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A causal structure-based multiple-criteria decision framework for evaluating the water-related ecosystem service tradeoffs in a desert oasis region

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ABSTRACT

Study region: Qira oasis, a typical catchment alluvial fan composed by agriculture and natural shrubs at the south margin of Taklimakan Desert, China

Study focus: Water management modeling involves causal interaction effects of various water-related ecosystem services (ESs) under multiple-criteria water management alternatives, measuring expected benefits of water-related ESs. Many multi-criteria decision tools have been developed to mitigate some of major challenges of ESs tradeoffs. However, few formal ES trade-off frameworks have focused on the multiple-criteria alternatives assessment and indifference point identifications of water-related ES. This paper proposes a causal structure-based multiple-criteria decision framework to model water-related ESs, and to detect the points where the decision makers would be indifferent between two alternatives and to compare with the optimum recommendation value using Bayesian networks (BNs) with analytic hierarchy process (AHP).

New hydrological insights for the region: The study confirms that the proposed causal structure-based multiple-criteria decision framework is a promising approach to modeling possible climate, irrigation, and water policy scenarios and to examining influences of those scenarios on water-related ESs. The framework can be used to effectively recommend optimum water management alternatives and to identify the indifference points by combining BNs into AHP under stakeholder participation. The framework also provides a qualitative and quantitative assessment to reduce the conflicts and uncertainties of multiple-criteria weights in diagnosing water-related ES trade-offs, owing to different stakeholder preferences.

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1. Introduction

The important contribution of ecosystem services (ESs) to the well-being of humans has received broad-scale public recognition in ecosystem management (Millennium Ecosystem Assessment, 2005; Egoh et al., 2007; Remme et al., 2021). Maintaining the components and functions of ecosystems have become necessary to ensure the provision of ecosystem services at present and in the future (Egoh et al., 2008; Shackelford et al., 2019). With the complexity of the ESs including both tangible and intangible services, the ecosystem management strategies need to combine biophysical, eco-environmental, socioeconomic, cultural and political factors into the recommendations, decision-making processes, and implementation of the decisions while involving the interests of stakeholders (Carmona et al., 2011; Kragt et al., 2011; Mamitimin et al., 2015). In such numerous factors, water is essential in meeting the demands of both humans and the health of ecosystems (Pimentel et al., 2004; Bakker, 2012; Liu et al., 2013). As human requirements for water increase, the water-related ESs become more valuable (Brauman et al., 2007). The water-related ESs are often defined as the benefits obtained from ecosystems for which ecosystem composition, structure, and function depend on a supply of water (Schmalz et al., 2015; Chang and Bonnette, 2016; Chen et al., 2018; Luo et al., 2021). Water management has moved toward the governance of water-related ESs from previous comprehensive multi-purpose basin management, especially in arid regions (Cook and Spray, 2012). Therefore, the management of water-related ESs creates an opportunity to fill a vacuum by merging ES into integrated water management systems (IWRM) (Cook and Spray, 2012; Xue et al., 2017b).

Numerous qualitative and quantitative process-based modeling on ESs supporting sustainable water management has been conducted (Daily et al., 2009; Landuyt et al., 2013; Barton et al., 2020). According to many researchers, the water-related ESs managements are typically complex multidisciplinary and multiple-criteria decision-making issues involving uncertainty (Watthayu and Peng, 2004; Kragt, 2009, 2010). While the multiple-criteria decision-making solutions are classified into deterministic and stochastic categories, they depend on whether considering the uncertainty. Due to nonlinear and tedious restrictive conditions, it is often difficult to obtain "unique solution" and to consider the uncertainty in the deterministic type such as system dynamics, dynamic programming approaches, and pattern-oriented models (Carmona et al., 2011; Majumder, 2015; Blair and Buytaert, 2016). The stochastic decision approaches are the most suitable way in representing uncertainty based on probability theory (Pearl, 1988). Recently, Bayesian networks (BNs) as stochastically probabilistic approach has attracted considerable attention in ESs modeling and IWRM (Landuyt et al., 2013; Xue et al., 2017b). Due to their better characteristics including (1) possessing high flexibility and transparency; (2) treating multivariable complexity and uncertainty; (3) incorporating qualitative and quantitative data; (4) allowing stakeholder participation; and (5) updating and improving the model structures and parameters when new knowledge or data become available.

BNs have been widely applied to support multi-criteria decision analysis in many fields, including water management (Carmona et al., 2013), coastal ecosystem evaluation (Gawne et al., 2012; Lehikoinen et al., 2014), urban planning (Langemeyer et al., 2020; Guo et al., 2020), and diagnosis of hydropower production (Peng et al., 2018; Barton et al., 2016, 2020). Especially, BNs as an effective multi-criteria decision analysis tool has continuously appeared in the field of ESs management in the freshwater systems (Shenton et al., 2010; Barton et al., 2020). The BNs have been verified with a considerable capacity and superiority via probabilistic rather than deterministic interpretations between variables in ESs modeling and water resources management decisions (Smith et al., 2011; Chan and Pollino, 2012; Kelly et al., 2013). Due to defective system understanding and difficult parameterization, the stakeholder participation plays a key role in BNs modeling and exchange of knowledge (Carmona et al., 2013; Bertone et al., 2016; Dean, 2020; Dai et al., 2021), effectively eliciting inputs, judgments, and view acceptance in multi-criteria decision analysis (Heli et al., 2019). To date, the numerous BN models have successfully been used to multi-criteria decision analysis by coupling ESs into IWRM (Siew and Döll, 2012; Han-Saem et al., 2015; Xue et al., 2017b), but it is difficult to evaluate trade-offs and decisions involving the selection of the best alternatives across management objectives using BNs under uncertain environments.

The benefits of water-related ESs are multiple-criteria trade-offs and optimization problems, which need to evaluate the management objectives from a series of alternatives (Watthayu and Peng, 2004; Valipour et al., 2014). Despite the relationship between benefits of ESs and water management decision-making can be carried out in the BNs modeling based on raw data, the model results, stakeholder opinion or expert knowledge, the existing approaches/frameworks are not well performed to achieve the trade-offs and optimization between the multiple-criteria expected benefits of water-related ESs via involving stakeholder participation using BNs. Recently, to address the multiple-criteria ESs trade-offs and optimization problems, many multi-criteria decision approaches have been developed. The multiple attribute utility theory, outranking approaches, and compensatory methods are main categories of multi-criteria decision making due to their ease of implementation (Watthayu and Peng, 2004; Majumder, 2015; Marttunen et al., 2019; Krainyk et al., 2021; Wotlolan et al., 2021). While the multiple attribute utility theory can address the nonlinear nature of certain attributes, this method is not appropriate for trade-offs between characteristics of alternatives with more than three or four criteria (Saarikoski et al., 2016; Hallouin et al., 2016). The outranking approaches (e.g., ELECTRE (Roy, 1991)) and compensatory methods (e.g., AHP (Saaty, 2008)) allow qualitative and quantitative criteria to assess the trade-offs of certain criteria, but they are difficult to be applicable in uncertainty situations (Saarikoski et al., 2016).

Encouragingly, a hybrid approach combining BNs with AHP is considered as an ideal means with which to recommend decision alternatives/options, dealing with several criteria that may be conflicting and more uncertain (Park et al., 2015). AHP overcomes weight trade-off issue of several conflicting criteria in multiple-criteria BNs modeling owing to different expert or stakeholder preferences, while BNs can model uncertainty resulting from multiple-criteria quantification in AHP criteria weights via the conditional probability tables (Barton et al., 2020). The hybrid approach has largely been used in the defining tourists' preferences (Papić-Blagojević et al., 2012), tourist attractions (Huang and Bian, 2009), reliability analysis (Zubair, 2014), mobile information recommendation (Park et al., 2015). Recently, many multi-criteria decision analysis tools have been provided as effectively methodological framework to allow stakeholders for mitigating some of the major challenges of ESs tradeoffs (Langemeyer et al., 2016, 2018; Mustajoki et al., 2020). While the iterative participatory processes with stakeholders and decision makers are complement for feedbacks in the iterative model development, calibration, and verification (Chan et al., 2010), few formal causal structure-based multiple-criteria trade-offs frameworks, to date, have been proposed to focus on water-related ESs modeling and assessment using BNs with AHP under stakeholder participation. Moreover, the indifference points (i.e., points of subjective equality or Skiba points) are defined to detect the points where the decision makers would be indifferent between two alternatives (Friedlob and Ramsay, 1986; Scott and Antonsson, 2000; Wagener, 2003), and to compare with the optimum recommendation value. The identification of indifference points is, however, often lacking.

Oasis is a type non-zonal landscape supported by natural or artificial inland rivers in arid desert environment (Liu et al., 2018). The competition for water demands between artificial oasis ecosystems (e.g., agricultural land and urban system) and natural oasis ecosystems (e.g. desert vegetation and riparian forests) has drastically been aggravated by a lack of coordination regarding water-allocation conflicts between the two. In the face of water-use competition between eco-environmental protection and sustainable socioeconomic development in the oasis regions, the adaptive management approaches (e.g., scenario-based modeling and Bayesian networks) and more effective mathematical models (e.g., oasis dissipative hydrological model) have widely used to allocate water use between natural and artificial oasis ecosystems (Zhao et al., 2005; Lei et al., 2006; Xue et al., 2017a; b), However, the trade-offs and optimization of oasis water resources are impacted by the multiple-criteria decisions of ecosystem management options and the uncertainty involved. Therefore, a more effective multiple-criteria decision tool is urgently needed to implement such multidisciplinary problems in the oasis regions.

This paper aims to propose a causal structure-based multiple-criteria decision framework combining BNs with an AHP model to show how trade-offs, optimizations and recommendations between water management alternatives and the expected benefits of water-related ESs can be operationalized with stakeholder participation. The case application is conducted in the Qira oasis of south edge of Taklimakan Desert, Northwest China. As a typical dry irrigation region, the study area is facing severe conflicts between the demand for water by human activities and natural ecosystems owing to aggravating competition of water for agricultural, domestic, and industrial use. In this paper, the structure is given as following. The causal structure-based multiple-criteria decision framework is first described by the characteristics of the water-related ESs. Next, the study area used to test the proposed framework is described. And then, the BNs model development, AHP modeling, and multiple-criteria making decisions and recommendations are conducted. Furthermore, we evaluate the validity of models, analyze the response of optimization variables to the alternative water management strategies and discuss the uncertainties and possible further modeling in water-related ESs management. Finally, the conclusions and the future work are presented.

2. Causal structure-based multiple-criteria decision framework

The proposed causal structure-based multiple-criteria decision framework for trade-offs, optimization, and recommendations for different alternative water management systems and the expected benefits of water-related ESs consists of three steps (Fig. 1): (1) participatory BNs modeling based on an analysis of water-related ESs; (2) multiple-criteria decision analysis using BNs with AHP; and (3) decision-making and recommendations under different water management alternatives. In the multiple-criteria decision framework, the BNs are used to model the expected benefits of water-related ESs under the water management alternatives, whereas the AHP approach is applied to assess the trade-offs, optimization, and recommendations across management alternatives through criteria weight assignments.

2.1. *Participatory BNs modeling based on water-related ESs analysis*

BNs have been known as valuable tools with which to handle the complex and uncertain issues in environmental modeling (McCann et al., 2006; Uusitalo, 2007). They can be used to assess the synergistic effects of various disturbances in the decision-making process (Ayre and Landis, 2012) and to evaluate the management strategies used in building the decision support system (Cain, 2001; Papićblagojević Nataša et al., 2012). A BN is a multivariate causal model comprised of three elements (Bromley et al., 2005; Shenton et al., 2010):

- a set of variables (nodes) representing the system;
- a set of links describing the cause–effect relationship (conditional dependence) between the variables; and
- a set of probabilities measuring the belief of conditional dependence between the linking variables.

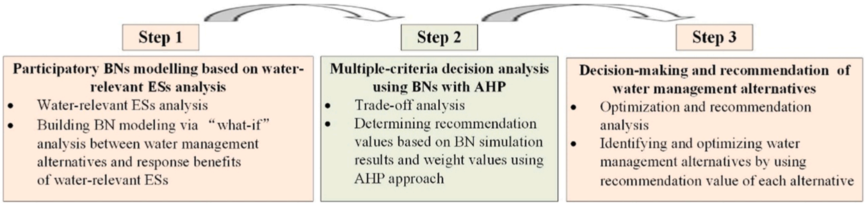

Fig. 1. Schematic diagram of the proposed multiple-criteria decision framework.

The three elements can be defined by two major elements (Aguilera et al., 2011): (1) the qualitative structure – a directed acyclic graph (DAG) that is built by a set of variables and links representing the cause-effect relationships; and (2) quantitative inference – conditional probability tables (CPTs) quantified by a set of probabilities measuring the belief of conditional dependence. The procedures involved in developing the BNs in modeling environmental systems are (Pollino and Henderson, 2010; Ayre and Landis, 2012): (1) identifying the objective of the model; (2) building a DAG with relevant variables and links; (3) assigning states to the variables; (4) specifying the prior probabilities in terms of CPTs; (5) assessing the model performance using sensitivity analysis or expert knowledge; and (6) inferencing and updating the model with new data or evidence. If a set of variables are $X = \{x_1, x_2, \cdots x_n\}$ in the BNs modeling of an environmental system, then the joint distribution is equal to the product of all the conditional distributions attached to each variable. The statistical expression is written as:

$$p(x_1,\ x_2,\ \ldots, x_n) = \prod_{i}^{n} p(x_i | pa(x_i))\ \forall x_1,\ x_2, \ldots, x_n \in \Phi_{x_1},\ \Phi_{x_2}, \ldots, \Phi_{x_n}, \tag{1}$$

Where $p(x_1,\quad x_2, \ldots, x_n)$ stands for the joint distribution of variables $X = \{x_1, x_2, \cdots x_n\}$, $pa(x_i)$ represents the parent variables of variable x_i and Φ_{x_i} refers to the set of all possible values of variable x_i. Each marginal distribution can be calculated by the joint distribution in Eq. (1). There is no need to determine the joint distribution itself. The conditional distribution can be estimated by efficient algorithms, experimental or field data, process-based model results, or the elicited beliefs of experts (Madsen and Jensen, 1999; Borsuk et al., 2006; Wang et al., 2009).

Active involvement and negotiation by public participation can flexibly, transparently, and effectively reach a common perspective in decision-making processes (Lynam et al., 2007; Carmona et al., 2011). BNs have been widely used as participatory modeling tools in environmental modeling and ultimately achieve a visual explanation of reality under public participation (Lynam et al., 2007; Reed, 2008). This study first identifies the water-related ESs, and then analyzes the trade-off and synergy between different users of water and the expected benefits of water-related ESs. A participatory BN model is developed by "what-if" analysis between the different water management alternatives and the expected benefits of water-related ESs to implement the scenario analysis.

2.2. Multiple-criteria decision analysis using BNs with AHP

AHP, first proposed by Saaty (1977), is a useful model with which to solve multi-criteria decision issues and has been applied in numerous research fields, such as planning, selecting a best alternative, and resource allocation and conflict resolution (Zubair, 2014). The AHP conducts the decision-making problems through a hierarchical structure with a limited number (usually four or five) of levels (Saaty, 1980; Jablonsky, 2005). The first level sets a key goal for the multiple-criteria decision issues, whereas the last level is the decision alternatives or scenarios. The levels between the first and last level are usually the criteria of the decision problems. Moreover, the secondary goal and sub-criteria are basic elements involved in the AHP structure (Saaty, 1994; Papićblagojević Nataša et al., 2012) (Fig. 2). The process of multi-criteria decision-making in the AHP model is carried out using following four steps (Saaty, 1994; Park et al., 2015):

- structuring the AHP hierarchy;
- making a pairwise comparison of each alternative to obtain the judgmental matrix;
- computing the weights of alternatives; and
- conducting decision-making with calculated weights.

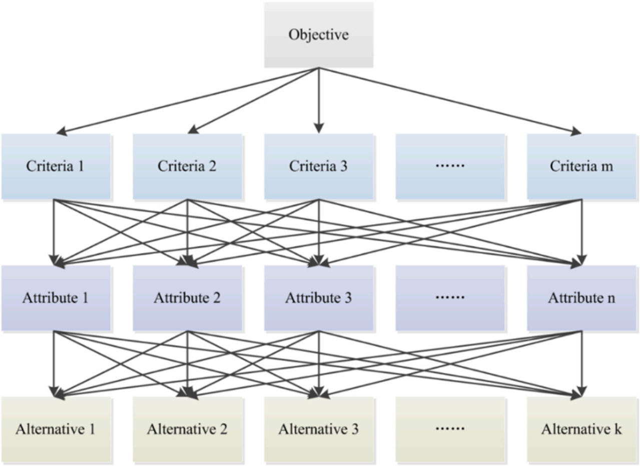

Fig. 2. Schematic diagram of the hierarchical structure of an AHP model with four levels.

The pairwise comparison matrix obtaining a priority vector is an important task in these four steps. Each value in the matrix is defined by the relative importance value shown in Table 1 after a questionnaire survey or expert judgment (Saaty, 1994; Papićblagojević Nataša et al., 2012; Park et al., 2015):

$$A = \left(a_{ij}\right)_{n\times n} = \begin{pmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \dots & \vdots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{pmatrix}, \tag{2}$$

where A represents the pairwise comparison matrix, and a_{ij} is the relative importance value in the ith row and jth column:

$$a_{ij} = \frac{1}{a_{ji}},\ a_{ji} > 0,\ i,\ j = 1,\ 2,\ \dots,\ n \tag{3}$$

With respect to the pairwise comparison matrix, the weighting coefficients can be obtained by determining the principal eigenvector of comparison matrix (Liang et al., 2017):

$$\begin{pmatrix} a_{11} & a_{12}\cdots a_{1n} & \\ a_{21} & a_{22}\cdots a_{2n} & \\ \vdots & \vdots \quad \dots & \vdots \\ a_{n1} & a_{n2}\cdots a_{nn} & \end{pmatrix} \begin{vmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{vmatrix} = \lambda_{max} \begin{vmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{vmatrix} \tag{4}$$

where $W_{max} = (w_1, w_2, \dots, w_n)^T$ is the maximal eigenvector of matrix A and λ_{max} is the maximal eigenvalue of matrix A.

The weighting coefficient vector $w_i$of indicator i can be calculated by normalization of the maximal eigenvector (Liang et al., 2017):

$$w_i = w_i \Big/ \sum_{i=1}^{n} w_i \tag{5}$$

If P_{ij} is an inferred probability set of BN models with j states in ith criterion, then the recommendation values of the alternatives can be determined by (Park et al., 2015):

$$R_{ij} = P_{ij}\cdot w_i \tag{6}$$

where i is the criterion $1, 2, \cdots n$. j is the states of variables $1, 2, \cdots l$. l refers to the number of states of the ith criterion.

As a measure of the reliability of the results, the goodness of judgment can be evaluated by the consistency radio (C_R) in the AHP model. The C_R is determined by dividing the consistency index (C_I) by the random index (R_I) (Saaty, 1990; Bevilacqua and Braglia, 2000). The hierarchies in the AHP model are considered acceptable if $C_R \le 0.1$.

The main advantage of the AHP model is the use of pairwise comparisons to obtain the weights of the measurements by consulting the stakeholders, managers, decision-makers, or experts (Erdogan et al., 2017). This study used an BN models with AHP model to determine the recommendation values based on the simulation results of the BNs and the weight values of the AHP (Fig. 3). The use of an AHP model overcomes a practically difficult issue in BNs modeling in multiple-criteria trade-offs situations.

2.3. Decision-making and recommendations of water management alternatives

According to the recommendation values determined here, the optimum value of the alternatives can be obtained by selecting the maximum recommended value (Park et al., 2015) (Fig. 3):

$$R_{optimal\quad value} = \max_{i=1,2,\cdots n,\ \ j=1,2,\cdots l} R_{ij} \tag{7}$$

In this paper, the largest $R_{optimal\ value}$ of all combinations of attributes is considered as the optimum recommendation value of the water management alternatives. Furthermore, the indifference points are determined as halfway between this minimum accepted recommendation value of the alternative and the largest rejected recommendation value of the alternative by Eq. 6 (Caulkins et al., 2015).

Table 1
Relative importance values in the pairwise comparison (Saaty, 1990; Park et al., 2015).

Importance	Definition
1	Element A and element B are equally important
3	Element A is a little more important than element B
5	Element A is more important than element B
7	Element A is much more important than element B
9	Element A is absolutely more important than element B

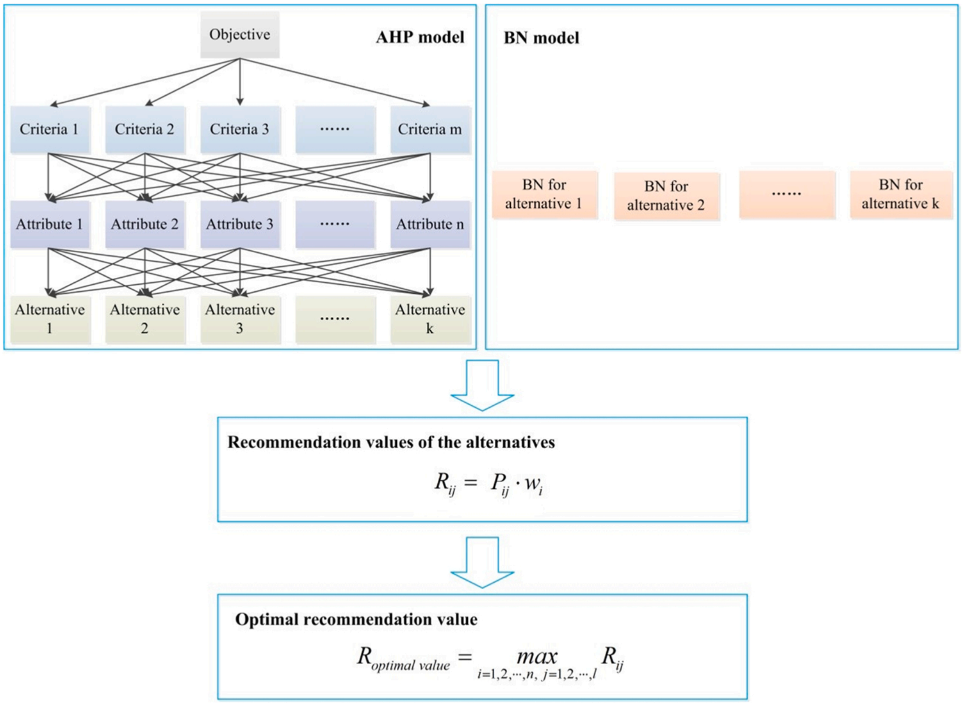

Fig. 3. Process for determining the recommendation values by combining BNs with AHP model.

3. Study area

The Qira oasis is situated in the downstream of the Qira River catchment of Xinjiang, Northwest China and covers approximately 274.63 km^2 (80°43′ E–80°53′ E, 36°57′ N–37°05′ N) (Fig. 4). It is a typical alluvial fan in which the agricultural and natural oases are the main landscape types (Bruelheide et al., 2003; Xue et al., 2016). The Qira oasis has an annual mean temperature of 11.9 °C, accumulated precipitation of 35 mm, and pan evaporation of 2600 mm (Liu et al., 2018; Chang et al., 2022). The water supply in the Qira oasis relies on river runoff, which is generated from glacier and/or snow-melt water, as well as precipitation in the alpine valley of the Kunlun Mountains, flows through the Qira oasis and eventually pours into the arid Taklimakan Desert (Bruelheide et al., 2003; Xue

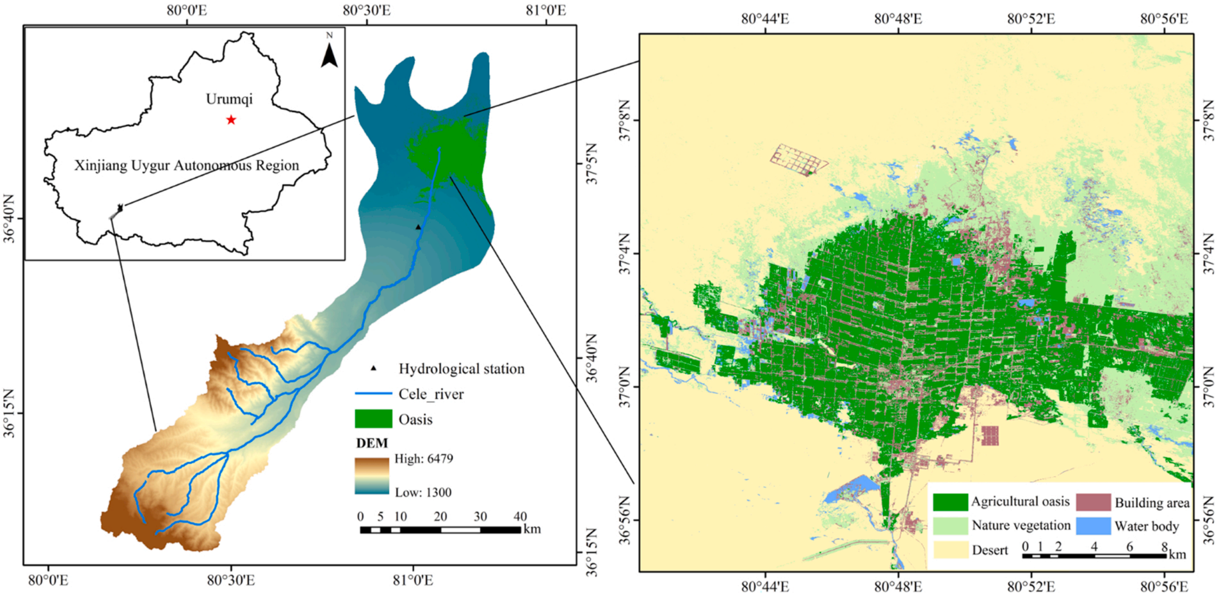

Fig. 4. Location of the Qira oasis in Xinjiang, Northwest China and major land use types.

et al., 2017a). Its annual average runoff during 1985–2010 is 1.27×10^8 m^3. Extremely low precipitation, strong evaporation, and highly vulnerable ecosystems are the major characteristics of this desert (Bruelheide et al., 2003; Xue, b et al., 2017).

Agricultural oasis is the main land use type. The natural oasis, including riparian forests (e.g., *Populus*) and dense shrubs (e.g., *Tamarix* and *Phragmites*), is chiefly distributed in the desert–oasis ecotone, which consists of semi-shrubs and perennial herbaceous grasses (e.g., *Calligonum*, *Tamarix chinensis*, and *Alhagi sparsifolia*) (Chang et al., 2022). The ecosystems in the Qira oasis are experiencing serious problems due to the over-utilization of water for agricultural irrigation, together with increasing demands for water for domestic and industrial use. The excessive use of water for agricultural irrigation threatens the health of natural oasis ecosystems. Many ecological issues have emerged, such as the deterioration of groundwater quality, the degradation of riparian forests and desert shrubs and grasslands, and lowering of the groundwater table that maintains the growth of the desert vegetation (Xue et al., 2015).

Based on the principles of IWRM and ESs together with a multiple-criteria decision framework, managing water resources is crucial for achieving sustainable water development and ecological security in terms of identifying reasonable water allocation and management strategies in a coordinated way (Hotan Water Resources, 2013; Liu et al., 2018; Xue et al., 2017b). The Qira oasis was selected for study because it can be used as a universal case of many typical irrigation regions in which the ESs face threats as a result of increasing competition of water for agricultural, domestic, industrial, and ecological water uses worldwide, especially in arid regions. In addition, a key consideration is that the data in the study area can easily obtained with the support of the Cele National Station of Observation and Research for Desert–Grassland Ecosystems of the Chinese Academy of Sciences.

4. Model development and description

4.1. Development of a participatory BN model

The BN model was developed under public participation and underwent four recursive phases of (1) identifying the issues and cause-effect variables, (2) designing the casual loop diagram, (3) implementing BN inferences or diagnosis, and (4) evaluating the model robustness. The participatory BN model was built to run from March 2015 to August 2016 (Table 2). The 28 participants in the Qira oasis were classified into four groups (researchers, water management experts, stakeholders, and the water manager). Six departments (the water conservancy bureau, the agricultural bureau, the meteorological bureau, the forestry bureau, the environmental protection bureau, and the village committee) were identified as the stakeholders. Every department stakeholder is adopted two representatives (i.e., a head and a professional) based on their well-rounded understanding of the issues. The policy-maker and decision-maker in Qira oasis was the water manager at the Qira Water Management Institute, which releases water management policies and plans. Six professional water management scientists were consulted in the model development, data elicitation, and verification. The researchers offered the participants a water-related ESs background and obtained their feedbacks (Zorrilla et al., 2010; Xue et al., 2017b).

The participatory BN model was constructed by face-to-face discussions and evaluations among stakeholders, domain experts, and water managers, as well as researchers. All the participants identified the variables, states and their relationships, while also defining the plausible structure of the BN model and eliciting sound specialized knowledge. The quantitative data used to populate the CPTs were collected from a variety of sources, including the scientific literature, monitoring hydrometeorological data, socioeconomic data, model results, documentary databases, government statistics, and expert judgment. The obtained data sources are divided into two

Table 2
Participatory BN model development process in the Qira oasis area (Xue et al., 2017b).

Participatory process	Objectives	Date	Format	Participants (no.)	Knowledge resource
Identification	1) Identify potential participants 2) Identify the relevant variables 3) Identify the possible scenarios	March 2015	Group meeting	Research team (9)	Literature review, professional knowledge
Design	1) Construct the logic of the BN 2) Obtain the relevant data from multiple resources	September 2015	Group meeting, stakeholder interview, expert interview, water manager interview	Research team (9), stakeholders (12), expert team (6), water manager (1)	Literature review, professional knowledge, expert knowledge
Implementation	1) Insert the CPTs into the BN 2) Implement the BN model and analyze results	January 2016	Group meeting	Research team (9)	Literature review, professional knowledge
Evaluation	1) Evaluate the model results 2) Recommend the scenario management	August 2016	Group meeting, stakeholder interview, expert interview, water manager interview	Research team (9), stakeholders (13), expert team (6), water manager (1)	Literature review, professional knowledge, expert knowledge

Note: research team is Professors, Ph.D. and Master's degree students in research team; stakeholders are representatives of Water Conservancy Bureau Agricultural Bureau, Meteorological Bureau, Environmental Protection Bureau, Forestry Bureau, and Village committee; expert team is water management experts of Xinjiang Institute of Ecology and Geography; water manager is head of Water Management Institute.

types. The quantifiable data such as hydrometeorological and socioeconomic data can be parameterized by EM algorithm, while the unquantifiable data such as water management policies and measures are obtained by expert assessment. When building the BN structure, the CPTs are elicited to simulate the results via variable parameterization. Moreover, the developed BN model was assessed and updated by the participants in the participatory process. An integrated cause and effect structure of the BN was eventually built after achieving a consensus from all the participants (Fig. 5). The final structure of the BN was presented in the Netica software package with a total of 56 variables and 74 links (Fig. 6). The structure of the BN model showed the flow of water via the water supply and demand analysis carried out in the Qira oasis. The seven end variables used as output variables presented the expected benefits of the water-related ESs. The detailed development processes in the participatory BN model, including the participatory process, model construction, data collection could be found in Xue et al. (2017b). An explanation of each variable and the states representing it are described and given in Table A1 of Appendix.

4.2. *AHP modeling*

The AHP hierarchy structure was created as four levels (Fig. 7). The top level was defined as the total objective of expected benefits maximization from water-related ESs. The evaluation criteria which impact the total goal are set at the second level and are related to seven different aspects: biodiversity, grassland degradation, land desertification, groundwater safety, agricultural income, drinking water security, and soil salinization. These criteria are then divided into several sub-criteria associated with water security factors at the third level, including ecological water demands, water for urban greenbelts, water for man-made shelterbelt, spring irrigation, the available agricultural water, groundwater quality, and groundwater depth. The lowest level comprised 225 water management alternatives. These alternatives were set as a combination of different management scenarios.

The weight coefficients of the decision alternatives were calculated by pairwise comparisons after the AHP hierarchy structure of decision-making problems had been defined. Table 3 shows an example of the pairwise comparison matrix of criteria regarding the goal. The comparison matrix of the sub-criteria against the criteria and the comparison matrix of water management alternatives with respect to the sub-criteria were quantified. To optimize the water management alternatives, the comparison matrix of the alternatives was defined at the same level of importance.

The 225 water management alternatives in the AHP hierarchical structure were a combination of different management scenarios. These scenarios were defined as the assembly of states in the variables of the developed BN. The variables included groundwater extraction (three states), groundwater quality (three states), ecological water demands (five states), and the irrigation quota (five states).

5. Results and discussion

5.1. *Model validity*

To ensure their reliability and accuracy, the BN and AHP models were validated by sensitivity analysis and degree of consistency, respectively. Sensitivity analysis is considered as one of the more effective approaches to evaluating BN models (Charnley and

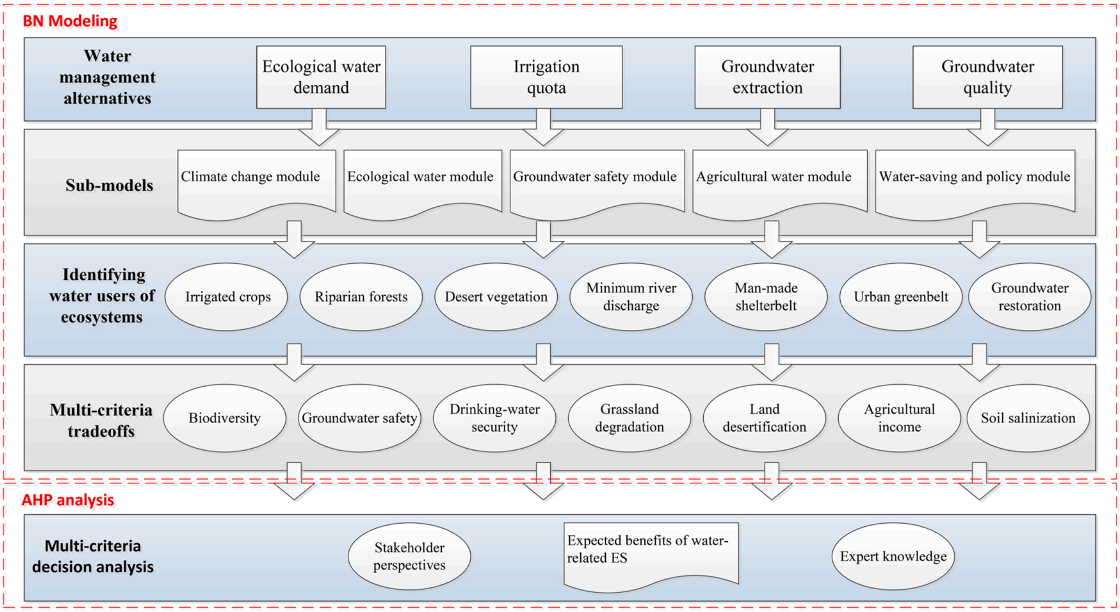

Fig. 5. Cascade of model structure in water-related ES tradeoffs and decisions analysis.

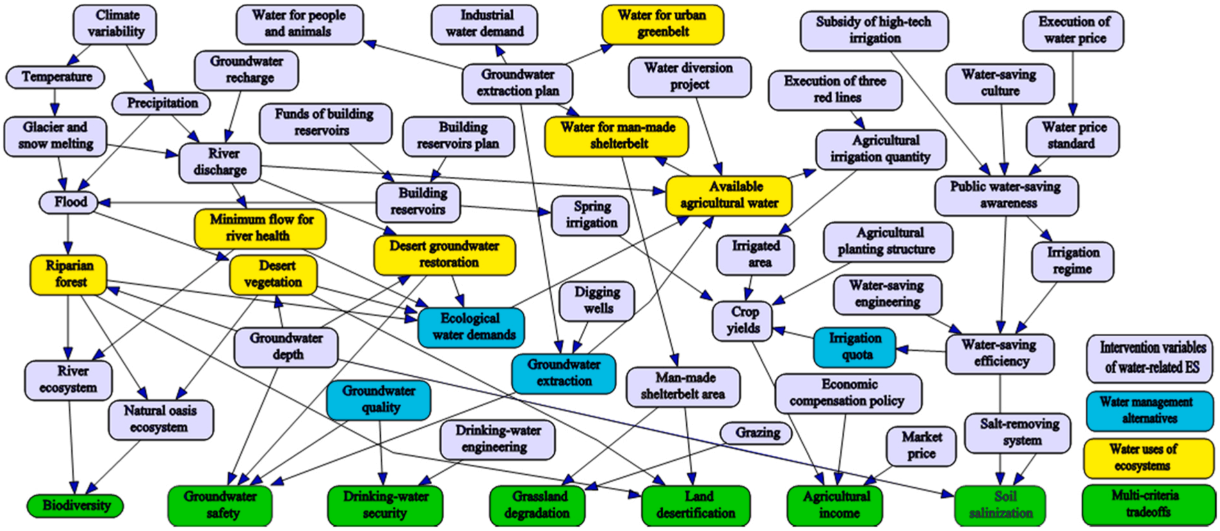

Fig. 6. Participatory BN model structure based on water-related ESs in Qira oasis (adapted from Xue et al. (2017b)).

Engelbert, 2005; Kragt, 2009; Chan et at, 2010) and is conducted to detect the sensitivity of the BN target variables to the input variables using mutual information (Rowe and Frewer, 2004; Barton et al., 2008). The seven variables for the expected benefits of water-related ES were defined as the target variables on which to carry out the sensitivity analysis. The sensitivity results were verified with the reliability and reasonability reported by Xue et al. (2017b). The knowledge of local experts and the judgment of stakeholder perspectives were used to evaluate the acceptability and plausibility of the modeling results. These validities matched well with anecdotal evidence in the scientific literature.

In addition, all the C_R values for different criteria were < 0.10—that is, the consistency radio in the AHP is appropriate and it can be confirmed that the modeling results are reliable and acceptable.

5.2. Multiple-criteria decision-making and recommendations using BN with AHP

The AHP model provided weight coefficients of 0.03, 0.04, 0.13, 0.14, and 0.30 for biodiversity, grassland degradation, land desertification, groundwater safety, and agricultural income, and weight coefficients of 0.33 and 0.04 for drinking water security and soil salinization, respectively (Fig. 8). Drinking water security and agricultural income, accounting for about 30 %, were larger weight coefficients in the expected benefits of water-related ESs. According to the weight coefficients calculated in the sub-criteria, the groundwater quality, groundwater depth, and spring irrigation were the main criteria (accounting for about 25 %) with respect to the water management alternatives.

Since the government and managers in the study area pay more attention to ecological and agricultural water tradeoffs under groundwater security, the groundwater extraction, groundwater quality, ecological water demands, and irrigation quota are selected as the decision variables. Consequently, a total of 225 scenarios were set to simulate the expected benefits of water-related ESs under the different state combinations of four water management variables. Fig. 9 illustrated BN model simulation example with elicited CPTs in combination of water management alternatives. According to Eq. 6, the recommendation values were calculated as shown in Fig. 10. For example, the recommendation value was 0.24 under the combination of < 1 g/l groundwater quality, 9857–10,728 m^3/ha irrigation quota, < 22.80 million m^3 groundwater extraction, and < 40.29 % ecological water demands in Fig. 10a. The optimum alternatives are determined by assessing the maximum recommended values. The baseline of maximum recommended value is defined as greater than 0.37 according to value differences. The water management alternatives are recommended as the 12 scenarios, which were determined by the different combinations of groundwater extraction, groundwater quality, ecological water demands, and irrigation quota (Table 4).

5.3. Response of optimization variables to water management alternatives

The impacts of water management alternatives on the optimization variables (spring irrigation, agricultural irrigation area, man-made shelterbelt area, amount of agricultural irrigation, water for man-made shelterbelt, water price standards, and water-saving efficiency) were assessed. The scenario simulations were conducted by testing the changes in the probability values in the states of each optimization variable under the different water management alternatives. Based on the recommendation values using the BN model with AHP, the 15 scenarios were simulated to show the probability of changes in the optimization variables in the BN model. The scenarios are easily examined by specifying the state of the water management alternatives.

Fig. 11 shows the probability variations of the optimization variables under different water management alternatives using the BN model with AHP. The magnitude of probability variations describes the strength of the influence of different scenarios (Mamitimin

Table A1
Variables, variable states, detailed explanation, and information sources used in eliciting CPTs (Xue et al., 2017b).

Variable	States	Explanation	Information sources
Climate variability	Yes, no	Climate change impacts on the variation of water resource	Literature values (Xue et al., 2015)
Water-saving culture	Good, poor	Water-saving awareness in Muslim religious culture	Survey results
Groundwater depth	< 4, 4–10, > 10	Groundwater depth (m)	Qira water resources planning report (2013)
Groundwater quality	< 1, 1–3, > 3	Groundwater quality (g/l)	Qira water resources planning report (2013)
Groundwater recharge	< 22.63, 22.63–29.20, > 29.20	Groundwater recharge (million m^3)	Hotan Water Resources Planning (2013)
Building reservoirs	Yes, no	Building reservoirs to relieve the pressure among water demands	Results of stakeholder interviews
Digging wells	Yes, no	Exploiting groundwater based on groundwater resource evaluation	Results of stakeholder interviews
Groundwater extraction plan	Increasing, decreasing	Groundwater extraction policy	
Execution of three red lines	Good, poor	Water policy from quantity, quality, and water-using efficiency	Results of stakeholder interviews
Execution of water price	Good, poor	Water considered as good to increase water-saving consciousness	Results of stakeholder interviews
Funds of building reservoirs	Sufficient, insufficient	Support of fund is indispensable for building reservoirs	Results of stakeholder interviews
Building reservoirs plan	Yes, no	Building reservoirs policy	Results of stakeholder interviews
Subsidy of high-tech irrigation	High, low	Economic stimulation for promotion of high-tech irrigation	Results of stakeholder interviews
Economic compensation policy	Yes, no	Economic compensation policy in three red lines	Results of stakeholder interviews
Water diversion project	Yes, no	Water diversion plan for ensuring water supply	Results of stakeholder interviews
Drinking-water engineering	Good, poor	Engineering plan for ensuring drinking-water health	Results of stakeholder interviews
Water-saving engineering	Good, poor	Anti-seepage engineering of channels	Results of stakeholder interviews
Grazing	Overgrazing, normalgrazing	Grazing intensity in the human activities	Results of stakeholder interviews
Groundwater extraction	< 22.80; 22.80–23.26; > 23.26	Groundwater extraction in water consumption (million m^3)	Qira water resources planning report (2013)
Irrigated area	< 8057, 8057–11,326, $> 11,326$	Agricultural irrigated area (ha)	Statistical Yearbooks of Xinjiang Province (2002–2013)
Water price standard	< 0.02, 0.02–0.05, > 0.05	Water price standard (RMB/m^3)	Results of stakeholder interviews
Man-made shelterbelt area	< 1071, 1071–2240, 2240–3500, 3500–3850, > 3850	Man-made shelterbelt area (ha)	Results of stakeholder interviews
Irrigation quota	< 8142, 8142–9857, 9857–10,728, 10,728–12,128, $> 12,128$	Agricultural irrigation quota (m^3/ha)	Qira water resources planning report (2013)
Agricultural planting structure	Plan 1, plan 2, plan3	Cultivated area: forest area: pasture area= 61.22:36.49:2.29 (Plan 1), 50.36:47.39:2.25 (plan 2), 43.60:54.45:1.95 (plan 3)	Hotan Water Resources Planning (2013)
Ecological water demands	< 40.29 %, 40.29 %– 50.84 %, 50.84 %– 53.48 %, 53.48 %– 58.75 %, > 58.75 %	Percent of river runoff	Calculated outputs in the model (Xue et al., 2015)
Temperature	< 0.44, 0.44–1.37, > 1.37	Annual mean temperature (°C)	Literature values (Xue et al., 2015)
Precipitation	< 134.48, 134.48–162.02, > 162.02	Annual accumulated precipitation (mm)	Literature values (Xue et al., 2015)
Glacier and snow melting	< 51, 51–63, > 63	Annual glacier and snow melting (million m^3)	Hotan Water Resources Planning (2013)
Flood	Increasing, decreasing	Flood events	Results of stakeholder interviews
River discharge	< 104, 104–129, > 129	Annual river discharge (million m^3)	Literature values (Xue et al., 2015)
Riparian forest	Under 17, over 17	Water demand for riparian forest (million m^3)	Calculated outputs in the model (Xue et al., 2015)
Minimum flow for river health	Under 1.60, over 1.60	Minimum flow for ensuring river health (million m^3)	Calculated outputs in the model (Xue et al., 2015)
Desert vegetation	Under 10.50, over 10.50	Water demand for desert vegetation (million m^3)	

(continued on next page)

Table A1 (*continued*)

Variable	States	Explanation	Information sources
			Calculated outputs in the model (Xue et al., 2015)
Desert groundwater restoration	Under 19.10, over 19.10	Desert groundwater restoration (million m^3)	Calculated outputs in the model (Xue et al., 2015)
River ecosystem	< 1.60, 1.60–5, > 5	Water demand for ensuring river ecosystem (million m^3)	Calculated outputs in the model (Xue et al., 2015)
Natural oasis ecosystem	< 50, 50–61.40, > 61.40	Water demand for ensuring natural ecosystem (million m^3)	Calculated outputs in the model (Xue et al., 2015)
Spring irrigation	Sufficient, insufficient	Water demand accounting for 35% of total consumption in spring	Results of stakeholder interviews
Crop yields	< 235.90, 235.90–239.70, > 239.70	Crop yields (thousand tons)	
Market price	High, low	Crop market price	Results of stakeholder interviews
Salt-removing system	Good, poor	Salt-removing engineering	Results of stakeholder interviews
Water for man-made shelterbelt	< 12,989.70, 12,989.70–27,168, > 27,168	Water demand for man-made shelterbelt growth (thousand m^3)	Qira water resources planning report (2013)
Water-saving efficiency	< 0.43, 0.43–0.62, > 0.62	Water-saving efficiency in the irrigation system	Qira water resources planning report (2013)
Available agricultural water	< 0.13, 0.13–0.15, > 0.15	Agricultural water supply (billion m^3)	Qira water resources planning report (2013)
Public water-saving awareness	< 50 %, 50 %– 80 %, > 80 %	Percent of farmer surveys	Survey results
Irrigation regime	Drip irrigation, sprinkler irrigation, flood irrigation	Three irrigation regime	Hotan Water Resources Planning (2013)
Agricultural irrigation quantity	< 98,520.70, 98,520.70–100,625.10, > 100,625.10	Agricultural irrigation (thousand m^3)	Qira water resources planning report (2013)
Industrial water demand	Under 270.40, over 270.40	Water demand for industrial development (thousand m^3)	Qira water resources planning report (2013)
Water for people and animals	Under 2307.80, over 2307.80	Water demand for people and animals (thousand m^3)	Qira water resources planning report (2013)
Water for urban greenbelt	Under 80, over 80	Water demand for urban greenbelt (thousand m^3)	Qira water resources planning report (2013)
Agricultural income	< 0.30, 0.30–0.35, > 0.35	Agricultural total income (billion RMB)	Statistical Yearbooks of Xinjiang Province (2002–2013)
Biodiversity	Good, medium, poor, extremely poor	Biodiversity based on species and growth	Results of stakeholder interviews
Groundwater safety	High, medium, low, extremely low	Groundwater condition based on depth and quality	Results of stakeholder interviews
Drinking-water security	< 8.60, 8.60–25.60, 25.60–44.20, > 44.20	Drinking-water people with risk (thousand people)	Qira water resources planning report (2013)
Soil salinization	< 10.08, 10.08–16.80, 16.80–21, > 21	Area insulted from salinization (ha)	Qira water resources planning report (2013)
Grassland degradation	Good, medium, poor, extremely poor	grassland growth condition	Results of stakeholder interviews
Land desertification	< 104.26, 104.26–259.77, 259.77–628.50, > 628.50	Land area suffered from desertification disaster (km^2)	Results of stakeholder interviews

et al., 2015). Although the effects of combinations among the different water management alternatives can alleviate water pressure and conflict at the spatio-temporal scale, spring irrigation is still insufficient, with about a 45% chance for agricultural water demand in spring (Fig. 11a). The results imply that there is no efficient reservoir upstream in the Qira River to store water for agricultural irrigation in spring. This also verifies that the current water management alternatives are insufficient to completely meet the requirements of spring irrigation, which comprises 35 % of the annual agricultural water demand (Xue et al., 2017b).

By contrast, the areas of agricultural irrigation and man-made shelterbelts have high increasing chances as the groundwater extraction and irrigation quotas increase (Fig. 11b, c). For example, > 11,326 ha agricultural area and 3500–3850 ha man-made shelterbelt area are higher than 10.10 % and 30.00 %, respectively, under > 23.26 million m^3 groundwater extraction, < 1 g/l groundwater quality, > 58.75 % ecological water demands, and 10,728–12,128 m^3/ha irrigation quota compared with the a priori condition. This also results in an increase of probability in the agricultural irrigation quantity and the amount of water for man-made shelterbelt (Fig. 9f, g). For instance, > 27,168 thousand m^3 water for man-made shelterbelt is higher than 48.8 % under > 23.26 million m^3 groundwater extraction < 1 g/l groundwater quality, > 58.75 % ecological water demand, and 10,728–12,128 m^3/ha irrigation quota compared with the a priori condition.

However, the increase in the agricultural irrigation quantity and water for man-made shelterbelt leads to a significant decrease of probability in the water price standard and water-saving efficiency (Fig. 9d, e). < 0.02 RMB/m^3 water price standard and < 0.43

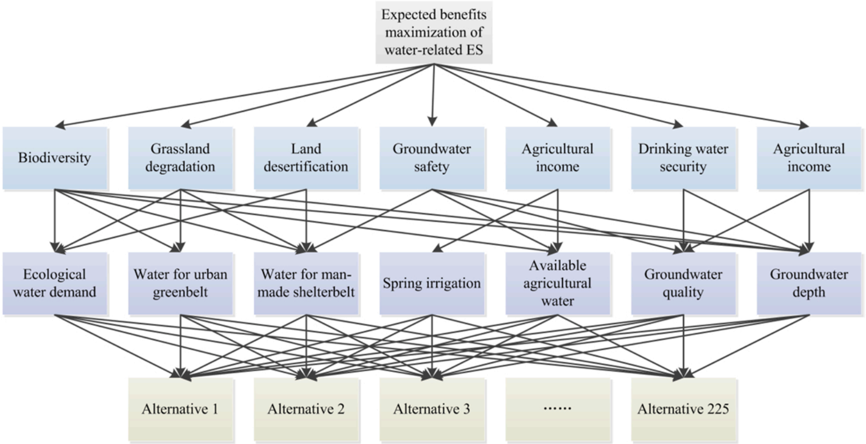

Fig. 7. AHP hierarchy scheme.

Table 3
Pairwise comparison matrix of the criteria with respect to the goal.

Term	Biodiversity	Grassland degradation	Land desertification	Groundwater safety	Agricultural income	Drinking water security	Soil salinization
Biodiversity	1	1/3	1/7	1/5	1/8	1/6	1/2
Grassland degradation	3	1	1/5	1/5	1/7	1/7	1/2
Land desertification	7	5	1	1/2	1/5	1/3	5
Groundwater safety	5	5	2	1	1/3	1/3	3
Agricultural income	8	7	5	3	1	1/2	7
Drinking water security	6	7	3	3	2	1	8
Soil salinization	2	2	1/5	1/3	1/7	1/8	1

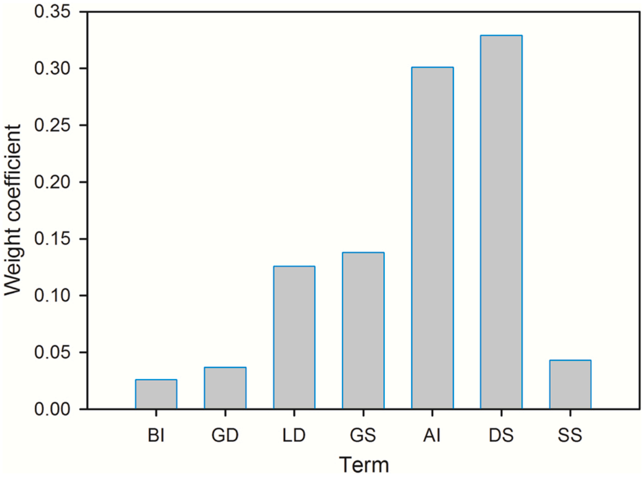

Fig. 8. Weight coefficients of biodiversity (BI), grassland degradation (GD), land desertification (LD), groundwater safety (GS), agricultural income (AI), drinking water security (DS), and soil salinization (SS).

water-saving efficiency were < 4.40 % and 26 %, respectively, under > 23.26 million m^3 groundwater extraction < 1 g/l groundwater quality, > 58.75 % ecological water demands, and 10,728–12,128 m^3/ha irrigation quota compared with the a priori condition. This shows that a low irrigation water price and water-saving efficiencies affect the cost of water and pressure on water use in the arid Qira oasis.

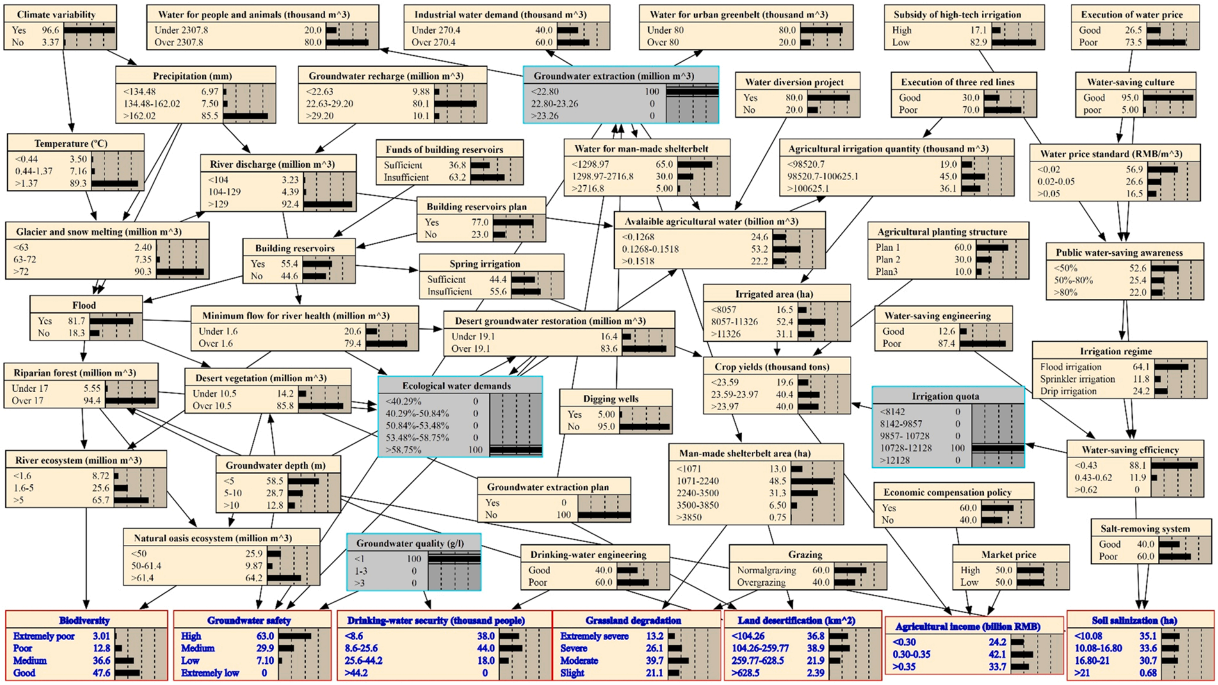

Fig. 9. BN model simulation example with elicited CPTs in the water management alternative.

5.4. *Uncertainties and further modeling for water-related ESs*

Although the BN model can effectively cope with the uncertainties in the ESs modeling (Poppenborg and Koellner, 2014) and AHP provides reliable recommendations for water management alternatives in multiple-criteria decision-making (Park et al., 2015), various uncertainties exist in the proposed multiple-criteria decision framework assessments due to the complex relationships in water-related ESs modeling. These uncertainties result from the combined effects of the inherent variations in water supply, conflicts in water use, water-saving practices, and water management policy.

Based on the principle of maximum recommended values, four water management alternatives are optimum. The first alternative is < 22.80 million m^3 groundwater extraction, < 1 g/l groundwater quality, > 58.75 % ecological water demands, and 10,728–12,128 m^3/ha irrigation quota (recommended value for 0.40). This recommendation chases the groundwater extraction and irrigation quota as little as possible after meeting the demands of the groundwater quality and ecological water demands. The second alternative is < 22.80 million m^3 groundwater extraction, < 1 g/l groundwater quality, > 58.75 % ecological water demands, and $> 12,128$ m^3/ha irrigation quota (recommended value for 0.42). This recommendation chases the groundwater extraction as little as possible and gives an adequate irrigation quota after meeting the demands of groundwater quality and ecological water demands. The third alternative is 22.80–23.26 million m^3 groundwater extraction, < 1 g/l groundwater quality, > 58.75 % ecological water demands, and 10,728–12,128 m^3/ha irrigation quota (recommended value for 0.41). This recommendation chases the moderate groundwater extraction and irrigation quota after meeting the demands of groundwater quality and ecological water demands. The fourth alternative is 22.80–23.26 million m^3 groundwater extraction, < 1 g/l groundwater quality, $> 58.75\%$ ecological water demands, and $> 12,128$ m^3/ha irrigation quota (recommended value for 0.43). This recommendation chases the moderate groundwater extraction and irrigation quota adequately after meeting the demands of groundwater quality and ecological water demands.

According to the definition of the indifference points or Skiba points, the alternative of < 22.80 million m^3 groundwater extraction, < 1 g/l groundwater quality, 40.29 %– 50.84 % the ecological water demands, and 9857–10,728 m^3/ha irrigation quota (recommended value for 0.27), and the alternative of < 22.80 million m^3 groundwater extraction, < 1 g/l groundwater quality, 50.84 %– 53.48 % ecological water demands, and 8142–9857 m^3/ha irrigation quota (recommended value for 0.27). This reflects that low ecological water demand is indifferent between two alternatives in the decision of managers. Furthermore, the alternative of 22.80–23.26 million m^3 groundwater extraction, < 1 g/l groundwater quality, 40.29 %– 50.84 % ecological water demands, and 9857–10,728 m^3/ha irrigation quota (recommended value for 0.27), and the alternative of 22.80–23.26 million m^3 groundwater extraction, < 1 g/l groundwater quality, 50.84 %– 53.48 % ecological water demands, and 8142–9857 m^3/ha irrigation quota (recommended value for 0.27). This implies that the medium groundwater extraction indifferent between two alternatives. In general, the decision makers would be indifferent intermediate level of recommended values between two alternatives, which can shift the Skiba point in such a way that the Optimal recommended value will be reached. This also verifies the existence of Skiba point in ecosystem service modeling (Friedlob and Ramsay, 1986; Scott and Antonsson, 2000; Wagener, 2003; Caulkins et al., 2015).

With agricultural water use accounting for 97.7% of the total water supply in this arid oasis (Xue et al., 2017a), improving the

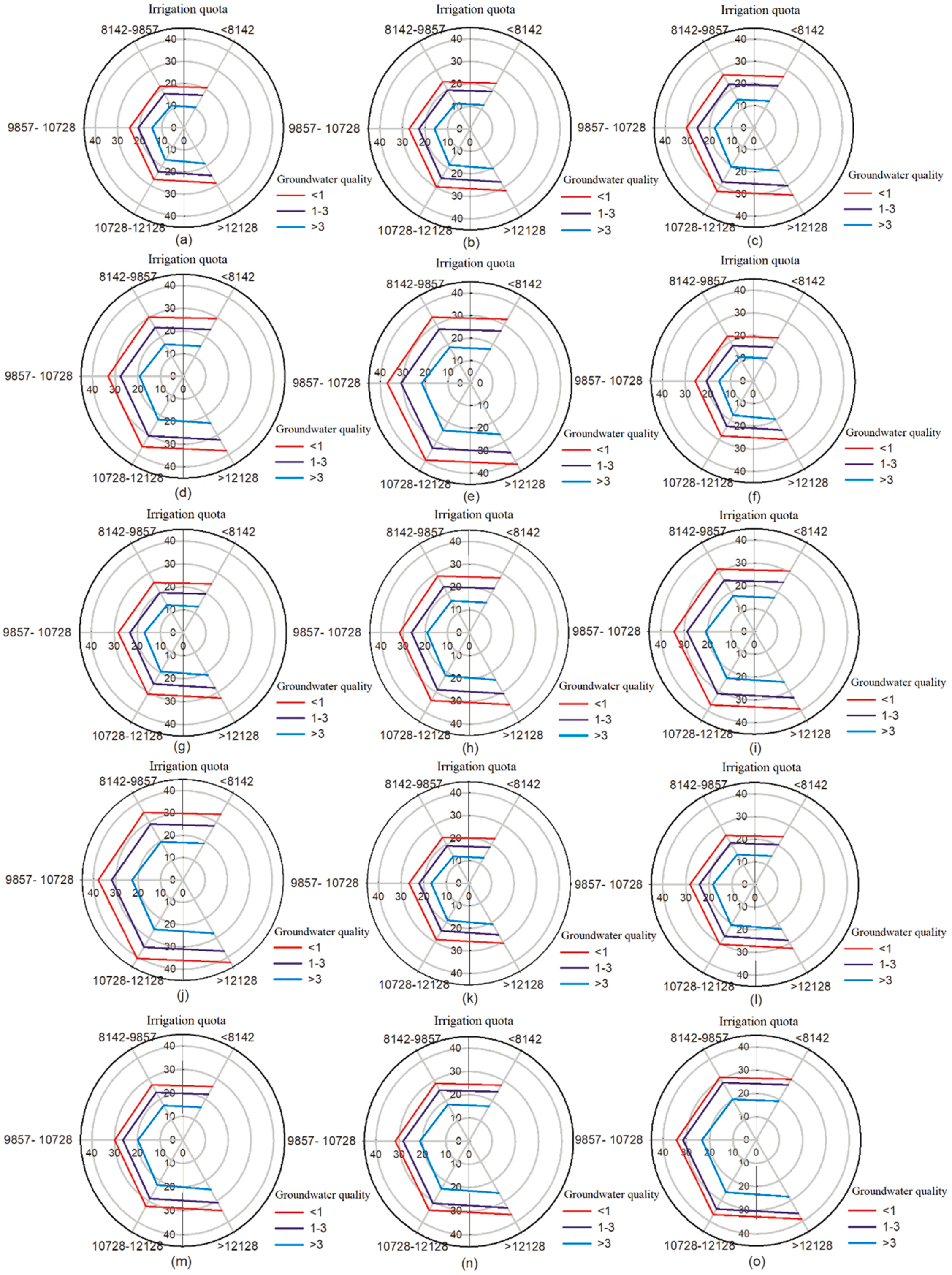

Fig. 10. Recommendation values (%) of four-dimensional water management alternatives under the certain combination of groundwater extraction, ecological water demands, groundwater quality, and irrigation quota: (a)-(e) low groundwater extraction and ecological water demands from extremely low to high states; (f)-(j) medium groundwater extraction and ecological water demands from extremely low to high states; (k)-(o) high groundwater extraction and ecological water demands from extremely low to high states. Note that the states of groundwater extraction and ecological water demands are explained in Table A1 of Appendix.

Table 4
Recommended combination results modeled in multi-criteria decision framework.

Combination Scenarios	Groundwater extraction (million m^3)	Groundwater quality (g/l)	Ecological water demands (%)	Irrigation quota (m^3/ha)
CS1	Low (<22.80)	Good (<1)	Medium (53.48%–58.75%)	High (>12,128)
CS2	Low (<22.80)	Good (<1)	High (>58.75%)	Low (9857–10,728)
CS3	Low (<22.80)	Good (<1)	High (>58.75%)	Medium (10,728–12,128)
CS4	Low (<22.80)	Good (<1)	High (>58.75%)	High (>12,128)
CS5	Medium (22.80–23.26)	Good (<1)	Medium (53.48%–58.75%)	Medium (10,728–12,128)
CS6	Medium (22.80–23.26)	Good (<1)	Medium (53.48%–58.75%)	High (>12,128)
CS7	Medium (22.80–23.26)	Good (<1)	High (>58.75%)	Low (9857–10,728)
CS8	Medium (22.80–23.26)	Good (<1)	High (>58.75%)	Medium (10,728–12,128)
CS9	Medium (22.80–23.26)	Good (<1)	High (>58.75%)	High (>12,128)
CS10	Medium (22.80–23.26)	Medium (1–3)	High (>58.75%)	High (>12,128)
CS11	High (>23.26)	Good (<1)	High (>58.75%)	Medium (10,728–12,128)
CS12	High (>23.26)	Good (<1)	High (>58.75%)	High (>12,128)

efficiency of water use via water-saving measures is crucial in alleviating conflicts over water in regional sustainable development. Therefore, to save the water currently used for agricultural irrigation for other water requirements, particularly the ecological water demands, the third optimum alternative is more suitable for the current study area. Although an increase in the price of water can improve the efficiency of agricultural water use (Mamitimin et al., 2015), additional adjustments (e.g., upgrading the irrigation system, reducing water losses from leakage, applying advanced irrigation techniques, and agricultural policies such as economic compensation) can effectively improve the water management alternatives for sustainable development (Pang et al., 2014; Xue et al., 2017b).

Instead of deriving a final optimum result from the multiple-criteria decision-making process, the objective of this study is to propose a generalizable assessment framework to develop a water-related ESs model to support multiple-criteria decisions in water management systems, particularly in arid and semiarid regions. This framework provides a flexible and objective evaluation method, allowing the integration of additional knowledge and data into the assessment using the hybrid approach of AHP and BN. However, some important issues remain unresolved. The structures of the BN model are hierarchical and acyclic. This is an important weakness of BN in environmental and ecosystem services modeling mechanistically and dynamically (Landuyt et al., 2013). Numerous studies have pointed out that the absence of feedback loops is a restriction of BN model (Uusitalo, 2007; Aguilera et al., 2011).

According to Aguilera et al. (2011) and Landuyt et al. (2013), the BN model to combine multiple other models is better potential to handle the feedback issue of environmental modeling under stakeholder participations. This study developed the BN model combined with AHP under stakeholder participations, considering the feedbacks in model development. This process is embodied in the iterative participations (Chan et al., 2010). Such hierarchical decision-making processes have widely been accepted in environmental and ecosystem services modeling around the world, such as groundwater management in Denmark (Henriksen, 2010), catchment-based water resource management in the Kongulai catchment of Australia (Chan et al., 2010), ecosystem services modeling in the Haean watershed of Germany (Poppenborg and Koellner, 2014), regional water resources management in Guadiana Basin of Spain, and estuarine dynamics in the Neuse River Estuary in North Carolina of America (Alameddine et al., 2011).

Despite the participatory BN development combined with AHP is strictly conducted by iterative participatory feedback processes, the spatial and temporal variations were not considered in the water-related ESs modeling. To support feedback loops in the temporal or spatial dynamics, either additional variables, separate casual networks for each temporal and spatial state, the integration of other models into BN modeling, or the time-sliced model (i.e., Dynamic Bayesian network) are more suitable and acceptable for further study (Uusitalo, 2007; Pollino and Henderson, 2010; Duespohl et al., 2012; Castelletti and Soncini-Sessa, 2007).

6. Conclusions

This paper proposes a causal structure-based multiple-criteria decision framework illustrating how the hybrid approaches of AHP and BN can be used to model water-related ES and to identify the indifference points. The proposed framework in this paper comprises three steps: (1) BNs modeling based on water-related ESs analysis; (2) multiple-criteria decision analysis using BNs with AHP, and (3) decision-making and the recommendation of water management alternatives. The BN model builds multiple water-related ESs in decision-making contexts, providing a flexible and powerful tool for ESs modeling and scenario analysis. The AHP model is used to identify the relative importance of each decision-making criterion. The weighted values of the expected benefits of water-related ESs are quantified to cope with multi-criteria decision-making that involves trade-offs and optimization among various ESs.

The case analysis in the Qira oasis of Northwest China confirmed that the proposed multiple-criteria decision framework combining the BN into an AHP model is a promising approach with which to model ESs and to recommend optimum water management alternatives. The proposed framework is particularly well-suited for detecting the points where the decision makers would be indifferent between two alternatives and to compare with the optimum recommendation value by modeling the expected benefits of water-related ESs. The use of transdisciplinary approaches combining BN models into an AHP model allows for trade-offs, optimization, and recommendations between multiple and conflicting decision alternatives in an uncertain environment. The framework is considered as an effective tool providing a qualitative and quantitative assessment method that improves the disadvantage of each approach and can solve transdisciplinary and multiple-criteria decision issues. It is not limited to the ESs modeling in multiple-criteria decision-making.

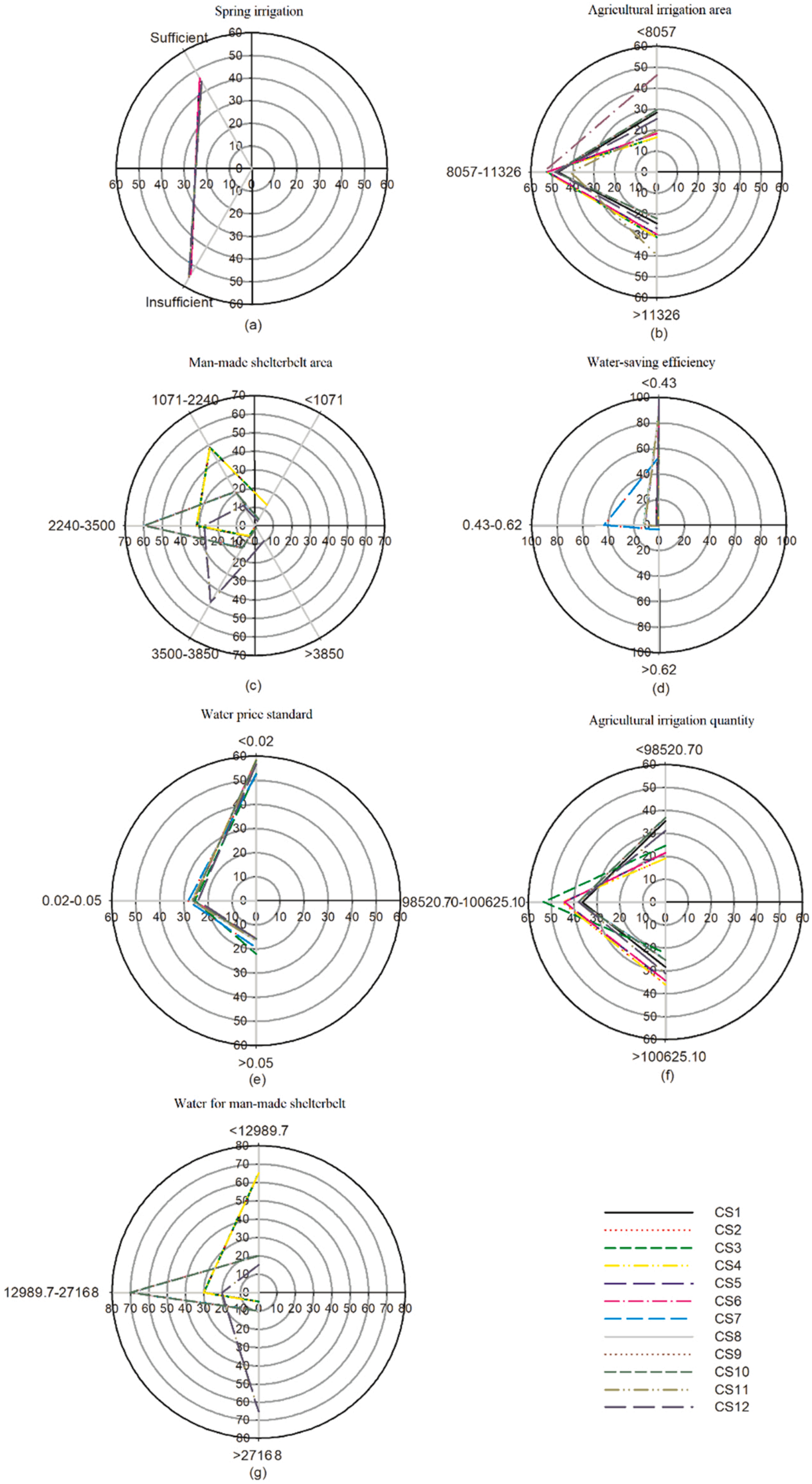

Fig. 11. Probability variations (%) of optimization variables under different water management alternatives. (a) Spring irrigation, (b) agricultural irrigation area, (c) man-made shelterbelt area, (d) water-saving efficiency, (e) water price standard, (f) agricultural irrigation quantity, and (g) water for man-made shelterbelt.

To make the multiple-criteria decision framework more plausible and reliable, further work needs to consider the spatial and temporal variations in water-related ESs modeling.

Compliance with Ethical Standards

NA.

CRediT authorship contribution statement

Jie Xue: Conceptualization, Writing - original draft. **Jiaqiang Lei:** Supervision. **Fanjiang Zeng:** Data curation, Resources, Supervision. **Huaiwei Sun:** Writing - review & editing. **Jingjing Chang:** Validation. **Zhiwei Zhang:** Methodology, Software.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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