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Basin/Reservoir System Integration for Real Time Reservoir Operation

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Abstract This paper demonstrates the basin/reservoir system integration as a decision support system for short term operation policy of a multipurpose dam. It is desired to re-evaluate and improve the current operational regulation of the reservoir with respect to water supply and flood control especially for real time operation. The most innovative part of this paper is the development of a decision support system (DSS) by the integration of a hydrological (HEC-HMS) and reservoir simulation model (HEC-ResSim) to guide the professional practitioners during the real time operation of a reservoir to meet water elevation and flood protection objectives. In this context, a hybrid operating strategy to retain maximum water elevation is built by shifting between daily and hourly decisions depending on real time runoff forecasts. First, a daily hydro-meteorological rule based reservoir simulation model (HRM) is developed for both water supply and flood control risk. Then, for the possibility of a flood occurrence, hourly flood control rule based reservoir simulation model (FRM) is used. The DSS is applied on Yuvacık Dam Basin which has a flood potential due to its steep topography, snow potential, mild and rainy climate in Turkey. Numerical weather prediction based runoff forecasts computed by a hydrological model together with developed reservoir operation policy are put into actual practice for real time operation of the reservoir for March – June, 2012. According to the evaluations, proposed DSS is found to be practical and valuable to overcome subjective decisions about reservoir storage.

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1 Introduction

The management of reservoir systems requires comprehensive and integrated decision making strategies. Very different optimization methods have been applied to improve the efficiency of dam operations (Faber and Stedinger 2001; Ahmed and Sarma 2005; Kumar and Reddy 2006; Cheng et al. 2008; Sreekanth et al. 2012; Bolouri-Yazdeli et al. 2014; Ming, et al. 2015; Schwanenberg et al. 2015). The simulation models remain a prominent tool in practice for reservoir system planning and management (Yang et al. 1995; Davis and Hanbali 2005; Suiadee and Tingsanchali 2007; Charley 2010; Rani and Moreira 2010; Alemu et al. 2011). The researchers pointed out the improved linkage between optimization studies with real time implementations using simulation models which operators more readily accept (Yeh et al. 1993; Wurbs 1993; Labadie 2004; Hossain and El-shafie 2013). Moreover, the majority of water resources development agencies and researchers have focused on Decision Support Systems (DSS) based basin/reservoir modeling systems that combine computer based tools, models and data in order to get quick and supportive results (Ahmad and Simonovic 2000; Holmes et al. 2005; Wurbs 2005; Ngo et al. 2008; Ahmad and Prashar 2010; USACE 2010). Herein, this paper describes a methodology including a DSS for improved reservoir operation among different aspects of a multi-purpose dam and it's real time implementation through a case study of Yuvacık Dam reservoir. A generalized simulation model HEC-ResSim 3.0 (Hydrological Engineering Center-Reservoir System Simulation) (Klipsch and Hurst 2007) which has been used in several applications (Babazadeh et al. 2007; Duren 2009; USACE 2010) is selected to cope with the interaction between storage calculation and operational decisions.

The main objective of the study is to develop and implement an integrated DSS to maximize the reservoir storage at the end of a flood season, while ensuring the daily and the hourly releases through downstream channel within the acceptable limits. The novel part is to develop a DSS for multi-purpose reservoir management based on current hydrodynamic conditions and provide operators insight into practical facets of implementation of models during real time operation. The proposed integrated DSS methodology has the following main assets: (i) It includes the integration of hydrological modeling system (HEC-HMS) and reservoir simulation model (HEC-ResSim); (ii) HEC-HMS is coupled with numerical weather prediction data and used for real time runoff forecasts; (iii) A hybrid operating strategy is built to keep water supply reliability together with flood protection by shifting between daily and hourly decisions depending on real time runoff forecasts. Daily hydro-meteorological rule based reservoir simulation model (HRM) and hourly flood control rule based reservoir simulation model (FRM) are developed for flood risk and water supply purposes. (iv) In conventional simulation studies specified rules are defined with limitations while prioritizing Rule Curves (RCs) as main storage targets. However, in our approach we do not only take the limitations and optimized storage targets (monthly RCs) into account, but also daily variable objectives depending on the dynamic hydro-meteorological rules are considered. (v) The dynamic hydro-meteorological conditional rules and operating strategies within the system are developed by an interactive involvement of decision makers.

2 Study Area

Drainage basin (258 km^2) of Yuvacık Dam Reservoir (Fig. 1) is located in the north-western part of Turkey. The dam is the main water supply of 1.5 million inhabited of Kocaeli. The basin is within 40° 30′ – 40° 41′ northern latitudes and 29° 48′ – 30° 08′ eastern longitudes and elevation ranges between 80 and 1548 m, while the hypsometric mean elevation is 893 m. The earth-filled dam has an effective storage capacity of approximately 51.2 hm^3 at maximum operating level of 169.30 m. This capacity is relatively limited for the reservoir vis-à-vis the average annual inflow potential of 180 hm^3 and demand of 142 hm^3. Due to this situation, excess water must be stored above flood control levels and operational decisions play an important role on flood and/or shortage risk. 14.60 hm^3 of effective storage is kept behind the radial gates above spillway crest elevation of 159.95 m, 36.60 hm^3 of water is stored between spillway crest elevation and minimum operation level of 112.50 m. In order to ensure both flood control and efficient water supply, three regulation periods are 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).

The 12 km length downstream channel passes initially from a narrow valley near a rural district and thereafter flows into the Marmara Sea after a sharp curvature by a manmade channel next to industrial and urban areas. There is a risk of flooding for the downstream area due to both spillway releases and tributary creeks. Concerning the physical conditions, water authoritires of the region set the upper drainage discharge

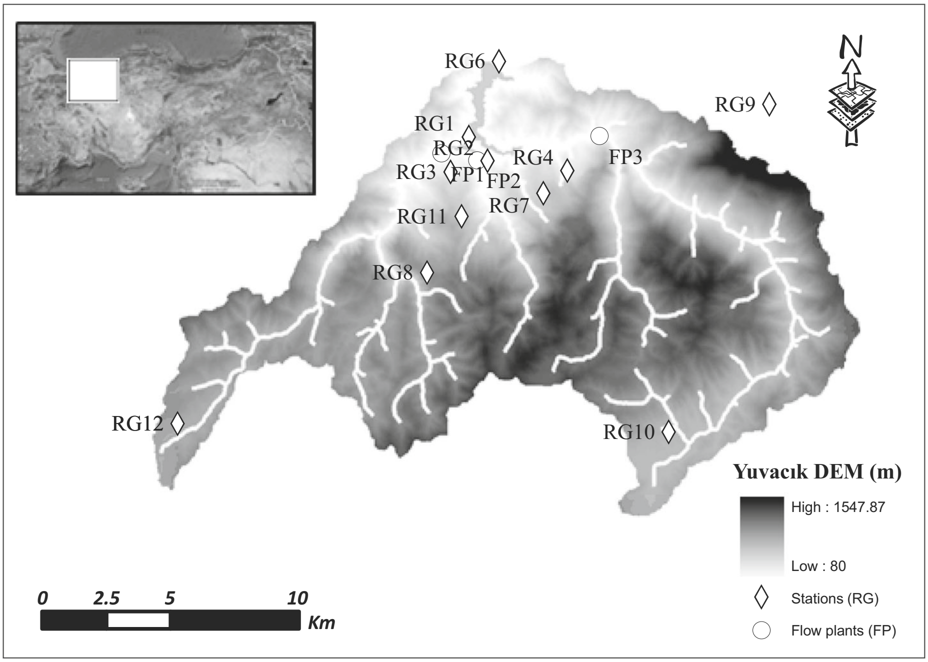

Fig. 1 Location and Digital Elevation Model of Yuvacık Dam Basin

limits to 100 and 200 m^3/s, for allowable operation and extreme flood event conditions, respectively.

Since most of the dam reservoirs in Turkey are operated by State Hydraulic Works (DSI), operation of a reservoir by a private company is one of the pioneer applications in Turkey. Several hydrologic modeling studies were conducted to develop an early warning system together with runoff forecasting for the dam basin (Yener et al. 2007; Şensoy et al. 2009; Yavuz et al. 2012). In earlier studies (New Castle 2001; Thames Water 2001; Rao et al. 2001), monthly operating RCs for water supply and flood control levels (FCLs) for flood protection were developed using rather limited observed data. Considering the water supply reliability, hedging curves (derived using RCs) were converted to drought zones or alarm levels by national/local authorities and reservoir operators as shown in the graph (Online Resource 1).

3 Data

3.1 Hydro-meteorological and Reservoir Data

Eleven meteorological stations are installed in and around the basin for data collection and online transmission (Fig. 1). The high basin relief causes considerable snow accumulation in winter and high snowmelt contribution during early spring months. Snow depth is measured at 5 snow stations. The reservoir physical data, observed reservoir levels, inflow, and evaporation data are also provided as input to the reservoir model. Four controlled radial gates are defined by their discharge curves.

3.2 Numerical Weather Prediction Data and Runoff Forecasts

Mesoscale Model 5 (MM5) modeling system, developed by Pennsylvania State University/ National Center for Atmospheric Research, daily mean temperature and total precipitation data are used in hydrological model application to forecast runoff 1–2 days ahead. MM5 data of 4.5 km spatial resolution are compared with ground observations and bias corrections (linear scaling) are applied to increase the consistency before input into the model. HEC-HMS (Hydrologic Modeling System) (Scharffenberg and Fleming 2010) hydrological modeling program that is developed by USACE (U.S. Army Corps of Engineers Hydrologic Engineering Center) is used together with Numerical Weather Prediction (NWP) data for runoff forecasting. Yavuz et al. (2012) calibrated and validated the hydrological model (HEC-HMS) for various rainfall and snowmelt events in between the years 2006–2011. Daily inflows are forecasted for 2012 and the results are directly used through improved reservoir simulation system.

3.3 Hypothetical Inflow Scenarios

Simulating and testing several probable flood events provide operators and insight to analyze the alternative strategies and take precautions before a real time event. There is no observation that warrants a flood control operation in the historical data set, thus hypothetical inflow scenarios are used and results are discussed. Hypothetical inflow scenarios are generated either using scaled up version of observed records or flood hydrographs derived from different return periods.

4 Methodology

A simulation model is a representation of a system used to predict the behavior of it for alternative scenarios. In spite of the fact that RCs are generated for the operation of any reservoir, they are generally independent from on time hydro-meteorological and physical conditions of the basin. The curves could be generated concerning the purpose of the operation and sometimes this purpose creates conflicting objectives. In this paper, there is an integration of two components namely; hydrological model and reservoir simulation model as presented in Fig. 2. The scope of the study is to develop a reservoir simulation integrated decision support tool both for water supply and flood control purposes, thus, the decision support tool is comprised of daily and hourly strategies. Daily decisions are taken to define the amount of water stored and/or released depending on current conditions. It is critical to determine timing and quantity of maximum storage during reservoir filling process, thus daily operation model, HRM, takes current hydro-meteorological conditions and targets to store water behind the radial gates as late as possible to provide sufficient water until the end of summer season. In case high inflow values are forecasted during critical reservoir levels, hourly FRM is operated to spill excess water in advance from the spillway and success criterion is defined to achieve the initial daily level again at the end of the event.

4.1 Operational Model Structure with HEC-ResSim

HEC-ResSim developed by USACE, is chosen to achieve the reservoir simulation studies. The basic decision logic for water storage or release is based upon the RC that describes target elevation. Firstly, physical data including both the reservoir pool and outlet works narrow the allowable range. Secondly; rules and *if-then-else statements* restrict this range. Finally; release or storage decisions are done with respect to RC regarding mutual rule restrictions. On the other hand, ResSim provides “specified rule types” which eliminates RC (target) and releases the desired amount of water. In this study, current operational restrictions are defined as limitation rules and RCs are defined as target levels. Moreover, new specified rules are generated within statements and scripts.

4.2 Development of New Strategies for Daily Operation with HRM

HRM is developed for daily short term operation where decisions depend on the amount of water released/stored concerning available water and demand in advance without increasing a flood risk. Since it is difficult to define a target elevation meeting requirements for both water supply and flood control, maximum water level (169.00 m) suggested as RC in terms of water sustainability. However, spillway releases are controlled by user defined hydro-meteorological forcing rules. Proposed reservoir simulation model is developed in accordance with the hydrological regime, meteorological conditions of the basin, the pre-developed operating guidelines and the experiences gained in nearly 15 years of reservoir operation. Operational decisions and hydro-meteorological conditions during 2007–2011 water years were analyzed and simulation rule sets are developed with control strategies. The user defined hydro-meteorological rules are summarized in Table 1.

1st Rule (Water supply condition): This rule is defined to provide flow into water treatment plant for city water supply.

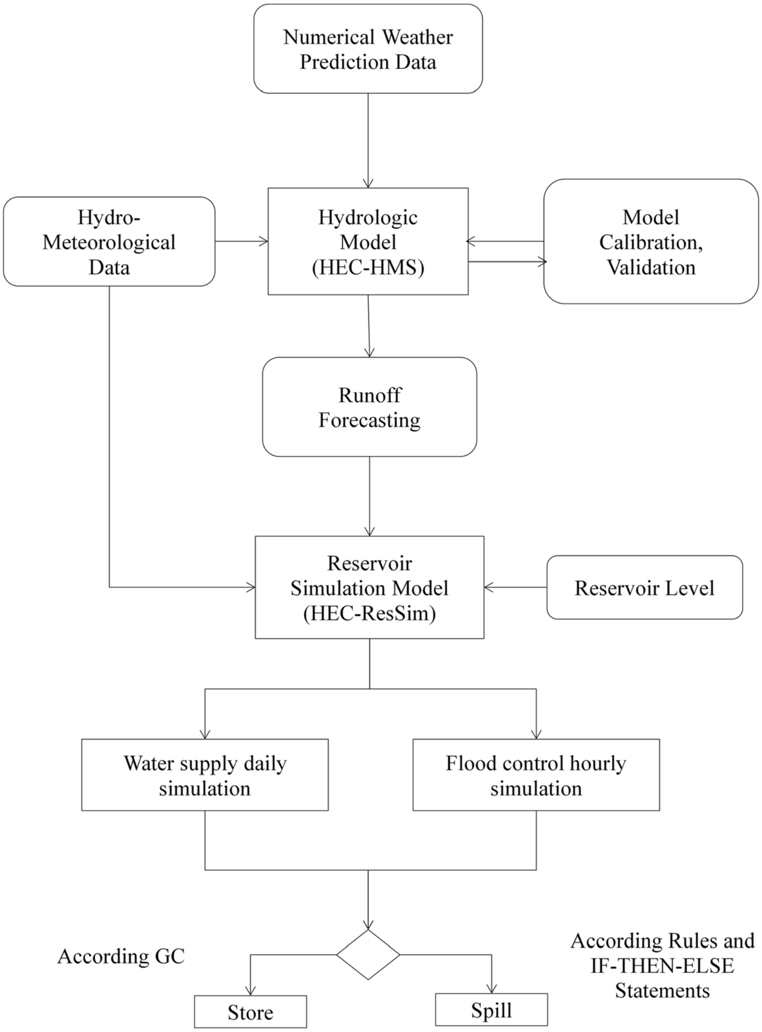

Fig. 2 Flow chart of the integrated basin/reservoir system modeling

2nd Rule set (Fall-winter condition): Since volume of the reservoir is small compared to inflows, it is observed that water is not kept behind the radial gates from October to February.

3rd Daily rule set (Snow accounting): Critical operational decisions have to be taken during March-April due to both decreasing snow water equivalent (SWE) in the basin and increasing streamflow as a result of snowmelt. The most important judgment is to decide when the gates will be closed. Since there is no fixed date due to dynamic meteorological conditions, basin average SWE value is considered as a criterion together with critical reservoir levels. If snow pack exists at the automatic snow stations representing the hypsometric mean elevation of the basin, there is a volume of water that is expected to fill the reservoir. We calculated the minimum SWE value which will fill the reservoir without new rainfall according to past observations and operators' experiences on

Table 1 Operational HRM rules

Number	Regulation Name	Season	Current Reservoir Level (m)	Snow condition wrt Hypsometric Mean (H_{RG-8})	Snow condition wrt High Altitude (H_{RG-9})	Current Inflow (m^3/s)	Spill Decision Criteria	Spill Amount (m^3/s)
1	Water supply	Pre-flood Main flood Post-flood	$H>H_{min}$	–	–	–	City demand	Q_D
2	Fall-winter	Pre-flood	$H\geq H_{gate}$	–	–	–	H_{gate}	$\geq$ In
3	Snow accounting	Main flood-1	–	$H_{RG-8}>0.2$ and H_{RG-8} is increasing	$H_{RG-9}\geq 1.0$ m	–	Snow water equivalent, H_{cr1}, H_{cr2}	$\geq$ In
			$H\geq H_{cr1}$	$H_{RG-8}<0.2$	$H_{RG-9}\geq 1.0$ m	–		
			$H\geq H_{cr2}$	$H_{RG-8}<0.2$	$H_{RG-9}<0.2$ m	–		
4	Recession of inflow	Main flood-2	$H\geq H_{cr2}$	–	–	$In\leq Q_{crit}$	Recession scenarios	S_j (Eq. 4)
5	Instantaneous increase of inflow	Main flood-2	$H\geq H_{cr2}$	–	–	$In>Q_{crit}$	Inflow	$\geq$1.5 In
6	Downstream channel	Main flood	–	–	–	–	Channel constraint	<100

H current pool elevation (m), H_{min} minimum conservation pool elevation (m), H_{gate} spillway crest elevation (m), H_{cr1} first critical gate elevation (164 m), H_{cr2} Second critical gate elevation (167 m), *In* current inflow into reservoir (m^3/s), Q_{crit} minimum discharge for recession (m^3/s), Q_D demand (m^3/s) effective snow line. The conditional rules described with water level and snow pack provide flexibility to determine the time (varying each season) to close the gates during the flood season and also avoid subjective decisions. These conditions depend on the observations of the water levels and the snow depths in relation with SWE at the hypsometric mean (represented by RG-8 at 953 m) and the higher elevations of the basin (represented by RG-9 at 1340 m).

4th Rule set (Recession of inflow condition): Although NWP data integrated hydrological model provides short term runoff forecasts; inflow for the rest of the season cannot be predicted. Future inflows are the main uncertainty for reservoir operators; thus operating strategies may be developed according to expected inflow trends. Taking the decision according to the lowest possible inflows during April and May (the worst scenario in terms of water sustainability) would be effective when the inflow continuously decreases in the recession period. To that end, expected volume is calculated considering the past observations and current water demand as shown in the additional information (Online Resource 2). Since recession is observed at low flow conditions, an upper limit value of 12 m^3/s (according to the past observations) is assigned into the model. Recession formula is applied when the reservoir level reaches high values (167 m) and inflow rates are in the recession.

5th Rule set (Instantaneous increase of inflow condition): Each inflow fluctuation causes a critical situation when reservoir level elevation is greater than 167 m during April and May. A storm event observed during this period shows a rapid recession of the hydrograph after storm event that is different from a general recession trend. Operators prefer to release the water during these storm events and after the completion of an event spillway gates are closed back. Hence, a set of rules are developed to control high inflows during recession periods.

6th Daily approach rule (Downstream channel capacity): A maximum release rule is defined as a function of date and assumed downstream channel capacity is 100 m^3/s.

All these rules generated for HRM model are given in Online Resources 3.

4.3 Development of New Strategies for Hourly Operation with FRM

In case of a flood risk, it would be necessary to release water before the occurrence of an event, where the flood capacity does not satisfy flood control without exceeding channel capacity. FRM is intended for those occasions in which the event is larger than that can be managed by the current flood pool/enlarged outlet combination. Reservoir operators can initiate a release to spill excess water from the reservoir in advance of the flood heeding the forecast information. A forecast module dealing with generalized rule accounting on upcoming forecasted event that will initiate water release for pre-emptive purposes has not been developed in ResSim yet. FRM rules are:

- **1st Rule (Water supply condition):** Same as HRM.
- **2nd Rule (Downstream channel capacity):** Same as HRM.
- **3rd Rule (Flow rate of change limit):** This rule specifies a step by step change in a release operation during a flood event.
- **4th Rule (Pre-release condition):** The designated strategy is based on the volume of the forecasted event hydrograph. The main idea is to calculate the required amount of release

that does not exceed channel capacity. On the other hand, initial reservoir level should be equal to the final reservoir elevation at the end of the hourly operation. Therefore, a rule is scripted to initiate spillway discharges in advance (6 or 12 h) according to the magnitude of the flood and current flood pool volume. Thus, a distribution component of the rule: *Release Duration* should be selected by the operator. Then, *Required Release in Advance* is calculated by the equation below (Eq. 1):

$$D_{eq}\left(m^3/s\right) = V_{eq}/T_r \tag{1}$$

where; D_{req} (m^3/s) is *Required Release in Advance* (m^3/s); V_{req} is *Required Release Volume* (the minimum volume of release necessary to avoid the flood in m^3); T_r is *Release Duration* (hr).

5 Discussion of Results

HRM model is validated using daily 2007–2011 data and the goodness of performance is discussed in the following sections. FRM is validated with two scenarios; the applicability and efficiency of proposed method is discussed by evacuation adequacy of flood without any damage and consistency of resultant reservoir levels with the daily water supply target. Finally, HRM is tested with a real time operational application for 2012 snowmelt season using MM5 based inflow forecasts and results are discussed.

5.1 Daily HRM Results

Since each water year has different precipitation and runoff characteristics, it is important to find general and reliable simulation rules that are flexible for various hydro-meteorological conditions. Each rule and constraint has advantages and disadvantages that depend on season, inflow characteristics and snow potential. HRM is validated for 2007 – 2011 water years (Fig. 3). The results are presented in comparison to observed operational levels which are operated by decision maker without any operational model. Operators take decisions by considering several parameters/conditions and scenarios, management objectives were subject to many interpretations. Though the simulations are based on objective decisions depending on the predefined rules, the rules are defined concerning the past observations and actual practice of the operators, therefore there is a high correlation between simulated and observed levels (Fig. 3).

The initial water elevation of 2007 is low due to a very drought period of 2006. So, to show the effect of simulation, a fictitious higher initial reservoir elevation value is assigned (Fig. 3a). The results of 2007 are not reflected in the summary tables due to this special characteristic of the year.

Some indicators and factors are taken into account to evaluate the performance of the simulation approaches. These indicators can be considered as effectiveness of the rules, water supply sufficiency, spilled amount of water, maximum water level considered together with drought zones, FCL exceeded days, mechanical efficiency of radial gate operations, flood storage index, end-of-month storage satisfaction ratio. Proposed methods provide reasonable and applicable results according to the defined performance criteria for the validation period.

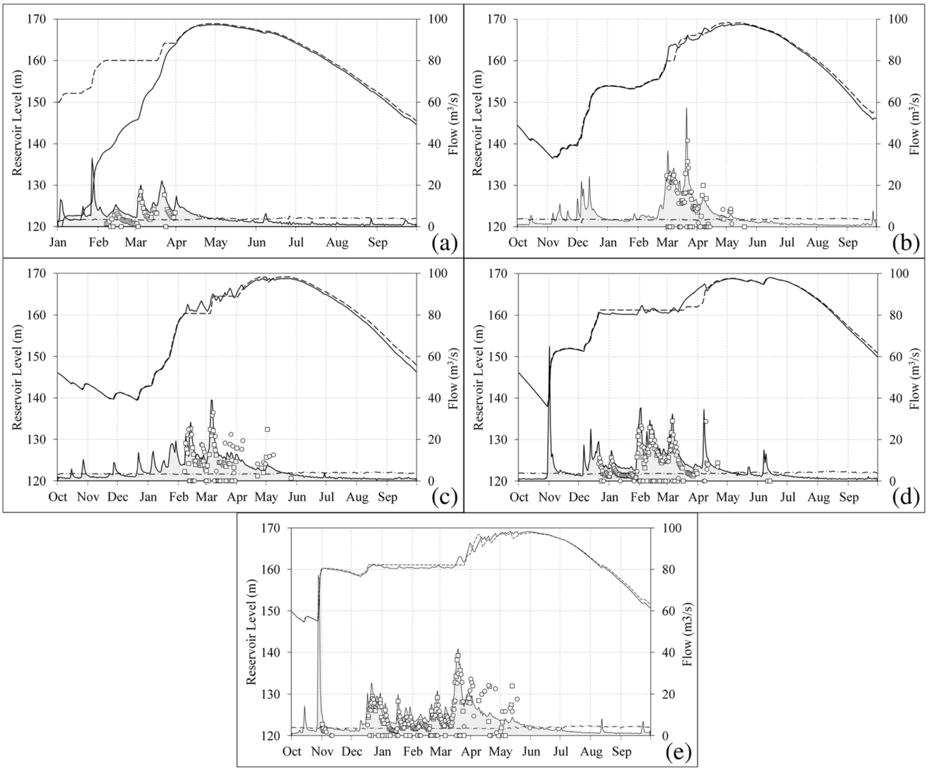

Fig. 3 HRM results: (**a**) 2007, (**b**) 2008, (**c**) 2009, (**d**) 2010, (**e**) 2011

5.1.1 Effectiveness of the rules

Concerning the parameterization of different rules and tradeoff between their objectives, it is targeted to define the impact of the rules on the daily reservoir operation results. Therefore, duration in days when a rule is active are investigated and presented in Table 2 from daily simulation results (parentheses indicate the number of days when the release/storage decisions taken according to that rule during the operation).

The effectiveness of the rules is analyzed according to their functionality and they give insight for the verification of the methodology. It should be emphasized that low

Table 2 Effectiveness of the rules on daily reservoir operation decisions

Years	Forcing Rules				Emergency Rules	
	Rule 1	Rule 2	Rule 3	Rule 4	Rule 5	Rule 6
2008	H (365)	I (0)	M (17)	H (53)	L (2)	L (1)
2009	H (365)	M (24)	H (28)	M (58)	L (1)	I (0)
2010	H (365)	H (71)	H (26)	M (61)	I (0)	I (0)
2011	H (365)	H (82)	H (26)	H (51)	L (1)	L (3)

H high (≥66), *M* medium (5 – 65), *L* low (1 – 5), *I* ineffective (0) effectiveness is not a measure of necessity. It seems that rules 1–4 are forcing rules whereas even the rare usage of others (rule 5 and rule 6) is emergency rules for operation. High variability of rule usage shows the flexibility of rules for different conditions. For example, 2nd rule was not effective in 2008 due to low reservoir level whereas 82 times used in 2011 (Table 3). 3rd rule causes the storage of water in stepwise manner in relation with snow pack availability (Fig. 3).

5.1.2 Spillway releases and end-of-month storage satisfaction ratio

Spillway releases are controlled within acceptable limits, thus there is no flood risk for downstream part. Reservoir elevations fall into drought levels at the end of the summer period (August - September) of 2008 and 2009 both for observed and proposed methods. Reservoir elevations at the end of the simulation period (30 September) are presented in Table 3. The simulation model provides higher storage levels at the end of the water year.

End-of-month storage satisfaction ratio represents the ability of the operation without falling into drought zones. Since there are four drought zones and one no risk zone, five fractional goal values (w_j) are set for each condition.

$$w_j = \begin{cases} 1.00 \; if & H_j^{res} > H_j^{DZ1} \\ 0.75 \; if & H_j^{DZ1} \geq H_j^{res} > H_j^{DZ2} \\ 0.50 \; if & H_j^{DZ2} \geq H_j^{res} > H_j^{DZ3} \\ 0.25 \; if & H_j^{DZ3} \geq H_j^{res} > H_j^{DZ4} \\ 0.00 \; if & H_j^{DZ4} \geq H_j^{res} \end{cases} \quad \text{for j} = 1, 2, \ldots \text{n} \tag{2}$$

where H_j^{res} is the reservoir level at the end of month j, H_j^{DZ1}, H_j^{DZ2}, H_j^{DZ3}, H_j^{DZ4} are the first, second, third and fourth drought zone level at the end of month j, respectively.

The satisfaction ratio of end-of-month storage is defined in Eq. (3). Perfect operation which does not fall into drought zone is equal to 1, whereas 0 indicates inefficient operation.

Table 3 Performance assessment of HRM

Years	Reservoir elevation on 30 September		End-of-month storage satisfaction ratio (PF season)			Flood storage index according to different FCL (MF season)						The number of gate openings (MF2 season)	
						Q_{100} FCL		Q_{250} FCL		Q_{500} FCL			
	Sim (m)	Obs (m)	Q_{100} FCL Ope	Q_{500} FCL Ope	Sim	Sim	Obs	Sim	Obs	Sim	Obs	Sim	Obs
2008	147.60	146.12	0.69	0.38	0.75	0.74	0.84	0.63	0.70	0.50	0.55	8	4
2009	148.01	146.32	0.69	0.38	0.75	0.74	0.83	0.63	0.70	0.51	0.55	6	12
2010	150.94	146.98	0.75	0.66	1.00	0.86	0.88	0.75	0.74	0.63	0.58	5	5
2011	151.59	150.67	0.75	0.50	1.00	0.90	0.81	0.78	0.70	0.62	0.57	12	12

Sim simulated, *Obs* observed, *Ope* operation, *FCL* flood control level, *PF* post-flood, *MF* main flood

$$I_s = \frac{\sum_{j=1}^{n} w_j}{n} \tag{3}$$

In order to compare the effectiveness of the proposed HRM method, two new simulations are carried out using Q_{100} FCL and Q_{500} FCL as operating RCs. This index is calculated for post-flood season (June – September) for each year and the results are presented in comparison to proposed simulation (Table 3). Indices give better results for the proposed methodology.

5.1.3 Flood storage index and mechanical operation

Although, it is not possible to operate the reservoir without exceeding the FCLs for water supply purposes, it is still an important criterion to supply water with a minimum risk. Effective flood prevention storage v_j^f is introduced to denote the flood storage available at the end of each day (modified from Wang and Liu 2013). If the end-of-day elevation is below FCL, it is equal to the volume of the flood control pool; otherwise, it is the actual storage available, as show in Eq. (4).

$$v_j^f = \begin{cases} v_j^{act} \; if \; v_j \leq v_j^{FCL} \\ v_j^{FCL} \; if \; v_j > v_j^{FCL} \end{cases} \quad for \; j = 1, 2, \dots n \tag{4}$$

where v_j^f is effective flood storage for jth day, v_j^{act} is the actual volume of the flood prevention pool for jth day; v_j is the end-of-day storage for jth day, v_j^{FCL} is the storage corresponding to FCL for jth day.

Flood storage index is defined by the ratio of total effective flood storage over the total volume of storage corresponding to FCL, as shown in Eq. (5). This index is calculated with respect to FCLs (Q_{100} and Q_{500}) for main flood season (Table 3). According to results, simulated and observed indices are similar to each other as expected, however the simulated operation show better performance than observed operation especially for 2010 and 2011 wet years.

$$I_f = \frac{\sum_{j=1}^{n} v_j^f}{\sum_{j=1}^{n} v_j^{FCL}} \tag{5}$$

Another concern is that, it is not mechanically efficient to open and close the radial gates often during a daily operation. Hereby; "number of gate openings" (Table 3) are presented to compare the simulations in terms of mechanical efficiency.

Finally, according to water supply, spillway discharges, flood control and mechanical efficiency, an objective and robust simulation model concerning current/future hydro-climatic and physical conditions of the basin and reservoir is developed as a part of DSS to be used in real time applications.

5.2 Results for Hourly Simulations (Scenario-A & Scenario-B)

In this part of the study, we analyzed the efficiency of FRM using hypothetical inflow scenarios for hourly strategies (Scenario-A & Scenario-B). These scenarios are:

Scenario – A: an observed flood event occurred during October 31th to November 08th, 2009 is simulated. However; the magnitude and the date of the storm event is changed to end up with a flood risk during the daily operation. While the actual event occurred during October, the scaled new event is assumed to occur when the reservoir is almost full. The scenarios can be summarized as "What would the operation strategy be, if 31 October – 08 November 2009 flood event (the highest observed inflow since 1999) whose peak flow is scaled up to 150 m^3/s would be observed during 15 – 20 May 2008?"

Scenario – B: Since the hourly strategies are necessary especially for critical period when initial pool elevation is higher than available flood control levels, a scenario is carried out to test the effectiveness of the approach by using flood hydrograph of Q_{100}. The scenarios can be summarized as "What would the operation strategy be, if Q_{100} flood event whose peak flow equal to 597 m^3/s would be observed during 15 – 20 May 2008?"

First of all, the flood event must be operated with pre-release approach so that spillway releases do not exceed downstream channel capacity. Pre-release activity can be considered successful when it provides the following targets:

1. Pre-release flows discharged from the spillway should not exceed flood peak.
2. Achieve to refill the reservoir at the end of the event so that daily target can be satisfied.

The results are shown in Fig. 4a and b for Scenario A and Scenario B with release time of 36 and 12 h, respectively. The simulation method achieves to attenuate the flood event as high as 66.5 and 187.5 m^3/s discharge release through the drainage channel, so 1st target is satisfied. Since the method provides to refill the reservoir pool at the end of the event (goes back to daily water supply policy level), hourly strategy is successful as well.

5.3 Case study – Real Time Operation with Flow Forecast

Real time operation of a reservoir necessitates current hydro-meteorological data, NWP, forecasted streamflows and scenarios. A DSS integrating all these data and conditions is put into practice for the real time operation of 2012 snow-melt season. Since high snow depth values were observed at RG-8 and RG-9 as shown in the graph (Online Resource 4) during 2012 winter period, the inflows increased with a fast response during and after snowmelt period. One day ahead reservoir inflow forecasts produced by the hydrological model based on MM5 data are directly used in HRM process. Lookback data that forms the initial conditions

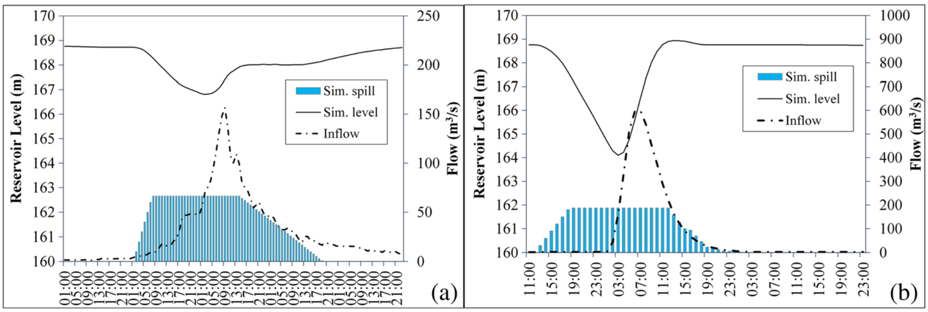

Fig. 4 FRM results: (**a**) Scenario-A, (**b**) Scenario-B

are given as the current reservoir observation level. The pre-release is accomplished 1 day ahead according to model outcomes. The results are given in Fig. 5 in comparison with the observed levels according to the decisions of operators' independent from the simulations. A close relation between the observed and simulated reservoir levels can be attributed to the consistency of the flood forecasts and well suited HRM rules.

6 Conclusions

This article proposes an operational DSS which is applicable and useful to the profession for a multi-purpose reservoir operation. This is done by integrating hydrological model with daily and hourly combined strategies with HRM and FRM approaches to avoid water shortage during summer and flood risk during the critical (refilling) period. The basic idea is to put pre-releases into practice using NWP based streamflow forecasts and objective decision tools according to current and future hydro-meteorological conditions using proposed DSS. The methodology is tested for a multi-purpose single reservoir system in Turkey as a case study. As conclusions; firstly, daily HRM propose appropriate reservoir levels considering on time hydro-meteorological observations, period of season, physical constraints of operational levels, outlet works and drainage channel; secondly, hourly FRM are successful on an hourly basis when flood events cannot be regulated within daily decisions.

The development phase and real time operation is conducted with personal communication between model developers and the operating personnel. Finally, the simulations are integrated simultaneously with a hydrological modeling application which provides weather prediction (MM5) based streamflow forecasts in real time and tested for 2012 critical period. HRM is

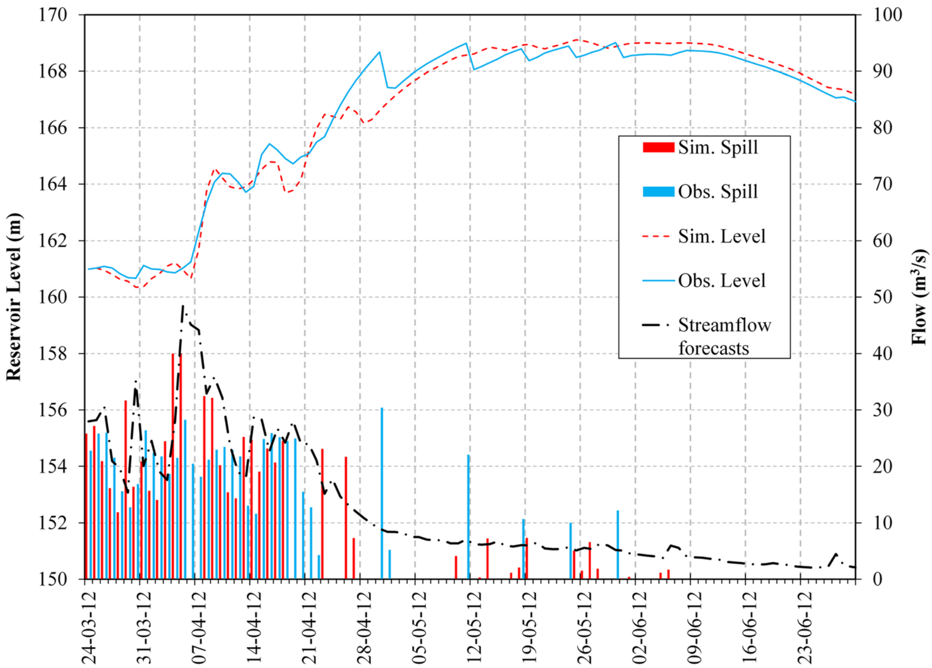

Fig. 5 Real time operation using MM5 based inflow forecasts with proposed method (2012)

well-suited with real time pre-release oriented application. Since most upper basin reservoirs are fed by snowmelt and they are in stress to release water through downstream, the results are promising to be directly used in real time operations for similar snowmelt fed basins. In conclusion, the proposed approach is fully data driven, rule based, robust, flexible, user oriented and the knowledge can be transferred to other reservoir or reservoir systems.

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