Chapter 9

Changing Hydrology of the Himalayan Watershed

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/54492

1. Introduction

The Himalayan region is a source of ten major river systems that together provide irrigation, power and drinking water for 1.3 billion people i.e. over 20% of the world's population. The supply and quality of water in this region is under extreme threat, both from the effects of human activity and from natural processes and variation [1]. Population growth is already putting massive pressure on regional water resources, affecting water resource in terms of demand, water-use patterns and management practices. The change in hydrological cycle may affect river flows, agriculture, forests, biodiversity and health besides creating water related hazards [2]. The need for suitable strategies for climate resilient development has policy and governance implications [3]. Adaptation to climate change is the area that should be strengthened through policy advocacy supported by evidence through rigorous research and verified information.

Re-assessment of true catchments yields under existing and future scenarios of landuse and climate changes is very essential to devise watershed management strategies which can minimize adverse impacts both in terms of quantity and quality. Since trends are still unclear, the extent to which changes can be attributed to variable environmental changes is difficult to determine. It has become imperative to assess ongoing hydrological changes and changes that might occur in future to devise appropriate adaptation measures to foster resilience to future climate change, thereby enhancing water security.

In the present study, SWAT model developed by United States Department of Agriculture (USDA) [4] has been used to evaluate surface runoff generation, soil erosion and quantify the water balance of a Himalayan watershed in the Northern Pakistan. The response of watershed yield to historical landuse evolution and under variable landuse and climate change scenarios has been studied in order to mitigate the negative impacts of these changes and promote development activities in this region. The study would provide basis to recommend changes in the water management regimes so as to address future adaptation issues.

1.1. Modeling hydrological processes

Dealing with water management issues requires analyzing of different elements of hydrologic processes taking place in the area of interest. As such processes are taking place in a combine system that exists at a watershed level, thus the analysis must be carried out on a watershed basis. Understanding of relationship between various watershed characteristics such as morphology, landuse and soil, and hydrological components are very essential for water resources development in any area. Since the hydrologic processes are very complex, their proper comprehension is essential and for this watershed models are widely used. Most of the watershed models basically simulate the transformation of precipitation into runoff, sediment outflow and nutrient losses. Changes in landuse including urbanization and de(/re)forestation continue to affect the nature and magnitude of surface and subsurface water interactions and water availability influencing ecosystems and their services. One can formulate water conservation strategies only after understanding the spatial and temporal variations and the interaction of these hydrologic components. The alarming rate of soil erosion in context of changing landuse and climate in the Himalayan region calls for urgent attention for this problem. Assessment of erosion is a very difficult task when executed using conventional methods and requires to be done repetitively. The use of an appropriate watershed model is thus essential to deal with such problems.

Choice of watershed development model depends upon the hydrologic components to be incorporated in the water balance. The most important hydrologic elements from the water management point of view are surface runoff, lateral flow, baseflow and evapotranspiration. In presenting an appropriate view of reality, model must remain simple enough to understand and use. There are a number of integrated physically based distributed models, among which researchers have identified Soil and Water Assessment Tool (SWAT) as the most promising and computationally efficient [4]. The model is an integrated physically based distributed watershed model that has an ability to predict the impact of land management practices on water, sediment yield and agricultural chemical yield [5]. Distributed models also take the spatial variability of watershed properties into account.

1.2. Model description

The SWAT is a process-based continuous daily time-step model that offers distributed parameter, continuous time simulation, and flexible watershed configuration [6]. It has gained international acceptance as a robust interdisciplinary watershed modeling tool. Two methods are used for surface runoff estimation in SWAT *i.e.* the SCS curve number and Green-Ampt infiltration. This study is based on the use of curve number for surface runoff and hence stream flow simulation. A SWAT model can be built using the Arc-View interface called AVSWAT which provides suitable means to enter data into the SWAT code. Main processes include water balance calculations (i.e. surface runoff, return flow, percolation, evapotranspiration, and transmission losses), estimation of sediment yield, nutrient cycling and pesticide movement.

The spatial heterogeneity is represented by means of observable physical characteristics of the basin such as landuse, soils and topography etc. Model inputs include physical characteristics of the watershed and its sub-basins i.e. precipitation, temperature, soil type, land slope, Manning's n values, USLE K factor, and management inputs like crop rotations, planting and harvesting dates, tillage operations, irrigation, fertilizer use, and pesticide application rates. Model outputs include sub-basin and watershed values for surface flow, ground water and lateral flow, sediment, nutrient and pesticide yields. The main basin is divided into sub-basins which are further divided into hydrologic response units (HRU) composed of homogeneous landuse, soil types, relevant hydrological components and management practices. Sediment yield is estimated by the Modified Universal Soil Loss Equation (MUSLE; [7]. The model has been applied worldwide for the purpose of simulating sediment flow [8], modeling hydrologic balance [9], evaluation of the impact of landuse and landcover changes on the hydrology of catchments [10]. The model provides a flexible capability for creating climate change scenarios evaluating a wide range of "what if" questions about how weather and climate could affect our systems.

1.3. Equations of watershed hydrology

The hydrologic process in a watershed is simulated by the following water balance equation:

$$SW_t = SW + \sum_{i=1}^{t} \left(R_i - Q_i - ET_i - P_i - QR_i \right) \tag{1}$$

where: SW_t is the final soil water content (mm), SW is the initial soil water content minus the permanent wilting point water content (mm), t is time in days, R is rainfall (mm), Q_i is surface runoff (mm), ET_i is evapotranspiration (mm), P_i is percolation (mm) and QR_i is lateral flow (mm). The surface runoff is predicted by the following equation:

$$Q = \frac{\left(R - 0.2s\right)^2}{R + 0.8s} \text{for } R > 0.2s \tag{2}$$

$Q = 0.0 \qquad \text{for } R < 0.2s$

$$s = 254\left(\frac{100}{CN} - 1\right) \tag{3}$$

Where, Q = daily surface runoff (mm): R = daily rainfall (mm), S = retention parameter (mm); CN = curve number.

Lateral flow is predicted by:

$$q_{lat} = 0.024 \frac{\left(2SSC \sin \alpha\right)}{\theta_d L} \tag{4}$$

Where, q_{lat} = lateral flow (mm/ day); S = drainable volume of soil water per unit area of saturated thickness (mm/day), SC = saturated hydraulic conductivity (mm/h); L = flow length (m); α = slope of the land: θ_d = drainable porosity

The base flow is estimated by:

$$Q_{gwj} = Q_{qwj-1}.e^{\left(-\alpha_{gw}.\Delta t\right)} + w_{rchrg}.\left(1 - e^{\left(-\alpha_{gw}.\Delta t\right)}\right) \tag{5}$$

Where, Q_{gwj} = groundwater flow into the main channel on day j; α_{gw} = base flow recession constant; Δt = time step. The computed runoff from each element is integrated using a finite difference form of the continuity equation relating moisture supply, storage and outflow.

1.4. Description of study area

Rawal watershed covers an area of 272 sq km within longitudes 73º 03´ - 73º 24´ E and latitudes 33° 41´ - 33° 54´ N comprising parts of Margalla hills and Murree mountains in the southern Himalayas of Pakistan (Figure 1). About 47% of the watershed area lies in the Islamabad Capital Territory while the rest in Punjab and Khyber Pakhtunkhwa (KPK) provinces, so it is well connected through a metalled road with other parts of the country. Korang is the main river flowing in the watershed that receives runoff from watershed via four major and 43 small streams [11]. Rawal dam is constructed on Korang river, which supplies 22 million gallons per day of water for drinking and other household needs to Rawalpindi city and a limited water for irrigation use to Islamabad area. The elevation ranges between 523 meters and 2145 meters above mean sea level (masl). Physiographically, the watershed comprises of 34% hilly area (Elev. <700 masl), 62% Middle mountains (Elev. within 700-2000 masl) and 4% High mountains (Elev. >2000 masl).

The Himalayas serve as a divide between Central Asia and South Asia. The Indo-Eurasian plates collision resulted in the formation of new relief and topography, which consists of series of mountain ranges located in the north and west of Pakistan, commonly known as the Himalayan Mountain System [12]. The principal uplift occurred during the middle or late Tertiary period, 12 to 65 million years ago. The study area lies in sub-humid to humid sub-tropical continental highlands. The hottest months are May, June and July. The mean maximum temperature ranges between 17.6ºC and 40.1ºC while mean minimum temperature between 2.1ºC and 21.6 ºC. The winter months are from October to March. The highest temperature was recorded as 46.6ºC in 2005 and the lowest as -3.9ºC during 1967 [13]. Mean annual rainfall of 1991-2010 period is about 1232 mm. The occurrence of rainfall is highly erratic both in space and time. Over 60 percent of the annual rainfall occurs during monsoon season i.e. from July to September. Most of the rainfall is drained out rapidly due to steep slopes and dissected nature of the terrain. Springs and streams are the main source of water for drinking and other domestic requirements. A prolonged dry season may cause water shortage in some parts of the area.

Underlying rocks consist of poorly compressed and highly folded and faulted Murree series that are moderately to severely eroded, shallow clayey loams of very low productivity [14]. The soils formed over shale are clayey while those developed on the sandstone are sandy loams to sandy clay loam in texture. The flora is mainly natural with xeric, broad-leaved deciduous, evergreen trees and diverse shrubs on the southern slopes. The dominating plant species are *Carissa spinarum* (Granda), *Dodonaea viscosa* (Sanatha) and *Olea ferruginea* (Wild Olive). Sub-tropical pine zone occupies steep and very steep mountain slopes [15]. Agriculture is practiced in small patches of land as terrace cultivation.

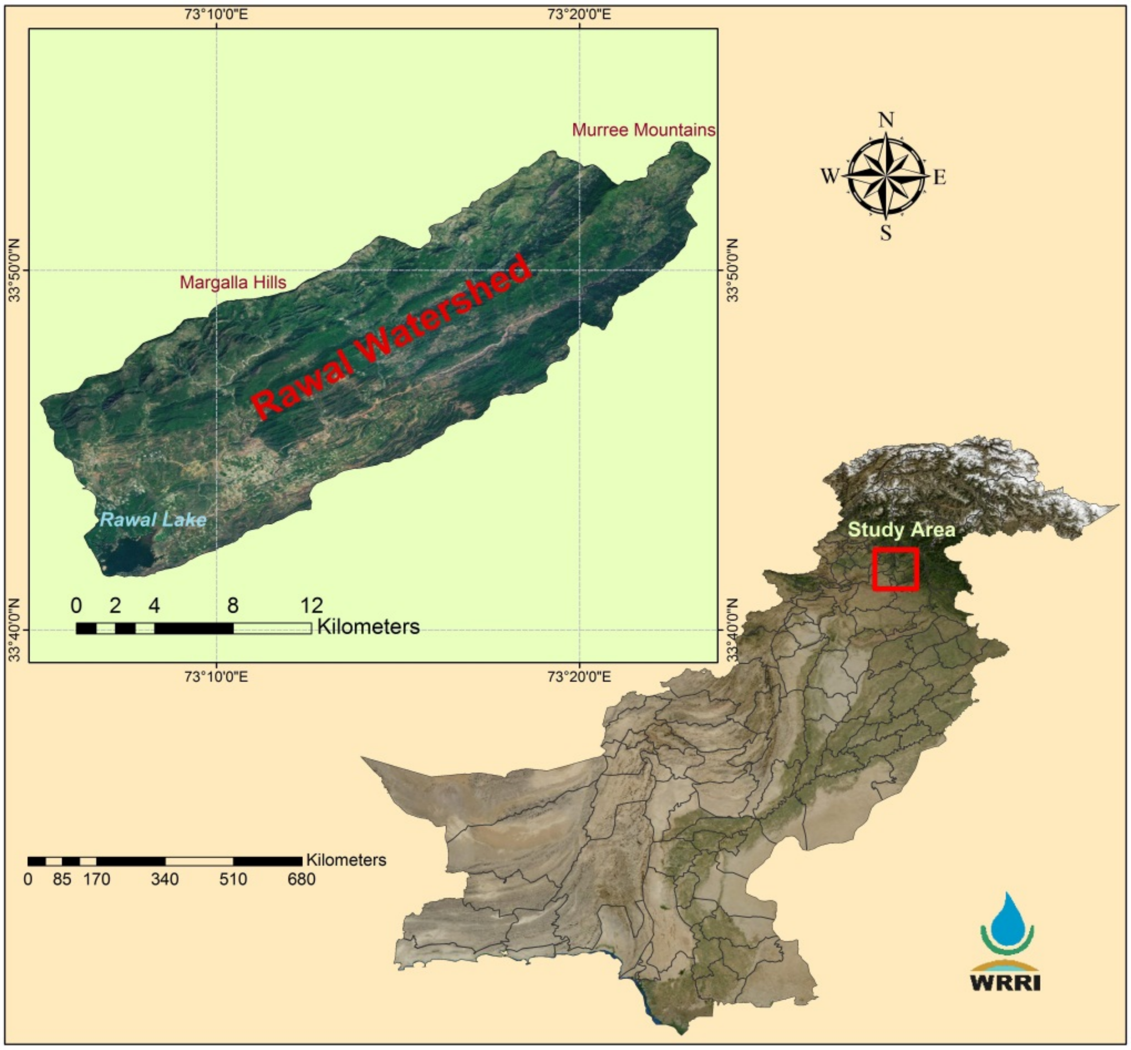

Figure 1. Location map of the study area

1.5. Main environmental issues

The watershed is confronting problems of rapid urban development and deforestation due to which its landuse is changing gradually. The population growth and addition of a number of housing colonies in the Rawal Lake catchment area are adversely affecting the regime of water coming into Rawal Lake. The activities like illegal cuttings due to high market value of forest wood and intensive use of forest wood for household needs (cooking, heating, timber etc.), ineffective forest management and forest disease etc. are accelerating the deforestation rate in the watershed area [16-17]. Destruction of aquatic habitat and a reduction of water quality are some of the negative impacts of deforestation. Extensive cattle grazing and fuel wood cutting by the local communities have deformed the plants to bushes [18]. The removal of a forest cover from steep slopes often leads to accelerated surface erosion and dramatically increases the frequency of land sliding and surface runoff. The storage capacity of the Rawal Lake which was 47,230 acre-ft when it was developed in 1960, has been reduced almost 34 percent due to sedimentation generating from natural and human induced factors in its catchment area [16]. The use of pesticides and herbicides in agriculture is a source of toxic pollution [19]. Many housing schemes, recreational pursuits e.g. Lake view point, Chatter and Valley parks etc. and farmhouses have been developed in the watershed. The construction of roads, pavements and other structures reduce the infiltration area that ultimately affect the recharging of the aquifer of the twin cities. No systematic study has been undertaken yet to document the landuse variability in the watershed.

2. Materials and methods

2.1. Data used

In the present study, the basic watershed data used to extract spatial input for SWAT model were hydrologic features, soil distribution, landuse information, and topography. The remote sensing technique has potential application in landuse monitoring and assessment at desired scales. RS images of LANDSAT-TM (Thematic Mapper) of period 1992 and LANDSAT-ETM + (Enhanced Thematic Mapper Plus) of 2000 and 2010 periods (Path-Row: 150-37) were used to delineate landuse/landcover of the watershed area on temporal basis. The LANDSAT ETM + sensor is a nadir-viewing, 7-band plus multi-spectral scanning radiometer (upgraded ver. of TM sensor) that detects spectrally filtered radiation from several portions of the electromagnetic spectrum. The spatial resolution (pixel sizes) of the image data includes 30 m each for the six visible, near-infrared, and short-wave infrared bands, 60 m for the thermal infrared band, and 15 m for the panchromatic band. The climatic parameters i.e. daily temperature (max& min) and precipitation data recorded at Satrameel observatory (73º 12´ 50'' E, 33° 45´ 57'' N & Elev: 610 m) maintained by Water Resources Research Institute had been collected for period 1991-2010. The discharge data of Korang river available on monthly basis from Small dams organization was acquired for the same period for model calibration and validation. The soil map developed by Soil Survey of Pakistan was utilized to extract soil data attributes for the study area.

http://dx.doi.org/10.5772/54492

2.2. Data preparation

The base map of the study area was prepared through generating and integrating thematic layers of elevation, physiography and infrastructure using ArcGIS 9.3 software. An integrated hydrological, spatial modeling and field investigations approach was adopted to achieve the study output. The boundaries of the watershed and sub-basins were delineated using Aster 30m DEM of the area in SWAT model 2005 software. Elevation map comprising of four classes i.e. >1600m, 1200-1600m, 800-1200m and <800m range, was prepared from Aster 30m DEM data (Figure 2). The image data was georeferenced using Universal Transverse Mercator (UTM) coordinate system (Zone 43 North). The satellite images were analyzed through visual and digital interpretation techniques to observe spatial variability of landuse. The visual interpretation was performed for qualitative analysis while digital interpretation for quantitative analysis of the image data. The false color composite of 5, 4, 2 (RGB) of LANDSAT image data was selected to extract signatures of representative landcover types from the image. In this bands combination, landcover is visible in true color i.e. vegetation in green, soil in pale to reddish brown and water in shades of blue color. The built-up area is shown in mixed pattern of white, brown, and purple colors due to variable types and density of constructed area, mixing of new and old settlements, presence of land features like lawns, parking sides, water ponds, roads/tracks etc. The signatures were evaluated using error matrix and an overall accuracy of more than 95 percent was achieved.

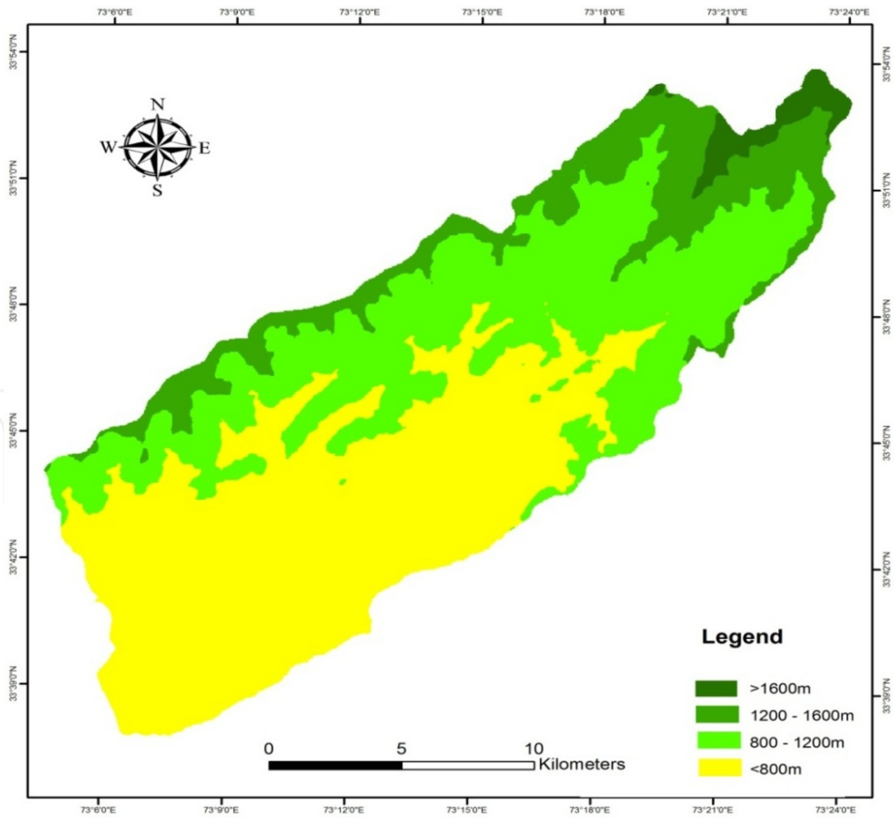

Figure 2. Elevation increases gradually towards northeast in the study area

The classification of the images was performed using supervised method following maximum likelihood rule mostly used to acquire reliable classification results. The classification output was supported with Normalized difference vegetation index - NDVI data that helps in segregating vegetative areas from non-vegetative [20]. The index which is based on the spectral characteristics of green vegetation cover in the area uses *TM3* and *TM4* bands of LANDSAT ETM+ image as given in the following equation:

$$NDVI = \left(TM4 - TM3\right) / \left(TM4 + TM3\right) \tag{6}$$

The classification of the images was performed to obtain seven major landuse/landcover classes which include conifer forest, scrub forest, agriculture, rangeland, soil/rocks, settlement and water. The images were recoded and later filtering technique was applied to remove noisy/misclassified pixels from the recoded image data. The doubtful classes were modified after ground truthing i.e. performing field survey in the target areas. Finally change analysis of landuse/landcover classes was performed using spatial modeling functions of ERDAS Imagine 9.2 software.

2.3. Model baseline establishment

Main procedures in the model running includes: (a) development of streams and sub-basins databases, (b) landuse and soil data input within sub-basins, (c) Input variable parameters of climate and management options, (d) compilation of input data and running the model for generating output results. The entire watershed had been divided into 15 sub-basins by choosing a threshold area of 500 ha. A total of 73 HRUs were generated in those sub-basins. A threshold of 5% was defined landuse distribution and 15% for soil distribution over sub-basin area. The low percentage for landuse was used to accommodate conifer coverage distributed in patches over northeastern parts of the watershed area. The importance of land uses lies mainly in the computation of surface runoff with the help of SCS curve during the model operation [6]. Three soil classes were identified and mapped i.e. sandy clay loam over northwestern hilly terrain, sandy clay loam over valley area in the northeast and sandy loam over low plains in the southwestern part of the watershed area.

The subcomponents of the water balance identified for use in analyses are total flow (water yield) consisting of surface runoff, lateral and base flow, soil water recharge; and actual evapotranspiration. These components are expressed in terms of average annual depth of water in millimeters over the total watershed area. For estimation of sediment yield, C factor values were used on the basis of soil erosion study [21] carried out previously in Pothwar region. The C value of 0.176 was assigned to soil/rocks while 0.2 was assigned to agricultural land class. Higher C values indicate more risk of soil erosion. The conservation practice factor P was assigned value of 1 on account of no significant conservation practice present in the watershed area [22].

2.4. Model calibration

Calibration and validation of the SWAT model was performed using monthly river flows data of 1991-2010 period. Data pertaining to year 1991 to 2006 had been used for calibration and the rest for validation of the model. The purpose of model validation is to assess whether the model is able to predict field observations for time periods different from the calibration period [23]. Although the model was run for years 1991 to 2006, the first 6 years of the simulated output were disregarded in the calibration process, since these are required by the model as a warm-up period. This period is essential for the stabilization of parameters (e.g groundwater depth), as the results sometimes vary significantly from the observed values. Thus the final calibration period was from January 1997 to December 2006. The calibration accuracy was checked by calculating several indexes which include Nash & Sutcliffe coefficient (*NTD*), Root Mean Square Error (*RMSE*) and the correlation coefficient R^2 of the time series. The Nash & Sutcliffe coefficient [24] is an estimate of the variation of a time series from another as given by following equation:

$$NTD = 1 - \frac{\sum_{i=1}^{n}\left(Q_{obs,i} - Q_{sim,i}\right)^2}{\sum_{i=1}^{n}\left(Q_{obs,i} - \bar{Q}_{sim,i}\right)^2} \tag{7}$$

And root mean square error- *RMS* was computed using following equation:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left[Wi\left(Q_{sim,i} - Q_{obs,i}\right)\right]^2} \tag{8}$$

Where, Q_{sim} = simulated time series, Q_{obs} = observed time series, $\bar{Q}_{sim}$= numerical mean for the simulated time series, W = weight and n = total number of measurements. A Nash & Sutcliffe coefficient approaching unity indicates that the estimated time series is almost identical to the observed one. The results of these tests are summarized in Table 1. The *NTD* index reached the value of 0.80, signifying a quite precise calibration. Later the model was validated using the same indexes, for the period of January 2007 to December 2010. The results of statistical analysis indicated a Nash Sutcliff efficiency of 0.80. The simulated river flows matched well with the observed values (Figure 3).

Index	Calibrated period	Validated period
NTD	0.80	0.80
RMSE (mm)	17.0	30.4
R^2	0.81	0.91

Table 1. Criteria for examining the accuracy of calibration and validation processes

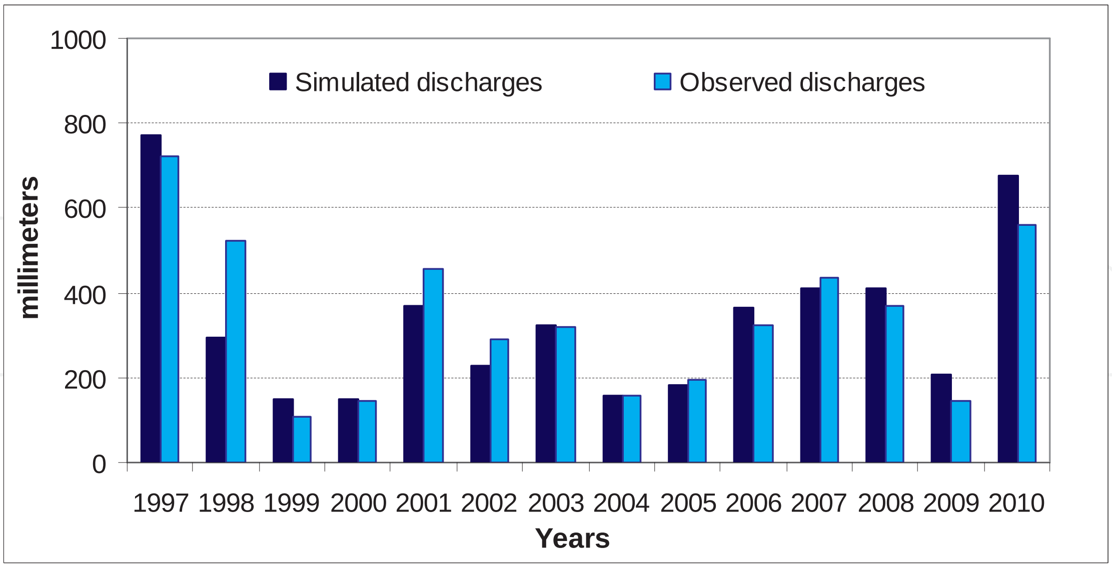

Figure 3. Time series of simulated and observed annual discharges for the Rawal watershed, period 1997-2010

3. Results and discussion

3.1. Assessment of changing landuse/landcover

Comprehensive information on the spatial and temporal distribution of landuse/landcover is essential for estimating hydrological changes at watershed level. The landuse/landcover condition of the watershed was estimated for three different periods i.e. 1992, 2000 and 2010 (Figure 4). Major landcover change was observed in the scrub class which indicated a reduction of about 4,515 ha during 1992-2010 period (Table 2). The rate of decrease in its coverage was about 1.5% per annum. The scrub wood is mostly used as fuel at local level due to non-availability of other energy sources. Major part of it had been converted into agriculture and built-up land, while in some areas it has changed into rangeland due to extensive wood cutting. These results are verified by the findings of [25] which highlighted maximum decrease in scrub forest during 30-year period i.e. 1977-2006 in Rawalpindi area. The settlement class had shown almost four times increase in coverage i.e. from 2.6% in 1992 to 8.7% in year 2010. The average rate of increase in this class was about 90 ha y^{-1}. The rate was over 45 ha y^{-1} during 1992-2000 while it was about 125 ha y^{-1} during 2000-2010 period indicating rapid urbanization in the last decade (Figure 5). The conifer forest had shown a decline at a rate of about 2.1% y^{-1} within last two decades. Although FAO [26] had reported deforestation at a rate of about 1.5% annually in the country, but due to high urban development, the rate of forest decline was higher in the watershed area. The agriculture coverage indicated an average increase of about 26 ha annually during 1992-2010 period. The rate of increase was about 3.4% y^{-1} during 1992-2000 while it was 0.3% y^{-1} during 2000-2010 period. The situation indicates intense agriculture activity in the former decade that seems replaced by rapid growth in urban development in the later decade.

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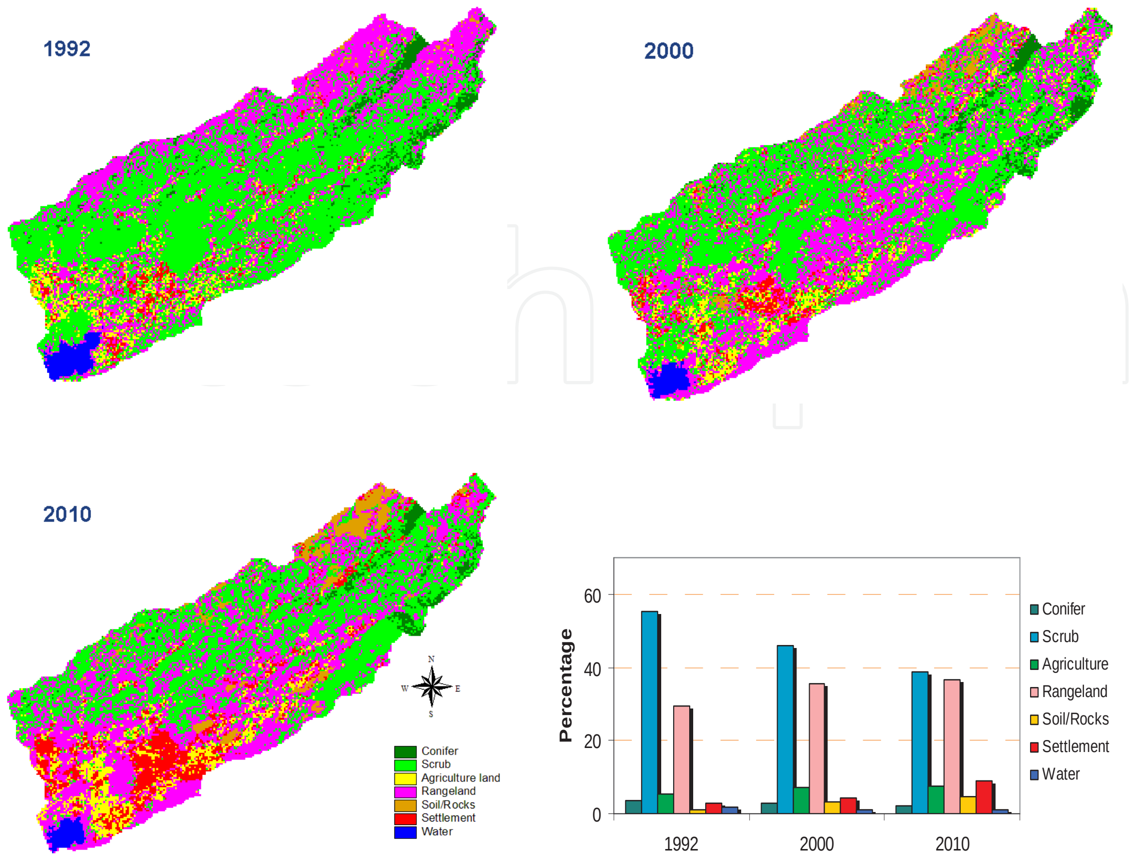

Figure 4. Spatio-temporal variations in landuse/landcover in Rawal watershed area during 1992-2010 period

Landuse	1992		2000		2010		1992-2010	
	Area (ha)	%	Area (ha)	%	Area (ha)	%	Change (ha)	Change %
Conifer	1006	3.7	762	2.8	626	2.3	-381	-1.4
Scrub	15069	55.4	12485	45.9	10554	38.8	-4515	-16.6
Agriculture	1496	5.5	1958	7.2	2013	7.4	517	1.9
Rangeland	8024	29.5	9629	35.4	9982	36.7	1958	7.2
Soil/Rocks	326	1.2	870	3.2	1306	4.8	979	3.6
Settlement	762	2.8	1170	4.3	2421	8.9	1659	6.1
Water	517	1.9	326	1.2	299	1.1	-218	-0.8
Total	27200	100	27200	100	27200	100	-	-

Table 2. Detail of landuse/landcover variations during 1992-2010 period

Figure 5. Growth of urbanization is causing rapid landuse change in the Rawal watershed area

The changes in landuse/landcover were variable on different elevation ranges during 1992-2010 period. The conifer forest has shown a decrease from 134 ha to 102 ha at greater than 1600m elevation range while this was from 343 ha to 238 ha within 1200-1600m elevation range during 1992-2010. The scrub class indicated a decrease of about 11 percent within 800-1200m range while 65% in less than 800m elevation range. In contrary to this, agriculture class had shown a increase of about 65% within 800-1200m range while 29% increase in less than 800m elevation range. About 86% settlement class was found below 800 m elevation during year 2010 indicating most of the urban development in the low lying areas of the watershed.

3.2. Model simulation

The model simulated an average water yield of about 378.6 mm/yr using base landuse of 2010 in the watershed area. About 49% of the yield was contributed by surface runoff and the rest by groundwater in the form of sub surface flows and springs etc. More than 70% of the annual yield was contributed during months of July, August and September. The surface runoff was found higher in the month of August i.e. over 83 mm while it was about 51 mm during July and 31 mm in September. The runoff was dominant over lower sub-basins likely due to higher impervious cover here than in the upper sub-basins of the watershed. The groundwater discharge to stream flows was maximum in the month of September and more than 70% of the discharge occurred during period from August to December. The long-term average soil loss in the watershed was estimated over 17 tons $ha^{-1}\,y^{-1}$ i.e. ranging from 0.4 to 36 tons $ha^{-1}\,y^{-1}$ in different sub-basins. These estimates of soil loss matched closely with the results of [22] which indicated soil loss ranged from 0.1 to 28 tons $ha^{-1}\,y^{-1}$ averaging 19.1 tons $ha^{-1}\,y^{-1}$ at Satrameel study site in this watershed.

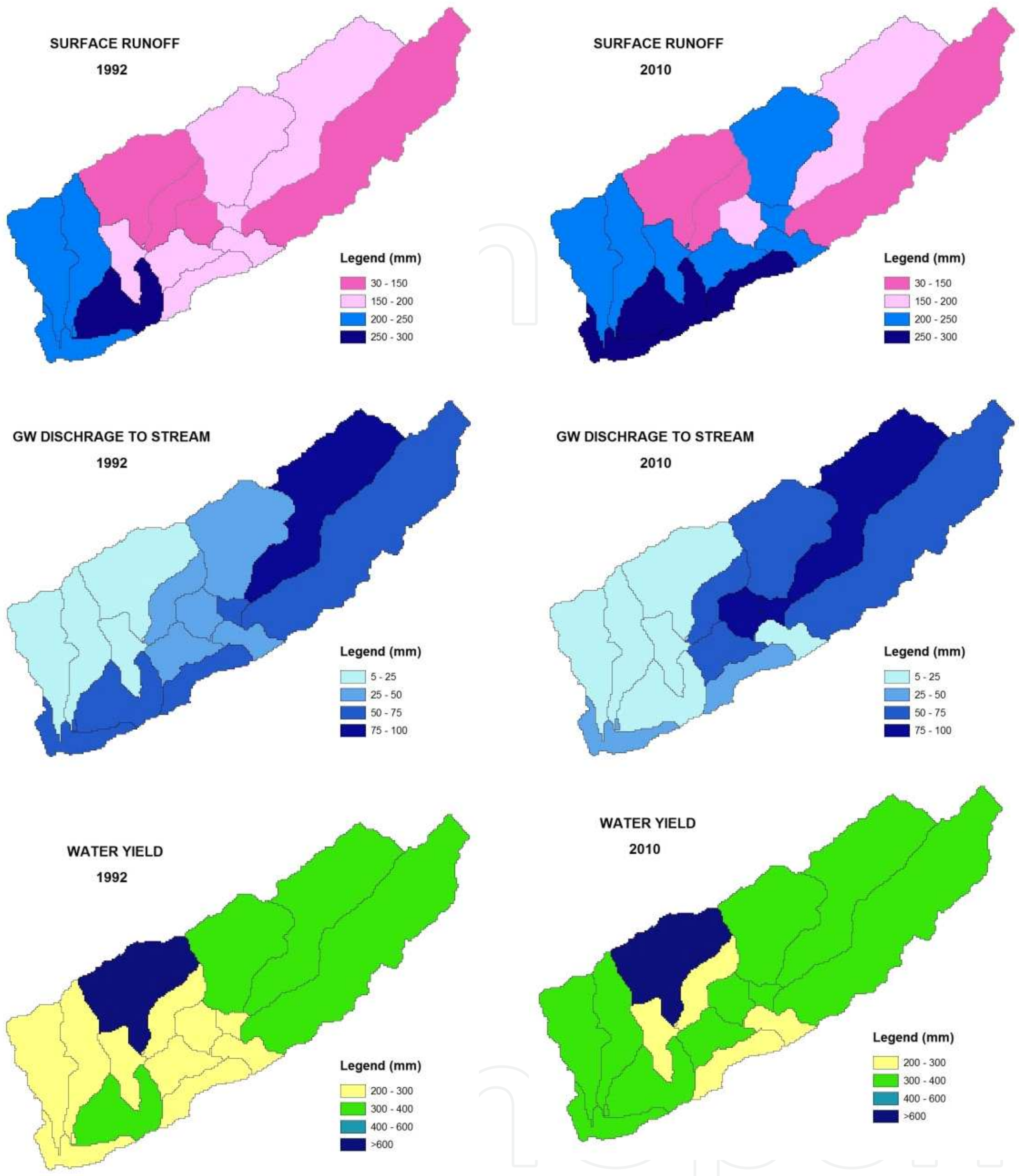

Figure 6. Comparison of the hydrological response of Rawal watershed to landuse conditions of 1992 and 2010 indicates dominant impact of landuse changes (i.e. urban development) in the southern low lying sub-basins on various hydrological parameters.

The model simulations showed a strong correlation between landuse evolution and the watershed runoff at the outlet. The change in landuse between years 1992 and 2010 indicated an increase of about 6% in the water yield and 14.3% in the surface runoff. The sub-basin wise hydrological response of the watershed during 1992-2010 period is shown in Figure 6. The sub-basins in the southern valley plains of the watershed indicate increase in surface runoff and water yield while decrease in groundwater contribution to the streams. The situation shows higher influence of urban landuse on hydrology of the low lying sub-basins as compared with sub-basins at higher elevations in the northeast of the watershed. Hydrologic changes due to increased impervious area and soil compaction generally lead to increased direct runoff, decreased groundwater recharge, and increased flooding, among other problems [27]. The combined effect of landuse and hydrological variations had exaggerated the problem of soil erosion resulting in an increase of about 17.4% in the sediment yield of watershed during 1992-2010 period. The increase in sediment yield can be attributed to the increase in surface runoff condition during this period (Figure 7). The zone of low sediment yield i.e. <5 tons ha^{-1} y^{-1} has shown a significant decrease while zones of medium sediment yield i.e. 5-10 tons ha^{-1} y^{-1} and high sediment yield i.e. >15 tons ha^{-1} y^{-1} a relative increase in the southeastern sub-basins of the Rawal watershed during 1992-2010 period (Figure 8).

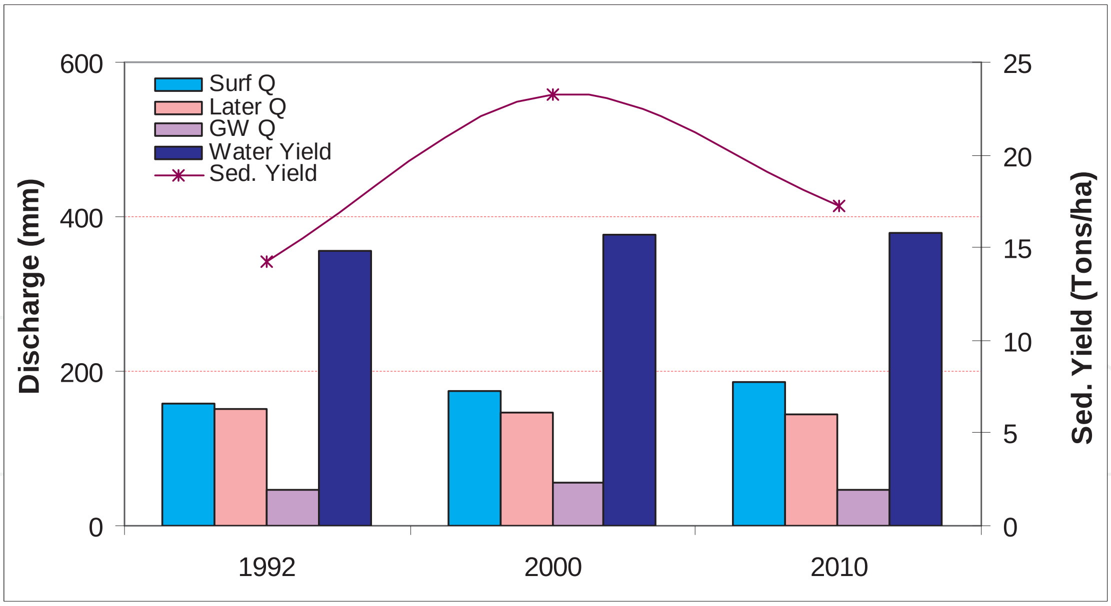

Figure 7. Hydrological parameters like surface runoff, water yield and sediment yield indicate an overall rise in values in reponse to landuse changes occurred within 1992-2010 period

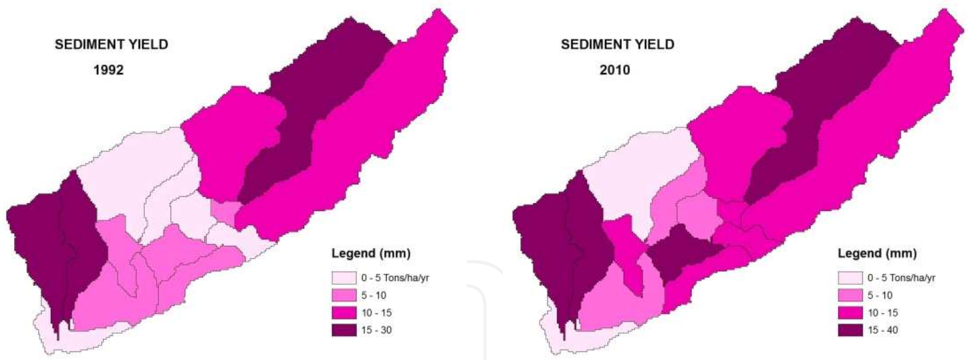

Figure 8. Temporal analysis of avarage annual sediment yield in the watershed during 1992-2010 peiod

3.3. Scenarios of extreme conditions

Different scenarios of landuse and climate change were developed to observe the response of water and sediment yields to the expected extreme conditions in future. The first three scenarios are related to probable changes in landuse/landcover of the watershed in future. As most of the landuse changes are taking place due to growth in urbanization i.e. development of built-up, agriculture land, deforestation/ afforestation in the area, so it formed the basis of these scenarios. The percentage coverage of landuse in the watershed under base line and three scenarios is shown in Table 3 and in map form in Figure 9. The other scenarios are based on the prediction scenarios of climate change for this region i.e. +0.9 ºC and +1.8 ºC change in temperature during 2020 and 2050 [28] and changes in precipitation. These were formulated in consultation with experts from the Intergovernmental Panel on Climate Change (IPCC) and are consistent with the scenarios generated using the Model for Assessment of Greenhouse gas Induced Climate Change (MAGICC) software. The analysis of different scenarios is given below:

- In the first scenario, all the rangeland below 800m elevation is assumed to be converted into built-up land (About 20% increase in the settlement class). It is based on our study findings that most of the urban development has been occurred in the low valley areas below 800m elevation during the last two decades. The runoff estimates in urban areas are required for comprehensive management analysis. The scenario indicates a decrease of about 0.1% in the water yield while an increase of about 12.1% in the sediment yield from that of the base year 2010 (Table 4). The surface runoff has shown an increase of about 0.2% while lateral discharge a decrease of about 2% due to increase in the impervious area during 2010 in the watershed.

- In the second scenario, all the scrub forest below 1200m elevation is assumed to be converted into agriculture land (About 31% increase in agriculture land) keeping other landuse conditions same as of base year 2010. This scenario is also based on our study findings that major agriculture development has occurred below 1200 m elevation during the last two decades in the watershed area. The scenario indicates an increase of about 3.6% in the water yield and about 73.6% in the sediment yield from the base year 2010. The surface runoff increases by 4.4% while lateral discharge decreases by 5.6% due to decrease in the scrub forest coverage.

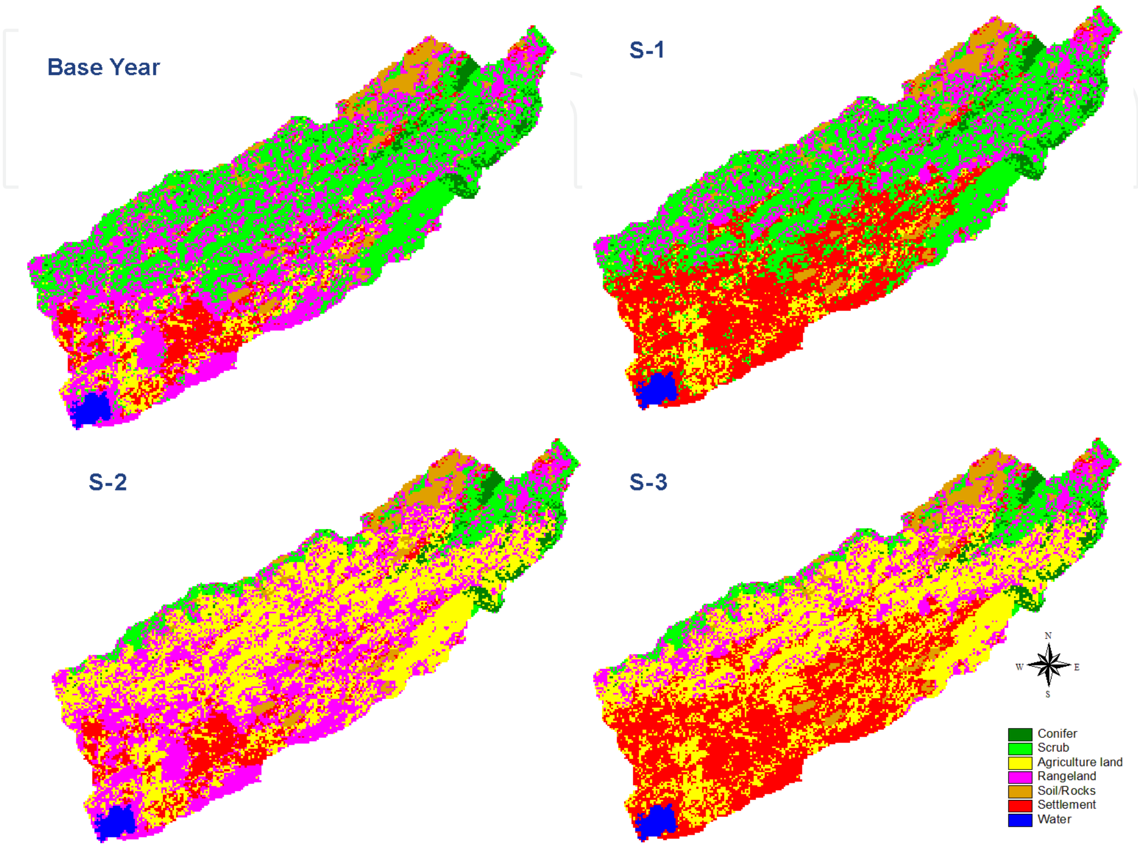

Figure 9. Landuse/landcover status during base year and three landuse change scenarios

Landuse	Base year 2010	Senario-1	Senario-2	Senario-3
Conifer	2.3	2.3	2.3	2.3
Scrub	38.8	38.8	7.7	7.7
Agriculture	7.4	7.4	38.5	38.5
Rangeland	36.7	16.3	36.7	16.3
Soil/Rocks	4.8	4.8	4.8	4.8
Settlement	8.9	29.3	8.9	29.3
Water	1.1	1.1	1.1	1.1
Total	100.0	100.0	100.0	100.0

Table 3. Percentage coverage of landuse in base year 2010 and under three landuse change scenarios

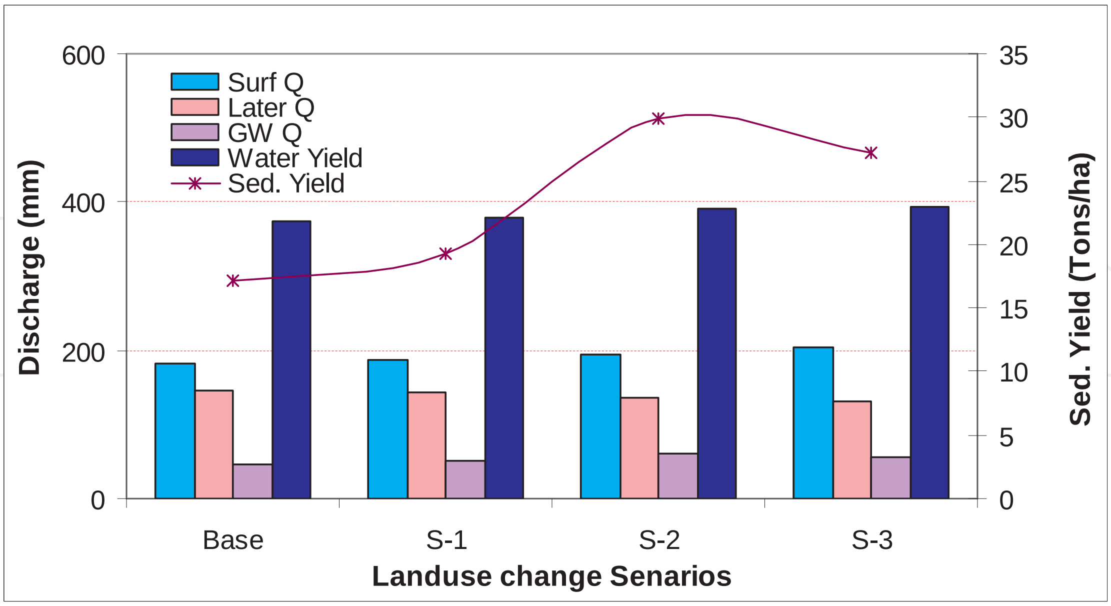

Figure 10. Hydrological response of the watershed under base year and three landuse change senarios

No.	Scenarios	Surf. Runoff %	Water Yield %	Sediment Yield %
S-1	Urban develop. Below 800m elevation (converting rangeland into built-up land)	0.2	-0.1	12.1
S-2	Agriculture develop. below 1200m elevation (converting scrub forest into agriculture land)	4.4	3.6	73.6
S-3	Combining scenarios 1 & 2	10.5	4.1	58.1
S-4	+0.9°C temperature in 2020	-0.8	-1.3	13.1
S-5	+1.8°C temperature in 2050	-2.1	-3.0	28.3
S-6	Increase of 10% rainfall in 2020 with no change in temperature	24.5	19.1	26.1
S-7	Increase of 0.9°C temperature & 10% rainfall in 2020	23.6	17.8	41.8
S-8	Increase of 1.8°C temperature & 10% rainfall in 2050	22.1	15.8	58.1
S-9	Increase of 0.9°C temperature & decrease of 10% rainfall in 2020	-22.7	-19.0	-13.6
S-10	Increase of 1.8°C temperature & decrease of 10% rainfall in 2050	-23.8	-20.6	-1.5

Table 4. Percentage changes projected for surface runoff, water yield & sediment yield under different landuse and climate change scenarios using base conditions of 2010

- The third scenario is based on the combination of the 1st and 2nd scenarios i.e. increase in built-up and agriculture land below 800m and 1200m elevations, respectively. The scenario indicates an increase of about 4.1% in the water yield and 58.1% in the sediment yield of watershed. The surface runoff indicates an increase of about 10.5% while lateral discharge decrease of about 9% due to decline in the scrub forest cover and growth in the urban development. The scenarios 2&3 have also indicated an increase of 1.1% and 0.6% in actual evapotranspiration due to temperature variations. The hydrological response against different landuse change scenarios is shown graphically in Figure 10.
- The scenarios 4 to 10 are based on future climate changes in the watershed area and respective response of the water and sediment yields with the assumption that no change in landuse/landcover of base year 2010 will take place over the time. The rise of about 0.9°C temperature in year 2020 and 1.8°C in year 2050 indicates decrease of about 1.3% and 3.0% in the water yields of the watershed. Increase in temperature may result in higher evaporation rates that would affect the behavior of water yield.
- In scenario-6, increase of 10% in rainfall during 2020 keeping same temperature conditions as of base year 2010 has shown an increase of about 19% in the water yield and 26% in the sediment yield of the watershed. Similar increase in rainfall with same temperature conditions as of scenarios-4 and 5 i.e. +0.9°C in 2020 & +1.8°C in 2050, projects nearly 18% and 16% increase in the water yields and about 24% and 22% increase in the surface runoff as shown under scenarios-7 and 8 in Table 4. The sediment yield has also shown an increase ranging between 41% and 59% in these scenarios. The increase in rainfall usually causes increase in magnitude of floods which ultimately creates soil erosion and land degradation problems.
- On the other hand decrease of 10% in rainfall with same temperature conditions as of scenarios-4 and 5 projects decrease of about 19% and 21% in the water yields which ultimately lowered the sediment yield from that of base condition of 2010.

3.4. Risk mitigation of sediment yield

Appropriate strategies have to be defined separately for different landuse conditions for minimizing the risk of soil loss and sediment yield involved in scenarios of extreme conditions. In order to reduce high sediment yield from sub-basins with rapid urban development, the unplanned urbanization needs to be controlled by appropriate laws and means. In the non-urban areas, proper soil and water conservation measures can be adopted to mitigate the risk of soil erosion.

In high risk zone of sediment yield, mainly dissected gullies are more susceptible to soil erosion. The problem of gully erosion can be solved to great extent through restoration of vegetative cover for which proper structures could be placed to provide protection long enough to give vegetation a start. The structures may be of temporary or permanent in nature keeping in view the nature of problem. Conservation structures to reduce velocity of the runoff can also be developed to control the extent of gully erosion. In medium risk zone of soil erosion, modifying the cross section and grade of channel to limit the flow velocities can be performed to stabilize the gullies. The conservation measures like terracing, contour bunding and diversion channels can be adopted in the contributory watershed to control excessive surface runoff causing gully erosion. These practices will also provide additional moisture for growing crops and vegetative cover thus help reducing gully erosion. In low risk zone of soil erosion, contour benches having small bunds crossway the slope of the land on a contour may be established to reduce the erosion risk. High intensity rainfall during monsoon season invariably cause over saturation harmful for plants. The situation can be avoided through provision of water ways and grassy outlets to dispose off the excessive runoff. The risk of erosion can also be minimized through adopting practices like strip farming, terracing, contour farming besides modifying bunds and minor land leveling in the cultivated area of watershed.

4. Conclusions

The recent changes in landuse/landcover conditions have brought significant impact on water flows, sediments and threat to eco-hydrology of the Himalayan area. The rapid growth in urbanization has increased the demand for land for development purposes consequently forest and water resources are coming under enormous pressure. The general trends of landuse change are gradual decline in coverage of scrub and coniferous forest, increase in urban development and somewhere in agriculture area. The increase in built-up land in the valleys has reduced the recharge source of groundwater which needs to be protected through controlling unplanned growth of urbanization. The rise in global warming accompanied with high variability in precipitation projects extreme changes in water balance and ultimately deterioration of the land quality. It is essential to regulate the urban development properly, affordable substitute-fuels for household use should be made available and an extensive community reforestation programme is undertaken to improve the fragile eco-system of the region. An integrated adaptation strategy needs to be developed at national and regional levels to cope with future implications of hydrological changes through focusing key policy areas and improving adaptive capacities of the communities at risk. Existing knowledge and data gaps need to be filled by systematic observations and enhanced capacities for research since these will be fundamental for developing climate change adaptation and mitigation programmes for the Himalayan region in future.

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