Evaluation of reservoir operation flexibility under variable hydrological conditions with user defined rules

GOKCEN UYSAL[1], AYNUR SENSOY[1], A. ARDA SORMAN[1], TURKER AKGUN[2] & TOLGA GEZGIN[2]
1 Anadolu, University Iki Eylul Campus, Civil Engineering Department, Eskisehir 26555, Turkey
gokcenuysal@gmail.com
2 Akifer Su Hizmetleri Ltd. Sti, Izmit Icme Suyu Aritma Tesisleri, Baskiskele, Kocaeli 41190, Turkey

Abstract The aim is to operate Yuvacık Reservoir without any flood and drought risk for long-term water supply, to raise the reservoir elevation as high as possible before the inflow recession period starts, which is generally observed in early May. User-defined operating rules are determined, taking hydrological conditions (snow potential, inflow, season and current level) into consideration to construct the simulation model with five years of daily data in which a drought and a wet year are included. In this study, a robust simulation model is analysed for 2001–2005 to investigate the reservoir operation flexibility. In conclusion, the extended period results show that the simulation model is sensitive to the hydrological changes and is applicable for real time operation of the reservoir.

Key words HEC-ResSim; long term; reservoir simulation model; variable hydrological conditions

INTRODUCTION

Hydrological conditions are the main drivers of reservoir management and directly affect the operational decisions made due to its variable and uncertain structure. An effective reservoir management and its strategies should be based on the hydrological response and the current situation of the system. Effective operation of water resources remains on the agenda of governmental institutes and private companies who deal with multi-objective management considering water supply, water allocation and flooding problems. Management of reservoir systems from planning to operation is very challenging since the problem deals with many complicated variables and uncertainties, such as inflows, return flows, storages, diversions, inter/intra-basin water transfers, irrigation, and industrial and/or municipal water supply demands (Rani & Moreira, 2010). An optimum solution sometimes consists of conflicting decisions based on reservoir-system-regulation plans. A reservoir-system-regulation plan, operating procedure, or release policy is a set of rules for determining the quantities of water to be stored or released or withdrawn from a reservoir, or system of several reservoirs, under various conditions (Wurbs, 1993). The main problem is to decide how much water must be stored and/or released, especially for relatively small reservoirs, without making any water shortage in the long term due to emergency conditions in times of flood. Although several studies are focused on weather prediction and accordingly streamflow forecasting (Anderson *et al.*, 2002; Fleming & Neary, 2004; Lim *et al.*, 2010), operation of reservoir systems studies are rather limited to optimization or simulation model applications, and are inadequate, especially for real time operation.

Yeh (1985) provided an excellent review on various approaches to reservoir optimization and simulation and pointed out that, despite considerable progress, research related to reservoir systems analysis has been very slow in finding its way into practice, particularly at the level of the actual operators. Despite this determination, a deterministic solution has still not been obtained due to complexity and uncertainty of this issue. Therefore, an implementation of a basin/reservoir modelling system, which is effective in the evaluation of real-time operational works and alternative planning, especially during flood events, was developed and applied in Yuvacık Dam basin, Turkey.

The paper focuses on the flexibility of a pre-developed reservoir simulation model (Uysal, 2012) under variable hydrological conditions. Therefore, daily data during 2001–2005 are used in a simulation model, and flexibility of the simulation model is analysed with extended period simulations.

STUDY AREA AND OBSERVATION NETWORK

Yuvacık Dam basin is located in the southern part of Kocaeli City, with a 258-km^2 drainage basin. The city is located in the Gulf of Izmit in the Sea of Marmara, about 100 km east of Istanbul, on the northwestern part of Anatolia. Yuvacık Dam was constructed to provide industrial and drinking water demand for the 1.5 million people of Kocaeli City in 1999. The dam body is 110 m in height, 400 m in crest length, and 12 m in width. The dam experienced the 1999 Marmara Earthquake in its short history. It could serve for water supply in the wake of this big earthquake whose epicentre was too close to the dam location. The drought season observed in 2006 emphasized the importance of early warning, decision support and quick response tools on one occasion for operational managers, governments and end users.

Hydro-meteorological data (temperature, precipitation, snow depth, streamflow, etc.) are collected by several automated stations in and around the basin (Fig. 1). The data sets that were used to set up the reservoir simulation model include: reservoir area-elevation-volume curve, reservoir inflow, reservoir elevation, reservoir operating curves, reservoir operating rules, spillway rating curve, and water consumption. Reservoir operating rules are developed based on operating experience.

Since the basin elevation ranges between 80 and 1548 m, precipitation is observed as snowfall at higher altitudes during December to February. This situation causes snow accumulation and high snowmelt contribution during the early spring months. Snow depth is measured continuously at five stations (RG7, RG8, RG9, RG10, and RG12) in and around the basin. Moreover, snow course points were determined to measure both snow depth and snow water equivalent (SWE) values using snow tubes. These data are directly used as input both for hydrological modelling in streamflow estimation and reservoir simulation studies for release decisions, especially during the melting period.

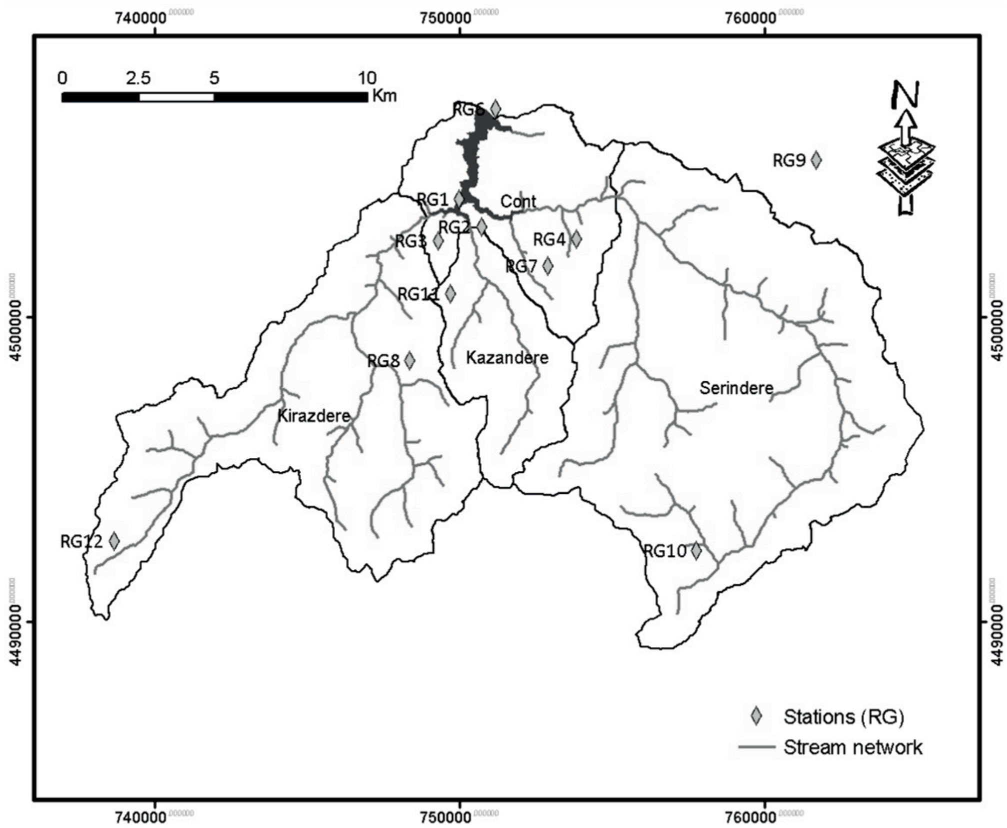

Fig. 1 Meteorological instrumentation network.

GENERALIZED RESERVOIR-SYSTEM SIMULATION MODELS

A simulation model is a representation of a system used to predict the behaviour of the system under a given set of conditions. Generally, simulation is based on constructing physical, operational conditions of the reservoir system. Wurbs (1993) describes a "generalized" term that is used to refer to a model designed to be readily applied to a variety of reservoir/river systems. The user develops the input data for the particular system of interest and executes the model, without being concerned with developing or modifying the actual computer code.

There are several generalized simulation models that are being used for water resources management systems. Wurbs (1993) also gave a brief summary of generalized models that have been applied by water management agencies to support actual planning and/or operation decisions, updated according to the state of art (Wurbs, 2005). The most popular simulation modelling softwares (Table 1) have been used in several studies and the projects are worth mentioning here.

HEC-ResSim (Klipsche & Hurst, 2007) is a generalized reservoir simulation system program which depends on the mass balance equation. Any reservoir system can be simulated using user-defined zones, rules and IF-THEN-ELSE statements. Once the physical conditions are represented, then several different reservoir operation approaches can be generated and operated to achieve a guide curve for target elevation.

Table 1 Reservoir simulation models (Wurbs, 2005).

Short name	Descriptive name	Model development organization
RiverWare	River and Reservoir Operation	Bureau of Reclamation, TVA, CADSWES http://animas.colorado.edu/riverware/
MODSIM	Generalized River Basin Network Flow Model	Colorado State University http://modsim.engr.colostate.edu
MIKE BASIN	GIS-Based Decision Support for Water Planning & Management	Danish Hydraulic Institute http://www.dhisoftware.com/mikebasin/
HEC-ResSim	Reservoir System Simulation	USACE Hydrologic EngineeringCenter http://www.hec.usace.army.mil/

PLANNING AND OPERATION OF RELEASE DECISIONS

Spillway discharges are critical in terms of releasing available water and storing excessive water. Yuvacık Dam has multi-purpose characteristics according to its physical and operational conditions. Effective reservoir capacity is relatively (effective volume of 52 hm^3) limited since the annual inflow is approximately four times more than its capacity. As a result the excess water must be stored above flood control levels so the decisions play an important role between flood and shortage risk from the operational point of view. Although, the spillway capacity is designed to be large enough, with 1560 m^3/s to control major floods, the downstream channel capacity is constrained with maximum 100 m^3/s spillway discharges. However, having a high flood potential due to its steep topography, mild and rainy climate, the basin shows fast flow response, especially to early spring and autumn precipitation events.

Current operation rules specify that the reservoir volume should be filled nearly full when recession period starts to ensure water supply during summer months without any shortages. However, determining this date includes many uncertainties regarding the unknown structure of inflows and flood events. Also, one of the challenging tasks can be achieved by filling the reservoir without unduly increasing the downstream flood risk due to spillway releases. Although, Operating Rule Curves (ORCs) for water supply and monthly Flood Control Levels (FCLs) for flood protection were developed using optimization, stochastic modelling and flood routing techniques after construction of the dam, there is no easy, objective, effective and robust technique or decision support tool that can be integrated with streamflow forecasts for reservoir operation. ORCs imply almost full level during the year, while FCLs indicate to evacuate water in times of flood risk months. Therefore, a reservoir simulation model that supports decision during spillway management was developed using data from 2007 to 2011 with user-defined rules (Uysal, 2012).

The simulation method divided into two approaches considering water supply and flood control. In the first step, reservoir operation rules are obtained using user defined rules and IF-THEN-ELSE statements through experienced operation strategies and long-term water supply conditions; thus water supply can be provided through all seasons. When the operational decisions seem to create a flood risk, the flood control approach is applied using pre-releases and new user defined rules. Then, the reservoir system can be operated regarding different scenarios, alternatives using both estimated and synthetic inflows. Furthermore, the simulation model must be sensitive for variable hydrological conditions. This can be done by testing the simulation model with enriched hydrological data in which extreme situations are observed.

RESULTS

Due to its multi-characteristic and restrictive structure, daily decisions for Yuvacık Dam are one of the challenging tasks. Decisions on controlled outlet must be accomplished taking several parameters and restrictions into consideration. Since the reservoir capacity is ¼ of the annual water demand and inflow, the regulation of a reservoir is a must. ORCs imply almost full level in the year, whereas monthly FCLs indicate water is evacuated in times of flood risk in order to provide extra flood protection volume. Regarding these circumstances, the reservoir simulation model is developed (Uysal, 2012) to decide the daily operating strategies of gated spillways, taking the hydrological conditions and the downstream conditions into consideration. In this study, an extended period simulation is carried out to test the applicability and flexibility of simulation model rules and operations sets. During development of the operating rules, RG-8 and RG-9 station snow depths are used as main data source for snow accounting rules. Inflow into reservoir, snow depths, water consumption, and evaporation daily data for 2001–2005 are provided as input for the model. There are three main criteria to test the effectiveness of the simulation model: reservoir elevations during March–May, water supply adequateness at the end of summer period and releases.

Two different simulation models are carried out in order to compare the efficiency of the proposed model. In the first run (Only Guide Curve operation, Sim-A), ORCs are defined as Guide Curve (GC) and simulation rules are only related to daily water demand and channel constraints, while in the second run (proposed method operation, Sim-B) the proposed model is developed with user-defined complex rules and scripts. The reservoir elevations are compared with FCLs in order to analyse flood risk, so the days when FCLs for different return periods (Q_{100}, Q_{250}, Q_{500}) exceeded for March–May are determined for each simulation (Table 2). Also, maximum reservoir levels are compared in Table 3.

Table 2 The number of FCL exceeded days for March–May period (2001–2005).

	Sim.-A			Sim.-B		
Years	Q_{100}	Q_{250}	Q_{500}	Q_{100}	Q_{250}	Q_{500}
2002	92	92	92	16	16	19
2003	72	78	84	22	22	26
2004	92	92	92	17	17	44
2005	78	81	87	0	22	38

Q_{100}, days when flood control level that corresponds 100-year probable peak exceeded; Q_{250}, days when flood control level that corresponds 250-year probable peak exceeded; Q_{500}, days when flood control level that corresponds 500-year probable peak exceeded.

Table 3 Maximum reservoir level.

Years	Sim.-A (m)	Sim.-B (m)
2002	168.87	169.00
2003	169.00	169.14
2004	168.74	169.73
2005	168.71	169.00

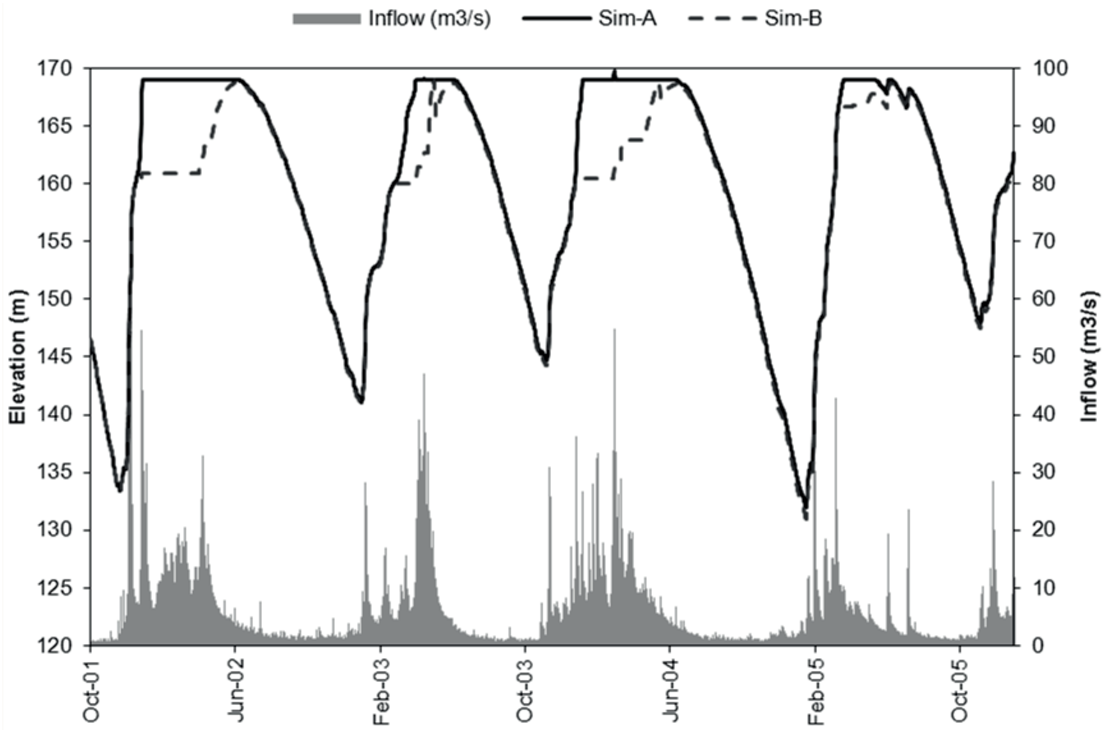

Fig. 2 Simulation results of reservoir operation (2001–2005).

The main outputs of the proposed simulation model (Fig. 2) are satisfactory in terms of reservoir level. The reservoir level is operated based on the water potential of the basin and it is increased step by step, especially beyond the radial gates during the snow melting period. While flood risk is minimized by late storage, there is no water shortage and spillways flows do not exceed channel capacity so the model can be used as a decision support tool for operators.

CONCLUSIONS

User-defined rule oriented simulation programs like HEC-ResSim enable reservoir operators to analyse both previous and new scenarios in terms of effective water management. A decision support alternatives and rules implemented hydrological model provides quick simulation and decisions for reservoir operation. Since the main idea is to set a reservoir/basin integrated management strategy for a multi-characteristic reservoir and real time operation application of a controlled reservoir with flow forecasting, it is valuable to search the flexibility of the decision model for variable hydrological conditions. The rules are derived from experiences during 2006–2011 and hydrological conditions, and tested by an extended period of 2001–2005 data. The results of the extended simulation system can be used with flow forecasts and synthetic flows, so this study provides objective decisions that depend on variable hydrological conditions, which can be a more reliable guide for the operator's decisions.

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