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Assessing Geomorphologic Characteristics and Demarcating Runoff Potential Zones using RS and GIS in *Patiala-Ki-Rao* Watershed of *Shivalik* Foot-Hills, Punjab

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ABSTRACT

Knowledge of geomorphologic characteristics is necessary for management of land and water resources in a watershed. These characteristics for *Patiala-Ki-Rao* watershed, located in *Shivalik* foot-hills of Punjab, were assessed using remote sensing and Geographic Information System (GIS). The form factor (0.27), circulatory ratio (0.53) and elongation ratio (0.59) indicated an elongated shape of the watershed, which might result in low-peaked hydrograph. Drainage characteristics of the watershed, namely drainage density (1.58 km.km^{-2}), drainage texture (6.4 number.km^{-1}), mean bifurcation ratio (2.4) and stream frequency (4.36 number.km^{-2}) indicated quick disposal and low retention of runoff. Slope was less than 10 % in 21.04 km^2 (41 % of watershed area), and 63.57 % and 16.39 % areas of the watershed were categorized as forest and agricultural lands, respectively. Furthermore, suitable runoff potential zones were identified by integrating thematic layers of slope, soil texture and land-use using GIS and multi-criteria decision making techniques. The high, moderate and low runoff potential zones covered 13.74 km^2 (26.73 %), 21.87 km^2 (42.55 %), and 15.79 km^2 (30.72 %) areas, respectively. The moderate to high runoff potential zones were mostly situated towards the upstream portion, whereas runoff potential was less in the downstream portion. Therefore, water harvesting and conservation treatment planning in the watershed is necessary for sustainable livelihood of the inhabitants.

Hydrology of a watershed depends mainly on response of watershed to rainfall (Sivapalan, 2005). Characterization of watersheds based on the most influential watershed characteristics is the best way to predict the watershed hydrology, as this provides a basis for planning conservation treatment for land and water management at watershed scale (McDonnell *et al.*, 2007). Watershed characteristics are classified into geomorphologic, topographic, soil, and land-use characteristics (Black, 1997; Uhlenbrook, 2003; Sivapalan, 2005). Study of geomorphologic characteristics of a watershed using morphometric analysis describes hydrology and drainage system of the watershed. It plays an important role in understanding hydrological response of a watershed (Dwivedi, 2011; Saha and Singh, 2017).

Morphometric analysis consists of linear, areal, and relief aspects, which are measured/estimated by the configuration of the watershed's surface, shape, and its dimensions (Agarwal, 1998; Reddy *et al.*, 2002). All these morphological parameters within certain range indicate the extent of runoff generation and erosion hazard of a watershed. The topographic characteristics of a watershed are vital in land capability assessment, and affect the quantity of runoff and soil loss (Kushwaha *et al.*, 2016). Land-use of the watershed affects the hydrological processes such as runoff, infiltration, base flow, and groundwater recharge, and modifies the production rates of runoff and sediments and their movement out of the watershed (Walling, 2009). Soil characteristics of the watershed also play an important role in understanding the hydrologic characteristics.

Soil texture directly affects the soil porosity, and determines its water-retention, flow characteristics, and rate of water intake, which ultimately have an impact on the quantities of runoff and soil loss (Deshmukh and Aher, 2014). Once the runoff and its erosive condition are known, the watershed can be restored by adopting suitable treatment measures (Bhargav and Tank, 2011; Kushwaha *et al.*, 2016).

Hydrologic characterization of watersheds is crucial in *Shivalik* foot-hills, locally known as *kandi* area. The *Shivalik* foot-hills are a part of the Himalayan mountain chain which continuously runs from Jammu and Kashmir, Himachal Pradesh, Punjab, Haryana and finally end up at Bhabbar tracts of Garhwal and Kumaon in Uttarakhand. The *Shivalik* foot-hills are facing serious problems of soil erosion, land degradation and sedimentation, which are reducing agricultural productivities (Bhardwaj and Kaushal, 2009). It is the eighth most degraded and delicate agro-ecosystem of the country (Bhardwaj and Rana, 2008). *Patiala-Ki-Rao* watershed, which is located in *Shivalik* foot-hills of Punjab, is facing similar problems. Therefore, the geomorphologic characteristics of *Patiala-Ki-Rao* watershed need to be studied for prediction of the runoff and soil erosion (Sarangi *et al.,* 2007; Sahoo *et al.,* 2008; Werkhoven *et al.,* 2008; Gebrehiwot *et al.,* 2011; Kushwaha *et al.,* 2016; Singh *et al.,* 2016; Rai *et al.,* 2017). In addition, integration of topography and land-use characteristics of watershed help identifying the potential sites of runoff generation. This information is useful for construction of water harvesting and conservation structures in the watershed.

Remote sensing in association with Geographic Information System (GIS) is useful in quantifying the geomorphologic parameters, and provides a suitable platform for data update, analysis and recovery in less time and cost and with improved precision (Vittala *et al.,* 2004; Das and Mukherjee, 2005; Kumar *et al.,* 2007; Premanand *et al.,* 2018). Hence, geomorphologic characteristics of *Patiala-Ki-Rao* watershed were assessed in this study, and suitable runoff potential zones were demarcated by integrating three thematic layers of slope, soil texture and land-use using remote sensing and GIS techniques.

MATERIALS AND METHODS

Description of Study Area

Patiala-Ki-Rao watershed having an area 51.40 km^2, was selected as the study watershed. It is located between latitude and longitude of 30º45′27.53″ N, 76º44′44.03″ E and 30º49′54.40″ N, 76º52′24.86″ E in *Shivalik* foot-hills of Punjab, as shown in Fig. 1. The watershed has a sub-humid climate. The average annual rainfall in the study area is 1110 mm, of which around 80% is received during the monsoon season between June and September months. The maximum temperature (41-43 ºC) and minimum temperature (3-5 ºC) are recorded in the months of May and January, respectively (Yadav *et al.,* 2005; Sushanth *et al.,* 2018).

Data Used

The Survey of India (SOI) toposheet (No. 53 B/9) at 1:50000 scale was used to delineate the watershed. Slope map of the watershed was drawn from Digital Elevation Model (DEM) obtained from the USGS Earth Explorer. Fifty soil samples, distributed over the watershed, were collected during post-monsoon season and analyzed in the laboratory of the Department of

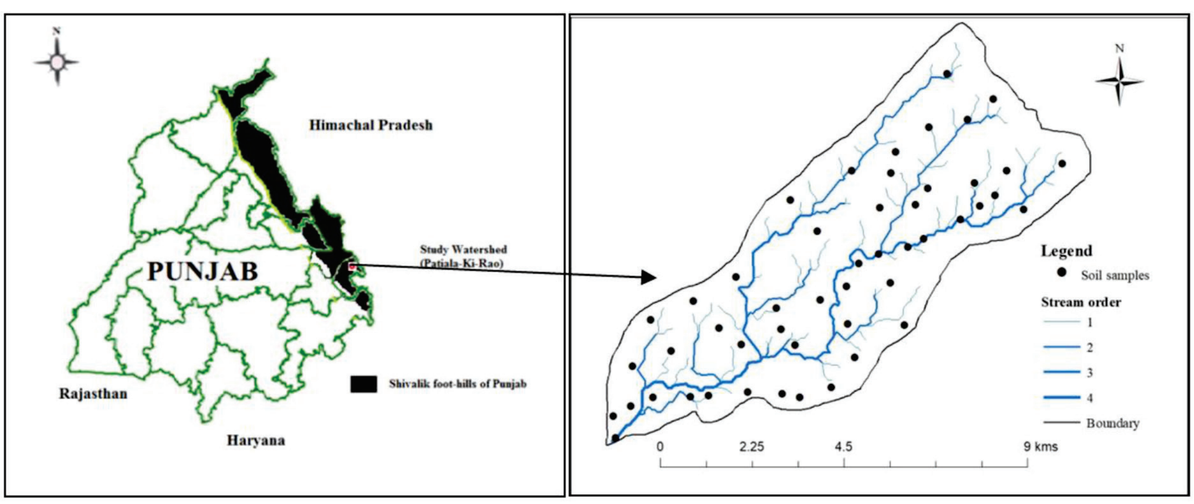

Fig. 1: Location map of *Patiala-Ki-Rao* watershed along with soil sampling sites and stream order map

Soil Science, Punjab Agricultural University, Ludhiana, for particle size distribution to determine soil texture. Satellite data (processed and classified Landsat image of March 10, 2016) was collected from Punjab Remote Sensing Centre (PRSC), Ludhiana to know the information of land-use.

Digitization of Watershed

The watershed boundaries were delineated on tracing paper from characteristics of contour lines shown in the SOI toposheet. The traced watershed was scanned and added into GIS environment. The scanned image was then geo-referenced by assigning real-world coordinates for different points obtained from the toposheet by using Universal Transverse Mercator projection and World Geodetic System 84 datum. Then, features from the traced map were digitized by on-screen digitization in polygon format.

Assessment of Watershed Characteristics

Geomorphologic characteristics

Details of all quantitative geomorphologic characteristics, calculated using GIS, are reported in Table 1. The watershed length, perimeter and area were calculated from digitized watershed using *Calculate Geometry* option. Details about stream order, total stream length, number of streams for each order, and total number of streams were taken from the stream network map. The stream network map was delineated from the DEM using *Flow Accumulation* tool. Stream ordering was done by using *Stream Order* tool following Strahler method for assigning a numeric order (Gleyzer *et al.,*2004).

Table 1. Details of geomorphologic characteristics of watershed

Sl. No.	Parameter	Formula used	Source
		Linear aspect	
1.	Stream order (U_n)	The streams are ranked by stream ordering system based on hierarchic ranking of streams.	Horton (1945)
2.	Stream length (L_u)	Stream length is calculated in GIS.	
3.	Bifurcation ratio (R_b)	$R_b = N_u / N_u+1$ where, N_u = Number of streams of any given order N_u+1 = Number of streams in the next higher order	Schumn(1956)
4.	Length of overland flow (L_o)	$L_o = 1/ D_d \times 2$ where, D_d = Drainage density, km.km^{-2}.	Horton (1945)
		Areal aspect	
5.	Drainage density (D_d)	$D_d = (\Sigma L_u)/A_u$ where, A_u = Area of the watershed, km^2.	Strahler (1957)
6.	Drainage texture (T)	$T = \Sigma N_u/P$ where, P = Watershed perimeter, km.	Horton (1945)
7.	Stream frequency (F_s)	$F_s = \Sigma N_u /A_u$	Horton (1932)
8.	Form factor (R_f)	$R_f = A_u / L_b^2$ where, L_b = Maximum watershed length, km.	Horton (1932)
9.	Circulatory ratio (R_c)	$R_c = 4\pi A_u / P^2$	Miller (1953)
10.	Elongation ratio (R_e)	$R_e = \sqrt{(4A_u/\pi)} / L_b$	Schumm (1956)
		Relief aspect	
11.	Relief (z)	$z = E_h - E_l$ where, E_h = Highest elevation in watershed, m; E_l = Lowest elevation in watershed, m.	Hadley and Schumm (1961)
12.	Relief ratio (R_h)	$R_h = H / L_{bmax}$ where, H = Maximum watershed relief, km;qL_{bmax} = Maximum watershed length, km.	Schumm (1956)

Topographic characteristics

Topographic elevation and slope maps were prepared from the DEM of the watershed using GIS. Topographic elevation map was developed by classifying the DEM into different elevation segments by using *Natural Breaks* (Jenks) method (Chen *et al.,* 2013). Slope map was prepared by using *Spatial Analyst* tool (slope) on the DEM, and was classified.

Soil characteristics

The particle size distribution of the soil was determined from samples of the top 300 mm soil layer collected as per the standard procedure (Jackson, 1973) from 50 locations uniformly-distributed over the watershed (Fig. 1). The textural analysis was done by using the International Pipette Method (Gupta, 2009). Particle size analysis of soils was obtained only at 50 locations in the area, and hence, it required interpolation to understand spatial distribution of soil texture (Christos *et al.,* 2009). In this study, interpolations of soil texture at 50 sites were performed in GIS using *Spatial Analyst* tool following Inverse Distance Weighting (IDW) method for preparation of textural distribution maps. The IDW is a deterministic method of interpolation with a known set of points. The assigned unknown points are calculated with a weighted average of the known points. This method gives better results when the samples are spaced apart (Sakata *et al.,* 2004). In the interpolation process, particle size analysis data was added into GIS environment along with the digitized watershed.

Land-use characteristics

Classified vector-format Landsat image (using supervised classification method with overall accuracy of 90 % and Kappa coefficient of 0.9) was added into GIS environment along with digitized watershed. Each land-use class was on-screen digitized in polygon format. The areas of different land-uses were calculated from the polygons by using *Calculate Geometry* option (Sushanth *et al.,* 2018).

Identifying Suitable Runoff Potential Zones

In this study, suitable runoff potential zones were demarcated using multi-criteria decision making technique by integrating thematic layers of topography (slope), soil texture and land-use (Adham *et al.,*2018). The Analytic Hierarchy Process (AHP) is a multi-criteria decision-making tool widely used by decision makers and researchers for planning, selecting the best alternative, resource allocations, resolving conflict, optimizations, etc. (Vaidya and Kumar, 2006). The criteria (both themes and their classes) involved in the AHP were prioritized by judging the importance of one criterion over another. Therefore, each criterion was assigned suitable numerical values on the Saaty (1990) scale to express the comparative importance (Table 2). The judgment on relative importance of different criteria was based on the authors' expertise and literature survey (Bekele *et al.,* 2009). The resulting pair-wise comparison matrix was used to obtain the Eigen value of each criterion, which represents its importance weight (Saaty, 1990). Weights of themes and their classes were combined by using *Raster Calculator* tool following weighed linear combination technique, given as follows (Malczewski, 1999):

$$S = \sum w_i \times x_i \qquad ...(1)$$

Where,

S = Suitability of runoff potential,

w_i = Weight of theme i, and

x_i = Score of class i.

In addition, the consistency of the assigned weights was evaluated by computing consistency ratio (CR) as given below:

$$CR = \frac{(\lambda max - n)/(n-1)}{RI} \qquad ...(2)$$

Where,

λ_{max} = Maximum Eigen value of the matrix,

Table 2. Numerical expression of comparative importance scaling

Numerical value	Comparative importance
1	Equal importance
3	Moderate importance of one over another
5	Strong importance of one over another
7	Very strong importance of one over another
9	Extreme strong importance one over another
2, 4, 6, 8	Intermediate values between two adjacent judgments

Source: Saaty (1990)

n = Number of themes/factors compared, and

RI = Random consistency index (a value that depends on the number of elements that are being compared).

The judgment is considered acceptable if value of CR is less than 0.1 (Saaty, 1987).

RESULTS AND DISCUSSION

Geomorphologic Characteristics

Length and perimeter of *Patiala-Ki-Rao* watershed were 13.72 km and 35 km, respectively. The geomorphologic characteristics are presented and discussed below.

Linear aspects

The stream network map of the study area is shown in Fig. 1. The details of stream order, number of streams, stream length and mean stream length are presented in Table 3. The number of streams was found to be inversely-related to the order of streams. From field visits, it was noted that stream width of higher order streams were greater than that of the lower order streams. Above results reflected that the watershed had a good stream network, and was able to dispose excess runoff quickly. The length of 1st order stream was maximum (35.3 km), and that of the 4th order was minimum (5.12 km). The mean stream length was maximum (568.33 m) in case of the 4th order and was minimum (296.61 m) for the 1st order streams. Total length of streams and the mean stream length of each order decreased with increase in the stream order. Hence, the smaller stream lengths reflected a finer texture of stream network and high slope, and thus, these streams generated more runoff for same depth of rainfall.

The average bifurcation ratio (R_b) of the watershed was estimated as low (2.4), which indicated that the stream pattern was not affected by structural disturbances (Dwivedi, 2011). Higher R_b values (>5) resembled strong structural control in stream pattern (Dwivedi, 2011). The computed value of the average length of overland flow (L_o) was 317.5 m. The L_o value of watershed was quite high (>300), which indicated high slopes, long flow paths and more runoff (Sukristiyanti *et al.,* 2018).

Areal aspects

Drainage density of the watershed was 1.58 km.km^{-2}, which was very low (<2 km.km^{-2}) indicating low peaked hydrograph and low runoff from the watershed outlet (Sukristiyanti *et al.,*2018). Drainage density (D_d) indicates the closeness of spacing of channels, and may be classified as very low (<2 km.km^{-2}), low (2-4 km.km^{-2}), moderate (4-6 km.km^{-2}), high (6-8 km.km^{-2}), and very high (>8 km.km^{-2}) (Sukristiyanti *et al.,*2018). Drainage texture (T) provides information on the relative spacing of drainage lines, which is classified into very coarse (<2), coarse (2-4), moderate (4-6), fine (6-8), and very fine (>8) drainage texture (Smith, 1954). The value of drainage texture of watershed was 6.4, and was classified as fine texture. It indicated good availability of runoff for water harvesting in the watershed, but quick depletion at the outlet. Stream frequency (F_s) indicates close correlation with drainage density of the watershed. The stream frequency of watershed was low (4.36 number.km^{-2}), which indicated that the topography was not very undulating and significant volume of rainfall infiltrates into the soil, resulting in low surface runoff from the outlet.

The value of form factor Rf > 0.7854 indicates a perfectly circular basin, while smaller R_f values indicates maximum elongation of the watershed (Horton, 1932). In this study, the R_f value of 0.27 indicated that the watershed was elongated in shape and resulted in low to moderate runoff from the outlet. Circulatory ratio (R_c) of watershed was 0.53, indicating that the watershed was moderately elongated in shape having moderate discharge of runoff and moderate permeability of subsoil conditions. Elongation ratio

Table 3. Details of stream order and length of streams

Sl. No.	Stream order	Number of streams	Stream length, km	Mean stream length, m
1.	1	119	35.30	296.61
2.	2	58	24.82	427.91
3.	3	38	15.71	413.42
4.	4	9	5.12	568.33
5.	Total	224	80.95	—

Table 4. Assigned and normalized weights for themes and scores for their classes along with consistency ratios

Sl. No.	Characteristic	Theme weight	Class	Assigned class score	Normalized class score	Consistency ratio
1.	Slope, %	0.6333	2-6	5	0.0348	0.0542
			6-13	6	0.0678	
			13-22	7	0.1344	
			22-33	8	0.2602	
			33-72	9	0.5028	
2.	Soil texture (clay content, %)	0.2605	14-19	3	0.0364	0.0511
			19-23	5	0.0535	
			23-28	7	0.1408	
			28-32	8	0.2641	
			32-36	9	0.5051	
3.	Land-use	0.1062	Agricultural land	5	0.094	0.0418
			Built-up land	8	0.3229	
			Fallow land	7	0.226	
			Forest land	3	0.034	
			Grassland	4	0.0482	
			Stream/water body	9	0.4749	

(R_e) values can be grouped into three categories, namely circular (0.9), oval (0.9-0.8), and less elongated (0.7) (Strahler, 1964). The R_e value of the watershed was 0.59, which indicates that watershed is less elongated in shape resulting into generation of moderate quantities of runoff from outlet as well as low values of peak rate of runoff.

Relief aspects

The relief of the watershed was 267 m and relief ratio (R_h) was 0.02, which was moderately low. But, the R_h value in the upper part of the watershed was high (>0.02), which indicated steep slope of watershed resulting into generation of high volume of runoff. At the same time, the R_h value in the lower part of watershed near to the outlet was low (<0.02), which indicated plain topography resulting into generation of very low volume of runoff.

Topographic Characteristics

Topographic elevation map of the study area is shown in Fig. 2. It is evident from Fig. 2 that minimum elevation was 336 m MSL (mean sea level) at the outlet and maximum elevation of 603 m MSL was at the remotest boundary of the watershed. Also, majority of the area (29.53 km^2) lied between elevations of 436 m and

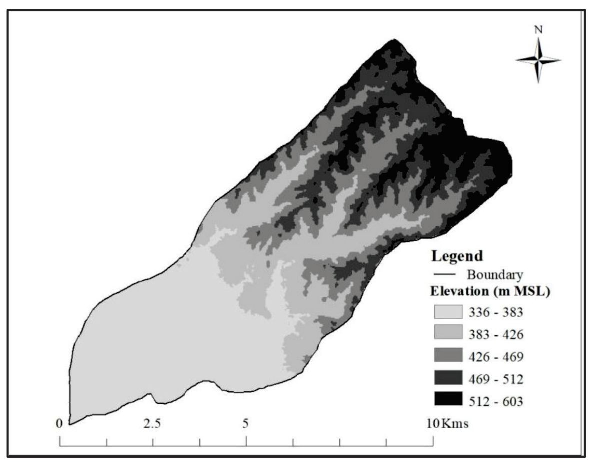

Fig. 2: Topographic elevation map of the *Patiala-Ki-Rao* watershed

603 m MSL. Slope map of the watershed is shown in Fig. 3. The slope within the watershed varied from 2.3 % to 72 per cent. The average slope was 17.19 %, which was quite high, and indicated moderately high amount of runoff generation. About 59 % of the watershed area had more than 10 % slope, and the slope at some points was as high as 72 per cent. The lowland area of the watershed was much flatter as compared to the upstream area. The runoff generation from upstream areas would be quite high, and there was good scope of constructing water harvesting structures in this area.

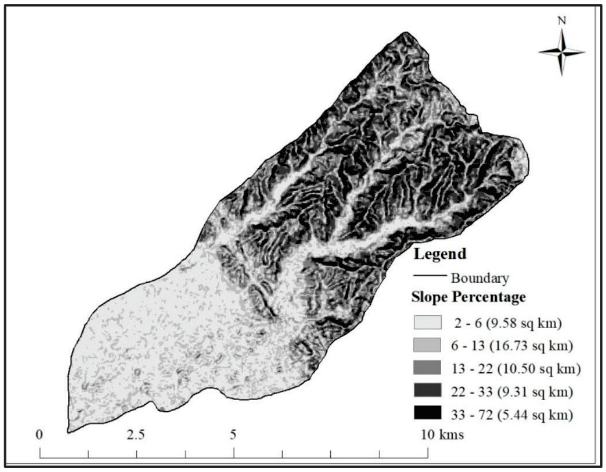

Fig. 3: Slope map of the *Patiala-Ki-Rao* watershed

Soil Characteristics

The major soils of the study area vary from loamy to sandy loam and clay loam with low to medium moisture retention capacity (Yousuf *et al.,* 2015). That means soils in the watershed are in general light textured. Distribution of sand, silt and clay particles in the watershed are shown in Fig. 4 (a-c). Sand content was maximum (63-70 %) in fallow lands with no irrigation, and was minimum (37-50 %) in agricultural lands with adequate irrigation facilities. Silt content was maximum (33-41 %) in banks of streams where excess eroded particles are deposited, and in over-irrigated agricultural lands. Silt content was minimum (3-18 %) in undisturbed forest lands and built-up lands. Clay content was maximum (32-36 %) in grasslands and forest lands due to inadequate drainage facilities. Clay content was minimum (14-19 %) in built-up lands. It is evident from Fig. 4 that the soils in the sloppy uplands of the watershed are relatively heavy-textured (clay loam) due to undisturbed forest area that may generate moderate amount of runoff. But the soils of the area that is near to the outlet are light-textured due to disturbances of urbanization. These soils may reduce the quantity of runoff passing through the outlet due to its high infiltration rate.

Land-use Characteristics

Areas under different land-uses are given in land-use map of the study area as shown in Fig. 5. During the year 2016, forest had been the main land-use in the watershed, followed by agriculture, and the forest covered 32.67 km^2 (63.57 %) of the watershed area. The areas under agriculture, built-up, grassland, streams, fallow land and water bodies were 8.42 km^2 (16.39 %), 7.04 km^2 (13.71 %), 1.42 km^2 (2.75 %), 0.95 km^2 (1.85 %), 0.59 km^2 (1.17 %), and 0.29 km^2 (0.57 %), respectively. Forests are located in the upland areas where land slope is high; and agricultural, built-up, and fallow lands are located in the lowland areas where the topography is comparatively plain. Hence, this indicated low to moderate quantities of runoff from the watershed outlet.

From above watershed characteristics, it is clear that the generation of runoff within the watershed was moderate to high, whereas runoff towards the watershed outlet was low to moderate. Hence, potential areas of runoff generation need to be demarcated to identify suitable locations for constructing rainwater harvesting and conservation structures.

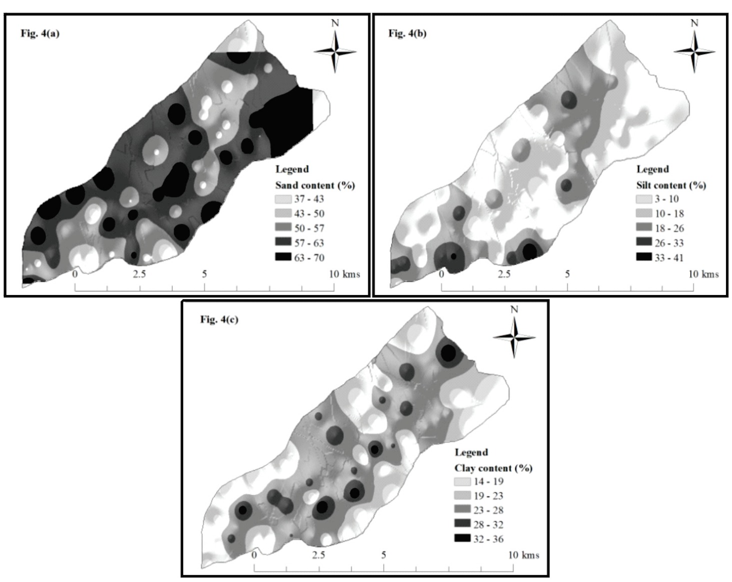

Fig. 4: Distribution of (a) sand, (b) silt, and (c) clay soils over the watershed

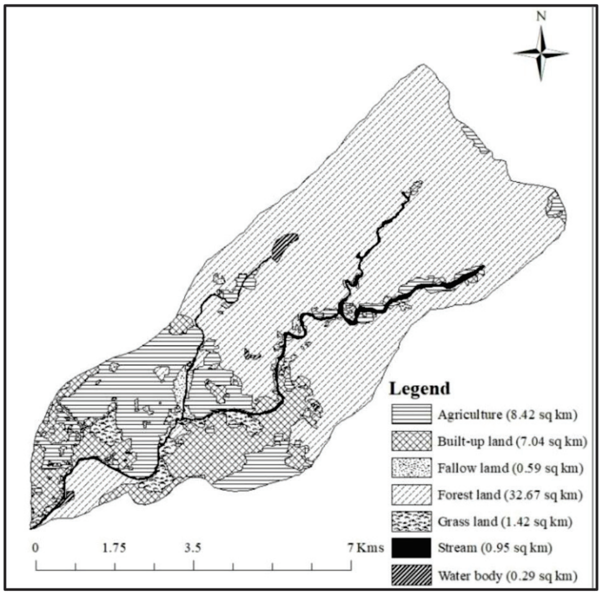

Fig. 5: Land-use map of *Patiala-Ki-Rao* watershed for the year 2016

Runoff Potential Zones

Theme weights and class scores, both assigned and normalized, are presented in Table 3. Consistency ratio of all three thematic layers of slope, soil texture, and land-use was found to be less than 0.1, indicating that the judgement on weight and score assignments was acceptable. The different classes of each theme were reclassified to numerical values (Table 3) in GIS environment. The final map produced by integrating all thematic layers was classified into three classes of high, moderate and low runoff potential, and is shown in Fig. 6. The areas under low, moderate and high runoff potential zones were 13.74 km^2 (26.73%), 21.87 km^2 (42.55 %), and 15.79 km^2 (30.72 %), respectively.

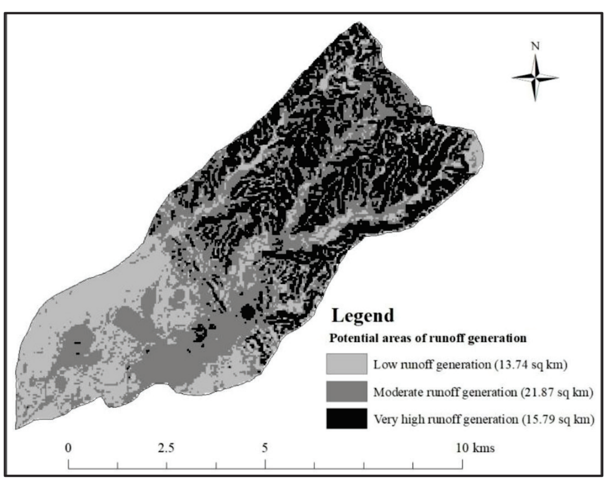

Fig. 6: Map demarcating suitable runoff potential zones

It is evident that runoff potential in a major part of the upstream area was high, which might be due to the steeper slope, heavy-textured soils, and dense hydrological networks. In the downstream area, a large portion of the area had low runoff potential due to presence of plain agricultural lands, and light-textured soils; and a minor part had moderate runoff potential due to presence of plain built-up, and fallow lands. Hence, there exists a good scope for constructing water harvesting structures in the study area, and utilizing the harvested runoff in the lowland agricultural area where the topography is almost plain. In case runoff water is allowed to flow in the lowland plain area near the outlet, it would get enough infiltration opportunity time, and the quantity of runoff passing through the outlet would be significantly low.

CONCLUSIONS

Land and water resources development mainly depends on the hydrologic response of a watershed. Hydrologic response of the *Patiala-Ki-Rao* watershed was studied based on geomorphologic, topographic, soil texture and land-use characteristics using remote sensing and GIS techniques. The results of these characteristics indicated that runoff generation in the watershed was moderate to high, and runoff at the watershed outlet was low to moderate. GIS-integrated map of three thematic layers, i.e., slope, soil texture and land-use showed that some parts of the watershed had high runoff potential. Hence, the runoff generated in those parts might be effectively utilized in plain agricultural lands by constructing water harvesting structures for efficient use of land and water resources in the watershed. This might, in turn, help in sustaining the livelihood of inhabitants.

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