Response of hydrological factors and relationships between runoff and sediment yield in the Sub Basin of Satluj River, Western Himalaya, India

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doi:10.6088/ijcser.002020102

ABSTRACT

Runoff and sediment yield assessment is the most complex hydrological phenomenon to comprehend due to tremendous spatial variability of watershed characteristics and precipitation patterns. A number of natural and anthropogenic factors influence the water and suspended sediment flux of a river basin along its pathway. In the present study Satluj River which is located in the Western Himalayan ranges state of Himanchal Pradesh, India. Daily data have been used to examine the relationships between rainfall, runoff and in a remote sensing and GIS environment. For this study Rampur, Suni and Kasol three metrological stations datasets of rainfall, runoff and sediment yield for Satluj basin during 1980 to 2005 have been used. Eighteen different hydro environmental variables were derived from different spatial, non spatial and metrological datasets to calculate the characteristics of the basin. The terra ASTER digital elevation model (DEM) with 30 meter spatial resolution has been used. The performance of the long term trend analysis of rainfall, runoff and sediment yield was evaluated using statistical and graphical methods.

Keywords: DEM, Rainfall, Runoff, Sediment Yield, Hydro Environmental Parameters, Coefficient of Determination

1. Introduction

A watershed is a hydrologic unit which produces water as an end product by interaction of precipitation and the land surface. The quantity and quality of water produced by the watershed are an index of amount and intensity of precipitation and the nature of watershed management. In some watersheds the aim may be to harvest maximum total quantity of water throughout the year for irrigation and drinking purpose. In another watershed the objectives may be to reduce the peak rate of runoff for minimizing soil erosion and sediment yield or to increase ground water recharge. Sediment yield is defined as the total sediment output from a basin over a specified time period, with suspended sediment as the dominant component. Estimation of sediment yield are essential for water resources analysis, modeling and engineering (Walling and Webb 1996), in investigation of continental denudation rates (Summerfield and Hulton , 1994), in studies of drainage basin response to change in climate (Glazyrin and Tashmetow, 1995). Various interrelated geologic, hydrologic, and topographic factors cause sediment yield to vary widely from region to region (Ritteret al., 2002). Studies have addressed the
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Volume 2 Issue 1 2011

The relationship between sediment yield and its controlling factors through correlation and regression analysis at the global and regional scales. Variables expressing basin relief characteristics and runoff magnitude tend to be most strongly associated with sediment yields at global scale (Jansen and Painter, 1974).

The Satluj river basin as a whole receives a good amount of rainfall throughout the year, which flows through the Western Himalayan region. Apart from the hill topography, faulty cultivation practices and deforestation within the basin result in huge loss of productive soil and water as runoff. The high rate delivery of sediment deposited into reservoirs, constructed Dams and fresh water lakes which blocked the actual capacity of reservoirs and Dams. It also reduces the infiltration capacity of ground water cause the subsurface and underground water level continuously decreasing It has been aimed to develop a tool to couple climate change scenarios and watershed modeling in order to aid watershed management under the changing climate of the 21st century.

Ali and de Boar (2007) evaluated the spatial and temporal pattern of sediment yield in upper Indus river basin. Lu and Higgitt (1999) studied sediment yield and runoff relationship with mean elevation. Jain (2000) used the trapezoidal formula for assessment of sedimentation in Bhakra reservoir, the estimated capacity in between the maximum and minimum observed levels was obtained and average rate of loss of capacity in this zone came out to be 20.47 Mm$^3$ per year. The rationale of the study are examine the major factors controlling sediment yield in the Satluj basin using different remote sensing , GIS, hydrological and metrological datasets.

2. The Study Area

![Figure 1: Showing the study area Satluj Basin (up to Kasol).](image-url)
For the present study, Satluj Basin has been opted for the analysis which is one of the main tributary of Indus river system with total drainage area of 23927 km² (figure 1). It falls in the Western Himalayan ranges from 31º 00´ 00´´ to 33º 00´ 00´´ North and 76º 50´ 00´´ to 79º 00´ 00´´ East. These rivers are fed by snowmelt and rainfall during the summer and by groundwater flow during the winter. The river originates from the lakes of Mansarover and Rakastal in the Tibetan Plateau at an elevation of about 4500 m a.m.s.l. The topographical setting and abundant availability of water provides a huge hydropower generation potential, and hence several hydropower schemes exist or are planned on this river.

The study basin covers outer, middle and greater Himalayan ranges, but its major part lies in the greater Himalayas. Due to the wide range of altitudes and precipitation patterns, a diverse climate is experienced in the basin. The lower part of the basin has tropical and warm temperate climates, whereas the middle part has a cold temperate climate. In the upper part, the climate is very cold and in the uppermost part, which is a perpetually frozen area (permafrost), the climate is similar to the Polar Regions. In the upper part of the basin, most of the precipitation is produced by the westerly weather disturbances during winter in the form of snow. The lower part of the basin receives only rain, whereas the middle part gets both rain and snow. Owing to the large differences in seasonal temperatures, due to large altitude range, the snowline is highly variable in the course of the year, descending to an elevation of about 2000 m during winter and retreating to above 5000 m after the summer season.

3. Methodology

The present study utilizes a number of different hydrological and environmental data variables for investigating major factors that analyses runoff and sedimentation in the study area Kasol is a part of Satluj River basin. For the present study eighteen variables calculated and derived from geospatial, topographical and metrological datasets. A hydro-meteorological observation network was set up in the Satluj River basin. The rainfall is observed at 10 stations namely Bhakra, Berthin, Kahu, Suni, Kasol, Rampur, Kalpa, Rackchham, Namgia and Kaza. For the present study rainfall, runoff and sediment yield data during 1980 to 2005 for three main gauging stations Rampur, Suni and Kasol were obtained from BBMB (Bhakra Beas Management Board), India. The processing of meteorological data was done using different statistical methods which is incorporated in the Table 1. The statistical and trend analysis of different hydro - environmental parameters were calculated using Statistica (Statistical Software) & GIS Software ArcGIS 9.3.

All hydrological variables were derived from the sediment and runoff data (Table 2). The mean, maximum and minimum values of the topographic and other environmental variables for each sub basin were obtained from a statistical file obtained after clipping the respective database using the delineated sub basin boundaries from the DEM (figure 2 –A). Based on these extracted parameters, a number of maps portraying the variability of the major variables were developed. The trend analysis of rainfall, runoff and sediment yield relationship was analyzed for three main locations Rampur, Suni and Kasol during 1980 to 2005. Long term scenarios of rainfall at Rampur, Suni and Kasol during 1980 to
2005 change were set to simulate responses of runoff and sediment yield in a typical watershed at the Satluj River basin. Rainfall and runoff relationship divided into two seasonal periods i.e. Monsoon period and Non Monsoon period respectively. The temporal variations in the results showing the specific distribution and pattern of the rainfall – runoff and runoff – sediment yield due to long term changes which is actually dependent on the different factors and variables used in the study (Table 1).

Hydro – environmental variables mean annual sediment yield SY, mean annual discharge Q, drainage area A, basin length Lb, channel length Lc, minimum-maximum elevation, mean elevation, standard deviation of the elevation, upstream channel elevation El ch, basin relief R, relief peakedness R pk, hypsometric integral HI, slope, mean surface slope and standard deviation of the slope derived from the different spatial and temporal real time data sets. These variables can be used directly as input in many hydrological studies as Table 2.

Evaluations of hydrologic model utilize a number of statistics and techniques. Usually these tools include “goodness of fit” or relative error measures to assess the ability of a model to simulate reality. The following graphical and numerical performance criteria were used in the present study. Coefficient of determination ($R^2$) describes the proportion of the total variance in the measured data that can be explained by the model. It ranges from 0.0 to 1.0, with higher values indicating better agreement, and is given by,

$$R^2 = \frac{\sum_{i=1}^{N}[O(i) - O_{avg}] [S(i) - S_{avg}]}{\left[\sum_{i=1}^{N}(O(i) - O_{avg})^2\right]^{0.5} \left[\sum_{i=1}^{N}(S(i) - S_{avg})^2\right]^{0.5}}$$

Where, $O(i)$ is the $i^{th}$ observed parameter, $O_{avg}$ is the mean of the observed parameters, $S(i)$ is the $i^{th}$ simulated parameter, $S_{avg}$ is the mean of model simulated parameter and N is the total number of events.

Table 1: Showing prospective variables, definitions, and data sources

<table>
<thead>
<tr>
<th>Hydro - Environmental Parameters</th>
<th>Definition</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>SY (mg/lit)- Mean Annual Sediment Yield</td>
<td>Sediment transported by the annually at a stream gauging station</td>
<td>National Institute of Hydrology, Roorkee, India</td>
</tr>
<tr>
<td>Q (Cumec)- Mean Annual Discharge</td>
<td>Long term average discharge at the basin outlet</td>
<td>National Institute of Hydrology, Roorkee, India</td>
</tr>
</tbody>
</table>

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4. Results and discussion

4.1 Relationship between Runoff, Sediment Yield and Sub basin variables

Precipitation is a major factor controlling the hydrology of the region or a given watershed. Rainfall, runoff and sediment yield is the most complex hydrological phenomenon to comprehend due to tremendous spatial variability of watershed characteristics and precipitation patterns. For this purpose annual and average monthly rainfall and runoff data from 1980 to 2005 were plotted to analyze the rainfall-runoff...
relationship for three main sub basins Rampur, Suni and Kasol in the Satluj River basin. The average monthly rainfall and runoff linear regression equation $R^2$ is used for the evaluation of the study. For this study we derived 18 hydro – environmental factors which are directly and indirectly responsible for runoff and sediment yield production. Annual mean precipitation is the main controlling factor for analysis the runoff and specific sediment yield relationships. The $R^2$ for the Monthly Runoff and Sediment Yield (1980 – 2005) is 0.45, 0.50, 0.56 for monsoon period and 0.29, 0.43, 0.42 is for Non Monsoon period respectively (Chart 1, 2 & Chart 3).

Table 2: Showing Hydrological Environmental parameters of three sub-basins Rampur, Suni & Kasol respectively

<table>
<thead>
<tr>
<th>Hydro Environmental Factors</th>
<th>Rampur</th>
<th>Suni</th>
<th>Kasol</th>
</tr>
</thead>
<tbody>
<tr>
<td>SY (mg/lit)- Mean Annual Sediment Yield</td>
<td>226326.699</td>
<td>409442.092</td>
<td>465523.131</td>
</tr>
<tr>
<td>Q (Cumec)- Mean Annual Discharge</td>
<td>113968.635</td>
<td>140618.072</td>
<td>147747.423</td>
</tr>
<tr>
<td>A(sqkm)-Drainage Area</td>
<td>4421.89</td>
<td>4810.75</td>
<td>4896.337</td>
</tr>
<tr>
<td>Lb (Km)- Basin Length</td>
<td>233.97</td>
<td>277.732</td>
<td>286.062</td>
</tr>
<tr>
<td>Lc (Km)- Channel Length</td>
<td>300.04</td>
<td>354.96</td>
<td>390.799</td>
</tr>
<tr>
<td>EL min (m)- Minimum Elevation</td>
<td>840</td>
<td>633</td>
<td>529</td>
</tr>
<tr>
<td>EL max (m)- Maximum Elevation</td>
<td>6752</td>
<td>6752</td>
<td>6752</td>
</tr>
<tr>
<td>EL (m)- Mean Elevation</td>
<td>3770.64</td>
<td>3667.138</td>
<td>3613.61</td>
</tr>
<tr>
<td>EL st.dev.- Standard Deviation of the Elevation</td>
<td>1692.46</td>
<td>1752.209</td>
<td>1781.32</td>
</tr>
</tbody>
</table>
The character of the topography of a drainage basin significantly influences the quantity of the precipitation pattern (like high intensity rainfall) resulting runoff and sediment yield. The steeper a slope, the greater is the gravitational force acting to remove earth materials from the slope. In fact, the rate of movement of rocks and soil particles is directly related to the sine of the angle of slope inclination. The average slope of a drainage basin can be expressed simply as a ratio of basin relief to basin length. Sediment yields increase exponentially with an increase in this relief-length ratio. The relation between the texture-slope product and sediment yield is such that a high sediment yield can be expected from basins with a large drainage density and steep slope (figure 2- B).
Figure 2: Showing Digital Elevation Model (A) and Slope (B) of the study area of Satluj Basin (Rampur, Suni & Kasol)
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**Chart 2**: Showing Monthly Relationship between Runoff and Sediment Yield during 1980 to 2005 with Monsoon and Non-Monsoon periods respectively of Suni.

The coefficient of determination ($R^2$) for the Monthly runoff and sediment yield was obtained as respectively for the calibration period (1980 – 1994) i.e. 0.9119, 0.9106, 0.93 for Rampur, Suni and Kasol respectively (chart 4, 5 & 6). The discharge and sediment yield values were plotted against each other in order to determine the goodness-of-fit criterion of coefficient determination ($R^2$) for both parameters. The analysis reveals that the monthly comparison showed a better correlation than the daily values.

Model verification and validation are essential for comparing the observed and predicted data in any modeling studies. The model validation was carried out for daily and monthly surface runoff and sediment yield for the years 1995 to 2005(chart 7, 8 and 9). The regression model in this study was applied by applying coefficient of determination
approach. The coefficient of determination ($R^2$) for the Monthly runoff and sediment yield was obtained as respectively for the validation period (1995 – 2005) i.e. 0.5409, 0.6676, 0.6997 for Rampur, Suni and Kasol respectively. The validation results shows comparative difference between the discharge and sediment values for monthly and daily time periods respectively. The comparison between the sediment yield and discharge shows valuable correlation between each other for the three gauging locations Rampur, Suni and Kasol.

**Chart 4**: Monthly Calibration between Runoff and Sediment Yield during 1980 to 1994 of Rampur.
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Chart 5: Monthly Calibration between Runoff and Sediment Yield during 1980 to 1994 of Suni

\[ y = 0.0047x^{1.922} \]
\[ R^2 = 0.9119 \]


\[ y = 0.0006x^{1.3313} \]
\[ R^2 = 0.93 \]
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5. Conclusion

The availability of high resolution, global temporal, real time and spatial datasets provides an opportunity for examining major controls of specific sediment yield and runoff. The hydrologic and climatic variables extracted from different spatial and temporal datasets provide detailed spatial patterns of the various environmental characteristics in the Satluj basin. These extracted environmental factors values used to develop multiple regression models for estimating runoff and sediment yield in the different regions of the basin. Mean annual rainfall (P) is the main controlling factor for the monsoon part of the basin. This part of the basin has less relief but is subjected to effective monsoon rainfall, which becomes the dominant factor in controlling erosional process and in transporting the sediment along the Himalayan topographic regions.

The models of runoff and sediment yield presented in this paper link hydrological variables and environmental characteristics on a regional scale, and allow the prediction of specific sediment yield at Rampur, Suni and Kasol. The models, however, do not explain all the observed variation in specific sediment yield in the basin, which emphasizes the importance of and need of physically – based, spatial distributed models. But these derived hydro – environmental factors can be used as input for any hydrological studies. The coefficient of determination (R2) for monthly runoff for validation period was obtained 0.5409, 0.6676, and 0.6997 respectively. The values of R2 can be considered reasonably satisfactory for calculating runoff and sediment yield from
a remote watershed with observe gauging sites Rampur, Suni and Kasol for Satluj basin respectively.

6. References


3. Anil Mishra and Takeshi Hata (2006), a grid based runoff generation and flow routing model for the Upper Blue Nile basin. Hydrological Sciences 51(2).


