Development of a Multi-Reservoir Flood Control Optimization Model; Application to the Karkheh River Basin, Iran

A. Abrishamchi, M. Dashti, and M. Tajrishy
Professor, Department of Civil Engineering, Sharif University of Technology,
P.O. Box 11398.9313, Tehran; abrisham@sharif.edu
Grad. Student, Department of Civil Engineering, Sharif University of Technology,
Tehran; m_dashti@alum.sharif.edu
Associate Prof, Department of Civil Engineering, Sharif University of Technology,
Tehran; tajrishy@sharif.edu

ABSTRACT

Flood control as an important purpose of reservoir systems faces a wide range of natural, social and political challenges, mainly due to different uncertainties. Over the time, these uncertainties call for necessary changes in the original plan of the systems. Therefore, construction of new flood control systems as well as the storage reallocation and reservoir reoperation of existing ones are essential for adapting the systems to new information, conditions and policies. Furthermore, multipurpose nature of the multi-reservoir systems requires considering conflicts among various purposes. In this paper, a multiobjective optimization model is developed for analyzing such conflicts in a changing environment. The developed model is applied to Karkheh Reservoir system in the west of Iran. Karkheh reservoir system has six large multipurpose reservoirs in its first master plan from which two have already been constructed. In this study, three storm based flood events were generated and used in the optimization model. The results have demonstrated a large trade-off among different reservoir purposes, and showed the merits of considering such conflicts.

INTRODUCTION

Expanding energy needs and rapid growth in population centers have placed new pressures on reservoir systems to provide increased hydropower production and reliable water supply. On the other hand, through the focus of this population growth in floodplain area, beside the other purpose, flood control is becoming more important for insuring the safety of these damage centers. Hence, during operation of these complex systems, serious conflicts can arise between different uses (Labadie, 2000).

Over the past decades, several types of optimization models for operation of reservoir flood control systems have been introduced. Burton et al (1963) presented quite efficient solution for single reservoir system flood control with using the dynamic programming (DP). Windsor (1973) introduced the basic formulation of the modified form of linear programming model for determining the optimum operation of a multireservoir flood control system. He points out that by introducing binary variables for each forced spill condition representing outlet rating curves in a model with nonlinear constraints can cause the feasible set to be non-convex. Unver and Mays (1990) have proposed a combination model of nonlinear programming and simulation to reduce the problem size of real-time flood control operation with short time period. A limitation of this method is that the first partial derivatives of the objective and constraint functions with respect to the controllable variables must be definable. In addition, as noted in the paper, nonlinear programming cannot guarantee a global optimum. Wasimi and Kitanidis (1983) developed a state-space model “for short-term forecasting of river flows” that also is meant to be used for real-time reservoir operation. The optimization problem is solved using linear quadratic Gaussian (LQG) control. It was found in their study that the method was “suitable for operation under moderate flood conditions when capacity constraints are not likely to become binding.” Watkins (1999) to support flood control planning and operations studies by the U.S. Army Corps of Engineers, has developed a mixed-integer linear programming model for flood control optimization (FCMIP). Given a set of inflow hydrographs at various locations in a river basin, along with flood damage functions at key control points, the model makes reservoir release decisions that reduce flood damage consistent with the goals and priorities of system operation. Although FCMIP extends the Windsor (1973) formulation by addressing non-convex hydraulic relationships and adding penalty functions to quantify operators’ aversion to undesirable reservoir storage levels. FCMIP also relies on modern computers and algorithms to solve large planning problems. Also, Needham et al (2000), Braga and Barbosa (2001), and Wei and Hsu (2007 and 2008) present other optimization model based on LP or MILP formulation for flood control problem.

Necessities of a multiobjective view in operation of multipurpose reservoir system have conducted recent researches to the developing of multiobjective operation models for considering the various conflicts between flood control and other significant purposes of reservoir system. Malekmohammadi et al. (2008), Afshar et al. (2009), and Yinghai et al. (2010) are several researches that have considered such conflicts.

One of the important conflicts that arises in flood season is that the reservoir needs to allocate some parts of its storage for flood control to ensure the safety of dam reservoir and downstream damage centers, while for power generation benefits, the reservoir is expected to store water as much as possible, which requires a high water level. The aim of this paper is to present a multiobjective optimization model for considering conflict between flood control and hydropower generation in multireservoir flood control systems and to develop a set of efficient solutions for operation of system. To test the applicability of the developed model, we implement the model on Karkheh reservoir system and extract the different set of efficient solutions under different development scenarios and various flood events.

MULTIOBJECTIVE APPROACH

Requiring reliable water storage for water supply and hydropower generation along the need to flood control for preventing from consequences of flood events are the main purpose of operation of reservoir systems. These extensive ranges of purposes have been the original source of providing decision making challenges in all reservoir operation problems. Generally, flood control besides its main positive effect, -controlling hazardous flood events and making the downstream damage safe- also have two major negative effects on the other reservoir purpose, that may cause challenging conflicts for operators of reservoir system; 1) reducing potential of hydropower generation in flood seasons due to allocation a part of reservoir storage as a flood control capacity, and 2) risk of decreasing the reservoir reliability in water supply after flood event because inability of natural inflows for restoring the evacuated storage of reservoir for flood control.

In this study, we recognize the conflict between flood control purpose for reducing the flood damage at downstream areas and hydropower generation purpose. Naturally, when we try to control the flood damage more at downstream, we should accept the more reducing in hydropower generation; since in this text, reduction of hydropower generation called hydropower generation damage in contrast of downstream damage that represent flood damage at downstream areas. According to different aspects of these two kinds of damage, we cannot sum them in one term as objective function, so we have to use the Multiobjective approach to handle this conflict. The result of Multiobjective approach is obtaining the Pareto Curve instead of one optimal solution. Figure 1 shows a typical Pareto Curve and schematic representation of two extreme alternatives of this curve.

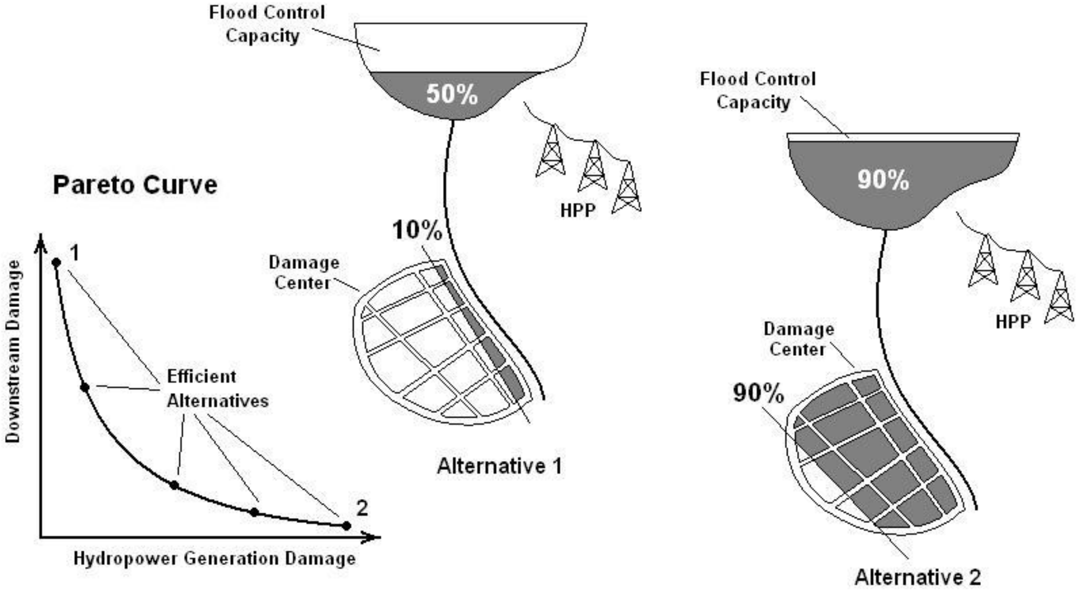

Figure 1. A typical Pareto Curve and schematic representation of two efficient alternatives of this curve. Alternative 1 represents the situation with minimum hydropower generation damage and alternative 2 represents the situation with maximum downstream damage.

BASIC FORMULATION

To implement the multiobjective approach of study, we develop a multiobjective MILP optimization model. The basic formulation of the model is pointed out as following.

Objective Function

The two objectives considered in the model are:

1. Minimizing the peak flow at control points to reduce the downstream damages

$$\mathrm{Min}\sum_{j=1}^{n} D_j^{DS}$$

$$D_j^{DS} = f_j^{PFD}(\mathrm{PF_j})$$

$$\mathrm{PF_j} = \max(R_{i,t}) \quad t \in [1,\ldots,T]$$

where j = index of downstream damage center; n = number of downstream damage centers; and D_j^{DS} = downstream damage at damage center j.

2. Minimizing the allocated flood control storage before the flood event to reduce the hydropower generation damage

$$\min\sum_{i=1}^{m} D_i^{HP}$$

$$D_i^{HP} = f_i^{HPD}(\mathrm{FCS_i})$$

$$\mathrm{FCS_i} = \mathrm{S_i^{max}} - \mathrm{S_i^1}$$

where i = index of reservoir; m = number of reservoirs; and D_i^{HP} = hydropower generation damage of reservoir$i$.

Constraints

1. Physical Constraint. Physical constraints define the limitations for storage capacity and maximum outlet capability over the horizon operation time. The reservoir storage ranges from maximum possible storage (S_i^{max}) to minimum require storage (S_i^{min}), that is

$$S_i^{min} \leq S_{i,t} \leq S_i^{max}$$

The flood discharge capacity of reservoirs is a function of storage volume this function is called rating curve and determines the capability of flood evacuation facilities.

$$R_{i,t} \leq R_{i,t}^{max}$$

$$R_{i,t}^{max} = f_i(S_{i,t})$$

where $R_{i,t}$ = release of reservoir i at period t; $S_{i,t}$ = storage volume of reservoir i at period t; $R_{i,t}^{max}$ = maximum possible release of reservoir i at period t; f_i = rating curve of reservoir i.

Also, due to physical and operational limitations of spill structures, the magnitude of change in release through in each two neighbor time periods is restricted by a constant value (ACR), that is

$$\left|R_{i,t} - R_{i,t-1}\right| \leq ACR_i$$

2. Reservoir Routing Equation. This constraint is based on the principle of continuity and states that during any time period the summation of natural inflow and artificial inflow (from upstream reservoir release) minus the outflow (release) must equal the change in reservoir storage. Evaporation losses from reservoirs during flood periods are generally an insignificant portion of the total flow and are therefore not included in the model (Windsor, 1973). On the assumption that the flow varies linearly during each discrete time period t, the continuity equation stated as below

$$(I_{i,t} + I_{i,t+1}) + (O_{i,t} + O_{i,t+1}) - (R_{i,t} + R_{i,t+1}) = \frac{2}{\Delta t}(S_{i,t+1} - S_{i,t})$$

where Δt = time interval that selected in hours for obtaining to a suitable routing; $I_{i,t}$ and $I_{i,t+1}$ = natural inflows to reservoir i at the start of time period t and $t+1$, and $O_{i,t}$ and $O_{i,t+1}$ = artificial inflows to reservoir i at the start of time period t and $t+1$

3. River Routing Equation. This equation states the routing of flows through each routing reaches. The Muskingum method is used for routing; this method based on the principle of continuity and assumes that channel storage is divided two parts (prism storage and wedge storage) which are weighted function of the inflow and outflow of routing reach. Following equation is general form of Muskingum routing equation

$$O_{i,t} = \left(\frac{\Delta t - 2KX}{2K(1-X) + \Delta t}\right) R_{j,t} + \left(\frac{\Delta t + 2KX}{2K(1-X) + \Delta t}\right) R_{j,t-1} + \left(\frac{2K(1-X) - \Delta t}{2K(1-X) + \Delta t}\right) O_{i,t-1}$$

where i = index of downstream reservoir; j = index of upstream reservoir; K = travel time of flood wave through routing reach; through; X = dimensionless weight ($0 \leq X \leq 0.5$), and O and R = respectively outflow (artificial inflow of downstream reservoir) and inflow (release of upstream reservoir) to the routing reach. The magnitude of the routing coefficients may vary to some extent depending on the degree of flooding, and there may be some local inflow from the uncontrolled drainage areas through routing reach, and if it is desirable, these items may be accounted for in the analysis (Windsor, 1973).

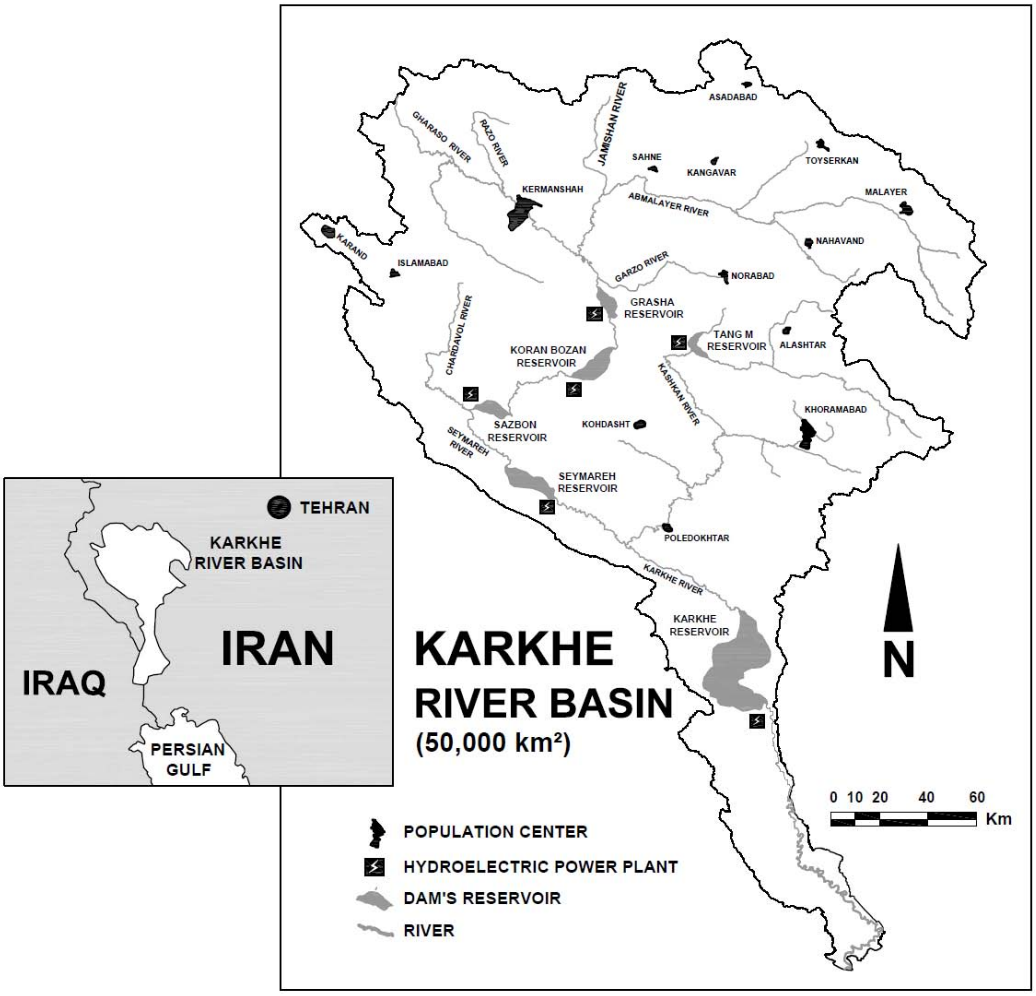

Figure 2. Map of Karkheh River Basin and its multipurpose reservoirs system.

CASE STUDY

The presented multiobjective optimization model is applied to Karkheh River Basin reservoirs system that is shown in Figure 2. Karkheh River Basin with a drainage area about 50,000 km² comprises three major tributaries: Seymareh, Kashkan, and Karkheh Rivers. Based on the first master plan of the River Basin, Karkheh reservoir system has six large multipurpose reservoirs (Garsha, Koran Bozan, Sazbon, Seymareh, Tang Mashoreh, and Karkheh) from which two reservoirs (Seymareh and Karkheh) have already been constructed. This multireservoir system with active storage about 14 billion cubic-meters and the hydropower generation potential about 2,000 MW forms a very suitable case for testing the applicability and efficiency of the developed multiobjective model in considering the conflicts between different purposes of system in complex reservoirs systems. In addition, to compare the effects of constructing the other four unconstructed reservoirs on reduction of flood damage, the model is run for two different system configurations.

MODEL IMPLEMENTATION AND RESULTS

The input data for model implementation consist of inflow, damage function –including both pick-flow and hydropower damage function, and reservoir system characteristic. The inflow data used for this study were generated by rainfall-runoff model and based on historical records spanning 54 years, from 1954 to 2007. Three generated flood events with return periods 25, 50, and 100 years are used as inflow of model in different scenarios. We applied the optimization model for two scenarios of reservoir system configuration: 1) Current condition-operating of Karkhe and Seymareh reservoir and 2) Complete development of the system-the operation of all of six reservoirs.

Pareto Curves for Flood Control System Planning

The main results of developed multiobjective optimization model are Pareto curves that show the different efficient solutions for the operation of a certain reservoir system under a specific flood event. The Figure 3 shows the Pareto curves of two scenarios of system configuration for all of the three flood events.

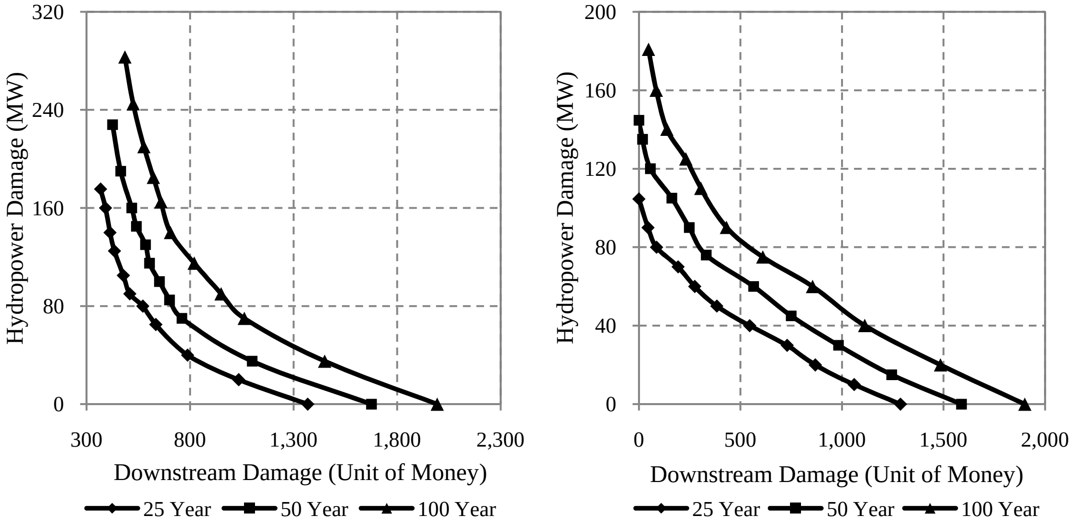

Figure 3. Pareto curves of two scenarios of system configurations. Left: Scenario of current situation –operation of two reservoir, Right: Scenario of developed situation - operation of all of six reservoirs.

As shown in Figure 3, the scenario of developed situation of reservoir system obviously provides better efficiency for flood control and hydropower generation. According to this Figure, just in scenario of developed situation of reservoir system, there are solutions with non-downstream damage, and even under this situation with increasing the intensity of flood event –flood event with return period 100 years- this solution is obtainable. Also, for both of scenarios, the slope of Pareto curve at the beginning is significantly sharper than other parts of curves that shows the necessities of accepting much greater hydropower generation damage for small values of downstream damage. However, this situation for second scenario –right curves- is less obvious, and the trend of efficient solution in this scenario is more smooth.

Planning for Flood Control Capacities

Determining the required flood control capacities of reservoirs for each efficient solution of Pareto curve maybe is the most practical result of the model. In fact, this result shows that how much empty storage as flood control capacity should be allocated for obtaining to a determined downstream and hydropower damage. Since, there are several efficient solutions, and the combination of flood control capacities is different for each one, here we show these result for three superior solutions -solution with minimum possible downstream damage, solution with maximum downstream solution (case without flood control capacities), and solution with moderate downstream damage. Tables 1 and 2 show these results for both of configuration scenarios.

Table 1 Required flood control capacities for three superior solutions of the Pareto curves of scenario of current situation and 50-year flood event

Reservoir	Downstream Damage (Unit of Money)		
	Minimum	*Moderate*	*Maximum*
	426	604	1,676
	Required Flood Control Capacity (MCM)		
Seymareh	629	158	0
Karkhe	295	784	0

Table 2 Required flood control capacities for three superior solutions of Pareto curves of scenario of developed situation and 50- year flood event

Reservoir	Downstream Damage (Unit of Money)		
	Minimum	*Moderate*	*Maximum*
	0	331	1,588
	Required Flood Control Capacity (MCM)		
Garsha	439	0	0
Koran Bozan	119	495	0
Sazbon	5	0	0
Seymareh	60	0	0
Tang M	139	0	0
Karkhe	176	327	0

The results show the significant role of Seymareh Reservoir in current situation and Garsha Reservoir in developed situation in flood control for obtaining the minimum downstream damage. However, with increasing the amount of downstream damage –the moderate downstream damage- these combinations were changed significantly. As, in the first scenario, the role of Karkheh Reservoir becomes more important, and in the second scenario, just Koran Bozan and Karkheh Reservoir require flood control capacity.

In addition to values of flood control capacities of reservoirs for obtaining a specific damage –both of downstream and hydropower- the operation policies during the flood event are important. Figure 4 shows such policies for Seymareh and Karkhe Reservoirs for the first scenario of system configuration. Despite of some minor differences, we can recognize a general shape in both reservoir storage and release curves. In the first part, the reservoirs try to evacuate the enough empty storage for storing the flood flow, so the storage of reservoir decreased rapidly and the pick flow of release occurred in this part. In second part, the storage of reservoir increases to maximum level, and in third part, the reservoir tries to regulate the flood flow and declines the value of release.

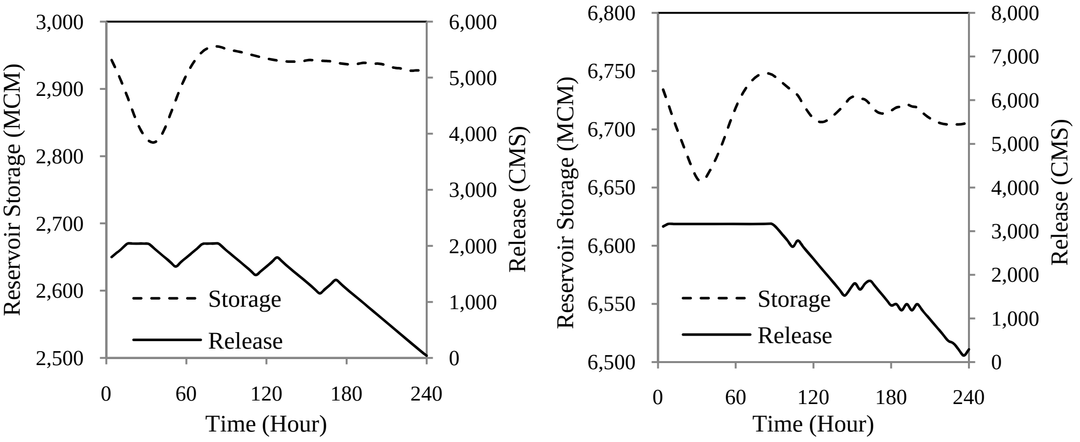

Figure 4 Reservoir storage and release curves for minimum downstream damage in the scenario of current situation and 50- year flood, Left: Seymareh reservoir; Right: Karkheh reservoir

CONCLUSION

A multiobjective, multireservoir MILP model has been developed for optimizing the downstream and hydropower generation damage simultaneously in reservoir flood control system and searching for the efficient solution of reservoir operations, Pareto curve. The resulting optimization model was solved by a commercially available solver. The methodology has been applied successfully to the reservoir flood control system of Karkheh river basin in two different scenarios of reservoir system configurations. Besides the providing the deep insights about different capabilities of multipurpose reservoir system for flood control, the results of model offer the required information for long-term and short-term operation of reservoir system. So, it can be used as a practical tool for evaluation, planning and operation of reservoir flood control systems.

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