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A GIS-Based Modelling for Identifying High Priority Areas for Groundwater Recharge

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Abstract: At semi-arid areas that dominant portion of required water for agriculture is provided by exploitation of groundwater, these resources encounter with more deterioration. Thus identifying of potential runoff generating sites and estimation of runoff depth can be a significant step for storing runoff for agricultural activities and groundwater recharge. The main purposes of this study are use of GIS (geographic information system) ability for identifying of potential runoff generating sites, and thus identifying high priority areas for groundwater recharge in the Gharehchay River watershed in the north of Hamedan province, Iran. Potential runoff generating sites were identified by using watershed features same as slope, land use and hydrological soil groups. Afterward, CN I (Curve Number I) technique, which is one of the eight derivations of the NRCS-CN (natural resources conservation services curve number) method, was utilized to calculate rainfall-runoff depth in the study region. Finally, map layers were ranked in order of highest priority to lowest priority, based on the criteria of each dataset, and high priority areas for groundwater recharge were identified by integrating potential runoff map, runoff depth and depth to groundwater maps. Spatial analysis revealed that 51% of the study region has a high priority for groundwater recharge.

Key words: GIS, runoff potential map, runoff depth estimation, groundwater recharge, high priority maps.

1. Introduction

In semi-arid regions, prediction of temporal and spatial distribution of rainfall is difficult. As a result, appropriate management of the resulting runoff is highly significant [1]. Two factors are main reason of water scarcity in these areas: (1) a small fraction of rainfall infiltrates to the root zone, and (2) the successive happening of dry storms in the middle of the season, that therefore lead to the water scarcity during the growing season [5]. Owing to these conditions runoff storing is extremely important since rainfall-runoff can be stored and efficiently used to preserve sustainable agricultural [2]. In addition, efforts made to save rainfall-runoff could increase growing crop varieties, which are limited to rainfed varieties due to water scarcity and deficiency of irrigation resources [3]. However, runoff harvesting activities may have some negative effects on downstream of regions, where runoff storing is happening. These consequences comprise the lake of water to rivers downstream and have detrimental effects on ecosystem and other water users [4]. Different types of surface runoff including; sheet, rill, gully and stream flow are utilized for runoff harvesting [5]. As an important surface water system, river flow has significant influence on many other environmental systems and, also on quality of human lives. For example, a healthy river flow system maintains the water supply to lakes, ponds and other water bodies [6]. In return, there are different structures for confining water in fields, including farm

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dams or reservoirs, groundwater recharge systems, check dams, tanks and bunds [7]. In semi areas, that surface runoff has a little storage for domestic and agriculture activities; groundwater is the major source of water in these areas. With agriculture development and the increasing of groundwater exploitation, lack of water will result in water stress of plants in these areas and may finally result in desertification and severe environmental damage such as land subsidence in plains. Therefore, with computing temporal and spatial changes of depth to groundwater and identifying of potential runoff generating sites, we can identify high priority areas for groundwater recharge and in addition to use stored water for domestic and agriculture activities, maintain groundwater in desirable level and prevent severe environmental damage due to groundwater stress.

In addition to identifying of potential runoff generating sites, estimation of runoff depth for evaluation of potential runoff generating in a watershed, for groundwater recharge, is an important factor. Generally, accurate data on runoff in a catchment are scarce and only accessible in a few zones. Therefore, there is a critical demand to produce information on rainfall-runoff and sediment yield for effective development of the watershed [8]. To fulfill this goal, various techniques have been developed and implemented for estimation of rainfall-runoff from data scarce basins [9]. There exist various procedures for estimation of runoff from data scarce basins whereas the NRCS-CN (natural resources conservation services curve number), USDA 1994 method is the most commonly used technique for ungauged watershed networks, which has shown a quick and precise estimator of surface runoff [10]. Since its beginning, the NRCS-CN technique has been extensively tested by hydrologists, water policy makers, engineers, and foresters for estimation of rainfall- runoff.

GIS (geographical information system) prepares an appropriate environment because of providing a structure for collecting, storing, handling, converting and showing spatial and non-spatial information for specific aims [11]. Recent progresses in technology and GIS sciences lead to easy and unlimited access to the spatial data and easy processing of data without the need for expert expertise to manipulate and analyze vast spatial datasets. Hence combining spatial properties of basins has become more effective, which improve understanding and demonstration of hydrological processes in the nature. Therefore, the capability of GIS for hydrological modeling is remarkable [12]. Consequently, a great number of studies have been carried out to use GIS capabilities for hydrological modeling [13]. Ref. [7] demonstrated that GIS is a suitable tool for specifying runoff potential regions and finding proper regions for rainwater storing in India. Ref. [4], in a study on the Potshini catchment in South Africa, determined sites with high level of suitability for runoff producing using soil map, land use map and rainfall information.

The main goals of this study are use of GIS capability for determining sites with high potential of runoff generation, and so high priority areas for groundwater recharge and estimation of rainfall-runoff at the Gharehchay River watershed in the north of the Hamedan province, Iran. To accomplish this aim, it was urgent to recognize and acquire the adequate data, expand the needed databases and identify how this information is to be used in a GIS interface.

2. Materials and Methods

2.1 Study Area

The study region is Gharehchay river watershed, which with area of 9,728 km^2 is located in the north of Hamedan province, Iran. It is demarcated by latitude 34°35′ N to 35°40′ N and longitude 48°10′ E to 49°30′ E. The river rises in the Zagheh Mountains and Alafat Valleys, between Hamedan and Malayer Counties, and flows between Kourijan, Famenin and Ghahavand and finally after passing from Markazi province, enters into the Qom Lake in Qom province.

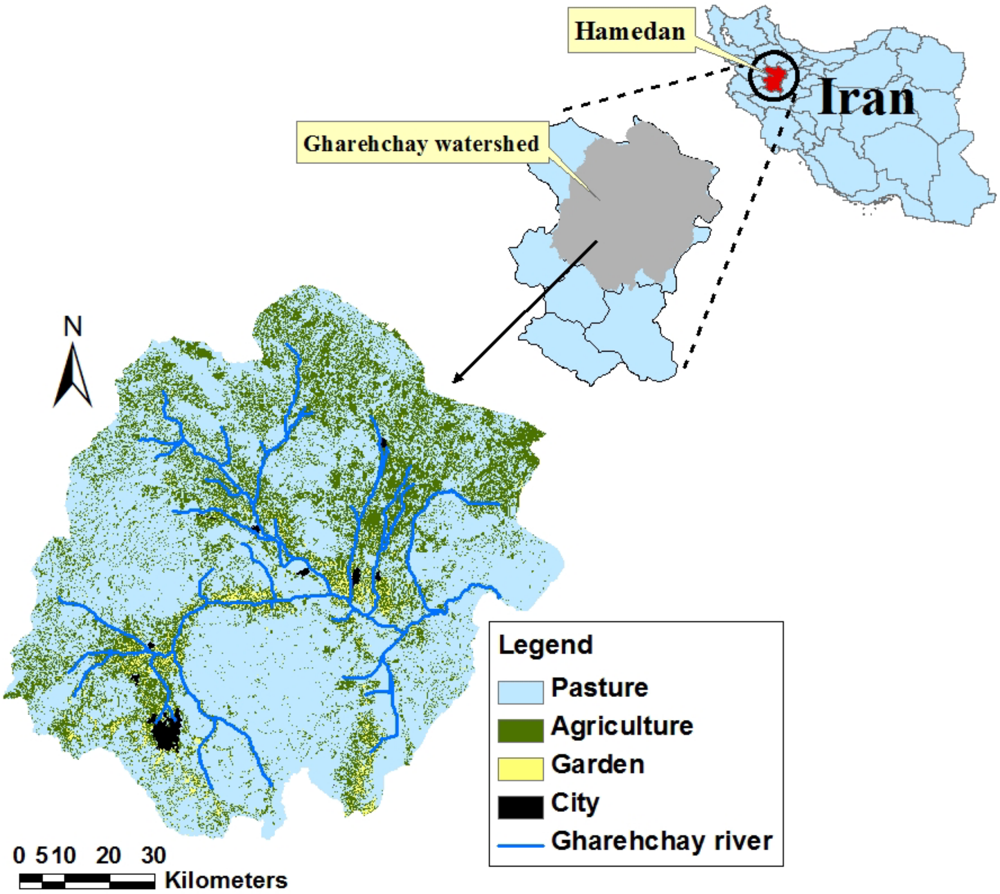

Fig. 1 Location of study area, and the land use detail for the Gharehchay watershed.

Table 1 Area and percentage of the hydrological soil groups and land uses in the study area.

Land use	Area (km^2)	Area (%)	Hydrological soils groups	Area (km^2)	Area (%)
Pasture	6758	69.4	A	232.77	2.33
Agriculture	2679	27.5	B	2,479.24	25.4
Garden	222.89	2.29	C	1,175.89	12
City	68.11	0.81	D	5,840.4	60.27

Topographically, the Gharehchay watershed has gentle slopes (lower than 5%). The highest and lowest elevation is from 1,550 to 3,550 m asl, respectively (Fig. 1).

2.2 Data Acquisition

In this study, the input data required such as soil type, land use, DEM (digital elevation model), rainfall depths and depth to groundwater from Gharehchay watershed were acquired. DEM was utilized to derive an elevation dataset of the watershed. The DEM has a 90 m horizontal resolution. The watershed has been divided into four land use types, including pasture, agriculture, garden and city that make up 69.4, 27.5, 2.29 and 0.81 percent of the study area, respectively (Fig. 1 and Table 1). The CN values for these various land uses were determined from the CN handbook tables. Based on the infiltration rate values, the soils of the study region were classified into four hydrological groups for CN-based runoff calculation: A (2.33%), B (25.4%), C (12%), and D (6.27%) (Table 1). The average annual rainfall data of 15 weather stations, located in the study region, were utilized related to the period from 1995 to 2014 to obtain the runoff depths by NRCS-CN method. The yearly average observed depth to groundwater of 143 groundwater observation wells over the period 1981-2014 were used for identifying high priority zones for groundwater recharge (Fig. 6a).

2.3 Procedure for Producing Runoff Potential and High Priority Regions for Groundwater Recharge

Runoff harvesting technologies are extremely dependent on various factors including location, physiographic, environmental, technological, social and economic conditions [4]. Hence, suitable techniques are particularly expanded for specific areas and cannot easily be repeated in other regions [7]. The techniques illustrated in this research are suitable for identifying of potential runoff producing areas and high priority zones for groundwater recharge, with attention to depth to groundwater in the study area, and important factors for runoff harvesting, described above, are not taken into account. From a hydrological viewpoint, different environmental properties like topography, soil, land cover rainfall characteristics, and initial moisture conditions, will affect watershed response [14]. Landscape characteristics are particularly important to generate rainfall-runoff output and thus GIS technologies become increasingly significant because of their ability to present spatial data accurately [11]. There are several factors including soil type, slope steepness and land use, which are suitable for selecting runoff generating. Slope steepness is a significant factor for selecting and performing water harvesting structures [2] particularly for surface runoff generation. In addition, the soil capacity for absorption, storage and release of water indicates that soil is an important factor for regulation of hydrological response of a watershed [15]. Soils with high and low clay content tend to produce high and low storm flows, respectively [16]. In this study, the categorized features including hydrological soil groups, land use, slope, rainfall depth and depth to groundwater were combined and analyzed utilizing Arc-GIS Version 9.3 [13, 17] as part of the procedure for determining potential runoff generating areas and high priority zones for groundwater recharge. A great number of spatial analyst tools were used to solve several spatial issues, i.e. computing slope, depth to groundwater, CN values calculation, and reclassifying values. Fig. 2 depicts the different procedures employed for using the obtained datasets to produce suitable output information.

2.4 NRCS-CN Method for Runoff Estimation

The NRCS-CN technique relies on the water balance equation and two basic assumptions [18]. The first assumption is based on the equality relationship between the ratio of the value of direct surface runoff Q to the total rainfall P and the ratio of the value of infiltration F_c to the value of the potential maximum retention S. The second assumption creates a relationship between the initial abstraction I_a and potential maximum retention. Hence, the NRCS-CN technique comprises the following relationships:

Water balance relationship:

$$P = I_a + F_c + Q \tag{1}$$

Proportional equality assumption:

$$\frac{Q}{P - I_a} = \frac{F_c}{S}. \tag{2}$$

I_a-S assumption:

$$I_a = \lambda S. \tag{3}$$

where P is the sum of rainfall; I_a the initial abstraction; F_c the cumulative infiltration F_c excluding I_a; Q the direct runoff; S the potential maximum retention or infiltration; and λ the regional parameter dependent on geologic and climatic factors ($0.1 \leq \lambda \leq 0.3$). Analyzing the rainfall and runoff data from investigational small basins was used to develop relationship between I_a and S [18] and is indicated as $I_a = 0.2S$. The NRCS-CN technique is demonstrated as an integration of the water balance relationship and proportional equality assumption:

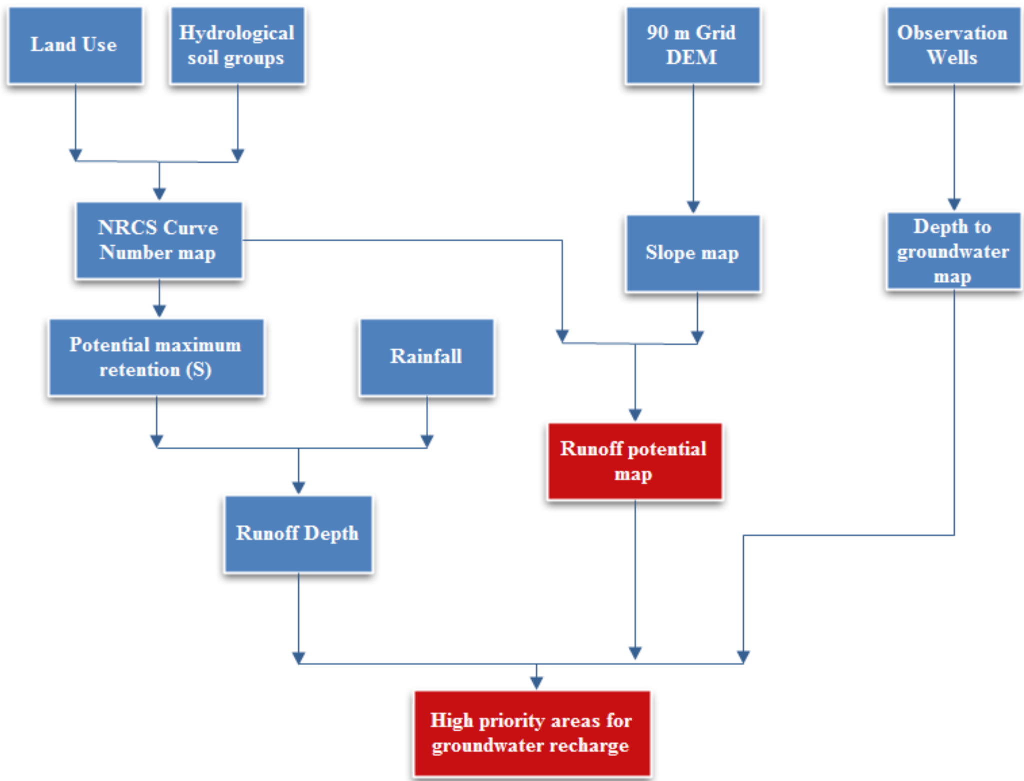

Fig. 2 Conceptual scheme for generating runoff potential sites and identifying high priority areas for groundwater recharge for the Gharehchay watershed.

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S}. \quad (4)$$

This equation is a relationship between the potential maximum retention storage *S* and CN, which is a function of land use, soil type and antecedent moisture condition of watershed. The CN is dimensionless and its value changes from 0 to 100. The *S*-value in mm is computed using CN by the following equation:

$$S = \frac{25400}{CN} - 254. \quad (5)$$

Nowadays, scientists have offered eight derivations of the standard NRCS-CN procedures [10]. Ref. [19] assessed NRCS-CN technique and three derivations of this technique for calculation of rainfall-runoff depths in Banha watershed and results were compared with recorded data for the period from 1993 to 2001. Results showed that between the four utilized techniques, the modified CN I method was the most precise technique with efficiency factor (*F*) and coefficient of determination (R^2) 0.92 and 0.82, respectively. In this research CN I technique was used for calculation of runoff depth in the study region. The modified CN I procedure is based on the zero initial abstraction assumption (I_a = 0), which considers promptly ponding for estimation of the runoff depth Q from a specified rainfall depth *P*. Utilizing this assumption in the standard NRCS-CN proportionality hypothesis (Eq. (2)), the equation for rainfall-runoff estimation is computed as follows:

$$Q = \frac{P^2}{S + P}. \quad (6)$$

The advantage of the modified CN I method over standard NRCS-CN is accounting for the situations dominating in watershed systems under high-intensity rainfall events. It means that two extremely dry and wet scenarios, which may generate runoff and were not considered in the original NRCS-CN method due to its assumption of runoff occurring only after fulfilling the initial abstraction I_a requirements, are considered by modified CN I method [19].

3. Results and Discussion

3.1 Data Processing

3.1.1 Slope

A slope map, indicated as percentage slope, for the study region was computed from DEM of the basin. For analytical goals, the slopes were classified into four classes; namely, less than 5%, 5% to 10%, 10% to 15% and greater than 15% that make up 69%, 15%, 5.7% and 10.3% of the study area, respectively (Fig. 3).

3.1.2 NRCS Curve Number

The NRCS-CN technique combines land cover and hydrological soil groups and generates the curve number [16]. The curve number is an indicator illustrating a basin's runoff response to a rainfall [16] and hence describes the ratio of rainfall that allocates to runoff [12]. Curve number varies from 0 to 100 where higher numbers depict a higher ratio of surface runoff. There is a reverse relationship between the values of the CN and the potential maximum retention *S*. If the CN = 100, it means that the basin is impermeable and value of *S* is equal to zero, inversely, if the CN = 0, it means that the basin is absolutely permeable and value of *S* is ∞. The NRCS-CN method needs data on soil type to categorize the hydrological soil groups (A, B, C, and D). Table 1 represents the area and percentage of the study region made up by each group. For estimation of CN values, land use and hydrological soil groups should be integrated with each other. Each land use and hydrological soil groups show different CN values that can be obtained from standard CN tables. In this paper, CN values were accessed through the SCS handbook [18], which provides some empirical values of CN for known soil types (Table 2).

CN values were computed for each combination of the land use and different hydrological soil groups by the HEC-GeoHMS extension [20] and were transformed into raster datasets to comply with the data requirements of ArcGIS Spatial Analyst for runoff depth estimation (Fig. 4).

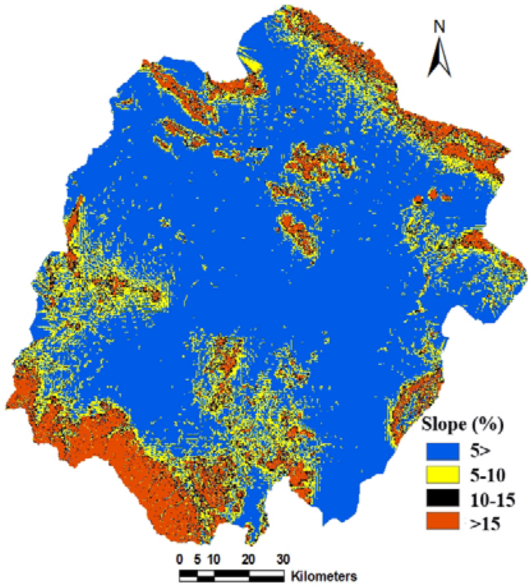

Fig. 3 Categorizing slope of the study area to the four slope classes.

Table 2 CN values for integrating of hydrological soil groups and land uses.

	Hydrological soil groups			
Land use	A	B	C	D
Pasture	49	69	79	84
Agriculture	67	77	83	87
Garden	43	65	76	82
City	57	72	81	86

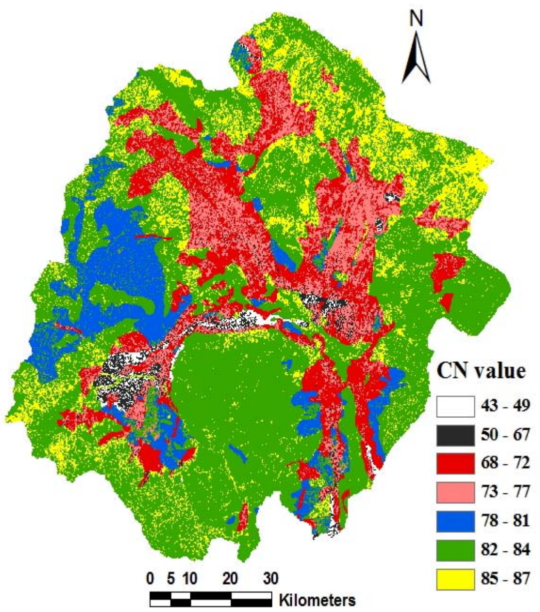

Fig. 4 CN values map for the study area.

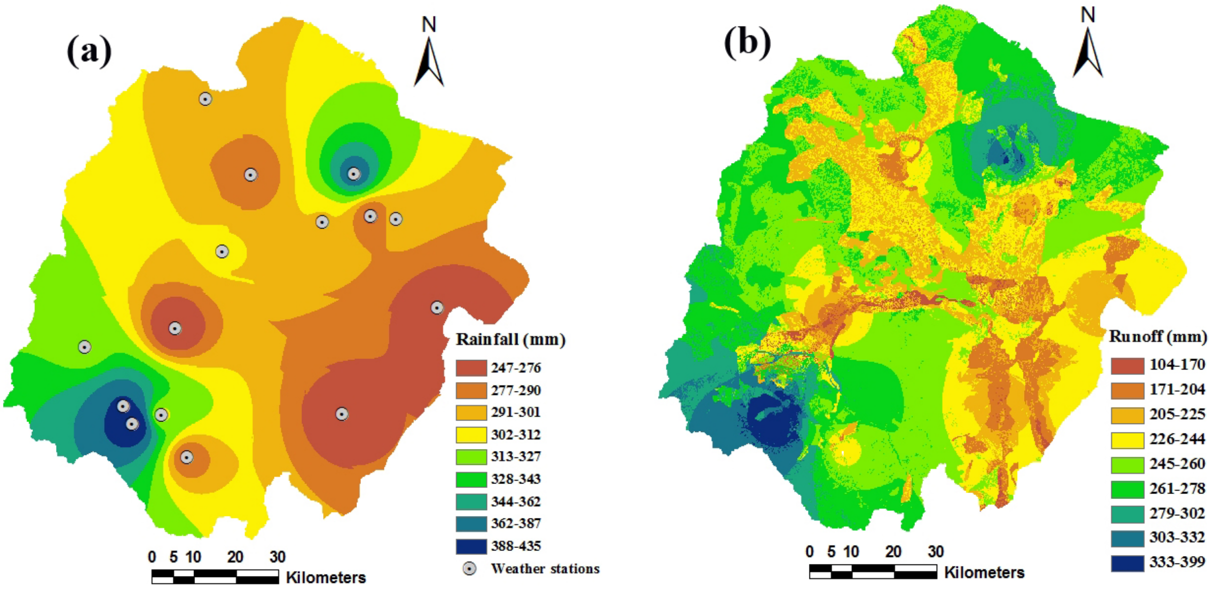

Fig. 5 (a) Average annual rainfall map of the study area and location of the weather stations, (b) annual runoff map of the study area.

3.1.3 Runoff Depth Estimation

According to Eq. (6), surface runoff estimation procedure needs two maps, including rainfall depth and the potential maximum retention *S*. For this objective, spatial distribution of the average annual rainfall depth of 15 weather stations was estimated by the IDW (inverse distance weighting) technique and rainfall map of the study region was produced (Fig. 5a). Afterward CN-map and Eq. (5) were utilized to compute the S-map in mm. Eventually, map of runoff depth in mm was estimated by combination of S-map and rainfall depth-map using Eq. (6) (Fig. 5b).

3.1.4 Depth to Groundwater Map

For detecting the distribution of depth to groundwater in the region, the yearly average observed depth to groundwater of 143 groundwater observation wells over the period 1981-2009 was interpolated using the simple kriging method. Simple kriging is a predictor from kriging family that has been used by the various researchers in the world for different uses. Ref. [21] compared kriging methods (including OK (ordinary kriging), SK (simple kriging), and UK (universal kriging)), the IDW method, and the RBF (radial basis function) method to select an optimal interpolation technique for producing spatial distribution of depth to groundwater in the Minqin oasis located in northwest of China. Obtained results showed that simple kriging is the most suitable technique for estimation of depth to groundwater in the area (in terms of root mean squared errors and correlation coefficients between interpolated values and observed values). Based on these results, the simple kriging method for spatial interpolation of depth to groundwater in the study area was utilized and the resulted map was used for specifying high priority regions for groundwater recharge in the next steps. Afterwards the depth to groundwater map was classified into four classes; namely, low (< 20 m), medium (20 to 35 m), high (35 to 55 m) and very high depths (> 55 m) that make up 15.5%, 61.7%, 17.4% and 5.4% of the study area, respectively (Fig. 6b).

3.2 High Priority Modeling

The final stage was to combine the different parameters in order to determine high priority areas for groundwater recharge. For this purpose, single ranked maps of each effective factor were combined. To make simpler high priority processing, numeric values allocated to each class in each map (Table 3). The map layers including the slope; CN, runoff and

Table 3 Ranks associated with map layers, low rankings describe areas with a high priority.

Slope (%)	Interval class	5% >	5-10%	10-15%	➢ 15%
	Rank	4	3	2	1
CN (dimensionless)	Interval class	43-54	54-66	66-78	78-87
	Rank	4	3	2	1
Runoff depth (mm)	Interval class	104-178	179-252	253-325	326-399
	Rank	4	3	2	1
Depth to groundwater (m)	Interval class	20 >	21-35	36-55	> 55
	Rank	4	3	2	1

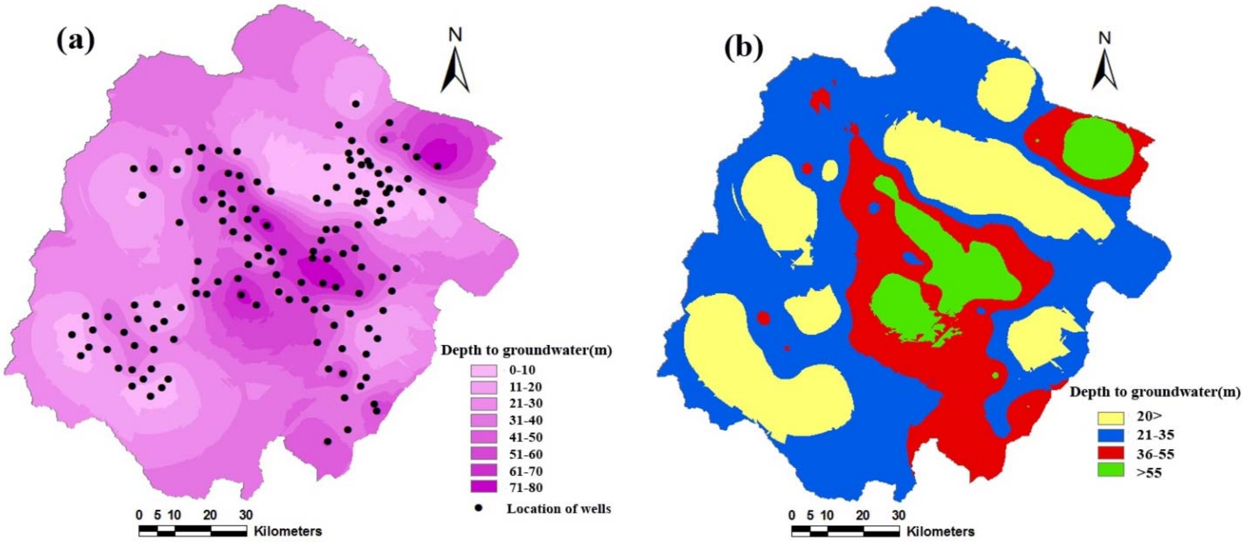

Fig. 6 (a) Depth to groundwater map and location of observation wells in the study area (b) classifying of depth to groundwater map into four classes.

groundwater depth were utilized to carry out high priority analysis. Each map layer was ranked based on its values and from a range of highest to lowest priority, and each map being dedicated an identical weighting. Firstly, slope and CN values maps were ranked based on criteria for surface runoff generation and then were combined to develop runoff potential map. Afterwards, depth to groundwater map ranked in order of highest priority to lowest priority and was combined with the runoff potential map and rainfall-runoff depth to produce the map of high priority regions for groundwater recharge.

3.2.1 Runoff Potential Map

Slope and the CN maps were utilized to determine the runoff potential. Before combining the slope and CN map, ranked values needed to be allocated to the relative classes to make priority map. Based on the assigned criteria for the slope characteristics for runoff generation, the steeper areas have higher potential of runoff generation, and based on this concept the four slope groups were ranked from lowest to highest priority. For the CN map, higher amount of CN have high proportion of surface runoff and are therefore potentially most suitable for runoff generation (Table 3). Consequently, the potential runoff map derived, which was a four-class qualitative grid map because of combining the previously mentioned factors and is shown in Fig. 7. This map was utilized as input information for identifying high priority areas for groundwater recharge. Fig. 7 represents that a moderate proportion (15.85%) of the study region has a very high potential to produce surface runoff while another parts of the watershed have high, medium and low runoff generation potential that make up 58.3%, 23.9% and 1.95% of the watershed area, respectively.

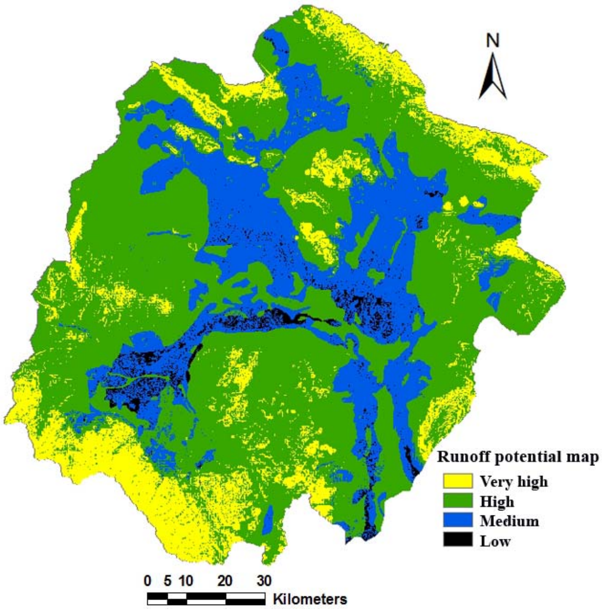

Fig. 7 Runoff potential map of the study area.

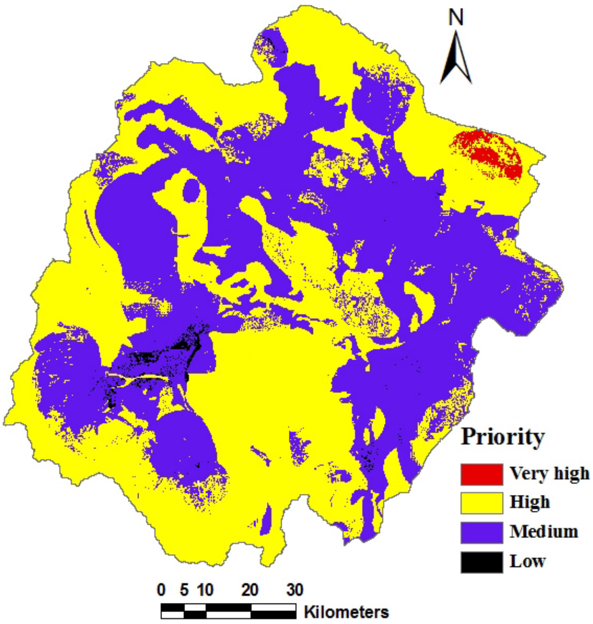

Fig. 8 High priority areas for groundwater recharge.

3.2.2 High Priority Areas for Groundwater Recharge

To support the high priority modeling, the three maps including runoff depth, runoff potential, and depth to groundwater map, were reclassified into numeric values ranked from highest to lowest priority for recharge of groundwater. Mentioned three maps were ranked accordingly and were combined with each other. Combining these maps resulted in a map produced that represents high priority areas for groundwater recharge in the study region (Fig. 8). As shown in Fig. 8, 51% of the Gharehchay watershed has high priority for groundwater recharge.

4. Conclusions

A method for identifying high priority areas for groundwater recharge was developed through utilizing GIS. For this purpose several effective factors were combined based on the criteria of each dataset. This study combines the two most advantageous components, i.e. the estimation of rainfall-runoff from ungauged basins and utilization of potential runoff map to identify high priority areas for groundwater recharge. Specific to this study was consideration of spatial and temporal rainfall data as a runoff regulating system letting this method be simple and maintaining validity. The area of the Gharehchay watershed that has high priority for groundwater recharge is about 51% of the entire study region. These results are a remarkable step allowing managers to specify the source areas that highly need construction of groundwater recharge systems to maintain depth to groundwater in desirable condition and preventing unlimited groundwater exploitation. Surface water generated from rainfall-runoff process in a basin is a potential water resource; therefore, estimation of runoff depth can be used to assess the total amount of runoff that can be recharged into the groundwater. The application of GIS as a tool to make this process easy is represented in this study, in order to enhance the level of precision for finding regions for groundwater recharge owing to the capability of GIS to employ spatial data in an integrative procedure and to show this spatially via maps.

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