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Spatial trends in surface runoff and influence of climatic and physiographic factors: A case study of watershed areas of Rawalpindi district

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Abstract

Effect of climatic and physiographic factors on surface runoff is critical to study for soil conservation and water harvesting. In this study, the spatial variations of climatic and physiographic factors and their spatial correlation with surface runoff was investigated. The rainfall and temperature records were used for mapping climatic factors. Digital Elevation Model (DEM) was utilized in estimation and mapping of physiographic factors as well as watershed delineation and runoff estimation. The models were generated using runoff and influencing factors (rainfall, temperature, slope and elevation). The relationship between runoff and influencing factors was derived by developing statistically sound regression models. The spatial correlation indicated that the maximum surface runoff was generated in the areas receiving high rainfall (>1450 mm) whereas, runoff tend to decrease with rise in temperature above a certain value (18 ˚C). The runoff also showed significant variability with slope and elevation changes. Maximum change in runoff was predicted by one unit change in temperature followed by elevation, slope and then rainfall. The regression model was found to be adequately fit to the predicted runoff by using influencing factors. The study identified potential water harvesting sites for sustainable water supply in Rawalpindi district.

Keywords: Runoff, hydrology, water sustainability, rainwater harvesting, soil conservation

Introduction

Sustainable development of water resources is necessary to achieve multi-dimensional social and economic growth of a country (Meshram *et al*., 2015). Watershed is an area of land that drains all the streams and rainfall water to a common point (USGS, 2017). Watersheds show variations in their hydrological response to the particular climatic and physiographic conditions of a region. These variations arise due to the surface and subsurface hydrological processes. The interaction of spatial, physiographic and climatic factors determines the hydrological response of a watershed (Kirkby *et al*., 2002).

Hydrology deals with the nature, movement and environmental functions of natural water (Younger *et al*., 2002). The runoff generated due to heavy rain influences the hydrological cycle. The surface runoff within a watershed is an important indicator for the assessment of water yield potential. Watershed potential is greatly helpful in designing soil and water conservation strategies (Shi *et al*., 2009). The variations in runoff can largely be explained by climatic factors. Long-term variations in runoff are highly consistent with climatic factors. The annual runoff magnitude is directly influenced by precipitation (Du and Shi, 2012). The rainfall intensity, its duration, distribution and magnitude have greater impact on runoff and sediment yield (dos Santos *et al*., 2017). Air temperature has minimal effect on runoff compared to rainfall. However, temperature may become more influential if it continues to increase over time (McCabe and Wolock, 2011).

Geographical information system (GIS) is helpful in mapping hydrological factors, watershed delineation and estimation of surface runoff (Mekonnen *et al*., 2016). Digital Elevation Models (DEMs) provide a sampled arrangement of elevation for ground positions at regular intervals. DEMs offer suitable terrain illustration such as land surface, hydrological limits and landscape traits (incline and angle). DEMs are frequently utilized for automated derivations of watersheds by identifying drainage features along with ridges, channel networks, drainage patterns and quantifying sub catchment together with size, length and slope (Garbrecht and Martz, 1999; Deng and Bauer, 2007). GIS based approach is usually applied to identify water flow direction and flow accumulation for every grid point in DEM (Jenson and Domingue, 1988). This tool can also be used for identification of potential rainwater harvesting sites (Munyao *et al*., 2010).

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Physiographic characteristics such as elevation and slope are decisive in watershed related studies. Elevation surface in rainfall-runoff simulations is commonly represented by raster-based DEM (Wu *et al*., 2007). There is a strong correlation of surface runoff and elevation of the watershed (Garcia-Martino *et al*., 1996). Slope length along gradient regulates water flow and has important contribution in runoff generation (Garg *et al*., 2013). Water flow in the streams is greatly influenced by the physical properties of the catchment area. Size of watershed is an important element as well that contributes to stream flow (Rajib and Venkatesh, 2015). However, interception of rainfall and surface and subsurface storage capacities are directly influenced by the vegetation cover within a catchment (Battany and Grismer, 2000).

Spatial correlation is used to derive dependencies between various physiographic and climatic factors (Govorov *et al*., 2017). The relationship between runoff and contributing factors has always been complicated. There is a need for better understanding of these factors influencing runoff over uneven geographical distribution (Kirkby *et al*., 2002). Present study investigated the spatial variation of climatic and physiographic factors and their influence on surface runoff. The derived correlation was used to develop statistically sound regression model to describe the relationship between runoff and contributing factors. Moreover, rainwater harvesting is an exigency for Pakistan due to critically intensifying water scarcity (Javed *et al*., 2016). Present study also identified potential rainwater harvesting sites in Rawalpindi district.

Material and Methods

The study area

The focus of present study was district Rawalpindi, situated at northern part of Punjab province, Pakistan. The district is spread over an area of 5,285 square kilometres. It comprises of seven administrative territories (tehsils) namely Rawalpindi, Taxila, Gujar Khan, Kalar-Syedan, Kahuta, Kotli Sattian and Murree (Figure 1). District Rawalpindi is situated at 33.4095 °N latitude and 72.9933 °E longitude. The elevation ranges between 300 and 2790 meters above the sea level. Climate varies between various

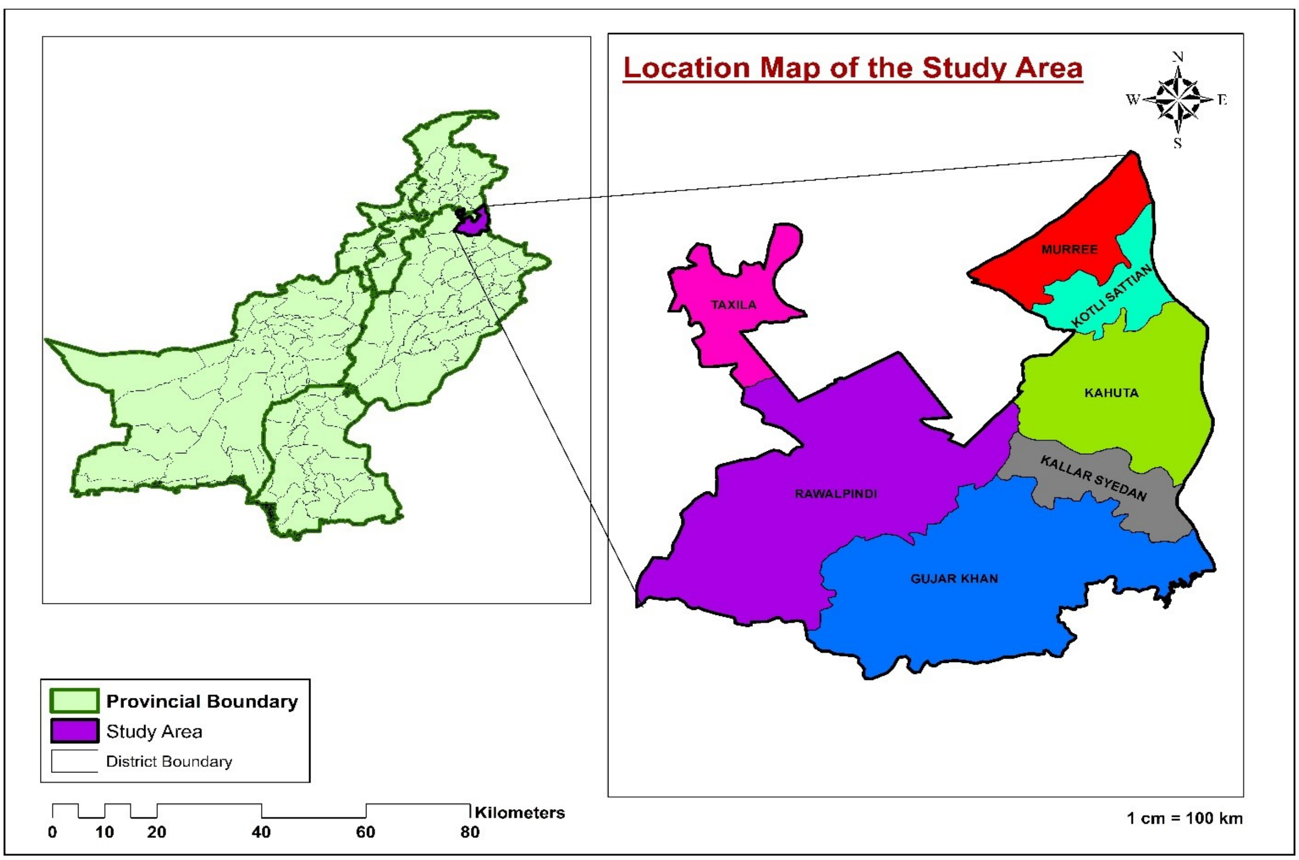

Figure 1: Map of the study area

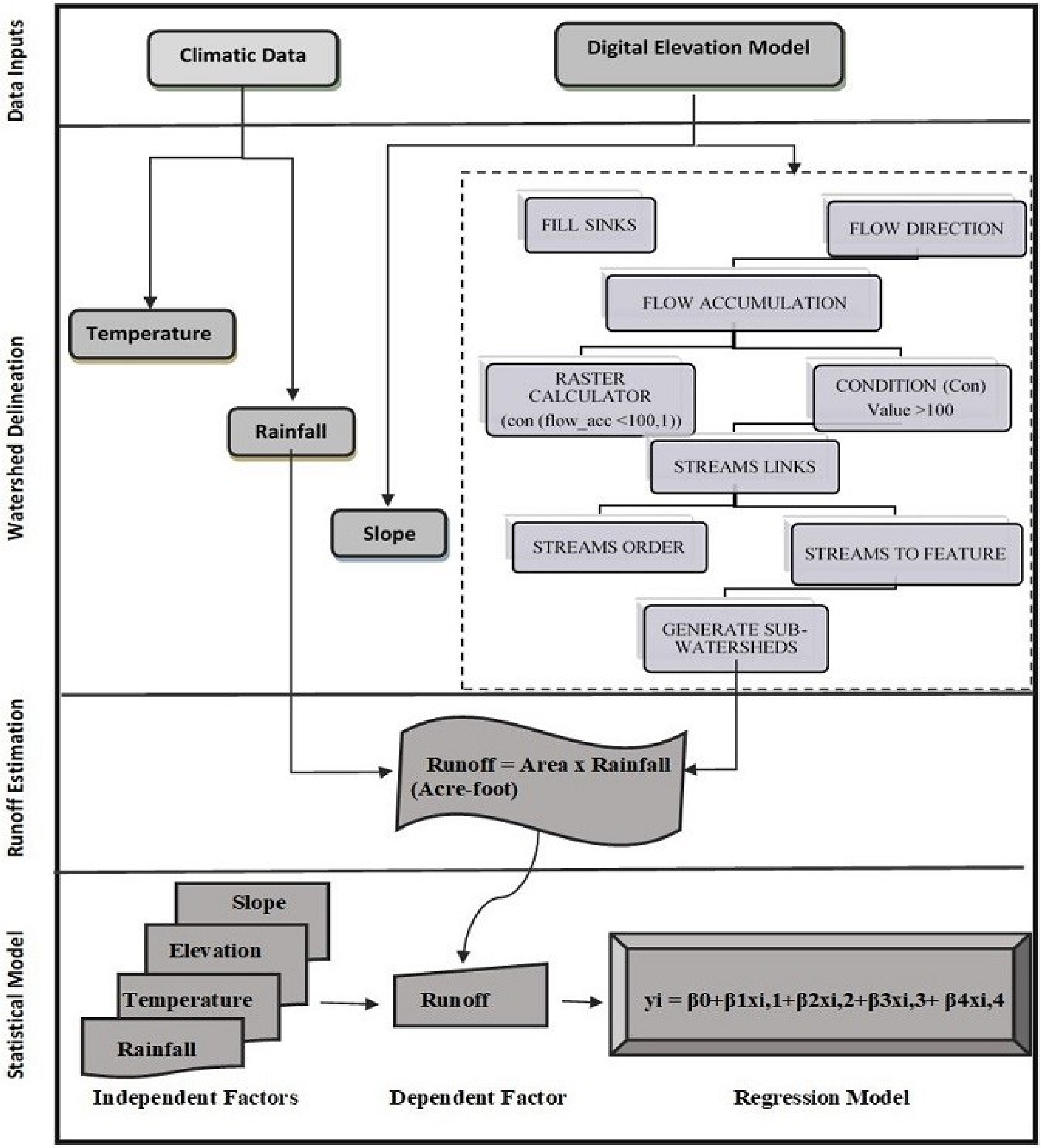

Figure 2: Flow chart of research design

parts of the district. Northern part of the district has severe winter and mild summer (e.g. Murree) while Southern part has hot summer and moderate winter (e.g. Gujar Khan). The mean maximum temperature ranges from 25.6 °C to 39.4 °C in June and the mean minimum temperature ranges from 3.2 °C to 16.7 °C in January. Mean annual precipitation is 1550 mm with maximum in tehsil Murree. The topography of the land mainly comprises of hills whereas southern part of district is generally plain (DOI, 2012). The northern part is located in the mountainous terrain of Margala hills, Hazara and Kala Chitta Ranges. The terrain gradually falls off towards the Kurang River in the East and Lai Nullah in the West that joins the Soan River in the Southern side (EIA, 2005).

Study design

The rainfall and temperature records for the period of 30 years (1988-2008) were obtained from Pakistan Meteorological Department (PMD) Islamabad. These records were used for mapping of climatic factors. ASTER DEM of 30 meters spatial resolution was obtained from the United States Geological Survey (USGS website: https://earthexplorer.usgs.gov/). The DEM was utilized in estimation and mapping of physiographic factors. Watershed delineation and runoff estimation were performed using DEM and climatic data. The models were generated for runoff prediction based on influencing factors (rainfall, temperature, slope and elevation). Data flow in present study is given in Figure 2.

Mapping of influencing factors

Hydrology toolset of ArcGIS 10.2.2 was used for the interpolation of mean annual rainfall and mean annual temperature of the study area. Observatory stations for climatic data (temperature and rainfall) of the study area are shown in Figure 3. Since, the point data was available; Inverse Distance Weight (IDW) interpolation method was used. The maps of climatic factors were generated. The DEM was used as a source of elevation data for the study area. Slope was calculated from DEM using spatial analyst

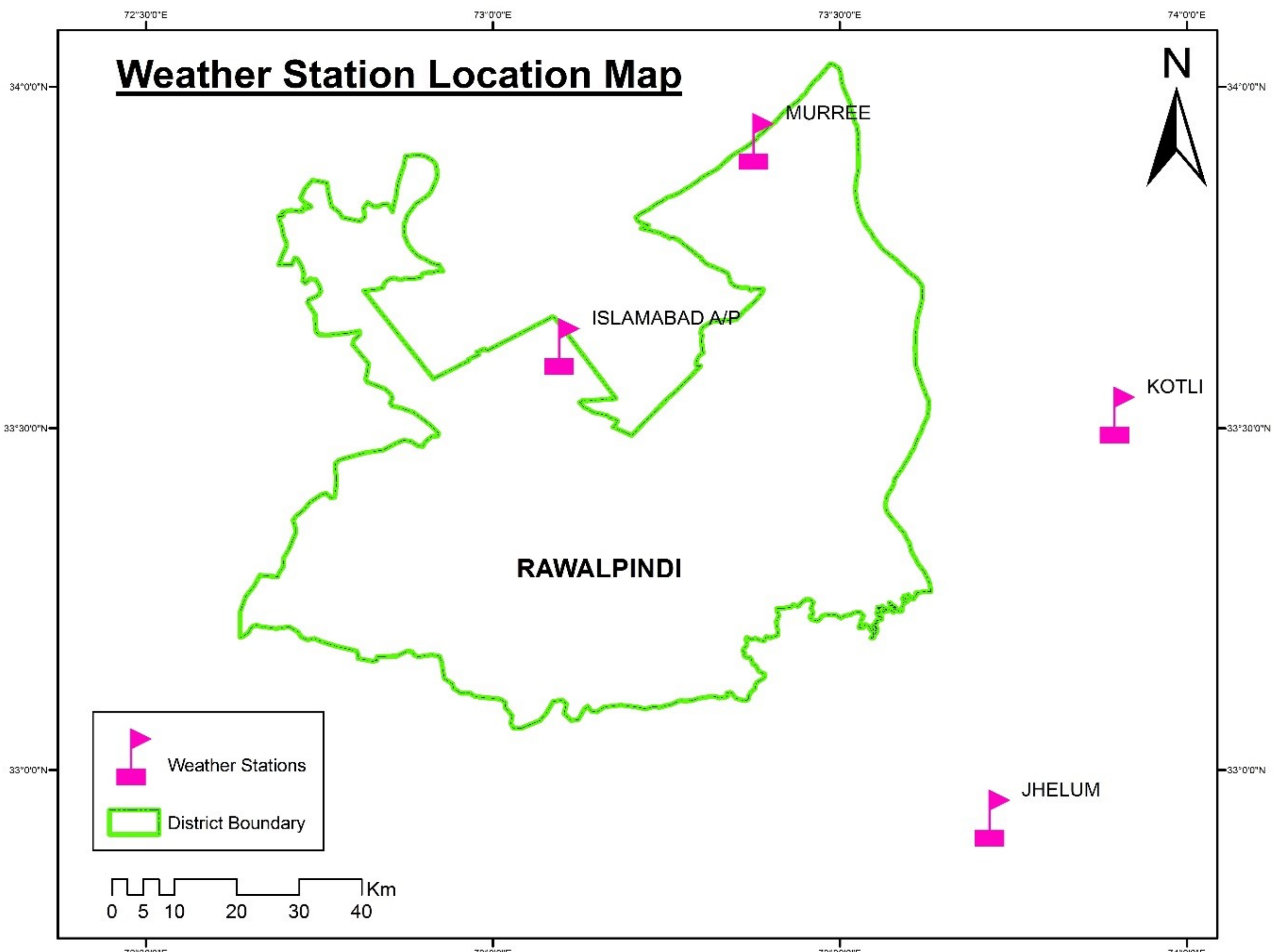

Figure 3: Location of weather stations in the study area

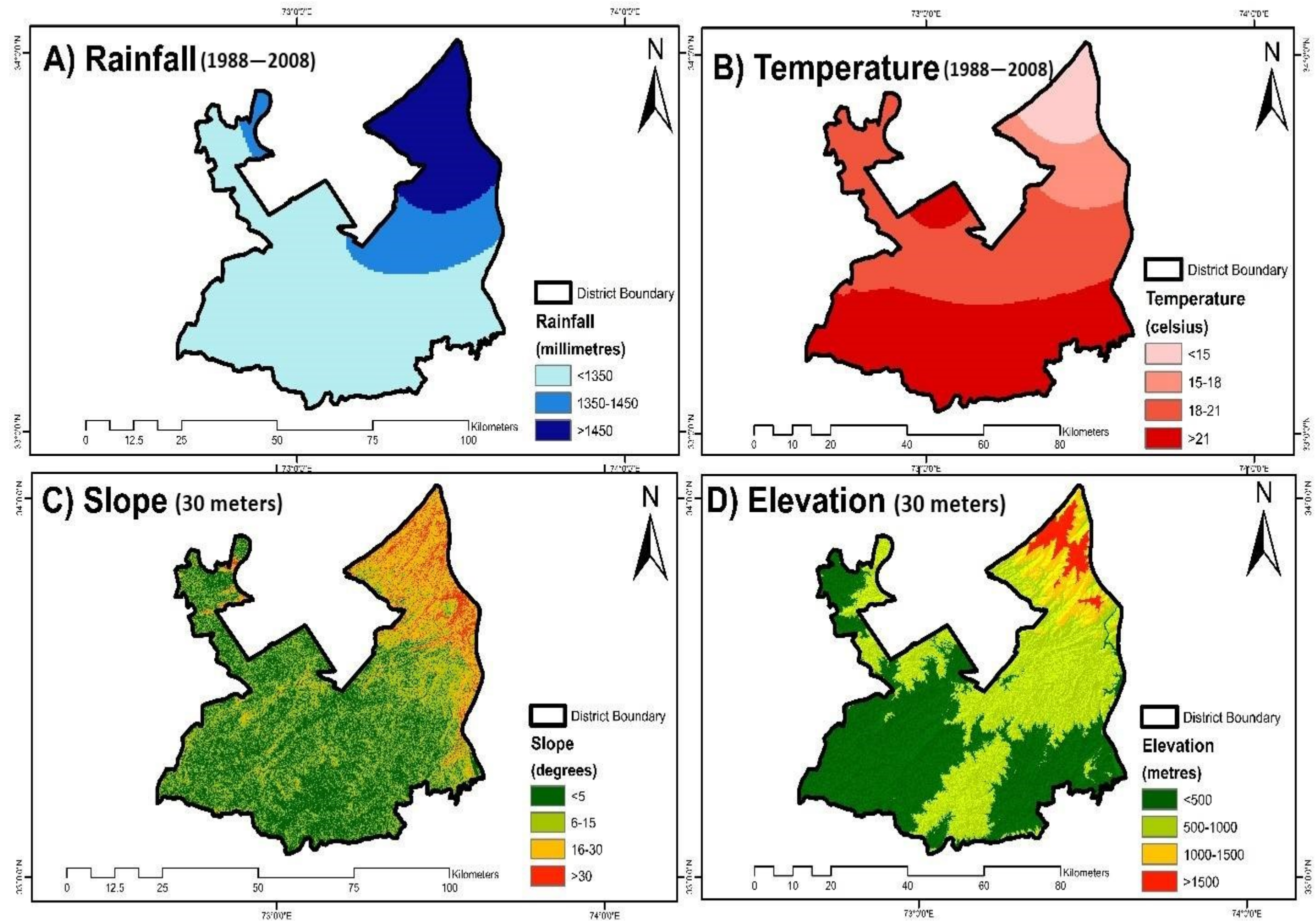

Figure 4: Spatial map of influencing factors for the study area

tool of hydrology toolset in ArcGIS 10.2.2. Maps of influencing factors (rainfall, temperature, slope and elevation) of the study area are shown in Figure 4.

Watershed delineation and runoff estimation

Hydrology toolset of ArcGIS 10.2.2 was used for assessment and modeling of hydrological characteristics. DEM was used as an input for computing elevation statistics for the watershed delineation. Various drainage patterns along with channel networks, channel properties (flow direction, flow accumulation and stream definition) together with size, length and slope were obtained. Stream network was delineated by using the output from flow accumulation tool of hydrology toolset. The stream order tool was used to assign numeric order to links in a stream network and finally watersheds were delineated from stream order.

A variety of models are available for estimating runoff generated by rainfall e.g. empirical models, conceptual models and physical models (Sitterson *et al*., 2017). As spatial variability is not considered in conceptual models and large amount of data is required to run the physical models: Therefore, empirical modelling approach was employed in this study because of its simplicity in calculations and implementation (Dawson & Wilby, 2001; Pechlivanidis *et al*., 2011). Net runoff from an impervious catchment surface was estimated utilizing the precipitation records and size of catchment adjusted by its runoff coefficient (Lancaster and Marshall, 2008). Runoff calculation method is indicated in Equation 1.

$$Q = K \times P \times A \qquad \text{Equation 1}$$

where,

Q = Runoff (liters) A = Area of catchment (m^2)
P= Precipitation (mm) K = Constant

The value of constant is less than or equal to 1. It is generally calculated by weighted average percentage of the land cover. The runoff for each catchment was calculated in the raster calculator of ArcGIS 10.2.2 using Equation 1. The runoff potential was converted from liters to Acre-foot using 'SI' unit as:

1 Acre-foot = 1233481.85 liters.

Statistical analysis

Spatial correlation between runoff and the contributing factors was calculated in ArcGIS 10.2.2 using band collection statistics tool and correlation matrixes were generated. Correlation matrix indicated the strength between the variables at various ranges. Maps of the study area were divided in total 116 grids of resolution (6750 x 6750 meters) to extract the sampling data for statistical analysis. Logarithmic transformation was used for ease of interpretation and it helped to reduce the skewness (Manikandan, 2010). Multiple linear regression analysis was performed on data and model was developed. The regression model used influencing factors i.e. rainfall, temperature, slope and elevation to predict the outcome of runoff. Co-efficient of determination (R^2) was calculated to check closeness of data to the fitted regression line.

Table 1: Results of watershed delineation in the study area

Area of district (sq. km)	5285
Number of watersheds	2687
Streams length (km)	7818
Net runoff (MAF)	2.47

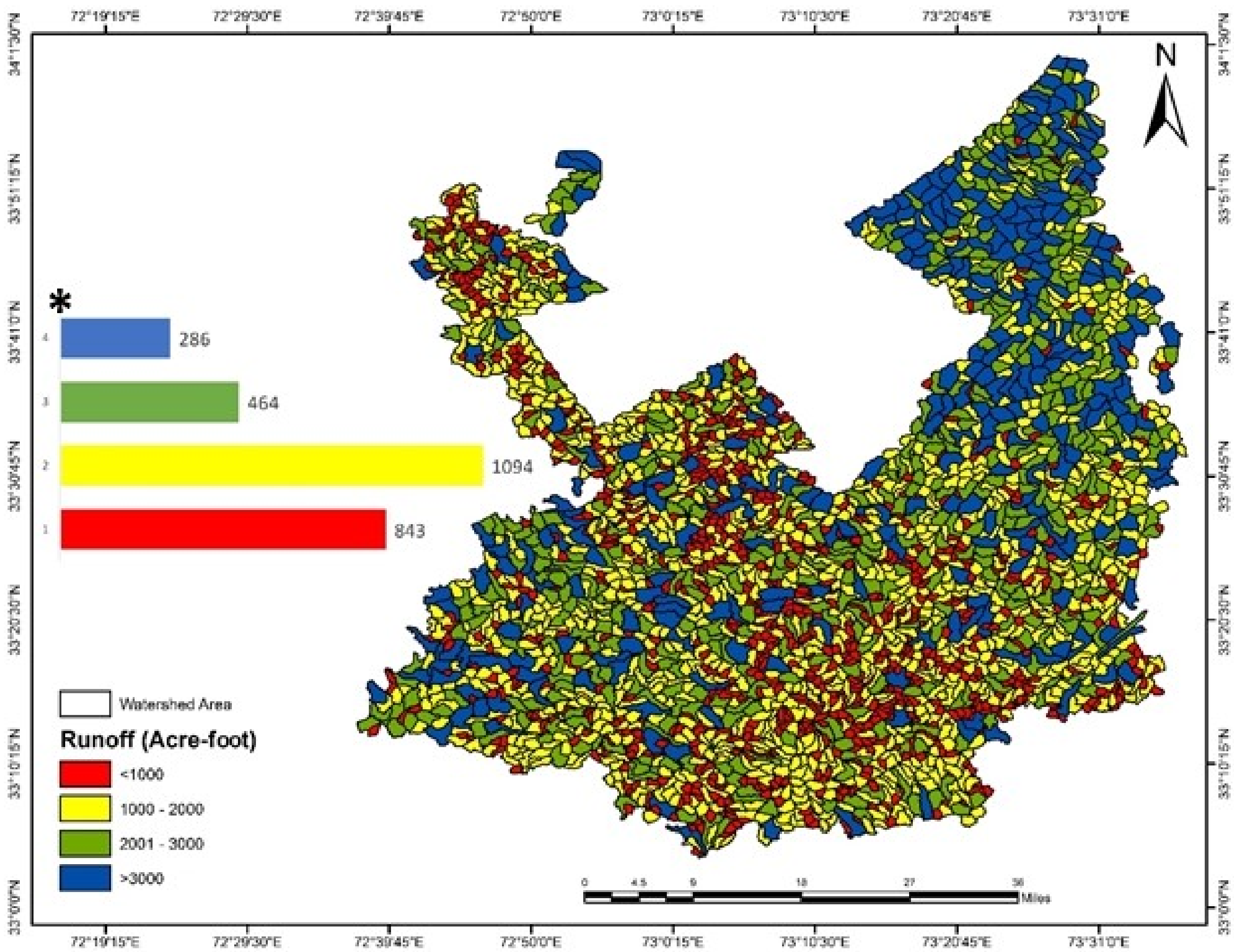

Figure 5: Runoff potential/yield of sub-watersheds in the study area

Results and Discussion

Watershed delineation and estimated runoff

Hydrologic model with the coordination of GIS provided the delineated watersheds. In total 2687 sub-watersheds were delineated with stream length of 7818 km in the study area as given in Table 1. The net runoff estimated in all the watersheds was found to be 2472000 acre-ft per annum. The bifurcation of the runoff indicated that 843 watersheds in the area had runoff less than 1000 acre-ft. per annum while 286 watersheds had maximum runoff of beyond 3000 acre-ft. Maximum number of watersheds (1094) had runoff greater than and equal to 1000 acre-ft to the range of less than and equal to 2000 acre-ft. The number of watersheds having runoff between 2000 to 3000 acre-ft per annum was found to be 464 (Figure 5). Past studies stressed upon the need of rainwater harvesting in the Pothwar region to meet the increasing demands of water. There is large number of small basins in Pothwar region suitable for water harvesting taking into consideration the amount of runoff generated (Ghani *et al*., 2013). Javaid *et al*. (2016) stressed to explore and identify the best rain water harvesting sites to fulfill the increasing demands of food and agriculture activities in the region. Present study properly highlighted the potential and suitability of rainwater harvesting sites in the district of Rawalpindi.

Spatial correlation between run-off and contributing factors

The spatial correlation between surface runoff and contributing factors (climatic and physiographic) was derived in ArcGIS 10.2.2 as shown in Figure 6. The highest correlation (0.7) was found between runoff and area of watershed. This illustrated that water flow in a watershed was largely dependent on the catchment area (Rajib and Venkatesh, 2015). The time for draining the runoff to the outlet is longer in larger watershed compared to small watershed (Balasubramanian, 2017). Climatic factors including rainfall and temperature showed remarkable correlation with runoff as well. Rainfall and runoff indicated positive correlation of 0.35. Shang *et al.* (2019) also verified that there was a direct correlation between rainfall and runoff as the runoff changes were consistent with the rainfall changes. However, the correlation between runoff and temperature was negative (-0.36). McCab and Wolock (2011) also found that increase in temperature resulted in reduction of surface runoff.

Physiographic factors including slope and elevation indicated positive correlation of 0.27 and 0.25, respectively, with surface runoff but their effect was slightly low compared to the climatic factors. The amount of runoff increases in the sloppy watersheds due to greater velocity of runoff (Balasubramanian, 2017). Vegetation cover on the slope of watershed can also play a significant role on the amount of runoff generated (Rashid *et al*., 2015). Garcia-Martino *et al.* (1996) also stated that rate of surface runoff was positively and significantly correlated with elevation of watershed.

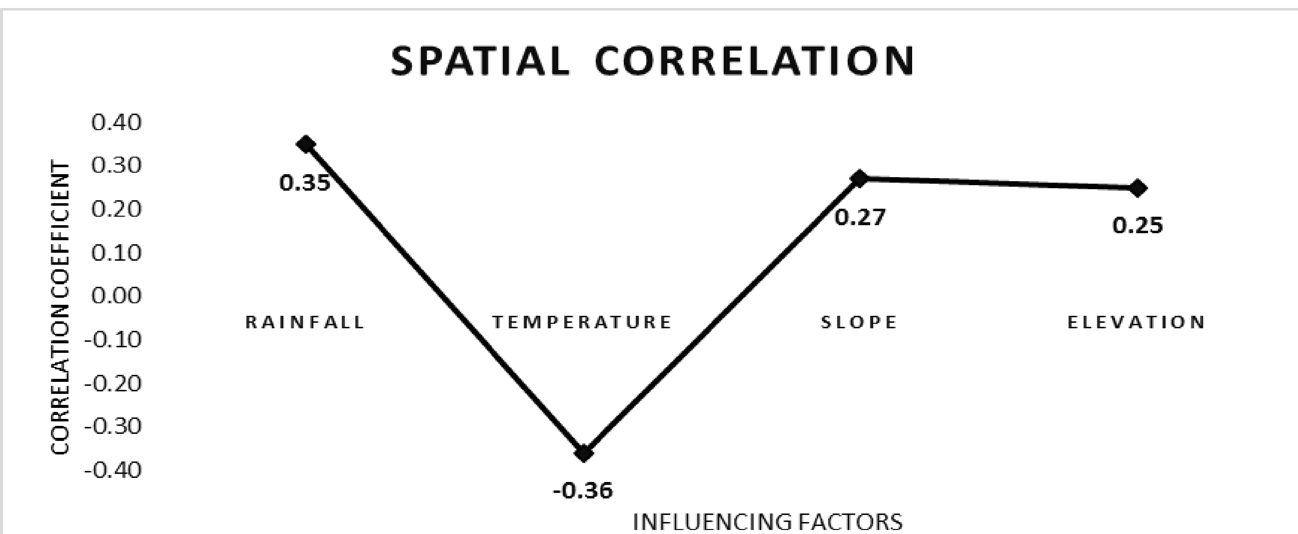

Figure 6: Spatial correlation between runoff and influencing factors in the study area

The values of correlation were not significantly high for climatic and physiographic factors except area of watershed because spatial variability of these factors was quite complicated. Therefore, separate correlation matrix was generated for each factor for better understanding of strength between runoff and each influencing factor.

Spatial correlation between run-off and climatic factors

The spatial correlation matrix indicated that correlation (0.17) existed between rainfall and runoff at the watersheds receiving rainfall between 1250 to 1350 mm. However, strength between rainfall and runoff increased as the amount of rainfall increased as shown in Figure 7(A). The dependency between rainfall and runoff was found to be high (0.31) at the watersheds receiving maximum rainfall (>1450 mm). High rainfall yields high runoff and there is a direct correlation between rainfall and runoff as stated by Mohamadi and Kavian (2015).

Strength of relationship between runoff and temperature was high at watersheds with mean temperature less than 15℃. However, the value of correlation coefficient turned to negative with increase in temperature and vice versa. The values were 0.29 and 0.20 when temperature was below 18℃ whereas -0.13 and -0.23 when temperature was above 18℃ as shown in Figure 7(B). High temperature tends to increase the rate of evapotranspiration which generally results in reduction of surface runoff (McCab and Wolock, 2011). Shang *et al*. (2019) found that increase in evapotranspiration is not coinciding with the variability of climatic factors (temperature, rainfall). When the amount of rainfall decreases coupled with increase in temperature, the amount of runoff reduces significantly. However, the amount of runoff increases with the increase in precipitation along with decrease in temperature.

Spatial correlation between run-off and physiographic factors

Correlation matrix depicted that dependency between runoff and slope was negative (-0.25) in the areas where slope was less steep (<5 degree). As the slope became steeper i.e., >15 degree, the strength between runoff and slope was found to be positive (0.20) in those watershed areas shown in Figure 7(C). According to Fang *et al*. (2008), the increase in slope steepness and length resulted in

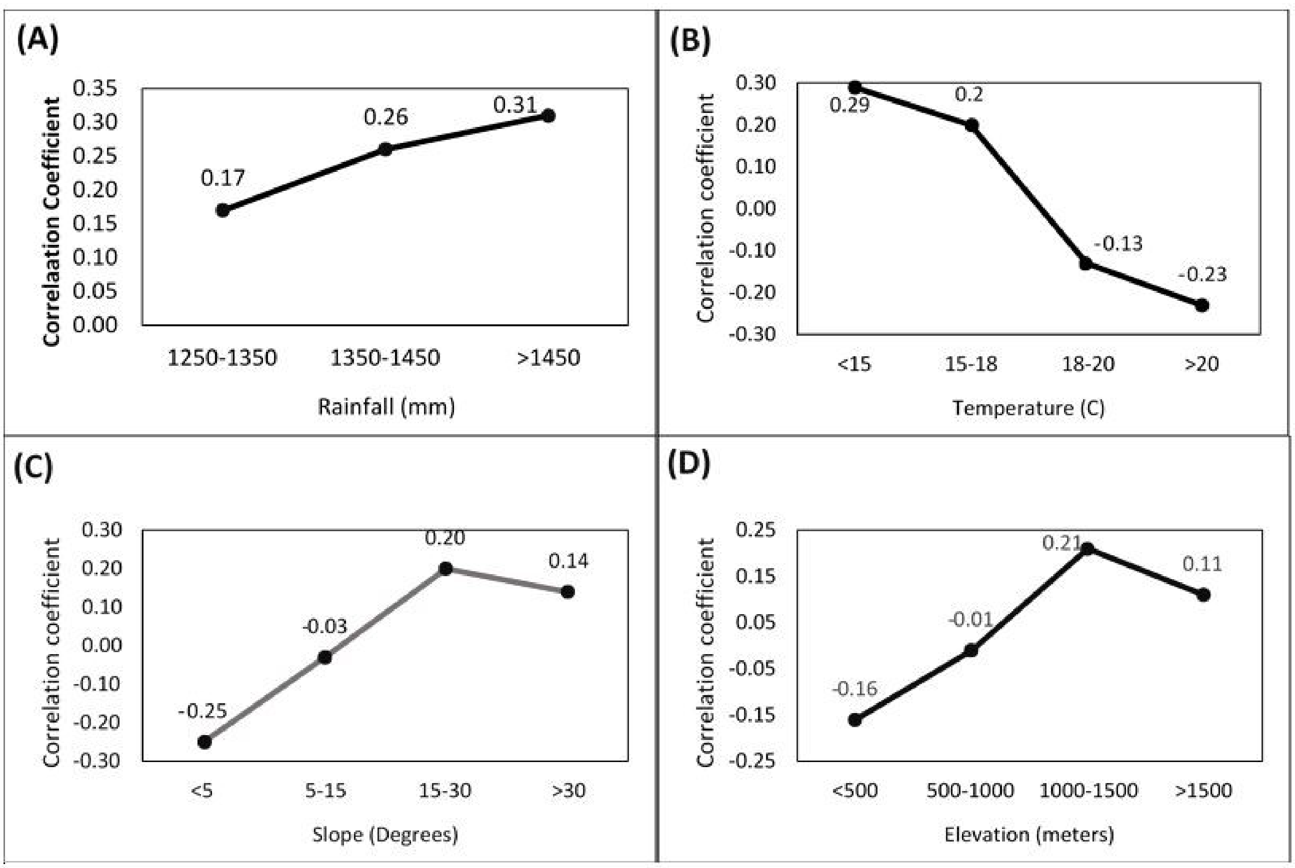

Figure 7: Spatial correlation among runoff and contributing factors

increased surface runoff due to encrusted surface and higher soil moisture content on downslope side. However, the correlation between runoff and slope, dropped from 0.20 to 0.14 in the areas where slope steepness exceeded 30 degree. Warrington *et al*. (1989) stated that there was a range of critical slope (30 degree) beyond which the rate of infiltration increased (due to low flow density) and the amount of runoff slightly decreased.

Runoff and elevation showed similar trend as runoff and

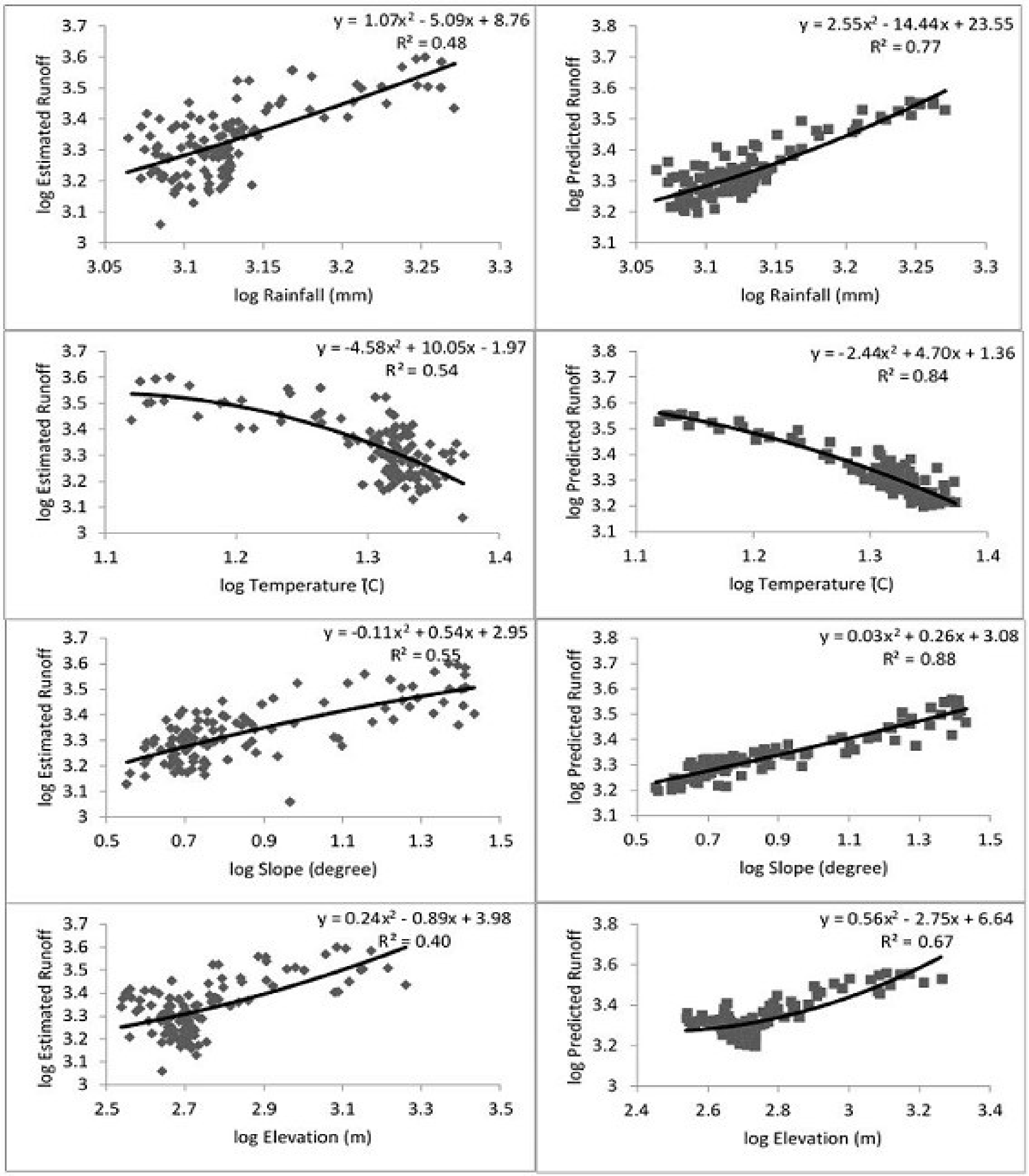

Figure 8: Line fit plots of runoff yield and influencing factors

slope. Spatial correlation was negative (-0.16) between runoff and elevation at the areas where elevation was low (<500 meters) as shown in Figure 7(D). Positive correlation (0.21) was found between runoff and watershed areas located at higher elevation (1000 to 1500 meters). The runoff increases with rise in elevation because rainfall is associated with the elevation and increased rainfall leads to higher runoff (Garcia-Martino *et al*., 1996). The dependency between runoff and elevation slightly dropped (0.11) as the elevation further increased from 1500 meters in the study area.

Regression models of surface runoff and influencing factors

The four-factor multiple regression analysis was performed using the climatic and physiographic factors (rainfall, temperature, slope and elevation) as independent variables and runoff as dependent. From regression model, R^2 was found to be 0.62 or 62 percent variance in runoff was explained by the geographical and climatic factors. It was evident from the analysis that maximum change in runoff (-1.36 acre-ft) would occur with one unit change in temperature. The change in one unit (1 mm) of rainfall would result in minimum change in runoff (0.15 acre-ft). The regression model showing the relationship between surface runoff and influencing factors is given as follows:

$$Runoff = 5.5 + 0.15\,log(rainfall) - 1.36\,log(temperature) + 0.24\,log(slope) - 0.39\,log(elevation) \quad \text{Equation 2}$$

The relationship between runoff and influencing factors was derived using linear, polynomial, power and exponential regression models. The analysis indicated that one-degree polynomial curve best fitted the data. Maximum change (88 percent) found in runoff can be explained by slope. Whereas, rainfall, temperature and elevation explained 77 percent, 84 percent and 67 percent variance found in runoff respectively. The regression models for all the influencing factors for both estimated and predicted runoff is given in Figure 8.

Conclusions

Present study provided better understanding of interrelationship between surface runoff and influencing factors. District Rawalpindi has a great potential of rainwater harvesting as surface runoff generated by rainfall was estimated to be 2472000 acre-ft per annum. However, the strength or dependency of surface runoff with physiographic and climatic factors varies spatially within the region. Slope explained maximum change in runoff followed by temperature, rainfall and then elevation. Furthermore, this study presented a statistical model to predict outcome of surface runoff in watersheds using the influencing factors. The results highlighted how climatic and physiographic factors generating runoff within watersheds fit together. Maximum change in runoff was predicted by one unit change in temperature followed by elevation, slope and then rainfall. The outcomes of the study can be utilized to formulate GIS based models describing the location and potential of rainwater harvesting sites within the watersheds as affected by climate and physiography of the area.

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