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Nonstructural Flood Control using Multi-reservoir Operation

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ABSTRACT— *Nonstructural flood damage minimization through optimizing a short term multi-reservoir system operation is considered in this paper using a simulation-based optimization model. The well known evolutionary computation technique of particle swarm optimization (PSO) has been combined with a simulation model of river flood routing. The hydraulic routing model includes numerical solution of unsteady gradually varied flow equations by Preissmann method. The developed model has been used in a three-reservoir system as a real case study southwest of Iran. The results show applicability and efficiency of the proposed simulation-optimization model in determining optimal reservoir releases.*

Keywords— Multi-reservoir operation, Simulation, Optimization, Hydraulic flow routing, PSO

1. INTRODUCTION

Short term reservoir operation deals with making decisions for reservoir releases on future short time intervals from some minutes to a few hours. Simulation and optimization models have been widely used in solving this problem.

Some studies consider hydrologic river routing method as simulation model. Windsor [1] used recursive linear programming (LP) technique to determine optimal reservoir operation for a multi-reservoir flood control system. Yazicigil [2] developed an LP optimization model for daily operation of a single reservoir system with main purpose of flood control. Wasimi and Kitanidis [3] combined an optimization model and a flow routing model for daily operation of a multi-reservoir system under flooding conditions. Can and Houck [4] compared LP and goal programming (GP) models for hourly flood control operation of a multi-reservoir system. Loaiciga and Marino [5] developed a control-estimation model which used a state-space formulation consisting an unconstrained optimization technique. Karbowski [6] presented an analysis method for optimal flood control problem of cascade system of reservoirs. Niewiadomska-Szynkiewicz et al. [7] used predictive methods for hourly flood control operation in a river basin with the objective of peak flow minimization. Niewiadomska-Szynkiewicz and Napiorkowski [8] used CRS method to optimize multi-reservoir operation under flooding conditions. Goppert et al. [9] combined an optimization dynamic programming (DP) model for flood control in urban areas. Zagona et al. [10] and Biddle [11] used RiverWare simulation model for hourly optimization of multi-reservoir flood control operation with LP model. Cheng [12] developed a fuzzy optimization model for multi-reservoir flood control. Shim, K. C. and Shim, S. B. [13] presented a decision support system (DSS) for optimization of real time multi-reservoir operation using DP model. Needham et al. [14] used mixed integer linear programming (MILP) technique for flood control of a river basin. Shim K. C. [15] and Shim K. C. et al. [16] developed a DSS with different subsystems for integrated flood control of a multi-purpose multi-reservoir problem. Niewiadomska-Szynkiewicz [17, 18] presented a software package called flood control multi-reservoir water system (FC-MWS) for optimal operation of multi-reservoir systems under flooding conditions. Niewiadomska-Szynkiewicz [19] used two different types of optimization algorithms including controlled random search (CRS) and evolutionary strategy (ES) to reduce flood damages downstream of reservoir systems. Niewiadomska-Szynkiewicz et al. [20] used a computational technology named computing grids as a decision making tool for real time multi-reservoir operation under flooding conditions. Wei and Hsu [21] developed an MILP multi-purpose optimization model for hourly operation of a multi-reservoir system affected by tidal effects. Wei and Hsu [22] presented a real time optimization-simulation operation model to determine reservoir releases under flooding conditions. Choudhury [23] presented a weighted pre-emptive goal programming model formulation for coordinated reservoir operation including uncontrolled flows. Saavedra et al. [24] used shuffled complex evolution optimization algorithm to minimize downstream peak floods through operation of a two-reservoir system.

Some other studies concentrate on hydraulic river routing method as simulation model. Dysarz and Napiorkowski [25, 26] investigated flood control problem for a system of reservoirs using CRS optimization technique. Dessalegne et al. [27] used genetic algorithm (GA) optimization technique for solution of one-dimensional unsteady flow in order to optimize operation of cascade system of reservoirs. Napiorkowski and Dysarz [28] developed a DSS for flood control of a multi-reservoir system. Malekmohammadi et al. [29] developed a simulation-optimization model for flood management in river-reservoir systems. Malekmohammadi et al. [30] used ELECTRE-TRI method for ranking optimal solutions obtained by GA which has been developed for multi-objective operation optimization of a cascade system of reservoirs with flood control and water supply objectives. Bayat et al. [31] developed a simulation-optimization model to minimize spatial flood damages at downstream areas of a single-reservoir system by combining PSO optimization algorithm with simulation model of hydraulic flood routing.

Reviewing different studies on flood control operation of reservoirs show that many of them have concentrated on single-reservoir operation optimization, and a few of them which deal with multi-reservoir systems operation optimization employ hydrologic river routing methods. The goal of this study is to integrate the PSO evolutionary algorithm with a hydraulic river routing technique as the simulation model for short term optimal operation of multi-reservoir systems.

The structures of the proposed simulation-optimization model, its formulation, and the solution approach are explained in the next section. Then the results of application of the developed model in a real three-reservoir system are presented. Finally the paper ends up with summary and conclusions.

2. SIMULATION-OPTIMIZATION MODEL

Although simulation models can provide a more detailed representation of hydrosystems operations, yet they may not be efficient in determining the optimal system's design and operation. Simulation-optimization models linking an existing simulation model to optimization algorithms are advantageous; as they incorporate both simulation and optimization approaches. In a river-reservoir system under flooding conditions, a flow simulation model considering physical constraints of the system operation can be integrated with an optimization model, where the best set of reservoir releases as control variables is determined. That is to say, optimization algorithms are applied to decide about some controllable variables while simulation methods evaluate the system response for each combination of controllable variables. Therefore, short term reservoir operation optimization under flooding conditions can be formulated as combination of a simulation model, which simulates system hydraulics for known flood hydrographs and operation policies and a systematic search method which improves reservoir operations by optimizing release schedules or parameters of an operation policy so as to minimize flood damages.

2.1. Model formulation

The problem of optimal operation of river-reservoir systems deals with minimization of flood damages under constraints such as hydraulic physical rules and operational constraints on reservoir releases and water elevations at specified control points. The main components of an optimization model tackling this problem are the objective function and a set of constraints of the model.

The objective function is minimization of total flood damage that is a function of discharges and depths at damaging areas:

$$min\ FD\left((Q_p)_i,(y_p)_i\right) \quad , \quad i=1,...,n_d \tag{1}$$

where FD is total flood damage, $(Q_p)_i$ and $(y_p)_i$ are respectively the peak discharge and depth at damage point i and n_d is the total number of damage points.

Model constraints are designated in two categories: hydraulic and operational. Hydraulic constraints, defined as hydraulic equations considered in flow routing models, represent flow in the system. Hydraulic routing constraints are full dynamic one-dimensional equations of unsteady gradually varied flow (Saint-Venant equations), including continuity and momentum equations in all computational reaches and also continuity equation in the reservoir which is a relationship between inflow to the reservoir, releases from it and the resulting change in its storage volume. Hydraulic constrains can be expressed as follows:

$$f_{routing}(I_{j,t},R_{j,t},y_{x,t},Q_{x,t},\partial Q_{x,t}/\partial x,\partial Q_{x,t}/\partial t,\ldots)=0 \tag{2}$$

$$S_{j,t+1}=S_{j,t}+\Delta t\,(I_{j,t}-R_{j,t}) \tag{3}$$

where $I_{j,t}$ and $R_{j,t}$ are respectively inflow to and release from reservoir j of cascade system of reservoirs; $y_{x,t}$

and $Q_{x,t}$ are flow depths and discharges at different spaces and times. These variables and their partial derivatives with respect to space *x* and time *t* are interrelated through a nonlinear function f . $S_{j,t}$ and $S_{j,t+1}$ are two successive values of storage volume for reservoir *j*.

Operational constraints are inequalities describing variables ranges, operational purposes, capacities, etc. , as follows:

$$R_{j,\min} \le R_{j,t} \le R_{j,\max} \;,\; \left|R_{j,t+1} - R_{j,t}\right| \le \Delta R_j \;,\; S_{j,\min} \le S_{j,t+1} \le S_{j,\max} \qquad (4)$$

where $S_{j,\min}$ and $S_{j,\max}$ are respectively minimum and maximum bounds for storage volume at *j*th reservoir. Similarly, $R_{j,\min}$ and $R_{j,\max}$ are minimum and maximum bounds for releases from reservoir *j*, respectively. ΔR_j is the maximum allowable difference between two successive releases from reservoir *j*.

The simulation model performs flow routing in the river through a hydraulic routing model. Although hydrologic methods are generally simple and fast, they may not be enough in some specific situations. For instance backwater flow conditions occur when a flood passes a river tributary where a precise estimation of flow movement cannot be obtained by hydrologic routing methods. Distributed hydraulic flow routing may be used because of the ability to compute flow discharge and depth variations in time and space, as precise estimation of damage due to a flood can depend on both temporal and spatial distributions of flow discharge and depth. Hydraulic routing methods are based on solving equations of unsteady flow in open channels. The principle equations are continuity and momentum equations known as Saint-Venant equations. Preissmann method [32], as an implicit finite difference scheme, is used in this study in order to solve the equations.

Since the structure of the model in the present paper is the integration of a flow simulation model with an optimization algorithm, PSO [33], as a meta-heuristic population based global optimization technique, is used in this study. The PSO has proven to be a fast converging algorithm compared to other global optimization techniques like genetic algorithms [34]. It has been successfully applied in a number of water resources applications such as basin-scale optimal water allocation [35, 36, 37], optimal hydropower systems design and operation [38], multiobjective reservoir operation [39], storm water network design [40], optimal design of cascade stilling basins [41], optimal operation of single-reservoir flood control systems [31]. Existence of local optima could adversely affect the quality of PSO solutions. The "Function stretching technique" [34] has been used in this study to assist the PSO algorithm avoid local optima.

This study uses the PSO algorithm linked to hydraulic flow routing model for short term optimal operation of river-reservoir systems.

2.2. Solution procedure

Some hydraulic constraints of simulation-optimization model related to hydraulic flow routing in the river (simulation model) are satisfied implicitly; while operational constraints and reservoir continuity equation (as a hydraulic constraint) are considered explicitly by the PSO algorithm.

First, optimization model generates randomly a set of decision variables (reservoir releases) which are used in the simulation model, where flow discharges and depths at control damage points are calculated by solving hydraulic routing equations. The objective function of the optimization model can be evaluated based on what calculated by the routing model. Then another set of decision variables is generated through evolutionary equations of the PSO. This procedure is repeated until one of the predefined termination criteria are met, which are: 1) a certain predefined iteration number and 2) values from the best objective function stop improving over some iterations.

3. APPLICATION

The model explained has been applied in optimization of multi-reservoir operation of a cascade system of reservoirs southwest of Iran. The problem is a part of a dam-break study project on Dez and Karun river-reservoir systems as the most important surface water resources in Iran. The three-reservoir system consists of Upper Gotvand (UG), Godar Landar (GL) and Karun1 (KR1) dams on Karun river. Great Karun is the largest river in Iran with an 800-kilometer length originating from the Zagros mountains and flowing northeast to southwest toward the Persian Gulf. The main tributary of Karun is Dez river which intersects with Karun at some point north of Ahwaz city. The most downstream (UG) dam site is located in Khuzestan province, 30 kilometers from Shushtar city and 12 kilometers from Gotvand city. The damaging areas are located downstream of UG dam. In figure 1, a schematic representation of the whole study area and Karun river-reservoir system is presented. Table 1 shows the main characteristics of existing reservoirs.

Table 1: Some characteristics of existing dams

Dam	Height (m)	Minimum Storage Volume (MCM)	Initial Storage Volume (MCM)	Maximum Storage Volume (MCM)
UG	180	1290	4097	5177
GL	177	180	211	268
KR1	200	1675	3143	3580
DEZ	203	1116	4228	4450

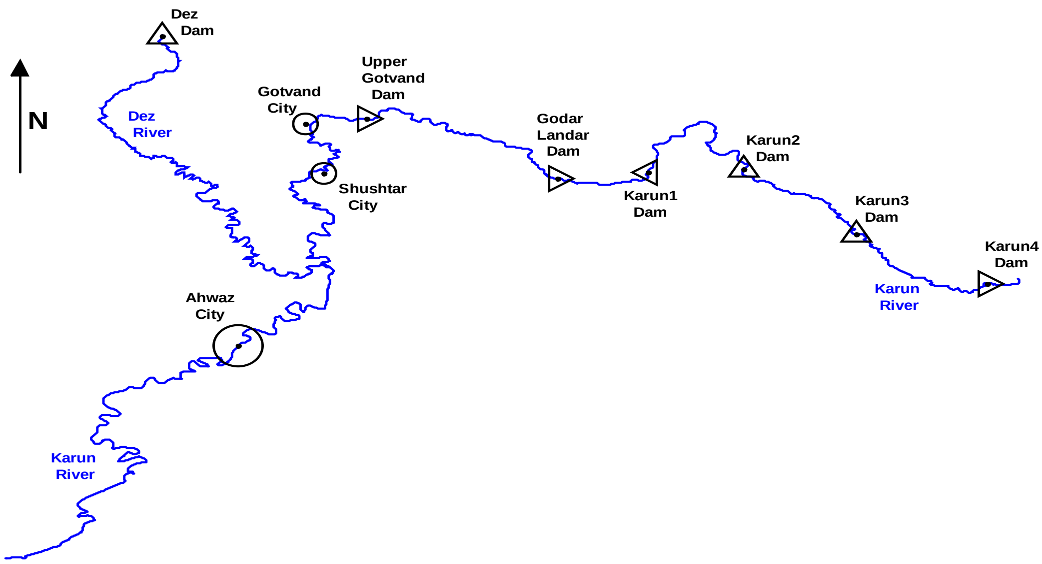


Figure 1: Schematic representations of Karun river-reservoir system

Since GL dam is of run-of-river type with a small storage capacity, no direct controllable releases as independent decision variables need to be considered. So the focus of this study is on developing a framework for determining optimal reservoir releases for UG and KR1 cascade dams under flooding conditions to minimize downstream flood damages. Furthermore, optimal releases from Dez reservoir as a single-reservoir operation optimization problem which results in lateral flow hydrograph into Karun river downstream of UG dam between Shushtar and Ahwaz cities has been considered. Releases from UG reservoir are routed in Karun river in order to determine depths and discharges at damage points and the resulting flood damages according to estimated damage functions.

The flood damage function used is a function of combination of flow depths and durations at damage points as well as the river safe discharge as follows:

$$min\ FD = \sum_{i=1}^{n_d} FD_1\left(y_{i,t}\right) + \sum_{j=1}^{n_x}\left((Q_p)_j - Q_S\right) \qquad (5)$$

where FD_1 is the flood damage function, n_d is number of damage points (figure 2), $(Q_p)_j$ is peak discharge at *j*th node of river reach, n_x is total number of river reach nodes and Q_S is the river safe discharge, which is equal to 6000 m^3/s in the area under study (Water Research Institute 2010). Evaluation of the total flood damage requires calculating flow depths and discharges at different damaging points in all time steps during floods.

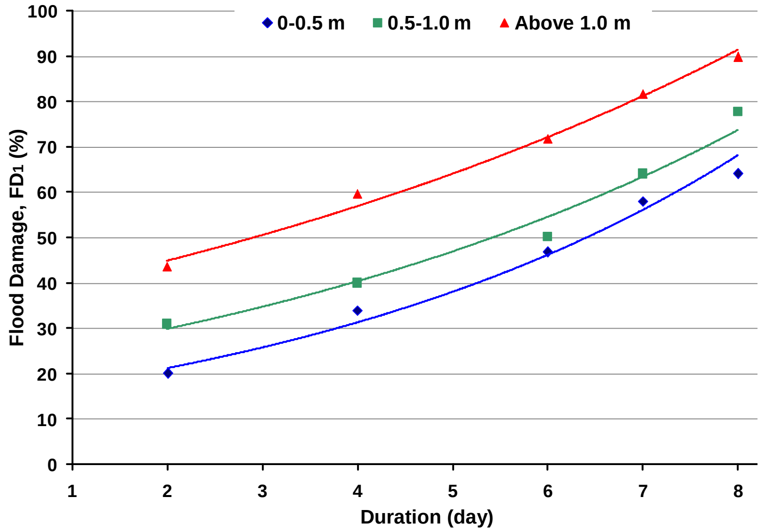


Figure 2: Flood damage function as a function of flow depth and its duration [42]

Figures 3 and 4 show storage vs. elevation and storage vs. release capacity (rating) curves for existing dams, respectively. Flood hydrographs with base time of 150 hours and 10000 years of return period estimated by flood frequency analysis [43] has been considered as inflow hydrographs to KR1 and Dez reservoirs.

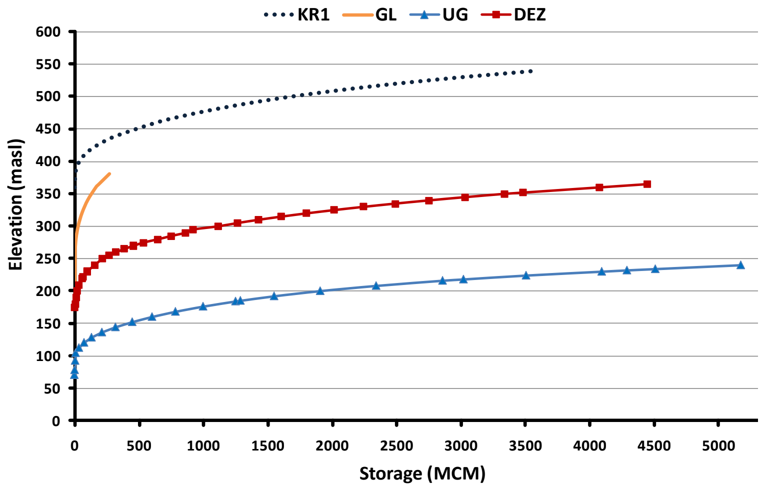


Figure 3: Storage vs. elevation curves of existing dams

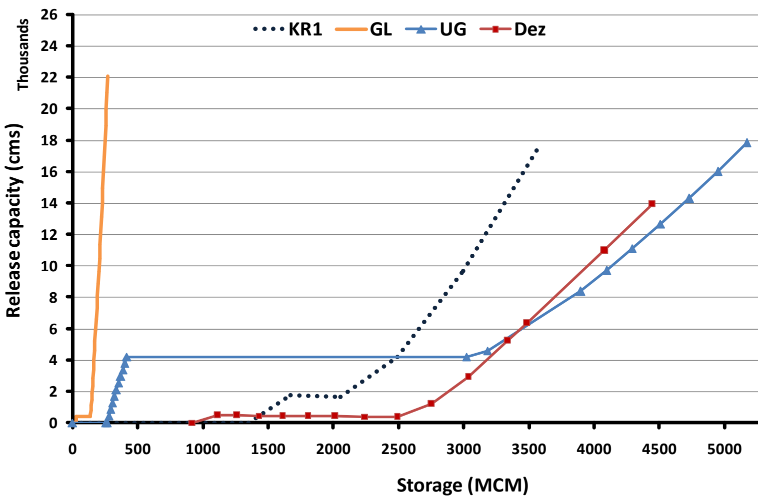


Figure 4: Outflow capacity curves of existing dams

Releases from Dez reservoir in single-reservoir problem and from KR1 and UG reservoirs in multi-reservoir problem are considered as decision variables and flow depths and discharges at damage points and river nodes computed by the hydraulic routing model are state variables. According to a parametric representation of hydrographs of reservoir releases for KR1 and UG dams, a total number of 16 variables (8 variables for each reservoir) are to be optimized.

The single-reservoir problem should be solved, first and the resulting optimal releases from Dez reservoir would be routed in Dez river to obtain flow hydrograph at junction with Karun river. Figure 5 shows inflow and best outflow hydrographs of Dez reservoir and associated routed flow hydrograph at intersection with Karun river.

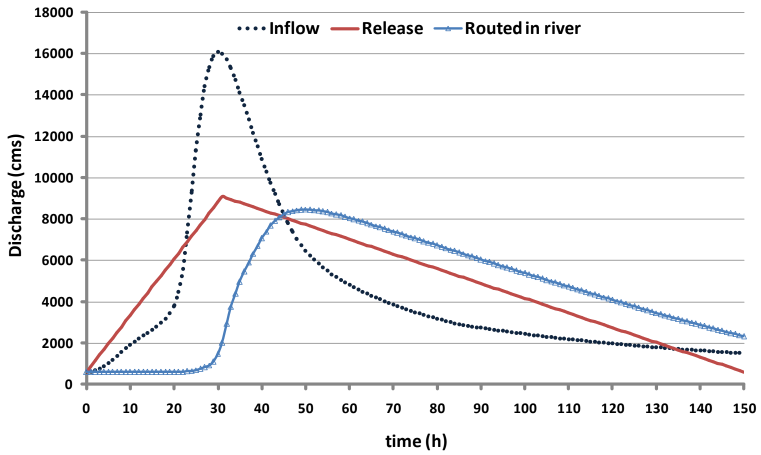


Figure 5: 10000-year inflow flood hydrograph compared to optimal reservoir release hydrograph at Dez dam and routed hydrograph at intersection with Karun river

Results are presented in figures 6 and 7. Figure 6 shows the known inflow flood hydrograph to KR1, the most upstream reservoir and optimum releases from KR1 and UG reservoirs obtained by the simulation-optimization model. Releases from KR1 flow directly into GL reservoir and releases from GL are obtained after reservoir routing considering reservoir constraints. Releases from GL are considered as inflow to UG reservoir with the same manner and releases from UG go through the downstream river reach to be routed hydraulically in order to estimate flood damages at damaging areas. Figure 7 shows the storage volumes variations at different reservoirs during the flood period. As can be seen, all of reservoirs have benefited from their maximum storage capacity in decreasing peak flows of flood hydrographs especially peak releases from UG dam.

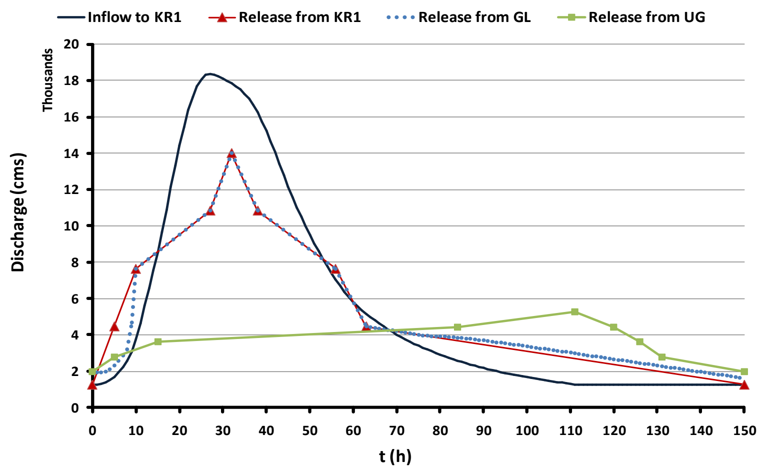
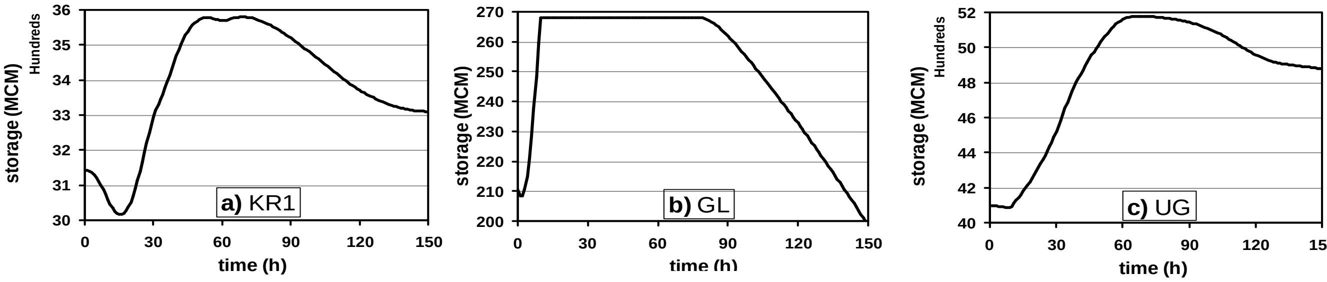


Figure 6: 10000-year inflow flood hydrograph to KR1 dam and optimal releases from KR1 and UG reservoirs and simulated releases from GL



When the incoming flood volume to KR1 reservoir begin to increase, releases from the reservoir will increase too in order to reduce the flood peak flowing into the downstream reservoir. After the peak flow passes, discharges decrease (at hour 27) with a peak attenuation of about 24 percent and a translation time equal to 5 hours. It is of interest to note that the rate of decrease in reservoir releases is less than that in inflow (especially between hours 38-56) in order to use flood control volume as much as possible. This trend continues until the storage volume reaches the maximum allowable storage volume (at hour 68). Then the decrease rate of releases is tuned in such a way that reservoir's flood control volume is depleted for future flood control purposes.

The release hydrograph from GL which is almost the same as its inflow hydrograph flows directly into UG reservoir and the response of this reservoir to the incoming flood hydrograph is almost the same as KR1 in decreasing flood discharges. Comparing inflow and optimal release hydrographs, one can see a peak flow attenuation of 62 percent with a translation time of 79 hours. These significant values at UG reservoir compared to those at KR1 (24 percent and 5 hours, respectively) is due to larger flood control volume of UG reservoir, which is almost 2 times larger.

The simulation-optimization model has presented a solution which has a great decrease in flood damage values compared to its first evaluations based on randomly generated solutions by PSO (figure 8); so the model has a good efficiency in minimizing flood damages and preparing optimal operation of the multi-reservoir systems.

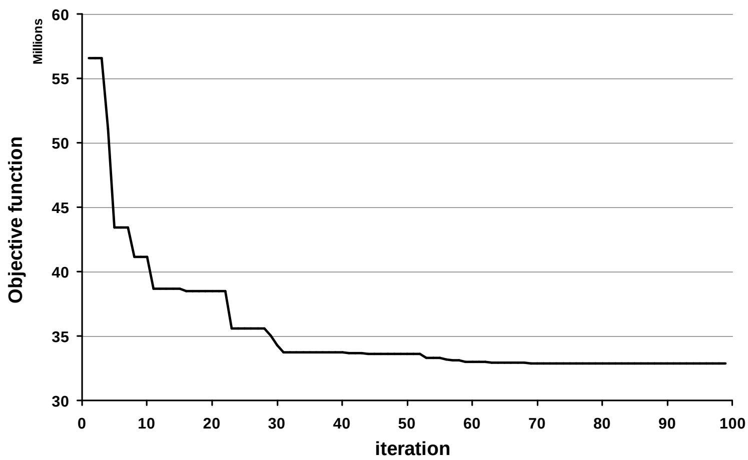


Figure 8: Objective function values of the g-best solution at different iterations of PSO model

4. SUMMARY AND CONCLUSIONS

In this study, a simulation-optimization model was presented for optimizing multi-reservoir systems operation under flooding conditions, in which PSO evolutionary algorithm was linked to a hydraulic river routing simulation model.

At first, the simulation-optimization model structure, formulation and solution procedure were explained. Then the multi-reservoir model was applied in a three-reservoir system including KR1, GL and UG Dams built on Karun River located in southwest of Iran. A single-reservoir optimization model was firstly applied to determine optimal release hydrograph from Dez reservoir which was routed then as a lateral flow hydrograph into Karun river.

Optimization of the multi-reservoir system operations led to significant decreases in peak flows of flood hydrographs releasing from the reservoirs (24 and 62 percent of peak attenuation and 5 and 79 hours of peak translation at respectively KR1 and UG reservoirs). This shows the importance of optimizing coordinated short term operation of multi-reservoir systems in flood damage reduction studies.

The reservoir operation can be accomplished by operators through tuning the openings of different outlet structures of dams such that reservoir storage volume at every time gets to optimal storage volume based on the model results. Using a forecast-based approach in which forecasts on future inflows are made for the model to be applied in real time reservoir operations is an aspect which should be considered in future studies.

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6. REFERENCES

[1] Windsor, J. S. Optimization model for the operation of flood control systems, Water Resources Research, 9: 1219-1226, 1973.

[2] Yazicigil, H. Optimal operation of a reservoir system using forecasts, Ph.D. Dissertation, Purdue University, West Lafayette, 1980.

[3] Wasimi, S. A. and Kitanidis, P. K. Real-time forecasting and daily operation of a multi-reservoir system during floods by linear quadratic Gaussian control, Water Resources Research, 19: 1511-1522, 1983.

[4] Can, E. K. and Houck, M. H. Real-time reservoir operations by goal programming, Journal of Water Resources Planning and Management, ASCE, 110: 297-309, 1984.

[5] Loaiciga, H. and Marino, M. An approach to parameter estimation and stochastic control in water resources with an application to reservoir operation, Water Resources Research, 21(11): 1575–1584, 1985.

[6] Karbowski, A., Optimal flood control in multi-reservoir cascade systems with deterministic inflow forecasts, Water Resources Management, 7: 207-223, 1993.

[7] Niewiadomska-Szynkiewicz, E., Malinowski, M. and Karbowski, A. Predictive methods for real-time control of flood operation of a multi-reservoir system: methodology and comparative study, Water Resources Research, 32 (9): 2885–2895, 1996.

[8] Niewiadomska-Szynkiewicz, E. and Napiorkowski, J. Application of global optimization methods to operational control of multi-reservoir systems, 3rd International Conference on Hydro-Science and Engineering (ICHE), Brandenburg University of Technology at Cottbus, Germany, 1998.

[9] Goppert H., Ihringer, J., Plate, E.J. and Morgenschwei, G. Flood forecast model for improved reservoir management in the Lenne River catchment, Germany, Hydrological Sciences-Journal-des Sciences Hydrologiques, 43(2): 215-242, 1998.

[10] Zagona, E. A., Fulp, T. J., Goranflo, H. M. and Shane, R. M. RiverWare: A general river and reservoir modeling environment., Proc. 1st Federal Interagency Hydrologic Modeling Conf., 113–120, 1998.

[11] Biddle, S. H. RiverWare applications at TVA., Proc. ASCE Water Power Conference, ASCE, Reston, Va. , 1999.

[12] Cheng, C. Fuzzy optimal model for the flood control system of the upper and middle reaches of the Yangtze River, Hydrological Sciences, 44(4): 573-582, 1999.

[13] Shim, K. C. and Shim, S. B. Optimal predictive flood control for river-reservoir operation system, Proceedings (Abstract Volume) of the XXVIIIth IAHR Congress, p. 435, Paper on CD ROM, Graz, 1999.

[14] Needham, J., Watkins, D., Lund, J. and Nanda, S. Linear programming for flood control on the Iowa and Des Moines Rivers., Journal of Water Resources Planning and Management, ASCE, 126(3): 118–127, 2000.

[15] Shim, K. C. Spatial decision support system for integrated river basin flood control, Ph.D. Dissertation, Dept. of Civil Engineering, Colorado State Univ., Ft. Collins, Colo. , 1999.

[16] Shim, K. C., Fontane, D. G. and Labadie, J. W. Spatial decision support system for integrated river basin flood control, Journal of Water Resources Planning and Management, ASCE, 128(3): 190–201, 2002.

[17] Niewiadomska-Szynkiewicz, E. Software environment for simulation of flood control in multiple-reservoir systems, 5th International Conference on Hydro-Science and Engineering (ICHE), Faculty of Environmental Engineering, Warsaw University of Technology, 2002.

[18] Niewiadomska-Szynkiewicz, E. FC-MWS: A software environment for flood operation in multi-reservoir systems,

Acta Geophysica Polonica, 52(1): 91-103, 2004b.

[19] Niewiadomska-Szynkiewicz, E. Computer simulation of flood operation in multi-reservoir systems, Simulation, 80(2): 101-116, 2004a.

[20] Niewiadomska-Szynkiewicz, E., Karpowicz, Michal and Kozakiewicz, A. Application of grid technologies to multi-reservoir systems management during flood, Acta Geophysica Polonica, 53(4): 473-485, 2005.

[21] Wei, C.-C. and Hsu, N.-S. Multi-reservoir Flood-Control Optimization with Neural-Based Linear Channel Level Routing Under Tidal Effects, Water Resources Management, 22: 1625-1647, 2008a.

[22] Wei, C.-C. and Hsu, N.-S. Multi-reservoir real-time operations for flood control using balanced water level index method, Journal of Environmental Management, 88: 1624-1639, 2008b.

[23] Choudhury, P. Reservoir flood control operation model incorporating multiple uncontrolled water flows, Lakes & Reservoirs: Research and Management 15: 153–163, 2010.

[24] Saavedra Valeriano, O., Koike, T., Yang, K. and Yang D. Optimal dam operation during flood season using a distributed hydrological model and a heuristic algorithm, Journal of Hydrological Engineering, ASCE, 15: 580-586, 2010.

[25] Dysarz, T. and Napiorkowski, J.J. Determination of reservoir decision rules during flood, Acta Geophysica Polonica, 50(1): 135-149, 2002a.

[26] Dysarz, T. and Napiorkowski, J.J. Global optimization method for determination of reservoir decision rules during flood, 5th International Conference on Hydro-Science and Engineering (ICHE), Faculty of Environmental Engineering, Warsaw University of Technology, 2002b.

[27] Dessalegne, T., Nicklow, J. and Minder, E. Evolutionary computation to control unnatural water level fluctuations in multi-reservoir river systems, River Research and Applications, 20: 619–634, 2004.

[28] Napiorkowski , J.J. and Dysarz, T. Decision Support System for flood control in transboundary Nysa Klodzka catchment, Integrated Water Management of Transboundary Catchment-A Contribution from TRANSACT, Conference Proceedings, Venice, Italy, 24-26 March, 2004.

[29] Malekmohammadi, B., Zahraie, B. and Kerachian, R. A real-time operation optimization model for flood management in river-reservoir systems, Journal of Natural Hazards, 53: 459-482, 2010.

[30] Malekmohammadi, B., Zahraie, B. and Kerachian, R. Ranking solutions of multi-objective reservoir operation optimization models using multi-criteria decision analysis, Expert Systems with Applications, 38: 7851–7863, 2011.

[31] Bayat, B., Mousavi, S. J. and Montazeri Namin, M. Optimization-simulation for short-term reservoir operation under flooding conditions, Journal of Water Supply: Research and Technology-AQUA, 60.7: 434-447, 2011.

[32] Cunge, J.A., Holly F.M. and Verwey, A. Practical aspects of computational river hydraulics, Pitman publishing Inc. 1980.

[33] Eberhart, R. C., Simpson, P. and Dobbins, R. Computational intelligence PC tools, Academic Press, 1996.

[34] Parsopoulos, K. E. and Vrahatis, M. N. Recent approaches to global optimization problems through particle swarm optimization, Natural Computing, 1: 235-306, 2002.

[35] Shourian, M., Mousavi, S. J., Menhaj, M. and Jabbari, E. Neural network-based simulation-optimization model for optimal water allocation planning at basin scale, Journal of Hydroinformatics, IWA, 10(4): 331-343, 2008a.

[36] Shourian, M., Mousavi, S. J. and Tahershamsi, A. Basin-wide water allocation planning by integrating PSO algorithm and ModSim, Journal of Water Resources Management, 22(10): 1347-1366, 2008b.

[37] Mousavi, S.J. and Shourian, M. Adaptive sequentially space filling meta-modeling for optimal water-quantity allocation at basin scale, Water Resources Research, vol. 46, W03520, doi: 10.1029/2008WR007076, 2010a.

[38] Mousavi, S. J. and Shourian, M. Capacity optimization of hydropower storage projects using particle swarm optimization algorithm, Journal of Hydroinformatics, IWA, 12: 275-291, 2010b.

[39] Baltar, A. M. and Fontane, D. Use of Multiobjective Particle Swarm Optimization in Water Resources Management, Journal of Water Resources Planning and Management, 134 (3): 257-265, 2008.

[40] Afshar, M.H. Rebirthing particle swarm optimization algorithm: application to storm water network design, Can. J. Civ. Eng. 35(10): 1120–1127, 2008.

[41] Bakhtyar, R. and Barry, D.A. Optimization of cascade stilling basins using GA and PSO approaches, Journal of

Hydroinformatics, 11(2): 119-132, 2008.

[42] Duttaa, D., Herath, S. and Musiake, K. A mathematical model for flood loss estimation, Journal of Hydrology, 277, pp24–49, 2003.

[43] Water Research Institute Report on dam break studies on Dez, Karun and Karkheh river-reservoir systems, 2010.