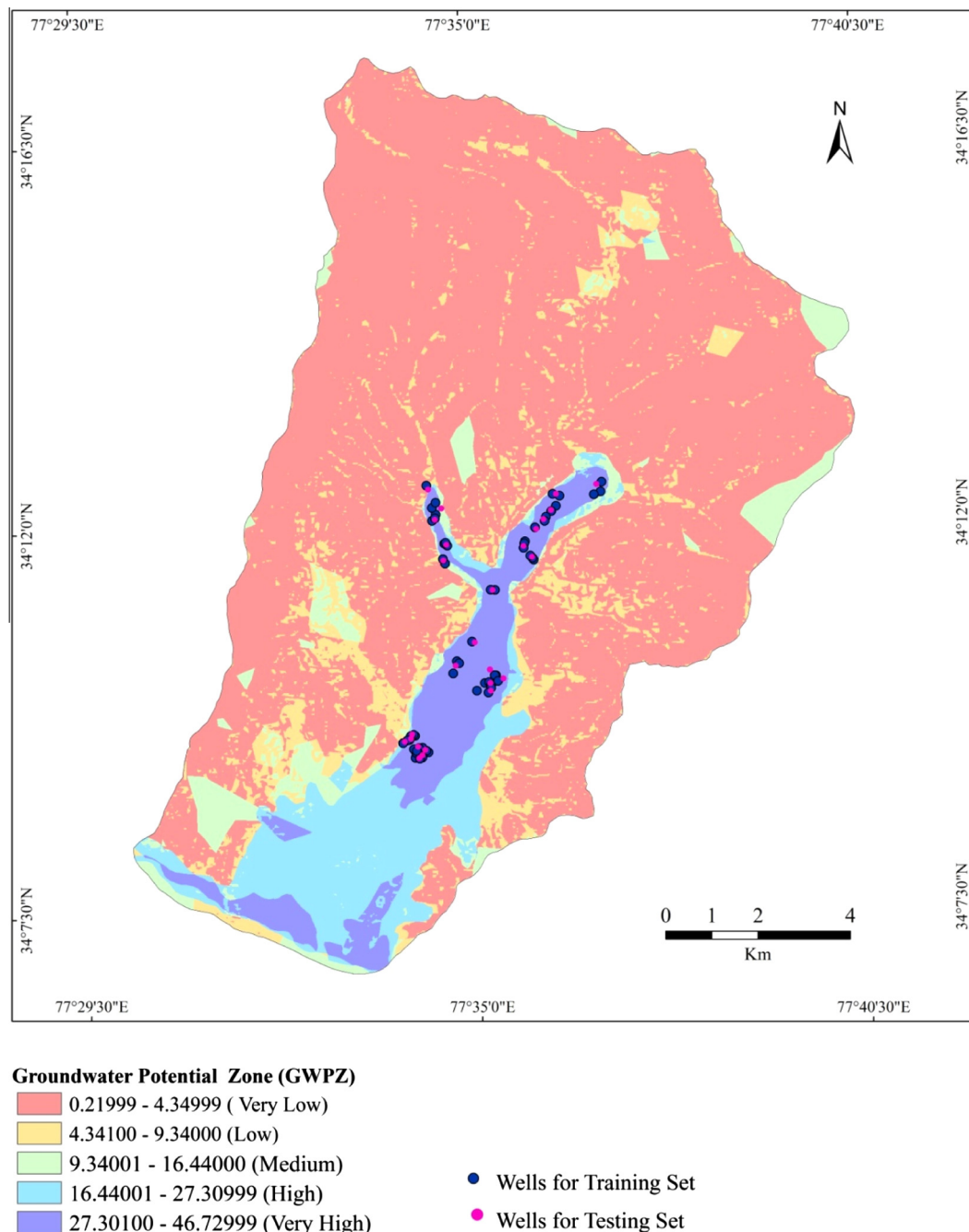
Figure 5 Groundwater potential zonation map derived from FR method.

and Ghosh, 2013). The high lineament density and low slope categories influence the infiltration of water into the ground in the presence of deep buried pediment deposit in the study area. The deep buried pediment formation is acting as a groundwater accumulation zone in the study area that receives water from snow or glacial covered area through fractures and drainages. The results also show that very high and high groundwater potential zones fall in high drainage density class, since the drainage systems in the study area were controlled by structural features like fractures/joints. These structural features were acting as a transmitting medium for infiltration of groundwater in the Leh valley. However, some of the earlier studies (Mogaji et al., 2011; Chowdary et al., 2009) show that

the high drainage density has possibility of low groundwater potential, which is due to the presence of massive rock or an impervious layer beneath it. However, the present study area is covered by fractured rock formation and drainage systems were controlled by those fractures moreover the drainage systems are acting as a source of groundwater recharge medium. The low and very low potential zones are found in the surroundings of this central part, where higher slope and the presence of lower drainage density made the region unfavorable for groundwater potentiality.

The integration was taken up both with all thematic data layers and also with its different combinations to evaluate the influence of different causative factors on groundwater

Table 3 Groundwater potential zonation derived from frequency ratio methods.

Groundwater potential zone	Class	No of pixel	Percentage (%) of area
Very high potential zone	27.31000–46.72999	55,669	3.19
High potential zone	16.44001–27.30999	80,058	4.59
Moderate potential zone	9.34001–16.44000	148,636	8.51
Low potential zone	4.35000–9.34000	210,360	12.05
Very low potential zone	0.21999–4.34999	1,250,875	71.66

Table 4 Statistics of different influencing parameters for GWPZ derived from FR analysis.

GWPZ parameters	Minimum	Maximum	Mean	Standard deviation
Excluding land use and land cover	0.17999	34.70999	5.99340	6.96896
Excluding hydro geomorphological features	0.21999	40.25999	5.99535	7.26510
Excluding slope	0.21990	43.38000	5.99419	8.39271
Excluding geology	0.15999	40.25999	5.99551	7.26315
Excluding lineament density	0.00000	36.95000	5.99276	8.81278
Excluding drainage density	0.21999	40.22999	5.99255	8.29210
Excluding groundwater level	0.21999	44.59000	5.99315	9.05292
Adding all parameters	0.21999	46.72999	6.99325	9.21219

potentiality index of the study area (Table 4). Standard Deviation (SD) values indicate that parameters which have high influence of groundwater potential are groundwater level (SD = 9.052), followed by lineament density (SD = 8.812), slope (SD = 8.392), drainage density (SD = 8.292), hydro geomorphology (SD = 7.265), geology (SD = 7.263), and land use and land cover category (SD = 6.968).

4.1.1. Validation of FR model
The AUC values range from 0.5 to 1.0, in which a value near to 1.0 indicate highest degree of accuracy and a value near to 0.5 indicates inaccuracy in the model (Fawcett, 2006). On the basis of the relationship of AUC value and prediction accuracy, it can be divided into the following classes: 0.9–1.0 (excellent), 0.8–0.9 (very good) 0.7–0.8 (good), 0.6–0.7 (average) and 0.5–0.6 (poor) (Naghibi et al., 2015). In the present study, the success and prediction rate curves were measured using area under curve value (AUC) method (Fig. 6). From the AUC values calculated by using a training set of 60 spring wells to measure the success rate curve, it was observed that the success rate measured as 0.8125. However, success rate alone is not a suitable method to determine the prediction capacity of any model because success rate is calculated on the basis of training data set which has been already used for constructing the GWPZ model (Zabihi et al., 2016). Hence, the prediction rate curve was derived using test data set of 26 spring wells which were not utilized for preparation of GWPZ in the FR model. The prediction rate indicates the prediction capacity of the model as well as predictor variables to predict GWPZ (Lee and Pradhan, 2007). The AUC value of

prediction rate curve is 0.7723. Thus, considering AUC value of success rate curve and prediction rate curve, it can be concluded that the model gives very good results in the present research.

4.2. Water budget of Leh valley

Traditionally, Ladakh systems water consumption and sanitation are in harmony with nature. The compost pit toilets used by local community required no water and hence, no drains either. Contemporary lifestyles require high consumption of water and consumption for people from outside this ecologically sensitive region is exponentially more than what it would be for the native Ladakh community. For example, flush toilets, which are non-existent till a decade or so back, use as much as 15 l of water per use and are most certainly a contributor to the growing demand for water in the Leh town. The guesthouse owners meet the increase in water demand by indiscriminate and uncontrolled digging of bore wells, as observed in fields. According to Public Health and Engineering (PHE) Department of Ladakh Autonomous Hill Development Council (LAHDC) Leh, the daily demand of water would be around 50 l/d for the resident population. But it could rise to 75 l/d on average due to increase of incoming tourists. Since, the floating tourist population is fluctuating; determination of exact figure of water consumption is very difficult. For the water budget calculation, average monthly supply of water and average monthly demand of water are taken into consideration. Total demand of water in May, June, July, August, and September months are 79,794,964, 83,984,400, 92,644,242, 85,558,842, and 75,495,857 l respectively. The total supply of water to the local communities by PHE for each month from May to September was 82,650,750 l/month. So, the total demand for water is higher than the total water supply in June, July and August months. The probability of water deficiency is high in August and less in September. The probability for water deficiency in the Leh valley due to increased influx of tourist population is roughly estimated to 58.71% (Table 5). To meet the demand of water during the tourist season the local community mainly depends on groundwater, observed to be extracted from bore or tube wells. In these circumstances there is requirement for sustainable development of groundwater resources in the area.

4.3. Sustainable groundwater management

The present scenario at the Leh area calls for implementation of sustainable aquifer replenishment program in the valley. In this situation, constructing artificial recharge structures is an important method of groundwater harvesting. Based on the parameters such as groundwater level, natural gradients from
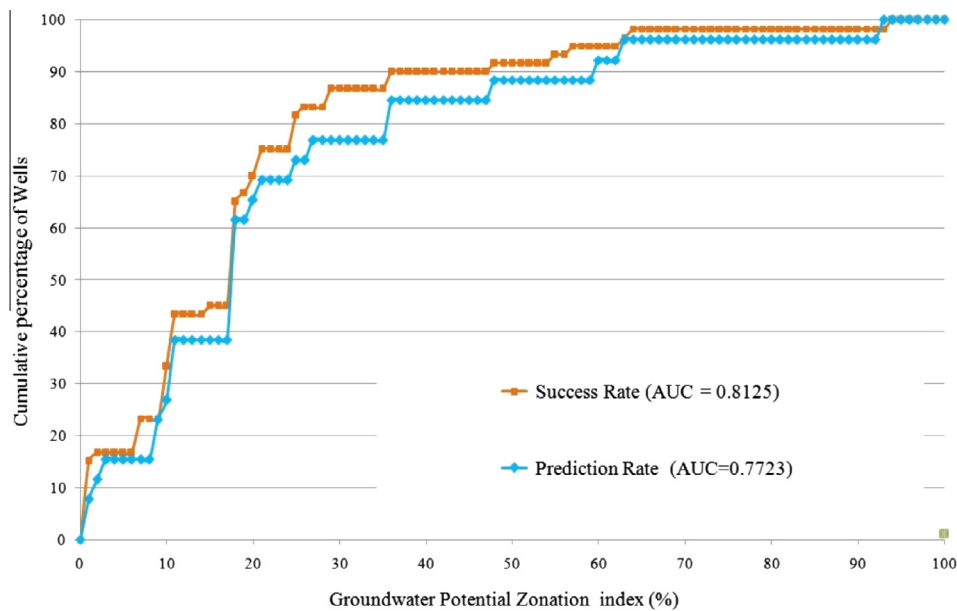
Figure 6 Validation derived from AUC method.

Table 5 Water budget measurement of Leh valley.

Months	May	June	July	August	September	May–September
No. of tourists	26,310	33,908	46,843	37,756	20,883	165,650
Average minimum days of stay	5	5	5	5	4	4.8
Most likely number of days of stay	7	7	8	7	6	7
Average maximum days of stay	9	10	10	9	8	9.2
Water consumption by tourists (in l)	13,248,694 ± 2,723,343	17,438,400 ± 4,262,651	26,098,242 ± 6,368,261	19,012,842 ± 3,908,117	8,949,857 ± 2,161,595	83,061,642 ± 18,861,044
Total demand (in l)	79,794,964	83,984,400	92,644,242	85,558,842	75,495,857	417,478,307
Total water supply (in l)	82,650,750	82,650,750	82,650,750	82,650,750	82,650,750	413,253,750
Water deficit[*] (in l)	−2,855,786	−1,333,650	−9,993,492	−29,082,092	+ 7,154,893	−4,224,557

[*] − symbol indicates for shortfall of water supply and + symbol indicates for over flow of water supply.

Table 6 Suitable sites for artificial recharge for sustainable groundwater management through natural gradient.

Sl. No.	Well location	Ground water potential	Well elevation (in m)	Nearest spring elevation (in m)	Difference of elevation (in m)	Distance between nearest spring and well (in m)
1	Ibex Colony	Moderate (12.68–23.78)	3370	3420	50	1075.73
2	Skalzanglig	Very high (34.10–46.13)	3340	3400	60	1531.72
3	Chengspa	Very high (34.10–46.13)	3535	3540	5	716.71
4	Skara Yokma	Very high (34.10–46.13)	3395	3400	5	221.56
5	Skara	Very high (34.10–46.13)	3380	3400	20	540.83
6	Karzo	Very high (34.10–46.13)	3525	3530	5	104.80
7	Chubi	Very high (34.10–46.13)	3530	3540	10	112.70

spring well source to artificial recharge locations, groundwater exploitation from existing wells, and subsurface lithology, seven highly favorable locations were identified for artificial recharge for sustainable groundwater management (Table 6). The groundwater level in these sites varies from 6 m to 24 m which are falling in shallow and medium groundwater level zones. The shallow water level area is also considered for long term sustainable development of groundwater of Leh. The deep and very deep groundwater level zones can be suggested to minimize the utilization of groundwater resources. To fulfill the water demand of locals in such unfavorable regions, the water should be distributed through motor pumps from springs or shallow aquifers. The subsurface information was obtained from bore well cross-section to be considered to develop the artificial recharge through a natural process. The source of artificial recharge from springs to recharge wells are identified using proximity analyses and the considered distance between both locations < 1600 m. The spring locations are located at higher elevations than the artificial recharge wells, so that, the recharge wells get water through a slope gradient by natural processes. The elevation difference between the spring and the recharge wells varies from 5 m to 60 m. Considering the above condition, Ibex Colony, Skalzangling, Chengspa, Hospital, Skara-Yokma are ideal locations for recharging water naturally from springs.

5. Conclusions

Based on this study, it is concluded that the very high and high GWPZ in the region is located in the valley portion of Leh. During the field visits, it has been observed that there is a possibility of more development in this sensitive region in terms of construction of built-up area in the near future due to migration of local and tourist populations. In this regard, to get the drinking and domestic usable water, they will depends on bore or tube wells. Now a days drilling of bore wells is an unregulated activity in Leh, and this needs to be brought under LAHDC regulations with a thorough and efficient monitoring of bore wells. The spring well locations need to be conserved and protected and these sources should be optimally utilized in order to meet the water requirement of the community living in its vicinity. Spring maintenance and management should be a community based process that means local community should take necessary step to conserve it along with local government agent. The Leh community has historically led a life of self-subsistence and probably it is just the right time to make a proper action for community based groundwater management in this region.

Acknowledgements

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