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RESEARCH ARTICLE

Assessment of groundwater potential zones in an arid region based on catastrophe theory

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Abstract Evaluation of groundwater potential is a multi-criteria and multi-level comprehensive assessment system that needs judgment of decision makers in making decision. To avoid subjectivity or the preference of decision makers in the assessment, catastrophe theory based evaluation method is proposed in this study which calculates the importance of one criterion over other by its inner mechanism and thus, avoid subjectivity. The proposed method is applied for the assessment of groundwater potential zones in the arid region of lower Balochistan province of Pakistan. The groundwater is considered as a system with five sub-systems namely, geology, soil, drainage density, slope and rainfall. Seventeen sub-system indicators of groundwater potential are selected for modeling groundwater potential zone. The catastrophe theory is applied to derive the relative weights of indicators in predicting groundwater potential. Thematic maps of sub-systems are integrated within a geographical information system and the groundwater potential zones of the integrated layer are calculated by using the weights of indicators. The results are verified by existing number of tube wells operating in the study area. It has been found that the number of tube wells is more in the area where the groundwater potential is high. The study reveals that catastrophe theory is suitable for assessing groundwater potential.

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Introduction

Groundwater is recognized as one of the most important and dependable sources of water supply in all climatic regions across the world (Todd and Mays 2004). In the arid region like Balochistan province of Pakistan, groundwater plays the major role in food production and drinking water supply. A good knowledge of the occurrence and availability of groundwater is therefore necessary for the management of groundwater resources as well as to supply sufficient water to growing population. There are many factors affecting the occurrence and movement of groundwater, which include topography, lithology, geological structures, and depth of weathering, extent of fractures, primary porosity, secondary porosity, slope, drainage patterns, landform, land use land cover, and climate (Jaiswal et al. 2003). It is necessary to identify and quantify these factors for generating groundwater potential model for a particular area. A Geographic Information System (GIS) can be used effectively for this purpose to combine different hydrogeological themes objectively and analyze those systematically for demarcating groundwater potential zone (Shahid et al. 2000).

In the past many studies have been carried out for the delineation of groundwater potential zones. The application of GIS techniques in mapping groundwater potential has increased rapidly since early 1990s (Jha et al. 2007). It has been applied to demark groundwater potential zone in different parts of the world (Chi and Lee 1994; Krishnamurthy and Srinivas 1995; Sander et al. 1996; Ravindran and Jeyaram 1997; Edet et al. 1998; Shahid et al. 2000; Sankar 2002; Srinivasa Rao and Jugran 2003; Sikdar et al. 2004; Shankar and Mohan 2006; Jha et al. 2007, 2010; Madrucci et al. 2008;

Preeja et al. 2011; Rahman et al. 2012; Rashid et al. 2012; Jasrotia et al. 2013). In GIS modelling, weights are assigned to obtain the relative importance of one criterion over the other. Several weighting methods have been developed for this purpose, which are mainly classified as subjective and objective methods. In subjective weighting methods, the weights are derived according to the knowledge and preferential judgment of decision makers. On the other hand, mathematical models are used to derive weights in objective weighting methods. In earlier studies of the delineation of groundwater potential zones, researchers have applied subjective weighting methods, such as, weighted linear combination (WLC) (Vijith 2007), Analytical Hierarchy process (AHP) (Chowdhury et al. 2009), weighted aggregation method (WAM) (Prasad et al. 2008), weighted sum model (WSM) (Preeja et al. 2011), etc. The groundwater potential models based on subjective weighting are heavily influenced by the preference and judgment of decision makers. To avoid subjectivity, we propose catastrophe theory to assign weights of different criteria in this study. The proposed catastrophe theory based evaluation method does not involve the decision maker's preference; it calculates the importance of one criterion over others by its inner mechanism and thus, greatly reduces the subjectivity (Yang et al. 2012). The catastrophe theory has been applied in different fields of sciences including hydrology, such as, discontinuities in hydrological data (Ghorbani et al. 2010), water security (Wang et al. 2012, Yang et al. 2012) water quality (Liang et al. 2012) and flood risk (Li 2011).

The main objective of the present study is to assess the groundwater potential zone by using catastrophe theory. The evaluation system of catastrophe theory is based on number of multiple criteria indicators. The main criteria selected in this study for the evaluation of groundwater potential zone are geology, soil, drainage density, slope and rainfall. The lower region of Balochistan province of Pakistan is selected as the study area.

Study area

Balochistan is a mountainous, desert and an arid province of Pakistan. The province is the lowest in terms of population and biggest in terms of area. The climate of the province lies in the region of arid and semi-arid, and the rainfall patterns vary from Mediterranean to monsoonal (Gils and Baig 1992). The rainfall is scanty and unevenly distributed. Flooding and water harvesting covers fifty percent of irrigation and the rest is carried out by canals, karezes, springs and groundwater. Groundwater is always considered as one of the most important sources of irrigation. Domestic water requirements are also largely met from groundwater (Khan and Mian 2000). The groundwater monitoring has revealed that the water level is depleting in many parts of the province (FAO 2002). Management of groundwater resources based on accurate information of groundwater potential is therefore necessary to achieve sustainability.

Balochistan is divided into several districts for administrative purposes. The area selected for the present study includes five districts of Balochistan namely, Panjgur, Kech, Gwader, Awaran and Lasbela. Figure 1 shows the location of study area in the map of Pakistan. The districts under study are situated in the lower part of Balochistan. The combined area of these districts is 95019.69 km^2.

The mean temperature of the study area is 24.8 C° and the annual average rainfall is 141 mm. The south-west monsoon is the main feature of precipitation climatology of the area which starts from June and lasts till September. The elevation of the area ranges from 1 m to 980 m above the mean sea level. The area is drained by number of major and minor rivers; most of those drained into Arabian Sea. The drainage pattern in the area is dendritic in nature.

Methodology

Catastrophe theory

Catastrophe theory is originated from the topology branch of mathematics. It was developed by French scientist Rene Thom in 1960s. The basic purpose of Catastrophe theory is to deal with the phenomena of discontinuity (Benham and Kozak 1976; Wang et al. 2011). The catastrophe method which is based on catastrophe theory draws on analytical hierarchy, utility function and fuzzy evaluation to obtain catastrophe fuzzy membership functions by normalized treatment of bifurcation set. The dependency of state variables on control variables is determined by catastrophic fuzzy membership functions, rather than weights assigned by the users. In addition, different control variables have different impacts on the state of variables in catastrophe theory (Feng et al. 2008; Wang et al. 2011). Initially, the system is divided into subsystems with different indicators according to the inner mechanism of system being assessed. The initial data is normalized using catastrophe theory and fuzzy mathematics to give optimal or cleanest data. The multidimensional catastrophe fuzzy membership functions assign values ranging from 0 to 1 to resolve incompatibility of various initial data (Wang et al. 2011).

There are seven catastrophe models namely, fold catastrophe, cusp catastrophe, dovetail catastrophe, butterfly catastrophe, swallowtail catastrophe, hyperbolic umbilical catastrophe and parabola umbilical catastrophe. The models are shown in

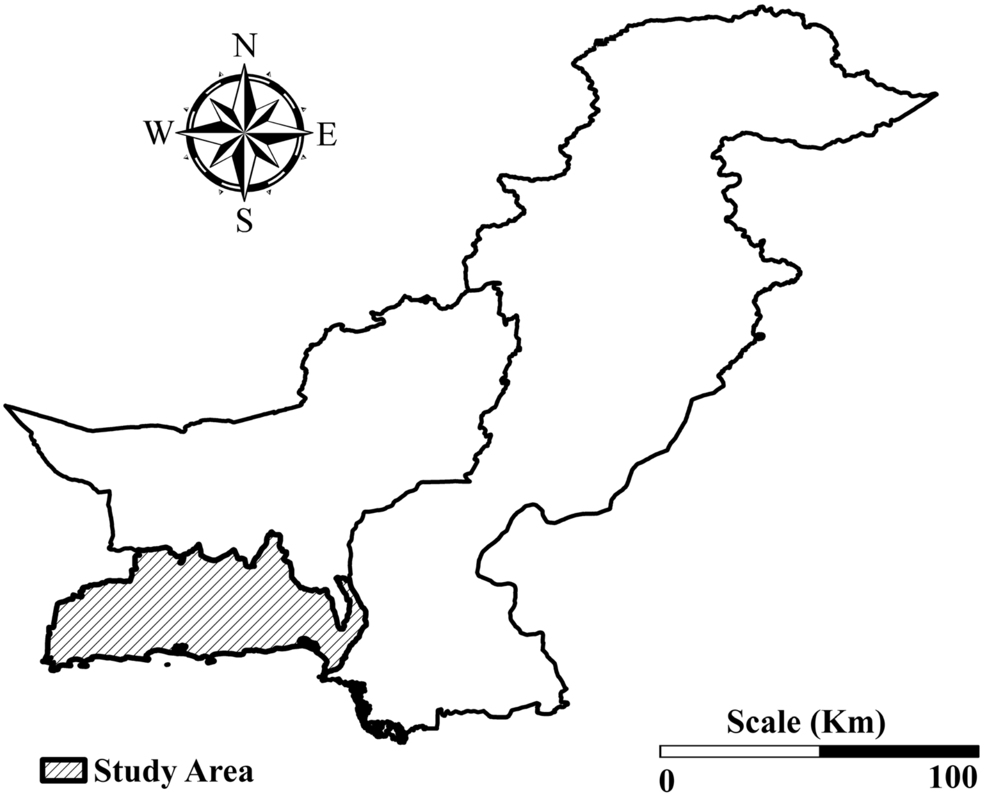


Fig. 1 Location of the study area in the map of Pakistan

Table 1, where x is state variable, and a, b, c and d are control variables (Wang et al. 2012).

Application of catastrophe theory in assessing groundwater potential zones

The catastrophe theory is applied to assess groundwater potential zones using following steps: (i) selection of indicators; (ii) standardization of data; (iii) normalization; and (iv) computation for groundwater potential zone. The steps are discussed below in details.

Selection of indicators

There are many factors which contribute to the occurrence and movement of groundwater, such as, geology, geomorphology, soil, drainage density, lineament density, surface water body, land cover, slope, rainfall, etc. The selection of indicators mainly depends on the objective of study. In the previous studies of groundwater potential assessment, various indicators were used for delineating groundwater potential zones which have significant influence on the occurrences of groundwater. The selection of number of indicators mainly depends on the availability of data, therefore the indicators varies from one study to another. However, the selection of appropriate indicators is very important in order to assess the groundwater potential zone accurately.

The occurrence and movement of groundwater are controlled mainly by porosity and permeability of the surface and underlying geology. The same lithology having different soil units will have variable porosity and permeability, thereby causing changes in the potential of groundwater. Surface

Table 1 Seven types of catastrophe models

Catastrophe model	Control parameters	State Variables	Potential function
Fold	1	1	$V_a(x)=1/3x^3+ax$
Cusp	2	1	$V_{ab}(x)=1/4x^4+1/2ax^2+bx$
Dovetail	3	1	$V_{abc}(x)=1/5x^5+1/3ax^3+1/2bx^2+cx$
Butterfly	4	1	$V_{abcd}(x)=1/6x^6+1/4ax^4+1/3bx^3+1/2cx^2+dx$
Oval umbilici point	3	2	$V_{abc}(x,y)=x^3-xy^2+a(x^2+y^2)+bx+cy$
Elliptic umbilici point	3	2	$V_{abc}(x,y)=x^3-xy^2+a(x^2+y^2)+bx+cy$
Parabolic umbilici point	4	2	$V_{abc}(x,y)=x^2y+y^4+ax^2+by^2+cx+dy$

hydrological features like topography, drainage density, etc., play an important role in groundwater replenishment. High relief and steep slopes impart higher runoff, while the topographical depressions help in an increased infiltration. An area of high drainage density experiences high surface runoff and low groundwater recharge compared to a low drainage density area. Hence, identification and quantization of these features are important in generating groundwater potential model of a particular area (Shahid et al. 2000). Considering the facts mentioned above, in the present study, the groundwater is considered as a system with geology, soil, drainage density, slope and rainfall sub-systems that define groundwater potential.

Each sub-system has its own indicators to show the potential for groundwater resources. The elements in the system and sub-systems have a strong relation with each other. For example, higher slope bears high drainage and results in less infiltration. Similarly higher drainage density results in low groundwater potential as it is an inverse function of permeability. The detail of the sub-systems and their indicators with codes are shown in Table 2. The indicators which have significant influence on groundwater potential are considered in this study.

Standardization of data

In multiple criteria decision making methods, different attributes or indices have different units of measurement. It is not possible to use the same units in analyzing data in the model. Therefore, standardization of data is necessary. The standardization process makes the data dimensionless. The following equations are used to standardize the attributes in the present study.

Table 2 Indicators of groundwater potential

Sub-system	Indicators	Code
Geology (B1)	Gravel	C1
	Alluvium	C2
	Mudstone/Sandstone/Limestone	C3
	Mixed Shale	C4
Soil (B2)	Loamy & Gravelly	C5
	Rocky & Gravelly	C6
Drainage Density (B3)	Low	C7
	Medium	C8
	High	C9
Slope (B4)	Low Slope	C10
	Moderate Slope	C11
	High Slope	C12
	Steep Slope	C13
Rainfall (B5)	Poor	C14
	Good	C15
	Moderate	C16
	Excellent	C17

The equation used for standardization of 'larger the better' indices:

$$x_i' = \frac{x_i - x_{i\ (min)}}{x_{i\ (max)} - x_{i\ (min)}} \tag{1}$$

The equation used for standardization of 'smaller the better' indices:

$$x_i' = 1 - \frac{x_i - x_{i\ (min)}}{x_{i\ (max)} - x_{i\ (min)}} \tag{2}$$

where, *i* is the index or attribute, x_i is the original value of *i*, and $x_{i\ (max)}$ and $x_{i\ (min)}$ are maximum and minimum values.

In the present study, geology, soil and rainfall are considered as "larger the better" indices because higher values of those indices indicate higher groundwater potential. For example, higher values of geology and soil mean higher specific yield and porosity which may results in higher potential for groundwater. Similarly, the higher values of rainfall indicate more possibility of groundwater recharge and therefore, more potential for groundwater. On the other hand, the slope and drainage density are considered as "smaller the better" indices as higher slope and drainage density are favorable for high run-off and low groundwater recharge, and hence indicates low potential for groundwater.

Normalization for catastrophe theory

Generally, normalization of raw data is done after dividing the system into subsystems. Normalization formula is the basis of catastrophe model. The formulas used for normalizing catastrophe model are given in Table 3.

The catastrophe progression of each control variable can be computed from the initial fuzzy subordinate function based on normalization formulas. During the process of computation, two principles are applied, i.e., a complementary and a non-complementary principle (Wang et al. 2011; Zhang et al. 2009). The non-complementary principle means the control variables of a system, such as a, b, c, and d, cannot offset each other. Therefore, when finding the value of the state variable x using the normalization formulas, the smallest of the state variable values corresponding to the control variables, i.e., $x=\min\{x_a, x_b, x_c, x_d\}$ is chosen as the state variable value of the whole system. On the other hand, the complementary principle implies that the control variables complement each other so that each of them tends to reach the average value, i.e., $x=(x_a+x_b+x_c+x_d)/4$ (Zhang et al. 2009). In the present

Table 3 Normalization formulas for catastrophe theory (Ching-Hsue et al. 1996)

Control Variable	State Variable	Name	Normalization formula
2	1	Cusp	$x_a=a^{1/2}$ and $x_b=b^{1/3}$
3	1	Swallowtail	$x_a=a^{1/2}$, $x_b=b^{1/3}$ and $x_c=c^{1/4}$
4	1	Butterfly	$x_a=a^{1/2}$, $x_b=b^{1/3}$, $x_c=c^{1/4}$ and $x_d=d^{1/5}$
5	1	Wigwam	$x_a=a^{1/2}$, $x_b=b^{1/3}$, $x_c=c^{1/4}$, $x_d=d^{1/5}$ and $x_e=e^{1/6}$

study, complementary principal is used to compute the catastrophe progression of each control variable.

Computation of groundwater potential zones

In order to assess the groundwater potential zones, initially the maps of geology, soil, drainage density, slope and rainfall are generated by using ArcGIS. The overlay tool in ArcGIS is used to identify the groundwater potential index in the study area. The groundwater potential index is calculated in ArcGIS by the following equation:

$$GWPI = G_wG_r + S_wS_r + D_wD_r + E_wE_r + R_wR_r \tag{3}$$

where, G, S, D, E, and R represent geology, soil, drainage density, slope, and rainfall, respectively. The subscripts, w and r represent weight and rank, respectively. Catastrophe theory discussed above is used to calculate weights and ranks.

Results and discussions

Preparation of maps

To identify the groundwater potential zone, the maps of geology, soil, drainage density, slope and rainfall are prepared in ArcGIS. The geology and soil maps are prepared by digitizing the existing geology and soil maps of Balochistan obtained from the ATLAS of Pakistan. The drainage density and slope maps are prepared from ASTER DEM data while the rainfall map are prepared by interpolating the annual rainfall recorded at 11 rainfall stations distributed over the study area. For this purpose, the average rainfall data are collected from Pakistan Meteorological Department. The data for the number of tube-wells operating in each district of the study area are obtained from Agricultural statistics of Balochistan 2010–2012 (Agricultural statistics of Balochistan, 2011). The preparation of maps is described below.

Fig. 2 Geology of the study area

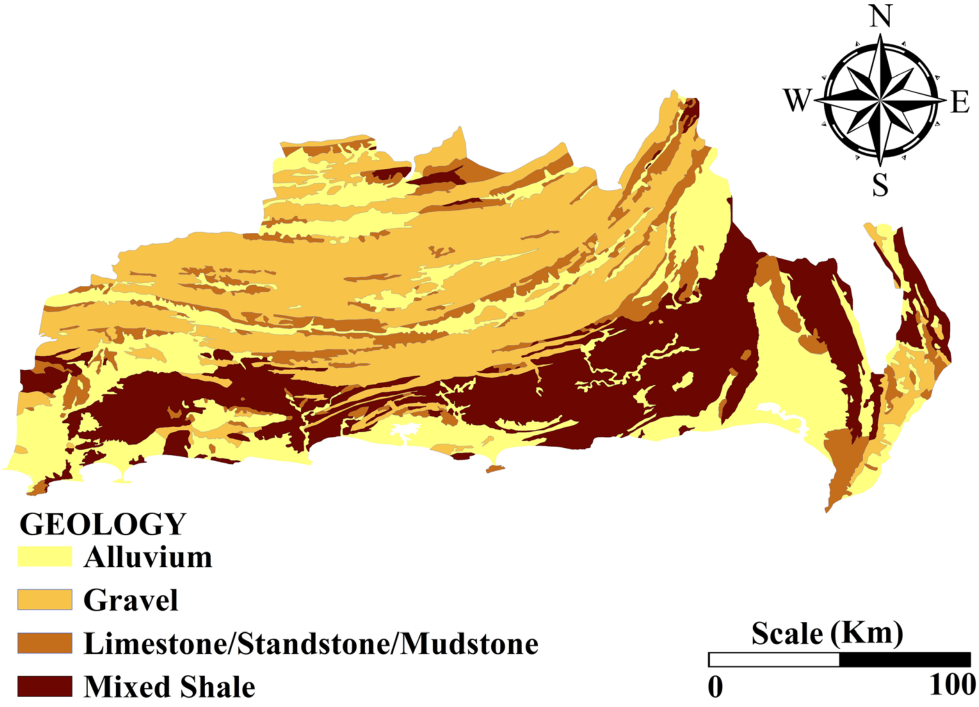
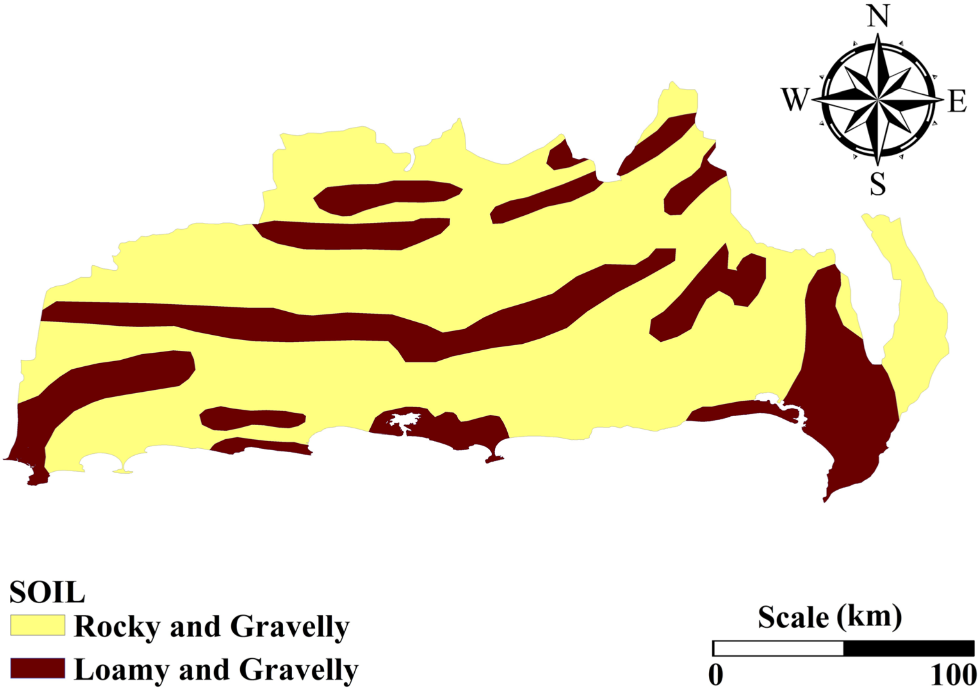


Fig. 3 Soil map of the study area



Geology

The geologic map of study area is prepared by digitizing the existing geological map of Balochistan in ArcGIS. The geological map of the study area is shown in Fig. 2. Four geologic formations are observed in study area namely, (i) alluvium, (ii) gravel, (iii) mixed shale, and (iv) mudstone-sandstone-limestone.

The mixed shale is found to dominate over other formations. It found to occur in 35.73 %. One the other hand, gravel is found

Fig. 4 Drainage density map of the study area

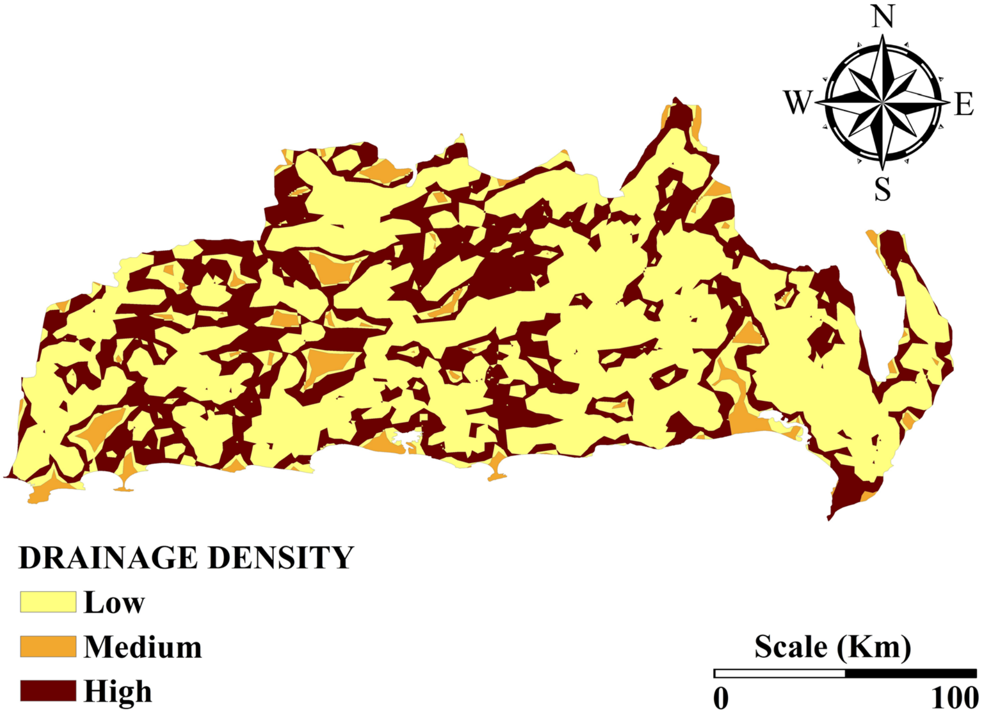
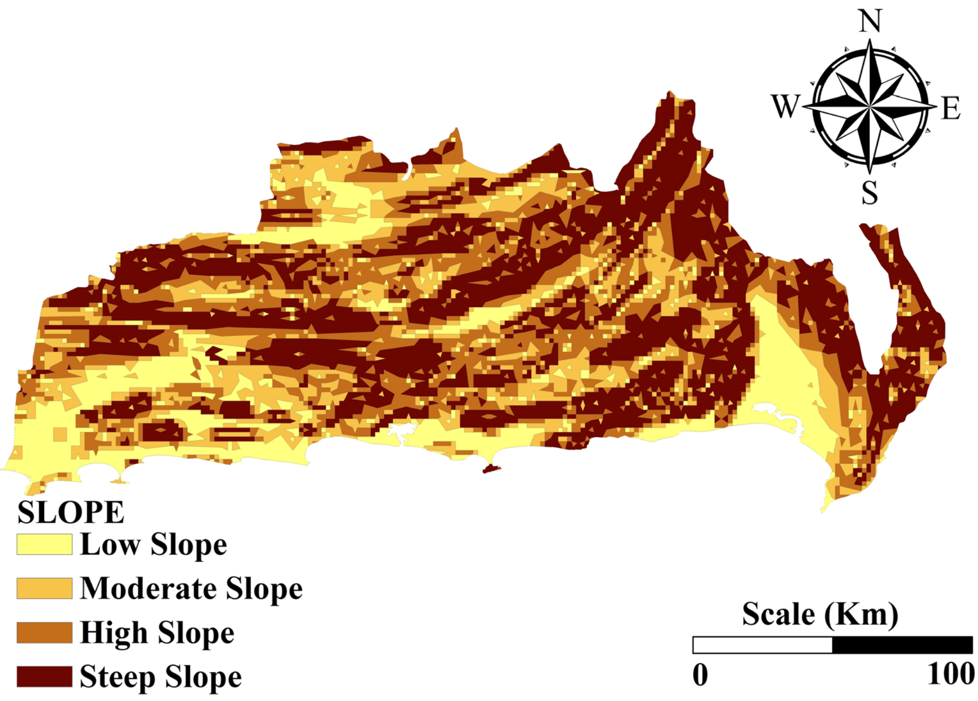


Fig. 5 Slope map of the study area



to occur only in 11.78 % area. The geologic formations are scattered in different parts of study area. The hydrogeological properties of these formations differ from each other as they mostly depend on the compactness of pores. The gravel is considered as most suitable for groundwater potential as it is highly porous, and has high permeability and specific yield values.

Soil map

The soil map (Fig. 3) is also prepared from the existing soil maps of Balochistan of Pakistan. The figure shows that the study area is covered by two types of soil: (i) loamy gravelly soil and (ii) rocky loamy gravelly soil. About 72 % of the total area is covered by rocky gravelly soil. The loamy gravelly

Fig. 6 Map showing distribution of annual rainfall in the study area

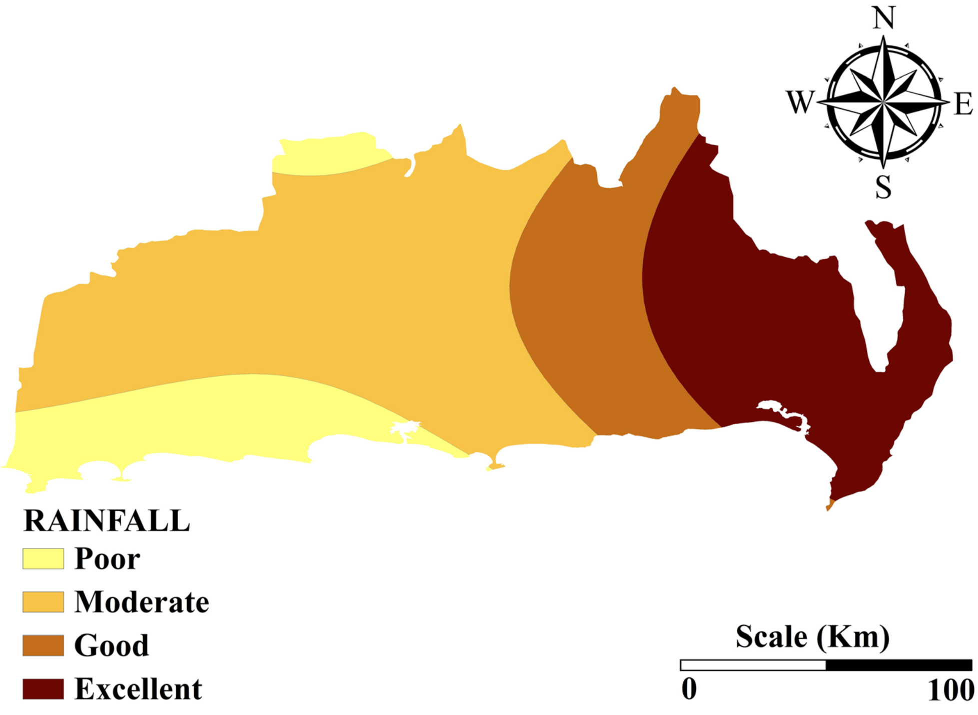


Table 4 Calculated values of the indicators of groundwater potential

Sub-system	Indicators	Index Value	Standardized Value
Geology (B1)	Gravel	0.24	0.61
	Alluvium	0.275	0.76
	Mudstone/Sandstone/Limestone	0.33	1.00
	Mixed Shale	0.1	0.00
Soil (B2)	Loamy & Gravelly Soil	0.58	1.00
	Hilly & Gravelly Areas	0.24	0.00
Drainage Density (B3) (%)	Low	0.001	1.00
	Medium	0.025	0.51
	High	0.05	0.00
Slope (B4) (%)	Low Slope	0.025	1.00
	Moderate Slope	0.075	0.67
	High Slope	0.125	0.33
	Steep Slope	0.175	0.00
Rainfall (B5) (mm)	Poor	102.33	0.00
	Good	118.33	0.24
	Moderate	140	0.57
	Excellent	168	1.00

soils are scattered in different places of the area. The rocky gravelly soil cannot hold water and the water usually drains very easily from this type of strata. Loamy soil, on the other hand, can retain moisture and absorb water. The permeability of gravelly soil is high compared to loamy soil.

Drainage density

The drainage density map of the study area is prepared from the drainage map and shown in Fig. 4. The drainage density of the study is classified into three classes: (i) low drainage area with density less than 2 %, (ii) medium drainage area with density between 2 % and 5 %, and (iii) high drainage area with density above 5 %. It can be seen from the map that low drainage areas are dominant in the study area.

Slope

Steep slopes impart higher runoff, while the topographical depressions help in an increased infiltration. Therefore slope plays an important role in groundwater recharge and defines groundwater potential. The slope map of the study area, shown in Fig. 5 is prepared from ASTER DEM data. The slopes in the area are classified into four classes: (i) low slope (<5 %), (ii) moderate slope (5 % to 10 %), (iii) high slope (10 % to 15 %), and (iv) steep slope (>15 %). It can be seen from the figure that the slopes in most parts of the study area are belong to moderate class, ranges between 5 % and 10 %.

Rainfall

Rainfall plays major role in recharging groundwater. Therefore, areas with higher rainfall are generally considered

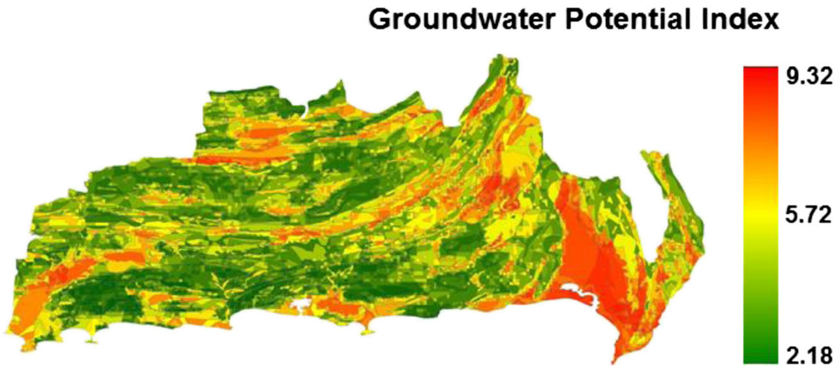


Fig. 7 Map showing groundwater potential of the study area

Table 5 Number of tube-wells in different districts of the study area (Agricultural statistics of Balochistan 2011)

District	No. of Tube wells
Awaran	2,915
Gwader	138
Lasbela	2,101
Panjgur	1,481
Turbat	134

as potential zone for groundwater exploitation. The rainfall map of the study area is prepared by interpolating the annual rainfall recorded at 11 rainfall stations distributed over the study area. The rainfall map of the study area is shown in Fig. 6. According to annual rainfall amount, the study area is divided into four classes: (i) low rainfall zone with rainfall less than 110 mm, (2) moderate rainfall zone with rainfall between 110 mm and 140 mm, (3) good rainfall zone with rainfall between 140 mm and 170 mm, and (4) excellent rainfall zone with rainfall is more than 170 mm.

Application of Catastrophe theory for demarking Groundwater potential zones

The sub-systems and their indicators, and the average values of the indicators for the whole area are given in Table 4. The indicator values are standardized (given in fourth column of Table 4) to calculate the weights of sub-system using normalized formulas of catastrophe theory. According to Table 4, the indicators of groundwater sub-systems namely geology, slope and rainfall meet the butterfly model, indicators of soil meet the cusp model, and indicators of drainage density meet the swallowtail model. The index values for the geology in Table 4 are the specific yields of groundwater by different geological units, such as, gravel, alluvium, etc. The index values for soil are the porosity of different soil features. The specific yields of geological units and porosity of soil features are taken from USGS standards. The index values for drainage density, slope and rainfall are the average values for different classes observed in the study area. The index values are standardized according to Eqs. 1 and 2. For example, the indicator gravel in the Table 4 has an index value of 0.24 which lies in sub-system geology. In geology $x_{i\ (min)}$ is mixed shale which has an index value of 0.1 and $x_{i\ (max)}$ is mudstone/sandstone/limestone which has an index value of 0.33. The sub-system geology is considered as "larger the better" index and therefore, Eq. 1 is used for standardization which produced a value of 0.61.

After standardization of raw data, the normalized values are obtained from normalization formulas of Catastrophe theory given in Table 3. For example, the values of the indicators of geology sub-system are calculated using the butterfly model as, XC1=((0.6)^0.5)=0.8, XC2=((0.76)^0.33)=0.9, XC3=((1)^0.25)=1, and XC4=(0)^0.2)=0. The average of the indicators of geology sub-system, B1=(XC1+ XC2+ XC3+ XC4)/4=0.67. Similarly applying the same procedure, we get B2=0.50, B3=0.60, B4=0.66 and B5=0.61. The values are then ranked from 1 to 5. As geology has the highest

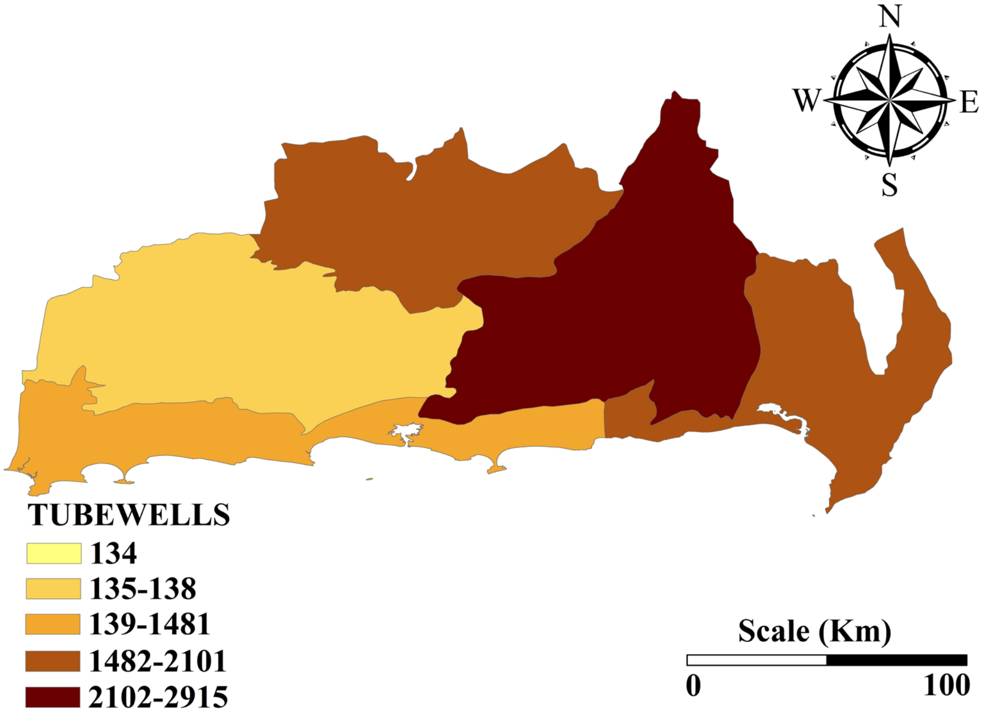


Fig. 8 District-level distributions of operating tube-wells in the study area

value, it is ranked as 5. Slope is ranked as 4, drainage density is ranked as 3, rainfall as 2 and the soil as 1. The values for geology, soil, drainage density, slope and rainfall are inserted in Eq. 3 to calculate the groundwater potential index (GWPI) using the overlay tool of ArcGIS.

After integrating the maps of geology, soil, drainage density, slope and rainfall using Eq. 3 in ArcGIS, the map of groundwater potential is obtained which is shown in Fig. 7. The integrated map of groundwater potential zone produced 336 polygons; each polygon has a value within a range of 2.18 to 9.32 which indicates groundwater potential of that polygon. The higher values indicate high potential for groundwater, while the lower values indicate poor groundwater potential. Therefore, the red colored zones in the map have high groundwater potential, the yellow colored zones have moderate groundwater potential, and the green colored zones are poor in groundwater potential.

The map shows that groundwater potential in the study area varies widely within a short distance. Most parts of the study area have high as well as low groundwater potential zones. However, the study indicates that overall, the east part of the study area is more potential to groundwater resources compared to other parts.

Validation

No study has been carried out so far to reveal groundwater potential of the region. Therefore, it is not possible to verify the obtained results with the findings of previous studies. In the present study, the groundwater potential zone map is verified by comparing it with the map of number of operational tube-wells in the study area considering that more tube-wells are operating in high potential zone. The number of tube wells in each district is shown in Table 5. A map showing the district level distribution of tube-wells in the study area is shown in Fig. 8.

The number of tube wells in Awaran and Lasbela districts are found high. When compared with groundwater potential zone map, it is observed that high and very high groundwater potential zones are situated in these two districts. Similarly, the number of tube-wells is found to be less in Turbat and Gwader districts where groundwater potential is very low. This indicates the efficacy of the proposed method in mapping groundwater potential.

Conclusion

This paper presents the results of the study carried out for the assessment of groundwater potential zones by using catastrophe theory. The catastrophe theory is used to reduce the subjectivity in groundwater potential zone assessment. The application of the method in lower regions of Balochistan reveals that groundwater potential zone is high in Awaran and Lasbela districts, moderate in Panjgur, and low in Turbat and Gwader districts. There are many hydrological and hydrogeological factors that define groundwater potential. In the present study, five factors are considered to prepare the map groundwater potential zone. The study reveals that the catastrophe theory can reduce the subjectivity in groundwater potential zone assessment. It can also identify the groundwater potential zone efficiently.

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