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Determination of the Optimal Level of Water Releases from a Reservoir to Control Water Quality

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Abstract: The increase of pollution loads and of the diversity of pollutants threatening water resources calls for sophisticated management of water resources. This paper shows that the thermal stratification of water in reservoirs and the variation of its density with reservoir depth make it possible to manage sudden water-pollution events by controlling water release as a function of lake depth to minimize effects associated with the release of polluted water from reservoirs. The best outlet level of a reservoir to release polluted water is selected in this paper using the technique for order performance by similarity of ideal solution (TOPSIS). The latter is a multicriteria decision-making (MCDM) tool for managing water quality in reservoirs. The application of MCDM is illustrated with the management of reservoir releases to cope with the sudden spill of 30 m^3 of methyl tertiary butyl ether (MTBE) into the Amirkabir reservoir (Iran). The CE-QUAL-W2 calibrated model is used to simulate the spreading of MTBE in the reservoir. Pollutant spreading is predicted under four seasonal pollution scenarios and one scenario considering all seasons simultaneously. This allows for the consideration of the effects of climatic and water demand conditions on reservoir water quality. This paper's results show that the water should be released from the low-elevation gate in spring and winter and from the high-elevation gate in summer and autumn to optimally manage the sudden release of MTBE spills in the Amirkabir reservoir. **DOI: 10.1061/(ASCE)HZ.2153-5515.0000295.** *© 2015 American Society of Civil Engineers.*

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Introduction

Recent publications dealing with optimization models have included several domains of water resources systems, such as reservoir operation (Ashofteh et al. 2013a, 2015a), levee layouts and design (Bozorg Haddad et al. 2015b), design operation of pumped-storage and hydropower systems (Bozorg Haddad et al. 2014), and algorithmic developments (Ashofteh et al. 2015b). However, in the analysis of some systems, it is not possible to develop an optimization algorithm for solving the problem. In such cases, simulation models [such as the Monte Carlo approach (Ashofteh et al. 2015c)] can be used as an appropriate tool. To derive operating policy (either through the use of optimization or simulation models), a few of these research studies have considered the transition probabilities (Ashofteh et al. 2013b). In addition, only a few of these works dealt with the qualitative management of water resources systems [such as Bozorg Haddad et al. (2015a)].

The growing demand for safe water has spearheaded research on optimal ways to control water quality. One case in point is the modeling of water quality in reservoirs to respond to the sudden release of pollutants. Because of wide-ranging properties among pollutants in water one must choose a suitable model to simulate the behavior of contaminants in reservoirs. One of the strategies that is used at the time of the entry of pollutants into the reservoir is to determine the appropriate outlet level by simulation models. Nandalal and Bogardi (1995) used the dynamic reservoir simulation model (DYRESM) and a nonlinear programming (NLP) model to determine appropriate locations for reservoir outlets in order to affect the quality of water released from the reservoir. The quality of released water from the reservoir was a constraint. The model was used to obtain a suitable operation policy for water release in the Rais-Ali Delvari dam (Iran). Elçi (2008) examined the effect of thermal stratification on water quality in the Tahtali reservoir (Turkey) by using field observation and statistical analysis. Their results indicated that air temperature, wind speed, and humidity were important parameters in the thermal stratification in the reservoir and had an effect on its water quality.

To determination of the appropriate outlet for a pollutant requires a pollutant simulator capable of simulating thermal stratification in a reservoir. The two-dimensional model CE-QUAL-W2, as well as models such as DYRESM and SNTEMP, can simulate thermal stratification in reservoirs (Norton and Bradford 2009). The following review of pertinent publications demonstrates the viability of CE-QUAL-W2 to simulate water quality in stratified reservoirs.

Gelda et al. (1998) applied the U.S. Army Corps of Engineers' water quality modeling (2D) (CE-QUAL-W2) to the Cannonsville reservoir (located in Delaware County, New York). The model was calibrated with temperature data collected at six locations within the reservoir over the April–November period of 1995 (with a weekly time interval). Their study succeeded in simulating temperature regimes in different climatic periods with the CE-QUAL-W2 model.

Etemadi-Shahidi et al. (2009) investigated the total maximum daily load (TMDL) of total dissolved solids (TDS) from the

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Karkheh reservoir (Iran). The CE-QUAL-W2 model was implemented to simulate TDS and temperature data (over two years). Their results indicated a 50% reduction of the TDS loads that improved water quality.

Rangel-Peraza et al. (2012) investigated thermal stratification, dissolved oxygen (DO), and TDS concentrations in the Aguamilpa reservoir (Mexico). The CE-QUAL-W2 model was used to simulate the temporal variations of water quality. Temperature-depth profiles indicated a large stratification in the lower part of the reservoir near the dam. Profiles of DO concentration exhibited some degree of anoxia in the bottom water that was attributable to decomposition of vegetation and organic matter via soil erosion and runoff from the basin accumulating at the bottom of the reservoir. Their results indicated that the CE-QUAL-W2 model helped water resource managers to better understand the dynamics of physical-chemical processes that govern the water quality in the reservoir.

Bonalumi et al. (2012) investigated the effects of a planned 1,000 MW pumped-storage (PS) scheme on water temperature and particle mass concentration in two basins (Switzerland). The upper basin was a reservoir receiving large amounts of fine particles, while the lower basin was a natural lake. Stratification and particle concentrations in the two basins were simulated with and without PS for four different hydrological conditions. The results showed that the PS operations led to an increase in temperature in both basins.

Saadatpour and Afshar (2013) developed a pollution spill response management model (PSRMM). This model consisted of a spatial-system-analyzing (SSA) model, a 2D hydrodynamic and water quality simulation model (CE-QUAL-W2), and a multi-objective particle swarm optimization (MOPSO) algorithm. The CE-QUAL-W2 model was coupled with the MOPSO algorithm to obtain an optimal reservoir operation strategy in the Ilam reservoir (Iran). Their results showed that the proposed model was a successful tool to manage the sudden spill of pollution in the reservoir.

The above studies showed the ability of CE-QUAL-W2 model to simulate pollutants in reservoirs. The pollutant considered in this study (MTBE) is somewhat different from those of the cited studies. MTBE is from a family of soluble and volatile organic compounds (VOCs). Heald et al. (2005) used pollutants from this family of compounds in their research. They examined the effect of hydrodynamics, evaporation, and first-order decay factors in the simulation of volatile organic compounds in lakes using a one-dimensional, process-based, numerical model. Acceptable results were obtained from their research (McCord and Schladow 1998; Stocking and Kavanaugh 2000).

Shokri et al. (2013) developed a modified CE-QUAL-W2 model capable of simulating MTBE fate and transport in reservoirs based on the research of Heald et al. (2005). Shokri et al. (2013) applied a two-objective optimization algorithm for quantitative-qualitative reservoir operation. Their results showed that MTBE pollution was decreased about 60%, with a reduction of 36% in demand by using their optimization model.

The previous studies have shown the importance of using an appropriate tool to select optimal management alternatives for water quality in reservoirs based on pollution simulations. Several previous studies have established that the CE-QUAL-W2 model can be considered an effective model for simulation of water quality in reservoirs. Various studies have also demonstrated that thermal stratification (during this process, layers of water have different temperatures) in reservoirs causes changes in water quality at different depths. Therefore, the elevation at which water is withdrawn from a reservoir affects the water quality of released water as well as that of the water within the reservoir. Hence, one of the ways to manage the release of polluted reservoir water is through the optimal selection of the depth of outlets for water release. The complexity of reservoir operation and the limited management options call for the selection of optimal strategies for managing water quality in reservoirs by using appropriate criteria.

MTBE is considered as an input pollutant to the Amirkabir reservoir (Iran) in this study. The CE-QUAL-W2 model is herein used for simulating MTBE in the reservoir and at different outlet levels. The decay rate of MTBE is considered in this study. This leads to accurate MTBE simulation predictions. Next, five performance criteria, namely, (1) the number of days of release of polluted water from the reservoir with MTBE concentration exceeding the permitted level, (2) the maximum concentration of MTBE within the reservoir, (3) MTBE mitigation, (4) qualitative reliability, and (5) qualitative vulnerability, are used for each gate elevation. Lastly, the best level of water release from the reservoir is selected by the TOPSIS multicriteria decision-making method. This paper illustrates the selection of an optimal reservoir outlet for water releases from a polluted reservoir to manage water quality using multicriteria decision making.

Methodology

A simulation model of water quality is introduced in this section and its characteristics are described. Subsequently, a method for multicriteria decision making is described. Four scenarios related to the pollutant (MTBE) entry into the reservoir are outlined. Lastly, criteria and modeling information used in the research are stated.

The CE-QUAL-W2 model herein employed is used to calculate the five-part evaluation criteria for each of the four scenarios of seasonal pollution. Inputs to CE-QUAL-W2 are reservoir geometry, reservoir structures, meteorological and hydrological data, the amount and type of input pollutant, and the location of pollutant entry. Due to the effect of climatic seasonal changes on the evaluation criteria and consequently on the selection of gate level, the four scenarios of seasonal pollution are considered.

Water Quality Simulation Model

CE-QUAL-W2 is a two-dimensional laterally averaged model that simulates pollution as a function of depth and length (Cole and Wells 2006). In this model, the cross section is assumed homogeneous laterally and variable vertically. Thus, it is useful to simulate water bodies in which changes in lateral pollution are slight. The features of this software include the following: (1) open source code and the possibility of software coding additions by users; (2) two-dimensional pollutant simulation capabilities in the vertical direction (i.e., changes of pollutant with depth in a lake) and horizontal direction (i.e., changes of pollutant over the length of a lake); (3) the possibility of thermal simulation of the reservoir; (4) the capacity to consider the effect of meteorological parameters, such as solar radiation, wind speed, and air temperature; and (5) the ability to simulate structures embedded in reservoirs.

Multicriteria Decision Making by TOPSIS Method

The TOPSIS multicriteria decision-making method was introduced by Hwang and Yoon (1981). This method relies on the concept that appropriate options have the minimal distance compared to the positive ideal solution (best option) and the maximal distance compared to the negative ideal solution (worst option). In this method,

m options are evaluated by n criteria (defining a matrix Z of order mn) according to Eq. (1)

$$[Z]_{ij}=\begin{bmatrix} z_{11} & z_{12} & \cdots & z_{1m} \\ z_{21} & z_{22} & \cdots & z_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ z_{m1} & z_{m2} & \cdots & z_{mn} \end{bmatrix}_{m\times n} \qquad i=1,2,\ldots,m \quad j=1,2,\ldots,n \tag{1}$$

in which $[Z]_{ij}$ = decision matrix; and z_{ij} = performance of option i in relation to performance criteria j.

This method assumes that the utility of each criterion is either increasing or decreasing. The TOPSIS method has the ability to prioritize and select the best option considering the effect of the criteria. For this reason, TOPSIS has the capacity to select appropriate decisions when management scenarios are provided (Lev 2001). The TOPSIS method involves the following steps.

Quantifying and Producing Dimensionless Matrix

The Euclidean norm is used to produce a dimensionless matrix. For this purpose, the performance of each option i associated with corresponding criteria j is normalized according to Eq. (2)

$$[DZ]_{ij}=\frac{z_{ij}}{\sqrt{\sum_{i=1}^{m} z_{ij}^2}} \qquad i=1,2,\ldots,m \qquad j=1,2,\ldots,n \tag{2}$$

in which $[DZ]_{ij}$ = dimensionless decision matrix.

Determination of Weighted Dimensionless Matrix

The dimensionless matrix ($[DZ]_{ij}$) from the previous step is multiplied by the weighted matrix of criteria according to Eq. (3)

$$[WDZ]_{ij}=W_{jj}\times[DZ]_{ij} \qquad i=1,2,\ldots,m \qquad j=1,2,\ldots,n \tag{3}$$

in which $[WDZ]_{ij}$ = weighted dimensionless decision matrix; and W_{jj} = weighted diagonal matrix of criteria.

Determination of the Positive Ideal Solution (*PI*) and Negative Ideal Solution (*NI*)

A positive ideal solution is defined as the vector of the best values of each matrix criterion (J^+), and a negative ideal solution is defined as the vector of the worst values of each matrix criterion (J^-). The best values for the positive criteria are the largest values and the best values for the negative criteria are the smallest values as expressed by Eq. (4) below. Also, according to Eq. (5), the worst values for positive criteria are the smallest values and the worst values for negative criteria are the largest values

$$PI=\{(\mathrm{Maximum}[WDZ]_{ij}|j\in J^+),(\mathrm{Minimum}[WDZ]_{ij}|j\in J^-)\} \qquad i=1,2,\ldots,m \qquad j=1,2,\ldots,n \tag{4}$$

$$NI=\{(\mathrm{Minimum}[WDZ]_{ij}|j\in J^+),(\mathrm{Mazimum}[WDZ]_{ij}|j\in J^-)\} \qquad i=1,2,\ldots,m \qquad j=1,2,\ldots,n \tag{5}$$

in which PI and NI = positive and negative ideal solutions, respectively; and J^+ and J^- = vector of the best and worst values of each matrix criterion, respectively.

Determination of the Euclidean Distance

The Euclidean distance of each option to the positive and negative ideals is determined according to Eqs. (6) and (7)

$$d^+=\sqrt{\sum_{j=1}^{n}([WDZ]_{ij}-[WDZ_j^+])^2} \qquad i=1,2,\ldots,m \qquad j=1,2,\ldots,n \tag{6}$$

$$d^-=\sqrt{\sum_{j=1}^{n}([WDZ]_{ij}-[WDZ_j^-])^2} \qquad i=1,2,\ldots,m \qquad j=1,2,\ldots,n \tag{7}$$

in which d^+ and d^- = Euclidean distance of each option to the positive and negative ideals, respectively.

Determination of the Relative Proximity

The final criterion of relative proximity to the ideal solution is computed according to Eq. (8)

$$F_i^*=\frac{d_i^-}{d_i^-+d_i^+} \qquad i=1,2,\ldots,m \qquad j=1,2,\ldots,n \tag{8}$$

in which F_i^* = relative proximity of each option to the ideal solution.

Ranking of Options

According to this ranking, an option whose F_i^* is larger than the F_i^* of another option is the better option of the two.

Study Region, Criteria, Information, and Scenarios

This section describes (1) the characteristics of the Amirkabir reservoir, its components, and location; (2) evaluation criteria; (3) management scenarios based on the time of pollution occurrence and the assumptions and limitations of the study; and (4) the data needed for the implementation of the CE-QUAL-W2 model.

Case Study

The Amirkabir dam was completed in 1961. The purposes of the dam are (1) flood control, (2) drinking water supply for the city of Tehran and agricultural water to Karaj, (3) and hydropower production. The Amirkabir dam is a double-arch concrete dam with a maximum height of 180 m above its foundation, floor thickness of 30 m, and crown width of 9 m. The maximum surface area of reservoir's lake is 4 km^2. The Amirkabir dam is located 63 km northwest of Tehran traveling 23 km along the Karaj-Chalus road. The catchment area is 764 km^2 and average runoff is 472 (10^6 m^3). The dam site impounds the Karaj River. The river originates in the Alborz Mountains and finally discharges at its downstream end to a salt lake near the city of Qom.

Modeling Information

A reservoir geometry file must be created. For this purpose, the reservoir geometry is extracted in discrete format from a topographic map with a scale of 1:5,000. Fig. 1 shows a longitudinal plan view of the reservoir created for the CE-QUAL-W2 software. In this Figure, reservoirs sections are numbered 1 through 21 and pollution enters through Section 10. Calculations are performed based on this view. Fig. 2 shows a vertical cross section of the Amirkabir reservoir that contains 46 layers with layer thicknesses of 1, 3, 5, and 10 m. Pollution enters the reservoir through layers 1–4 of longitudinal section 10.

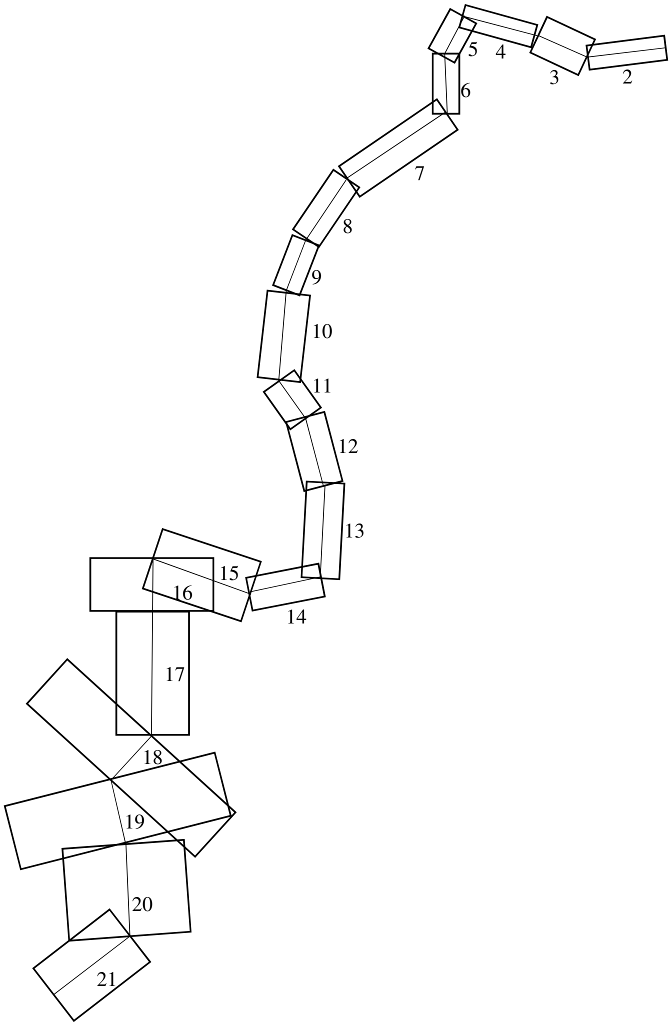

Fig. 1. 21 longitudinal divisions of the Amirkabir reservoir (plan view)

Type of Pollutant and Its Characteristics

It is assumed in this study that a tanker carrying MTBE fuel suffers an accident and releases the MTBE into the reservoir very rapidly. The volume of released MTBE is equal to 30 m^3. MTBE is more soluble in water than gasoline and toluene, and its volatility in water is lower than those of these two compounds, thus making MTBE potentially more hazardous than gasoline and toluene and their related hydrocarbon products. The U.S. Environmental Protection Agency (USEPA) reported a maximum contaminant level of MTBE in drinking water equal to 40 mg/m^3 (USEPA 2012).

The original version of the CE-QUAL-W2 model does not simulate volatile organic contaminants (VOC) (such as MTBE). Shokri et al. (2013) added this capability to the model, which is implemented in this study. It is noted that CE-QUAL-W2 was previously calibrated by Bozorg Haddad et al. (2014). Simulation parameters of volatilization and MTBE decay used in this research are molar weight equal to 88.15 g, molar volume equal to 119 cm^3/mol, first-order decay coefficient equal to 2×10^{-3} L/days, and Henry coefficient equal to 5.5×10^{-4} $m^3 \cdot atm/mol$ at 25°C. The Henry coefficient is equal to the amount of MTBE that is soluble in a volume of water at a constant water temperature and it is proportional to the gas pressure in the air overlying the lake's water.

Scenarios of Seasonal Pollution

Five scenarios of pollutant (MTBE) entry into the reservoir were considered: (1) in the middle of the spring season, (2) in the middle of the summer season, (3) in the middle of the autumn, (4) in the middle of the winter season, and (5) the combined results of all seasons. It is necessary to consider the various scenarios of MTBE input to the reservoir attributable to the variable effects of climatic conditions on MTBE solubility and lake dynamics. Meanwhile, the gate outlet levels that were considered for each scenario are presented in Table 1.

Evaluation Criteria

The evaluation criteria used in this study are as follows: (1) the number of days of release of polluted water from the reservoir exceeding the MTBE permitted level (40 mg/m^3); (2) the maximum concentration of MTBE within the reservoir when the concentration of MTBE in water released from the reservoir reaches the permitted level (40 mg/m^3); (3) pollutant mitigation, which equals the ratio of the total pollutant volume released through reservoir outlets to the total volume of MTBE input into the reservoir (as a percentage); (4) qualitative reliability, which equals the ratio of the number of days with the release of water from the reservoir with MTBE concentration below 40 mg/m^3 over the maximum number of days

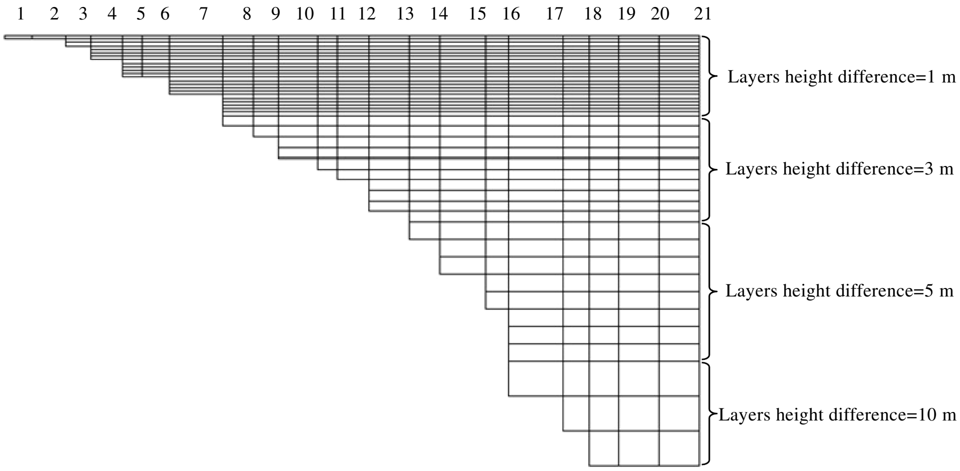

Fig. 2. Vertical cross section of the 46 layers used in the Amirkabir reservoir

Table 1. Characteristics of Gate Outlet Levels

Number	Gate outlet level (meters above sea level)
1	1,731
2	1,719
3	1,710
4	1,700
5	1,690
6	1,680
7	1,670
8	1,660

of MTBE released from the reservoir (as a percentage); and (5) qualitative vulnerability, which equals the largest concentration of MTBE released from the reservoir (in $\mathrm{mg/m^3}$).

By considering the eight reservoir outlet levels listed in Table 1 and comparing the cited five-part evaluation criteria for each outlet level, the best outlet level for each of the four scenarios of seasonal pollution was selected using the multicriteria decision-making method (MCDM). It is noted that these levels were selected with regard to the elevation grid used in the CE-QUAL-W2 software. The outlet levels are separated by an equal elevation difference.

Four dimensionless decision matrices (one for each of the four scenarios or seasons in which pollution may occur) with an order of 8×5 (8 rows and 5 columns) were considered and weighed by 5×5 diagonal matrices. The weight of each of the five evaluation criteria for each scenario of seasonal pollution was set equal to 20%. It was assumed in this study that all criteria have equal value. This implies that all the decision criteria are equally important. For this reason, each criterion has a 20% influence on decision making. An additional scenario (Scenario 5) was also considered in which all the data from the various seasonal scenarios were integrated into the decision-making process using the TOPSIS method and the proper outlet elevation were extracted. In this case, four decision matrices with dimensions 8×20 were constructed. The weighting matrix has dimensions 20×20. In the application of the TOPSIS method, the evaluation criteria are divided into two categories (positive and negative criteria) to find positive and negative solutions. The evaluation criterion for qualitative reliability is considered as a positive criterion, while the evaluation criteria of the number of days of release of water from the reservoir exceeding the permitted concentration, the maximum concentration of MTBE within the reservoir, pollutant mitigation, and qualitative vulnerability are considered as negative criteria.

Results

The calculated evaluation criteria for each of the four seasonal pollution scenarios are listed in Tables 2–6. Graphical presentation is shown in Fig. 3. It is evident in Tables 2–6 (and also Fig. 3) that if the performance of the two outlet levels equal to 1,731 and 1,719 m is compared for the four seasonal pollution scenarios according to the five-part evaluation criteria, the level 1,731 m is superior to level 1,719 with respect to evaluation criteria (1), (2), and (4), and inferior according to level 1,719 with respect to criteria (3) and (5).

If the performance of outlet level 1,731 is compared for the four seasonal pollution scenarios according to the five-part evaluation criteria, it is inferred from Tables 2–6 that (1) criterion (1) produces better performance for the first seasonal pollution scenario; (2) criteria (2), (3), and (5) produce better performance for the second seasonal pollution scenario; and (3) criterion (4) produces better performance for the first and fourth scenarios.

Table 2. Values of the First Evaluation Criterion for Four Scenarios of Seasonal Pollution; First Evaluation Criterion: The Number of Days of Release of Polluted Water from the Reservoir Exceeding the MTBE Permitted Level (40 $\mathrm{mg/m^3}$)

Gate outlet level (meters above sea level)	Scenarios (days)			
	(1) Spring	(2) Summer	(3) Autumn	(4) Winter
1,731	111	190	171	114
1,719	125	190	182	120
1,710	136	191	186	123
1,700	145	191	190	129
1,690	152	191	193	134
1,680	155	191	195	139
1,670	159	192	197	141
1,660	191	192	201	185

Table 3. Values of the Second Evaluation Criterion for Four Scenarios of Seasonal Pollution; Second Evaluation Criterion: The Maximum Concentration of MTBE within the Reservoir When the Concentration of MTBE in Water Released from the Reservoir Reaches the Permitted Level (40 $\mathrm{mg/m^3}$)

Gate outlet level (meters above sea level)	Scenarios ($\mathrm{g/m^3}$)			
	(1) Spring	(2) Summer	(3) Autumn	(4) Winter
1,731	10.312	0.0053	1.151	9.65
1,719	6.663	0.0053	0.918	7.40
1,710	3.958	0.0058	0.845	6.88
1,700	2.976	0.0058	0.774	5.42
1,690	2.186	0.0058	0.723	4.03
1,680	1.549	0.0058	0.685	3.53
1,670	1.961	0.0051	0.649	3.16
1,660	0.259	0.0051	0.588	0.71

Table 4. Values of the Third Evaluation Criterion for Four Scenarios of Seasonal Pollution; Third Evaluation Criterion: Pollutant Mitigation, the Ratio of the Total Pollutant Volume Released through Reservoir Outlets to the Total Volume of MTBE Input into the Reservoir (As a Percentage)

Gate outlet level (meters above sea level)	Scenarios (%)			
	(1) Spring	(2) Summer	(3) Autumn	(4) Winter
1,731	80.29	7.94	31.28	23.02
1,719	86.37	8.43	39.19	26.18
1,710	85.01	11.71	42.22	28.29
1,700	85.09	17.90	43.70	29.91
1,690	85.67	25.52	43.83	31.04
1,680	85.35	33.86	42.90	31.79
1,670	83.84	45.62	43.54	32.47
1,660	81.76	70.14	48.08	33.41

Our results show that for a given scenario of seasonal pollution a specific gate outlet level may be the best release option according to an evaluation criterion, while other gate levels may be preferable release options according to different evaluation criteria. On the other hand, assuming a given evaluation criteria, a specific gate outlet level may be the best release option according to a seasonal pollution scenario, while other gate levels may be preferable release options according to different scenarios of seasonal pollution. In view of the conflicts that arise in choosing an optimal outlet for water release, the TOPSIS was implemented to resolve the conflicts that arise in choosing release options. Prioritization results of optimal outlet levels by using TOPSIS were calculated and are

Table 5. Values of the Fourth Evaluation Criterion for Four Scenarios of Seasonal Pollution; Fourth Evaluation Criterion: Qualitative Reliability, Which Equals the Ratio of the Number of Days with Release of Water from the Reservoir with MTBE Concentration below 40 mg/m^3 over the Maximum Number of Days of MTBE Released from the Reservoir (As a Percentage)

Gate outlet level (meters above sea level)	Scenarios (%)			
	(1) Spring	(2) Summer	(3) Autumn	(4) Winter
1,731	54	29	39	54
1,719	48	29	35	51
1,710	44	29	33	50
1,700	40	29	31	48
1,690	37	28	30	46
1,680	36	28	30	43
1,670	34	28	29	43
1,660	21	28	27	25

Table 6. Values of the Fifth Evaluation Criterion for Four Scenarios of Seasonal Pollution; Qualitative Vulnerability, Which Equals the Largest Concentration of MTBE Released from the Reservoir (in mg/m^3)

Gate outlet level (meters above sea level)	Scenarios (g/m^3)			
	(1) Spring	(2) Summer	(3) Autumn	(4) Winter
1,731	327	35	258	128
1,719	326	30	369	141
1,710	354	60	480	159
1,700	384	105	449	182
1,690	418	142	474	201
1,680	432	191	473	208
1,670	433	255	547	215
1,660	435	331	548	233

presented in Table 7 for the four scenarios of seasonal pollution and the combined seasonal scenarios.

Table 7 shows that the best gate level in the entire year is that with elevation equal to 1,700 m above sea level. The best levels for water outlet in spring, summer, autumn, and winter were 1,660, 1,719, 1,731, and 1,670 m above sea level, respectively.

Table 7. Results of TOPSIS for Prioritizing Gate Levels for the Scenarios of Seasonal Pollution and All Seasons' Scenario

Priority	Gate level (meters above sea level)				
	First scenario: Spring	Second scenario: Summer	Third scenario: Autumn	Fourth scenario: Winter	Fifth scenario: All seasons
1	1,660	1,719	1,731	1,670	1,700
2	1,680	1,731	1,719	1,680	1,710
3	1,670	1,710	1,680	1,690	1,690
4	1,690	1,700	1,700	1,660	1,719
5	1,700	1,690	1,690	1,700	1,680
6	1,710	1,680	1,660	1,710	1,670
7	1,719	1,670	1,670	1,719	1,731
8	1,731	1,660	1,710	1,731	1,660

Concluding Remarks

The effect of choosing gates of different elevations to control MTBE pollution in a reservoir was investigated in this study. For this purpose, five performance criteria were used: (1) the number of days of MTBE release exceeding the permitted concentration, (2) the maximum concentration of pollution within reservoir, (3) pollutant mitigation, (4) qualitative vulnerability, and (5) qualitative reliability. Simulation of the behavior of pollutants under four scenarios of seasonal pollution (four seasons) was performed with the CE-QUAL-W2 model, which was previously calibrated with actual data. The best gate level for water release from the reservoir was selected with the TOPSIS for each seasonal pollution scenario and one scenario considering all seasons (this is also called the *entire year* scenario). The results showed that the best gate level corresponding to the entire year scenario was 1,700 m above sea level. The best levels of outlet in spring, summer, autumn, and winter were 1,660, 1,719, 1,731, and 1,670 m above sea level, respectively.

The approach proposed in this paper can be applied to the design of reservoir outlets to cope with the sudden release of pollutants to a reservoir or, when existing dams feature multilevel gates, to choose release outlets for optimal pollution control in a contaminated reservoir. This study considered polluted-water releases from one gate level. This paper's methodology can be extended to the evaluation of pollutant releases from multiple gates simultaneously.

Our results established that the optimal outlets in the first and fourth pollution scenarios are at levels of 1,660 and 1,670 m, respectively, which are at lower elevations than other outlets. Also, in the second and third scenarios, optimal outlets are at higher levels (i.e., 1,719 and 1,731 m), which lead to an improvement of the five evaluation indexes. Considering the level 1,700 m as the optimal level for the whole year may be appropriate if the probability of MTBE release events is equal in all seasons, which in reality is

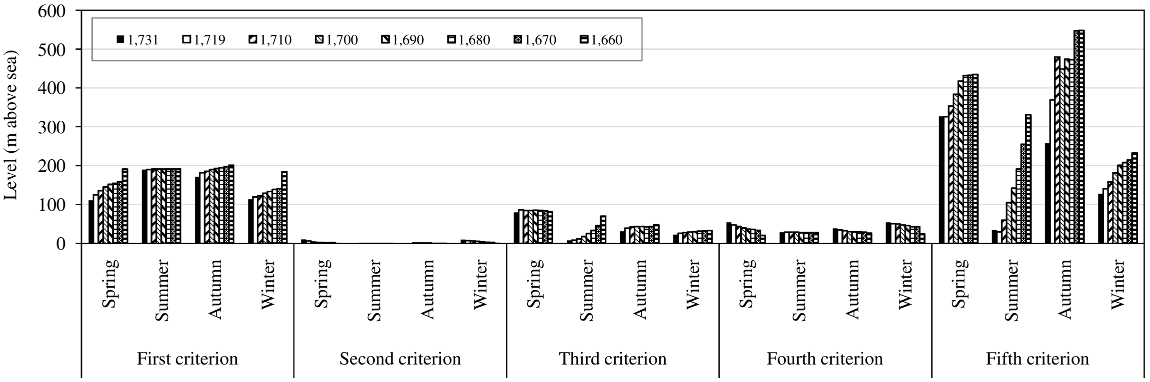

Fig. 3. Graphical presentation of results

not the case. A reasonable resolution of this conundrum would be to design a dam with two outlets whose levels are determined based on the results for the four seasonal scenarios. For example, if the levels 1,670 and 1,719 m are considered as the two optimal levels for the outlet of the dam based on the timing of the release of pollutant, only one of the outlets can be used.

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