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FLOOD INUNDATION MODELING AND FLOOD HAZARD ASSESSMENT FOR A REACH OF A RIVER

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ABSTRACT

In recent years the number and scale of water related disasters, flood in particular has been increasing. The losses from floods often offset years of hard-won social and economic development. The problem is further expected to be aggravated with the phenomena of climate change. Therefore, mitigation and managing of flood hazards has become a priority for alleviating poverty, ensuring socio economic progress, preserving our eco-systems and ensuring the gains of development. The paper presents flood inundation modeling and flood hazard assessment for a river reach. Floods of various return periods have been estimated for the seven stream flow gauging sites lying in the river reach under study using the L-moments approach. Based on the L-moment ratio diagram and $|Z_i^{dist}|$ *statistic criteria, GEV, GNO, GPA, distributions have been identified as the robust distributions for one site each and the GLO and PE-III for the two sites. The values of growth factors for 100 year return period floods for these sites are 2.018, 1.804, 1.410, 2.310, 2.585, 1.747, and 2.812. The ERDAS Imagine has been used for image processing and GIS Analysis. HEC-Geo-RAS module has been used for data base preparation for the mathematical modelling of river flow. HEC-RAS model has been for simulating the river flow for estimation of extent of flood inundation and depth of flooding for various return periods. The flood inundations for some of the years simulated by the HEC-RAS have been compared with the flood inundation mapped derived from the satellite data. Flood inundation has also been estimated considering that the flows are at danger levels at all the seven sites. The areas inundated for the return periods of 2, 10, 25, 50, 100, 200, 500 and 1000 years are estimated as 3890, 4809, 5253, 5618, 5917, 6577, 6928 and 7166 km*^{2}.

Keywords: *Flood frequency analysis, L-moments, Gradually varied flow, HEC-RAS, Flood inundation modelling, Flood hazard.*

INTRODUCTION

Flood is the most frequent natural disaster claiming loss of life and property compared to any other natural disaster. About one-third of all losses due to nature's fury are attributed to floods. There is every possibility that losses due to floods may increase in future due to rapid growth of population and increased encroachments of the flood plains for habitation, cultivation and other activities (Kumar et al., 2005). Some of the important policies on flood management have been described by Kumar et al. (2005). Various types of structural as well as non-structural measures have been envisaged to reduce the damages in the flood plains in India. Construction of embankments, levees, spurs, etc. have been implemented in some of the states. A large ++++++number of reservoirs have been constructed and these reservoirs have resulted in reduction of intensity of floods. The non-structural measures such as flood forecasting and warning are also being adopted. The flood forecasting and flood warning in India commenced in 1958, for the Yamuna River in Delhi. It has evolved to cover most of the flood prone interstate River basins in India. A Working Group of National Natural Resources Management System (NNRMS, 2002) standing committee on water resources for flood risk zoning of major flood prone rivers considering remote sensing input was constituted by the Ministry of Water Resources in 1999. The working group recommended flood risk zoning using satellite based remote sensing with a view to give thrust towards implementation of flood plain zoning measures. Currently, due to fast growing population and high economic growth India is facing innumerable challenges in planning, development and management of its water resources. Data collection, processing, storage, retrieval and dissemination using the state-of-art knowledge in information technology are being paid attention for use in sustainable development and management of water resources projects. Mani et al. (2014) presented flood hazard assessment with multi-parameter approach derived from coupled 1D and 2D hydrodynamic flow. The Decision Support System (Planning) (DSSP) for integrated water resources development and management and Real Time Decision Support System (RTDSS) developed under the World Bank funded Hydrology Project-II are some of the recent efforts for bridging the gap between the developed advanced technologies of water resources planning, designing and management and their field applications. There is also a need for taking more effective structural and non-structural measures of flood management and flood damage reduction based on long term reliable data, advance analyses and modelling procedures and antecedent rainfall forecasting using information based on radar, satellite based instrumentation and high resolution Numerical Weather Prediction (NWP) models. It also necessitates capacity building for implementation of these measures and bridging the gaps between the developed advance and robust procedures and their field applications.

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STUDY AREA

The flow simulation has been carried out for a major alluvial river in northern part of India. The main river stretch is about 250 km long and four major tributaries; two on left bank and two on right bank joins the main river. The index map of the study area is shown in Figure 2. There are seven GD sites located in the study stretch at various rivers. Their locations are marked by red line in the figure. GD sites 1, 2 and 7 are on the main river while others are on tributaries. The discharge data at GD sites 1 to 6 are used in the model setup. The length of tributaries from their respective gauging sites to the confluence with main river are considered for developing the model. At the GD locations, the surveyed river cross sections are obtained from Central Water Commission (CWC). Additional cross sections in the intermediate river stretch are extracted from DEM of the area. The details of development of Digital Elevation Model (DEM) are discussed below.

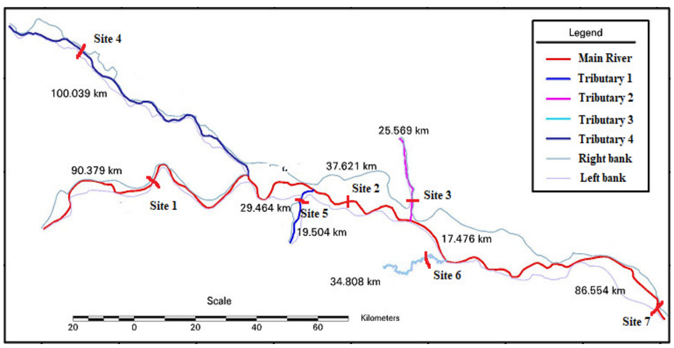

Figure 2: Index map of study area

Digital Elevation Model

Digital Elevation Model (DEM) is the representation of floodplain through gridded mesh of regularly spaced points and forms a major and important component, known as geometric data, of the HEC-RAS model setup. This data base can be developed in ARCGIS through a HEC GeoRAS module that uses floodplain representation as Triangulated irregular network (TIN) instead of DEM. To develop the TIN for the study area, the spot levels and contours from survey of India (SOI) toposheets are extracted. In addition, the alignments of major embankments are extracted from satellite images while the elevations of top of embankments are obtained from the State Water Resources Department.

METHODOLOGY

The methodology for flood hazard modeling and flood risk zoning for a reach of a river basin is briefly described as follows. The objective of the study are: (i) to develop L-moments based flood frequency relationships using the annual maximum peak flood series for the gauging sites of the river reach, (ii) to develop rating curves for the gauging sites of the river reach, (iii) to prepare flood inundation maps for the river reach, and (iv) to prepare flood hazard maps for the river reach. The flow chart illustrating various steps of flood inundation mapping flood hazard mapping, flood risk zone mapping and flood plain zoning is shown in Figure 2.

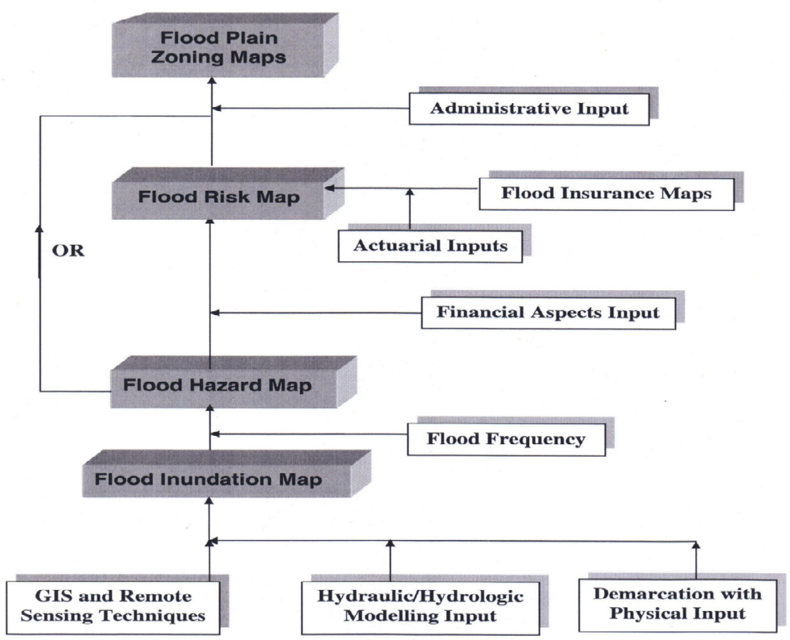

Fig. 1: Flow chart illustrating the general terminology of flood inundation mapping flood hazard mapping, flood risk zone mapping and flood plain zoning

Flood Frequency Analysis using L-Moments Approach

Floods of various return periods have been estimated for the river reach under study using the L-moments approach. The various frequency distributions viz. Extreme value (EV1), General extreme value (GEV), Logistic (LOS), Generalized logistic (GLO), Normal (NOR), Generalized normal (GNO), Uniform (UNF), Pearson Type-III (PE3), Exponential (EXP), Generalized Pareto (GPA), Kappa (KAP), and five parameter Wakeby (WAK) have been used. Based on the L-moment ratio diagram and $|Z_i|$ statistic criteria robust frequency distributions have been identified for the various stream flow gauging sites.

Stedinger et al., 1992 state that in a wide range of hydrologic applications, L-moments provide simple and reasonably efficient estimators of characteristics of hydrologic data and of a distribution's parameters. Like the ordinary product moments, L-moments summarize the characteristics or shapes of theoretical probability distributions and observed samples. Both moment types offer measures of distributional location (mean), scale (variance), skewness (shape), and kurtosis (peakedness).

Probability weighted moments and L-moments

(Hosking and Wallis, 1997) state that L-moments are an alternative system of describing the shapes of probability distributions and they arose as modifications of probability weighted moments (PWMs) of Greenwood et al. (1979). Greenwood et al. (1979) defined the probability weighted moments as:

$$\beta_r = E\left(x\{F(x)\}^r\right) \quad (1)$$

Which, can be rewritten as:

$$\beta_r = \int_0^1 x(F)F^r dF \quad (2)$$

Where, F = F(x) is the cumulative distribution function (CDF) for x, x(F) is the inverse CDF of x evaluated at the probability F, and r = 0, 1, 2, …, is a nonnegative integer. When r = 0, β_0 is equal to the mean of the distribution $\mu = E[x]$.

For any distribution the r^{th} L-moment λ_r is related to the r^{th} PWM (Hosking, 1990), through:

$$\lambda_{r+1} = \sum_{k=0}^{r} \beta_k (-1)^{r-k} \binom{r}{k}\binom{r+k}{k} \quad (3)$$

For example, the first four L-moments are related to the PWMs using:

$$\lambda_1 = \beta_0 \quad (4)$$

$$\lambda_2 = 2\beta_1 - \beta_0 \quad (5)$$

$$\lambda_3 = 6\beta_2 - 6\beta_1 + \beta_0 \quad (6)$$

$$\lambda_4 = 20\beta_3 - 30\beta_2 + 12\beta_1 - \beta_0 \quad (7)$$

Hosking (1990) defined L-moment ratios as:

L-coefficient of variation, L-CV (τ_2) = λ_2 / λ_1 (8)

L-coefficient of skewness, L-skew (τ_3) = λ_3 / λ_2 (9)

L-coefficient of kurtosis, L-kurtosis (τ_4) = λ_4 / λ_2 (10)

Screening of data using Discordancy measure test

Screening of data is conducted to check that the data are suitable for carrying out regional flood frequency analysis. Hosking and Wallis (1997) defined the Discordancy measure (D_i) considering if there are N sites in the group. Let $u_i = [t_2^{(i)}\ t_3^{(i)}\ t_4^{(i)}]^T$ be a vector containing the sample L-moment ratios t_2, t_3 and t_4 values for site i, analogous to their regional values termed as τ_2, τ_3, and τ_4, expressed in Equations. (8) to (10). T denotes transposition of a vector or matrix. Let be the (unweighted) group average. The matrix of sums of squares and cross products is defined as:

$$A_m = \sum_{i=1}^{N} (u_i - \overline{u})(u_i - \overline{u})^T$$

Hosking and Wallis (1997) defined the Discordancy measure for site i is defined as:

$$D_i = \frac{1}{3} N (u_i - \overline{u})^T A_m^{-1} (u_i - \overline{u})$$

Hosking and Wallis (1997) mention that the site i is declared to be discordant, if D_i is greater than the critical value of the Discordancy statistic D_i, which is given in a tabular form by the authors.

Test of regional homogeneity

Hosking and Wallis (1993) proposed a regional homogeneity test in which a test statistic H, named as heterogeneity measure has been defined. The test statistic (H) compares the inter-site variations in the sample L-moments for a group of the sites with what is expected from a homogeneous region. As stated by Hosking and Wallis (1993) the inter-site variation of L-moment ratio is measured as the standard deviation (V) of the at-site L-CV's weighted proportionally to the record length at each site. A number of, say 500, data regions are generated based on the regional weighted average statistics using a four parameter distribution e.g. Kappa distribution. The inter-site variation of each generated region is estimated and the mean (μ_v) and standard deviation (σ_v) of the computed inter-site variation is estimated. Thereafter, heterogeneity measure H is obtained as:

$$H = \frac{V - \mu_V}{\sigma_V} \quad (14)$$

For evaluation of heterogeneity of a region the L-moments based criteria are: if H < 1, the region is acceptably homogeneous; if 1 ≤ H < 2, the region is possibly heterogeneous; and if H ≥ 2, the region is definitely heterogeneous (Hosking and Wallis, 1997).

Identification of Robust Regional Frequency Distribution

For a homogeneous region, appropriate frequency distribution is identified by comparing the moments of the distribution to the average moments statistics from regional data. The best fit distribution is identified by assessing how well the L-skewness and L-kurtosis of the fitted distribution match the regional average L-skewness and L-kurtosis of the observed data (Hosking and Wallis, 1997). The goodness-of-fit measure for a distribution, Z_i^{dist} – statistic defined by Hosking and Wallis (1997) is expressed as:

$$Z_i^{dist} = \frac{\left(\bar{\tau}_i^{R} - \tau_i^{dist}\right)}{\sigma_i^{dist}} \quad (15)$$

Where, $\bar{\tau}_i^{R}$ is weighted regional average of L-moment statistic i, τ_i^{dist} and σ_i^{dist} are the simulated regional average and standard deviation of L-moment statistics i, respectively, for a given distribution. The fit is considered to be adequate if $|Z_i^{dist}|$–statistic is sufficiently close to zero, a reasonable criterion being $|Z_i^{dist}|$ –statistic less than 1.64.

Flood Inundation Modelling using HEC-RAS

Flow model for the river has been developed in HEC-RAS program. This program is capable of performing one-dimensional water surface profile calculations for gradually varied flow (GVF) in natural or constructed channels wherein subcritical, supercritical, and mixed flow regime can be simulated. The basic procedure for solving the steady state GVF from one cross section to the next as represented through

Fig. 3, solving the Energy equation with an iterative procedure called the standard step method.

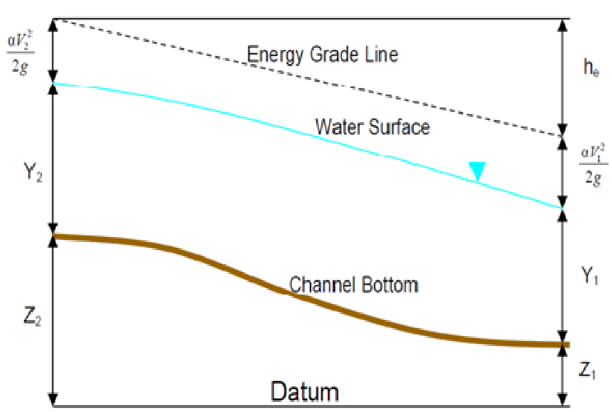

Fig. 3: Representations of gradually varied flow through Energy Equation

The Energy equation is written as follows:

$$Y_2 + Z_2 + \frac{\alpha_2 V_2^2}{2g} = Y_1 + Z_1 + \frac{\alpha_1 V_1^2}{2g} + h_e \quad (16)$$

Where Y_1 and Y_2 are water depth at cross sections, Z_1 and Z_2 are elevation of channel invert, V_1 and V_2 are velocity, α_1 and α_2 are velocity weighting coefficient, g is gravitational acceleration, h_e is energy head loss.

The energy head loss (h_e) between two cross sections is comprised of friction losses and contraction or expansion losses. The equation for the energy head loss is as follows:

$$h_e = L\bar{S}_f + C\left|\frac{\alpha_2 V_2^2}{2g} - \frac{\alpha_1 V_1^2}{2g}\right| \quad (17)$$

Here, L= discharge weighted reach length, $\bar{S_f}$= representative friction slope between two stations and C= expansion or contraction loss coefficient.

The determination of total conveyance and the velocity coefficient for a cross section requires that flow be subdivided into units for which the velocity is uniformly distributed. The approach used in HEC-RAS is to subdivide flow in the overbank areas using the input cross section in several n-value break points (locations where n-values change) as the basis for subdivision (Figure 4). Conveyance is calculated within each subdivision individually and later on summed up suitably for left over bank and right over bank. The main channel conveyance is normally computed as a single conveyance element. The total conveyance for the cross section is obtained by summing the three subdivision conveyances (left, channel, and right).

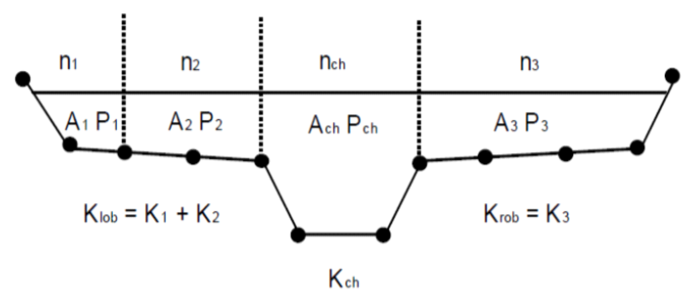

Figure 4: HEC-RAS default conveyance subdivision method

The unknown water surface elevation at a cross section is determined by an iterative solution of Equations (16) and (17). The program is constrained by a maximum number of iterations (the default is 20) for balancing the water surface. While the program is iterating, it keeps track of the water surface that produces the minimum amount of error between the assumed and computed values. This water surface is called the minimum error water surface. If the maximum number of iterations is reached before a balanced water surface is achieved, the program will then calculate critical depth (if this has not already been done). The program then checks to see if the error associated with the minimum error water surface is within a predefined tolerance (default value is 0.1 m). The energy equation is only applicable to GVF and the transition from subcritical to supercritical or supercritical to subcritical is a rapidly varying flow situation. Such situation occurs where significant changes in channel slope, bridge constrictions, drop structures and weirs, and stream junctions exist. In some of these instances empirical equations can be used (such as at drop structures and weirs), while at others momentum equation is used to compute the water surface profile. The functional form of the momentum equation that is used in HEC-RAS is as follows:

$$\frac{Q_2\beta_2}{gA_2} + A_2\overline{Y_2} + \left(\frac{A_1 + A_2}{2}\right) LS_0 - \left(\frac{A_1 + A_2}{2}\right) L\bar{S}_f = \frac{Q_1\beta_1}{gA_1} + A_1\overline{Y_1} \qquad (18)$$

Where: β = momentum coefficient that accounts for a varying velocity distribution in irregular channels

ANALYSIS AND RESULTS

Estimation of floods of various return periods, development of flow model, preparation of flood hazard maps, modelling of inundation when flood at each site is at danger level are described as follows.

Estimation of Floods of Various Return Periods

Floods of various return periods have been estimated for the seven stream flow gauging sites using the L-moments approach. Figure 5 shows the L-moment diagram for one of the gauging sites and the Table gives the Z_i^{dist} statistic values for seven sites of the study area.

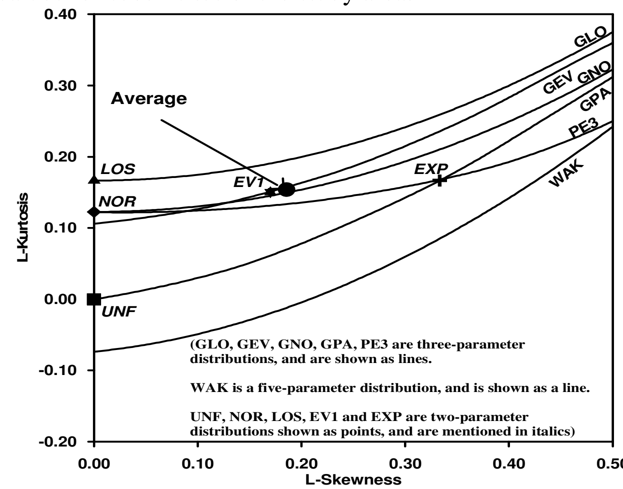

Figure 5: L-moment ratio diagram for river flow gauging Site 1

Floods of various return periods viz. 2, 10, 20, 25, 50, 100, 200, 500 and 1000 return periods have been estimated for the seven stream flow gauging sites of study area, using the robust identified frequency distribution for each of the stream flow gauging sites. Values of growth factors ($Q_T/\overline{Q}$) for various gauging sites are given in Table 3.

Table 1: Z_i^{dist} -statistic for various frequency distributions

Sl. No.	Distribution	Site-1	Site-2	Site-3	Site-4	Site-5	Site-6	Site-7
1	GLO	**-0.04**	0.37	0.35	1.91	0.72	**0.10**	1.03
2	GEV	-0.66	**-0.01**	-0.62	1.51	-0.26	-0.12	0.42
3	GNO	-0.50	-0.08	**-0.26**	1.38	0.03	-0.33	0.36
4	PE3	-0.50	-0.24	-0.33	1.12	**0.02**	-0.69	**0.17**
5	GPA	-1.77	-0.88	-2.19	**0.57**	-1.97	-0.76	0.90

The values of the parameters of the robust identified distributions for the stream flow gauging sites are given in Table 2.

Table 2: Values of parameters for various distributions for seven gauging sites

Site	Distribution	Parameters of the Distribution		
Site-1	GLO	ξ = 0.856	α = 0.238	k = -0.025
Site-2	GEV	ξ = 0.999	α = 0.174	k = -0.002
Site-3	GNO	ξ = 1.022	α = 0.210	k= 0.208
Site-4	GPA	ξ = 0.230	α = 0.978	k = 0.269
Site-5	PE3	ξ = 0.905	α = 0.162	k = -0.316
Site-6	GLO	μ = 1.000	σ = 0.339	γ = -0.166
Site-7	PE3	μ = 1.000	σ = 0.433	γ = 1.010

Table 3: Values of growth factors ($Q_T/\overline{Q}$) for various gauging sites

Gauging Sites	Return period (Years)							
	2	**10**	**25**	**50**	**100**	**200**	**500**	**1000**
	Growth factors							
Buxor	0.944	1.408	1.650	1.833	2.018	2.206	2.459	2.654
Gandhighat	0.999	1.383	1.555	1.680	1.804	1.927	2.089	2.212
Hathidah	1.022	1.259	1.331	1.374	1.410	1.442	1.478	1.968
Koelwar	0.848	1.908	2.335	2.596	2.812	2.991	3.182	3.299
Lalgang	0.905	1.419	1.793	2.148	2.585	3.127	4.051	4.949
Sripalpur	1.009	1.428	1.574	1.666	1.747	1.821	1.908	1.968
Trutipar	0.928	1.580	1.885	2.102	2.310	2.513	2.778	2.966

Development of Flow Model

A steady flow model for the study stretch is developed in HEC RAS. The calibration of the model is carried out for the river reach by comparing the inundation map developed from flow model and satellite image for the annual maximum flow of year 1997. The satellite image of IRS 1C L3 of 25 October 1997 is processed using ERDAS to delineate flood inundation extent. Comparison of flood inundation using HEC-RAS model and satellite images is shown in **Error! Reference source not found.**. The corresponding error in computation of inundation from HEC RAS model is computed as 8%. The model is further validated for annual maximum flood of year 1998 and 2000. The corresponding errors in computation of inundation for these two years are 6.9% and 9.35%, respectively.

Flood Routing for Various Return Periods

The model is further simulated for the floods of 2, 10, 25, 50, 100, 200, 500 and 1000 year return period. The water surface profiles (WSP) along the river and tributaries are computed. The flood inundation maps for various flood estimates are also developed. The flood inundation map for 1000 year return period is shown in Figure 6. The figure shows the location and magnitude of the inundation. The magnitude contains the information about depth as well as areal coverage. The maps show the area under inundation in km^2 and also the depth of water in meter. The water depth has been classified in 8 classes namely; 0-0.1, 0.1-0.5, 0.5-1.0, 1-2, 2-5, 5-10, 10-20 and >20. In fact water depth > 10 m mostly falls on the river course.

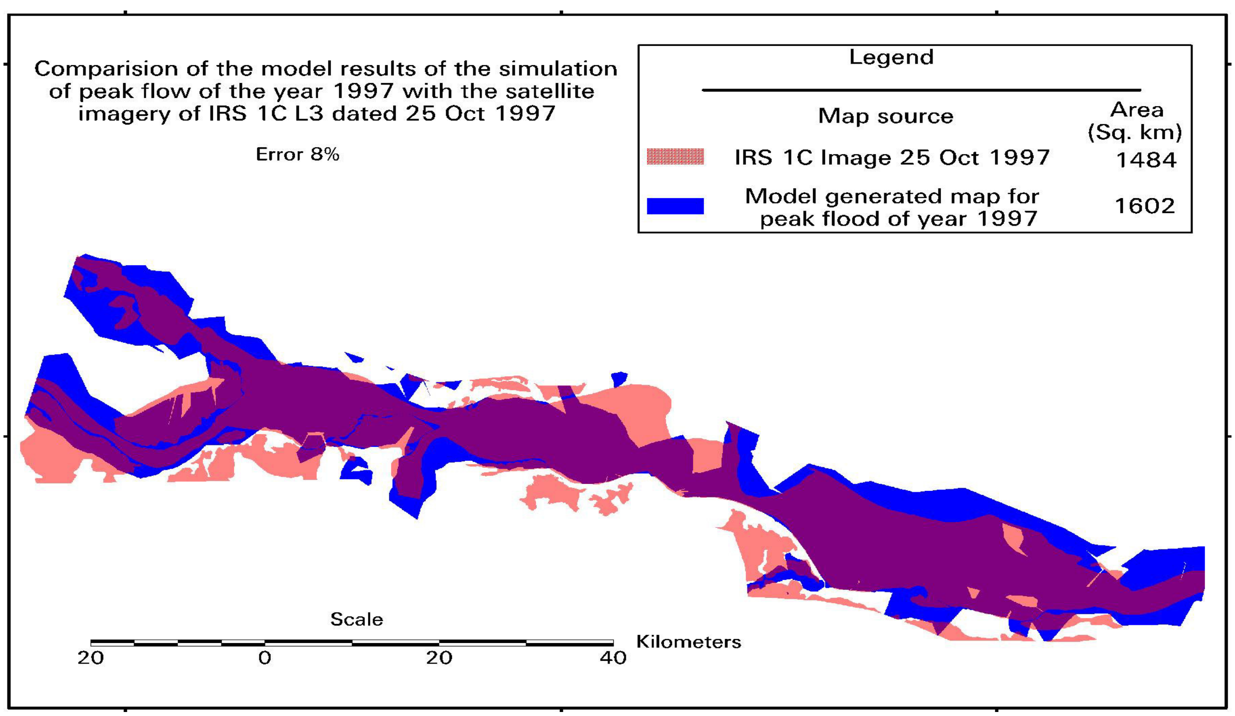

Figure 6: Comparison of flood inundation for 1997 using HEC-RAS model and satellite images

The area of inundation under these classes for floods of various return periods is shown in 4. The table shows that when discharge increases the total inundation also increases though the increase is more in the beginning and decreasinggradually for higher floods. The inundation map gives the information about the magnitude of depth at a particular location. Such maps are useful for regulating the activities in the flood plains. For examples; the area which are flooded with 2 year return flow should be avoided for human settlement, however, agricultural activities may be permitted. Similarly, with the information of maximum flood level in an area, the building-by-laws may be suitably modified to reduce the losses in case of flooding. Such maps are also useful accessing the risk in an area, for creating risk awareness, planning new developmental activities etc.

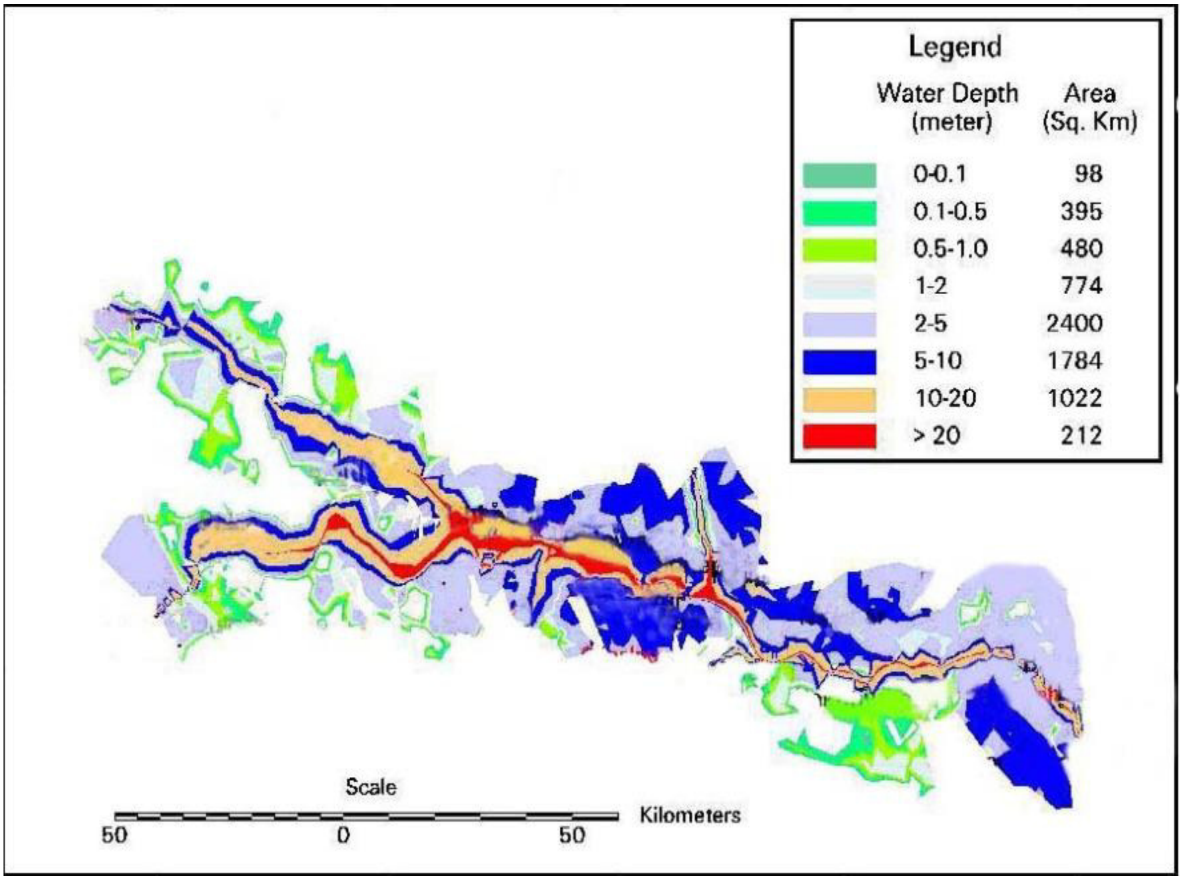

Figure 7: Flood plain area inundated and depth of flooding for 1000 year return period flood for the study area

Table 4: Inundation for floods of various return periods

Depth (m)	**Return periods (Years)**							
	2	**10**	**25**	**50**	**100**	**200**	**500**	**1000**
	Area in km^2							
0-0.1	55	6	94	89	93	114	100	98
0.1-0.5	229	281	281	341	339	363	383	395
0.5-1.0	286	312	335	403	431	426	481	480
1.0-2.0	506	648	583	647	690	763	781	774
2.0-5.0	1253	1669	1947	2033	2155	2404	2371	2400
5.0-10.0	849	998	1038	1077	1129	1379	1622	1784
10.0-20.0	696	829	879	910	945	966	999	1022
>20.0	14	66	96	118	136	163	190	212
Cumulative	**3890**	**4809**	**5253**	**5618**	**5917**	**6577**	**6928**	**7166**

Modelling of Inundation When Flood at Each site is at Danger Level

The danger level information at various GD sites in the study reach is also collected from CWC and the concerned State Government Departments. The rating curves are used for estimating the corresponding flood discharge at all GD sites. The HEC-RAS model is run for these floods to prepare the inundation maps corresponding to flooding situation when all sites are at danger levels as shown in 8.

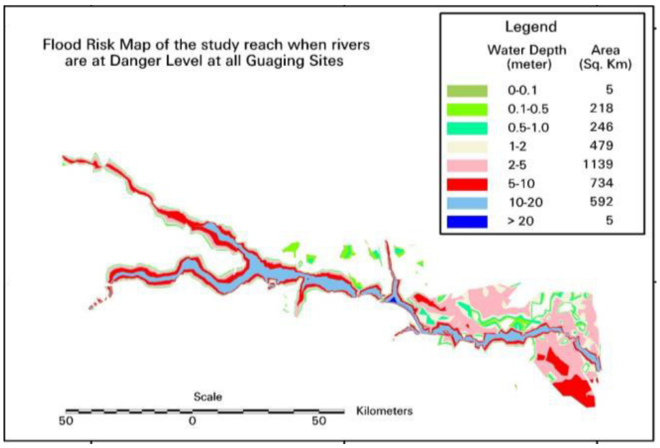

Fig. 8: Extent of inundation when all the seven sites are at danger levels

LIMITATIONS OF THE STUDY

The study has been carried out for developing flood hazard maps for a study area with constraints of the data availability. The available hydrological and topographical data have been used in the study. Though, the flood mapping through mathematical modelling needs detailed data base and very accurate and precise tools, work has been carried out with available data at various level of accuracy. Therefore, the study inherits certain limitations in view of data and mathematical models used. The limitations of the study are mainly as follows:

i. Lack of detailed topographical information for the study area and source is mainly elevation values extracted from SOI toposheets. Further, the non availability of river cross section data is another major limitation. In the reach of 250 km of main river only three survey cross sections are available, others are interpolated from DEM.

ii. Another major limitation of the study is the modelling approach for large alluvial river where the river spills during high flood and 1D flow assumption may not stand. However, extended river cross sections covering the entire flow width have been used to simulate the flood. Coupled flow models may probably performs better in such case.

iii. Further, the satellite imageries in the optical wavelength region are used for inundation mapping for model calibration and validation for peak flooding condition, the actual inundation may not be estimated due to cloud coverage. The use of microwave data corresponding to dates of annual peak flood might have improved the actual inundation mapping. Further, the information regarding breaching of an embankment etc. during the various periods of model calibration and validation would have resulted into improved flood inundation mapping.

CONCLUSIONS

In this study floods of various return periods have been estimated for the seven stream flow gauging sites lying in the river reach under study using the L-moments approach. Depth of flooding and inundation for various return periods have been simulated using the HEC-RAS model. The flood inundation extents simulated by the HEC-RAS model are compared with satellite based inundation maps and are used for calibration and validation of HEC-RAS model. The calibration of the model is carried by comparing the inundation map developed from flow model and satellite image for the annual maximum flow of year 1997. The corresponding error in computation of inundation from HEC-RAS model is estimated as 8%. The model is further validated for annual maximum floods of the years 1998 and 2000. The corresponding errors in computation of inundation for these two years for validation of extent of the simulated flood inundation are 6.9% and 9.35%, respectively. The flood inundation maps for various return periods are computed that may be used by the practitioners and public for land use planning as well as flood damage reduction. The maps have been prepared showing the area under inundation and depth of flood. The water depth has been classified in 8 classes namely; 0-0.1, 0.1-0.5, 0.5-1.0, 1-2, 2-5, 5-10, 10-20 and >20 m. The water depth > 10 m mostly falls in the river course.

The flood forecasts issued by the operational agencies in India are conventionally in the form of stage values at the various sites. However, if these forecasts are issued along with the area likely to be inundated and the depth of flooding, then these would be more effective and useful for the organizations involved in flood mitigation and management and the public. The calibrated and validated hydrologic model, as described in the study may be coupled with a distributed rainfall-runoff model using the antecedent rainfall forecasts based on radar, satellite based instrumentation and high resolution Numerical Weather Prediction (NWP) models and may be used for simulation of flood inundation, depth of flooding and risk associated with the flooding in real time for flood mitigation and management. Presently, there are many uncertainties in forecasting heavy rainfall and the uncertainty should be minimised, quantified and presented as an integral part of the forecast. It would help in providing improved flood hazard warning and lead to better flood management and flood damage reduction.

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