Impact of Soil sealing on the genesis of urban flood in Peshawar, Pakistan

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Abstract

Anthropogenic activities are consistently modifying surface covers changes. Such alterations have been producing negative impacts on surface and groundwater sources by escalating surface runoff and reducing infiltration to recharge the aquifers. In this research an attempt has been made to explore the rapid expansion of built environment, its trend and impacts on the increasing surface runoff and the genesis of urban flood in Peshawar, Pakistan. The study area has been experiencing rapid population growth and urban expansion, which has been continuously consuming the fertile farmland and replacing the natural ground by the artificial impermeable surfaces. The required data for this study was acquired through primary and secondary sources from various organizations. Remote Sensing (RS) and Geographic Information System (GIS) were used to monitor and detect the development of built environment and its probable impacts on the accelerated surface runoff. Analysis reveals that Physical, infrastructural and socio-economic developments were the major factors of land take and conversion of natural ground into Impervious Surface Covers (ISC). Such modifications have been producing negative effects on urban environ and water resources of the study area. Finding of the study reveals that rapid population growth is responsible for the increase in built-up areas, urban expansion and infrastructural developments, during the study period (1981–2014) have increased the impermeable surfaces from 3.70% to 16.27%. Consequently surface runoff has also been intensified, which has in certain cases created urban and flash floods. Rapid urban growth and the resultant physical and infrastructural developments need to be properly checked and monitored so that its adverse impacts on the generation of urban flash floods could be minimized.

1. Introduction

Globally, when natural permeable ground covers experiences modifications, it is usually substituted by the artificial Impermeable Surfaces. These human induced interventions can be seen anywhere over the earth surface, however cities around the globe are generally favored for such changes. Impervious surface covers (ISC) and contiguous built environment are the common and most frequently occurring characteristics of urban centres and are resulting surface cover changes as well as sealing the soil (Turok & Mykhnenko 2007; Wessolek 2008; Prokop et al. 2011). In urban areas pavements and buildings are the major physical developments often associated with infrastructural and socio-economic improvements contribute to the process of soil sealing (Breuste, 2011). The adverse effects of such impervious surfaces are commonly observed on human health and urban environment in the form of increasing surface as well as atmospheric temperature and accelerating runoff which often augment the risk of urban flash flood (Paul and Meyer 2001; Konrad 2003; Yuan and Bauer 2007; Scalenghe and Marsan 2009; Imhoff et al. 2010; Niemelä et al. 2010; Salvati et al. 2011; Myint et al. 2013). Likewise the increasing trend of built-up areas have used up the fertile farm land and produced serious implications to urban food security and ecology near the major urban centres (Burghardt 2006; Montanarella 2007; Samiullah 2013).

The resultant soil sealing from surface cover changes have been fluctuating and intensifying surface runoff since human evolution and revolution. In such cases attempts have always been furnished to measure the quantitative relationship between Land Use Land Cover (LULC) and the escalated surface runoff. However, reliable and general model has to be developed for predicting the LULC impact with runoff generation (Kokkonen and Jakeman 2002). Historically studies have always been carried out to know the relationship between urban LULC changes and its probable effects on hydrological imbalance. It has been generally recognized that usually frequently occurring small scale floods are often triggered by the urban infrastructural developments rather than the larger rare ones which are affected to a lesser extent by LULC changes (Hollis 1975).

For a reference period the observed and modeled runoff were compared by using Lumped calibrated models (Schreider et al. 2002). And it has been investigated that changes in land uses have affected runoff generation of the catchment areas. Similarly, correlating runoff with land use changes several other approaches have also been adopted (Braud et al. 2001; De Roo et al. 2001; Fohrer et al. 2001; Wooldridge et al. 2001). The essence of such approaches was that any changes in land use pattern have always impacted surface runoff generation. Predictions on the basis of certain methodologies have been made that the increasing trend in built environment has intensified surface runoff.

However, the application of different models and approaches are probably helpful on small and meso scale rather than large scale for which such methods become impractical and approaches could be adopted (Hundecha and Bárdossy 2004). To assess the impact of land use change on the catchments at meso scale certain hydrological models have been described by Bronstert et al. 2002; Brath et al. 2003 and Ranzi et al. 2002. The main theme of all these methods and approaches is that changes in land uses and the development of sealed surfaces have been accelerating runoff and generating urban flash floods.

2. District Peshawar: The Study Area

The rapidly growing and physically expanding district of Peshawar is not only the provincial capital of Khyber Pakhtunkhwa (KP) province but is also the integral part of Peshawar valley. Total area of the district is 1,257 square km. Peshawar is among the historical cities of the world with geostrategic and socio-economic importance. Geographically, the district is surrounded by the district of Mohmand in the north and Khyber district from the west. District Kohat is located to the south. Charsadda and Nowshera districts are in the north and east of the study area. The latitudinal and longitudinal extension of the study area is from 33° 44' N to 34° 15' N and 71° 22' E to 71° 42' E (GoP 1999; Samiullah 2013; Rahman et al. 2016; Khan 2019; Khan et al. 2019; Rahman et al. 2019; Figure 1).

The major factors of land take and soil sealing identified in Peshawar are rapid population growth, urban expansion, physical and infrastructural developments. Soil sealing by impervious materials have accelerated surface runoff and resulted urban flash floods (Rahman et al. 2016; Khan 2019; Khan et al. 2019; Rahman et al. 2019). Peshawar is a fertile featureless plain consisting of fine alluvial deposits mainly in its central part. The cultivable land of the district consists of porous, light and rich soil with a mixture of sand and clay and is favorable for cultivating a number of crops. Soil of the district has been classified into River alluvial, flood plain, piedmont and loess plains (Figure 2). Climate of Peshawar is subtropical continental type where both winter and summer seasons experiences severity. Average annual rainfall recorded at Peshawar Met Station and Agriculture Research Institute (ARI) Tarnab is over 400 millimeter.

3. Materials And Methods

Data for this study were obtained from both primary and secondary sources. Data regarding average daily, monthly and annual rainfall were collected from ARI Tarnab and Regional Meteorological Department, Peshawar. Topographical maps of the study area were obtained from Survey of Pakistan (SoP). Digital Elevation Model (DEM; of 30 Meters resolution) of the Shuttle Radar Topographic Mission (SRTM) and LANDSAT images of 1981 and 1991 were downloaded from the open source of the United States Geological Survey (USGS) database. SPOT images of 2009 and 2014 were acquired from Space and Upper Atmospheric Research Commission (SUPARCO).

The collected data were analyzed through statistical and cartographic techniques. Geographical Information System (GIS) was used to carry out spatio-temporal changes in built-up environment and to quantify the surface runoff of all the six urban drainage basins using Curve Number (CN) method. ArcGIS 10.2 and ERDAS imagine 2014 were used to prepare various maps of Land Use Land Cover (LULC) and watershed delineation of the rivers and streams in district Peshawar.

Satellite images of LANDSAT (1981 and 1991) and SPOT (2009 and 2014) were analyzed to extract built-up areas and consequently LULC maps were prepared. Supervised Maximum Likelihood Classification (SMLC) technique was applied to classify the multi-spectral temporal images of 1981, 1991, 2009 and 2014 into different LULC classes (Figure 3). The multiple LULC classes provided excellent result, however these classes signatures were further analyzed using the histogram technique to separate the bands used in the LULC classes. The study area was cropped and signatures were created for LULC classes. Histogram equalization was performed to evaluate the training samples of LULC. SMLC was also used to classify and calculate the statistics of LULC classes. Finally, raster calculator was used to calculate the statistic of LULC in term of area and percentages.

Watershed delineation of rivers and streams of district Peshawar was carried in ArcGIS 10.2 using Arc Hydrology tool. Digital Elevation Model of Shuttle Radar Topographic Mission (SRTM) of 23rd September 2014 was used. Four DEMs of 30 m Resolution were added to ArcGIS, which were merged into a single Mosaic to cover the entire drainage basins (Figure 4). Curve Number (CN) values depends upon the watershed cover conditions and soil type. In the model, the same are represented as cover type, Hydrologic Soil Groups (HSG), hydrologic and moisture conditions. HSG is group of soil having similar runoff potential under similar storm and cover conditions associated with runoff CN (Table 1). The same was assigned certain CN values as per the guidelines of Natural Resource Conservation Service (NRCS) of the United States Department of Agriculture. Based on infiltration rate and runoff potential, NRSC has classified soil into four Hydrological Soil Groups (HSG) as A, B, C and D (USDA 1986; NEH-4 1997; Hong and Elder 2008).

In Peshawar valley, soil has been formed by different geomorphic agents in various periods and follow the international standard. It is helpful for surface runoff calculation on the basis of Curve Number (CN) method. The replacement of natural ground cover by Impervious Surface Cover (ISC) disturb the soil profile and thereafter it requires new CN values for different surface covers keeping in view the guidelines of NRCS. On the basis of LULC and soil types CN values were assigned and CN Grid map of Peshawar district was prepared in GIS. CN Grid map was a base for calculation of surface runoff.

In this study, volume of surface runoff was calculated using Curve Number (CN) method (Eq. 1). It is one of the most widely used model for runoff estimation and prediction, which is still opted over the other models (Hawkins, 1993; Ponce & Hawkins, 1996; King et al, 1999; Mishra et al., 2003; Schneiderman et al, 2007; McGinley et al., 2013; Troolin & Clancy, 2016; Vannasy & Nakagoshi, 2016; Acosta et al, 2018; Khan 2019).

$$Q = (P - Ia)^2 / (P + S - Ia) = (P - 0.2S)^2 / (P + 0.8S) \quad \text{…………Eq. 1}$$

Where, Q is Runoff volume, P is Precipitation, Storage Index (S) = (1000/CN) -10, and Ia is Initial abstraction.

Table. 1. Land cover and Hydrological Soil Groups

Land Cover	CN of Hydrological Soil Group			
	A	B	C	D
Water Bodies	-	-		-
Evergreen (Needles)	34	60	73	79
Evergreen (Broad Leaf)	30	58	71	77
Deciduous (Needle Leaf)	40	64	77	83
Deciduous (Broad Leaf)	42	66	79	85
Mixed Forests	38	62	75	81
Closed Shrub lands	45	65	75	80
Open Shrub lands	49	69	79	84
Woody Savannas	61	71	81	89
Savannas	82	80	87	93
Grasslands	49	69	79	84
Permanent Wetlands	30	51	71	78
Crop land	67	78	85	89
Urban & Built-up areas	80	85	90	95
Cropland / Natural vegetation	52	69	79	84
Permanent Snow & Ice	-	-	-	-
Barren / Sparsely vegetated	72	82	83	87

Source: Modified after USDA, 1986; NEH-4, 1997; Hong & Elder, 2008

4. Results And Discussion

Spatio-temporally district Peshawar has witnessed rapid population growth, urban expansion, physical and infrastructural developments (GoP 1999; Khan 2001; Samiullah 2013; Rahman et al. 2016; Khan 2019; Khan et al. 2019; Rahman et al. 2019). Urban growth and expansion has consequently consumed fertile farmland in and around the city. Similarly, infrastructural and physical changes have substituted natural permeable ground by the artificial impervious and sealed surfaces.

4.1 Spatio-Temporal Expansion of Built-up environment

During the study period (1981 – 2014) built-up area in the district has increased from 3.7 % to 16.27 %. In 1981 the sealed surfaces in Peshawar were 4,635 hectares (ha) which enlarged to 7,182 ha (5.7 %) in

1991 (Table 2). Built environment further increased to 16,986 ha (13.5 %) in 2009. While LULC analysis of SPOT image 2014 (Table 3; Figure 5 & 6) has indicated further expansion in impervious surfaces and accounted it for 20,451 ha (16.27 %). With the same pace sealed surfaces of the study area are predicted to be 22 % by the year 2030. Built-up environment is continuously encroaching over the fertile agriculture land. Residential sector is one of the major consumer of farmland and used up 8,748 ha of fertile land during the period of 1991-2009 (Samiullah 2013; Rahman et al. 2016; Khan 2019; Khan et al. 2019; Rahman et al. 2019).

Table 2. District Peshawar temporal change in Built-up areas (1981- 2014)

S.No	*Year*	*Built up Area (ha)*	*Percentage*	*% Increase in Built up Area*
1	1981	4,635	3.70	-
2	1991	7,182	5.70	2.0
3	2009	16,986	13.50	7.8
4	2014	20,451	16.27	2.77

Source: Extracted from LANDSAT (1981; 1991) and SPOT (2009; 2014) images

Table 3. District Peshawar Land Use Land Cover in 2014

S.No	*LU LC type*	*Area (ha)*	*Percentage (%)*
1	Agriculture	84,596.1	67.30
2	Built up	20,451.39	16.27
3	Barren land	15,234.84	12.12
4	Water bodies	4,588.05	3.65
5	Forests	829.62	0.66
	Total	**125,700**	**100**

Source: SPOT image 2014

4.2 District Peshawar: Drainage System

The drainage system of Peshawar flow towards the east and finally confluence with River Kabul and considered as a central spine drainage basin (Figure 7). In the study area, a total of six sub-drainage basins of streams and rivers were delineated including the watersheds of Budhni, Bara and Zindai rivers and the streams of Mera, Garhi and Kala as well as their perennial and seasonal tributaries (Figure 8). The watersheds of these rivers and streams within the study area are considered as part of urban drainage basins (Figure 9). In this study, focus has been made on the urban watersheds and the impact of built-up environment on the surface water resources of the study area.

5. Surface Runoff

Surface runoff volume generation from the impervious as well as pervious surfaces within the urban watersheds of rivers and streams in district Peshawar have been calculated by using Weighted Average Volume and Weighted Average Curve Number (CN) Techniques. The input data for these methods are rainfall, area of the surface covers and CN of various surfaces. The same amount of rainfall events of 33 millimeters (mm) of 31st May 1981, 15th August 1991, 6th April 2009 and 11th March 2014 were selected. The spatio-temporal growth of sealed surfaces within the urban watersheds of rivers and streams have already been analyzed in Arc GIS 10.2. Curve Numbers of different surfaces for the whole district were also calculated in Arc GIS 10.2 and a detail CN map was prepared which was based on the Soil and Land Use Land Cover (LULC) data of 2014 (Fig. 10a). CN map of the study area has revealed that built-up areas have shown the highest CN value of 98 as compared to other surface covers where it was less than 70 (Fig. 10b). However, the maximum CN value within the urban watershed of 100 was also observed for water bodies which was excluded in the calculation. As according to the international standards CN values are not applicable to water bodies. Having maximum CN values the built environment also generate the highest Surface runoff as compare to the natural ground cover and unsealed surfaces (Fig. 11).

5.1 Surface Runoff within urban drainage basins

Spatio-temporally urban drainage basins of the two major rivers Budhni and Bara have shown remarkable growth and expansion of built environment. Although a large catchment area of these rivers lies outside the district boundary in the adjoining Khyber district, however due to the availability of climate data and rapid growth of built-up areas within the district, surface runoff was calculated for the urban drainage basins of these rivers. Similarly, the spatio-temporal increase of surface runoff for River Zindai, Mera, Kala and Garhi streams have also been calculated. It has been determined that having maximum built-up areas the urban watershed of River Budhni has also generated greater volume of surface runoff followed by the urban catchments of Zindai and Bara rivers. Streams within the district boundary have lesser share of impervious surfaces have generated a small amount of runoff volume within their urban drainage basins. The increase in surface runoff has always been escalated and triggered flooding events within the district.

Built environment within the urban drainage basin of River Budhni has been shown remarkable growth and expansion from 2,648.45 ha (7.22%) in 1981 to 11,032.63 ha (30.06%) in 2014. As a consequence runoff volume generation has also been escalated especially from the impervious surfaces (Fig. 12). In 1981, the built-up areas within the urban watershed of River Budhni were 7.22% from which runoff volume generation was 9 Cumecs while it was 39 Cumecs (81%) from the impermeable surfaces. The runoff volume generation from impervious surfaces on 31st May 1981 was about 19% of the total runoff. However on 15th August 1991 for the same amount of rainfall (33 mm) the runoff volume from the sealed surfaces has been escalated to 15 Cumecs (29%) when the built environment within the urban drainage basin was 12.27%. Runoff volume from the pervious surfaces has been reduced from 39

Cumecs in 1981 to 37 Cumecs (71%) in 1991. On 14th April 2009, the runoff volume generation from the impermeable surfaces further increased to 33 Cumecs (51.6%) as the built-up areas within the urban drainage basin were 26.68% and runoff volume from the unsealed surfaces has been reduced to 31 Cumecs (48.4%). Similarly, on 11th March 2014 the runoff volume generation from the sealed surfaces (30.06%) has further been augmented to 38 Cumecs (55.9%) and runoff from the permeable surfaces has been reduced to 30 Cumecs (44.1%). Total runoff volume in the urban watershed of River Budhni has been increased from 48 Cumecs (1991) to 68 Cumecs (2014) experiencing an overall increase of 20 Cumecs (41.67%). However, increase in the runoff volume has only been experienced by the impermeable surfaces (322.22%) and runoff from the permeable surfaces has shown reduction of about 30%.

As compare to the urban watersheds of other rivers and streams in district Peshawar built-up areas accounts more in the urban drainage basin of River Budhni consequently, runoff volume generation from the impervious surfaces is also maximum which will further increase over time. Another important fact about the urban drainage basin of River Budhni is that not only surface runoff volume generation is maximum but the flow of the drains and Kathas of the main city are also towards this river. Similarly, a number of perennial and seasonal streams which passes through the planned developed areas of Regi Lalma and Hayatabad townships as well as other areas of the district also join this river. Due to which fluvial as wells as flash floods are often experienced in its urban watershed during the rainy seasons. Likewise, urban and flash floods have regularly been observed after a slight amount of rainfall.

The urban watershed of River Bara has also shown escalation in Runoff volume from ISC i.e. 1 Cumec in 1981 to 10 Cumecs in 2014 (Fig. 13). Urban drainage basin of River Bara receive runoff water from southeast of the main city. However, more than 93% of its total drainage basin lies outside the district boundary in the adjoining Khyber district and sometime flood is also experienced in the surrounding of the city when it rains in the upper catchment areas which confirm the famous Pashto proverb that it has been raining over Tirah (a locality in Khyber district) and washed away horses and donkeys in Khalisa (a Locality in the northeast of Peshawar). Another important fact about the urban drainage basin of River Bara is that it receives drainage from the built-up areas in the south of the city along Kohat road, some areas along the Grand Trunk (GT) Road, ring road and other adjacent areas. These areas are also flooded during the rainy seasons.

Analysis of runoff volume generation from the impervious as well as pervious surfaces within the urban watershed of River Zindai indicated that it has been augmented from the built-up areas while from the natural ground covers it has shown reduction. Total runoff volume from 1981 to 2014 has been escalated from 53 Cumecs to 60 Cumecs (Fig. 14). However this increase has only been experienced from the built environment, which has been augmented from 1 Cumec to 11.3 Cumecs. Natural ground and the permeable surfaces have shown reduction in runoff volume from 52 Cumecs in 1981 to 48.7 Cumecs in 2014. River Zindai receive drainage from a number of streams coming through the district of Khyber and entering into the study area from southwest. Combine water of these streams have developed urban drainage basin within the district boundary. Surface runoff volume generation from the sealed surfaces within the urban watershed of River Zindai was lesser than Budhni and more than Bara. However flooding during the rainy season is often experienced not only due to the localized rain but also in the adjacent district Khyber where most of the tributaries of River Zindai have their sources. Combine water then flow into River Bara where situation becomes more aggravated during the rainy season.

Built environment within the urban drainage basins of streams in district Peshawar have small area due to which runoff volume generation is also lesser as compare to the major rivers. However from the analysis of the spatio-temporal growth of built environment within the urban watersheds of these streams it has been revealed that Garhi stream which has totally urban watershed, the built-up areas are also more as a result runoff volume generation is maximum followed by Mera stream. In the urban watershed of Kala stream the built-up areas are less due to which runoff volume generation from the sealed surfaces is also minimum (Fig. 14; 15; 16).

6. Conclusion

The increasing trend of sealed surfaces within urban drainage basins of major rivers and streams have been generating problems to water resources of the study area. Surface water are affected by the accelerated surface runoff volume due to the fact that water moves faster over the sealed surfaces rather than infiltrating through them. Spatio-temporally the urban watersheds have been experiencing rapid growth and expansion in terms of built-up areas. As a consequence the runoff volume generation has always been escalated over time resulting urban, flash, pluvial as well as fluvial floods. During the study period (1981 to 2014) the maximum increase in runoff volume has been observed in the urban drainage basin of River Budhni followed by River Zindai, River Bara, Garhi, Kala and Mera streams. River Budhni receives water from the main built-up areas of the district where the increase in impervious surfaces are also greater, as a result fluvial and pluvial floods have been observed in its basin. In its urban drainage basin runoff volume from the impervious surfaces has been increased from 9 Cumecs (1981) to 38 Cumecs (2014). Similarly River Bara also receive rain and drainage water from some parts of the city. River Bara is joined by River Zindai which has itself developed watershed from a number of streams coming through the district of Khyber. During the study period urban parts of the watersheds of these rivers have also been recorded escalation. In the watershed of River Zindai runoff volume from the impermeable surfaces has been escalated from 1 Cumec to 11.5 Cumecs. Similarly, during the same period runoff volume generated by the sealed surfaces in the urban drainage basin of River Bara has also been augmented from 1 Cumec to 10 Cumecs.

A number of streams which have developed independent drainage and are considered as part of the major rivers have also been recorded escalation in the runoff volume generation. Garhi stream having a total urban watershed has shown maximum increase in runoff volume from 1 Cumec in 1981 to 2.3 Cumecs in 2014. However, having lesser expansion of built environment within the urban parts of the two other streams Mera and Kala have also observed minimum surface runoff from the built-up areas. Large part of the major rivers and their tributaries have catchment areas outside the district boundary and non-localized rainfall in their upper catchments also contribute to urban flash flood within the district.

Declarations

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Figures

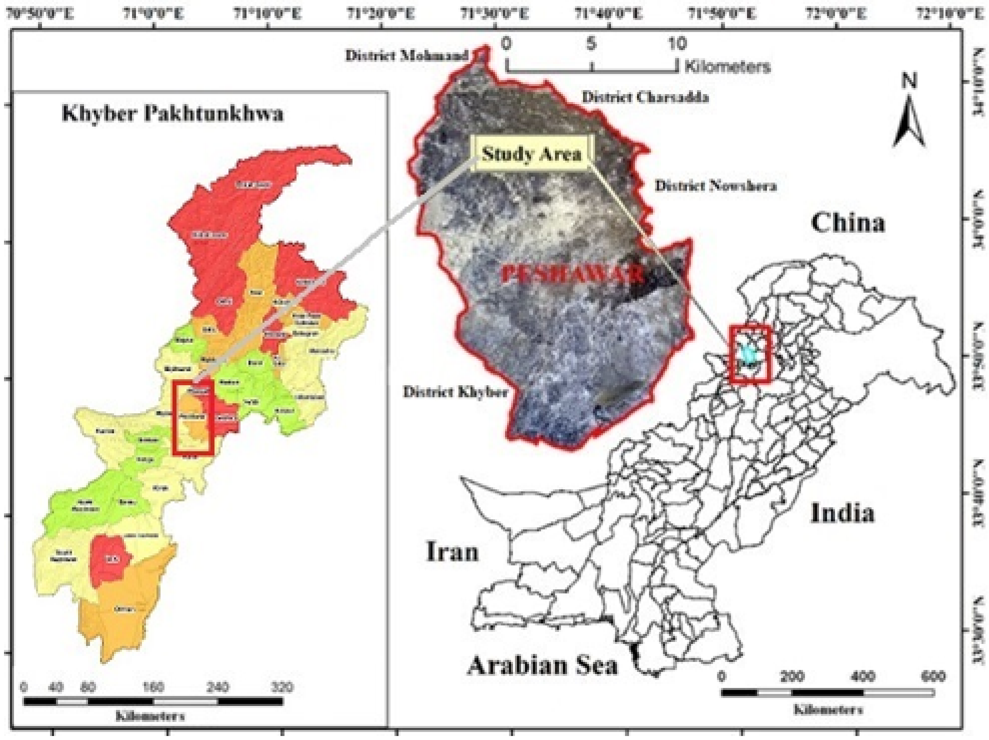

Figure 1

Location of the Study area (District Peshawar).

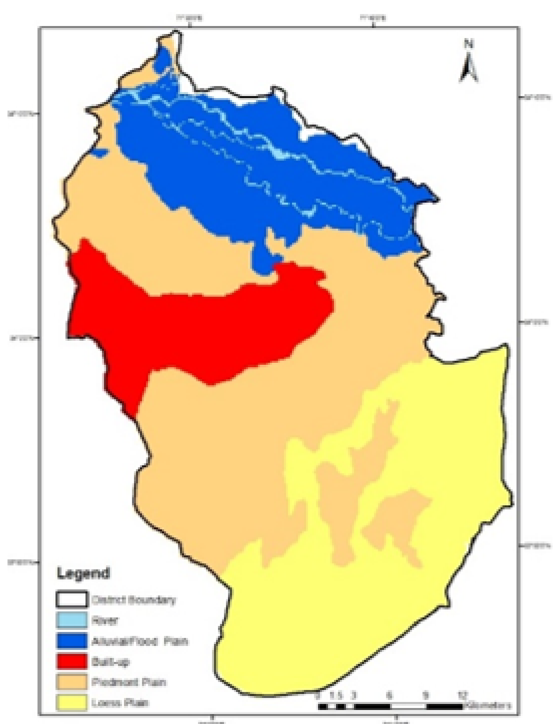

Figure 2

Peshawar, Soil & Surface Deposits.

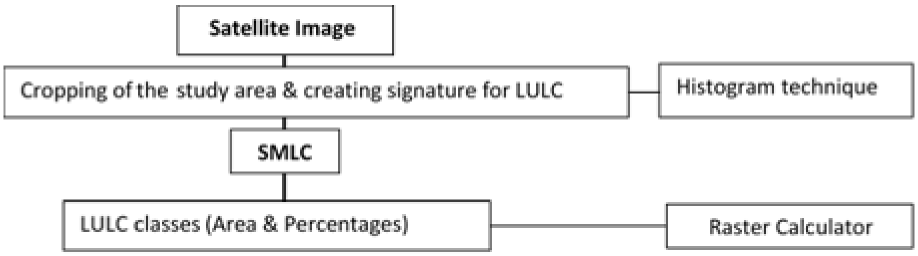

Figure 3

Extraction of LULC from Satellite images

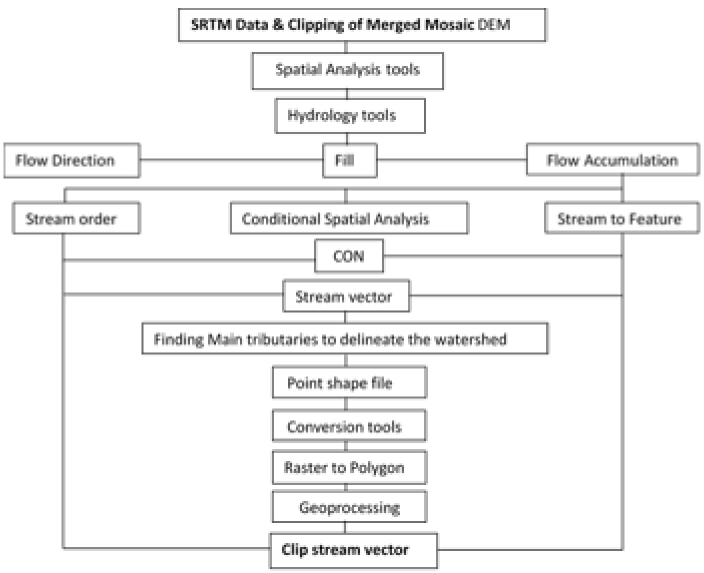

Figure 4

Methodology for Watershed Delineation

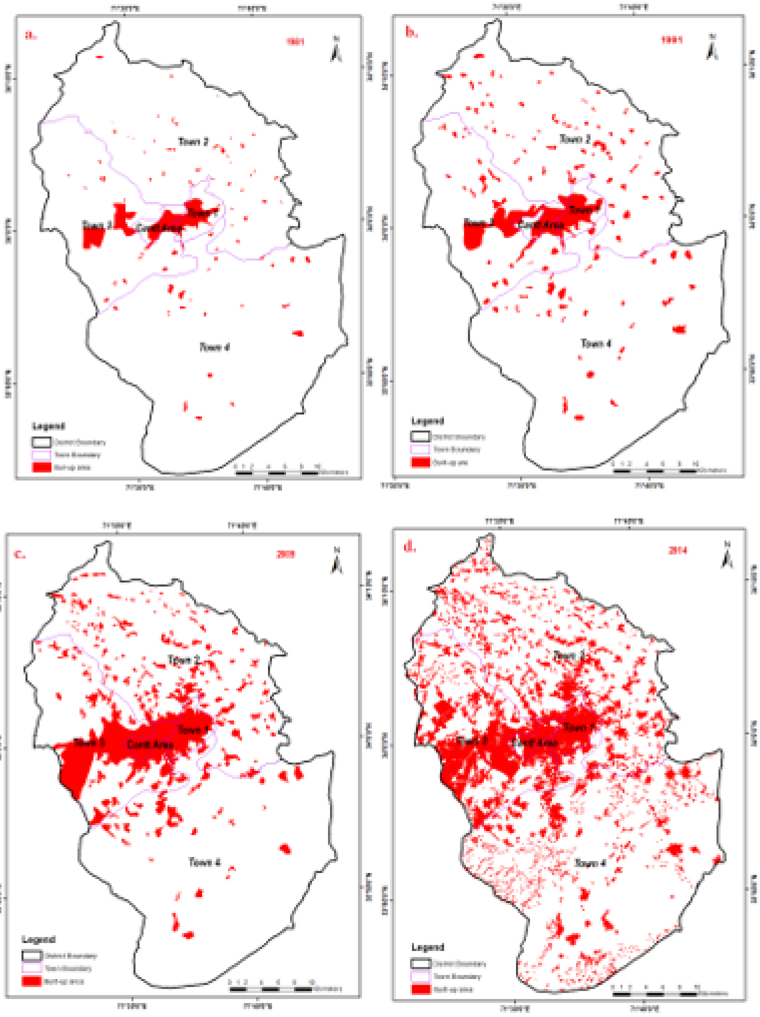

Figure 5

District Peshawar Spatio-temporal growth of Built-up areas. a. 1981, b. 1991, c. 2009, d. 2014

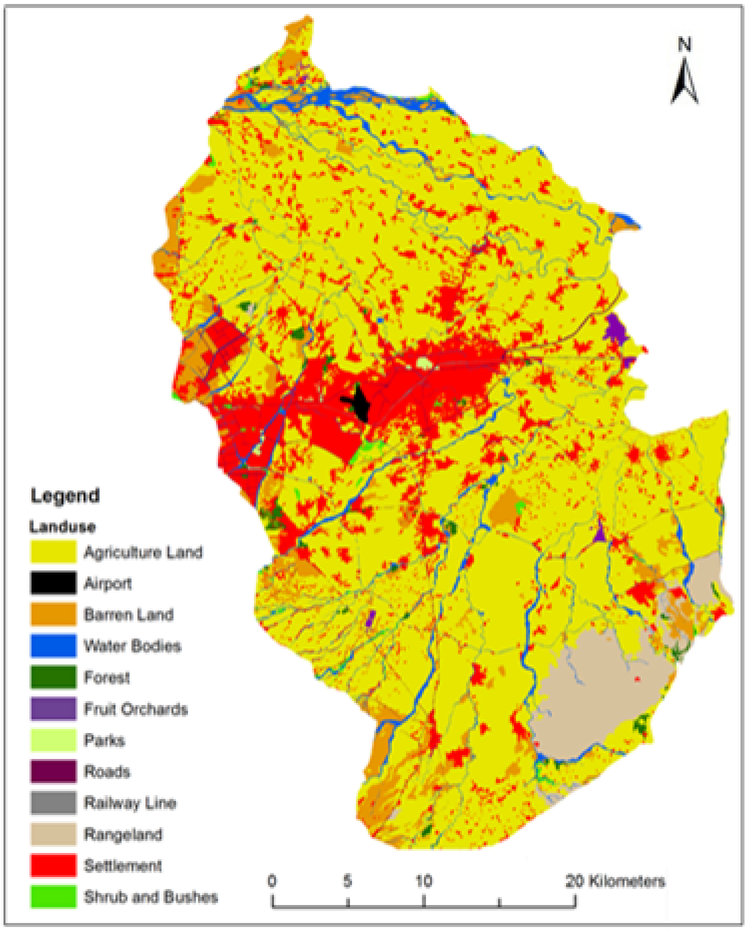

Figure 6

Land use Land cover of District Peshawar. Source: SPOT image 2014

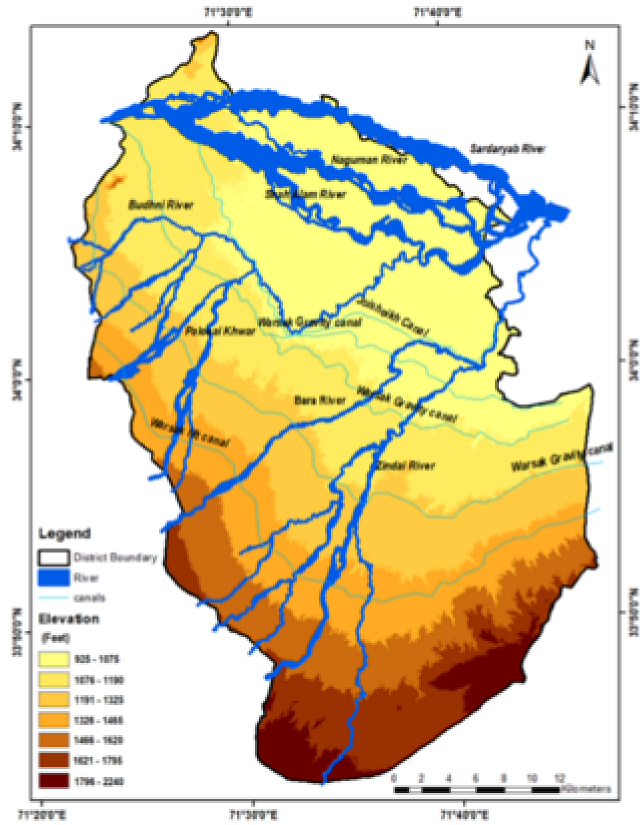

Figure 7

Peshawar, Surface Hydrology

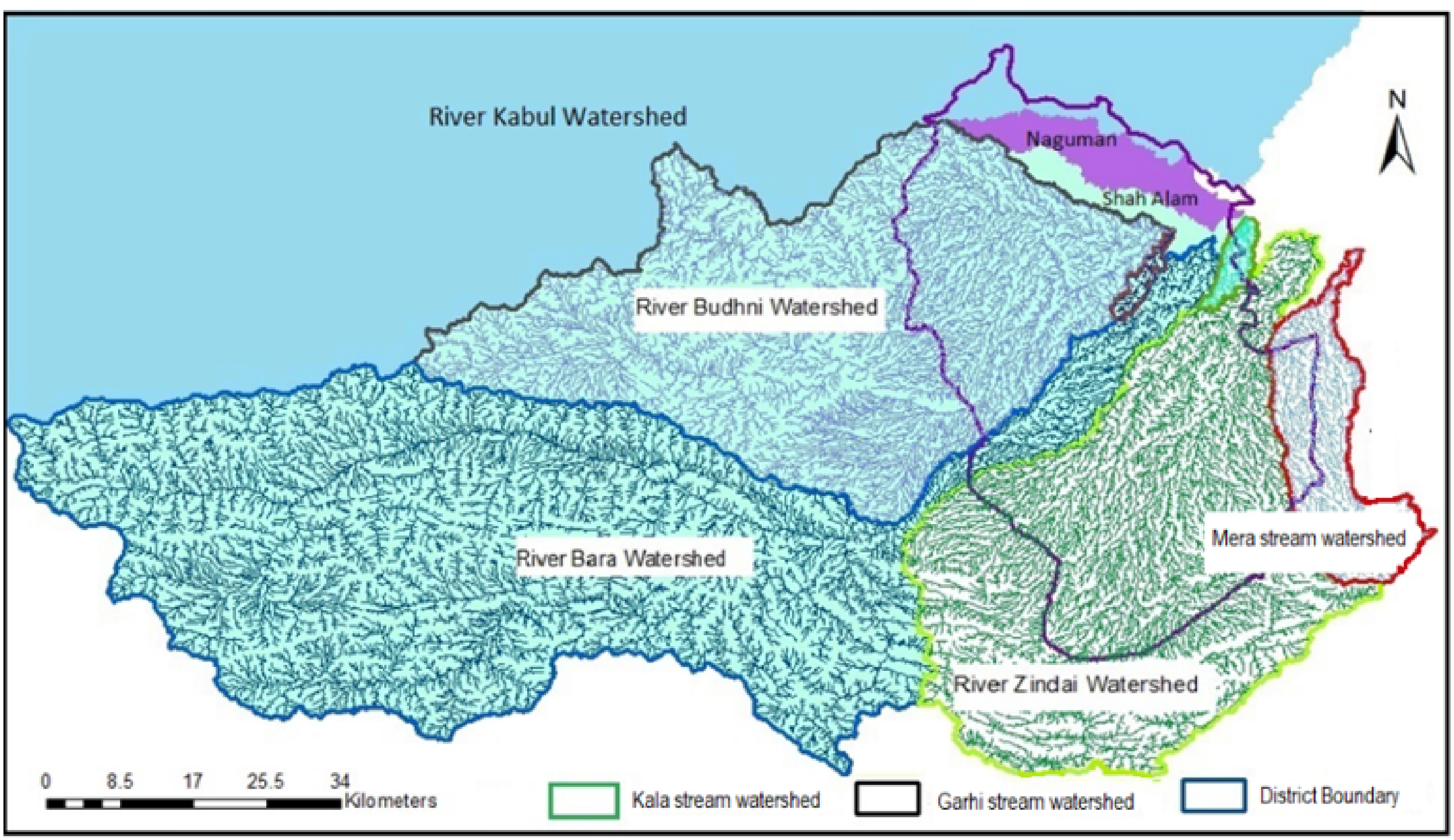

Figure 8

Drainage basins of major Rivers and Streams extracted from SRTM image

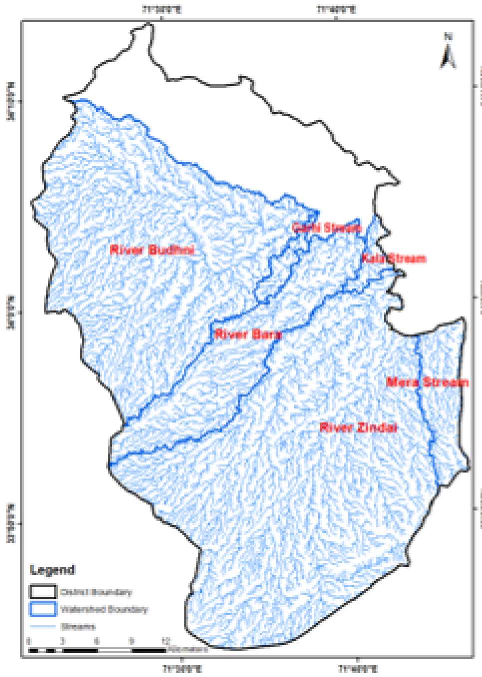

Figure 9

District Peshawar, drainage basins of major Rivers and Streams extracted from SRTM image

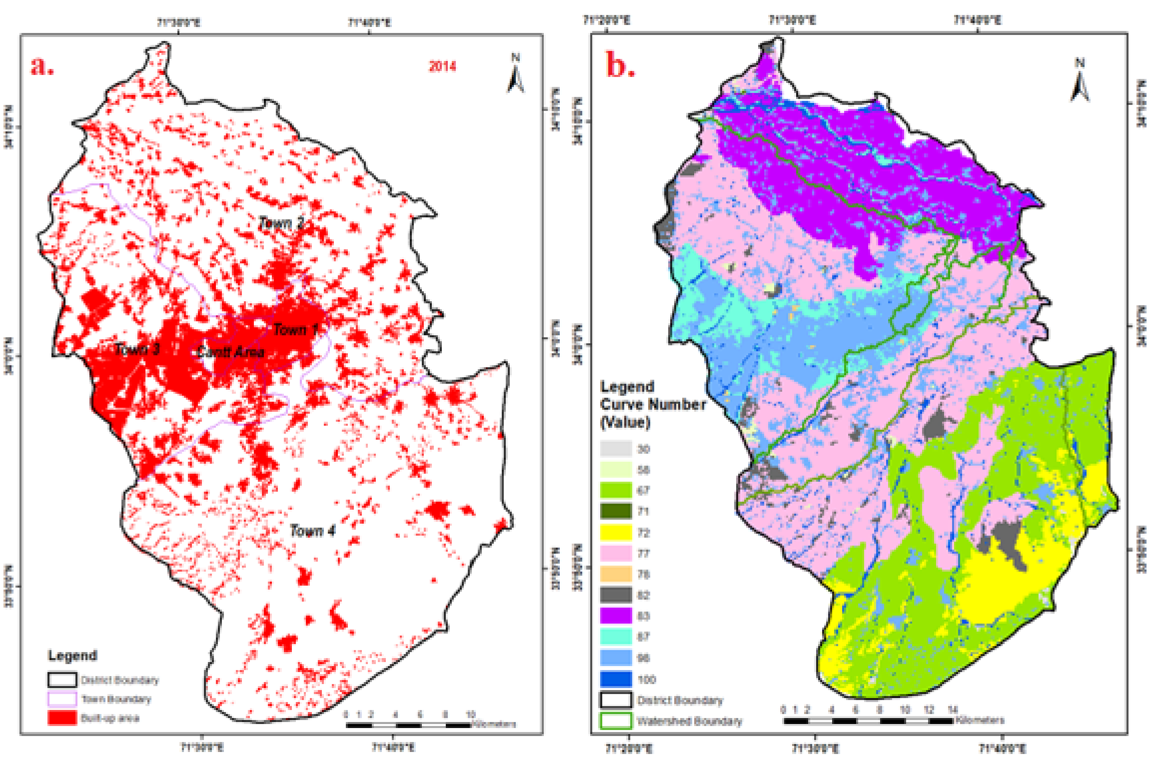

Figure 10

a. District Peshawar, Built-up areas (2014). b. Curve Numbers

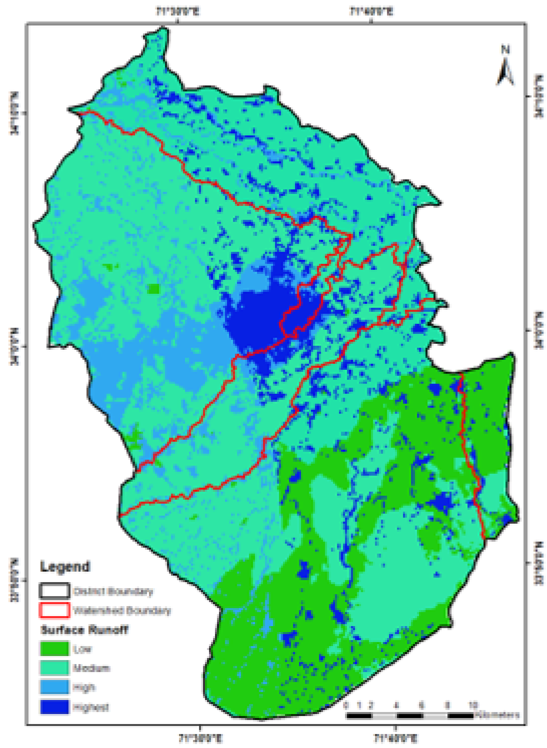

Figure 11

District Peshawar, Spatial distribution of Surface Runoff

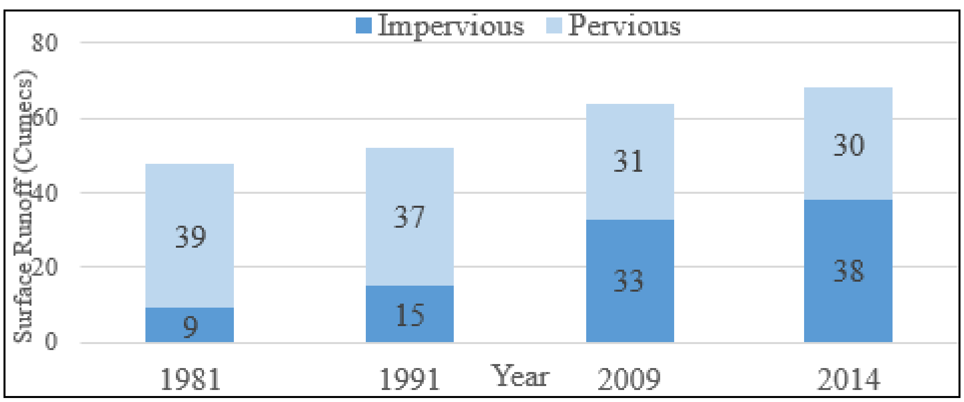

Figure 12

River Budhni, temporal increase in Surface Runoff within urban drainage basin

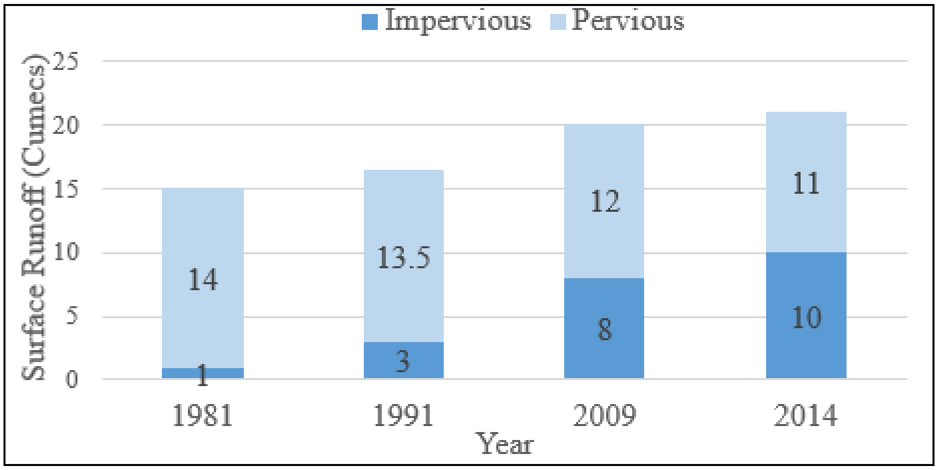

Figure 13

River Bara, temporal increase in Surface Runoff within urban drainage basin

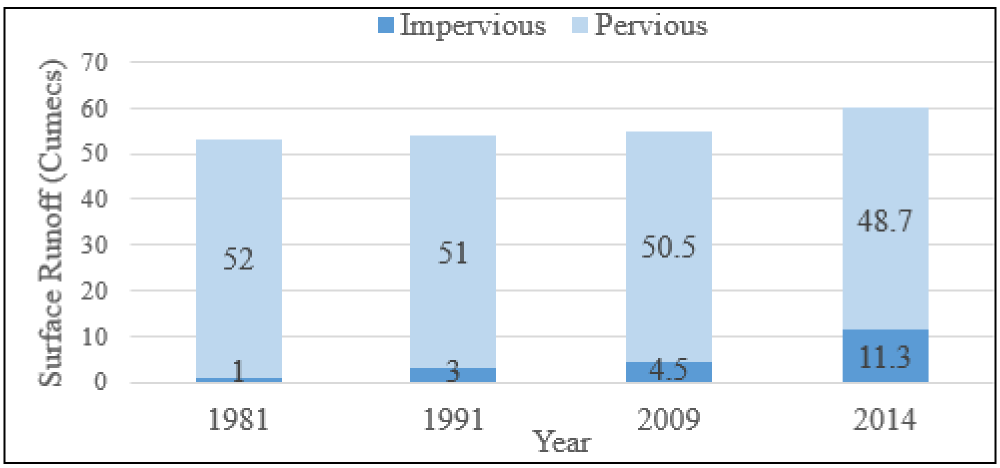

Figure 14

River Zindai, temporal increase in Surface Runoff within urban drainage basin

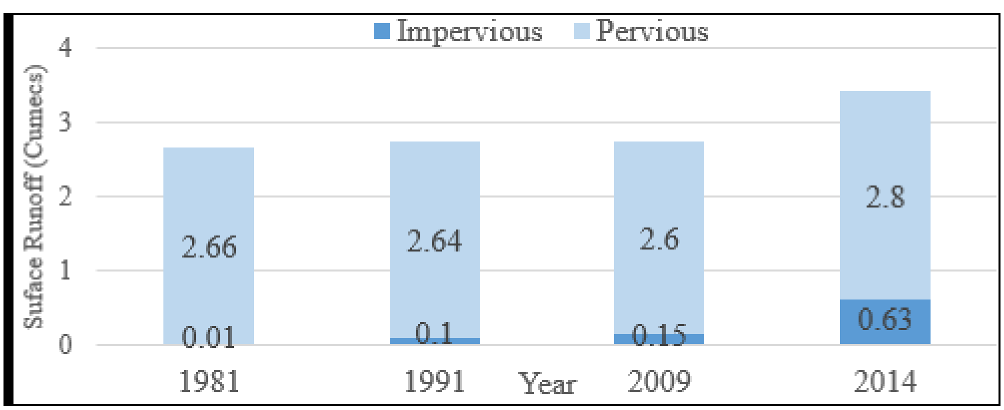

Figure 15

Mera Stream, temporal increase in Surface Runoff within urban drainage basin

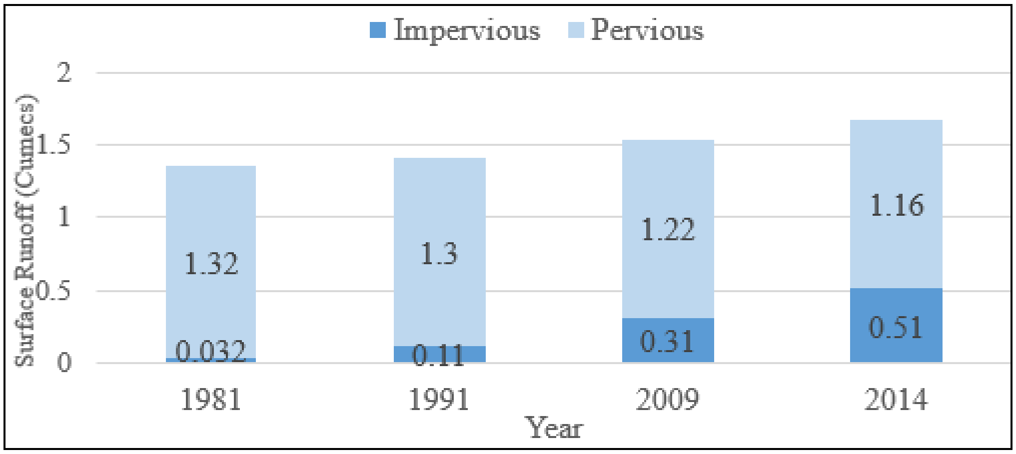

Figure 16

Kala Stream, temporal increase in Surface Runoff within urban drainage basin

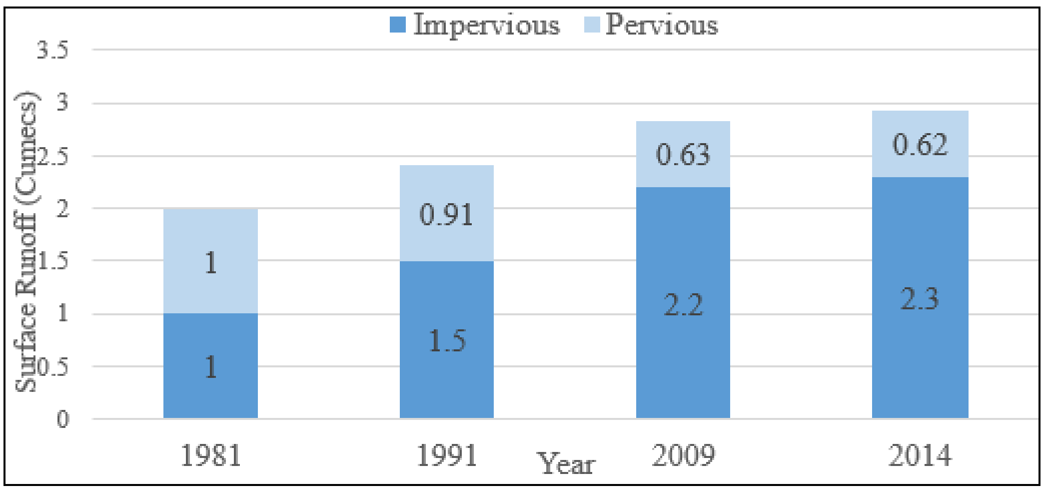

Figure 17

Garhi Stream, temporal increase in Surface Runoff within urban drainage basin