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Floodplain Modeling of River Jhelum Using HEC-RAS : A Case Study

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ABSTRACT

Extreme flood events in river Jhelum are a major disaster in the State of Jammu & Kashmir, India. In the present study HEC-RAS model was applied to two different reaches of river Jhelum located upstream and downstream of the historic city of Srinagar. The vulnerability of important areas and structures corresponding to 25, 50 & 100 year return period flood events was determined. The levels of the bunds of river Jhelum were found to be inadequate at many places for 100 year return period flood. The flood spill channel constructed for safeguarding Srinagar city was found to be ineffective for conveying optimized flow.

Introduction

Flood plain modeling is a comparatively recent engineering discipline which can focus on several different areas, including carrying out comprehensive floodplain studies, design of transportation features (such as roads and bridges) or other facilities, floodway development, and structural and non-structural solutions to flood problems. Floodplain studies provide water surface profiles and floodplain maps for land-use planning in flood prone areas. Floodplain studies often include the analysis of historic floods, which are used in model calibration to make sure the model can reproduce historic water surface elevations recorded during actual flood events. Floodplain studies also generally feature the computation of the water surface profile for at least the one-percent annual chance (100-year average return period) flood. The 100-year flood elevations from this profile are then transferred to a topographic map, illustrating the portions of the floodplain that will be inundated by the 100-year flood.

In order to address the floodplain hydraulics problem and to predict accurately, the complex response of floods, researchers/engineers utilize physical and numerical/ computational modeling techniques. Some of the computational programs which are in common use these days are WSP-2, TR20, FLDWAV, ISIS, MIKE-11, HEC-RAS, etc.

The present study aims to analyze the behavior of river Jhelum with the use of the hydraulic modeling software (HEC-RAS) developed by the "Hydrologic Engineering Center of U.S. Army Corps of Engineers”. The water levels at various cross-sections along river Jhelum were simulated for different flow rates corresponding to different return period floods. The effect of various bridges on water surface profiles was also incorporated in the analysis.

The river Jhelum was divided into two reaches. Reach-1 defines the geometry of the river Jhelum from Srinagar to Padshahibagh. Reach-2 encompasses the Srinagar city, extending up to Shadipora and includes the flood spill channel. The flood The flood spill channel (FSC) is an artificial channel which has been created to safeguard the city of Srinagar against the flood disasters. The flow rates were determined using standard probability distributions namely Gumbel's k-t Type, Pearson Type-III, Log Pearson Type-III, Fosters Type-I, & Fosters Type-III. The values of Manning roughness coefficient *n*, constituting an important parameter affecting the results, were determined by using three methods namely Strickler's method, Limerinos’ method and Cowan's analytical method. The boundary conditions for the model were determined from establishing best fit trends in Gauge-Discharge relationships.

Study Area

River Jhelum is the major river of Kashmir valley flowing from south to north-west. Owing to its geological role in the origin of Kashmir valley and life sustaining role, periodic hydraulic and hydrological studies of the river can't be ignored.

Every single drop of water, anywhere in the valley has to merge in the Jhelum that means any stream, rivulet and Nallah that flows in the valley ultimately merges into the Jhelum. The total length of the river is 212 Kms. Its basin lies between the Greater Himalayas and Pirpanjal range. The source of river Jhelum is Verinag spring, and it is being joined by various tributaries during its course and finally joins Chenab river in Pakistan. The river is sluggish except during the months when snow melts and heavy rainfall occurs thus resulting in floods. The study area is situated between 33°25´ to 34°30´ north latitude and 73°55´to 75°35´ east longitude. Fig.1 shows the location map of Kashmir Valley whereas Fig.2 shows the tributary map of river Jhelum.

Historical accounts suggest that the river has witnessed devastating floods since ages, many among which have created havoc in terms of their resultant destruction. The area which is mainly affected by floods is the Jhelum valley floor, stretching from District Anantnag in the south to District Baramulla in the north [1]. Even though flooding is frequently observed in the Jhelum floodplain, no comprehensive flood management (mitigation) strategy has been put in place. With the advancement of new technology and development of flood modeling tools such as HEC-RAS, these days, it is possible to model flood water level elevation, depth, distribution etc. in the temporal as well as spatial dimensions.

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HEC-RAS System

General

The HEC-RAS system contains four one-dimensional river analysis components : steady flow water surface profile computations; unsteady flow simulation; movable boundary sediment transport computations; and water quality analysis. A key element is that all four components use a common geometric data representation and common geometric and hydraulic computation routines. In addition to the four river analysis components, the system contains several hydraulic design features that can be used once the basic water surface profiles are computed [2], [3]. HEC-RAS has been present in the public realm for more than 15 years and has been peer reviewed. It is freely available for download from the HEC website and is supported by the US Army Corps of Engineers. It is also widely used by many government agencies and private firms. For these reasons, HEC-RAS was selected for the study.

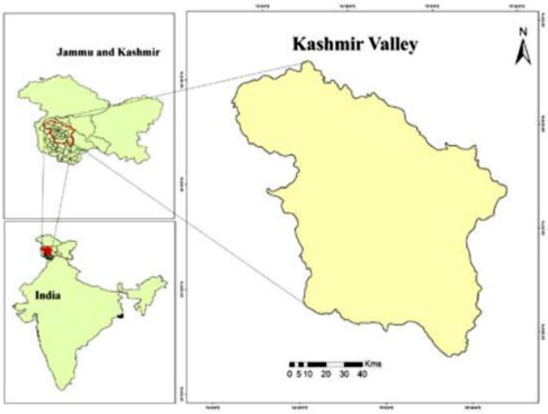

Figure 1. Location map of study area

Figure 2. Tributary/ catchment map of river Jhelum

Flood frequency Analysis

Computing the peak rate of runoff from a watershed involves an element of probability, which makes it more complex. A better way to solve the problem is to employ statistical methods using the runoff/flood peak data, when the basin is gauged for its runoff data. Peak Discharge data for last 50 years at two gauging sites, namely Sangam & Ram Munshibagh (Padshahibagh) were provided by Jammu & Kashmir State Irrigation & Flood Control Department. The data was subjected to standard methods of flood-frequency analysis. In order to investigate the suitable probability distribution for the flood peak series, various theoretical probability distributions for Gauging stations of Sangam and Ram Munshibagh were employed to determine the flow rates. The various types of probability distributions employed were Gumbel's k-t Type, Pearson Type-III, Log Pearson Type-III, Fosters Type-I, Fosters Type-III.

Statistical goodness of fit tests such as the Kolmogorov–Smirnov and Shapiro-Wilk were performed using a statistical software namely Origin Pro 8.0 to aid in the selection of suitable distribution. The various statistical parameters for flood frequency analysis of peak flow data at the two gauging sites are given in table1. It appears that a log-Pearson Type III would be the most acceptable distribution for the Jhelum river data. The actual data follow the distribution very well. Flood frequency curves using Log-Pearson Type-III for Sangam and Ram Munshibagh are shown in Fig. 3.

HEC-RAS Parameter Estimation

The Hydrologic Engineering Center's River Analysis System (HEC-RAS, version 4.1), a one-dimensional, hydraulic-flow model developed by the U.S. Army Corps of Engineers (USACE), was used to model the study reach of about 80 km of Jhelum river from Sangam to Shadipora along with the existing flood spill channel. The various input parameters of the HEC-RAS model include cross section and bridge geometry, Manning's rugosity coefficient *n*, and the boundary conditions.

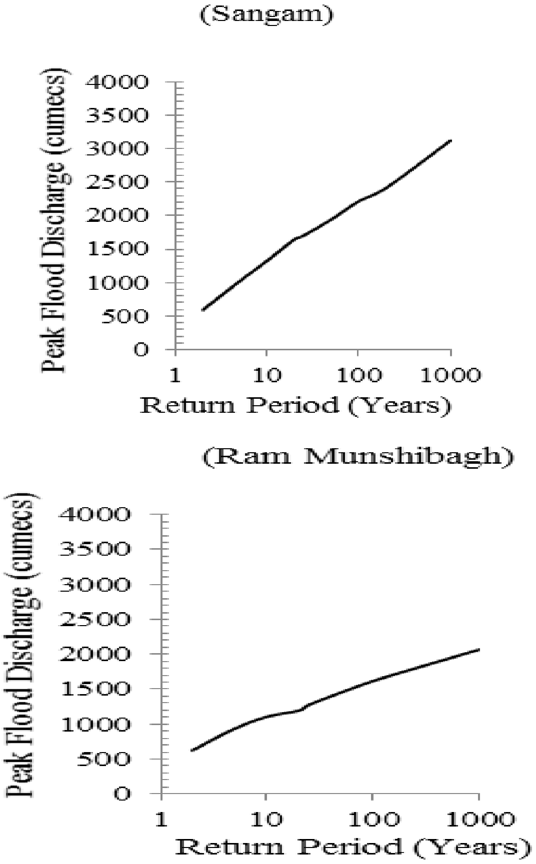

Figure 3. Flood frequency curves (Log Pearson Type-III)

Cross Section and Bridge Geometry

Boundary geometry for the analysis of flow in natural streams is specified in terms of ground surface profiles (cross sections) and the measured distances between them. For this study a total number of 120 cross-sections for the main river and 16 cross-sections for the flood spill channel were obtained from latest surveyed drawings provided by Jammu & Kashmir state Irrigation & flood control department. In addition, fifteen (l5) existing bridges, through the city of Srinagar, were modelled in order to analyse the vulnerability of deck levels to various water surface profiles. The geometric data pertaining to these bridges were also obtained from Jammu & Kashmir state Irrigation & flood control department.

Estimation of Manning's *n*

Estimation of Manning's roughness coefficient (or Manning's *n*) is very important to simulate open channel flows. Hydraulic roughness, or resistance, is defined as the primary factor influencing retarding or resisting forces exerted by channel boundaries on stream flow.

Following three methods were selected for the estimation of Manning's roughness parameter [4].

Flow-Dependent method

Limerinos in 1970 proposed the estimation of Manning's roughness coefficient *n* by "(1)".

$$n = \frac{0.11296R^{1/6}}{1.16+2.0log\left(\frac{R}{D_{84}}\right)} \qquad (1)$$

where R is hydraulic radius (cross-sectional area / wetted perimeter), and D_{84} is the channel bed surface sediment diameter for which 84 percent of the material is finer (All units in meters).

Flow-Independent method

Strickler in 1923 developed an empirical equation for estimating Manning's n based on the bed surface sediment diameter for which 50 percent of material is finer, D_{50} [5]. Strickler's equation for estimation of manning's n is given by "(2)".

$$n = 0.0474\ D_{50}^{1/6} \qquad (2)$$

Where D_{50} is in meters.

Cowan's Analytical Method

Cowan in 1956 proposed a procedure for estimating Manning's n that accounts for contributions of various factors, including vegetation, to total flow resistance. The procedure assumes linearity, which implies that resistance of contributing factors can be summed to establish total resistance. The Cowan's method as modified by Arcement and Schneider [6] designed specifically to account for floodplain resistance is given by "(3)".

$$n=(n_b+n_1+n_2+n_3+n_4)m \qquad (3)$$

where n_b is a base value, that represents the channel material, n_1 is an addition for surface irregularities, n_2 is an addition for variation in shape and size of channel, n_3 is an addition for obstructions, n_4 is an addition for vegetation, m is a correction for meandering.

Bed sediment samples were taken from 10 sampling sites along the river Jhelum and subjected to sieve analysis for the estimation of D_{84} and D_{50}. Subsequently the values of manning's n were determined using the Limernos', Strickler, and Cowan's methods. The averaged value of Strickler and Limerinos estimates was used as the base value for calculating composite roughness using Cowan's approach. Using Cowan's method the variation wasn't found to be much appreciable, an averaged value of manning's n equal to 0.0278 was used from Sangam to Kakapora and 0.0302 from Kakapora to Shadipora. Manning's n for flood spill channel was selected as 0.027 using Chow's tables [7].

Boundary Conditions

For steady flow models, the input boundary conditions are known water surface elevations on the upstream. Boundary conditions are necessary to establish the starting water surface at the ends of river system. Downstream boundary conditions at Padshahibagh & Shadipora is set to normal depth with average energy slope of 1 in 8000 (Irrigation & Flood Control Department). Known water surface elevations are calculated from Gauge discharge (G-D) relationships established for the gauging stations using gauge discharge data from year 1993-2012. The G-D relationships developed for different gauging sites are shown in Table 2. The known water surface elevations for flow rates of 100-year, 50-year and 25-year return period floods were calculated by using the equations given in Table 2 and the program then back-calculates a starting water surface elevation using Manning's equation.

Results and Discussions

The model gives the flood plain water surface profile in 2D view. The profile plots of the two reaches are given in Fig.4 and Fig.5. The profile plots indicate the variation of 100-year, 50-year, and 25-year flood water surface elevations at various cross-sections along the length of the reach. Flow was optimised at the junction of Jhelum and Flood spill channel and for the bridges also. These profile plots give an indication of the kind of effort involved to contain the water laterally corresponding to a particular level of protection.

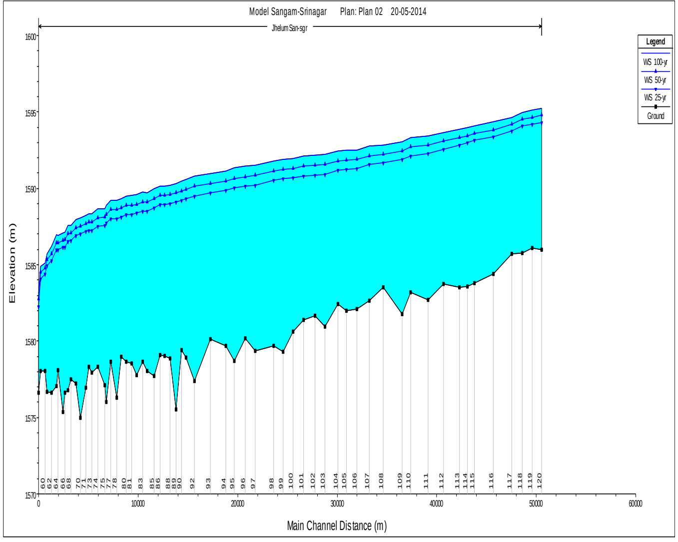

Figure 4. Profile Plot For Reach-1(Sangam-Srinagar)

Furthermore Fig.6 and Fig.7 respectively illustrate the variation of discharge and flow area along the length of river reach, indicating areas needing flood-protection measures. The dips in channel discharge conversely lead to increase in discharge in the subsequent floodplain making the areas vulnerable which can be also inferred from flow area plots.

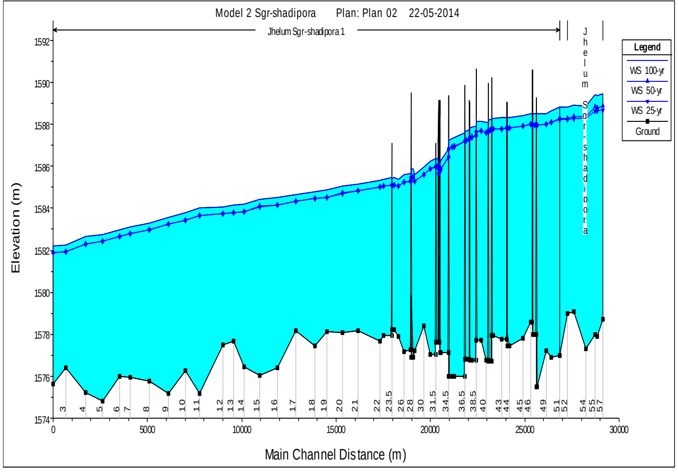

Figure 5. Profile Plot For Reach-2 (Srinagar - Shadipora)

The vulnerability of an area or location to flood of a particular magnitude is intimately related to the extent of lateral protection. The cross-sectional plots serve to deduce flood vulnerability of the existing bunds and other structures , and the surrounding floodplain. Sectors where the model imposed a vertical extension of the cross section are critical and need further analysis. Some of the critical cross-sectional plots are shown in Fig.8, and 9.

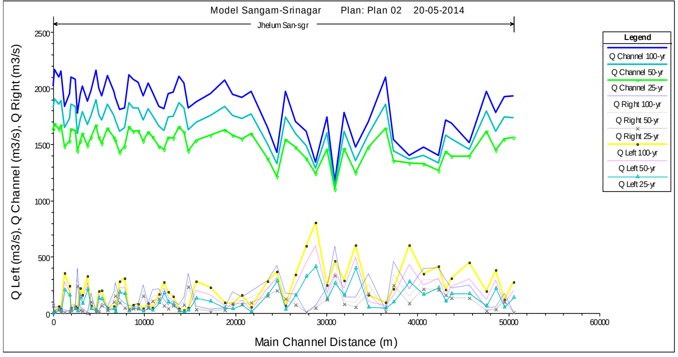

Figure 6. Disharge Variation with Channel Distance for Reach -1

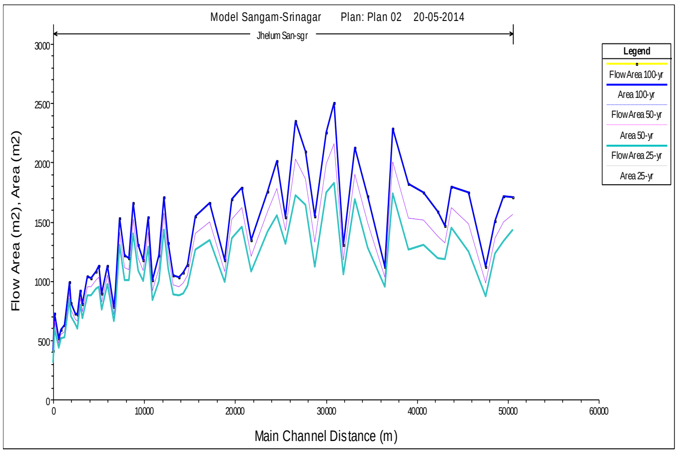

Figure 7. Disharge Variation with Channel Distance for Reach -1

Fig.8, which shows a cross section plot at (river section) RS 110 adjacent to Awantipora Shrine, depicts that the existing bund (elevation 1591.3 m) and the adjoining agricultural land on the left bank is vulnerable to even the 25-year return period flood. However, the famous Shrine at Awantipora located on the right bank at an elevation of 1597.8 m and other structures in the vicinity of RS 110 are safe from 100-year, 50-year and 25- year flood water elevations.

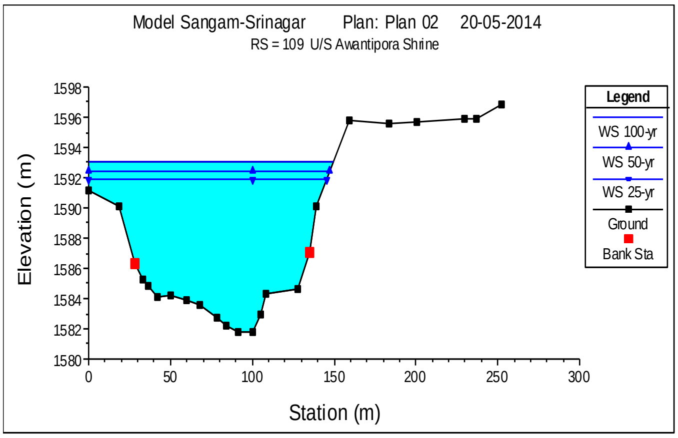

Figure 8 Cross-sectional plot at Awantipora Shrine (RS 109)

The cross section plots serve to deduce the vulnerability of important areas and places for 100-year, 50-year, and 25-year flood profiles. The deck levels of many bridges were found to be vulnerable to 100 as well as 50-year flood profiles e.g., the new Habbakadal bridge shown in Fig.9 is vulnerable to both the profiles with flood levels just 0.3-0.5m below the low chord of the bridge.

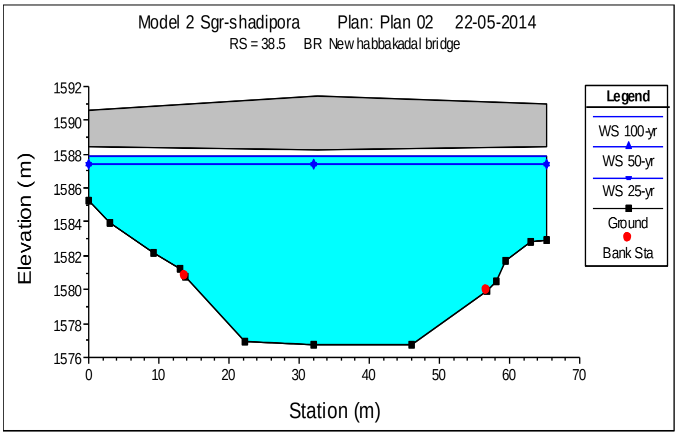

Figure 9. Cross-sectional plot showing new Habbakadal bridge (RS 38.5)

Calibration and Sensitivity Analysis

Any hydraulic model needs to be calibrated to the greatest degree of accuracy possible based on verification data. Owing to limitations and unavailability of actual data, model calibration was performed by comparing the output rating curves with the established G-D curves.

A comparison of the computed v/s established trend for Padshahibagh station is shown in Fig.10. The computed curves show small deviation from established trends for high water marks for all the curves though the initial rising trend doesn't agree with the established data at all key locations , which is a common occurrence [8].

It follows that the model is calibrated for high water marks which is the main concern and indicates good calibration with a tolerance of ±0.15m as suggested by FEMA (Federal Emergency Management Agency) guidance [8].

In order to ascertain the accuracy of adopted manning's *n* values sensitivity tests were carried out at four locations for the two reaches. Adopted Manning's *n* values were varied from ± 5% to ± 25% and compared to change in water surface elevations in order to assess the sensitivity of the model. The results of sensitivity analysis are shown in Fig.11. The sensitivity of water surface elevation to Manning’s roughness coefficient *n* is more when *n* values are increased than when *n* values are decreased.

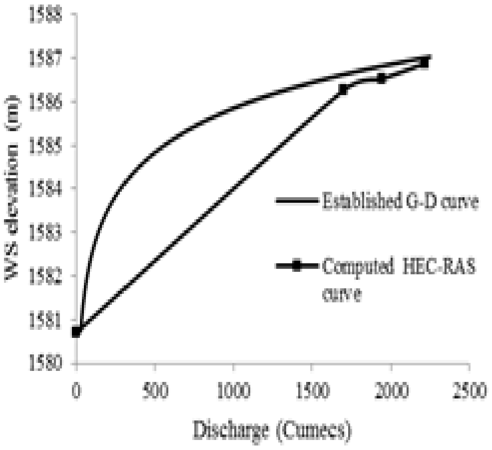

Figure 10. Computed v/s established trend at Padshahibagh

The maximum change in WS (water surface) elevation is 0.2 m at RS 14 (Reach 1). The roughness coefficient is very less sensitive in case of flood spill channel (FSC) with a maximum change of 0.03m.

Table 1. Statistical Parameters of Flood Frequency Analysis

Typeof Distribution	Sangam				Ram Munshibagh			
	Shapiro-Wilk Statistic	Shapiro-Wilk Probability	K-S Statistic	K-S Probability	Shapiro-Wilk Statistic	Shapiro-Wilk Probability	K-S Statistic	K-S Probability
Gumbel's k-t Type	0.913	0.428	0.140	0.277	0.942	0.768	0.118	0.382
Pearson Type-III	0.908	0.762	0.132	0.378	0.955	0.864	0.124	0.454
Log Pearson Type-III	0.984	0.972	0.098	0.673	0.998	0.988	0.078	0.784
Fosters Type-I	0.937	0.553	0.155	0.474	0.954	0.654	0.176	0.244
Fosters Type-III	0.924	0.587	0.121	0.254	0.937	0.552	0.158	0.218

Table 2 . Fitted Gauge Discharge (G-D) Relationships

Station	G-D Relationship	R^2	Remarks
Sangam	G= 1.2821ln(D)-2.9094	0.87	G = Gauge (in meters) D = Discharge (in Cumecs) R^2 = Coefficient of Regression
Padshahibagh	G = 1.4604ln(D) - 4.4992	0.92	
Ram Munshibagh	G= 1.2325ln(D) - 3.9269	0.88	
Shadipora	G = 1.5228ln(D) - 6.2134	0.82	

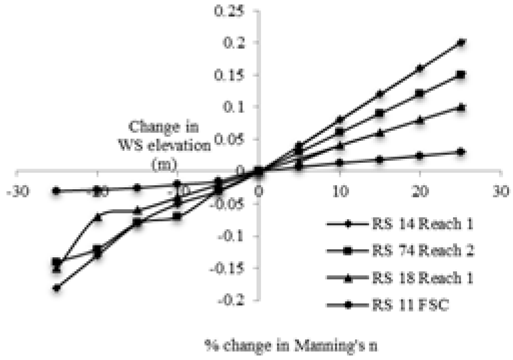

Figure 11. Results of sensitivity analysis

Some important findings/conclusions of the study are enumerated as under

1. Many areas were found to be inundated for 100-year and 50-year floods. The area included the open land in the right as well as left floodplain though left floodplain was found to be more active for the Reach-1 (Sangam-Padshahibagh).
2. At most of the locations constructed bunds get over topped for 100-year and 50-year flood profiles. This shows the necessity of construction of engineering structures such as dykes and levees along the river channel and through the city of Srinagar.
3. A substantial threat to many buildings including many religious structures was found for 100-year and 50-year flood profiles.
4. The flood spill channel (FSC) was found to be ineffective for conveying optimised flood flow. Many areas were found to be vulnerable along the FSC including Mehjoor Nagar, Rajhbagh, Rambagh, Tengpora, & Bemina.
5. The results of sensitivity analysis indicated that the main river reach is more sensitive to change in manning's *n* values than the flood spill channel reach. The maximum change in WS elevation was found to be 0.2m for river Jhelum and for FSC a maximum change of 0.03 m was recorded by varying *n* values by ± 25%.

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