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Application of Goal Programming in Flood Flow Modeling

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Abstract—The study presents a pre-emptive goal programming model formulation for a river system incorporating flows from gauged and ungauged subbasins. Incorporation of flows from both gauged and ungauged subbasins simplifies the optimization model resulting in accurate estimation of the downstream water flow. To derive optimal regulation of a river system under flood condition, multiple objectives with flow variables are used which are ranked in order of priority, and optimized sequentially to obtain an optimal solution for the problem. The model is applied in the Barak River basin (India), with three gauged and five ungauged water flows affecting the downstream flows in the river system. Downstream control point flows are zoned with prioritized objectives used to derive an optimal flow rate for reducing flood damage in the river basin. Model applications in the Barak River Basin show that damage at downstream locations could be substantially reduced if the water inflows are predicted well in advance.

Keywords— **River system; flood damage; goal programming; pre-emptive.**

I. Introduction

Multiobjective programming methods are extensively used in Multi-Criteria Decision Analysis and also in Reservoir operations. Wasimi and Kitanidis (1983) used the linear quadratic Gaussian Control in real time reservoir operations to reduce the dimensionality problems. Braga and Barbosa (2001); Wei and Hsu (2008); Wang et al. (2010) also focuses on multi objective reservoir operation models in flood control in a river system. Goal Programming (GP) method developed by Charnes et al. (1955) is extensively used for solving multi-objective optimization problem by a number of researchers in various fields and establish it as a reliable method to solve multi-objective optimization problems.

Pre- emptive goal programming (Can & Houcks 1984; Loganathan & Bhattacharya 1990) is a multi objective optimization method which allows the flexible expression of policy constraints as objective. Unlike many other multiobjective optimization approaches, this method avoids the practical problems associated with assigning and mitigating the values of relative weights (Schultz 1989). The potential for practical success of the goal programming approach in the Tennessee Valley Authority's planning model is also indicated by Shane et al. 1988. Zagona et al. (2001) and Eschenbach et al. (2001) reviewed and described the RiverWare decision support systems optimization capabilities for use in routine daily scheduling of large complex multiobjective reservoir system.

In large scale water system, for minimizing the flood damages in the downstream section, the reservoirs should be operated to best satisfy the objective of reducing the flood damage in the river basin. A weighted pre- emptive goal programming model formulation combined with multiple water inflows forecasting model is presented (Choudhury, 2010) for coordinated reservoir operation.

The pre- emptive goal programming approach is chosen for three main reasons: (1) Deterministic optimization is adequate given the relatively short time horizon for operational modeling. (2) GP can model the multiple objectives and physical aspects of reservoir system in effectively realistic manner and (3) GP is suitably efficient and robust to be used in daily operations. Attainment of goal is sought sequentially beginning with the higher priority goals. The goal of this study was to introduce a simplified flood control operation model that can efficiently handle both gauged and ungauged water flows. In the present study, the downstream flow for a number of flows in the upstream is computed with a single compact equation including both the gauged and ungauged subbasins in the river system. The model is applied in the Barak River Basin, India to suggest a reduced damage at downstream location for a set of non damaging water inflows.

II. GP Model

In conventional formulations of goal programming, policy goals are incorporated into the GP by adding deviational variables to the constraints and minimizing the deviation (Can and Houck 1983; Loganathan and Bhattacharya 1990). For a river network with multiple water inflows the equation with equivalent inflow (Choudhury, 2007) is formulated as,

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

Where, 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. In the case of a river system having N upstream and two downstream sections the constraint equations may be given as,

$$q_2^{d1} - c_2^1\left[\sum_{p=1}^{m1}\sigma^{p,r} i_2^p + \sum_{p=(m1+1)}^{n1}\sigma^{p,r}\bar{i}_2^p\right] = c_1^1\left[\sum_{p=1}^{m1}\sigma^{p,r} i_1^p + \sum_{p=(m1+1)}^{n1}\sigma^{p,r}\bar{i}_1^p\right] + c_3^1 q_1^{d1} \qquad (2)$$

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$$q_2^{d2} - c_2^2 \left[\sigma^{d1,r} q_2^{d1} + \sum_{p=1}^{m2} \sigma^{p,r} i_2^p + \sum_{p=(m2+1)}^{n2} \sigma^{p,r} \bar{i}_2^p \right] = c_1^2 \left[\sigma^{d1,r} q_1^{d1} + \sum_{p=1}^{m2} \sigma^{p,r} i_1^p + \sum_{p=(m2+1)}^{n2} \sigma^{p,r} \bar{i}_1^p \right] + c_3^2 q_1^{d2}$$
(3)

As presented above, $d1$ = potential downstream damage section 1; $d2$ = potential downstream damage section 2; n_1 and m_1 = total number of sub basins and the number of gauged sub basins in the upper river system; n_2 and m_2 = 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. The multiple coefficients for a given channel network can be estimated by

The goal constraints for the downstream control points are calculated as:

$$q_t^{d1} - \sum_{l=1}^{NZF_1} PD_t^{d1,l} + \sum_{l=1}^{NFZ_2} ND_t^{d1,l} = TQ^{d1} \text{ for } \quad t = 2,3,4,\ldots,T+1$$
(4)

$$q_t^{d2} - \sum_{l=1}^{NZF_1} PD_t^{d2,l} + \sum_{l=1}^{NFZ_2} ND_t^{d2,l} = TQ^{d2} \text{ for } \quad t = 2,3,4,\ldots,T+1$$
(5)

Where, NZF_1 and NZF_2 are number of flow zones above target and below a target level respectively and TQ^{d1} & TQ^{d2} are the target downstream flow at downstream section 1 and 2 respectively.

The positive and negative flow deviations in a zone l are constrained as,

$$PD_t^{d1,l} \le q_{\max_{d1,l}} \text{ and } ND_t^{d1,l} \le \bar{q}_{\max_{d1,l}}$$
(6)

$$PD_t^{d2,l} \le q_{\max_{d2,l}} \text{ and } ND_t^{d2,l} \le \bar{q}_{\max_{d2,l}}$$
(7)

The multiple objectives in a PGP problem are ranked in order of priority, and optimized sequentially to obtain an optimal solution. If the first or the highest priority in an operation problem is to have minimum flow in zones “l” at the downstream control point, the objective may be achieved by minimizing the flow deviations in zones “l” at the control points. The objective function in the first priority level can be written as,

$$Min.P1 = \sum_{t=2}^{T+1} (PD_t^{d1,l} + PD_t^{d2,l})$$
(8)

The model solution comprises equation 2 to 7 with equation 8, yielding an optimal solution for the first priority objective, $P1^*$. After obtaining an optimal solution for the first priority objective, the second priority objective is considered for optimization. The objective function in equation 8 is rewritten for the second priority objective, with equation 2 to 7 being solved with an additional constraint given by:

$$\sum_{t=2}^{T+1} (PD_t^{d1,l} + PD_t^{d2,l}) = P1^*$$
(9)

The additional constraint given by equation 9 restricts the effect of the second priority objective on the first priority objective. After optimizing the second priority objective, if more objectives exist, they are then considered in sequential order, one after another, each time adding a new constraint, and rewriting the equation 8 as per the new objective. The procedure will continue until all the objectives are satisfied.

III. **Application**

The Barak River basin in India, has a drainage area of 7224 sq. km and lies between 89°50′ to 94°0′ E longitude and 22°44′ to 25°58′ N latitude. The river Barak is an integral part of the Ganga- Brahmaputra- Meghna system and also the second largest river system in the north eastern region of India. The problem of flood and drainage congestion is very acute in the basin since the region is inundated by flood waves frequently resulting in huge losses and public suffering. In the present study, Barak river network within the state of Assam starting from Fulertal to Badarpurghat has been used. The present study examines the potential for flood damage mitigation at Annapurnaghat (APG) and Badarpurghat (BPG) and the study network is split into two smaller networks. The first network terminating at Annapurnaghat combining flows from six upstream sections and the second network covers the main river strech from Annapurnaghat to Badarpurghat, receiving flows from the upstream damage site Annapurnaghat with other three subbasin flows in the study area. Figure 1 shows the schematic map of the study area and the details of the subbasins are listed in Table 1. Three flood events are used in the study, the period of the events are: July 10- 17, 2004; July 19- 29, 2004; June 11- 21, 2006 and the details are shown in Table 2. Hourly recorded discharge data for the gauged sites Fulertal, Dholai, Maniarkhal, Annapurnaghat, Matijuri and Badarpurghat are obtained from the Central Water Commision (CWC), Shillong and CWC, Silchar. Rainfall records for the gauging sites in the study area are collected from the Regional Meteorological Centre (RMC) office at Guwahati.

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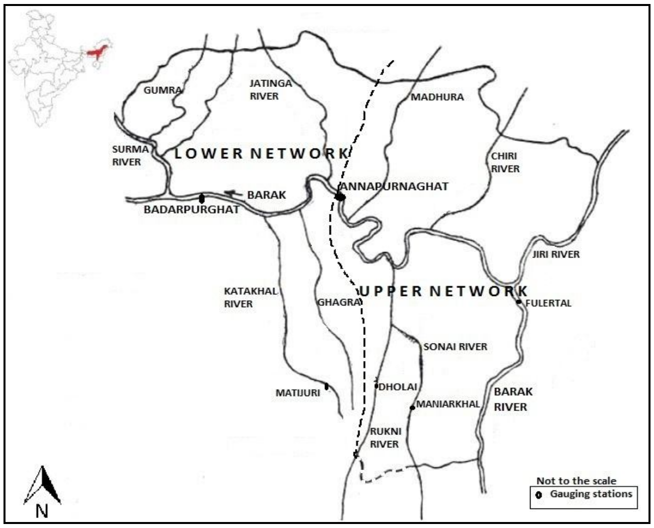

Figure 1: Schematic map of the study area

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

River	Drainage Area	Safe Flow	River	Drainage Area	Safe Flow
Jiri	1052.85	1898.00	Ghagra	409.39	1505.45
Chiri	438.66	2549.00	Dholai	1088.25	451.45
Madhura	349.43	2415.00	Katakhal	1504.68	1729.45
Jatinga	371.86	1927.35	Maniarkhal	384.65	764.41

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	4859.993	20.39	17.20	3650.902	4416.50
Event-2	16.69	16.26	4398.26	4870.75				
Event-3	15.7	15.68	3720.57	4759.86				

The PGP model is applied in the Barak River basin in India. The model is run, assuming known inflows at the main channel Fulertal with an interval of $\Delta t = 1h$ for the complete flood period of the selected events. As described earlier the study network, consists of nine channels and split into two smaller networks. Multiple inflow routing coefficient values used in the operation model are estimated on the basis of flow data for the flood event by the MatLab optimization function "lsqnonlin" (Version: 7.10.0.499, R2010a). To estimate the routing coefficients and model parameters for the upper river network, the water flows at Jiri, Fulertal, Chiri, Dholai, Maniarkhal, Madhura and Annapurnaghat are used. The flows at Annapurnaghat, Jatinga, Matijuri, Ghagra and at Badarpurghat are used for the lower network flow values. The model parameters and routing coefficient values used in the study are given in Table 3. The downstream control point flow at Annapurnaghat and Badarpurghat are zoned in such a way that the first zone represent the water flow below the critical discharge (safe flow), while the second zone is taken as representing the water discharge above the critical flow. The downstream control point flow zoning is summarized in Table 4.

Table-3: Routing coefficient for river system

River Network	C_1	C_2	C_3	Shift Factor					
				σ^{Jir}	σ^{Ful}	σ^{Chi}	σ^{Dho}	σ^{Man}	σ^{Mad}
Upper	0.101	0.100	0.799	0.067	0.711	0.205	0.100	0.572	0.275
Lower	0.200	0.100	0.699	σ^{APG}		σ^{Jat}	σ^{Mat}	σ^{Gha}	
				1.077		0.192	0.411	0.001	

Table- 4: Downstream section flow zoning

Zone	Target Flow (cumec)	
	APG	BPG
Zone I	3650- 4000	4416- 5000
Zone II	2000- 3650	3000- 4416

During flood control operation in a river system, the objectives are best served to produce non damaging flow at the downstream control point. For the present problem which is concerned with the flood damage at a downstream point, the water flowing through different subbasins should be determined on the basis of the damage point flow rate. Multiple inflow routing coefficients provide a comparative picture of these effects (Debbarman and Choudhury, 2015).

For the present problem, both the downstream control point flows have been zoned. The top priority is given to the goal that downstream flow is below the critical level. The objective is achieved by minimizing the flow deviations in zone I and zone II for the downstream control points.

The model is run to simulate the selected flood events, with flood duration of about 192, 262 and 263 hours, using observed water inflow from the main channel, Fulertal in the river system. The results and performance of the GP model is illustrated in table 5 below,

Table- 5: Performance of GP model at the downstream sections

Parameter	Downstream Section					
	APG			BPG		
	Event 1	Event 2	Event 3	Event 1	Event 2	Event 3
Observed Peak flow rate (cumec)	4048.63	4398.26	3720.57	4859.99	4870.75	4601.14
Peak flow rate (cumec)	3647.85	3631.00	3630.99	4412.03	4416.64	4416.49
Peak flow duration	84	59	90	60	48	120
Percentage reduction in peak flow rate	9.90	17.44	2.41	9.22	9.32	4.01

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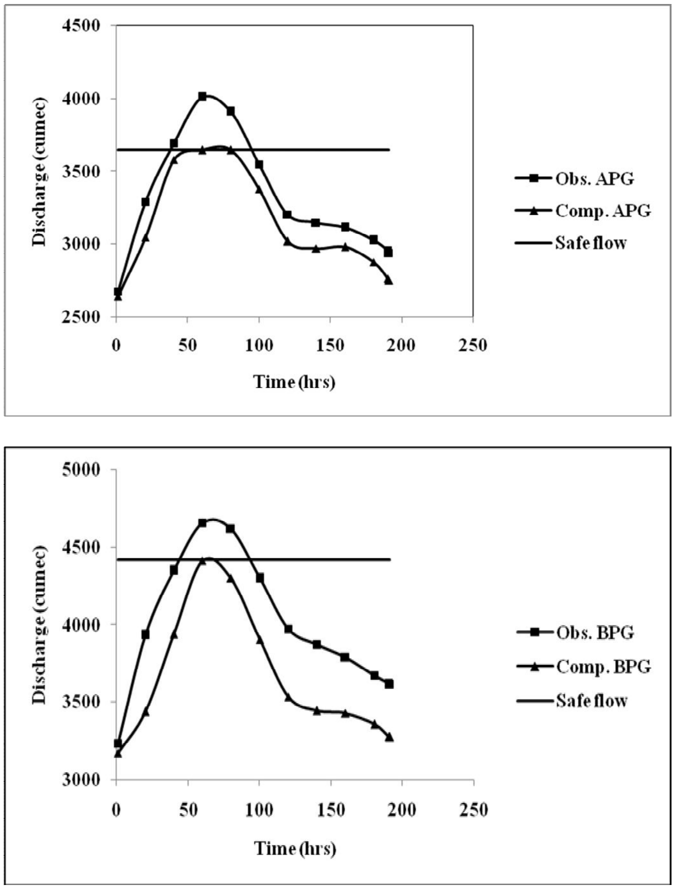

Figure 2: GP model outflow at APG and BPG for Event 1.

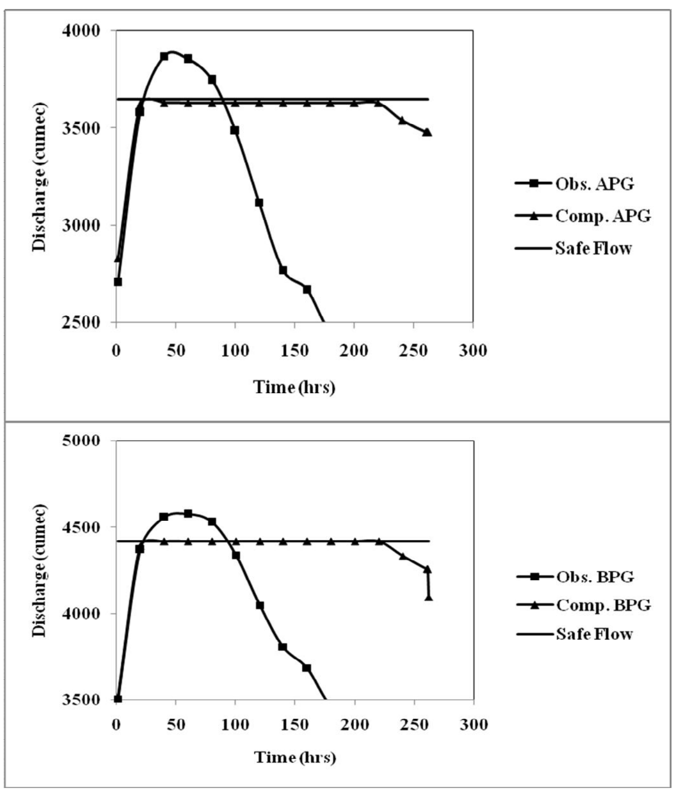

Figure 3: GP model outflow at APG and BPG for Event 2.

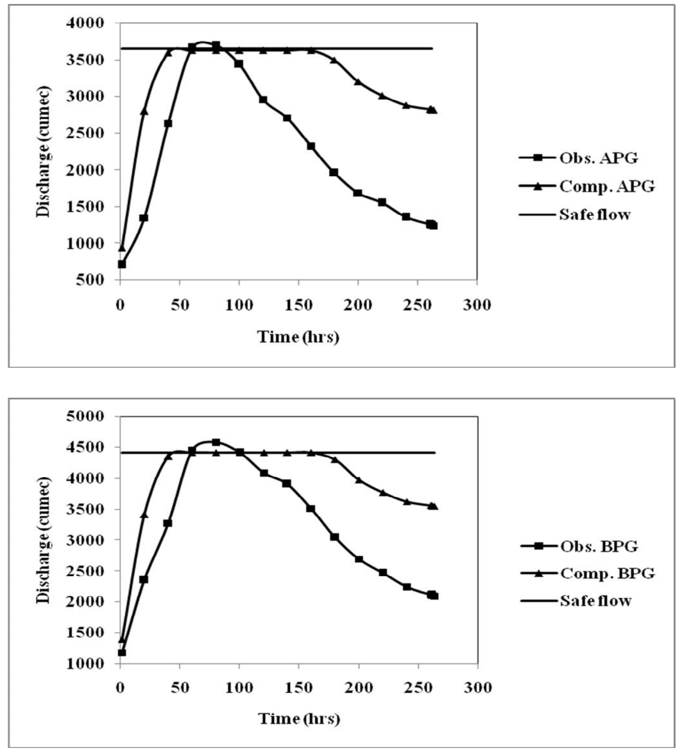

Figure 4: GP model outflow at APG and BPG for Event 3.

The results indicate that a safe water flow at downstream section, Annapurnaghat and Badarpurghat is possible with an average peak flow reduction of 10% and 8% respectively.

IV. Conclusion

A preemptive goal programming, PGP model formulation for a river system including the flows from both gauged and ungauged subbasins are presented in this study. Water flow routing from various upstream sites are computed by using a single compact equation. Integration of both the gauged and gauged subbasin flows in the study basin results in accurate estimation of the downstream flow. The model can be used to determine the optimal water flow for the study period. Model application to the selected flood eventsin the Barak river basin indicates a substantially reduced flow peaks at the donstream control points. The model resulted in safe flow for the entire period at both Annapurnaghat and Badarpurghat with a considerably reduced peak.

The present study,illustrates the integration of inflows from the gauged and ungauged subbasins for better understanding of the water system and the applicability of the Goal Programming techniques in the river basin management for flood control.

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