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Modified TODIM method for water reuse application: a case study from Iran

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ABSTRACT

Water reuse management is considered to solve water shortage problems and to organize the urban water supply situation especially in areas with limitations in water resources, arid climates, population growth, and increasing demand for water. Weighting of alternatives is one of the major challenges in recycled water allocation. TODIM (the acronym for interactive and multi-criteria decision-making in Portuguese) is a technique for considering the risk preferences of decision-makers based on prospect theory for weighting alternatives. But in TODIM technique, the scale measurement is exactly between zero and one and the scale transformation is not proportional to the outcome, so it cannot be combined with multi-objective optimization techniques such as goal programming and it cannot be used to reflect risk preferences for the highest and lowest alternatives. To overcome these disadvantages, a modified TODIM method is proposed for weighting water reuse alternatives. The results show that in this model, the sensitivity analysis can explore the robustness of the final solution and it can help decision-makers manage water reuse.

Keywords: Modified TODIM method; Water resource management; Water reuse; Risk preferences; Iran

1. Introduction

Water reuse has grown throughout the world as an alternative source of water. The social and environmental impacts of water reuse are an inherently multidimensional process that involves multiple stakeholders and multiple criteria [1] and the basic purpose of water resources management is to reduce the level of risk acceptance and increase the social, health, and economic benefits. The issue of optimal allocation of water resources has been promoted due to limited water resources and unlimited stakeholders' needs for water resources. Sustainable urban water systems should provide required services over a long-time perspective while protecting human health and the environment, with minimum use of scarce resources [2].

Using an optimization approach can handle the system's analysis process and can lead to transparent, sustainable, and cost-effective feasible plans [3]. Multi-criteria decision-making (MCDM) deals with several criteria in the decision-making process and refers to a general class of operations research models that are divided into two categories of decision problems: multi-objective programming (MOP) and multi-attribute decision-making (MADM) [4]. Combination of MADM which are commonly used to assess potential weights of alternatives with MOP approaches can be applied to find an optimal solution that could handle the management of limited resources such as water resources. As examples, Sharma and Balan [5] used the analytical hierarchy process and goal programming (AHP-GP)

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model to select the best supplier and Aznar et al. [6], and Ostadhashemi [7] used AHP-GP model for optimizing the appropriate plantation area for each species and agricultural valuation. Hadipour et al. [8] applied the AHP model for water reuse applications in the central areas of Iran.

MADM approaches are widely used in various applications where the purpose is to select the most appropriate of various alternatives or to assess potential weighting of alternatives for supporting decision-making in allocation problems on the basis of known criteria of a limited number of alternatives. The MADM method has a small and finite group of solutions based on a number of feasible ones [4,9]. Some of the MADM's selection criteria are the ability to sensitivity analysis and performance evaluation, flexibility, compatibility with other programs for optimal allocation, and simplicity application. AHP, analytic network process (ANP), utility additive (UTA), order preference by the resemblance to the ideal solution (TOPSIS), and TODIM are some basic methods under the MADM category [3]. The main drawback of the MADM approaches such as AHP method is the uncertainty problem imported from the pairwise comparison matrix, which includes some uncertain factors ordinary to environmental matters [10,11], generally, in comparing TODIM method with the existing methods, TODIM would be the preferable method to considering the subjectivity of decision-makers behaviors based on the prospect theory [12], in TODIM method, sensitivity analysis concept can be applied for different attenuation factor (θ) and the effects in weights of alternatives can be studied with particular operation formulas, also this method can be more scientific and reasonable in the application of MADM problems [13].

Fan et al. [14] extend the TODIM method with various formats of attribute values (crisp, interval, and fuzzy numbers) for solving the MADM problem. Li et al. [15] used an extension of TODIM combined with the interval intuitionistic fuzzy sets numbers to propose a fuzzy-based TODIM method. Sen et al. [16] used an extension of TODIM combined with grey numbers to propose a grey-based TODIM method. Gomes et al. [17] compared the classical TODIM and the Choquet-extended TODIM methods to rank the suppliers. Zhang and Xu [18] performed the performance analysis of regional sustainable water management using the HF-TODIM method. Huang et al. [19] extended the TODIM method based on the linguistic distribution assessments to assess and rank the failure modes in failure mode and effect analysis. Yu et al. [20] extended the TODIM method based on linguistic scale functions to obtain logical results in MCDM problems.

The definition of an instance of a combinatorial optimization problem (MADM with MOP) requires specify parameters, in particular coefficients of the MOP objective function [21]. A major issue of debate within the MOP community has concerned the use of proportionality axiom in normalization scheme for avoiding pitfalls in formulations [22,23]. In TODIM technique, the linear scale transformation (max–min method) is used to weight the alternatives, so in this method, the scale measurement is exactly between zero and one and consequently, the scale transformation is not proportional to outcome [24] and weights of the lowest and the highest alternatives are always zero and one, respectively. On the other hand, the results of sensitivity analysis of the lowest and highest alternatives for the different factor of the losses (θ) in the original formulation of this method show that the weighting coefficient for the lowest and the highest alternatives are always zero and one, and do not change weight coefficients of alternatives, therefore, the potential value of gains and losses, which can be adjusted by the attenuation factor θ in this approach cannot be used to reflect expert's risk preferences, nor can it handle hybrid MADM and allocation problems. These are the major drawbacks of this technique that have not been addressed in existing extensions of TODIM.

This paper proposes a modified TODIM method. The proposed approach is capable of studying the impact of changes in the factor of the losses on the weighting of the highest and lowest alternatives in practice and reflecting decision-makers' risk preferences with normalized weights that can be combined with MOP approaches directly.

In the context of water reuse management, Keremane and McKay [25] planned water reuse schemes for sustainable development by environmental and socio-economic dimensions. Gikas et al. [26] used an optimization model based on mixed-integer linear programming for calculating the financial benefits of water reuse. Lee et al. [27] performed an optimization framework that optimizes water reuse and renewable energy resources in buildings. Mcheik et al. [28] used the results of several scenarios in the reuse of treated municipal wastewater for table grapes irrigation in Jordan. Also, different modifications of AHP, TOPSIS, and ANP methods are used to solve complicated problems in management and planning of treated municipal wastewater and sludge reuse in agriculture and land development, construction, choice of operating system, service selection, wastewater treatment process selection, and selection of sustainable investment and green building material selection [29–33].

So far, the combination of MADM with MOP approaches has not been used to obtain an optimal allocation of recycled water in the context of water reuse management. This paper presents an extended TODIM method for weighting of urban water reuse alternatives by evaluating and analyzing experts' risk preferences which are capable of being combined with MOP methods.

In this paper, a case study that deals with weighting alternatives for water reuse are presented to show the effectiveness of the modified TODIM, and then a comparison of TODIM and modified TODIM methods is made and discussed by the demonstrative application in Najafabad, Iran.

2. Materials and methods

2.1. Methodology

2.1.1. TODIM and modified TODIM

The basic concept of the classical TODIM is to measure the overall value of each alternative over others under a prospect theory (Fig. 1) to establish a multi-attribute value function [34].

The procedures of the TODIM and proposed TODIM method are shown in Figs. 2 and 3. In both methods, attribute and alternatives values, based on selected criteria are presented in the formats of crisp numbers. Gradation scales to evaluate the alternatives according to the attributes are shown in Table 1.

The algorithms for the TODIM [14] and the proposed modified TODIM methods to a pairwise comparison of the criteria and facilitate analysis are summarized as follows.

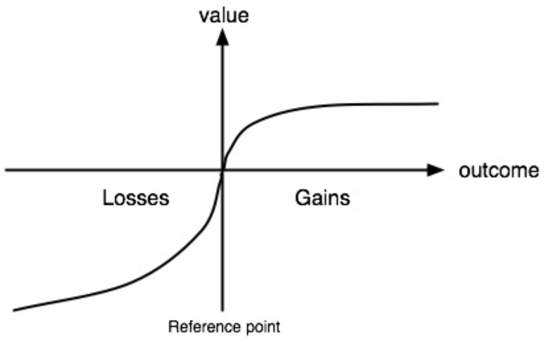

Fig. 1. Value function of prospect theory.

2.1.1.1. Common steps in both methods

- *Step 1*: Eq. (1) is used to normalize the original decision matrix $X = \left[x_{ij}\right]_{m\times n}$ (numerical evaluation for the alternatives regarding to all criteria) to matrix $Z = \left[z_{ij}\right]_{m\times n}$, where m is the number of alternatives, and n is the number of criteria. x_{ij} is a crisp number of the alternative (T_i) according to the attribute (E_c), $i,j \in M$, and $c \in N$.

$$z_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}},\ i,j \in M. \quad (1)$$

- *Step 2*: Eq. (2) is used to calculate the relative weight (w_{rc}) of the attribute (E_c) to the reference attribute (E_r), that is,

$$w_{rc} = \frac{w_c}{w_r}, \quad \text{where} \quad w_r = \max\left\{w_c \mid c \in N\right\}, \quad (2)$$

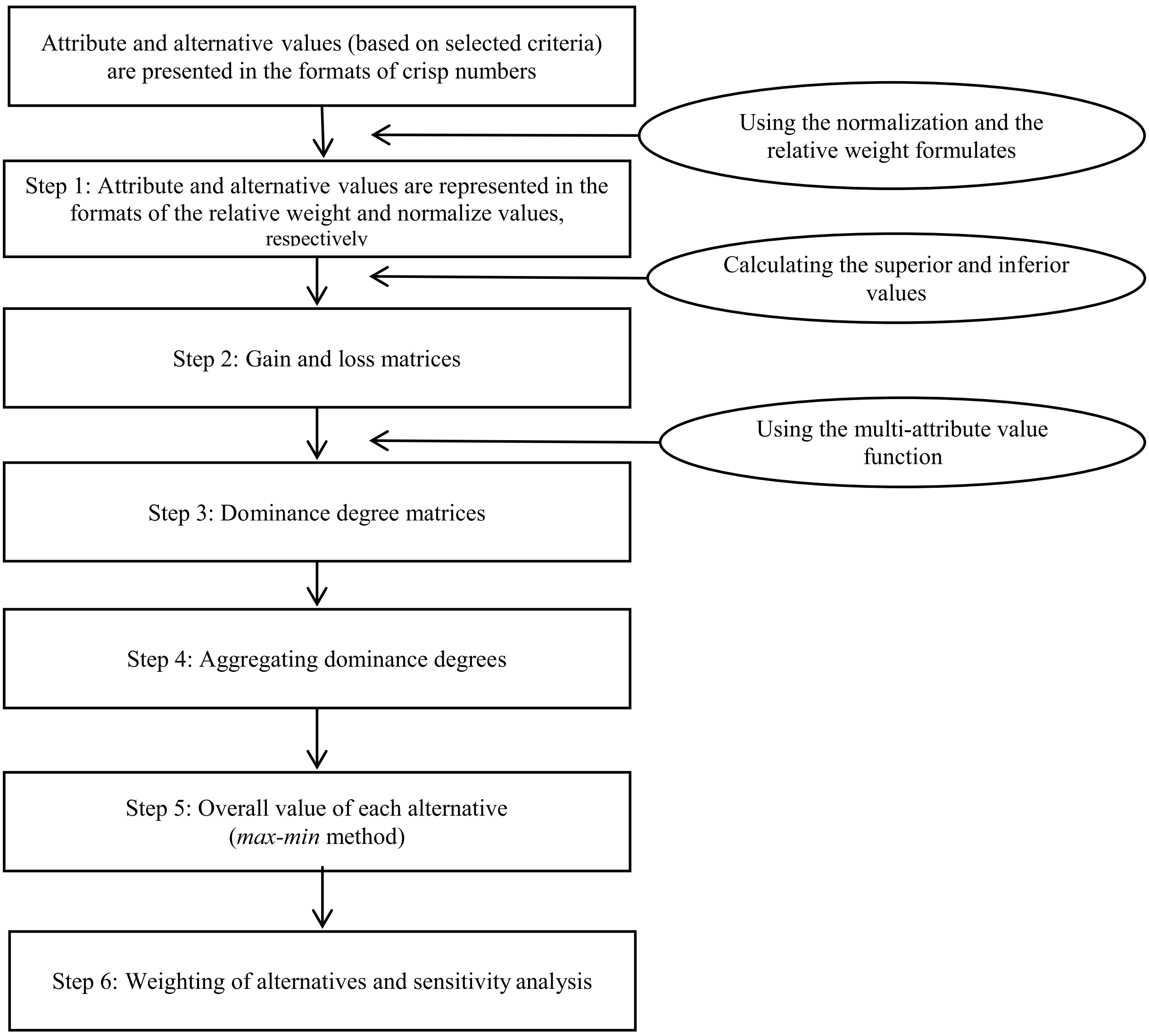

Fig. 2. Flow chart of TODIM method.

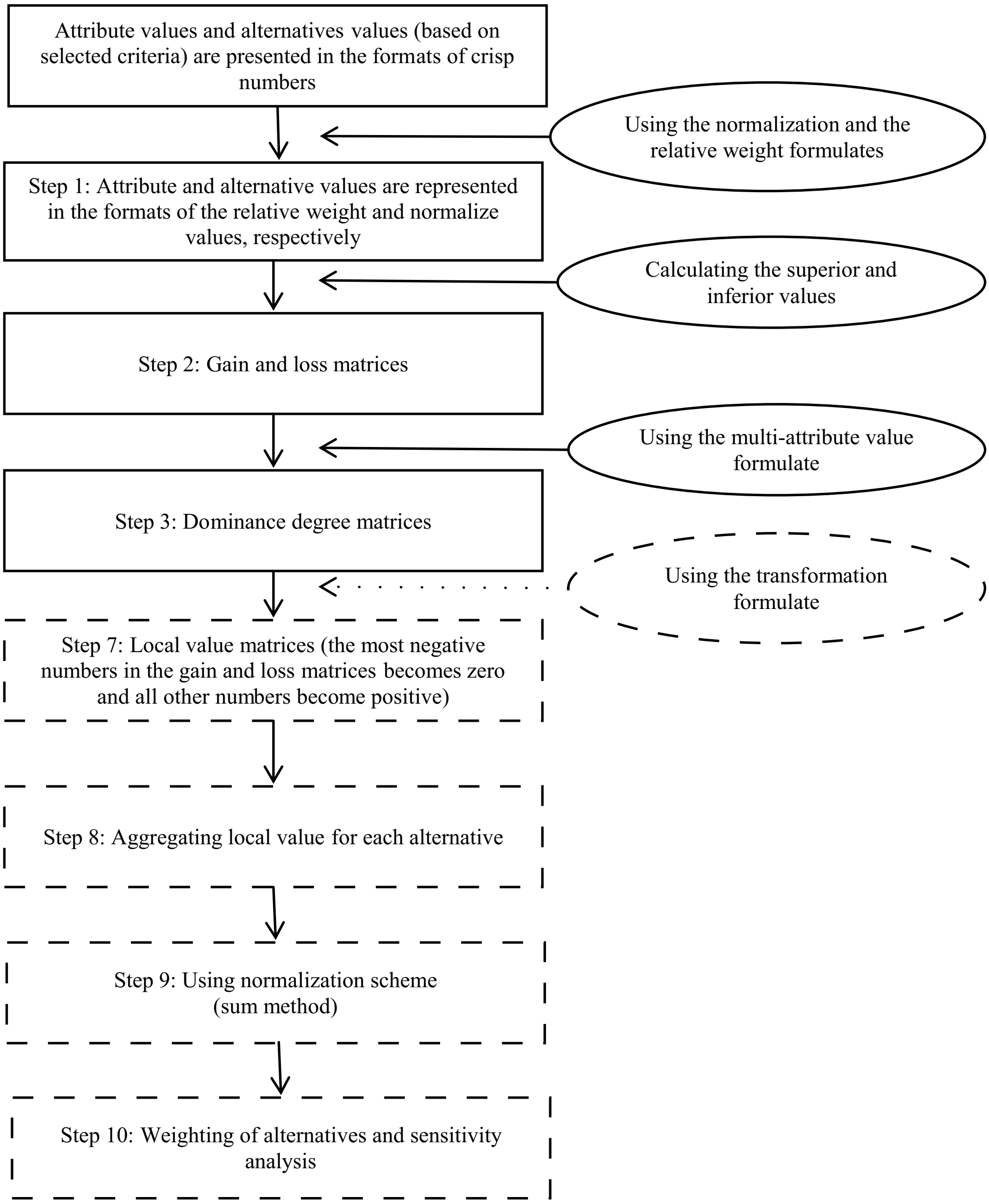

Fig. 3. Flow chart of the proposed modified TODIM method.

Table 1
Gradation scales for assessment in TODIM method [34]

Assessment of the alternatives in TODIM method (x_{ij})	Comparison of the criteria in TODIM method (w_j)	Priority values
Very poor (VP)	Very unimportant (VU)	1
Poor (P)	Unimportant (U)	3
Fair (F)	Equal (E)	5
Good (G)	Important (I)	7
Very good (VG)	Very important (VI)	9
Intermediate inputs between adjacent scale value		2, 4, 6, 8

where w_c is the normalized weight of a generic criterion c.

- *Step 3*: According to concepts of Prospect Theory that considers the aversion and the propensity to risk, Eq. (3) is used to calculate the dominance degree of alternative (T_i) over the alternative (T_j) concerning attribute (E_c), that is,

$$\Phi_c\left(T_i,T_j\right)=\begin{cases}\sqrt{\dfrac{\left(z_{ic}-z_{jc}\right)w_{rc}}{\left(\sum_{c=1}^{n}w_{rc}\right)}}, & \text{if } \left(z_{ic}-z_{jc}\right)>0,\\ 0, & \text{if } \left(z_{ic}-z_{jc}\right)=0,\\ \left(-\dfrac{1}{\theta}\right)\sqrt{\dfrac{\left(z_{jc}-z_{ic}\right)\left(\sum_{j=1}^{n}w_{rc}\right)}{w_{rc}}}, & \text{if } \left(z_{ic}-z_{jc}\right)<0,\end{cases} \quad (3)$$

where z_{ic}, z_{jc} are the assessments of alternatives i and j with respect to criterion (E_c). $z_{ic}-z_{jc}$ denotes the loss of alternative (T_i) over the alternative (T_j) concerning attribute (E_c) if $z_{ic}-z_{jc}<0$ and the gain if $z_{ic}-z_{jc}>0$. Firstly, the gain and loss matrices are built and then the dominance degree matrix is constructed by Eq. (3). w_{rc} is the trade-off weighting factor of the attribute (E_j) to (E_r), and the parameter θ represents the attenuation factor of the losses. Variation of this parameter leads to the different degree of loss and forms of the prospect value function in the negative quadrant, as illustrated in Fig. 4. Positive and negative quadrants of Fig. 4 represent the gains (symbolizes the aversion to risk when dealing with gains) and the losses (reflects the propensity to risk in the face of losses), respectively. The lower degree of loss corresponds to the greater θ. Therefore, sensitivity analysis should perform on θ, on the performance evaluations, the choice of the reference criterion and the criteria weights and due to the attenuation factor of the losses, most literature has used arbitrary values of θ in the TODIM implementation or evaluated the selected value of the parameter after performing the sensitivity analysis [35].

2.1.1.2. Specific steps of TODIM method

In the TODIM method, the process is continued as explained in steps 4–6:

- *Step 4*: Eq. (4) is used to calculate the overall dominance degree of alternative (T_i) over the alternative (T_j), that is,

$$\delta\left(T_i,T_j\right)=\sum_{c=1}^{n}\Phi_c\left(T_i,T_j\right),\ c\in N;\ i,j\in M. \quad (4)$$

- *Step 5*: Eq. (5) is used to calculate the overall value of alternative (T_i) over other alternatives, that is,

$$\xi\left(T_i\right)=\frac{\sum_{j=1}^{m}\delta\left(T_i,T_j\right)-\min\left\{\sum_{j=1}^{m}\delta\left(T_i,T_j\right)\right\}}{\max\left\{\sum_{j=1}^{m}\delta\left(T_i,T_j\right)\right\}-\min\left\{\sum_{j=1}^{m}\delta\left(T_i,T_j\right)\right\}},\ i,j\in M \quad (5)$$

- *Step 6*: Now, according to the $\xi(T_i)$ scores, the weighting of the alternatives (T_i) are indicated. Its values are between 0 and 1.

2.1.1.3. Specific steps of modified TODIM

The four well-known normalization procedures used in MADM, including (*N*1) linear scale transformation (max–min method), (*N*2) linear scale transformation (sum method), (*N*3) vector normalization, and (*N*4) linear scale transformation (max method). To help present the comparative study, model *N*1 and model *N*2 are briefly described.

N1: max–min method This method considers both the maximum and minimum performance ratings of alternatives during calculation. The normalized value x' is obtained by:

$$x'=\frac{x-x_{\min}}{x_{\max}-x_{\min}}, \quad (6)$$

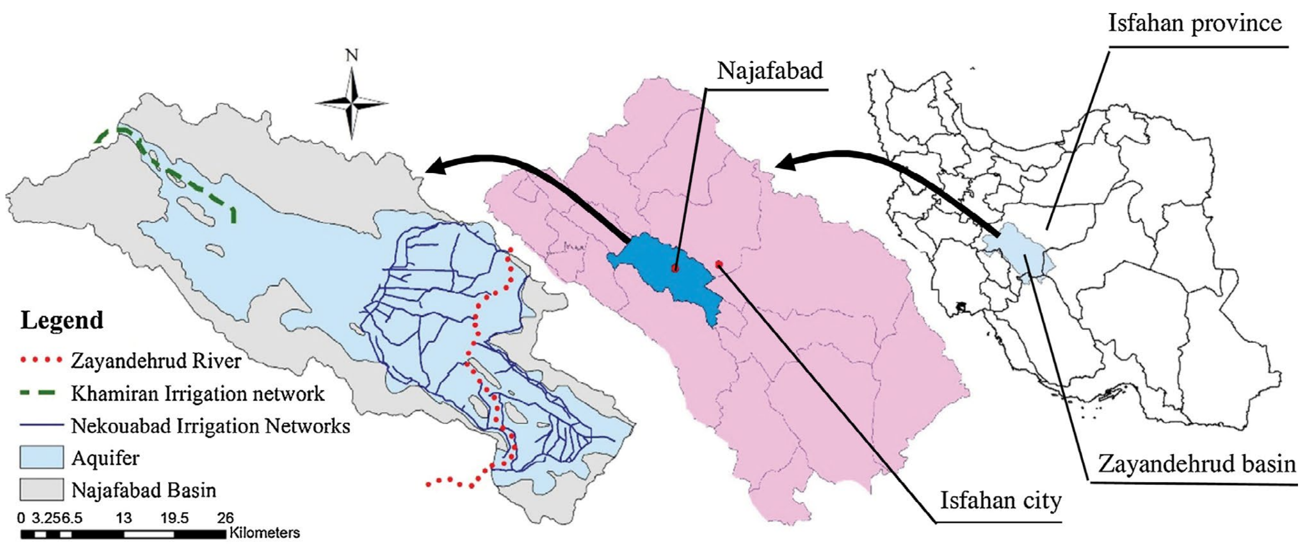

Fig. 4. Location of Najafabad plain and the irrigation networks.

where x is the performance rating of each alternative, $x_{\min}$ and $x_{\max}$ are the minimum and maximum performance rating among alternatives, respectively [24].

N2: sum method This method divides the performance ratings of each attribute by the sum of performance ratings for that attribute as follows [36]:

$$x' = \frac{x}{\sum_{i=1}^{m} x}, \tag{7}$$

where x is the performance rating of each alternative.

Eq. (5) based on these definitions of normalization methods is the linear scale transformation (max–min method) used to weight the alternatives in the TODIM method, in linear scale transformation (max–min) method the scale measurement is exactly between 0 and 1 and the drawback is that the scale transformation is not proportional to outcome [24], also, for this reason, the results of sensitivity analysis of the lowest and highest alternatives for the different factor of the losses (θ) show that the weighting coefficient for the lowest and the highest alternatives are do not change and are always zero and one.

If the output data of Eq. (4) are normalized by dividing them with their sum (linear scale normalization-sum method), the results of sensitivity analysis for different (θ) are varied and the scale transformation is proportional to the outcome, but this normalization scheme works well when all output is positive or zero and if output data contain some negative numbers (such as the value of losses) in this normalization procedure, we have a negative number as part of weighting index and the scale transformation is not proportional to outcome.

To solve this problem, firstly we need to modify and shift all output data of Eq. (3) by adding with the absolute of the most negative (minimum value of losses) so that the most negative one becomes zero and all other numbers become positive. Then, we can normalize the weights as usual.

In the proposed modified TODIM method, the process is continued as explained in steps 7–10:

- *Step 7*: After using and completing Eq. (3), Eq. (8) is used to calculate the new dominance degree of alternative (T_i) over the alternative (T_j) concerning attribute (E_c), that is,

$$\Phi'_c\left(T_i,T_j\right) = \Phi_c\left(T_i,T_j\right) - w_i;\, w_i = \min\{\Phi_c\left(T_i\right) \;|c \in N, i \in M\} \tag{8}$$

- *Step 8*: The Eq. (9) is used to calculate the overall dominance degree of alternative (T_i) over the alternative (T_j) by aggregating the new dominance degree values, that is,

$$\delta'\left(T_i,T_j\right) = \sum_{c=1}^{n} \Phi'_c\left(T_i,T_j\right) = \sum_{j=1}^{m} \delta\left(T_i,T_j\right) - \sum_{i=1}^{n} w_i, \tag{9}$$

- *Step 9*: Then linear scale transformation (sum method), Eq. (10), is used to calculate the final normalized weight of alternatives. This method divides the overall dominance degree of alternative (T_i) over the alternative (T_j), by the sum of the weights of the overall dominance degree of alternative (T_i) over the alternative (T_j), that is,

$$\psi\left(T_i\right) = \frac{\delta'\left(T_i,T_j\right)}{\sum_{j=1}^{m} \delta'\left(T_i,T_j\right)}, \quad i,j \in M. \tag{10}$$

- *Step 10*: Now, according to the $\psi(T_i)$ scores, weighting of the alternatives (T_i) are indicated.

For comparing the TODIM and modified TODIM methods, Eq. (5) is used to convert the normalized value of weights (T_i) in modified TODIM to overall values of weights in the original TODIM method:

$$\xi\left(T_i\right) = \frac{\psi\left(T_i\right) - \min\psi\left(T_i\right)}{\max\psi\left(T_i\right) - \min\psi\left(T_i\right)} = \frac{\dfrac{\delta'\left(T_i,T_j\right)}{\sum_{j=1}^{m}\delta'\left(T_i,T_j\right)} - \dfrac{\min\delta'\left(T_i,T_j\right)}{\sum_{j=1}^{m}\delta'\left(T_i,T_j\right)}}{\dfrac{\max\delta'\left(T_i,T_j\right)}{\sum_{j=1}^{m}\delta'\left(T_i,T_j\right)} - \dfrac{\min\delta'\left(T_i,T_j\right)}{\sum_{j=1}^{m}\delta'\left(T_i,T_j\right)}} = \frac{\dfrac{\delta'\left(T_i,T_j\right) - \min\delta'\left(T_i,T_j\right)}{\sum_{j=1}^{m}\delta'\left(T_i,T_j\right)}}{\dfrac{\max\delta'\left(T_i,T_j\right) - \min\delta'\left(T_i,T_j\right)}{\sum_{j=1}^{m}\delta'\left(T_i,T_j\right)}} =$$

$$\frac{\left(\sum_{j=1}^{m}\delta\left(T_i,T_j\right) - \sum_{i=1} w_i\right) - \left(\min\left(\sum_{j=1}^{m}\delta\left(T_i,T_j\right)\right) - \sum_{i=1} w_i\right)}{\left(\max\left(\sum_{j=1}^{m}\delta\left(T_i,T_j\right)\right) - \sum_{i=1} w_i\right) - \left(\min\left(\sum_{j=1}^{m}\delta\left(T_i,T_j\right)\right) - \sum_{i=1} w_i\right)} = \frac{\sum_{j=1}^{m}\delta\left(T_i,T_j\right) - \min\left(\sum_{j=1}^{m}\delta\left(T_i,T_j\right)\right)}{\max\left(\sum_{j=1}^{m}\delta\left(T_i,T_j\right)\right) - \min\left(\sum_{j=1}^{m}\delta\left(T_i,T_j\right)\right)}, \tag{11}$$

As can be seen, the global value of weights in a modified TODIM method is the same as the value of weights in TODIM method.

3. Study region

Najafabad plain is one of the sub-basins of the Zayandehrud River basin in the west of Isfahan province with an area of 1,712 km^2. Its minimum and maximum altitudes are 1,580 and 2,925 m, respectively. Fig. 4 shows the location of Najafabad plain and its irrigation networks.

3.1. Water resources

In recent years, in the study region, despite increasing water demand, due to climate changes, the decline of groundwater and surface water has created a crisis. Therefore, water reuse management is essential for managing water resources and organizing the urban water supply situation.

3.1.1. Groundwater

Najafabad aquifer has an area of 932 km^2 with an average thickness of 69 m (30–120 m). Fig. 5 shows the cumulative mean of piezometric level changes in its aquifer for a 34 y time period. The general characteristics of Najafabad aquifer are presented in Table 2.

3.1.2. Surface water

The Zayandehrud River is the most important surface water resource in the west of Najafabad region with a length of about 360 km. This river originates in Chaharmahal-va-Bakhtiary province in a rain-laden, alpine area of the Zagros Mountains at an altitude of about 4,000 m through the natural confluence of small and large rivers (about 160 km) in the west of Najafabad and terminating in the Gavkhooni wetland to the east of the city [37]. The total annual precipitation varies from 1,500 mm in the west and 150 mm in Najafabad plain to 50 mm in the east. Fig. 6a shows the monthly variation of long-term period discharge and Fig. 6b illustrates the annual discharge values over the last 21 y for Mousian hydrometric station along the Zayandehrud River from October 1996 to September 2016. The mean annual discharge in the long-term period is approximately 180 m^3 s^{-1} [38].

3.1.3. Potential for water reuse

The total population of Najafabad city was about 235,281 in 2016 [39]. Based on the population growth in previous years, the predicted water consumption per capita and the population for the next 25 y, the amount of wastewater production is estimated as an average of about 420 L s^{-1}. Table 3 shows the main features of the wastewater collection and treatment plant in Najafabad city [40]. Due to inadequate government funding, the construction of about 300 km of the wastewater collection system and modules 2 and 3 of Najafabad wastewater treatment plant will be supplied by the pre-sale of recycled water.

3.2. Alternatives

In this case study, based on submitted requests information, three candidates are selected as applicable water reuse alternatives, which are as follows: T_1: urban landscape irrigation, T_2: agricultural irrigation, and T_3: industrial demand.

3.2.1. Urban landscape irrigation

The green space irrigation is one of the largest water uses in Najafabad plain that includes landscaped areas around commercial and residences, freeway medians, parks, and playgrounds. Table 4 presents the total amounts of green space and parks area in Najafabad city. At present, the total area of the green space in Najafabad city is about 260 ha. There are 63 parks with about 120 ha area in Najafabad. The main planted species in the green space are cypress, mulberry, and acacia [41].

3.2.2. Agriculture irrigation

Table 5 [42] presents the total water requirement for the most important crops in Najafabad plain based on the efficiency of distribution and transmission irrigation systems.

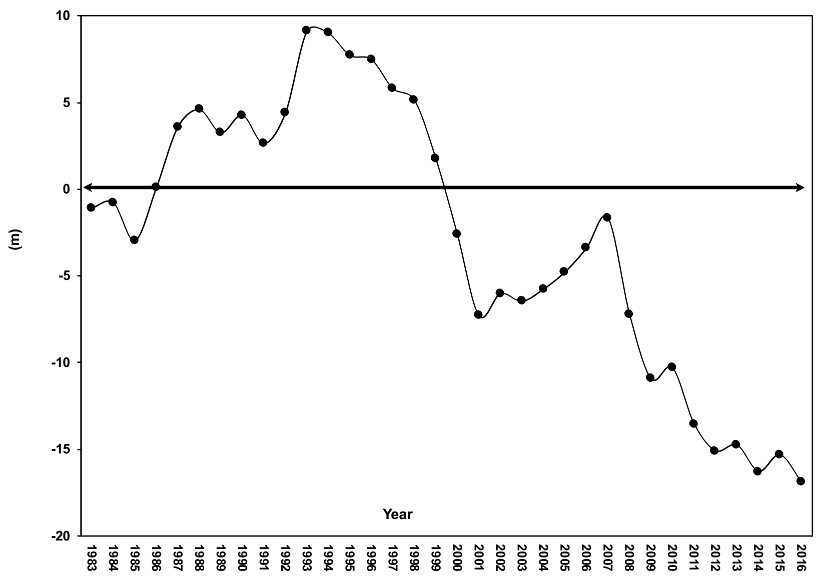

Fig. 5. Cumulative mean of piezometric level changes in Najafabad aquifer for a 34 y time period.

Table 2
General characteristics of Najafabad aquifer (ground water resources) [38]

Sub-basin	Aquifer		Specific storage (%)		Average piezometric level	
	Average thickness (m)	Maximum water storage capability (MCM)	Unconfined (U.C.)	Confined (C)	Beginning of period (October 1991)	End of period (September 2016)
Najafabad	69	3,297	2	–	19.9	35.2

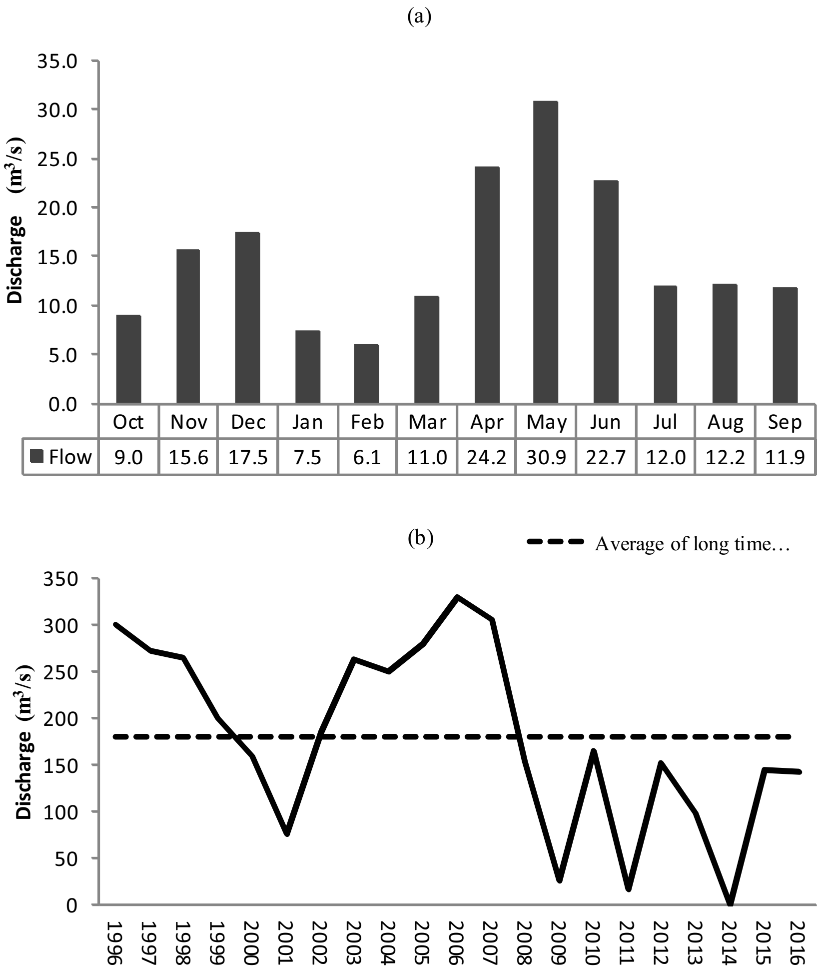

Fig. 6. Variation of the Zayandehrud River discharge in Mousian station (a) variation in monthly flow for a 21 y time period and (b) discharge records for each year (Zayandehrud River).

3.2.3. Industrial demand

Isfahan power plant is the major industry in Najafabad plain. This plant is located in the east of Najafabad plain. At present, the Isfahan power plant has been connected to the national electricity network through five electricity generators with a nominal capacity of 835 MW including two units of 37.5, one 120, and two 320 MW. The average amounts of water required for cooling and other processes in the Isfahan power plant are about 260 L s^{-1} [43]. The Zayandehrud River is a vital source for the water requirement of the Isfahan power plant. In recent years, low rainfall has occurred in the head of the Zayandehrud River, and in the face of climate change, water reuse is a possible strategy to respond to part of industrial water demand.

4. Results

4.1. TODIM and modified TODIM application

In this part, the TODIM and the modified TODIM methods are applied for weighting the water reuse alternatives in

Table 3
Main features of wastewater collection and treatment system in Najafabad city [40]

Name of city	Population		Wastewater collection system (km)		Diameter of wastewater collection system (mm)	Treatment system capacity (Number of people)			Wastewater treatment method
	Beginning (2016)	End of project period (2040)	Designed (km)	Erected (km)		Module1 (constructed)	Module2 (designed)	Module3 (designed)	
Najafabad	235,281	350,000	527	220	200–1,400	100,000	100,000	150,000	Lagoon activated sludge system (LASS)

Table 4
Green space and parks area in Najafabad city [41]

Nane of city	Green space area (m^2)	Covered population (capita)	m^2/capita	Parks area (m^2)	Covered population (capita)	m^2/capita
Najafabad	2,598,790	235,281	11	1,190,681	235,281	5

Table 5
Crop water requirement in Najafabad plain [42]

Season	Crop type	Planting date	Harvest date	Net water demand (m^3 ha^{-1})	Area (ha)	Crop water requirement (MCM)
Winter	Wheat	November	June	4,270	21,832	93.22
	Barley	November	May	3,590	4,982	17.89
	Onion	October	June	7,010	8,118	56.91
	Fodder	October	June	9,310	4,920	45.81
Summer	Rice	June	October	7,740	15,006	111.64
	Potatoes	February	June	6,240	5,744	35.84
All year	Vegetables	March	October	5,840	12,054	68.95
	Sugar beet	All year	All year	9,510	1,599	15.21
	Orchards	All year	All year	9,310	6,863	59.91

Najafabad region. At first, subjective judgments are obtained from questionnaires and the importance of the various criteria and alternatives are separately evaluated by three decision-makers. Their evaluations are represented in the formats of the numerical values (Table 1).

Table 6 indicates some important criteria that have been utilized in the literatures [44]. In the first step, according to Table 6, the five criteria including E_1: environmental criteria, E_2: risk-based criteria, E_3: economic criteria, E_4: social criteria, and E_5: functional criteria, were selected. Then the questionnaires were asked to evaluate the importance of each criterion.

4.2. Common steps

- *Step 1*: The decision matrix of alternatives is normalized based on selected attribute and relative weights of each attribute are calculated based on Eq. (1). The criterion weights, the decision, and the measurement of the normalized matrix are shown in Tables 7 and 8.
- *Step 2*: Criterion weight vector is provided by the decision-makers ranking. Relative weights of each criterion are calculated using Eq. (2) that are shown in Table 9.
- *Step 3*: Eq. (3) is used for the measurement of dominance degree matrices relating attributes for θ = 1°, that is,

$$\Phi_1 = \begin{bmatrix} 0.000 & 0.285 & 0.412 \\ -0.878 & 0.000 & 0.297 \\ -1.270 & -0.917 & 0.000 \end{bmatrix} \quad \Phi_2 = \begin{bmatrix} 0.000 & -0.509 & -1.393 \\ 0.089 & 0.000 & -1.297 \\ 0.245 & 0.228 & 0.000 \end{bmatrix} \quad \Phi_3 = \begin{bmatrix} 0.000 & 0.082 & -2.682 \\ -1.014 & 0.000 & -2.867 \\ 0.217 & 0.232 & 0.000 \end{bmatrix}$$
$$\Phi_4 = \begin{bmatrix} 0.000 & -1.201 & 0.170 \\ 0.438 & 0.000 & 0.470 \\ -0.465 & -1.288 & 0.000 \end{bmatrix} \quad \Phi_5 = \begin{bmatrix} 0.000 & -2.393 & 0.113 \\ 0.129 & 0.000 & 0.172 \\ -2.099 & -3.183 & 0.000 \end{bmatrix} \tag{12}$$

4.2.1. TODIM application steps

- *Step 4*: The overall final dominance matrix (δ) is calculated using Eq. (4).

In the negative quadrant of Fig. 4, different selections of θ lead to different values and various forms of the prospect function. For θ = 1°, the losses are the same as their real values [45] and for θ = 100°, the losses are more than their real values.

$$\delta_{(\theta=1)} = \begin{bmatrix} 0.000 & -3.736 & -3.380 \\ -1.235 & 0.000 & -3.225 \\ -3.371 & -4.928 & 0.000 \end{bmatrix} \tag{13}$$

- *Step 5*: The overall value of each alternative is calculated using Eq. (5).
- *Step 6*: According to the above steps, five modes of attenuation factors are derived (for θ = 1°–100°) and the weighting order of the three alternatives are calculated (Table 10 and Fig. 8). Also, sensitivity analysis should be performed on parameter θ and usually, θ > 0°. In this study according to above steps, parameter θ is changed by a certain percentage (for θ = 1°–100°), the model is run and the impacts of fluctuations in parameter θ on the weighting order of the three alternatives are observed (Fig. 7). As it is seen in Fig. 7, the model outputs are significant at 0 < θ < 10.

4.2.2. Modified TODIM application steps

- *Step 7*: After completing common step 3, Eq. (8) is used for the measurement of local value matrices related to the alternatives (T_i) for each criterion (E_c) respectively, that is,

$$\Phi'_1 = \begin{bmatrix} 1.270 & 1.202 & 0.412 \\ 0.392 & 0.917 & 0.297 \\ 0.000 & 0.000 & 0.000 \end{bmatrix} \quad \Phi'_2 = \begin{bmatrix} 0.000 & 0.000 & 0.000 \\ 0.089 & 0.509 & 0.096 \\ 0.245 & 0.736 & 1.393 \end{bmatrix} \quad \Phi'_3 = \begin{bmatrix} 1.014 & 0.082 & 0.185 \\ 0.000 & 0.000 & 0.000 \\ 1.231 & 0.232 & 2.867 \end{bmatrix}$$
$$\Phi'_4 = \begin{bmatrix} 0.465 & 0.087 & 0.170 \\ 0.903 & 1.288 & 0.470 \\ 0.000 & 0.000 & 0.000 \end{bmatrix} \quad \Phi'_5 = \begin{bmatrix} 2.099 & 0.790 & 0.113 \\ 2.228 & 3.183 & 0.172 \\ 0.000 & 0.000 & 0.000 \end{bmatrix} \tag{14}$$

- *Step 8*: Based on local value matrices, the overall dominance degree matrix (δ) of alternative (T_i) over the alternative (T_j) is calculated using Eq. (9), that is,

$$\delta'_{(\theta=1)} = \begin{bmatrix} 4.847 & 2.161 & 0.880 \\ 3.612 & 5.897 & 1.036 \\ 1.476 & 0.969 & 4.260 \end{bmatrix} \tag{15}$$

Table 6
Evaluation criteria utilized in literature of water supply and demand management options [44]

Evaluation criteria (abbreviation)	Objectives	
Environmental criteria (E_1)	Maintain river, local creaks, and wetlands	Effects on aquifer (groundwater level and pattern)
	Efficient resource use	Reuse and recycling of resources
	Protect land ecosystem	Effects on natural habitat area
Risk-based criteria (E_2)	Resilience	Failure duration or how quickly system returns to its satisfactory state after a failure
	Vulnerability	Magnitude of failure
Economic criteria (E_3)	Cost	Capital, maintenance, and operational cost
	Income	Products income
Social criteria (E_4)	Ability to meet user acceptance	Water quality acceptance by user
	Ability to meet community acceptance	Creates jobs, benefits, and negative impacts on local area, public education
	Health and hygiene	Safety, risk of infections
	Political approval	Ability to meet environmental or other regulations and management effectiveness
Functional criteria (E_5)	Optional, operational, maintenance, and construction flexibility	Ease of handling the system
	Durability and interactions between the system components	Infrastructure design life and effects on the environment and facilities

Table 7
Decision matrix in TODIM and modified TODIM methods

Alternatives	Attributes – decision matrix				
	E_1	E_2	E_3	E_4	E_5
T_1	8.667	3.000	2.000	2.333	4.333
T_2	5.000	3.667	1.000	9.000	8.667
T_3	1.000	8.000	9.000	1.333	1.000

Table 8
Measurement of normalized matrix in TODIM and modified TODIM methods

Alternatives	Attributes – normalized matrix				
	E_1	E_2	E_3	E_4	E_5
T_1	0.591	0.205	0.167	0.184	0.310
T_2	0.341	0.250	0.083	0.711	0.619
T_3	0.068	0.545	0.750	0.105	0.071

- *Step 9*: According to the above steps, with alteration in losses of attenuation factors (for θ = 1°–100°) the final normalized weights of the three alternatives and sensitivity analyses are determined. The results are shown in Table 11, Figs. 7 and 9.

In Table 11, if the normalized value of alternatives (T_i) are converted to global value by using Eq. (5), the results show that the global value of weights in the modified TODIM method are the same as the value of weights in TODIM method.

Table 9
Criterion weights in TODIM and modified TODIM methods

Criterion	E_1	E_2	E_3	E_4	E_5	Sum
W	0.3243	0.1757	0.0811	0.3649	0.0541	1.0000
W_{jr}	0.8889	0.4815	0.2222	1.0000	0.1481	2.7407

5. Discussion

In this section, TODIM and modified TODIM methods are discussed and compared as follows:

The weights of alternatives obtained by the TODIM method with different values of the factor of the losses are shown in Figs. 7 and 8. As can be seen in Fig. 7, the weights of sensitivity analysis outputs in the TODIM method are exactly between zero and one, so the TODIM technique cannot be combined with MOP techniques such as goal programming. Also, a straight line is coming for weighting of water reuse alternatives in Fig. 7. Straight lines for weighting mean that results of sensitivity analysis are not changed with different attenuation factors (θ) in the original TODIM method and the weights of the highest and lowest alternatives are always zero and one. So, sensitivity analysis cannot be considered for the lowest and the highest alternatives in the TODIM technique. Also, the scale transformation is not proportional to the outcome. Accordingly, the allocation of recycled water for the lowest alternative with zero-value weight cannot be done.

Table 10
Final weights and weighting according to global values in TODIM method

Ranking	Alternatives	Global value (ξ_i)				
		θ = 1°	θ = 5°	θ = 10°	θ = 50°	θ = 100°
2	T_1	0.3081	0.2663	0.2461	0.2173	0.2123
1	T_2	1.0000	1.0000	1.0000	1.0000	1.0000
3	T_3	0.0000	0.0000	0.0000	0.0000	0.0000

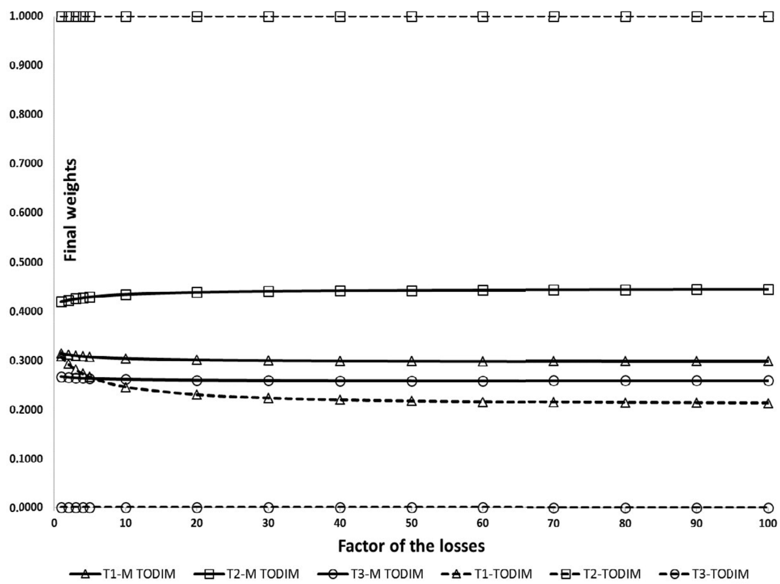

Fig. 7. Weights of alternatives vs. the factor of the losses in TODIM and modified TODIM methods.

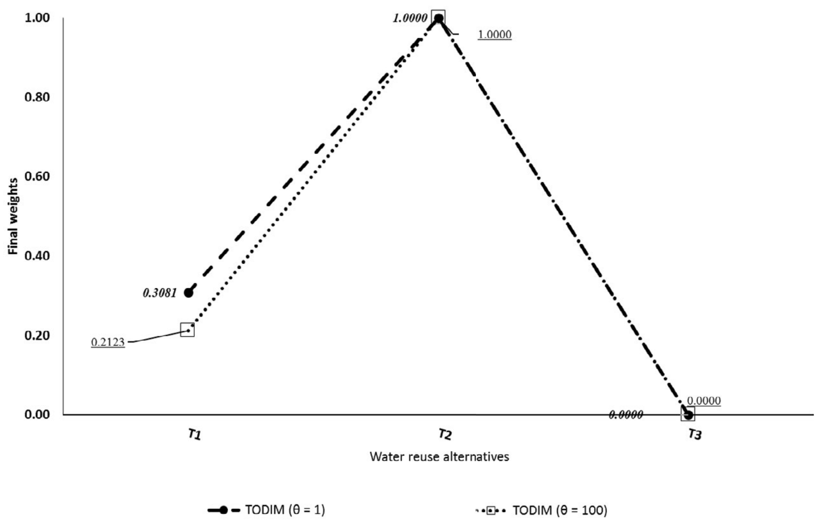

Fig. 8. Comparisons of the weight of alternatives according to TODIM method for θ = 1° and 100°.

The weights of alternatives obtained by the modified TODIM method with different values of the factor of the losses are shown in Figs. 7 and 9. As can be seen in Fig. 7, the weights of sensitivity analysis in the modified TODIM method are normalized with proportionality axiom, so the modified TODIM technique can be combined with MOP techniques such as goal programming. Also, the weights of the highest and lowest alternatives are sensitive to the value of θ. So, the modified TODIM approach is capable of improving the adaptability of TODIM to reflect risk preferences for

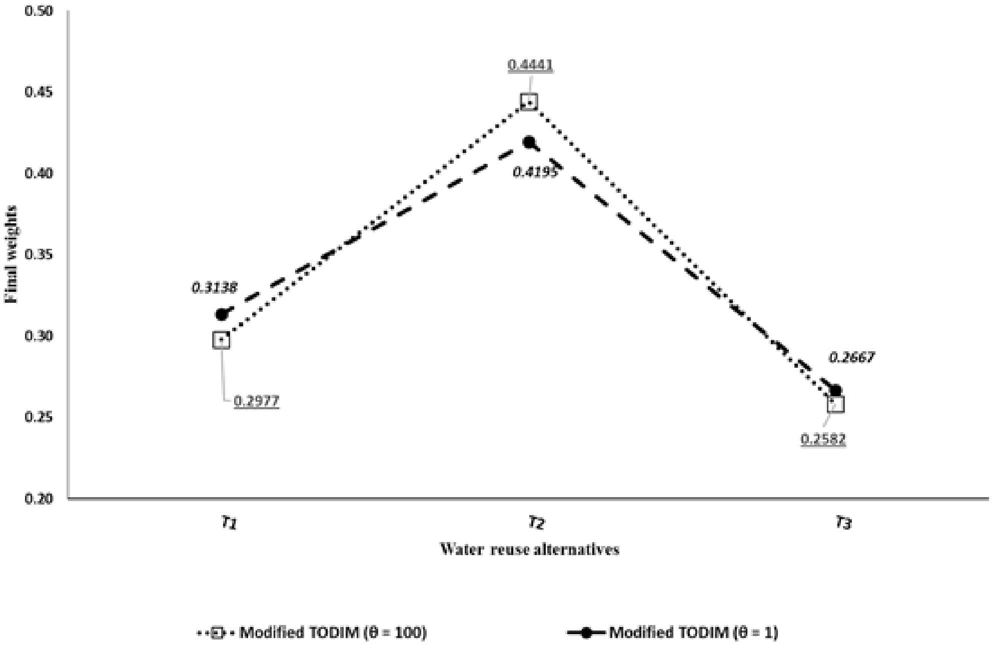

Fig. 9. Comparisons of the weight of alternatives according to modified TODIM method for θ = 1° and 100°.

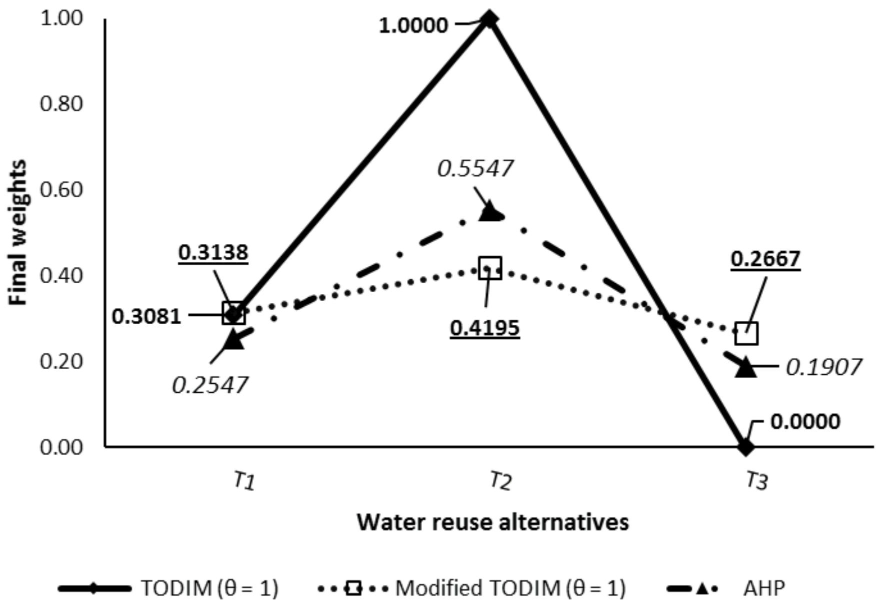

Fig. 10. Comparisons of alternatives weights according to TODIM, modified TODIM, and AHP methods.

all alternatives. Consequently, by using the modified TODIM method, the allocation of recycled water for the lowest alternative can be done.

The value of alternatives weights according to TODIM, modified TODIM, and AHP methods are shown in Fig. 10. As can be seen, the value of weights obtained from the modified TODIM and AHP methods are closely related. The advantage of the modified TODIM method to the AHP method is that it can consider the behavior of decision-makers based on the prospect theory. So, the sensitivity analysis concept can be applied for different attenuation factors (θ) by the modified TODIM method.

6. Conclusions

This is the first study that uses the TODIM method to find the weight of alternatives for recycled water based on economic, risk-based, functional, social, and environmental criteria in a region with water-stress and arid climate. But the weights obtained by TODIM method are not proportional to

Table 11
Final weights of alternatives in modified TODIM method (for θ = 1°–100°)

All criteria		θ = 1°		θ = 5°		θ = 10°	
Ranking	Alternatives	Normalized values (ψ_i)	Converted normalized value to global value (ξ_i)	Normalized values (ψ_i)	Converted normalized value to global value (ξ_i)	Normalized values (ψ_i)	Converted normalized value to global value (ξ_i)
2	T_1	0.3138	0.3081	0.3075	0.2663	0.3041	0.2461
1	T_2	0.4195	1.0000	0.4290	1.0000	0.4343	1.0000
3	T_3	0.2667	0.0000	0.2634	0.0000	0.2616	0.0000
All criteria		θ = 30°		θ = 50°		θ = 100°	
Ranking	Alternatives	Normalized values (ψ_i)	Converted normalized value to global value (ξ_i)	Normalized values (ψ_i)	Converted normalized value to global value (ξ_i)	Normalized values (ψ_i)	Converted normalized value to global value (ξ_i)
2	T_1	0.2999	0.2234	0.2987	0.2173	0.2977	0.2123
1	T_2	0.4407	1.0000	0.4425	1.0000	0.4441	1.0000
3	T_3	0.2594	0.0000	0.2588	0.0000	0.2582	0.0000

the outcome, and the weights of lower and higher alternatives are always zero and one, respectively, so the TODIM technique cannot be combined with multi-objective optimization techniques such as goal programming to allocate the recycled water to all alternatives.

In this study, the modified TODIM method is proposed, in which the normalization scale is proportional to the outcome and is capable of being combined with MOP approaches such as goal programming. The modified TODIM approach is capable of improving the adaptability of the TODIM method to reflect risk preferences for all alternatives including the lowest and the highest alternatives.

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