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Comparison of Different Reservoir Models for Short Term Operation of Flood Management

Gokcen Uysal[a,*], Bulut Akkol[a], M. Irem Topcu[a], Aynur Sensoy[a], Dirk Schwanenberg[b,c]

[a] *Civil Engineering, Anadolu University, 2 Eylul Campus, Faculty of Engineering, Eskisehir, 26555, Turkey*
[b] *Institute of Hydraulic Engineering and Water Resources Management, University of Duisburg-Essen, 45141, Germany*
[c] *Deltares, Operational Water Management, Rotterdamseweg 185, Delft, 2629HD, The Netherlands*

Abstract

Short-term operation of reservoir systems is challenging due to conflicting objectives and constraints as well as the need for taking robust decisions in real-time. This study compares simulation and optimization based decision support techniques in application to the mitigation of flood events. Two models are employed in the study to support the operators' decisions: (1) HEC-ResSim of USACE as a representative of a simulation-based approach, and (2) the RTC-Tools package of Deltares with an optimization approach. The methods are applied to a complex flood management problem at Yuvacik Dam, Turkey. A worst case scenario of an extreme flood event is used to evaluate the pros and cons of the models including a high initial water level exceeding the flood control pool. Objectives of the control are the maximization of water supply benefits, i.e. a full reservoir, at the end of the event as well as flood mitigation in the downstream river reach. In the first method, a script-based rule is defined in the GUI with user access to its parameters. The refinement of the reservoir operation is conducted manually by trial and error. Secondly, an optimization approach using Model Predictive Control (MPC) is used in combination with the IPOPT optimizer. The advantage of HEC-ResSim is the detailed representation of the gate management on the level of the individual gates. However, the implementation of the total release is partially up to user interaction and not necessarily optimal. RTC-Tools provides optimum releases on the project level, but not on the level of individual gates. Both approaches consider system constraints. Furthermore, an advantage of the optimization approach is its extension to probabilistic ensemble forecasts to consider forecast uncertainty in the decision by use stochastic optimization.

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* Corresponding author. Tel.: +90-222-321-35-50/6623; fax: +90-222-323-95-01.
E-mail address: gokcenuysal@gmail.com

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1. Introduction

Freshwater is getting scarce due to the rapidly increasing world population, hence effective management of water resources is becoming one of the most important issues in this era [1,2,3]. Reservoirs are important structures that store and release water based on decisions made by system operators [4]. Short term optimal operation of reservoir systems is a challenging task since the problem deals with many complicated variables such as inflows, storages, inter/intra-basin water transfers, flood protection, irrigation, industrial and/or municipal water supply demands and related uncertainties. Planning models incorporate a long-term operation policy in order to decide the size, location and number of reservoirs whereas operation models evaluate the short-term, event-based management of existing infrastructure in combination with hydrological forecasts. In a reservoir system, the objective of operation/planning is to maximize benefits, minimize costs, meeting various water demands, subject to mass balance equation and other related constraints. Once a reservoir system is planned, evaluations should be made to ensure that the system's performance fulfills actual water demands, which may change over time.

In a reservoir system, important features associated with operation models that make a problem computationally hard to solve are uncertainty, conflicting objectives and inclusion of nonlinear functions, such as hydropower generation, evaporation and other losses. Simulation models help to answer what if questions for user-defined alternative operational strategies and still stand a noticeable tool for reservoir systems [5,6,7,8]. Along with the rise of operational forecasting and management systems, new methodologies such as Model Predictive Control (MPC) receive growing attention in terms of optimization approaches. MPC is successfully applied to water resources: open channels [9], water systems [10], branching canals [11], flood problems [12], reservoir operation [13,14]. Key elements of MPC are [15]: (1) a model of the physical process to predict future trajectories of system states over a finite control horizon, (2) the calculation of a control sequence that optimizes an objective function, and (3) a receding horizon strategy. Two models are employed in the study to support the operators' decisions: (1) the Hydrologic Engineering Center – Reservoir Simulation System (HEC-ResSim) of the U.S. Army Corps of Engineers (USACE) as a representative of a simulation-based approach, and (2) the RTC-Tools package of Deltares with MPC optimization approach. The main aim of this paper is to discuss simulation and optimization based decision support techniques in application to the interactive mitigation of flood events and highlight their pros and cons.

2. Pilot Case: Yuvacık Reservoir

In this study, we focus on the implementation of short term decision-support for the flood management of Yuvacık Dam reservoir located in Turkey (Figure 1). The earth-filled dam constructed in 1999 is 108 m high with an effective storage capacity of approximately 51.2 hm^3 at maximum operating level of 169.30 m. A volume of 14.60 hm^3 is kept behind the radial gates; a volume of 36.60 hm^3 is stored between spillway crest elevation of 159.95 m and minimum operation level of 112.50 m. The operational elevations which are directly used in the reservoir system modeling are as illustrated in Figure 1. A Dam Management System (DMS) has been developed as a part of a Supervisory Control and Data Acquisition (SCADA) system by the reservoir operators. It provides data collection and transmission from automatic gauges.

Although we consider only a single reservoir, operation of the dam reservoir is complex due to its multi-purpose characteristics. The reservoir is operated for two main objectives: (i) water supply and (ii) flood control downstream of the dam. Yuvacık Dam Reservoir is designed to provide 142 hm^3 of drinking and domestic water annually for 1.5 million people of Kocaeli City in Turkey. Storage capacity of the reservoir is relatively limited concerning the average annual inflow potential of 180 hm^3. There is a 12 km length downstream channel which passes from a narrow valley near a rural district and flows into the Marmara Sea after a sharp curvature by a manmade channel next to industrial and urban areas. The maximum amount of water to be released during daily operation is set as 100

– 200 m^3/s by the regional water authority taking the drainage discharge conditions of the downstream canal into consideration.

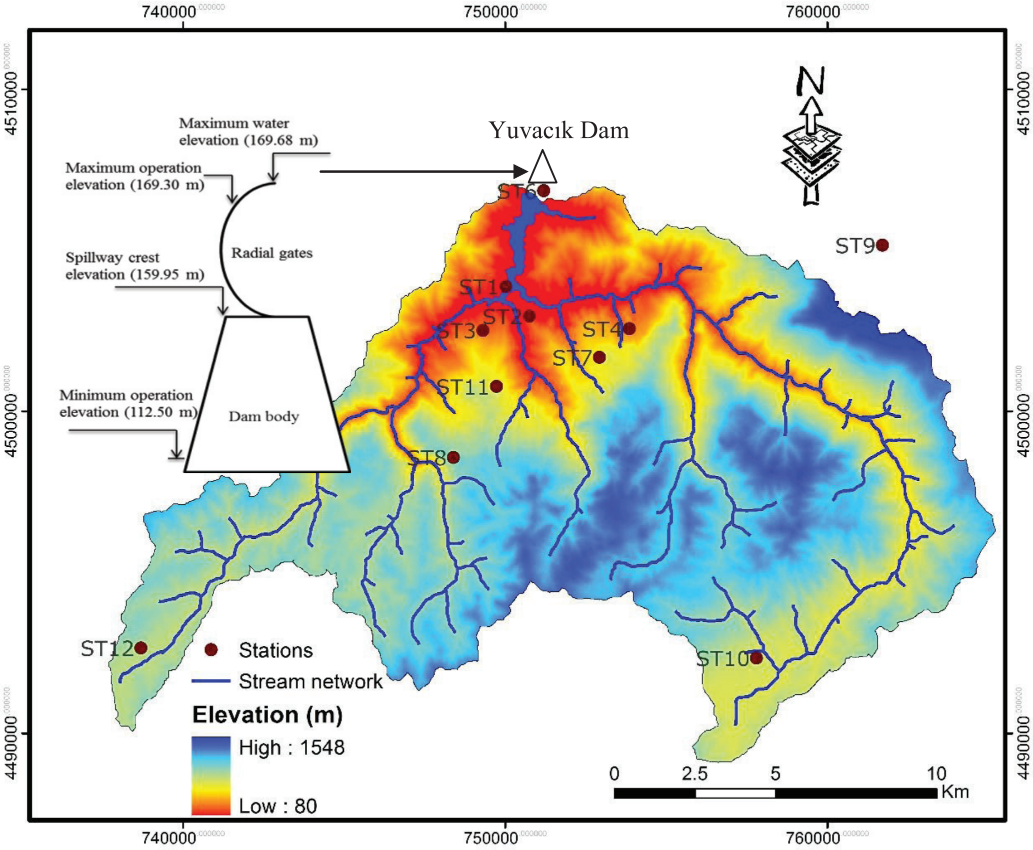

Fig. 1. Yuvacık Basin DEM, station network and critical elevations of the dam

3. Methodology and Application

The terms reservoir/river system, reservoir operation, or river basin management "modeling system" are used synonymously to refer to computer modeling systems that simulate the storage, flow, and diversion of water in a system of reservoirs and river reaches [16]. Two models are employed in the study to support the operators' decisions: (1) the Hydrologic Engineering Center – Reservoir Simulation System (HEC-ResSim) of the U.S. Army Corps of Engineers (USACE) as a representative of a simulation-based approach, and (2) the RTC-Tools package of Deltares with an optimization approach. For both models, the success criteria of short term operation are; (1) to avoid flood risk for downstream channel with the scenario flood hydrograph, (2) to achieve the initial daily level again at the end of the event (to turn back daily operation strategy).

The effective management of Yuvacık Dam Reservoir is directly related with the appropriate operation of water stored behind the radial gates. In the early history of the dam, Rao et al. [17] generated monthly Rule Curves (RCs) using Stochastic Dynamic Programming (SDP) optimization technique with Artificial Neural Network (ANN) and derived monthly Flood Control Levels (FCL) for monthly operation of Yuvacık Dam. Since daily strategies for water supply force storage in the reservoir always to be at the maximum water level which is in conflict with flood control strategies, these Rule Curves cannot be used solely in short-term operations. Uysal et al. [8] re-evaluated the present regulation of the dam with interactive involvement of decision makers in system development. Daily hydro-meteorological rule-based reservoir simulation model (HRM) and hourly flood control rule-based reservoir simulation model (FRM) were developed for flood risk and water supply purposes. In order to ensure both flood control and efficient water supply, three regulation periods were defined as; Pre-flood season (from 01 October to 28 February), Main flood season which is separated into Main flood-1 (from 01 March to 20 April) and Main flood-2 (from 01 April to 31 May) and Post-flood season (from 01 June to 31 September). In this study, a worst case scenario during Main flood-2 season is tested with two different method (simulation and optimization) using a hypothetical event (scaled up version of observed data) for flood mitigation. Meanwhile, this study is considered an alternative method investigation to FRM.

Elevation – area – volume curves that relate storage capacity to elevation and elevation – discharge curves for controlled outlets (spillway and intake) are introduced into models. Four controlled radial gates are defined by their discharge curves in the reservoir models. Beside the physical data of the reservoir, initial reservoir levels (from HRM approach), water supply flow, inflow, and evaporation data are also provided as input to the reservoir models.

3.1. Simulation model - HEC-ResSim

Alternative executions of a simulation model are conducted to analyze the performance of the system under varying conditions, such as alternative operating policies [18]. The simulation model HEC-ResSim 3.0 [19] is selected to tackle the interaction between storage calculation and operational decisions. It is used for research in water resources management to explore the link between decisions support system and reservoir simulation. Software and documentation are available free of charge and can be downloaded from HEC's internet page [20]. Equation (1) shows the mass balance or quantity equation for reservoirs.

$$S_j = S_{j-1} + I_j + R_j^1 - R_j^2 - R_j^3 - E_j \tag{1}$$

where S_j = the reservoir storage; S_{j-1} = the reservoir storage; I_j = the total volume of inflow into the reservoir; $R^1{}_j$ is the total volume of water supply flow; $R^2{}_j$ = the total volume of spillway release; $R^3{}_j$ = the total volume of environmental flow; E_j = the volume of evaporation, j = the time index.

Reservoir simulation model is applied to determine the magnitude and timing of spillway discharges depending on the future flood volume in advance. To that end, water supply and downstream channel capacities are defined by "maximum release rules". The constraint between consecutive spillway releases are introduced by "rate of change rules". Besides, several prescriptive rules in ResSim, a user-defined scripting is available that dramatically increases the flexibility of reservoir operations. In simulation modeling, a script-based rule is defined in the GUI with user access to its parameters. The refinement of the reservoir operation is conducted manually by trial and error. The details of this approach are described by Uysal et al. [8].

3.2. Optimization model - RTC-Tools

Contrary to the first approach, the decision variable is defined by the optimization, and not by the feedback rules. The RTC-Tools package of Deltares works with an optimization approach based on Model Predictive Control (MPC). It consider a discrete-time dynamic system according to Equations 2 and 3,

$$x^k = f(x^{k-1}, x^k, u^k, d^k) \tag{2}$$

$$y^k = g(x^k, u^k, d^k) \tag{3}$$

where *x*, *y*, *u*, *d* are respectively the state, dependent variable, control and disturbance vectors, and *f*(), *g*() are functions representing an arbitrary linear or nonlinear water resources model.

If being applied in MPC, Equations (2,3) are used to predict future trajectories of the state x and dependent variable y over a finite time horizon represented by $k = 1, ...,N$ time instants, to determine the optimal set of control variables u by an optimization algorithm. Under the hypothesis of knowing the realization of the disturbance d over the time horizon, for example the inflows into the reservoir system, the nonlinear MPC problem becomes:

$$\min_{\substack{u,x^* \\ u}} \sum_{k=1}^{N} J(x^k(u), y^k(x,u), u^k) + E(x^N(u), y^N(x,u), u^N) \tag{4}$$

$$\text{subject to } h(x^{*,k}(u), y^k(x,u), u^k, d^k \leq 0, k = 1,..., N \tag{5}$$

$$x^{*,k} - f(x^{*,k-1}, x^k, u^k, d^k) = 0 \tag{6}$$

where $J()$ is a cost function associated with each state transition, $E()$ is an additional cost function related to the final state condition, and $h()$ are hard constraints on control variables and states, respectively. The notation x^* refers to a subset of state variables which become independent optimization variables. In this case, the related process model becomes an equality constraint of the optimization problem.

For performance reasons and if the control variables are continuous, nonlinear programming such as Interior Point Optimizer (IPOPT) [23] uses derivatives of the objective function Equation (3) with respect to the control variables u and states x^* as well as the Jacobi matrix of the constraints in Equation (4) and (5). An optimization problem is set up by taking into account the three objectives below (Table 1). According to this definition, spillway release is kept below 100 m^3/s, reservoir elevation is set to 168.76 m which is daily reservoir strategy for selected period and wear and tear of spillway gates are set by adjusting consecutive spillway releases.

Table 1. Sub-objectives that make up the total cost function.

i	Sub-objective	Coefficient $[w_i]$	Formula
1	Flood downstream	10	$[\min(Q_t^{spill}$-100, 0)]^2
2	Level setpoint	10	$[\min(H_t^{res}$-168.76, 0)]^2
3	Wear and tear of structures	000.1	$[Q_t^{spill} - Q_{t-1}^{spill}]^2$

where H_t^{res} is reservoir, Q_t^{spill} is spilled amount and t is time index.

4. Comparison of Results

Short-term operation is accomplished by both the reservoir simulation approach using HEC-ResSim and the MPC optimization algorithm under RTC-Tools. A worst case scenario is created by considering flood season (in May) when reservoir is almost full according to water supply targets (168.76 m) and a scaled up flood hydrograph (which has 150 m^3/s peak discharge) is given as inflow to the reservoir. Preliminary results are given in terms of reservoir levels (in Figure 2) and spillway discharges (in Figure 3). Both models can mitigate the flood in safe manner by limiting spill to avoid flood risk in the downstream area. Also, both models achieve another success criterion of refilling the reservoir to the initial level at the end of the event. Main difference between the models is the timing of pre-releases. While ResSim offers pre-releases during the time when inflows increases, RTC-Tools, due to its optimization algorithm (by searching an optimal releases with open-loop optimization), sets the starting time of the release to the beginning of the event. This causes a later increase in the refill period in ResSim while RTC-Tools can refill the reservoir earlier. In the simulation model, wear and tear of the spillway gates is defined by a ‘rate of change’ rule, on the other hand this can be easily added to objective function in RTC-Tools. HEC-ResSim also provides the spillway discharges in terms of gate opening. Thus, one of the advantage of using HEC-ResSim is the detailed representation of the gate management on the level of the individual gates. Nevertheless, the implementation of the overall reservoir release parameters should be seriously defined by user and they are not ensured as optimal cases. RTC-Tools provides optimum releases on the project level, but not on the level of individual gates. Objective function and constraint can be easily updated according to new operation definitions.

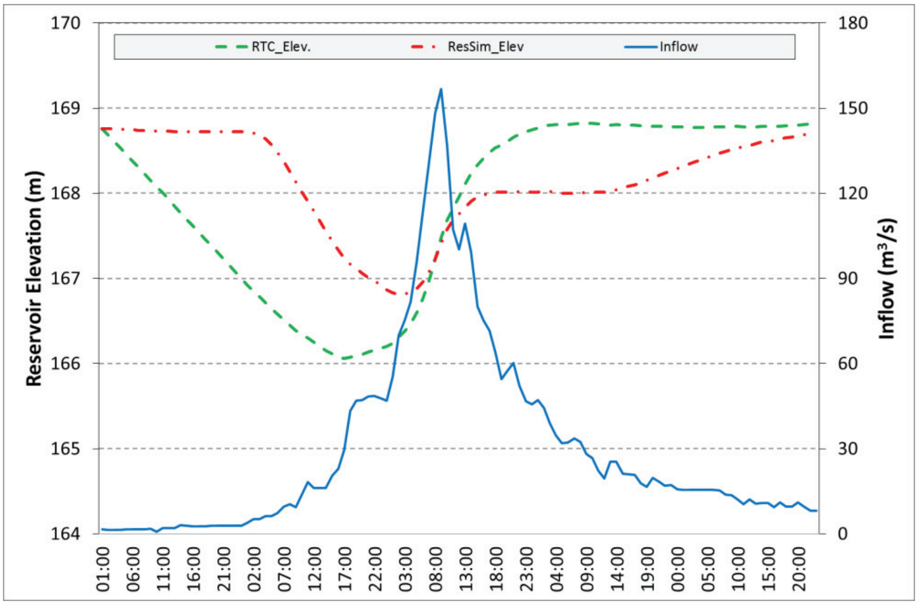

Fig.2. Comparative results of ResSim vs. RTC-Tools in terms of reservoir elevation with flood hydrograph

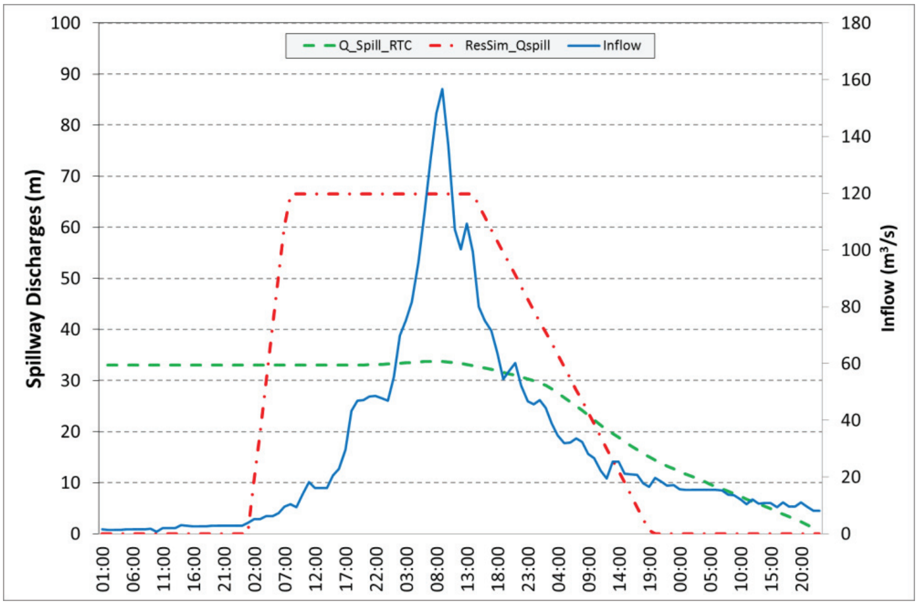

Fig.3. Comparative results of ResSim vs. RTC-Tools in terms of spillway discharges with flood hydrograph

5. Conclusions and Future Research

Real-time operation of multi-purpose storage reservoirs is challenging in case of conflicting objectives. The study compares different approaches for the short term management of flood operation of a multi-purpose dam. According to the results, each method has its own advantage and disadvantages. The optimization-based approach gives more objective results by having its mathematical structure compared to simulation based approach which has user defined parameters and does not always guarantee optimal solutions. While the start of the pre-release and maximum spillway discharge should be carefully selected by the operator by a trial-and-error approach in ResSim, RTC-Tools provides this as a result of the optimization. However, it should be noted that the objective definition is also sensitive to operators' decisions. Pre-release time is quite early in RTC-Tools due to open-loop optimization, and this strategy is not desired by operators since it increases the risk of refilling the reservoir in case of wrong alarm. To handle this, multi-stage stochastic optimization under closed loop strategy may be applied.

Developing a reservoir model in ResSim is easy to implement by its user friendly modules and rules, but relatively less flexible to manage streamflow forecasts due to lack of a forecast module. This situation necessitates to generate user defined scripts for each different event. On the other hand, it is also possible to operate spillways with different number of gates and to have operation results in terms of gate openings which is preferable by operators'. Furthermore, an advantage of the optimization approach is its extension to probabilistic ensemble streamflow forecasts to consider forecast uncertainty in the decision by use of stochastic optimization.

In order to use such models to support decisions, the observation network should be enriched and online transmission must be set. Yuvacık Dam case promotes to be set improved models for real time operation and the results shows the availability of flood mitigation without jeopardizing long term water supply targets. The study may be tested with deterministic or probabilistic streamflow forecasts in the future.

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