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Evaluation of Non Damaging Flow for a Set of Upstream Sub Basins in a River System

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Abstract

A model for evaluating non damaging flow for a set of sub basins in a river system is presented. Linear Programming technique incorporating multiple inflows routing scheme is employed to evaluate upstream flow conditions necessary for satisfying specified downstream flood flow conditions. Non damaging flow for the sub basins are determined by using river system properties. The model is applied to a river system in India having flows from gauged and ungauged sub basins; flow contributions from the ungauged basins are estimated by using unit hydrograph technique. Peak flow studies involving major and minor sub basins indicate relative importance of the basins in the study area. Results obtained in the study depict variations in the non-damaging flow with the flow in the main channel. Model applications show that for flood with peaks exceeding 7566 m^3/s regulating intervening basins only may not lead to safe flow at the downstream section(s). The model allows evaluating effectiveness of controlling the intervening basins in a river system; model

applications to a real life river system yield results that are useful in adopting flood control measures for the study area.

Keywords: Flood, River system, ungauged flow, Linear Programming, unit hydrograph

1. Introduction

Flood control alternatives available in the literature are used for mitigating flood damages in river reaches. Optimization techniques are generally used for planning, designing and assessing effectiveness of a flood control measure. Traditional and nontraditional optimization models such as Linear Programming, Non Linear Programming, Genetic algorithms, Fuzzy logic and Neural Networks models have been extensively used in planning and evaluating efficiency of flood control systems (Wasimi and Kitanidis, 1983; Unver and Mays, 1990; Chandramouli and Raman, 2001; Wang et al. 2010; Ferreira and Teegavarapu, 2012; Fu et al 2014).

Some of the model applications in river system flood control studies can be found in the works of Needham et al. (2000), Braga and Barbosa (2001) and Wei and Hsu (2007 and 2008). Choudhury (2010) used a preemptive goal programming model with multiple flow routing schemes for evaluating performance of a multi-reservoir system in India under flood condition. Debbarman and Choudhury (2015) recently applied multiple inflows based flood flow simulation model to estimate relative importance of the sub basins on the downstream peak flow rates in a river system.

In real life river basins channels draining different sub basins join the main channel reach at different locations; the channel flows combine downstream forming a common outflow. Downstream outflow being a function of the upstream flows flood control objectives for a river system may be achieved by adopting various control strategies for the upstream sub basins in the system. Depending on the location of the potential damage section in a river system controlling the main channel flow only may not lead to the intended flood benefits also, in many cases controlling the main channel may not be feasible due to high storage requirement, environmental and other physical and technical constraints. In such cases for downstream flood control, effectiveness of controlling the upstream sub basins along with partial or no regulation of the main channel in a river system needs to be evaluated.

Critical flow or safe drainage capacity of a river reach is the permissible maximum flow that passes through the reach without any flood losses. For a river system the common downstream outflow being dependent on the upstream flows and river network properties various sets of upstream flows producing safe downstream outflow(s) can be determined on the basis of known river system characteristics. A non-damaging flow set representing concurrent upstream flows in a river system is unique, produce safe downstream outflow and is characterized by the river system properties. For a specified downstream flow condition possible non damaging flow sets indicate the alternative solutions; out of which, the best solution for a case selected on the basis of technical, environmental and other considerations may implemented for downstream flood control.

The Barak River basin has a drainage area of approximately 7224 sq.km in the state of Assam, India. With the rain fall period extending from mid-April to mid-October the basin experiences two flood waves almost every year. Vast part of the valley with maximum flood prone area of about 4.33 million hectares is inundated by flood waves frequently; the problem of flood and drainage congestion is very acute in the valley resulting huge losses, and public suffering. Barak being an international river construction of major flow retaining structures in the upper reaches seems not possible in near future. In the absence of any control on the main river flow feasibility of controlling the lateral tributaries for flood damage mitigation in the valley needs to be explored.

In the present study, a Linear Programming (LP) model is presented to evaluate non damaging flow for a set of upstream sub basins in a river system. The model incorporates multiple flow routing schemes (Choudhury et al, 2002, Choudhury, 2007) to account for the river network and river reach properties. The model is used to analyze flood movement through two potential downstream damage sections in Barak River basin, India receiving lateral flows from multiple upstream gauged and ungauged subbasins. Non damaging flow for the sub basins for peak flows specified for the main channel is evaluated. Flow contribution from the ungauged basins is estimated by using Geomorphological Instantaneous Unit Hydrograph (GIUH) technique introduced by Rodriguez-Iturbe & Valdes (1979). The study results depict nonlinear variations in the non-damaging flows; model applications further reveal that, with flood peaks exceeding 7566 m^3/s in the main channel, regulating intervening sub basins doesn't lead to safe passage of the peaks though the downstream sections. Details of the models, their applications and results are given in the subsequent sections.

2. Models

2.1 River System Flow Propagation Model

On the basis of Muskingum equation *(Chow et al. 1988)*, the functional relationship between common downstream flow and the upstream flows in a river system involving river system parameters can be written as (Choudhury et al 2002, Choudhury, 2007)

$$q_{t+1} = C_1(\sum_{p=1}^{N} \sigma^{p,r} i_t^p) + C_2(\sum_{i=1}^{N} \sigma^{p,r} i_{t+1}^p) + C_3 q_t \quad (1)$$

Here, C_1, C_2 and C_3 are the routing coefficients for the equivalent imaginary channel replacing a river system having N upstream flows. $\sigma^{p,r}$ = shift/modification factor for transferring flow, i_t^p from a point p to r in the basin. The above model allows computing the common downstream flow rate efficiently on the basis of flow rates for several upstream sections. It is to be noted that in the absence of multiple flow routing model given by equation 1, either 'routing after superposition' or 'superposition after routing' schemes is required to be used for downstream flow computation which results to a larger model and may make the flow computation cumbersome and complicated for real life river systems. Equation 1 allows computing change in the downstream flow rate during a time interval for known changes in the flow rates at several upstream sections. For a river system, using known initial downstream flow rates at time t, relative effects of the upstream flows on the common downstream flow can be estimated by applying the model (Debbarman and Choudhury, 2015).

In that case, the common downstream flow rates at time $(t+1)$ are simulated on the basis of upstream flow rates and known initial downstream flow rates at time t; changes in the simulated downstream flow rates for a change in any of the upstream flow rate is computed to determine the relative effect of the tributary flow.

In the present study, the multiple inflows routing model is calibrated for a river system in Barak river basin, India. Model coefficients in equation 1 are estimated by applying non linear regression technique using hourly recorded flow rates for the gauged sub basins and the flow rates for the ungauged sub basins determined by applying GIUH technique. Estimated river system properties are used to formulate LP models for the river system for flood control studies. Details of the LP models are given in the next section.

2.2 LP Model

LP model representing maximization of drainage from individual sub basins in a set of upstream gauged and ungauged sub basins for downstream flood control in a river system can be written in standard LP format as

$$Maximize\ Z = \sum_{t=1}^{T} \sum_{p' \in (1,N)} i_t^{p'} \tag{2}$$

Here, N is the number of upstream sub basins in a river system with flow that unites downstream forming a common outflow. p' = set of upstream sub basins in which flow regulation is desired.

The above mentioned objective for a river system is to be achieved by satisfying the specified physical and other constraints. In the case of a river system having N upstream and two downstream sections the constraint equations may be given as

$$q_2^{d1} - c_2^1 \left[\sum_{p=1}^{m1} \sigma^{p,r} i_2^p + \sum_{p=m1+1}^{n1} \sigma^{p,r} \bar{i}_2^{\,p} \right] = c_1^1 \left[\sum_{p=1}^{m1} \sigma^{p,r} \bar{i}_1^{\,p} + \sum_{p=m1+1}^{n1} \sigma^{p,r} \bar{i}_1^{\,p} \right] + c_3^1 q_1^{d1} \tag{3}$$

Equation 3 is used to compute flow rate at the first downstream section representing outflow of the upper network on the basis of known initial flow rate. The lower network receives the outflow of the upper network as an inflow and for the second downstream section which is the outflow section of the lower network equation 3 is written as

$$q_2^{d2} - c_2^2\left[\sigma^{d1,r} q_2^{d1} + \sum_{p=1}^{m2} \sigma^{p,r} i_2^p + \sum_{p=(m2+1)}^{n2} \sigma^{p,r} \bar{i}_2^p\right] = c_1^2\left[\sigma^{d1,r} q_1^{d1} + \sum_{p=1}^{m2} \sigma^{p,r} i_1^p + \sum_{p=(m2+1)}^{n2} \sigma^{p,r} \bar{i}_1^p\right] + c_3^2 q_1^{d2} \quad (4)$$

Here, $d1=$ potential downstream damage section 1; $d2=$ potential downstream damage section 2; $n1$ and $m1=$ total number of sub basins and the number of gauged sub basins in the upper river system; $n2$ and $m2=$ total number of sub basins and the number of gauged sub basins in the lower river network. $c_{(*)}^1$ and $c_{(*)}^2=$ routing coefficients for the upper network and lower network respectively. $i_{(*)}^p$, $\bar{i}_{(*)}^p=$ flow rates for the p th gauged and ungauged sub basins respectively; $q_{(*)}^{d1}$ and $q_{(*)}^{d2}=$ outflow at downstream damage section 1 and 2 respectively.

Equations 3 and equation 4 are applicable for computing downstream flow rates for the upper and lower network respectively at the end of 1-st period only, as for the first period the initial flow rates for different sections in the river system are known.

For other periods with $t=2,3,4...T$ the outflow at the first and second downstream sections are estimated using equation 5 and 6 respectively.

$$q_{(t+1)}^{d1} - c_2^1\left[\sum_{p=1}^{m1} \sigma^{p,r} i_{(t+1)}^p + \sum_{p=(m1+1)}^{n1} \sigma^{p,r} \bar{i}_{(t+1)}^p\right] - c_1^1\left[\sum_{p=1}^{m1} \sigma^{p,r} i_t^p + \sum_{p=(m1+1)}^{n1} \sigma^{p,r} \bar{i}_t^p\right] - c_3^1 q_t^{d1} = 0\,;\ \forall t = 2,3,4\ldots(T-1) \quad (5)$$

$$q_{(t+1)}^{d2} - c_2^2\left[\sigma^{d1,r} q_{(t=1)}^{d1} + \sum_{p=1}^{m2} \sigma^{p,r} i_{(t+1)}^p + \sum_{p=(m2+1)}^{n2} \sigma^{p,r} \bar{i}_{(t+1)}^p\right] - c_1^2\left[\sigma^{d1,r} q_t^{d1} + \sum_{p=1}^{m2} \sigma^{p,r} i_t^p + \sum_{p=(m2+1)}^{n2} \sigma^{p,r} \bar{i}_t^p\right] - c_3^2 q_t^{d2} = 0\,;$$

$$\forall t = 2,3,4\ldots(T-1) \quad (6)$$

Equations 3 & 4 and equations 5 & 6 represent mass balance equation and are written in LP format keeping known variables on the right hand side of the equations. For a river system the feasible inflow-outflow hydrographs must satisfy the above mentioned mass balance constraints.

The physical constraints representing flow capacity for the channel sections in the river system can be specified as,

$$q_t^{d1} \le q_t^{d1,c} \text{ and } q_t^{d2} \le q_t^{d2,c}\,;\quad \forall t = 1,2,3,\ldots T \quad (7)$$

$$i_t^p \le i_t^{p,\max} \text{ and } \bar{i}_t^p \le \bar{i}_t^{p,\max}\,;\quad \forall t = 1,2,3,\ldots T \quad (8)$$

Here, $q_t^{d1,c}$ and $q_t^{d2,c}$ are the maximum permissible non damaging flow for downstream section 1 and 2 respectively and $i_t^{p,\max}$, $\bar{i}_t^{p,\max}$ represent channels flow capacity at the upstream sections. Equation (7) represents no flooding condition for the first and second downstream sections while, equation (8) ensures upstream flows not exceeding the respective safe channel capacity. Maximization of the objective function given by equation 2 subject to the above mentioned constraints yields flow sequences for the upstream sections ensuring maximum possible drainage of the individual sub basins and no flooding at the downstream section(s) during a period. In this case, equal drainage priority is assigned to all the upstream sub basins. To obtain the model solution for the case of maximum drainage from the intervening drainage areas, the objective function given by equation 2 is replaced by maximization of the downstream outflow rates over a time period and the model is solved subject to the constraints given by equations 3 through 8. In that case, the drainage priority for the sub basins are taken in order of the coefficients used in equation 1 and the resulting outflow sequences reflect maximum possible drainage by the river system from the intervening basin areas. The above presented models are used to determine the degree of flow control required in the sub basins for safe passage of floods through the downstream sections in a river system in Barak basin, India. Details of models applications and results obtained are given in the next section.

3. Applications

The Barak River basin in India lies between 89°50′E to 94°0′E longitude and 22°44′N to 25°58′N latitude; a river system in the basin with the main river reach extending from the upstream site Fulertal, in Assam to the downstream site, Badarpurghat is selected. Flow contribution from the upper part of the basin that enters into the study area is gauged at the upstream section, Fulertal in the main river, Barak. The major tributaries that join the main river in the study area: Rukni, Sonai, and Katakhal are gauged at Dholai, Maniarkhal and Matijuri respectively. Apart from these sub basins, five major ungauged sub basins drained by the rivers Jiri, Chiri, Madhura, Jatinga and Ghagra also join the main river in the study area. The outflow at Annapurnaghat in the upper river network represents combined flow from six upstream sections, and the outflow at the lower damage section, Badarpurghat is due to flow from the upper network entering through the upstream damage section, Annapurnaghat and the flows from other three sub basins in the study area. Figure-1 gives a schematic map of the river system and the details of the sub basins are listed in Table -1. Depending on the availability of precipitation data three flood events are selected for the study, the periods of the events are: July 10-17, 2004; July 19-29, 2004; June 11-21, 2006. Hourly recorded discharge data for the gauging sites at Fulertal, Dholai, Maniarkhal, A.P.Ghat, Matijuri, and B.P.Ghat are obtained from the Central Water Commission (CWC) offices at Shillong and Silchar. The details of flood event-1, event-2 and event-3 are shown in the Table 2. Hourly precipitation records for the gauging stations, located at Silchar and Lakhipur are collected from Regional Meteorological Centre (RMC) office at Guwahati. Figure-2 gives the precipitation record for Lakhipur during the flood events; length of the precipitation series used in the study is 288 hours, 384 hours and 336 hours respectively.

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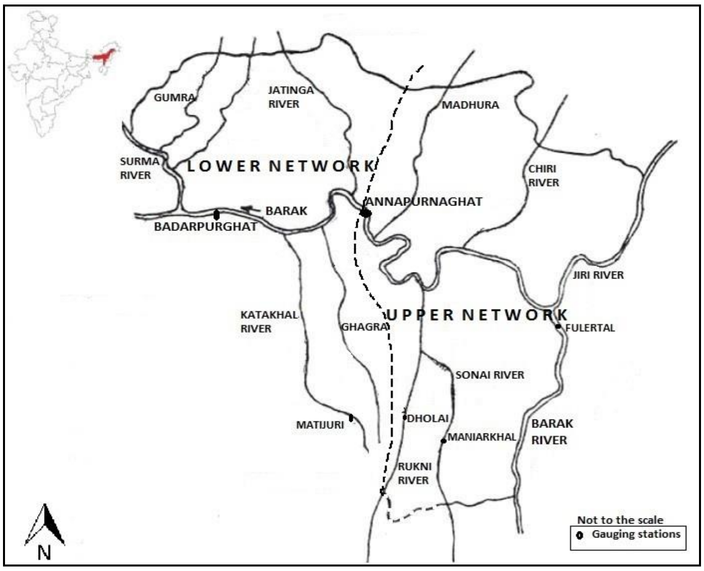

Figure 1. Map of the study area

Table 1. Details of the sub-basins in the study area

River	Drainage Area (sq.km)	Safe Flow (m^3/s)	River	Drainage Area (sq.km)	Safe Flow (m^3/s)
Jiri (UG)	1052.85	1898.00	Ghagra (UG)	409.39	1505.45
Chiri (UG)	438.66	2549.00	Dholai (G)	1088.25	451.45
Madhura (UG)	349.43	2415.00	Katakhal (G)	1504.68	1729.45
Jatinga (UG)	371.86	1927.35	Maniarkhal (G)	384.65	764.41

[Note: UG- ungauged subbasins; G- gauged subbasins]

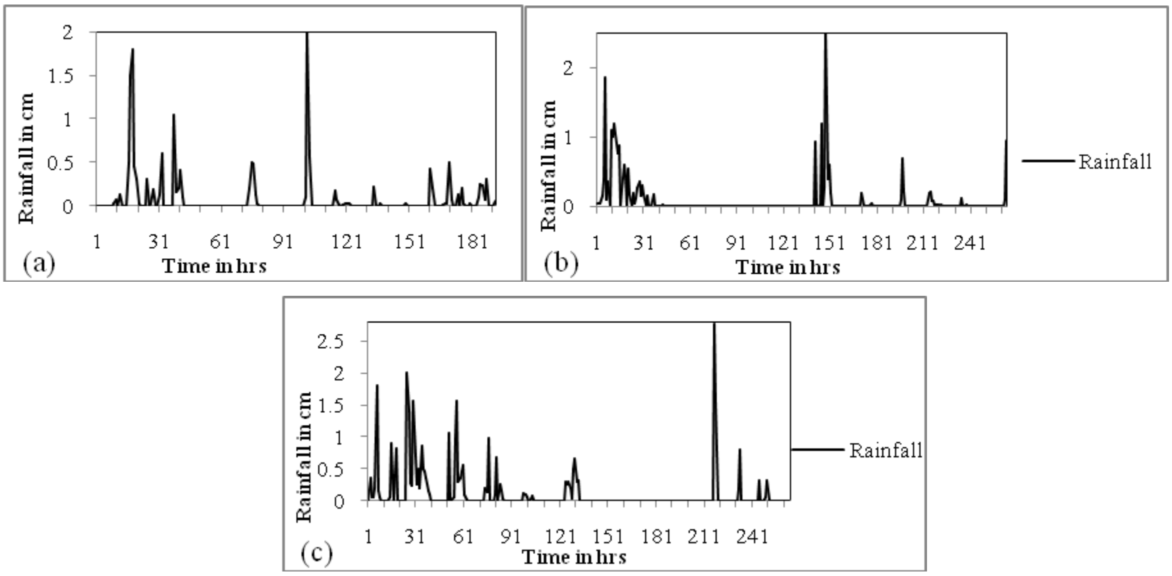

Figure 2. Hourly precipitation for Lakhipur in the study area- a) Event-1 (Jul 10th -17th ,2004),

b) Event-2 (Jul 19th -29th ,2004) and c) Event-3 (Jun 11th -21st ,2006)

Table 2. Details of the flood events used in the study

Flood Events	Highest Peak Flow Depth (m)		Highest Peak Flow Rate (m^3/s)		Safe Flow Depth (m)		Safe Discharge (m^3/s)	
	APG	BPG	APG	BPG	APG	BPG	APG	BPG
Event-1	16.36	15.93	4048.63	4859.99	20.39	17.20	3650.90	4415.00
Event-2	16.69	16.26	4398.26	4870.75				
Event-3	15.7	15.68	3718.74	4759.86				

[Note: APG: Annapurnaghat; BPG: Badarpurghat]

The LP model formulated for the river system is applied to evaluate the relative effects of the sub basins on the downstream peak flow rate at Badarpurghat and to estimate the permissible non damaging flow for the sub basins for different levels of flood flow at the upstream section, Fulertal in the main channel, Barak. Out of the eight intervening sub basins in the study area five sub basins, Jiri, Chiri, Madhura, Jatinga and Ghagra are ungauged; flow contribution from these drainage basins during the selected flood events are not available. To determine flow contribution from these sub basins, unit hydrograph technique is applied; employing GIUH model 1-h UH for the sub basins drained by the rivers Jiri, Chiri, Madhura, Jatinga, Ghagra are derived. Applying Geographic Information System (GIS) aided techniques available in ArcGIS 9.1, Hydrology toolbox in the Spatial Analyst Tool, the geomorphologic parameters of the basins as tabulated in the Table 3 are estimated. The estimated values are used in the GIUH model to develop the triangular IUH for the watersheds. IUH ordinate values spaced at an interval of 0.1 hr are lagged employing the technique described in the manual of evaluating flood-runoff characteristics of watershed [Flood–Runoff Analysis, ASCE (ISBN 0-7844-0187-X) by U.S. Army Corps of Engineers] to develop 1hr UH for the basins. Hourly excess precipitations for these basins during the selected storm events are operated on the respective UH, lagged and summed to determine the surface flow contributions. Surface flow contributions are augmented by the observed average lean period flow rates for the respective basins to determine flow contribution during the selected flood events. Geomorphological parameters and instantaneous unit hydrograph characteristics for the ungauged sub basins are listed in Table-3.

Table 3. Morphological parameters and IUH characteristics of the ungauged sub basins

Watershed	Slope	V(m/s)	L_Ω (km)	L (km)	R_A	R_B	R_L	q_p (hrs^{-1})	Q_p (cumec)	t_p (hrs)	t_b (hrs)
Jiri	0.29	7.56	48.09	104.48	4.56	4.21	2.44	0.30	884.38	1.91	6.61
Chiri	0.23	5.85	11.64	49.85	3.815	3.504	1.91	0.86	1057.31	0.65	2.30
Madhura	0.28	6.39	14.58	52.61	4.305	3.826	2.13	0.79	858.44	0.70	2.52
Jatinga	0.35	7.047	22.93	55.39	4.01	4.9	3.09	0.65	675.50	1.04	3.06
Ghagra	0.098	4.196	19.784	48.93	3.9	3.64	2.02	0.37	427.64	1.53	5.32

[NOTE: V= Dynamic Parameter Velocity; L_Ω= Length of the highest order stream; L= Length of main stream;

R_A = Area Ratio; R_B = Bifurcation Ratio; R_L= Length Ratio; Q_p= Peak Discharge; t_p= Time to peak; t_b= Base time]

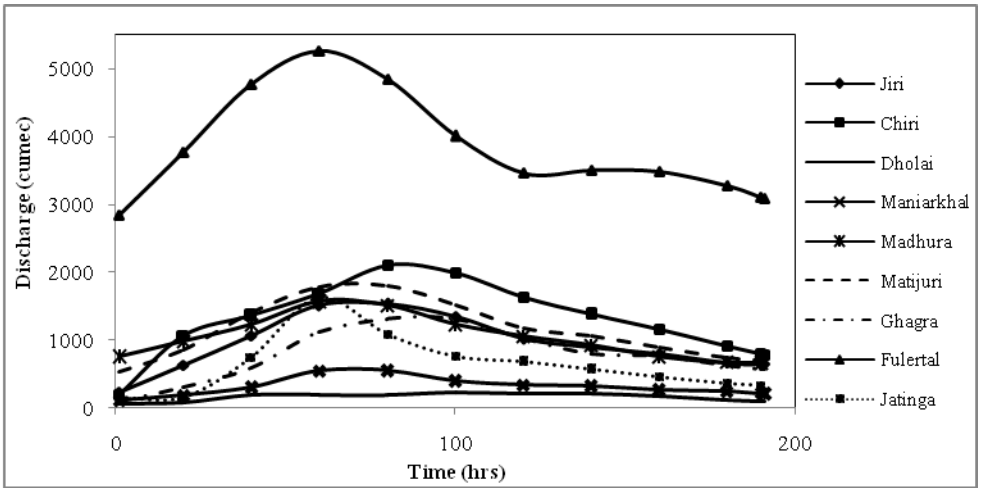

Figure 3. Flood event-1 in the study area

Flood event 1, given in figure-3 are used to estimate the model parameters in equation 1 by applying nonlinear optimization routine, "lsqnonlin" available in the optimization tool box, MatLab, version 7.9.0.529 (R2009b). Two objective functions that minimize the sum of the squared error between the observed and computed flow rates for the first downstream section, Annapurnaghat (Site A) and the second downstream section, Badarpurghat (Site B) are used to estimate the model parameters. To compute the flow rates at Site B flow rates for the first downstream section, Site A simulated by using flows rates of the upstream gauged and ungauged sub basins in the upper network are used. Estimated coefficients for the upper and lower river networks are listed in Table-4.

Table 4. LP Model routing co efficient for the river system

<table>
<tr><td rowspan="2">River Network</td><td rowspan="2">C_1</td><td rowspan="2">C_2</td><td rowspan="2">C_3</td><td colspan="6">Shift Factor</td></tr>
<tr><td>σ^{Jir}</td><td>σ^{Ful}</td><td>σ^{Chi}</td><td>σ^{Dho}</td><td>σ^{Man}</td><td>σ^{Mad}</td></tr>
<tr><td>Upper</td><td>0.101</td><td>0.100</td><td>0.799</td><td>0.067</td><td>0.711</td><td>0.205</td><td>0.100</td><td>0.572</td><td>0.275</td></tr>
<tr><td rowspan="2">Lower</td><td rowspan="2">0.200</td><td rowspan="2">0.100</td><td rowspan="2">0.699</td><td colspan="2">σ^{APG}</td><td>σ^{Jat}</td><td>σ^{Mat}</td><td colspan="2">σ^{Gha}</td></tr>
<tr><td colspan="2">1.077</td><td>0.192</td><td>0.411</td><td colspan="2">0.001</td></tr>
</table>

The coefficients are used in equation 1 to define the multiple flows propagation model for the river networks in the study area. It may be seen that equation 1 gives an estimate of the common downstream flow rate at time $(t+1)$ on the basis of downstream flow at time t and is useful in estimating relative effects of the upstream flows on the common downstream flow. Earlier applications of the model to the upper network in the study area indicate that flows from Dholai and Jiri sub basins have respectively, the highest and lowest impact on the peak flow rate at Site A (Debbarman and Choudhury, 2015).

In this study, the model is applied to the lower network and flow rate for the downstream flow section, Site B at time t is used for computing the reduction in the peak flow rate at time $(t+1)$ for no flow from a sub basin. Peak flow rates for flood event 1, 2 and 3 were simulated for Site B by using equation 1 are 4858.95 m^3/s, 4863.50 m^3/s and 4750.83 m^3/s respectively.

Table 5. Peak flow rate improvement at downstream section, Site B for regulating upstream sub basins one at a time

Upstream sub basins	Peak Flow Rate at Badarpurghat (m^3/s)			Peak Flow reduction (%)			Average Reduction (%)
	E-1	E-2	E-3	E-1	E-2	E-3	
Jiri	4848.94	4860.27	4740.8	0.21	0.07	0.21	0.16
Chiri	4846.38	4857.7	4731.85	0.26	0.12	0.40	0.26
Sonai at Dholai	4840.86	4826.83	4707.68	0.37	0.75	0.91	0.68
Rukni at Maniarkhal	4851.04	4851.06	4743.7	0.16	0.26	0.15	0.19
Madhura	4847.66	4859.00	4735.32	0.23	0.09	0.33	0.22
Jatinga	4849.37	4860.69	4740.27	0.20	0.06	0.22	0.16
Katakhal at Matijuri	4304.23	4404.17	4187.84	11.42	9.44	11.85	10.90
Ghagra	4853.60	4862.05	4745.47	0.11	0.03	0.11	0.08

Table-5 shows the relative impacts in terms of percentage reduction in the downstream peak flow rate at Site B when flow from a sub basin is fully controlled. The results obtained show that the effect of flow from Katakhal subbasin on the peak flow at Site B is the highest while, the effect of flow from the Ghagra subbasin is the lowest. The peak flow study results given in Table-5 depicts comparative importance of the sub basins in controlling downstream flood flow and shows that, if flood damage reduction at Site B is sought to be achieved by controlling one sub basin only, in that case, Katakhal sub basin should be considered first and be given the top most priority.

Controlling the main channel, Barak at the upstream section 'Fulertal' that combine drainage contribution from more than 50% of the basin area may not be feasible. In that case, evaluating effectiveness of the intervening sub basins on downstream flood control assumes greater significance. To evaluate the maximum possible flood than can be passed safely through the main channel, Barak with maximum possible drainage from the intervening sub basins, LP models are used with different flow ranges for the upstream section 'Fulertal' in the main channel. Maximum permissible non damaging flow rates for the sub basins are determined for the conditions of maximum possible drainage of the individual sub basins and the maximum possible drainage from the intervening basin areas. To accomplish these objectives, the LP models are run to maximize (i) the sum of the upstream flow rates and (ii) sum of the downstream flow rates in the river system for specified flood duration subject to the constraints given by equations 3 through 8.

Non damaging flow for the sub basins corresponding to a peak flow in the main channel at

Fulertal resulting maximum permissible non damaging downstream flows are evaluated for six flow ranges for the main channel, Barak. The ranges are used to identify the peak flow variation in the main channel, Barak for which regulation of the intervening sub basins is effective in ensuring downstream safe flow(s). The flow ranges used in the study are: Range-I: 3500-4000 m^3/s; Range-II: 4000-5000 m^3/s; Range-III: 5000-6000 m^3/s; Range-IV: 6000-7000 m^3/s; Range-V: 7000-7500 m^3/s and Range-VI: 7500-8000 m^3/s. LP models using each of the flow ranges for Fulertal are run for a period of 263 hours, which is same as the duration of the recorded flood event-3 for evaluating safe drainage conditions for the downstream sections, Site A and Site B. For a range of flow, the model resulted in 2897 number of constraint equations with 2903 number of variables. The models run resulted in flow sequences for the upstream sections that produce no flooding at the downstream sections. For a selected range there are several combinations of the upstream flows resulting maximum permissible non damaging flow at the downstream section(s). Each flow combination is feasible and represents that safe flow at the downstream section(s) can be resulted by maintaining upstream flows in a river system at the specified levels.

Permissible maximum non damaging flow rate for the sub basins corresponding to peak flow rates at Fulertal evaluated by applying the conditions of maximum drainage of the individual sub basins and maximum drainage from the intervening basin areas are listed in Table-6 and Table-7 respectively.

Table 6. Maximum Permissible Non Damaging Flow from the Sub Basins for the Condition of Maximum Drainage of the Individual Sub Basins

Sub basins		Non Damaging Maximum Flow Rates in (m^3/s) for Flow Ranges at the Upstream Section, Fulertal in the Main Channel					
		R- I	R- II	R- III	R- IV	R- V	R- VI
Jiri		883.22	785.66	228.96	0.00	0.00	0.00
Chiri		894.29	636.66	52.45	0.00	0.00	0.00
Sonai at Dholai		209.93	147.19	5.75	0.00	0.00	0.00
Rukni at Maniarkhal		354.90	250.69	10.84	0.00	0.00	0.00
Madhura		850.58	583.91	42.52	0.00	0.00	0.00
Jatinga		749.80	642.11	501.57	407.08	126.33	0.00
Katakhal at Matijuri		505.55	499.82	349.31	296.75	65.39	0.00
Ghagra		751.80	751.05	749.99	613.45	157.14	0.00
Peak flow (m^3/s)	U/S Fulertal	3717.31	4162.50	5023.64	6001.86	7000.00	7551.00
	D/S, AP Ghat	3535.30	3596.79	3624.27	3791.33	3860.84	4150.15
	D/S, BP Ghat	4162.33	4205.51	4146.20	4286.23	4211.39	4471.72
Drainage Volume (m^3)	D/S, AP Ghat	918×10^3	934×10^3	941×10^3	989×10^3	1009×10^3	1085×10^3
	D/S, BP Ghat	1076×10^3	1087×10^3	1091×10^3	1112×10^3	1145×10^3	1162×10^3

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Table 7. Maximum Permissible Non Damaging Flow for the Sub Basins for the Condition of Maximum Drainage from the Intervening Basin Areas

Sub basins		Non Damaging Maximum Flow Rates in (m^3/s) for Flow Ranges at the Upstream Section, Fulertal in the Main Channel					
		Range- I	Range- II	Range- III	Range- IV	Range- V	Range- VI
Jiri		974.22	837.20	515.50	0.00	0.00	0.00
Chiri		1074.91	931.01	135.45	0.00	0.00	0.00
Sonai at Dholai		259.93	152.96	33.19	0.00	0.00	0.00
Rukni at Maniarkhal		373.03	369.63	22.77	0.00	0.00	0.00
Madhura		1036.70	815.62	95.20	0.00	0.00	0.00
Jatinga		649.14	581.55	578.04	417.82	126.52	0.00
Katakhal at Matijuri		422.19	448.48	440.56	300.49	65.49	0.00
Ghagra		714.23	734.24	752.06	620.07	158.54	0.00
Peak flow (m^3/s)	U/S Fulertal	3911.95	4212.21	5223.53	6000.00	7000.00	7581.00
	D/S, AP Ghat	3614.30	3619.02	3627.71	3791.33	3860.84	4165.91
	D/S, BP Ghat	4333.91	4334.17	4335.46	4410.88	4415.25	4488.70
Drainage Volume (m^3)	D/S, AP Ghat	941×10^3	942×10^3	945×10^3	989×10^3	1009×10^3	1089×10^3
	D/S, BP Ghat	1123×10^3	1124×10^3	1125×10^3	1144×10^3	1148×10^3	1166×10^3

To obtain non damaging flow rates for the condition of maximum drainage from the intervening areas, objective function representing maximization of outflow at the downstream sections over a period is considered. Drainage volume resulted for the downstream sections for using constant non damaging flow rate from the sub basins given in Tables-6 & 7 and a constant flow from the upstream section, Fulertal given by the respective peak flow rate in a range are also listed in the Tables. From the results it may be seen that slightly higher drainage, about 3-5% resulted for using the condition of maximum drainage from the sub basin areas which is mainly because of different drainage priority assigned to the sub basins. During event-3 having a flood duration same as that of the LP model run period natural drainage through Site A and Site B were $612 \times 10^3\ m^3$ and $862 \times 10^3\ m^3$ respectively and the peak flow exceeded the respective safe limits.

Results given in Tables 6 and 7 shows that coordinated regulation of the sub basins in the system are helpful in improving drainage capacity and reduction in the flood damages. Figure 4 and figure 5 give flood flow for the downstream sections obtained by using the conditions of maximum drainage of the individual sub basins and maximum drainage of the intervening sub basins respectively for using constant permissible non damaging flow rate for the upstream sections while, figure 6 give the results of the LP models depicting flood flows at these sections for time varying flow at the upstream sections.

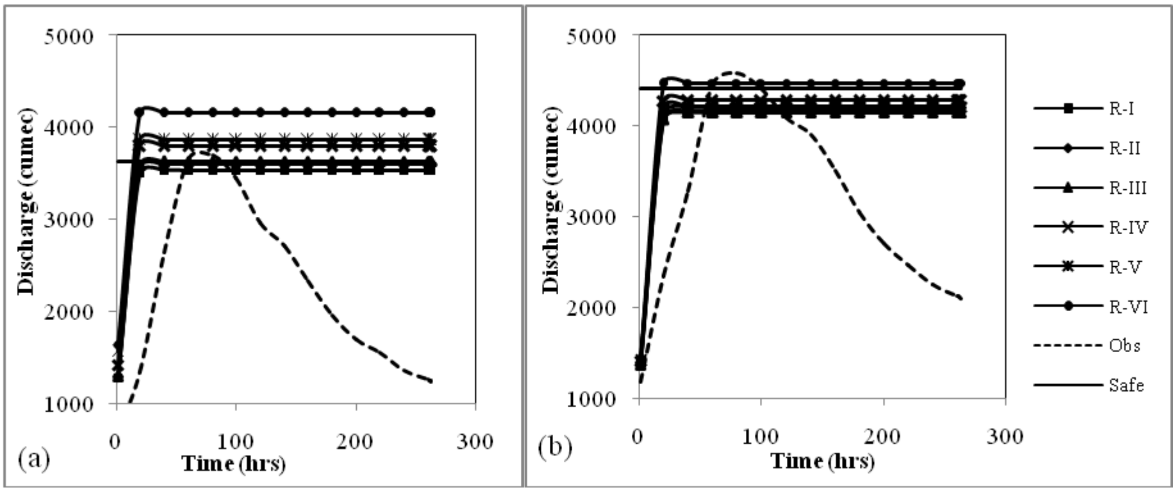

Figure 4. Flood flow at downstream sections (a) Site A and (b) Site B for the upstream flow combination: constant maximum (peak) flow at Fulertal in different ranges with corresponding constant permissible non damaging flow from the sub basins for the condition of maximum drainage of the individual sub basins.

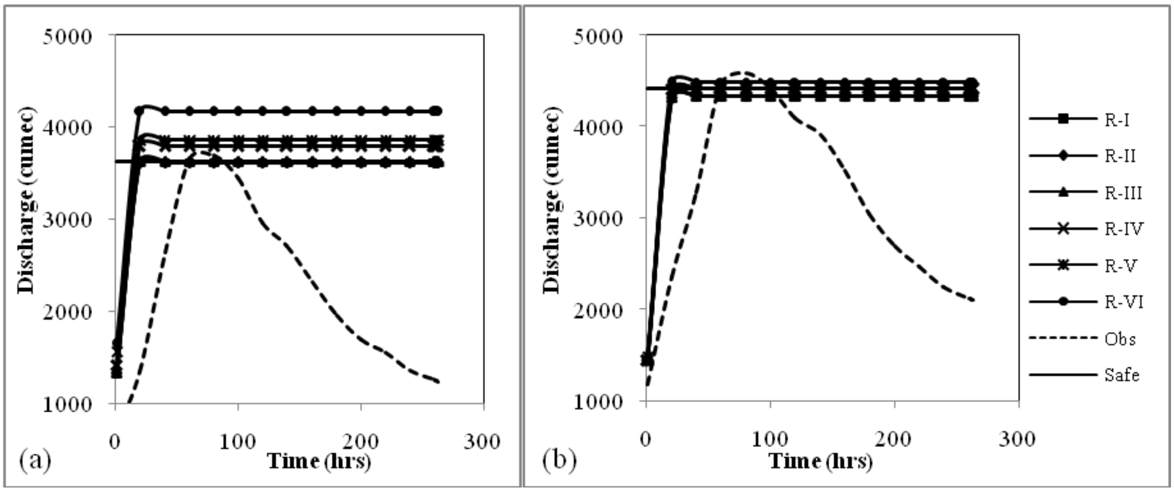

Figure 5. Flood flow at downstream sections (a) Site A and (b) Site B for constant maximum (peak) flow at Fulertal in different ranges with corresponding constant permissible non damaging flow from the sub basins for the condition of maximum drainage of the intervening basin areas.

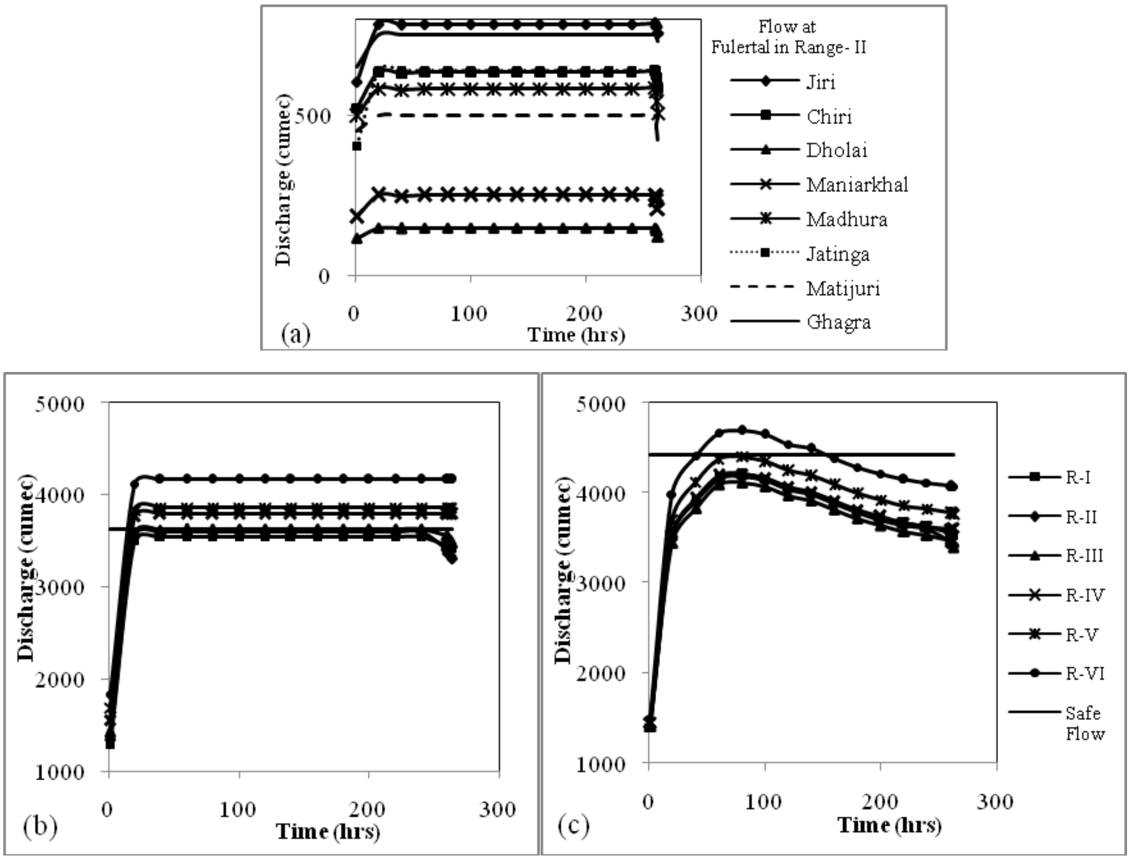

Figure 6. LP model results for maximum possible drainage of the intervening basin areas: a) sub basins flow for flow at Fulertal in range-II and (b) outflow at Site A (c) outflow at Site B for time varying flow at u/s Fulertal in different ranges.

It may be noted from figure (6a) that LP model also generates almost constant flow from the sub basins to satisfy the downstream flood flow criterion. Variations of the permissible maximum non damaging flow for the sub basins with flow rates at the upstream section, Fulertal in the main channel are given in figures (7a) and (7b). Figure (7a) shows the variations for the condition of maximum drainage of the individual sub basins during a period of 263 hours while, figure (7b) gives the variation for the condition of maximum drainage from the intervening basin areas over same time duration.

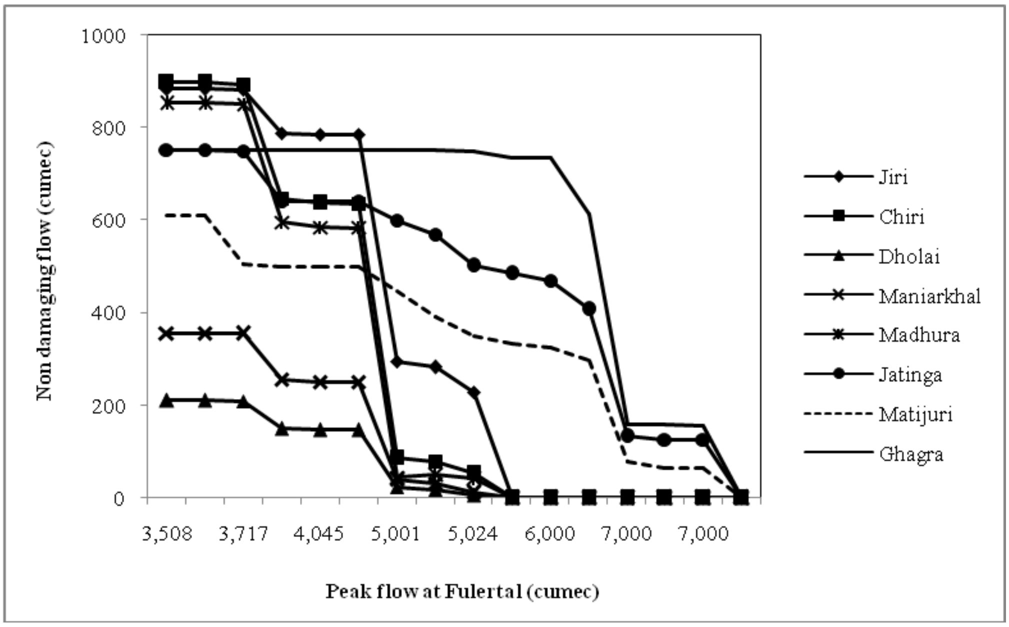

Figure (7a). Variation of non damaging flow for the sub basins with the peak flow at the main channel for the condition of maximum drainage from the individual sub basins

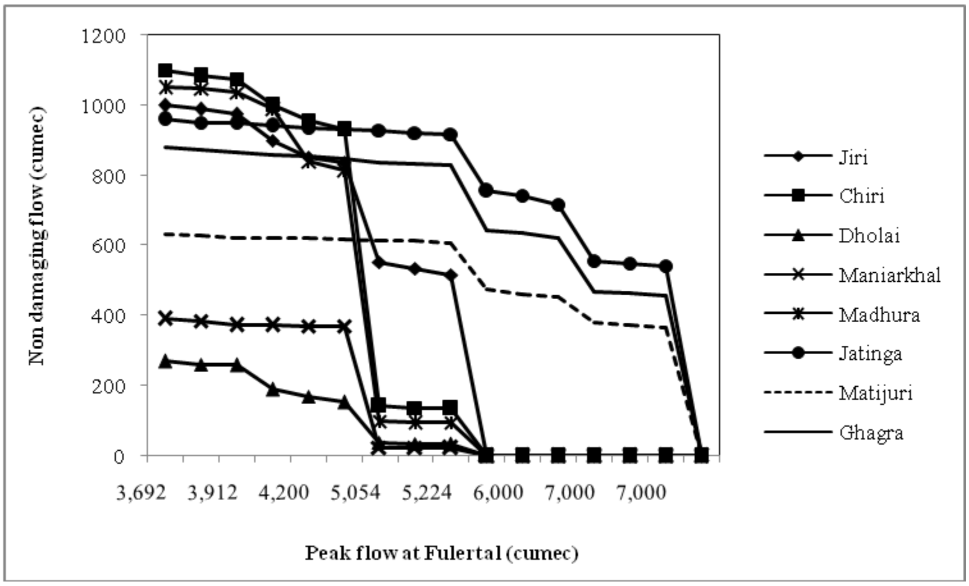

Figure (7b). Variations of non damaging flow with peak flow for the condition of maximum drainage from the intervening basin areas.

Considering the averaged peak flow for the sections Fulertal, Site A and Site B obtained from Tables-6 & 7 it can be seen that a flow of 5123 m^3/s at Fulertal in combination with almost no flow from the intervening sub basins drained by the rivers Jiri, Chiri, Sonai, Rukni and Madhura cause the peak flow rate at the first downstream section, Site A reaching the critical flow level, 3650 m^3/s while, for this flow combination, peak flow rate at the second downstream section, Site B remains below the danger flow level, 4416 m^3/s for the section. The averaged results depict that flood hydrographs with peaks less than equal to 5123 m^3/s at Fulertal can be passed through both the downstream sections without flooding, if drainage from the intervening areas is fully controlled. And, for peaks between 5123 – 7566 m^3/s though flooding will occur at the first downstream section but, flow rate at the second downstream section, Site B can be brought to safe level by partially controlling the sub basins flow joining downstream of Site A and fully controlling the sub basins joining upstream of Annapurnaghat. The study also show that for inflow hydrographs with peaks less than 5123 m^3/s and 7566 m^3/s at Fulertal unsafe flood flow, if any, at the downstream sections, Site A and Site B respectively are mainly due to lateral flow from the sub basins. Results obtained show that, for floods exceeding 7566 m^3/s at Fulertal and having no lateral flow minimum peak at Site A and Site B would be approximately 4157.5 m^3/s and 4479.5 m^3/s respectively, which are above the respective critical limit. Thus, for floods with peak more than 7566 m^3/s at Fulertal the intervening sub basins play a role in further aggravating the flood damages at the downstream damage sections, Site A and Site B. Model applications show that by regulating intervening sub basins full safety at one/two downstream sections can be ensured however, such regulations is not sufficient if the flood peaks exceed 7566 m^3/s at Fulertal. In such cases, controlling main channel in the upper reaches or controlling the sub basins that join the main river reach upstream to the study area seems essential. As defined by the river system characteristics the results given in figures (7a) and (7b) represent possible upstream flow combinations that ensure safe downstream outflows in the river system. Permissible maximum flow indicate the extent of flow regulation required in the sub basins and are thus, useful in selecting the best suited feasible flood control measures for the study area.

4. Conclusions

Application of the LP models for evaluating non damaging flow for a set of sub basins in a river system is presented. The technique allows identifying a number of concurrent flow sets for the upstream sections resulting maximum permissible non damaging downstream flows in a river system. Based on technical, financial and other considerations the best suited feasible solution for a case may be implemented for flood damage mitigation. In the present study, assuming that regulating main channel is not possible non damaging flow for the sub basins are selected; for a flow range, the selected non damaging flow sets, as given in Tables-6 and 7 are the flow rates concurrent to the peak of the model generated flow sequence for the main channel, Barak.

Non damaging flow sets representing alternative solutions are the maximum flow limits for the upstream basins that satisfy a specified downstream flood flow criterion. And, being governed by the river system properties have nonlinear interrelationship. In the present study, relationships between the non damaging flow for the sub basins and the main channel flow, depicted in figures (7a) and (7b) are evaluated by using six flow ranges. The flow ranges used in the study signify peak flow variation for the main channel, Barak for which regulation of the intervening sub basins is effective in controlling downstream flooding.

In the present study, LP model is applied for evaluating necessary flow conditions for the upstream sections for downstream flood control. The study river system has a number of ungauged sub basins; due to lack of data sets defining flood damage function based on channel discharge/ flow depth and non linear routing model for the river system is difficult.

In the absence of flood damage function and efficient nonlinear routing technique multiple inflows routing model that reduces to linear form with known coefficient values and a linear objective function is used for solving the problem. Incorporation of multiple inflows routing scheme in the optimization model leads to a more compact LP model with fewer constraint equations and ensures the model generated inflow and outflow sequences obey the fundamental continuity norm.

Models applications to Barak river system, in India show that for floods with peaks less than 7566 m^3/s at the upstream section in the main channel, Barak lateral flows from the intervening sub basins play an important role in downstream flood damages. And, if flood damage reduction is planned to be achieved by controlling one sub basin only, in that case, as indicated by the peak flow study results maximum benefit is expected for the sections, Site A and Site B from regulating the sub basins drained by the rivers Dholai and Katakhal respectively. Higher drainage, approximately 3-5% is resulted when some drainage priority is assigned to the sub basins; considering the drainage occurred during flood event 3 and the drainages given by the LP model as listed in Table 6 and 7 coordinated controls of the sub basins is proved to be helpful in reducing flood damages in the study area. The study demonstrates applicability of the LP model in assessing effectiveness of the sub basins in mitigating downstream flood damages in a river system. Model applications to a real life river system in India yield results that are useful in adopting flood control measures for the study area.

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