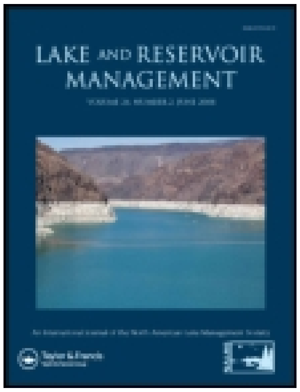

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Simulating hedging rules for effective reservoir operation by using system dynamics: a case study of Dez Reservoir, Iran

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Simulating hedging rules for effective reservoir operation by using system dynamics: a case study of Dez Reservoir, Iran

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Abstract

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Some of the most important challenges facing water managers are to increase water supply and reduce its demand. A single systematic method is needed to address both issues, such as the System Dynamics (SD) modeling approach. In this approach all the factors, parameters, and their influences on the problem are considered by causal loops and stock-flow diagrams. The multipurpose Dez Reservoir in southwestern Iran is a good case study for this approach, and we simulated 10 years under differing operation strategies to develop the most appropriate operation policy. A hydrologic time series analysis was conducted to generate simulated inflow to the reservoir, and differing policies, including hedging rules and a "goal-seeking hedge," were applied. By using performance criteria and a new measure entitled "corrected reliability,", the most appropriate scenarios were identified. We found that using the goal-seeking hedge in combination with water demand management offers the best chance for effectively meeting demands and minimizing supply shortages.

Key words: performance criteria, reservoir operation, time series analysis

High population growth combined with limited water resources has led to water shortages that present a serious challenge for many countries. As a result, many are developing management policies to address the problem. Loucks et al. (2005) and Mays and Tung (2002) provided an appropriate basis for traditional approaches to water resources planning. Wurbs et al. (1985) presented a review paper listing more than 700 references as a bibliography on techniques of reservoir operation. Yeh (1985) also conducted an appropriate review on different reservoir simulation and optimization approaches and noted that, despite improvements presented in the literature, a practical method for reservoir analysis has not yet been achieved, in part because operators are excluded from the policy-making process and partly because simplified computer programs and operation policies are not suitable for complicated, actual cases. Nonetheless, since 1985 there has been much work done in reservoir analysis using different practical methodologies.

One efficient tool in reservoir operation modeling that is attracting attention from water resources researchers is System Dynamics (SD), a simulation technique based on feedback of system elements. Keyes and Palmer (1993) developed an SD model for drought studies, and following that, Matthias and Frederick (1994) used SD modeling to study sea level variation in coastal regions. Along with these studies, Simonovic et al. (1997) and Simonovic and Fahmy (1999) used SD approach for long-term planning of water resources and policy analysis of the Nile River basin.

In recent years, use of SD as an effective simulation approach in various studies on water resources management has accelerated. Zhang et al. (2008) developed a complex SD model to integrate Tianjin, China, water resources management and then presented reasonable predictive results for policy-making on water resource allocation and management. Fagan et al. (2010) developed a dynamic system-modeling framework to provide a comprehensive set of dynamic performance metrics, integrating all subsystems of the water cycle. In Iran, Bagheri et al. (2010) adopted an SD modeling approach to examine the impacts of various

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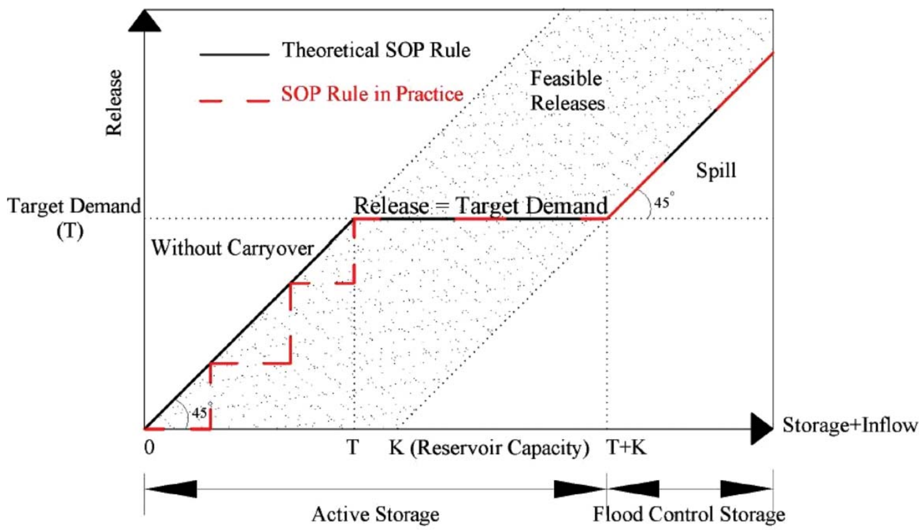

Figure 1.-Release function according to standard operating policy for reservoirs (color figure available online).

reconstruction projects as well as water management policies on the ability of the Bam urban water system to meet increased demand trends. In a recent study, Zarghami and Akbariyeh (2012) modeled Tabriz's urban water system using an SD approach to simulate conditions in the near future until 2020.

The simplest policy for reservoir operation is called "standard operating policy" (SOP), which strives to meet a target demand "T." In practice, operators avoid continuously changing release openings, so slopes would be implemented as steps in most situations (Fig. 1).

According to SOP, if the water availability (storage + inflow) is less than water demand, all the water will be released in the time period, and if it exceeds T plus the maximum reservoir capacity (K), a spill will occur (Loucks et al. 2005). In practice, most operators do not comply with SOP, and more appropriate policies are used. Hedging, a reduction in water supply with the aim of saving some water in the reservoir to mitigate future water deficits in case of an extended period of drought, is an important real-time reservoir operation policy (Zhao et al. 2011). Bower et al. (1962) first provided a systematic economic description of hedging rules for water resources systems; since then, hedging rules have become popular, and differing formulations have been presented by researchers. Draper and Lund (2003) listed the most common hedging rules (Fig. 2 and 3) as follows:

- One-point hedging, where a line (slope <1) connects the origin of the SOP diagram to a point on the target level of release. The less the slope of the line, the more the release is reduced in times of drought (Shih and ReVelle 1994).

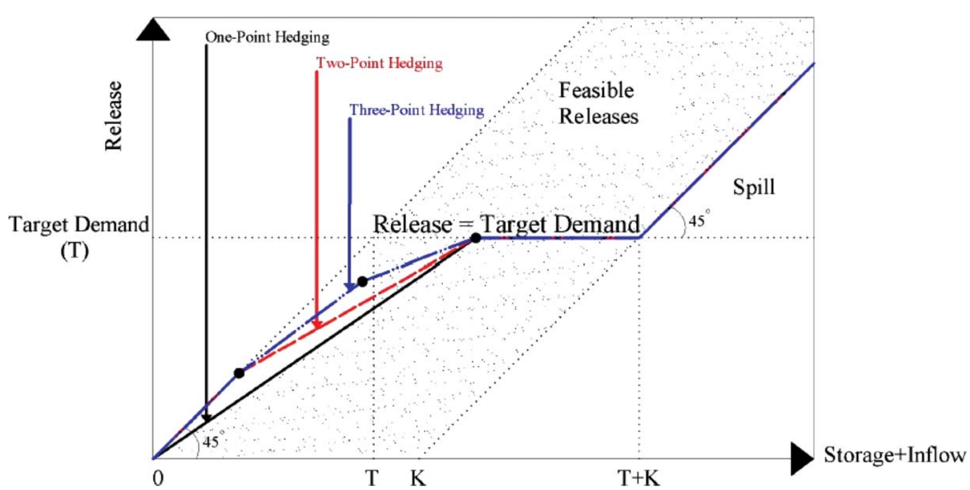

Figure 2.-One-point, 2-point, and 3-point hedging rules (color figure available online).

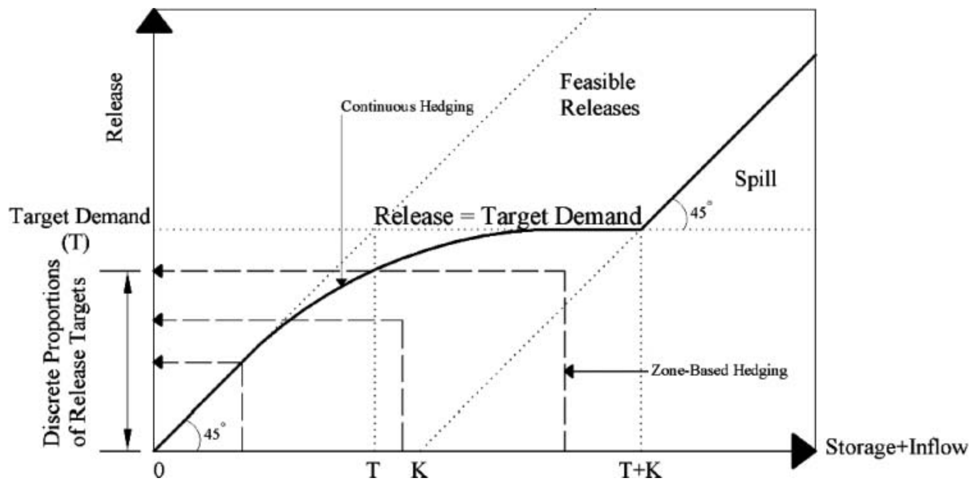

Figure 3.-Continuous and zone-based hedging rules.

- Two-point hedging, where a line (slope <1) connects a first point somewhere up from the origin on the shortage part of the SOP rule to a second point on the delivery target line (Bayazit and Ünal 1990, Srinivasan and Philipose 1996). By this strategy, releases are reduced abruptly below the demand to maintain some storage over the duration of an extended, anticipated drought.
- Three-point hedging, where an intermediate point is specified in the 2-point hedging rule, introducing 2 linear portions. Unlike 1-point hedging, this approach allows a less abrupt decrease in releases at the start of a drought, but then more dramatic reductions if the drought intensifies or lengthens.
- Continuous hedging, where the slope of the hedging portion of the rule is not constant and can vary continuously (Hashimoto et al. 1982). Thus the reductions below the demand are minimized at the start of a drought condition.
- Zone-based hedging, where hedging values are defined as discrete proportions of release targets for different zonal levels of water availability (Hirsch 1978). To some extent this rule is much easier for the dam operators to implement.

In recent studies, You and Cai (2008) applied theoretical hedging policies to Lake Okeechobee in south-central Florida to explore the potential advantages of hedging policies for reservoir operation. Rittima (2009) developed a reservoir operation model of Mun Bon and Lam Chae reservoirs in Thailand to simulate a variety of common hedging rules including 1-point hedging, 2-point hedging, and zone-based hedging. Following this study, Shiau (2009) evaluated the effects of hedging by using 2 conflicting objectives: (1) a total shortage ratio and (2) a maximum 1-month shortage ratio, which represent the long- and short-term water shortage characteristics for water supply, respectively. They also employed a multiobjective genetic algorithm to solve this optimization problem. Eum et al. (2010) calculated optimal water release for droughts by combining a future value function derived with a sampling stochastic dynamic programming model with a hedging rule. Guo et al. (2012) proposed a bi-level model and a set of water-transfer rules to solve the multireservoir operation problem in interbasin water transfer–supply projects. In this model, they considered water transfer and water supply together, so that the multireservoir system manager, at the upper level of the hierarchy, optimizes water–transfer curves to spatially allocate transboundary water resources. The individual reservoir manager can then optimize hedging rule curves to pursue the best water supply accompanying the action of water transfer.

These studies used several SD models to simulate reservoir processes; however, none evaluated different hedging rules in VENSIM (2010) or used a stochastic simulation of reservoir inflows, and few of the studies were conducted on multipurpose reservoirs. Therefore, in this study a comprehensive introduction of the real case of Dez Reservoir in Iran was introduced; then an SD modeling to evaluate the common hedging rule by comparison with a new type was developed; and finally the model was validated. We then compared the results by performance measures to find the most appropriate approach in real applications.

Case study

The Dez River, located in the southwestern part of Iran (Fig. 4), is formed by the joining of the Caesar and Bakhtiary rivers. Based on water volume, the Dez River is the second

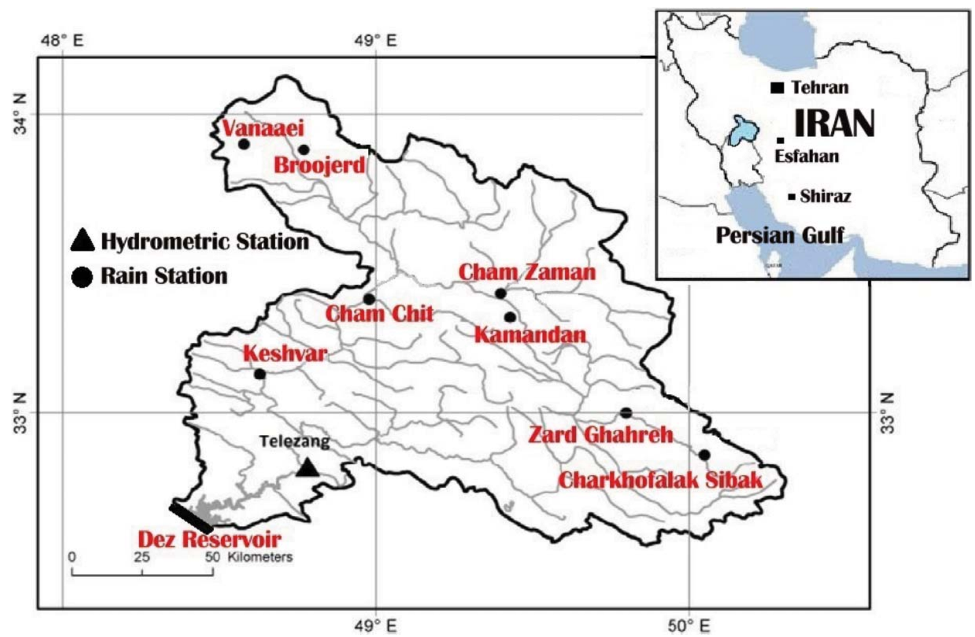

Figure 4.-Location of the Dez River and Dez Dam in Iran (color figure available online).

largest river in Iran, and the Dez Dam, with a height of 203 m, is one of the tallest arch dams in Iran. It was constructed on the Dez River in Khuzestan province to supply hydroelectric power, supply water for agriculture and urban demands, and to control flooding. Based on the observed flood hydrographs, January, February, March, May, November, and December are the flooding months in the study area (Malekmohammadi et al. 2011). The 3.3 billion cubic meter capacity and the 520 megawatt hydropower production are notable features of this reservoir, which irrigates about 125,000 ha of the downstream agriculture zones. These properties place this dam in a prominent water management role in southwestern Iran.

Methods

In this study, the SD approach was used to simulate reservoir operation. In the proposed methodology, the main steps are to define the dynamic hypothesis and develop causal loop and stock-flow diagrams (Sterman 2000). In SD, variables are either stocks, flows, or auxiliary. Stocks are accumulations, such as the amount of water in a reservoir. Generally, stock variables characterize the state of the system and create the information used to make decisions and determine actions. Flow variables define rates that can change stock variables. For example, the amount of water in a reservoir (a stock variable) is changed by inflows and outflows (flow variables; Simonovic 2009, Hassanzadeh et al. 2012). The stock value at any time (t) when the reservoir has one inlet and one outlet is calculated by:

$$Stock(t) = \int_{t_0}^{t} [Inflow(t) - Outflow(t)]\,dt + Stock(t_0), \qquad (1)$$

where, *Stock(t)* = Stock in time *t*; *Inflow(t)* = Inflow in time *t*; *Outflow(t) Outflow(t)* = Outflow in time *t*; and *Stock*(t_0) = Stock in time t_0. The auxiliary variables are neither stocks nor flows. They are functions of stocks or flows.

Dynamic hypothesis, causal loop, and stock-flow diagrams

In the context of SD, behavior of the main variables must be studied before drawing the causal loop and stock-flow diagrams. This process, called "presenting a dynamic hypothesis," is essential to accurately define and address differing aspects of the problem. If the dynamic hypothesis is properly established, then drawing causal loop, stock-flow diagrams, and formulating variables is easier.

The river inflow is expected to be oscillating and stochastic due to its dependency on precipitation, which is also a stochastic variable. The reservoir storage is directly related to river inflow so that in rainy months the reservoir storage increases and in dry months it decreases. The total water demand, including urban, agricultural, and environmental demands, exerts a major influence. These demands are controlled by population and agricultural zone growth rates.

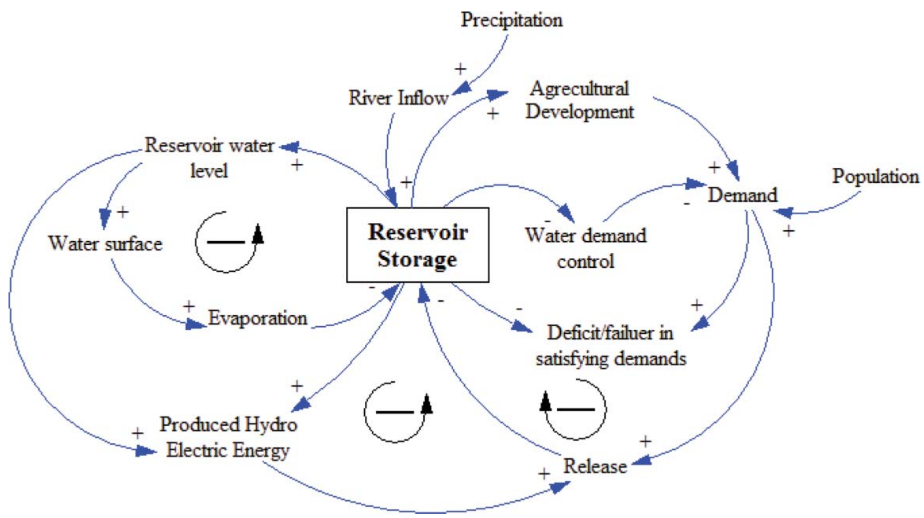

Figure 5.-Causal loop diagram for water management in Dez Reservoir (color figure available online).

According to the dynamic hypothesis and the relations among dependent and independent variables, causal loop and stock-flow diagrams were developed. The causal loop was developed to build stock-flow diagram and to formulate variables (Fig. 5). We then developed the stock-flow diagram of the SD model (not illustrated here due to space considerations).

Algebraic signs at the heads indicate the polarity of the relationship. A positive polarity indicates that an increase in the independent variable causes an increase in the dependent variable and vice versa. A negative polarity indicates that an increase in the independent variable causes a decrease in the dependent variable and vice versa. Positive loops reinforce and negative loops balance the main independent variable, which is the reservoir storage.

Parameter definitions

After the causal loops and the stock-flow diagram were determined, we identified critical points in the SD model and described the variables. The main assumptions in modeling are:

1. The monthly simulation time interval for the hydrologic time series analysis in this survey was from 1961 to 2011. By means of time series analysis (details presented later), data forecasting was conducted for 120 months (10 years), which was used as reservoir inflow in the SD model.
2. Satisfying urban water demand and hydropower energy production were assumed the higher priorities, and agricultural and environmental demands were lower priorities.
3. The Dez River basin has 125,000 ha of arable land that should be irrigated by Dez Dam outflow.
4. Computation of future demands was based on population growth.
5. During the forecasting interval, sediment volume of the reservoir was assumed constant and equal to the present sediment volume, which is about 700 million cubic meters (Mm^3). For a complete model the sedimentation ratio could be formulated with more detailed and also nonlinear relations; however these data were not available for this research.

Storage:

Reservoir storage in each time interval. The initial value (about $2 \times 10^9 m^3$) is set as the storage value at the beginning of the simulation interval. According to Loucks et al. (2005), the storage at the beginning of the second time interval of the year *y* can be computed by:

$$S_{2y} = S_{1y} + Q_{1y} - R_{1y} - E_{1y}, \tag{2}$$

where, S_{1y} is the previous reservoir storage, Q_{1y} indicates the total inflow in the previous month, R_{1y} is equal to reservoir spill and release of the previous month, and E_{1y} expresses the total evaporation of the month before.

Total inflow:

The Dez River flow, which is forecasted for 120 months (discussed in hydrologic time series modeling).

Evaporation:

Large numbers of empirical equations are available to compute the evaporation value, such as the formula of United States Geological Survey or United States Bureau of Reclamation:

$$E = 4.57T + 43.3, \tag{3}$$

where, E is the evaporation in cm/y and T indicates the mean annual temperature in C that can be computed from the height above sea level by some empirical relations.

f(Area-Storage) and f(Level-Storage):

To compute evaporation and spill, the water level-storage and water level-area diagrams (Fig. 6) of the Dez Reservoir were used and defined as a lookup graph in VENSIM.

Release:

Defined according to SOP (Fig. 1 and equation 4) as:

$$R_{1y} = \begin{cases} S_{1y} + Q_{1y} - K & \text{if } S_{1y} + Q_{1y} - R_{\min} > K \\ R_{\min} \quad \text{if} & K \geq S_{1y} + Q_{1y} - R_{\min} \geq 0 \\ S_{1y} + Q_{1y} & \text{Otherwise} \end{cases}, \tag{4}$$

where, K is the reservoir capacity, $R_{\min}$ is minimum release to be made if possible, S_{1y} is used to consider the previous reservoir storage, and Q_{1y} is the total inflow in the previous month.

Minimum release (R_{min}):

Equal to minimum demand, including minimum urban, agricultural, and environmental demands. Hydropower demand is considered in the next section.

Hydroelectric power production:

The primary function of the Dez Dam. The total megawatt-hours of energy produced in period t can be calculated by (Loucks et al. 2005):

$$MWH_t = 2.725 Q_t^T H_t e, \tag{5}$$

where, H_t is the storage head (vertical distance between the water surface elevation and the maximum of either the turbine elevation or the downstream discharge elevation), Q_t^T expresses the total flow through the turbines in period t, and e is the plant efficiency. Note that the Dez Dam is equipped with a 520 megawatt hydropower plant designed to produce about 2000 gigawatt-hours of hydroelectric energy

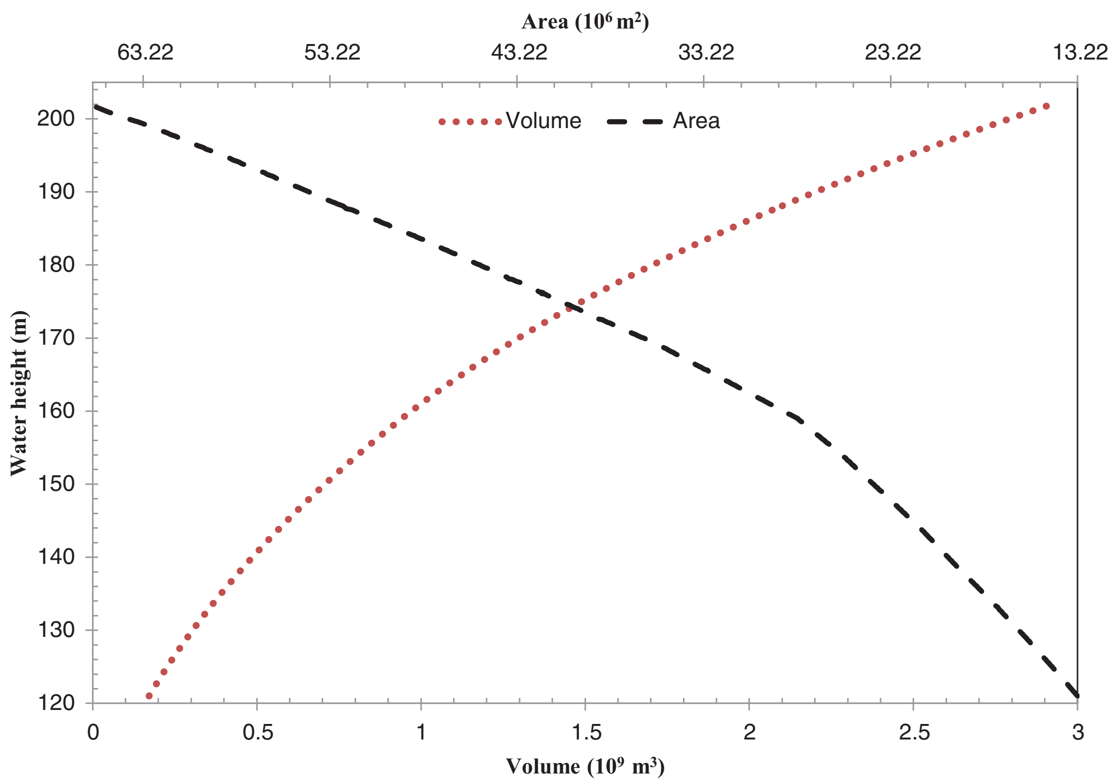

Figure 6.-Water height–volume–area graphs of Dez reservoir (color figure available online).

every year. In this study, supplying hydroelectric energy and satisfying urban water demand were the first priorities.

Flood control:

Throughout the flood-prone months, the reservoir should have sufficient available storage to accommodate probable flood volumes; according to Malekmohammadi et al. (2011), a 845.28 Mm^3 volume should be reserved for a 1000-year flood, and in our SD model, this recommendation was implemented for the flood-prone months.

Urban demand:

Computed from the population in each time interval as:

$$\textit{Urban demand} = \textit{Population} \times \textit{Water Per Capita}. \tag{6}$$

According to the Iran Ministry of Power and Energy local policies, 50% of the whole water demand in Khuzestan province, including 21 cities and 1200 villages, should be satisfied by Dez Dam. The total population of this area was estimated to be about 2,957,600 in 2011. The average urban water demand per capita in Iran is about 250 L/d, but because of the warm climate of Khuzestan province, this reaches 400 L/d, or an average monthly value of 12 m^3 per person. However, for more accurate modeling, instead of this average value, the actual monthly urban water demand per capita of the Khuzestan province was used (Fig. 7).

Population:

Statistics show a net growth rate in this area; therefore, the population at the end of the next month is calculated by multiplying the population in the present month by the net annual growth rate (i). After n months, the new population P is calculated from the initial population P_0 as:

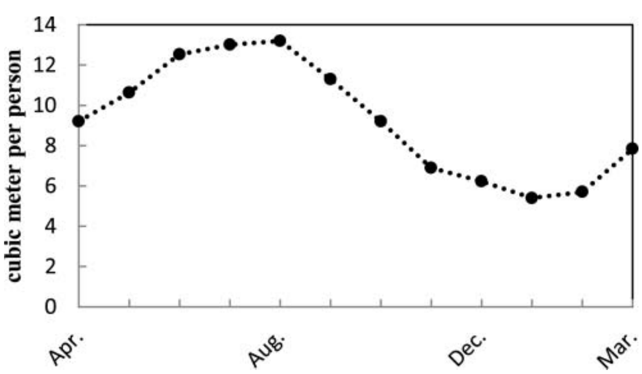

Figure 7.-Monthly pattern of urban water demand per capita in Dez reservoir area.

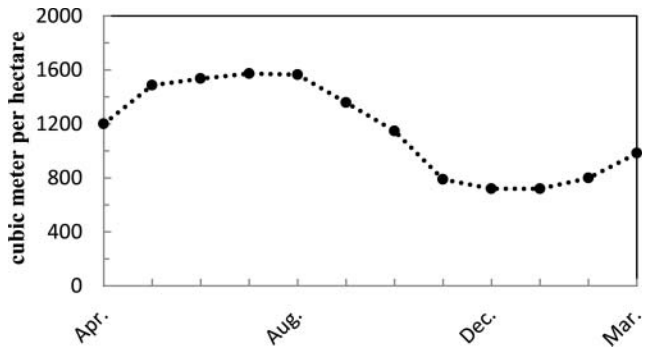

Figure 8.-Agricultural water demand per unit of area per month for Dez reservoir area.

$$P = P_0 \left(\frac{1+i}{12} \right)^n. \tag{7}$$

Agriculture demand:

About 125,000 ha of the agricultural lands in Khuzestan province is irrigated by the Dez Dam. Average required water per unit of irrigated area is about 967 (m^3/hec/month), but for more accurate modeling, instead of using the average value, the actual monthly required water per unit area based on the monthly agricultural consumption pattern was used (Fig. 8). It was further assumed that this monthly agriculture demand pattern remained constant during the simulation time interval.

Environmental demand:

To maintain acceptable environmental conditions downstream, the river should be maintained at a minimum flow. Although no method has been established to determine this environmental demand for the Dez Dam, a value based on literature values was computed as follows:

$$\begin{aligned}\textit{Environmental demand} &= 0.2 \\ &\times \textit{mean annual minimum flow} \\ &= 0.2 \times (16.394 \times 3600 \times 24 \times 30),\end{aligned} \tag{8}$$

in which 16.394 is the mean minimum flow in m^3 /sec and converted to m^3 /month.

After descibing these parameters, their formulas were incorporated into VENSIM (Table 1).

Hydrologic time series modeling for Dez River flow

The stochastic and seasonal characteristic of the reservoir inflows (river flow) suggested a seasonal hydrologic time series mode for this case study. The flow data (Fig. 9) were a nonstationary time series. This is confirmed by the Auto

Table 1.-Some variable formulations to be used in SD model.

Variable name	Formulation in VENSIM
Storage (m^3)	Storage = ∫ (Total Inflow − Evaporation − Release − Spillway)dt
Hydropower Flow (m^3/month)	IF THEN ELSE(Storage + Total Inflow-Evaporation> = Reservoir Capacity-Flood Controlling Volume(Help5), MAX(IF THEN ELSE(Storage +Total Inflow-Evaporation> = Minimum storage according to Power House Intake level, MIN(0.6*(Storage + Total Inflow -Evaporation-Sediment Volume), Minimum Needed Flow), 0), Flood Controlling Volume(Help5)-Reservoir Capacity+ Storage + Total Inflow-Evaporation),IF THEN ELSE (Storage + Total Inflow-Evaporation> = Minimum storage according to Power House Intake level, MIN(0.6*(Storage + Total Inflow -Evaporation-Sediment Volume), Minimum Needed Flow), 0))
Produced Energy (MWH)	2.725e-006*Hydropower flow*Water Level*Efficiency
Evaporation (m^3/month)	Evaporation = Area × (4.57 × Temp + 43.3)/100
Spillway (m^3/month)	IF THEN ELSE((Storage + Total Inflow-Release-Evaporation-Hydropower flow>Reservoir Capacity),(Storage + Total Inflow-Evaporation-Release-Hydropower flow-Reservoir Capacity),0)
Release (m^3/month)	IF THEN ELSE(R min< = Hydropower flow, 0, MIN(Storage + Total Inflow-Evaporation-Hydropower flow, R min-Hydro Power flow))
R_{min} (m^3/month)	(Agriculture Demand + Urban Demand + Environmental Demand)*Hedging Rule
Total Discharge (m^3/month)	(Release + Spillway + Hydropower flow)
Agriculture demand (m^3/month)	Agriculture terrain*Required Water per Area Unit(Help2)*Agriculture Demand Amendment
Urban flow (m^3/month)	IF THEN ELSE(Total Discharge>Urban Demand, Urban Demand,Total Discharge)
Agriculture flow (m^3/month)	IF THEN ELSE((Total Discharge-Urban Flow)>Agriculture Demand, Agriculture Demand,(Total Discharge-Urban Flow))
Down Stream flow (m^3/month)	Total Discharge-Urban Flow
Hydropower Loss (m^3/month)	IF THEN ELSE(Hydropower flow> = Minimum Needed Flow, 0, Minimum Needed Flow-Hydropower flow)
Total Shortfall (m^3/month)	Agriculture Shortfall + Urban Shortfall + Environmental Shortfall + Hydropower Shortfall

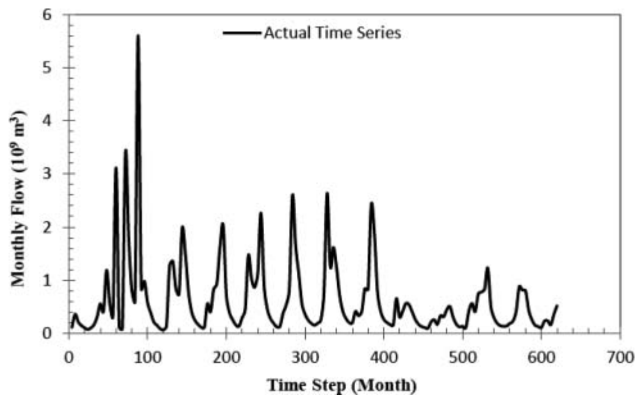

Figure 9.-Fifty-year time series of inflow to Dez River.

Correlation Function (ACF) and Partial Auto Correlation Function (PACF) histograms.

Differencing is one way to transform a nonstationary series, such as a seasonal series, to a stationary one (Salas et al. 1980). We fit an Autoregressive Integrated Moving Average (ARIMA) model with the first-order differencing to the time series data (Box et al. 1994) as follows:

$$\begin{aligned} Z(t) \quad & + 0.78\ Z_{t-1} + 0.62\ Z_{t-2} + 0.32\ Z_{t-3} \\ & + 0.86\ Z_{t-6} + 0.67\ Z_{t-7} + 0.54\ Z_{t-8} \\ & + 0.27\ Z_{t-9} = -645086.7 + \varepsilon_t \\ & + 0.68\ \varepsilon_{t-6} - 0.26\ \varepsilon_{t-8}. \end{aligned} \tag{9}$$

The normality test of residuals indicates that the estimated model was appropriate. We also compared synthetic data to the actual time series and confirmed the goodness of fit for the selected seasonal ARIMA model (Fig. 10). We used this model to generate time series of flow data and implemented it as a look-up variable in VENSIM.

Validating the SD model

Structure assessment tests

Structure assessment tests are used to assess whether a model is consistent with knowledge of a real-world system (Sterman 2000). Using the most recent 5 years of available storage volume data, the model results show acceptable correlation with the observations (Fig. 11).

Extreme condition tests

Some conventional tests are also used to assess the SD model in extreme conditions and to verify its logic (Sterman 2000). In the first case, we assumed that initial storage and total inflow were zero; hence, we expected parameters such as evaporation, release, storage, and spillway to become zero after simulation. In the second case we assumed the initial storage of the reservoir to be equal to its capacity, which means the reservoir is full and all output flows are equal to zero except total inflow and spillway; therefore, we expected to find equal values for the spillway and the total inflow. Both extreme validation tests yielded the expected results.

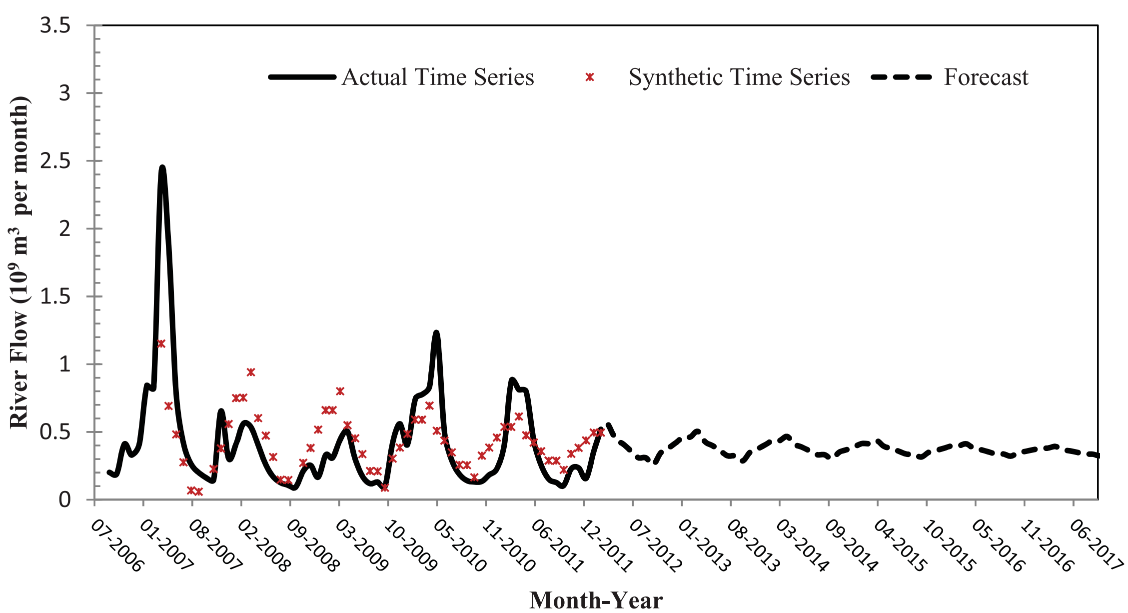

Figure 10.-Synthetic time series vs. actual data accompanied by forecasted time series (color figure available online).

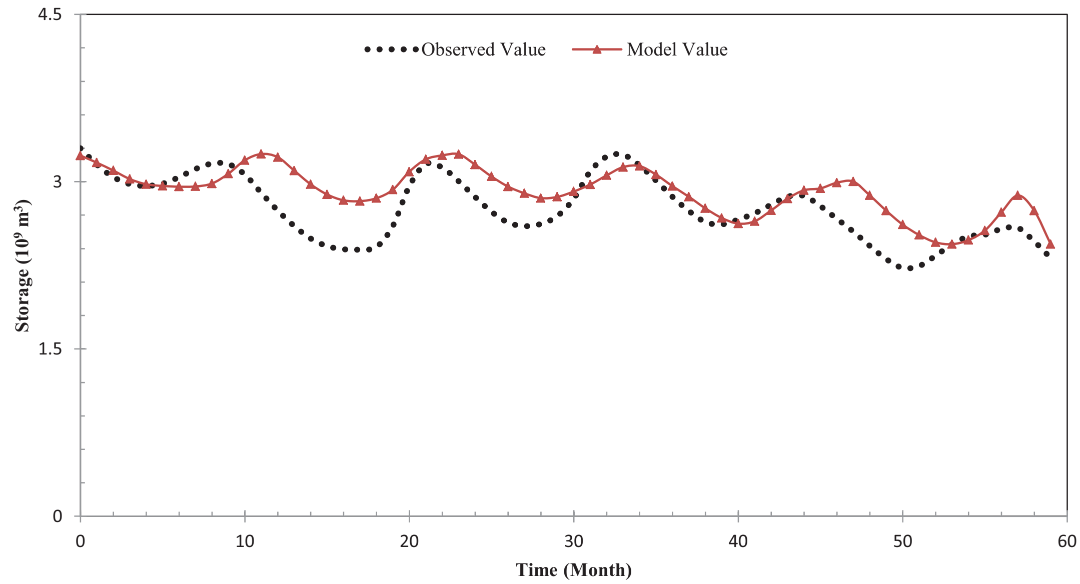

Figure 11.-Validating the Dez Reservoir SD model through storage parameter for 5 years (color figure available online).

Comparison among scenarios with performance criteria evaluation

Preliminary plan

For the preliminary policy, supplying required hydroelectric energy and urban demand be considered our first priority. In addition, if there is enough water storage, this policy will try to satisfy the whole demand (maximum of R_{min} and hydropower demand) every month. The results presented in Figs. 12–14 (representing simulated reservoir storage, the deficits in satisfying demands and the treatment of reservoir releases for different scenarios), respectively, show the efficiency of every policy. By applying the preliminary plan

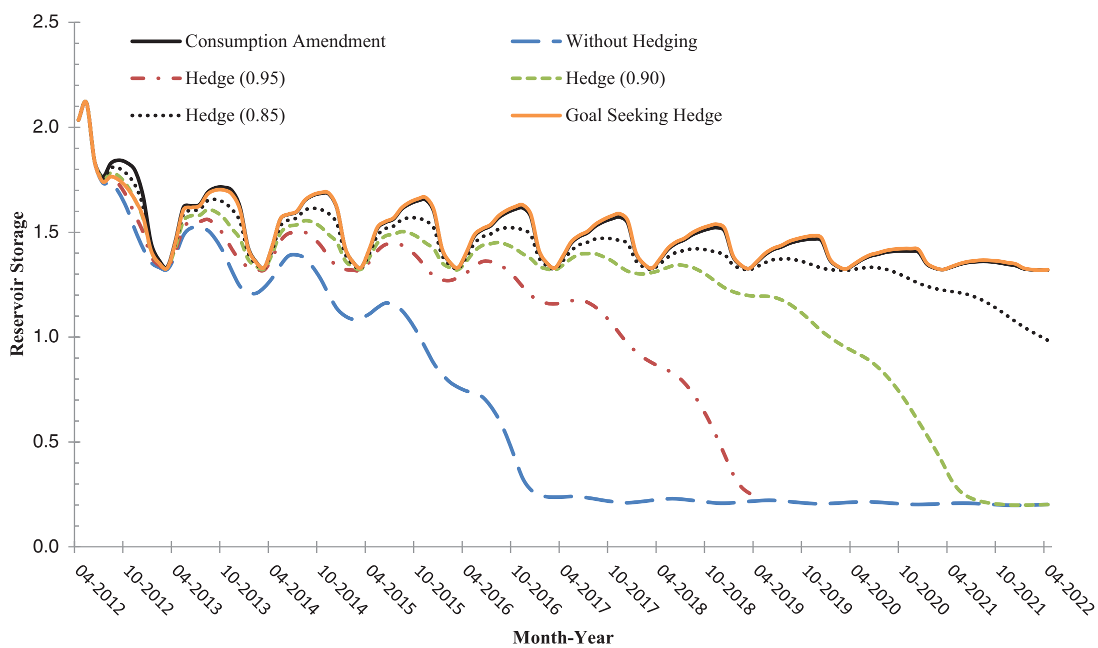

Figure 12.-Dez Reservoir storage (10^9 cubic meters) for differing hedging scenarios (color figure available online).

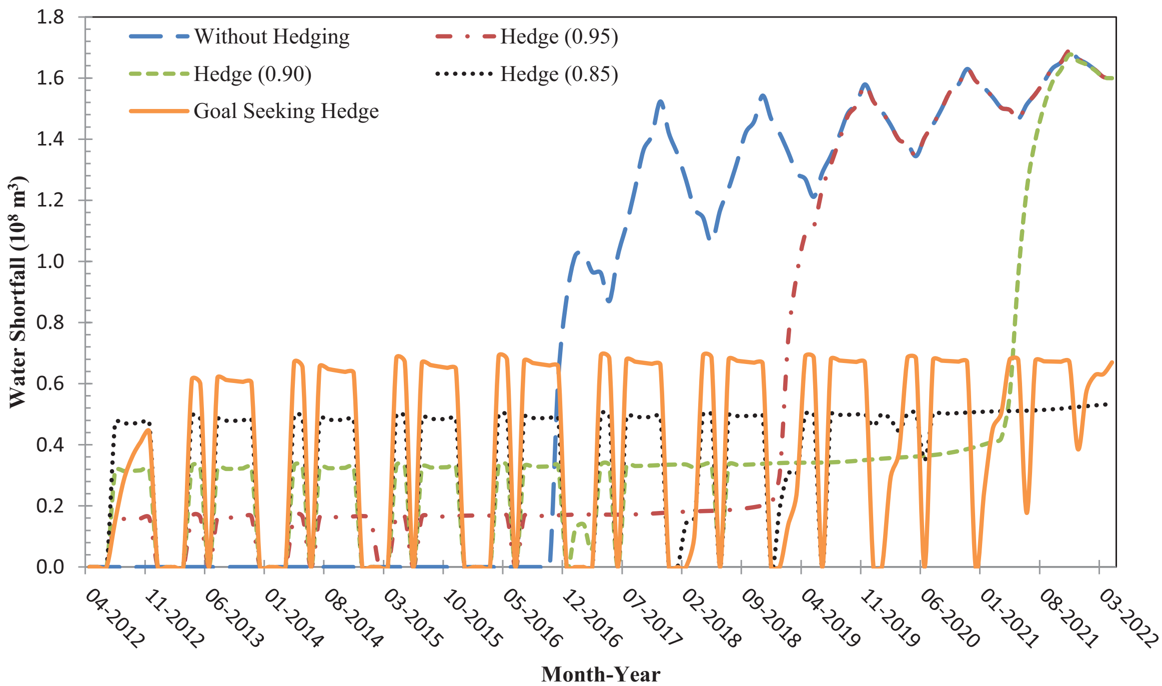

Figure 13.-Water shortfall diagram for different hedging scenarios (color figure available online).

(without hedging), the reservoir storage reached the value of 201 Mm^3; however, we had severe failures to meet all demands, such as shortfall of 160 Mm^3 by the end of the simulation period. The results of this policy are clearly unsatisfactory.

Using the hedging rule

In some cases, severe deficits in satisfying demands would have irreparable consequences on downstream agronomy or industries. Water resources engineers endeavor to reduce

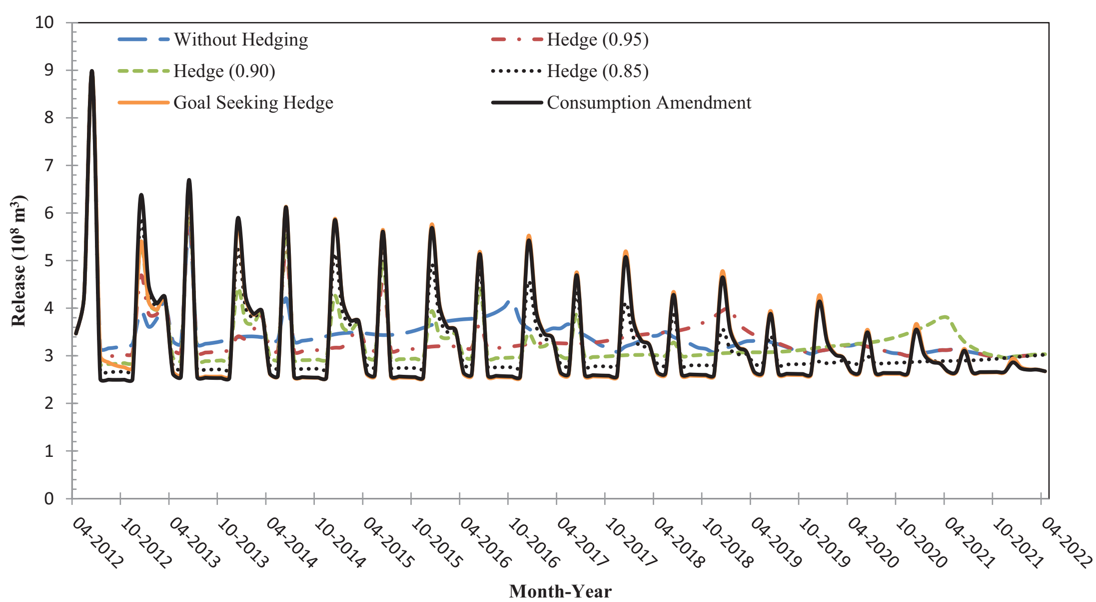

Figure 14.-Dez Reservoir releases for different hedging scenarios (color figure available online).

the severity of deficits by using methods like hedging rule. Under a hedging rule, demands are not satisfied completely in each simulation time period, even with adequate water storage. The goal of hedging is to hold a volume as insurance against the most severe deficits that might occur during drought. The simplest case, a 1-point hedge, is implemented by applying reducing coefficients like 0.85, 0.90, and 0.95 to the demands, which means that only 85, 90, or 95% of the target demands, respectively, would be satisfied in each time interval. The single-point hedge introduces obvious disadvantages by using a constant reducing coefficient across all months. We propose a different approach, the "goal seeking hedge." Our central assumption in this approach is that when extreme conditions are actually encountered, hedging can be relaxed so that the "insurance" built up by hedging during less-severe conditions is then used to combat the most severe effects. In this rule, instead of using a constant reducing coefficient, a variant coefficient is implemented that reflects the volume of deficits in the previous periods, so that in the more severe deficits, less hedging (more delivery) is applied as follows:

$$\begin{aligned} &\mathit{Hedging\ Coefficient}_i \\ &= \mathit{max}\left(\alpha, \left(1 - \frac{1}{i}\sum_{j=1}^{i}\frac{D(j) - v(j)}{D(j)}\right)\right), \end{aligned} \tag{10}$$

where, α is the lower limit of coefficient, $v(j)$ is the deficit volume, $D(j)$ is the total demand volume in each period, and i is the total number of time steps.

Our results indicate that by applying hedging rule, the reservoir condition improves, and by implementing the goal-seeking hedge, we can reach the most stable condition for the reservoir during the simulation process (Figs. 12 and 13). Thus, by applying the goal-seeking hedge, severe deficits in satisfying demands disappear. Further positive effects of this hedging rule are shown by using performance criteria.

Reducing demands by using special policies

In the Dez River basin, about 90% of water is consumed by agricultural demands; therefore, reduction in agricultural consumption through modernization of irrigation methods and equipment would greatly reduce water demand. In addition, the average water consumption per capita in Khuzestan is about 400 L/d, which is 3 times the average consumption per capita in Iran; therefore, the government could apply special policies to reduce water consumption, such as increasing water and energy costs for users, a tactic recently applied in other countries and elsewhere within Iran (Moshiri 2013). To simulate a 20% reduction in agricultural and urban water consumption as well as hydroelectric energy consumption, a parameter called "demand amendment" is included in the SD model. This 20% reduction in water consumption will improve the reservoir storage condition without applying the hedging rule (Fig. 12), and no deficits will occur during the simulation process (Fig. 13).

Evaluation of strategies by use of performance criteria

A performance evaluation was used to make a more accurate comparison among scenarios. According to Hashimoto et al. (1982), 3 kinds of criteria can be used to evaluate water resources systems:

(1) Reliability, which describes the likelihood of a system failure:

$$Rel = 1 - \frac{\sum_{j=1}^{M} d(j)}{T}, \tag{11}$$

where, $d(j)$ is the duration of the *jth* excursion into a failure period, M is the number of failure events, and T is the total number of time steps. This definition of reliability calculates the possibility of satisfying demands, but it does not consider the severity of deficits in each period; therefore, this criterion would not distinguish between a 1 Mm^3 deficit and a 100 Mm^3 deficit. This study uses a new type of reliability, the corrected reliability, to overcome this limitation:

$$\begin{aligned} &\mathit{Corrected\ Reliability} \\ &= \frac{1}{T}\sum_{j=1}^{T}\frac{D(j) - v(j)}{D(j)}, \end{aligned} \tag{12}$$

where, $v(j)$ is the deficit volume that corresponds to $d(j)$ and $D(j)$ is the total demand volume that corresponds to $d(j)$.

(2) Resilience, which indicates how quickly a system recovers from a failure:

$$Res = \left[\frac{\sum_{j=1}^{M} d(j)}{M}\right]^{-1}. \tag{13}$$

In this study, some of the scenarios reach conditions with no deficits, where $M = 0$, and these could not be evaluated using resilience criteria.

(3) Vulnerability, which indicates the severity of the consequences of a failure and is based on Kundzewicz and Kindler (1995) relation:

$$Vul = \max(v(j)). \tag{14}$$

Table 2.-Performance criteria and sustainability criterion evaluation results for different scenarios

Scenarios	Corrected Reliability	Resilience	Vulnerability (Mm^3)	Sustainability
1. Without Hedging	0.8709	0	136.94	0
2. Hedge (0.95)	0.8971	0.042	62.92	0.031
3. Hedge (0.9)	0.9192	0.0642	46.53	0.051
4. Hedge (0.85)	0.9152	0.0943	47.35	0.075
5. Goal-Seeking Hedge	0.9002	0.1313	60.27	0.098
6. Consumption Amendment	0.9917	0	0	—

Another formula for computing the vulnerability criterion was presented by Kjeldsen and Rosbjerg (2001):

$$Vul = \frac{1}{M} \sum_{j=1}^{M} v(j), \tag{15}$$

where, M is the number of failure events and $v(j)$ is the deficit volume corresponding to $d(j)$.

Numerous sustainability criteria in the analysis of water resources systems have been proposed (e.g., Loucks 1997, Matheson et al. 1997). According to Kjeldsen and Rosbjerg (2001), a sustainability index of S can be calculated for each scenario of i:

$$S(i) = Rel(i)\ Res(i) \left[1 - \frac{Vul(i)}{sum\ of\ Vul(i)\ from\ all\ scenarios}\right]. \tag{16}$$

From equations 11–16, the performance criteria and the sustainability criterion for different scenarios were calculated (Table 2). For the first and the sixth scenarios, the resilience criterion becomes zero for differing reasons (Table 2). In the first scenario (without hedging), the model cannot recover when it reaches the first failure, so the resiliency criterion becomes zero. In the last scenario the value for resiliency is zero because no deficits occurred during the simulation process; therefore, the sustainability criterion is irrational for the consumption amendment scenario and was not calculated.

Except for the last scenario (consumption amendment), the new type of hedging rule (goal-seeking hedge) clearly yields superior results and provides the most sustainable water use policy (Table 2).

Conclusions

In this study, 3 types of scenarios were considered and evaluated for effective reservoir management. In the preliminary plan, we attempted to satisfy all demand; however, the simulation showed that severe deficits may occur, and reservoir storage can reach a critical condition at the end of the simulation period. By applying the hedging rule as the second scenario, the average deficit in satisfying the demand is significantly reduced. In this process, a new type of hedging rule, termed the goal-seeking hedge, was also evaluated. This approach gave the highest value of the sustainability criterion and was more suitable than the common 1-point hedging. Nonetheless, according to performance criteria evaluations, the best and the most sustainable conditions can be achieved by applying a 20% consumption reduction. We conclude from this study that applying the goal-seeking hedge policy in addition to controlling water consumption through special policies will result in the best outcome.

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