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Research Article

Exploring Surface Runoff Potential and Water Harvesting Sites in Dera Ismail Khan Rod-kohi Area Using GIS and Remote Sensing

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Abstract: Hill-torrent floods are becoming a serious hazard owing to the changing climate in the arid region of Pakistan. A large amount of floodwater is lost due to mismanagement, which results in the loss of valuable lives and property downstream every year. In the present study, surface runoff potential was investigated and water harvesting sites were identified for sustainable irrigation in the rod-kohi region of Dera Ismail Khan district of Khyber Pakhtunkhwa province using GIS and RS techniques. Overall 533 water harvesting sites were identified with total runoff potential of over 154 million m^3 in the target hill-torrent region using geospatial modeling techniques coupled with ground information. For water harvesting interventions, 26 sites were finally selected over the plain to gentle slopes in unused land below 300 m elevation. Cost-effective earthen water reservoirs could be developed for future runoff water harvesting in this region. An integrated floodwater management approach encompassing containment of environmental degradation, institutional strengthening, and capacity building of the locals will have to be adopted for the effective development of this region in the future.

Keywords: Hill-torrent flood, Remote sensing, Rod-kohi, Water harvesting.

1. INTRODUCTION

Water shortage is a major obstacle in many arid and semi-arid regions of the world including Pakistan for sustainable development and poverty alleviation, which can be further aggravated by global climate change [1]. The potential hydrological effects of climate change are increasingly contributing to the uncertainty in water availability in the Indus basin [2-3]. Hill-torrent flood studies have been conducted in countries, like Egypt [4], Saudi Arabia [5-6], Nigeria [7], South Korea [8]. Pakistan is highly vulnerable to water stress in response to growing water demand and climate change [9-11]. Hill-torrent floods have an extreme impact downstream due to their flashy and unpredictable nature [12-13] and often result in serious economic, social, and environmental effects [2]. The growing food requirements of the country under a projected increase of 213 million in population till 2025 are exerting tremendous pressure on the agriculture sector and the natural resources like land and water, which are the medium of food production. Increasing water use is placing demands and constraints on the natural environment as water resources become depleted [14-15]. The last drought span (1998-2003) has also sensitized the planners and policymakers for the need for major investment in the water sector such as building new reservoirs and improving the operation of irrigation infrastructure. In this scenario, ensuring food security and triggering economic growth of the country require to elevate the efforts of water management at micro and macro levels. Hill-torrent flows and floods have potential prospects to meet the growing demands of water for agriculture in the country [16]. Rainwater harvesting (RWH) offers potential as a means to reduce the demand for potable water in non-consumptive use and is particularly important in the arid and semi-arid regions [17] to reduce the risk of extreme climate events like droughts/floods.

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The annual rainfall in the majority of the hill-torrent region of Pakistan is very low and patchy but brings a large amount of floodwater with each event [18]. During the 2010 flood, the hill-torrent region of Dera Ismail Khan (D.I. Khan) in Khyber Pakhtunkhwa province generated high floods that destroyed valuably cultivated and built-up land in the downstream (Fig 1). Despite water shortage in the area, a heavy amount of floodwater is lost due to mismanagement, i.e., unavailability of any kind of storage and modernized engineering structures to control the torrent flows [19-21]. The poverty in the area is miserable along with heavy flood flows calls for rational and systematic floodwater management to enhance agricultural productivity and economic growth in the region.

The Remote sensing (RS) technique provides an efficient way of studying the existing land resources and floodwater extent, whether in the inaccessible areas, minimizing the expenses involved in regular field surveys [22]. Bakir et al. [17] utilized GIS and RS techniques for rainwater harvesting in the Syrian Desert, Al-Badia. Saher et al. [16] applied GIS and RS techniques to identify the potential sites in the Vehowa command area in the western part of Punjab province for harnessing floodwater. Andrew Lo et al. [23] identified the best suitable sites for harvesting rainfall by using the SWAT model. There is a need to identify resource potential and suitable water management strategies to enhance agricultural productivity and economic growth in the Rod-kohi areas [24]. The main focus of this study is to assess surface runoff potential and identify water harvesting sites for sustainable irrigation in the rod-kohi region of D.I. Khan district using GIS and RS techniques.

1.1 Hill-torrent irrigation

The hill-torrent floods originate from high mountains of the Suleiman range in the west. The major problem of the hill-torrent areas is the variability in the amount and distribution of surface flows for irrigation use [25]. During flood season, the hill-torrent water (locally 'Rod Kohi- Rod mean torrent and 'kohi' means hill/mountain) is diverted to the agriculture lands by traditionally made sand diversion barriers through the torrent. The primary purpose of the irrigation cum flood control scheme to control the floods and manage this flood water more effectively and judiciously [26].

Risk types identified in this region include Excessive flood water availability; water shortage during drought; Siltation in channels owing to uplands' erosion; deposition of sedimentation in the fields; Salinity due to flood ponding; Inappropriate water application in the fields and non-observance of water rights. The design of any irrigation scheme is usually based on benchmark objectives like to equitably distribute the flood water as per requirement; to make sure the supply of irrigation water to all stakeholders; to reduce the community disputes on water issues, and to improve the socio-economic status of the community.

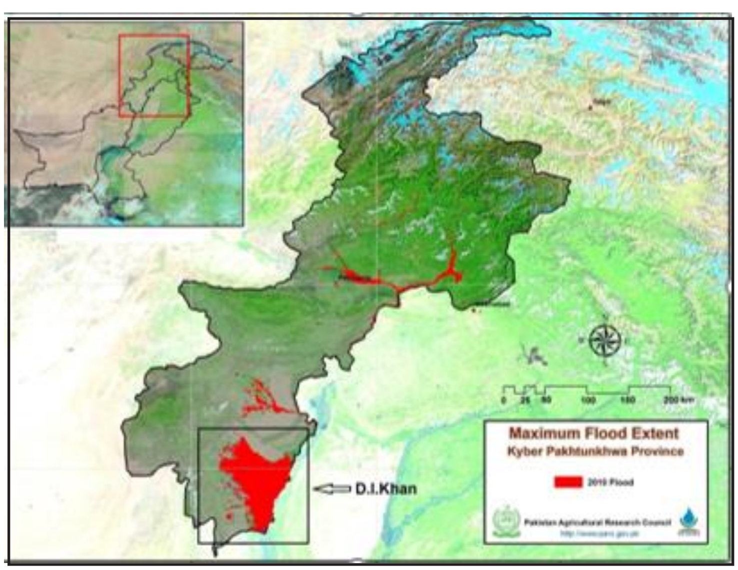

Fig 1. The extent of hill-torrent flood in D.I. Khan district, Khyber Pakhtunkhwa province during 2010

The high velocities of floodwater generally damage stream banks and degrade agricultural lands due to erosion [27]. The farmers construct fields by making embankments of about 1.5–3 m (1.8 m) depending on the type of soil, share in water, and other factors to store water. Embankment fields are filled up with water, which is allowed to soak in, after which the field is plowed and sown. Timings of the flood are late February to March for summer crops and heavy flood in monsoon from July to August for winter crops. Mostly farmers irrigate their fields at the end of August to mid of September depending on the embankment of the field. Later, when the favorable season come farmers sow their fields. The majority of the farmers keep livestock as back-up support for their livelihood.

1.2 Description of the study area

The hill-torrent region of D.I. Khan stretches over an area of 4982 km^2 (about 68% of the total district area) between longitudes 70° 11′ and 71°20′ E and latitudes 31° 15′ and 32° 32′ N on the west bank of River Indus in the southeastern part of Khyber Pakhtunkhwa province, Pakistan (Fig 2). The climate in the district is arid to semi-arid with hot summers and moderately cold winters. Mean annual rainfall ranges between 180–305 mm (1980-2009 period). More than 50 percent rains are received during the monsoon period (July-September), the rest in late winters and early spring from February to April. Mean temperature varies from 26°C to 44°C in the summer and 4°C to 20°C in the winter. The area consists of rugged topography with numerous dry, intermittent, and few perennial nullahs. The altitude of the area ranges between 150 m to more than 1200 m. The elevation gradually increases from the flood plain in the east towards the mountainous area in the west. The average slope is 2% ranging from Indus River to the foot of Suleiman Range. Gravel fans form distinct Piedmont zones while the sub-Piedmont zone is characterized by gentle slope and finer sediments (sand and silt). The piedmont plains are found in the local alluvium derived from adjoining mountains, where soils are generally medium to coarse textured partly gravelly (Fig 3). Gravel and sand deposits, braided stream pattern and bad-land topography characterize the Piedmont Plain. The soils belonging to Pleistocene Piedmont terraces are moderate to strongly calcareous mainly silty to clayey with low organic matter [25]. The soils on higher elevations have homogenized to moderate depths but others are invariably stratified. The Sub-Piedmont Plain contains fine-textured soils and is traversed by numerous small, meandering, dry channels, which have their origin in the Piedmont Plain.

Not all the runoff water is generated from inside the district boundaries but large runoff water, generally in the perennial form is coming from the

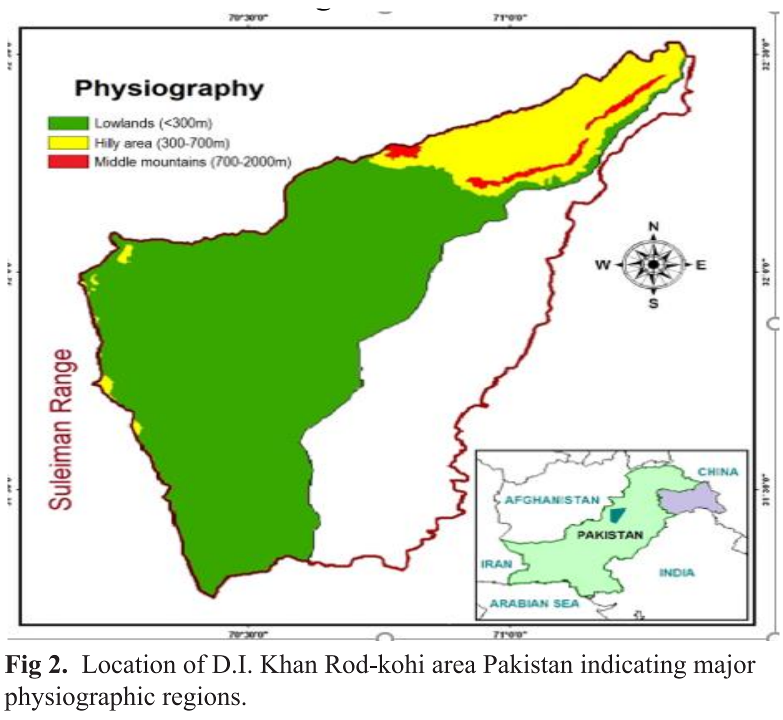

Fig 2. Location of D.I. Khan Rod-kohi area Pakistan indicating major physiographic regions.

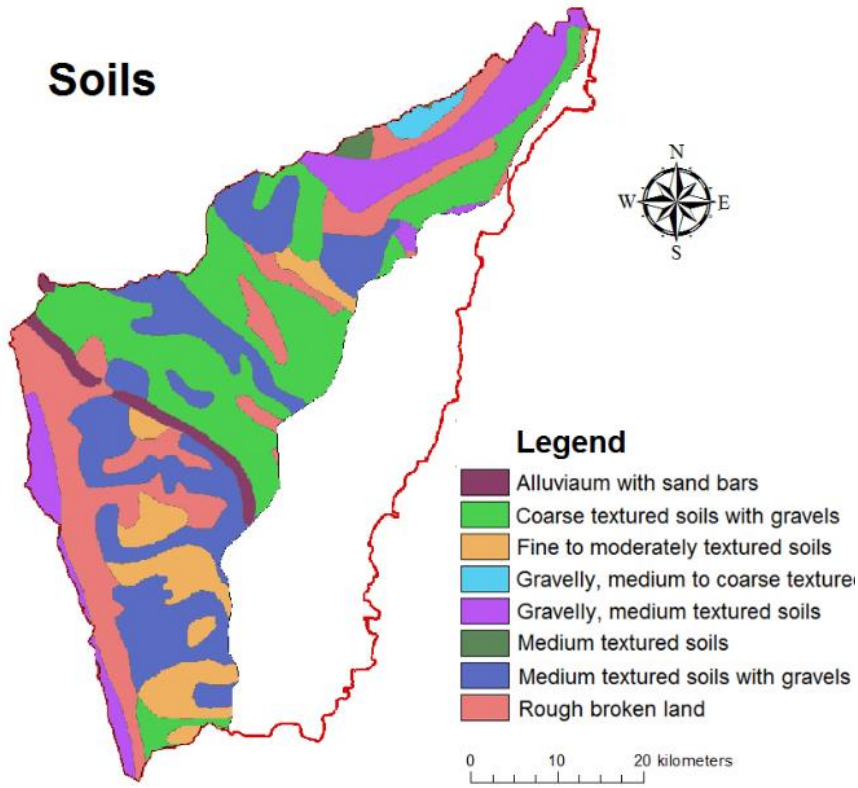

Fig 3. Distribution of soil classes in D.I. Khan Rod-kohi area.

catchments lying outside in the west in Baluchistan province. The main sources of income are subsistence agriculture and livestock rearing. Major crops in the summer are millet (bajra and jawar) and maize, and in the winter are wheat, chickpea, and oilseeds. Millet crops are grown given its deep root system, low water requirements, and better drought tolerance. Besides, vegetable and fruit crops are also grown where limited perennial water is available for sustainable farming in the area.

2. MATERIALS AND METHODS

2.1 Data used

The remote sensing data of LANDSAT 8 was acquired from the USGS site (http://glovis.usgs.gov/) for land use/land cover (LULC) analysis of the study area. The Google Earth images were used to supplement the image analysis and support in the selection of appropriate water harvesting sites. The digital elevation model (DEM) of the shuttle radar topography mission (SRTM) of 30 m resolution was downloaded from the web site (http://www.gdemaster.ersdac.or.jp/) for delineation of catchment boundaries, drainage network and physiographic zones based on elevation as defined by Hubert [28]. The zones include Lowland (<300 m); Hilly area (300-700 m); Middle mountain (700-2000 m) and High mountain (>2000 m). The rainfall data of 12 climate stations lying within and in the vicinity of the study area (Table 1) was acquired from the Pakistan Meteorological Department (PMD), Islamabad to generate a rainfall map. The elevation of these station ranges between 9 m and 1725 m, while annual rainfall varies between 76 mm and 698 mm. The soil map was acquired from Soil survey of Pakistan and related information from the soil survey report of D.I. Khan district [29]. Socioeconomics, land use, and ground control points (GCPs) data were collected through field surveys aided with the global positioning system (GPS).

2.2 Geospatial data preparation

The geo-databases and spatial data layers of topography, hydrology, soils, and land use were developed in ArcGIS software. The topographic features like drainage, locations, and boundaries were extracted from topo-sheets of a 1: 50,000 scale through scanning and on-screen digitization in GIS. The data layers were geo-referenced using Universal Transverse Mercator projection (Zone 42: datum WGS 84) for data integration and modeling. The Landsat 8 image data was processed and analyzed through visual as well as digital interpretation to analyze land cover/land use of the study area. The first step in the land cover classification is the stacking of layers obtained from USGS. Stacking the band layers give a composite image by combining separate base layers. Layer 2, 3, 4, 5, 6, 7 were stacked. For better results, the whole image was classified and in the end, the study area was then separated by sub-setting of image. Stacking of layers and image sub-setting was done in ERDAS imagine. Supervised Classification was performed in ArcMap through the Isocluster tool. It was categorized into 6 classes, i.e., forest, cropland, rangelands, rocks, bare soil, and water. The settlement was included in the bare soil class as the area is sparsely populated. Later quantitative analysis was performed to assess the extent of different land use classes in the area.

ArcSWAT model was downloaded from the web link: http://swat.tamu.edu/software/arcswat to delineate catchment boundaries and generate a river network. The outlet of the catchments (here sub-basins) was marked that served as a base to generate catchment boundaries from DEM using the Watershed delineation tool of the model. The SWAT operated in ArcGIS is a watershed model used to study the impact of agricultural and land-use management activities on the overall watershed health including streamflow and water quality [30]. The flowchart of the methodology followed in the study area is shown in Fig 4. The threshold value was set at 500 ha. The rainfall and elevation data of 12 climate stations (Table 1) were used to develop a regression equation between the two variables (Eq. 1) which was input in the raster calculator tool of ArcMap to generate rainfall map in raster format.

$$[R] = 0.26 * [DEM] + 103 \quad (1)$$

Where R represents mean annual rainfall (mm) and DEM represents elevation (m). The zonal statistics function of ArcMap was used to determine to mean annual precipitation at each catchment which was later applied to estimate rainfall volume (Q_{rv}). The surface runoff (Q_{sr}) was estimated through multiplying the rainfall volume (Q_{rv}) by runoff coefficient C (i.e., 0.26) derived from studies conducted by NESPAK [31] for the Suleiman region following Eq. 2.

$$Q_{sr} = Q_{rv*}\ 0.26 \quad (2)$$

The net runoff water potential (Qrp) was estimated using the surface runoff (Q_{sr}) and the water use (Q_{wu}) measured in m3 via water balance Equation 3:

$$Q_{rp} = Q_{sr} - Q_{wu} \quad (3)$$

The water use (Q_{wu}) was assessed from water diverted through existing flood management and

Table 1. List of Climate stations covering the study area

S. No.	Climate Station	Longitude (degree)	Latitude (Degree)	Elevation (m)	Annual Rainfall (mm)
1	Barkhan	69.56517	29.84872	1097	386.9
2	Zhob	69.44791	31.35591	1405	276.6
3	Hyderabad	68.34617	25.37951	28	124.7
4	Jacobabad	68.47583	28.28260	55	79.9
5	Multan	71.47382	30.19393	122	177.5
6	Nawabshah	68.32786	26.24199	37	105.4
7	Padidan	68.25849	26.77505	46	81.6
8	Pasni	63.45069	25.26475	9	91
9	Rohri	68.88000	27.68000	66	76
10	Sibbi	67.85718	29.54932	133	143.6
11	Parachinar	70.08733	33.91701	1725	698.2
12	D.I.Khan	70.89000	31.83000	171	269.3

irrigation schemes to sustain livelihood of the local communities. The irrigation schemes are generally meant to supply surface water for raising crops and orchards in the area. The low flows and part of the flood flows from streams are utilized for irrigation through construction of diversion channels over them. For domestic and other purposes, inhabitants generally prepare open ponds to store rain and runoff water for their use. The runoff water potential from all the catchments was summed up to acquire total runoff water potential in the study area.

3. RESULTS AND DISCUSSION

3.1 Rainfall variability and trend analysis

The rainfall exhibits high annual variability with an annual mean of about 292 mm of which 72% is received during the Kharif season (April-September) and the rest during Rabi season (October-March). In total rainfall, about 22.1% rains are received in the 1st quarter (January-March), 20.6% in the 2nd quarter (April-June), 51.5% in the 3rd quarter (July-September), and 5.8% in the 4th quarter (October-December) of the year. Overall rising trends in annual and monsoon rainfall were observed at D.I. Khan station during the 1980-2009 period (Fig 5). The trends were positive for both rabi and Kharif seasons, and also for all quarters except the second one, i.e., the slight declining trend in rainfall during the April-June period is likely due to a shift in rainfall pattern. The trend of yearly monsoon rainfall of the July-September period is comparable to the annual rainfall trend. The monsoon precipitation in Pakistan has been enhanced by 22.6 mm and winter rainfall by 20.8 during the 1901-2007 period [32]. Given that rainfall and urbanization are expected to increase following climate change, likely, flood risk will also increase [33]. In 20% of cases, annual rainfall exceeds 400 mm, and 48% cases exceed 300 mm. The monsoon exhibited more than 200 mm rainfall per annum in 25% cases of 40 years in D.I. Khan.

3.2 Assessment of Surface runoff potential

The study area was divided into three physiographic zones, i.e., lowlands (<300 m) over 90.1% area, hilly area (300-700 m) about 9.8%, and middle mountains (700–2000 m) over 0.1% area through the classification of DEM data in a GIS environment. The image classification of the area indicated rangeland over 48%, exposed rocks over 33%, open soil about 10%, and tree cover over 9% area (Fig 6). Overall 533 catchments were identified in the hill-torrent area, most of which, i.e., 84% lie over lowlands below 300 m elevation and 16% over the hilly area within 300–700 m elevation range.

The total runoff water potential estimated in 533 catchments was about 154 million m^3 (MCM). The annual water potential according to areal ranges of the catchments is shown in Table 2. The thematic layers of physiography, slope, soil, and LULC (as shown in Fig 6) were used to select 26 water harvesting sites. Sites were selected over the plain to gentle slopes, rangeland/barren lands below 300 m elevations (Table 3 and Fig 6). The soils of these catchments are mostly non-erosive that would favor the development of future water harvesting sites in the downstream. The major determinants of developing specific site intervention include topography; soil type; water and arable land availability; social acceptability (water rights); environment impact, and economic viability [31].

3.3 Water harvesting options

The construction of farm ponds/reservoirs and storage tanks ensures a sustainable water supply during the lean period of water availability, thus support climate risk reduction. These structures introduced with the consensus of both upstream and downstream communities not only help in reducing the risk of flood hazard but also aid in recharging the subsurface aquifer. Other benefits of these interventions include, funds incurred on flood relief activities and rehabilitation expenditure would be avoided; more water will be available for irrigation due to streamlined flow without any disturbance. People would be able to utilize this controlled water in a better way, as the intensity of the floodwater would be broken and only a manageable quantity

Table 2. Water potential in catchments according to the areal ranges

Area (km^2)	Number of catchments	Percentage sites in each areal range	Annual Potential (MCM)
0 - 3	200	37.7	3.5
3-7.0	131	24.7	27.78
7.0-13	119	22.4	51.29
13-21	56	10.5	42.36
21-50	25	4.7	28.91
Total	531	100	153.84

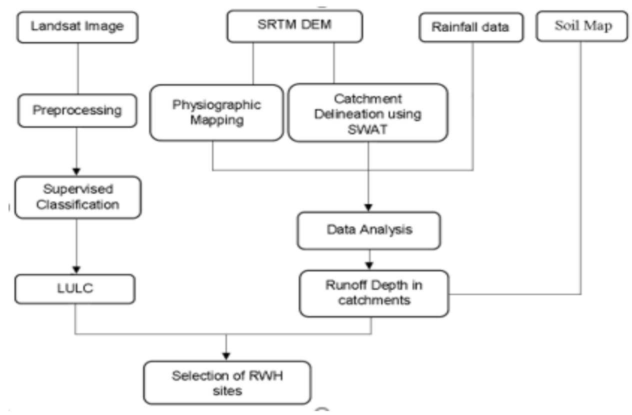

Fig 4. Flowchart of the methodology adopted in Present Study

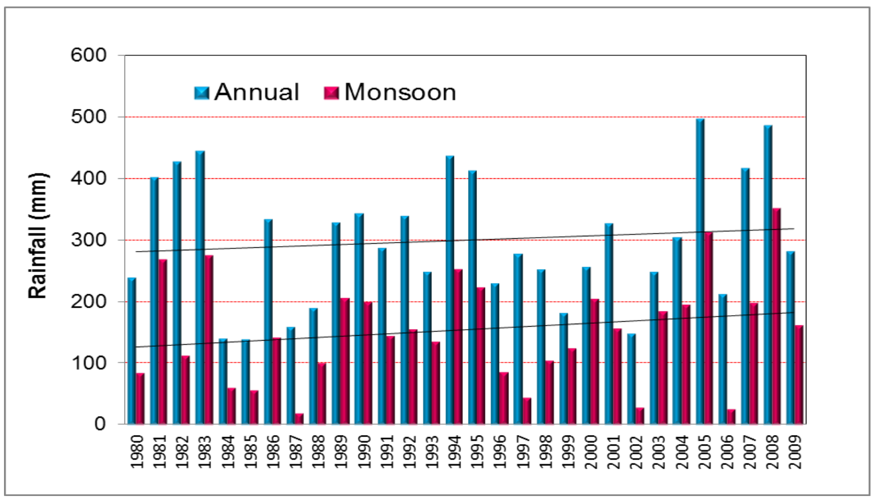

Fig 5. Annual and monsoon rainfall trends in D.I. Khan area.

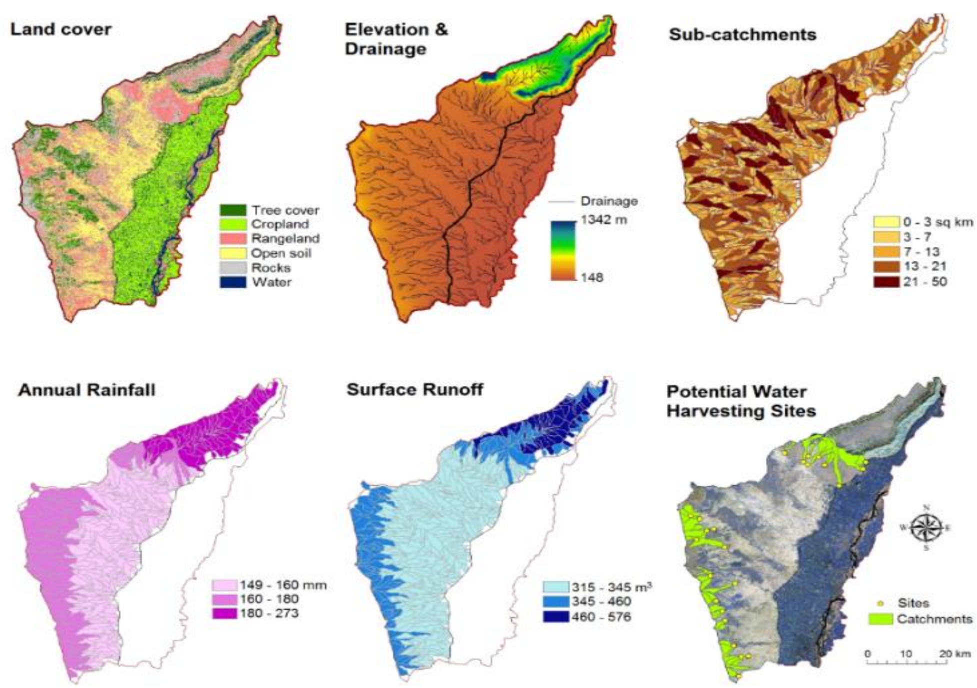

Fig 6. Thematic data layers generated for assessment of runoff water harvesting potential and sites in D.I. Khan rod-kohi area

Table 3. Water harvesting potential in selected catchments

S. No.	Longitude	Latitude	Catchment Area (km^2)	Annual Water potential (MCM)
1	70.38336	31.64535	35.50	1.16
2	70.43606	31.17832	11.75	0.38
3	70.26145	31.68336	5.36	0.18
4	70.30669	31.71843	21.52	0.70
5	70.38091	31.33268	7.74	0.25
6	70.42472	31.48964	18.09	0.59
7	70.27789	31.76967	3.82	0.13
8	70.32077	31.52701	13.96	0.46
9	70.98589	31.94353	49.54	1.62
10	70.34233	31.41939	13.15	0.43
11	70.23937	31.78589	10.90	0.36
12	71.00048	31.96983	13.37	0.44
13	70.82055	31.96869	6.14	0.20
14	70.79609	32.00337	18.61	0.61
15	70.75195	32.01038	5.65	0.19
16	70.31714	31.714145	9.65	0.32
17	70.41629	31.22651	6.96	0.23
18	70.44838	31.17862	10.90	0.36
19	70.88267	31.87787	38.04	1.25
20	70.33534	31.72368	8.92	0.29
21	70.36857	31.37447	5.11	0.17
22	70.47899	31.09504	9.83	0.32
23	70.23937	31.78616	8.44	0.28
24	70.64880	32.03028	5.69	0.19
25	70.74742	31.97381	24.12	0.79
26	70.73017	31.98712	25.37	0.83

of water would flow into their channels and on to their lands [26].

The farmers' perception about the hill-torrent floods is that they are instantaneous, not permanent, and are an unreliable source of irrigation and they have a high velocity which may cause severe damages if not managed properly. Through the application of mechanized agriculture technologies like tractors and bulldozers, farmers become able to control the flood and irrigate the land according to their needs as compared to the old system.

4. CONCLUSIONS

In the present study, surface runoff potential was assessed for irrigation in the rod-kohi region of D.I. Khan using GIS and RS techniques. The Remote sensing and GIS techniques coupled with ground information proved helpful in identifying potential sites for rainwater harvesting and developing flood management strategies for the difficult to access hill-torrent region. The Rod kohi area in D.I. Khan has vast potential for agriculture development due to the presence of abundant water which remains unutilized and goes unused into the Indus river. Surface runoff potential of about 154 MCM was estimated in the 533 catchments, which can be utilized for irrigation use through adopting conservation measures like construction of small/ mini dams, ponds, storage tanks, and establishment of a network of diversion and dispersion structures. For water harvesting interventions, 26 sites were finally selected over plain to gentle slopes of the unused land below 300 m elevation. Water conservation through the construction of series of small and mini dams may be adopted on some torrents to store excess water then release it as small perennial flows throughout the year. This will not only minimize the flood damages but also ensure regular irrigation supplies in the area. An integrated floodwater management approach encompassing containment of environmental degradation, institutional strengthening, and capacity building of the local's inefficient water use will have to be adopted for the effective development of this region in the future.

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