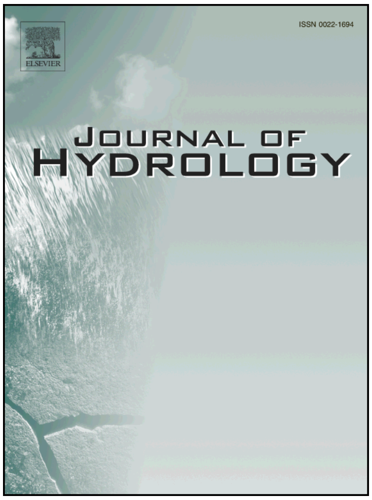

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A decision-making framework to model environmental flow requirements in oasis areas using Bayesian networks

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Abstract: The competition for water resources between agricultural and natural oasis ecosystems has become an increasingly serious problem in oasis areas worldwide. Recently, the intensive extension of oasis farmland has led to excessive exploitation of water discharge, and consequently has resulted in a lack of water supply in natural oasis. To coordinate the conflicts, this paper provides a decision-making framework for modelling environmental flows in oasis areas using Bayesian networks (BNs). Three components are included in the framework: (1) assessment of agricultural economic loss due to meeting environmental flow requirements; (2) decision-making analysis using BNs; and (3) environmental flow decision-making under different water management scenarios. The decision-making criterion is determined based on intersection point analysis between the probability of large-level total agro-economic loss and the ratio of total to maximum agro-economic output by satisfying environmental flows. An application in the Qira oasis area of the Tarim Basin, Northwest China indicates that BNs can model environmental flow decision-making associated with agricultural economic loss effectively, as a powerful tool to coordinate water-use conflicts. In the case study, the environmental flow requirement is determined as 50.24%, 49.71% and 48.73% of the natural river flow in wet, normal and dry years, respectively. Without further agricultural economic loss, 1.93%, 0.66% and 0.43% of more river discharge can be allocated to eco-environmental water demands under the combined strategy in wet, normal and dry years, respectively. This work provides a valuable reference for environmental flow decision-making in any oasis area worldwide.

Keywords: Bayesian network; Environmental flows; Oasis; Decision-making; Northwest China

1 Introduction

Competition for water resources between different water demands is the origin of many conflicts worldwide. In recent years, such conflicts have become increasingly intensified as water resouces decline and requirements increase around the world, especially in arid and semiarid regions (Garmona et al., 2011; Jury and Vaux, 2007). In these regions, water resources are an extremely vital natural resource, and there are severe threats due to the scarcity of water and the competition between water demands (Boehmer et al., 2000; Chen et al., 2005; Ling et al., 2011). Oasis, situated between mountainous areas and amongst the desert plains in arid and semiarid regions, is essential for human settlement, as well as for promoting biodiversity and combating desertification, and therefore require a stable water supply (Ye et al., 2010; Ling et al., 2013). Recently, however, the increase in water demands caused by human activities, such as agricultural irrigation in artificial oasis agroecosystems, has intensified the competition for water demands between artificial oasis ecosystems (e.g. agricultural land and urban vegetation) and natural oasis ecosystems (e.g. desert shrub-grass vegetation and riparian forests). The natural oasis ecosystem has been drastically and adversely affected by the excessive utilization of water resources in oasis agriculture, which is the main consumer of water (Rumbaur et al., 2015). The situation is aggravated by a lack of coordination regarding water conflicts bewteen the oasis agroecosystem and the natural oasis ecosystem. Therefore, the allocation of water amounts that can be extracted from the oasis agroecosystem for supporting the eco-environmental functions of the natural oasis ecosystem, as well as for meeting agricultural economic demands, has become one of the greatest challenges in achieving sustainable water resources management in these regions.

Approximately 70% of water resources are diverted for human activities (e.g. agricultural irrigation) from global river systems in the river basins throughout the world (Malano and Davidson, 2009; Calzadilla et al., 2010). Many rivers suffer from water extraction levels that are so high that the river water cannot reach the lower reaches of river basins (Cai, 2011). The situation has led to growing instances of dramatic impacts on ecosytem services such as wetlands, fresh water, riparian (Tugai) forests, and desert shrub-grass vegetation in arid and semiarid regions (Rumbaur et al., 2015). In oasis areas of arid and semiarid regions, the water supply mainly depends on river discharge (Bruelheide et al., 2003; CAWA, 2013; Rumbaur et al., 2015). River water becomes crucial for maintaining natural oasis ecosystems (e.g. riparian forests and desert shrub-grass vegetation), as well as artificial oasis ecosystems (e.g. farmland and urban vegetation). Over recent years, with the dramatic increase in oasis farmland extension, a large number of dams have been built in upstream and/or midstream areas in order that river water is extracted for anthropogenic activities (e.g. agricultural irrigation). The increased water demand in such severe water-deficit arid areas has led to the frequent drying-up of the lower reaches of many inland rivers (Xue et al., 2015). Many serious problems are exposed, such as vanishing aquatic ecosystem, the degradation of riparian forests, and the decline of the groundwater table. But most importantly, downstream natural oasis ecosystems, which act as a natural barrier to prevent desertification and sandstorms, via desert shrub-grass vegetation and riparian forests, have been severely weakened and, in some cases, almost entirely lost (CAWA, 2013; Rumbaur et al., 2015).

In the face of water-use conflicts between eco-environmental protection and sustainable socioeconomic development, maintenance of the water requirements for riverine and natural oasis ecosystems, which are considered the most important ecosystem services for the mitigation of desertification and soil erosion, is the highest priority in such arid regions (Xue et al., 2015). To define the water requirements for these ecosystems, environmental flow assessments are applied to determine the amount of water needed in a given ecosystem, and have become an important method in ecosystem protection/restoration and water resources management (Arthington et al., 2006; Sun et al., 2008; Poff et al., 2009; Pang et al., 2013). Many approaches to environment flow assessments, with their aim of ecosystem protection/restoration, have been developed and divided into four types: hydraulic, hydrological, habitat, and holistic (Tharme, 2003; Alcazar et al., 2008). However, it is difficult to identify reasonable objectives for environment flow assessments in establishing nonlinear ecological and hydrological relationships using these methods (Adams et al., 2002; Cai et al., 2011; Pang and Sun, 2014). Furthermore, the environment flow requirements reccommended for ecosystem protection are difficult for water-use stakeholders (e.g. those involed in agriculture) to accept, owing to the potential economic loss associated with adopting them, particularly against the background of limited water resources but limitless water demands for human activities and the eco-environment (Pang and Sun, 2014). Reaching a consensus between socioeconomically sustainable development and eco-environmental health under different options/scenarios of anthropogenic activities and eco-environmental needs has become crucial in implementing environmental flow assessments and decision-making in sustainable water resources management (William et al., 2008). Moreover, compromises may be necessary, involving not only the maintenance of eco-enviromental requirements at an appropriate level, but also the various stakeholders accepting the potential economic loss caused by environmental flow allocation (Barbier et al., 2008; Pang and Sun, 2014).

Water-allocation conflicts between anthropogenic activities and ecosystem protection/ restoration are affected by the complexity of ecosystem management options and the uncertainty involved, including the water availability, ecosystem management strategies , water management options, and agricultural economic measures. In recent years, the multidisciplinary approach has been applied to integrate sociopolitical and economic factors into eco-environmental management in practical decision-making (McCartney et al., 2009). It has been found that modeling such multidisciplinary decision-making problems requires comprehensive and effective tools that can be employed to implement various data sources and opitions/scenarios. Bayesian networks (BNs) are considered as a tool with great potential for supporting ecosystem management decision-making (Duspohl et al., 2012; Poppenborg and Koellner, 2014). Due to its flexible and transparent characteristics, BN becomes increasingly popular via directed acyclic graphs that represent causal relationships between variables (Cain, 2001). Therefore, it is an ideal tool for understanding the impacts of various options/scenarios in environmental flow decision-making, through knowledge integration and the implementation of sustainable management measures (Pang and Sun, 2014). Despite the many environmental flow assessment studies on various ecosystem functions in river, wetland or estuarine ecosystem services, few have focused on the application of BNs for maintaining multiple ecosystem services, to model environmental flow decision-making in oasis areas (Xue et al., 2015).

This paper proposes a decision-making framework to model environmental flow requirements in oasis areas. The framework considers the trade-offs between eco-environmental and agro-economic water requirements, and is conducted by BN approach. The method incorporates sociopolitical and economic factors into eco-environmental assessments. The decision-making criterion is established by intersection point analysis. The model is applied in a case study of the Qira oasis of Tarim Basin, Northwest China, and environmental flow decision-making recommendations are determined under different water management options/scenarios.

2 Methodology

The proposed decision-making framework for environmental flow requirements in oasis areas consists of three main components (Fig. 1):

- Agricultural economic loss assessment. Due to the water-use conflicts between ecosystem management and agricultural economic development, this part mainly estimates the agricultural economic loss caused by agricultural water shortage due to meeting environmental flow requirements.
- Decision-making analysis using BNs. This part develops BNs composed of the variables involved. The decision-making analysis is implemented by the BNs model and intersection point analysis.
- Environmental flow decision-making. Through model evaluation, the recommended environmental flow requirement is determined based on the inference of the BNs model, together with intersection point analysis. Furthermore, the recommendations for environmental flow decision-making in the oasis area are also established under different water management scenarios. .

2.1 Agricultural economic loss assessment due to meeting environmental flow requirements

The expression on the relationship between crop yield and water use was presented by Steduto et al. (2012), who have pointed out that crop yield reduction is related to the corresponding evapotranspiration deficit during the different growth periods. The crop yield (*Y*) with respect to evapotranspiration (*ET*) is expressed by (Doorenbos and Kassam, 1979; Steduto et al., 2012):

$$(1-\frac{Y_a}{Y_m})=K_y(1-\frac{ET_a}{ET_m}) , \qquad (1)$$

whereY_a is the actual crop yield (kg/km^2), Y_m is the maximum crop yield (kg/km^2), ET_a is the actual crop evapotranspiration (mm), ET_m is the maximum crop evapotranspiration (mm), and K_y denotes a crop yield response factor (dimensionless), which represents the influence of evapotranspiration deficits on the crop yield reductions.

If the corresponding yield reductions $(Y_m - Y_a)$ is replaced with Y_{wr}, and Q_{ws}/A is set to express the ratio of agricultural water shortage to crop planting area, which represents the agricultural water deficiency (i.e. evapotranspiration deficits $(ET_m - ET_a)$) after meeting environmental flow requirements, the crop production-reduction model is given as (Pang et al. 2013, Pang and Sun, 2014):

$$Y_{wr}=\frac{K_y Y_m Q_{ws}}{(1-\delta)ET_m A} , \qquad (2)$$

where Q_{ws} is agricultural water shortage (m^3) during the growth periods, A (km^2) is the planting area, and δ is the water-saving coefficient (dimensionless), which reflects the practical implementation effect of water-saving measures. The maximum crop evapotranspiration (ET_m) is estimated by (Allen et al. 1998; Steduto et al., 2012):

$$ET_m = k_c \times ET_0 , \qquad (3)$$

where k_c is the crop coefficient (dimensionless), which is the ratio between crop evapotranspiration and reference crop evapotranspiration during different growth periods, and ET_0 is reference crop evapotranspiration (mm).

Reference evapotranspiration (ET_0) can be calculated by the FAO Penman–Monteith model, which is expressed as (Allen et al., 1998):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} v_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 v_2)}, \tag{4}$$

where Δ is the slope vapour pressure curve (kPa/°C), R_n is the net radiation at the crop surface (MJ/m^{2}d), G is the soil heat flux density (MJ/m^{2}d), γ is the psychometric constant (kPa/°C), T is the average monthly air temperature (°C), v_2 is the wind speed at 2 m height (m/s), and $e_s - e_a$ is the saturated vapour pressure deficit (kPa).

Agricultural water shortage (Q_{wr}) can be determined by the difference in water quantity between agricultural water demand and actual water supply after meeting the environmental flows, which are the highest priority for reconciling the contradiction between ecosystem services and sustainable economic development (Pang and Sun, 2014):

$$Q_{wr} = \begin{cases} (1-\delta)Q_a - Q_0, & (1-\delta)Q_a > Q_0 \\ 0, & (1-\delta)Q_a \le Q_0 \end{cases}, \tag{5}$$

where Q_a is the agricultural water demand (10^{8}m^3), and Q_0 is the agricultural water supply after meeting the environmental flows for oasis ecosystem services (10^{8}m^3).

According to the water consumption in irrigation areas, the agricultural water requirement (Q_a) can be estimated by:

$$Q_a = k_c \times ET_0 \times A \,. \tag{6}$$

Agricultural water supply (Q_0) can be determined by the water balance rule, which is the integration between water supply (including river discharge, precipitation, groundwater, and water diversion projects) and water consumption (including industrial consumption, domestic water use, agricultural water supply, and environmental flow demands):

$$Q_0 = Q_r + Q_p + Q_g - Q_i - Q_d - Q_e \pm Q_t \,, \tag{7}$$

where Q_r is the river discharge (10^{8}m^3), Q_p is the precipitation (10^{8}m^3), Q_g is the water quantity extracted from groundwater (10^8m^3), Q_i is the water volume for industrial consumption (10^8m^3), Q_d is the water requirement for domestic utilization (10^8m^3), Q_e is the environmental flow requirements for maintaining various oasis ecosystem services (10^8m^3), and Q_t is the water volume transferred into or out of the research area.

The river discharge and precipitation can be calculated using hydrological and meteorological data in the study region, while the water quantity extracted from groundwater, water demands for industrial consumption and domestic utilization are obtained through the China Statistical Yearbook. With regard to the environmental flow requirements, Xue et al. (2015) have proposed a quantitative method to determine the environmental flows based on various ecosystem services in arid oasis areas. According to oasis ecosystem functions, the environmental flow demands are divided into both consumptive and non-consumptive water volumes. Water requirements for maintaining desert shrub-grass vegetation, desert and riparian forests, evaporative loss of river surface, and the maintenance of groundwater restoration are identified as consumptive environmental flows. Conversely, water demand for maintaining the riverine habitat and that for ensuring sediment transport are considered as non-consumptive environmental flows. Based on the rule of summation and compatibility rule (maximum principle) the environmental flow requirements in arid oasis areas are integrated by expression (Xue et al., 2015):

$$Q_e = W_e + W_f + W_{gr} + max(W_{bf}, W_{st}), \tag{8}$$

where W_e is the evaporation of the water surface in the river channel (10^8m^3), W_f is the water demands for different vegetation types (10^8m^3), W_{gr} is the water requirement of groundwater restoration (10^8m^3), W_{bf} is the water quantity for river base flows (10^8m^3), W_{st} is the water demand for sediment transport (10^8m^3), and $\max(a, b)$ denotes the maximum of parameters a

and *b*.

Maintaining environmental flow requirements will inevitably lead to economic loss in the agricultural production owing to shortage in water utilization for irrigation. The economic loss caused by agricultural water reduction can be calculated by the product of crop price and production reduction:

$$V = Y_{wr} v \,, \tag{9}$$

where V represents the economic loss during different growth periods (RMB), and v is the crop price (RMB/kg).

2.2 Decision-making analysis using BNs

BNs, also termed “Bayesian belief networks”, “Bayes nets”, “belief networks”, and also sometimes “causal probabilistic networks”, are being increasingly applied in environmental and ecosystem modeling, for quantifying management decisions whilst considering uncertainty and complexity (Uusitalo (2007) and Aguilera et al. (2011)). As an effective graphical decision analysis tool, BNs represent causal and interrelated relationships between variables based on their conditional probability distributions (Cain, 2001). Each variable is characterized by a finite amount of mutually-exclusive states, which can be defined as Boolean functions, Labeled type, Ranked form, Discrete Real, Integer interval, and continuous interval (Fenton N and Neil M (2013)). Since the dependencies between variables are probabilistically described through directed links, every link from one variable to another variable needs the definition of conditional probability tables (CPTs). The CPTs quantify the probabilities of the states of “child”variables given those of its “parent” variable or “parents” variables. Note that variables without “parents”are indicated by tables of marginal probability distribution (Borsuk et al., 2004; Poppenborg and

Koellner, 2014).

According to the ecosystem management decision objectives, the variables of the developed BNs can be classified into five categories: (1) decision-making variables: management decision variables, the key input variables of BNs; (2) incontrollable variables: environmental variables that cannot be controlled by management actions; (3) intervention variables: management variables in the input nodes ("parent nodes") for achieving the objectives; (4) intermediate variables: variables between the management actions and objectives; (5) objective variables: variables affected by decision-making actions and management options, the final output variables of the BNs (Cain, 2001; Duspohl et al., 2012; Landuyt et al., 2013). After the BNs are developed by expert knowledge or BNs learning, the CPTs can be elicited by direct measurements, empirical data, related model outputs, or expert opinion for model inference (Cain, 2001; Carmona et al., 2011; Pang and Sun, 2014).

In this paper, the BNs are applied to evaluate the trade-offs between agriculture and ecosystem water demands. According to the region's characteristics, management options, and the agricultural economic loss assessment (section 2.1), the networks for environmental flow decision-making are constructed and evaluated by expert knowledge and data information in oasis areas. To facilitate presentation of the BNs graphical structure, the variables in the BNs are stratified horizontally into five levels. Decision-making variables ("critical environmental flow"), incontrollable variables ("available water supply"), and intervention variables ("irrigation regime", "water-saving engineering", and "price of crops") are set as input nodes ("parent" nodes) in level 1. The intermediate variables reflect the agricultural economic losses involved in levels 2, 3 and 4. Level 5 denotes the total economic loss, the objective variable of the BNs, which is of great concern to stakeholders (particularly farms).

The development and inference of the BNs are implemented using the BN software tool AgenaRisk (Agena, 2007) (www.agenarisk.com; www.BayesianRisk.com), which is a sufficiently flexible and easy-to-use software package for constructing the DAG and eliciting the CPTs, and has been widely used in various fields (Fenton N and Neil M (2013)). The software is an effective technology to build CPTs in large-scale BNs, particularly for variables with many states (Fenton et al., 2007). Despite best efforts to construct the model properly, the number of probability values elicited from experts can be unfeasibly large. For example, suppose that the BNs of three variables have five states, respectively; the CPTs then have 125 cells. If we add another variable with five states, then this increases to 625 entries; and if we continue increasing the variables with large states, then there is clearly a problem of combinatorial explosion. Therefore, this study, based on the outcomes of the agricultural economic loss model and expert opinion, uses the ranked nodes (i.e. the state of node is ranked) as the state types to model qualitative judgments in the BNs. This is because a set of weighted functions (i.e., WMEAN, WMIN, WMAX, and MIXMINMAX) are sufficient to elicit almost any ranked-node CPT in practice, where the ranked node's parents are all ranked (Fenton et al. 2007; Fenton N and Neil M (2013)).

3.3 Environmental flow decision-making based on intersection point analysis

Once the DAG and CPTs are complete, the BNs can be applied to model environmental flow decision-making and to test what happens to the total objective variable (i.e. "total economic loss"), which is quantified as an indicator of environmental flow decision-making and management performance under different water management scenarios. Although agricultural economic loss resulting from the prioritization of environmental flow requirements cannot be acceptable to irrigation stakeholders (e.g. farmers), to evaluate the trade-offs between water for agriculture and water for ecosystems, the environmental flow requirements are recommended based on intersection point analysis between the probability for large-level total economic loss and the proportion for total economic output due to meeting environmental flows to maximize total economic output (Fig. 2).

In this study, the intersection point analysis is proposed by the general equilibrium analysis (Florenzano, 1985; Ianchovichina et al., 2001). According to the theory, the “interaction” between the increasing of agricultural economic loss and the decreasing of oasis ecosystem risk (i.e., oasis ecosystem risk safety at the cost of agricultural water for environmental flow requirements) under ensuring the environmental flows will result in an overall (or "general") equilibrium. When environmental flow requirements are higher, the probability of agricultural economic loss gradually increases based on BN model inference, and correspondingly oasis ecosystem risk probability (at the cost of agricultural economic output loss) gradually decreases. According to Ward (2003), the agricultural water haves to be sacrificed by providing environmental flow requirement for the oasis ecosystem risk safety. Namely, when lower environmental flow is provided, the probability of agricultural economic loss is smaller (correspondingly agricultural economic output becomes larger). However, the oasis ecosystem risk becomes larger. To quantify equally and expediently, the oasis ecosystem risk probability is expressed as the ratio of total agro-economic output to maximum agro-economic output (Li et al., 2007). Therefore, based on general equilibrium theory, the intersection point between probability of agricultural economic loss and the ratio of total agro-economic output to maximum agro-economic output curves is presented as the equilibrium point (i.e., decision-making point). Although the weakness of this analysis is difficult for irrigators due to “unaccepted” agricultural loss in providing water for environmental flows, the merits of this methodology will provide the tradeoff and equilibrium analysis between agricultural and environmental water use to ensure oasis ecosystem risk safety.

To simulate the influence of different water management scenarios on environmental flow decision-making in oasis areas, the BNs are implemented to analyze the response of management performance under different scenarios. Similarly, the environmental flow requirements are determined by intersection point analysis under each scenario.

3 Case study

A large number of oases are located between the mountainous areas and amongst the desert plains of Xinjiang, Northwest China (Tang et al., 1992; Xue et al., 2015), each possessing similar structures and characteristics. In this paper, Qira oasis, situated in the south rim of Tarim Basin in Xinjiang, is selected as a case study to model the decisions framework. Moreover, data can be easily obtained from Qira National Station of Observation and Research for Desert-Grassland Ecosystems, Chinese Academy of Sciences. The Qira oasis area situates in the lower reaches of the Qira River Basin (36°54´–37°09´N, 80°37´–80°59´E) and covers an area of 274.63 km^2 (Fig. 3). Due to annual precipitation of approximately 39 mm and strong evaporation of 2700 mm, the available water supply in the Qira oasis area depends mainly on river discharge, which is generated from a high-altitude valley in the Kunlun Mountains, before flowing through the Qira oasis area and finally discharging into the extremely arid desert. According to Qira hydrological station data, the runoff of the Qira River declined annually between 1960 and 2010 at a rate of -0.03×10^8m^3/10a. The decrease in the river runoff poses greater challenges associated with integrated water resources management in the Qira oasis area (Xue et al., 2015).

Based on different ecosystem functions, Qira oasis's ecosystems are divided into four types, including the riverine ecosystem, desert shrub-grass ecosystem, desert forest ecosystem, and farmland ecosystem. With regard to the desert shrub-grass ecosystem, remote sensing data from LandsatTM imagery show that the desert shrub-grass vegetation in Qira oasis is composed of high coverage grass (69.34 km^2) (60%-90% vegetation coverage), medium coverage grass (22.54 km^2) (20%-60% vegetation coverage), and low coverage grass (20.28 km^2) (5%-20% vegetation coverage). Moreover, the desert and riparian forests (mainly *Populus euphratica*) in Qira oasis covers 50 km^2, which accounts for 30.86% of the total coverage areas (Xue et al., 2015). Ensuring the health of the desert vegetation becomes crucial for desertification and sand storms (Xue et al., 2015). However, over recent years, with the dramatic increase in artificial oasis extension (especially farmland extension), a large number of dams have been built in the upstream area in order to extract river water for agricultural irrigation. The increase in water demand in this severely water deficient arid area has led to the frequent drying-up of the lower reaches of the Qira River. Many serious problems in the Qira area are being exposed, such as a declining aquatic ecosystem, riparian forest and desert shrub-grass degredation, and a lowering of the groundwater table. In short, the natural oasis ecosystem in the downstream area, which acts as a natural barrier to prevent desertification and sandstorms, via desert shrub-grass and riparian forests, has been severely weakened.

The agricultural ecosystem in the Qira oasis area, accounting for 97.7% of total water volumes, is the main water consumer . Approximately 82.1% of water resources extracted from the Qira River is used to supply agricultural irrigation, with the remaining 17.9% of water supply provided through extraction from groundwater (Hotan water resources planning, 2013). Since the

1960s, the total irrigation area has increased to 7711.7 ha (in the year 2012) from 6728.1 ha (in the year 1961). Correspondingly, the water extraction from the Qira River has increased significantly in the Qira oasis area. Due to the agricultural economy accounting for 85.7% of total GDP, the agricultural products are the most economic incomes in the area. The main economic crops in the Qira oasis area are wheat (winter wheat in this study), maize, cotton and Chinese date, which are cultivated in a rotation system (September–May, June–September, April–September, and March–November, respectively) and constitute almost 88.7% of agricultural acreage (Government office of Xinjiang province, 2002-2013).

To analyze and parameterize decision-making framework in water-use conflict using BN, the river runoff data is collected from the Qira hydrological station in the upstream of Qira oasis from 1958 to 2010, and the precipitation data are obtained from the Qira weather station in the Qira oasis area during 1960-2011 (Fig. 3). The domestic and industrial water utilization, the maximum yields, planting areas of main crops, and crop princes are obtained from statistics yearbooks recorded by the Government Office of Xinjiang Province, 2002-2012. The crop yield response factors (k_y) (Doorenbs and Kassam, 1979; Steduto et al., 2012) with respect to various crops during the different growth periods are listed in Table 1, and the crop coefficients (k_c) (Chen, 1995; Irrigation and drainage development center in China, 2005) and reference crop evapotranspiration (ET_0) during the different growth periods are shown in Table 2. Moreover, Fig. 4 illustrates the maximum crop evapotranspiration of main crops during different growth periods.

Moreover, to maintain the different functions of ecosystem services, Xue et al. (2015) quantified environmental flow requirements in the Qira oasis area, and calculated them as 0.752×10^8, 0.619×10^8 and 0.516×10^8 m^3 for the maximum, medium and minimum level, accounting for 58.75%, 48.36% and 40.29% of the natural river discharge, respectively. However, meeting environmental flows will inevitably result in water competition with agricultural demands, and the trade-offs between both have posed a serious challenge in this area. Therefore, based on the decision-making framework (section 2) and the characteristics of the agricultural structure in the Qira oasis area, the BNs are developed and showed in Fig. 5.

4 Results

Fig. 7 illustrates the BN simulation for the trade-offs between agro-economic and eco-environmental water demands in the Qira oasis area. The nodes and states in the BN are explained in Table 3. The wet, normal, and dry states in the "available water supply" variable represent the amount of water from water discharge in wet, normal and dry years, which are determined for 30%, 38% and 32% water supply rates by records at Qira hydrological station, respectively. Due to poor and ineffective irrigation technology, the flooding irrigation is the main irrigation pattern, taking up 74% of the total irrigation volume in the Qira oasis area. Furthermore, the water-saving engineering is also poor and only accounting for 25% of the total water-saving quantity. In the agricultural economic loss assessment, industrial and domestic water use, as well as crop prices, are obtained from the statistical yearbooks published by the Government office of Hotan city (2000–2012). According to the available data, the total agricultural economic outcomes are estimated by the production reduction due to agricultural water shortage, and crop prices.

According to the above outcomes of water allocation analysis, the CPTs of the variables associated with the agricultural economic loss assessment and expert knowledge are elicited using the AgenaRisk software. The results of the BN simulations are then presented as probability distributions extracted from each "child" variable. To model the impact of different levels of environmental flow allocation on agricultural economic loss, the critical environmental flow requirements are classified into seven states, and each state is divided into equivalent intervals from the environmental flow requirements quantified by Xue (2015) at different levels. Since the water-use trade-offs between agro-economic and eco-environmental water demands depend on the river discharge, the probability distribution of total economic loss is determined by the BN simulations under different available water supplies.

Appropriate environmental flow requirements can be identified using intersection point analysis. Since the probability of the total agricultural economic loss increases as environmental flow allocation rises, to reduce large-level economic loss caused by agricultural water shortage, the recommended flow requirements are determined based on the intersection point between the probability of large-level total economic loss due to supporting environmental flows in large level and the ratio of the economic total amount after meeting environmental flows to the maximum amount when satisfying environmental flows. The annual recommended environmental flow requirement is calculated as 50.24% of the natural river flow in wet years (Fig. 7a). Similarly, in normal and dry years, the annual environmental flow requirements are recommended as 49.71% and 48.73% of the natural flow, respectively (Fig. 7b and Fig. 7c).

To ensure a natural flow regime, the temporal variation proportion of natural river runoff is considered as the indicator of the temporal allocation of environmental flow requirements. Therefore, according to the proportion of temporal allocation, the recommended monthly environmental flow requirements for meeting multiple ecosystem functions in the Qira oasis area are illustrated in Fig. 8. The months from April to October are the main periods for maintaining the environmental flow requirements in Qira oasis. The river discharge during this period ensures greater than 93% of annual total environmental flow requirements.

5 Discussion

5.1 Model evaluation

Model structure and performance are essential to establish confidence for the specific purpose of the model (Poppenborg et al., 2014), so model understanding (Fish, 2011) and model reliability (Kareiva et al., 2011) are regarded as the two most critical factors in the BN’s structure and performance. To successfully develop arobust BN model, such factors mainly depend on model complexity. However, the model complexity will inevitably increase the uncertainty of model understanding and development. Therefore, balancing the complexity level and reducing the uncertainty of BN models have become crucial in model applications of this type.

The impact of model components on model complexity and uncertainty relies on the number of variables, node layers, the number of states per node, and the number of relationships between variables. According to Landuye et al. (2013), the variable layers of BN models should not be larger than six levels, and the number of relationships between variables can be as few as possible, in order that the model structure is highly transparent and easy to evaluate. Therefore, in this paper, the variable layers in the BN model are designed for five levels, and the number of relationships between variables is not larger than four. The number of variables and states influences complexity and uncertainty of the model through the size of the CPTs. Although a large number of states can diminish the amount of information lost through discretization, it generally increases the size of the CPTs and available data and/or expert opinion to elicit the CPTs. Fortunately, the AgenaRisk software package can automatically construct relevant CPTs with a minimal amount of expert knowledge, using ranked nodes (Fenton et al., 2007). This study applies this effective tool to overcome the difficulty of constructing the CPTs. The minimal use of expert elicitation in the CPTs' definition can then increase the model reliability.

However, as mentioned above, validation of the BN model is difficult and complicated owing to the limited availability of empirical data for model verification (Landuyt et al., 2013). Expert evaluation and sensitivity analysis in the graphical network structure are potentially alternative evaluation approaches (Aguilera et al., 2011). With respect to expert evaluation of the model structure itself, application of the BN model in water trade-offs has in fact been discussed in previous studies (e.g. Pang and Sun, 2014). This also ensures the reasonability of model structure in our model. Moreover, an extremely effective way to examine the validity of an expert-built BN model is to implement sensitivity analysis, which checks diagrammatically which variables have the greatest impact on any selected target variable (Fenton and Neil, 2013).

In this study, the variable "total economic loss" is set as the target variable. The "tornado graph" that shows which variables most impact on the target variable can be obtained automatically for sensitivity analysis in the AgenaRisk software (Fig. 9). From the visual perspective, the length of the bars corresponding to each sensitivity variable in the tornado graph is a measure of the influence of that variable on the target variable. Thus, the variables "economic loss for wheat", "economic loss for cotton", "economic loss for maize", and "economic loss for Chinese date", in turn, have the largest impact on the target variable "total economic loss". For example, the marginal probability for "total economic loss" is "large" (0.144) given the result of "economic loss for wheat" moves from 0.126 (when it is "small") to 0.229 (when it is "large"). This conclusion is consistent with the results for agricultural economic loss assessment. Furthermore, these sensitivity variables are the most valuable variables in reducing the uncertainty related to the probability distribution of “total economic loss”. Since the impact between the variables in the BNs decreases as the number of intermediate variables increases (Marcot et al., 2006; Poppenborg et al., 2014), the influence between the different levels in our BN model decreases gradually.

5.2 Scenario simulations

Once evaluated, the BN can be used to model environmental flow decisions under different water management scenarios. The scenarios are implemented by fixing the states of relevant “parent” variables selected as water management options, and then BN inference obtains a probability distribution of the “child” variables selected as management performance indicators. The objective of the scenario simulations is to identify the appropriate environmental flow requirements in the different management scenarios by evaluating the trade-off between water for eco-environmental health and that for socio-economic sustainable development.

In our work, the “irrigation regime” and “water-saving engineering” are considered as water management options in the developed BN. Since the two variables are respectively defined as three states under three availabilities of water supply, this will generate 27 possible outcomes of management strategies. The recommended environmental flow requirements among the various management strategies associated with the intersection point analysis at different levels of water supply, are determined and compared (Table 4). The results indicate that the recommended environmental flows are higher when irrigation regime technologies (from flood pattern to drip means) are better, and water-saving engineering are higher under the corresponding water supply level. For example, under the drip irrigation and high water-saving engineering, the recommended environmental flow requirement is the highest and accounts for 52.17% of natural river discharge in wet years. Meanwhile, it accounts for 50.37% and 49.16% of the natural flow in normal and dry years, respectively. This suggests that an additional 1.93% of river discharge can be allocated to eco-environmental water demands when the combined strategy is used in wet years.

However, although different water management measures are applied to model environmental flow decisions and to determine recommended environmental flow requirements accordingly, it is found that achieving the trade-offs between water demands for ecosystems and economic development may be difficult among the different stakeholders. Ensuring ecosystem water demands can satisfy eco-environmental administrators, but economic loss caused by water shortage under environmental flows allocation are not easy acceptable.

To alleviate the conflicts among water-use stakeholders in the region, practical and effective measures should include: (1) Stakeholder participation: the active participation of all relevant stakeholders with various interests can additionally contribute to improve mutual understanding between science, policy-makers, and among stakeholders (Winz et al., 2009; Garmona, et al., 2011); (2) Economic compensation: Ecological compensation that is defined as the agricultural economic compensation after ensuring environmental flow requirements has generally been regarded as an effective means to relieve water demand conflicts (Sisto, 2009; Pang et al., 2013); (3) Water trade: Buying water from agriculture to ensure environmental flow requirements are met has made conflict resolution more straightforward and effective in water-use trade-offs (Wheeler et al. 2010); (4) Building compensation funds: Stakeholder compensation for performing water-saving measures can further alleviate the conflicts caused by water shortage (Pang and Sun, 2014). For example, governments in Xinjiang have encouraged irrigation stakeholders to replace flood irrigation with drip irrigation.

This paper proposes a decision-making framework to determine the appropriate environmental flow requirements for ecosystem health in oasis areas using BNs. Such a framework provides flexibility and transparency due to incorporating additional agro-economic factors into the environmental flow assessments. The availability of water from river discharge, the ecosystem management options, the water management measures, and the development of the agricultural economy are included in the decision-making analysis. Although the previous researches quantified and assessed the environment flows by using many methods such as BNs model (Chan et al., 2012; Shenton et al., 2013; Pang and Sun, 2014), it is difficult to define the reasonable making-decision framework and criterion to obtain an acceptable environmental flow recommendation. In this study, the framework improves the understanding of how to integrate agri-economic factors into eco-environmental assessments by decision-making criteria. However, in fact, additional factors such as climatic change and agricultural policy can also have an impact and should also therefore be involved in the decision-making analysis. Thus, the framework proposed here only provides an effective approach to incorporate diverse information and water management strategies flexibly. To model environmental flow decisions more competently, a participatory object-oriented BN is highly necessary in the future, to evaluate trade-offs for water demands between eco-environmental health and agro-economic sustainable development under different water management scenarios.

6 Conclusions

To assist in confronting the conflicts between agro-economic and eco-environmental competition for scarce water resources in oasis areas, a decision-making framework that combines hydrological, socio-economic and eco-environmental factors is proposed for coordinating water-use conflicts. Due to the complexity and uncertainty in environmental flow decision-making analysis for the agricultural economy and ecosystems protection, BNs with transparency and flexibility are developed to model environmental flow decisions, and are simulated under different water management options/scenarios. Intersection point analysis, based on the probability of large-level total economic loss and the ratio of the economic total amount to the maximum amount when satisfying environmental flows, is considered as the decision-making criterion to determine the recommended thresholds of environmental flow requirements.

The case study in Qira oasis (Tarim Basin, Xinjiang) shows that the BN is a powerful method to evaluate the trade-off between agricultural and natural ecosystems. The environmental flow requirement is determined as 50.24% of the natural river flow in wet years. In normal and dry years, the environmental flow requirements are recommended as 49.71% and 48.73% of the natural flow, respectively. Under different water management scenarios, the recommended environmental flows are higher when irrigation regime technologies (from flood pattern to drip means) are better, and water-saving engineering are higher at the corresponding water supply level. Under high water-saving engineering and drip irrigation, the recommended environmental flow requirement is the highest, accounting for 52.17% of the natural river discharge in wet years, implying that an additional 1.93% of river discharge can be allocated to eco-environmental water demands when this combined strategy is used in wet years. Similarly, in normal and dry years, an additional 0.66% and 0.43% of river discharge can be recommended as the environmental flow requirements in the combined strategy of high water-saving engineering and drip irrigation.

Although BNs can be an effective tool in decreasing economic loss caused by maximum-level water shortage whilst ensuring environmental flows, it is merely for us to provide a flexible, open and practical recommendation, and other factors (e.g. climate change, human activities, agricultural policy, participation of stakeholders) may need to be included in specific cases. However, the decision-making framework proposed in this study can be widely used to deal with water-use conflicts in any oasis area, even larger areas, worldwide.

Acknowledgements

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References

Adams, S.M., Hill, W.R., Peterson, M.J., Ryon, M.G., Smith, J.G., Stewart, A.J., 2002. Assessing recovery in a stream ecosystem: applying multiple chemical and biological endpoints, Ecol. Appl. 12, 1510–1527.

Agena, Ltd. 2005. AgenaRisk Software Package, www.agenarisk.com.

Aguilera, P.A., Fernández, A., Fernández, R., Rumí, R., Salmerón, A., 2011. Bayesian networks in environmental modelling. Environ. Modell Softw. 26, 1376-1388.

Alcázar, J., Palau, A., Vega-García, C., 2008. A neural net model for environmental flow estimation at the Ebro River Basin, Spain. J. Hydrol. 349, 44–45.

Allen, R.G., Pereira, L,S., Raes, D., Smith, M., 1998. Crop evapotranspiration. Guidelines for computing crop water requirements. In: FAO Irrigation and Drainage Paper No. 56. Rome, FAO.

Arthington, A.H., Bunn, S.E., Poff, N.L., Naiman, R.J., 2006. The Challenge of Providing Environmental Flow Rules to Sustain River Ecosystems. Ecol. Appl. 16, 1311–1318.

Barbier, E.B., Koch, E.W., Silliman, B.R., Hacker, S.D., Wolanski, E., Primavera, J., Granek, E.F., Polasky, S., Aswani, S., Cramer, L.A., Stoms, D.M., Kennedy, C.J., Bael, D., Kappel, C.V., Perillo, G.M.E., Reed, D.J., 2008. Coastal Ecosystem–Based Management with Nonlinear Ecological Functions and Values. Sci. 319, 321–323.

Boehmer, K., Memon, A., Mitchell, B., 2000. Towards sustainable water management in Southeast Asia–experiences from Indonesia and Malaysia. Water Int. 25, 356-377.

Borsuk, M.E., Stow, C.A., Reckhow, K.H., 2004. A Bayesian network of eutrophication models for synthesis, prediction, and uncertainty analysis. Ecol Model. 173, 219-239.

Bruelheide, H., Jandt, U., Gries, D., Thomas, F.M., Foetzki, A., Buerkert, A., Wang, G., Zhang, X.M., Runge, M., 2003. Vegetation changes in a river oasis on the southern rim of the Taklamakan Desert in China between 1956 and 2000. Phytocoenologia. 33, 801-818.

Cai, Y.P., Huang, G.H., Tan, Q., Chen, B., 2011. Identification of optimal strategies for improving eco-resilience to floods in ecologically vulnerable regions of a wetland. Ecol Model. 222, 360–369.

Cain, J., 2001. Planning improvements in natural resources management. Guidelines for using Bayesian networks to support the planning and management of development programmes in the water sector and beyond. Centre for Ecology and Hydrology. Retrieved from http://64.40.97.24/downloads/BBN%20Guidelines%20-%20Cain.pdf

Calzadilla, A., Rehdanz, K., Tol, R.S.J., 2010. The economic impact of more sustainable water use in agriculture: a computable general equilibrium analysis. J. Hydrol. 384, 292–305.

Carmona, G., Varela-Ortega, C., Bromley, J., 2011. The use of participatory object-oriented Bayesian networks and agro-economic models for groundwater management in Spain. Water

Resour. Manage. 25, 1509-1524.

CAWA., 2013. Regional Research Network-Central Asian Water. Http://www.cawa-project.net/ (last access: 5 March 2015).

Chen, Y.N., Xu, Z.X., 2005. Plausible impact of global climate change on water resources in Tarim River Basin. Sci. China Ser. D. 48, 65–73.

Chen, Y.M., 1995. Main crop water requirement and irrigation of China. Water Resources and Electric Power Press, Beijing.

Doorenbos, J., Kassam, A.H., 1979. Yield Response to Water, Report No. 33, FAO, Rome.

Duespohl, M., Frank, S., Döll, P., 2012. A review of Bayesian networks as a participatory modeling approach in support of sustainable environmental management. J. Sustainable Development. 5, p1.

Fenton, N.E., Neil, M., 2013. Risk assessment and decision analysis with Bayesian networks. Boca Raton, FL: CRC Press.

Fenton, N.E., Neil, M., Caballero, J.G., 2007. Using ranked nodes to model qualitative judgments in Bayesian networks. IEEE T. Knowl. Data En. 19, 1420-1432.

Fish, R.D., 2011. Environmental decision making and an ecosystems approach Some challenges from the perspective of social science. Prog. Phys. Geog. 35, 671-680.

Florenzano, M., 1985. General equilibrium analysis. Cambridge University Press.

Government office of Xinjiang province, 2002-2013. Statistical Yearbooks of Xinjiang province. China Statistical Publishing House, Beijing.

Hotan water resources planning, 2013. Xinjiang Tarim River Basin Management Bureau.

Irrigation and drainage development center in China, 2005. Practical manual in the water-saving irrigation project. Water Resources and Electric Power Press, Beijing.

Ianchovichina, E,, Darwin, R,, Shoemaker, R., 2001. Resource use and technological progress in agriculture: a dynamic general equilibrium analysis. Ecol. Econ. 38, 275-291.

Jury, W.A., Vaux, H.J., 2007. The emerging global water crisis: managing scarcity and conflict between water users. Adv. Agron. 95, 1-76.

Kareiva, P., Tallis, H., Ricketts, T.H., Daily, G.C., Polasky, S., 2011. Natural capital: theory and practice of mapping ecosystem services. Oxford University Press.

Landuyt, D., Broekx, S., D'hondt, R., Engelen, G., Aertsens, J., Goethals, P.L., 2013. A review of Bayesian belief networks in ecosystem service modelling. Environ. Modell Softw. 46, 1-11.

Ling, H.B., Xu, H.L., Fu, J.Y., 2013. High- and low-flow variations in annual runoff and their response to climate change in the headstreams of the Tarim River, Xinjiang, China. Hydrol. Process. 27, 975–988.

Ling, H.B., Zhang, Q.Q., Xu, H.L., Shi, W., 2011. Regional climate change and its effects on the runoff of Manas River, Xinjiang, China. Chinese Geogra. Sci. 64, 2203–2213.

Li, W.D., Li, Z.Z., Wang. J.Q., 2007. Evaluation of oasis ecosystem risk by reliability theory in an arid area: A case study in the Shiyang River Basin, China. J. Environ. Sci-China. 19, 508-512.

Malano, H.M., Davidson, B.A., 2009. Framework for assessing the trade-off between economic and environmental uses of water in a river basin. Irrig. Drain. 58, 133–147.

Marcot, B.G., Steventon, J.D., Sutherland, G.D., McCann, R.K., 2006. Guidelines for developing and updating Bayesian belief networks applied to ecological modeling and conservation. Can. J. Forest Res. 36, 3063-3074.

McCartney, M.P., Shiferaw, A., Seleshi, Y., 2009. Estimating environmental flow requirements downstream of the Chara Chara weir on the Blue Nile River. Hydrol. Process. 23, 3751–3758.

Pang, A.P., Sun, T., Yang, Z.F., 2013. Economic compensation for irrigation processes to safeguard environmental flows in the Yellow River Estuary, China. J. Hydrol. 482, 129–138.

Pang, A.P., Sun, T., 2014. Bayesian networks for environmental flow decision-making and an application in the Yellow River estuary, China. Hydrol. Earth Syst. Sci. 18, 1641-1651.

Poff, L.N., Allan, J.D., Palmer, M.A., Hart, D.A., Richter, B.D., Arthington, A.H., Rogers, K.H., Meyer, J.L., Stanford, J.A., 2003. River flows and water wars: emerging science for environmental decision making, Front. Ecol. Environ. 1, 298–306.

Poppenborg, P., Koellner, T., 2014. A Bayesian network approach to model farmers' crop choice using socio-psychological measurements of expected benefits of ecosystem services. Environ. Modell Softw. 57, 227-234.

Rumbaur, C., Thevs, N., Disse, M., Ahlheim, M., Brieden, A., Cyffka, B., Duethmann, D., Feike, T., Fror, O., Gartner, P., Halik, U., Hill, J., Hinnenthal, M., Keiholz, P., Kleinschnit, B., Krysanova, V., Kuba, M., Mader, S., Menz, C., Othmanli, H., Pelz, S., Schroeder, M., Siew, T.F., Stender, V., Stahr, K.,Thomas, F.M., Welp, M., Wortmann, M., Zhao, X., Chen, X., Jiang, T., Luo, J., Yimit, H., Yu, R., Zhang, X., Zhao, C., 2015. Sustainable management of river oases along the Tarim River (SuMaRiO) in Northwest China under conditions of climate change. Earth Syst. Dynam. 6, 83-107.

Sisto, N.P., 2009. Environmental flows for rivers and economic compensation for irrigators. J. Environ. manag. 90, 1236-1240.

Steduto, P., Hsiao, T.C., Fereres, E., Raes, D., 2012. Crop yield response to water. Food and Agriculture Organization of the United Nations. PP. 6-9.

Sun, T., Yang, Z.F., Cui, B.S., 2008. Critical environmental flows to support integrated ecological objectives for the Yellow River Estuary, China. Water Resour. Manage. 22, 973-989.

Tang, Q.C., Chen, H.Y., 1992. Water resources and oasis construction in Tarim Basin. Chinese Geogra. Sci. 2, 173-182.

Tharme, R.E., 2003. A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. River Res. Appl., 19, 397–441.

Uusitalo, L., 2007. Advantages and challenges of Bayesian networks in environmental modelling. Ecol Model. 203, 312-318.

Ward, E.R., 2003. Border Oasis: Water and the Political Ecology of the Colorado River Delta, 1940-1975. University of Arizona Press.

Wheeler, S., Bjornlund, H., Zuo, A., Shanahan, M., 2010. The changing profile of water traders in the Goulburn-Murray Irrigation District, Australia. Agr. Water Manage. 97, 1333–1343.

William, W.L., Cheung, U., Rashid, S., 2008. Trade-offs between conservation and socio-economic objectives in managing a tropical marine ecosystem. Ecol. Econ. 66, 193–210.

Winz, I., Brierley, G., Trowsdale, S., 2009. The use of system dynamics simulation in water resources management. Water Resour. Manage. 23, 1301-1323.

Xue, J., Lei. J., Gui, D.W., Zhao, Y., Feng, X.L., Zeng, F.J., Zhou, J., Mao, D.L., 2015. Quantification of environmental flow requirements for supporting ecosystem services of oasis areas: a case study in Tarim Basin, Northwest China. Water, 7: 5657-5675..

Ye, Z., Chen, Y., Li, W., 2010. Ecological water demand of natural vegetation in the lower Tarim River. J Geogr Sci. 20, 261-272.

Table 1 Crop yield response factors (k_y) with respect to various crops during different growth periods.

Crops	Growth period											
	Mon.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Wheat	0.6	0.6	0.6	1	1	0	0	0	0	0.2	0.2	0.2
Maize	0	0	0	0	0	0.2	0.2	0.2	0.2	0	0	0
Cotton	0	0	0	0.85	0.85	0.5	0.5	0.5	0.5	0	0	0
Chinese date	0	0	0.6	1	1	0.2	0.2	0.2	0.2	0.2	0.2	0

Table 2 Crop coefficients (k_c) and reference crop evapotranspiration (ET_0) with respect to various crops during different growth periods.

Month	Crop coefficients (k_c)				Reference crop evapotranspiration (ET_0) (mm)
	Wheat	Maize	Cotton	Chinese date	
January	0.52	0	0	0	23.4
February	0.52	0	0	0	35.1
March	0.86	0	0	0.85	81.3
April	1.14	0	0.53	0.95	124.5
May	1.00	0	0.53	1.05	157.5
June	0.65	0.72	0.66	1.15	183
July	0	0.84	1.04	1.15	186.9
August	0	1.02	0.81	1.15	171.3
September	0	1.08	0.70	1.10	133.2
October	0.55	0	0.80	0.90	87.9
November	0.58	0	0	0.85	44.1
December	0.52	0	0	0	25.2

Table 3 Explanation of the nodes and states of the BN in the decision-making analysis in Qira oasis area.

Variable	Node	Explanation	States	Numerical equivalent
Implementation variables	Critical environmental flow requirements	Percentage of annual average runoff	Lowest	[40.29%, 42.93%)
			Very Low	[42.93%, 45.56%)
			Low	[45.56%, 48.20%)
			Medium	[48.20%, 50.84%)
			High	[50.84%, 53.48%)
			Very High	[53.48%, 56.11%)
			Highest	[56.11%, 58.75%]
	Available water supply	Water supply from river discharge $(10^8 m^3)$	Dry	(0, 0.8844]
			Normal	(0.8844, 1.077]
			Wet	(1.077, 1.265]
Intervention variables	Irrigation regime	Irrigation pattern for water use	Flood irrigation	—
			Spray irrigation	
			Drip irrigation	
	Water saving engineering	water transport engineering for defending seepage	Low	—
			Medium	
			High	
	Wheat price	RMB/kg	Low	(0, 2]
			Medium	(2, 2.05]
			High	(2.05,3]
	Maize price	RMB/kg	Low	(0, 1.5]
			Medium	(1.5, 1.9]
			High	(1.9,2.5]
	Cotton price	RMB/kg	Low	(0, 8]
			Medium	(8, 11]
			High	(11,15]
	Chinese date price	RMB/kg	Low	(0, 4]
			Medium	(4, 6]
			High	(6, 8]
Intermediate variables	Agricultural water shortages for wheat; maize; cotton; Chinese date	$10^7 m^3$	Small	(0, 1]
			Medium	(1, 2]
			Large	(2, 3]
	Production reductions for wheat; maize; cotton; Chinese date	Reduction percentage of annual yield	low	Under 10%
			Medium	(10%,20%]
			High	Over 20%
Partial objectives	Economic losses for wheat; maize; cotton; Chinese date	Losses percentage of annual RMB	Small	Under 10%
			Medium	(10%,20%]
			Large	Over 20%
Total objectives	Total economic loss	Total loss percentage of annual RMB	Small	Under 10%
			Medium	(10%,20%]
			Large	Over 20%

Table 4 Recommended environmental flow requirements, based on BN simulations and intersection point analysis, under different water management scenarios (% of the natural river discharge).

Available water supply	Water-saving engineering	Irrigation regime		
		Flood irrigation	Spray irrigation	Drip irrigation
Wet	High	50.74	51.25	52.17
	Medium	50.14	50.54	51.66
	Low	49.58	50.07	50.88
Normal	High	49.52	49.9	50.37
	Medium	48.99	49.38	49.96
	Low	48.42	48.96	49.67
Dry	High	48.46	48.97	49.16
	Medium	47.91	48.49	49.01
	Low	47.39	47.97	48.27

List of figure captions

Fig. 1. Three main components of the environmental flow decision-making framework.

Fig. 2. Decision-making criteria of the recommended environmental flow requirement.

Fig. 3. Location and topography of the study area.

Fig. 4. Maximum crop evapotranspiration of main crops during different growth periods.

Fig. 6. Bayesian networks representing the trade-offs between agricultural and ecosystem water demands in the Qira oasis area.

Fig. 6. BNs for the trade-offs between agro-economic and eco-environmental water demands in the Qira oasis area (WH denotes wheat, MA stands for Maize, CO refers to cotton, and CD is Chinese date).

Fig. 7. Environmental flow decision-making based on intersection point analysis in different level years: (a) wet year; (b) normal year; (c) dry year (Probability* denotes probability of agricultural economic loss and Ratio** refers to ratio of total agro-economic output to maximum agro-economic output in the legends).

Fig. 8. Recommended monthly environmental flow requirements in different level years.

Fig. 9. Sensitivity analysis based on “tornado graph” testing of the target variable “total economic loss” (WH denotes wheat, MA stands for maize, CO refers to cotton, and CD is Chinese date).

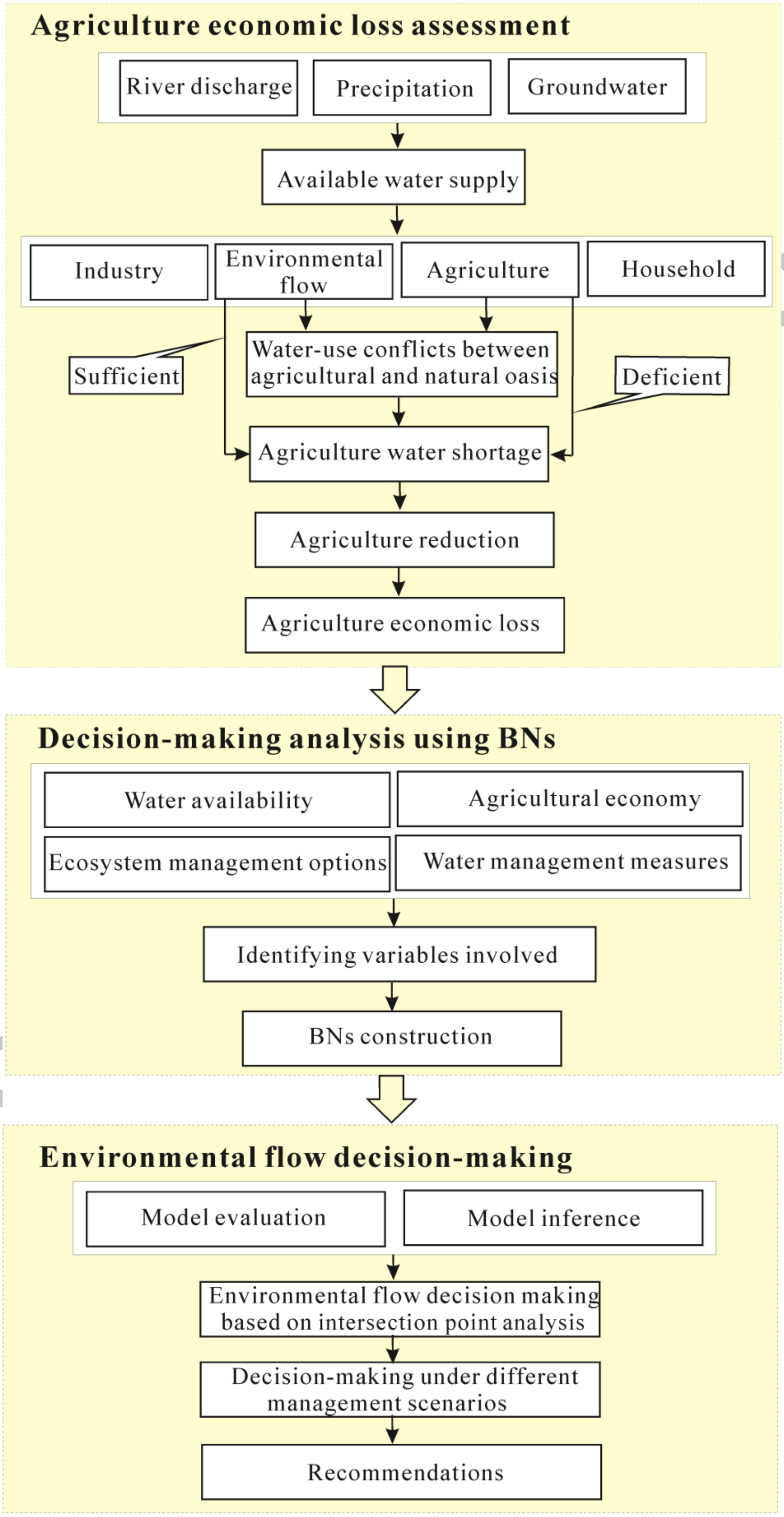
Agriculture economic loss assessment
River discharge
Precipitation
Groundwater
Available water supply
Industry
Environmental flow
Agriculture
Household
Sufficient
Water-use conflicts between agricultural and natural oasis
Deficient
Agriculture water shortage
Agriculture reduction
Agriculture economic loss
Decision-making analysis using BNs
Water availability
Agricultural economy
Ecosystem management options
Water management measures
Identifying variables involved
BNs construction
Environmental flow decision-making
Model evaluation
Model inference
Environmental flow decision making based on intersection point analysis
Decision-making under different management scenarios
Recommendations

Fig. 1

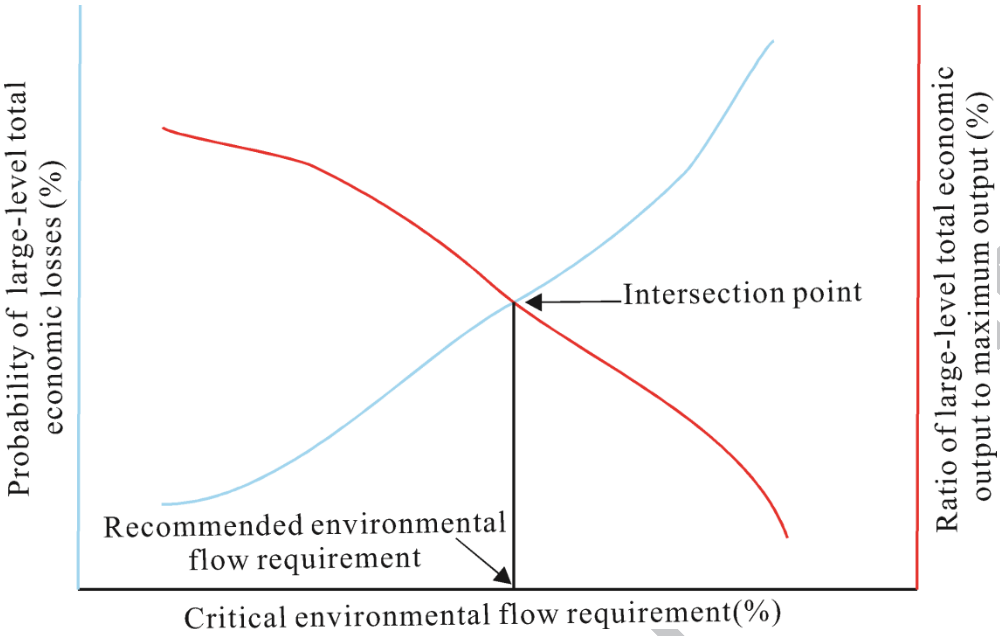
Probability of large-level total economic losses (%)
Ratio of large-level total economic output to maximum output (%)
Intersection point
Recommended environmental flow requirement
Critical environmental flow requirement(%)

Fig. 2

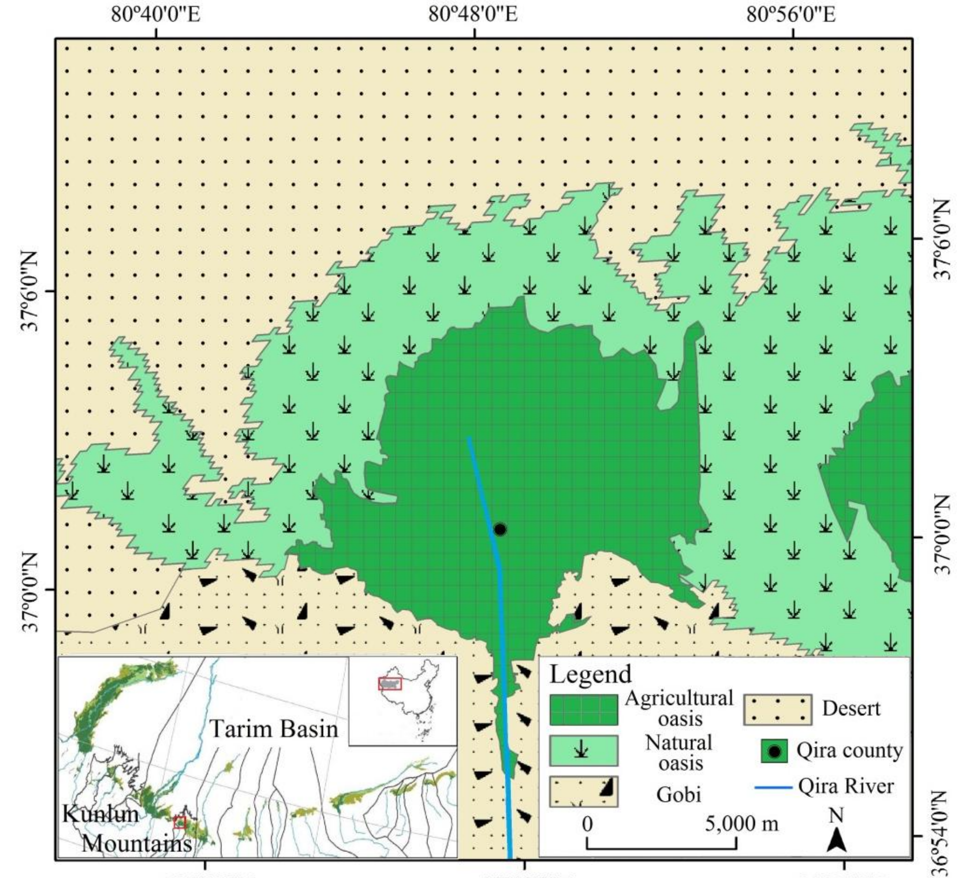
80º40'0"E
80º48'0"E
80º56'0"E
37º6'0"N
37º0'0"N
36º54'0"N
Tarim Basin
Kunlun Mountains
Legend
Agricultural oasis
Natural oasis
Gobi
Desert
Qira county
Qira River
0
5,000 m
N

Fig. 3

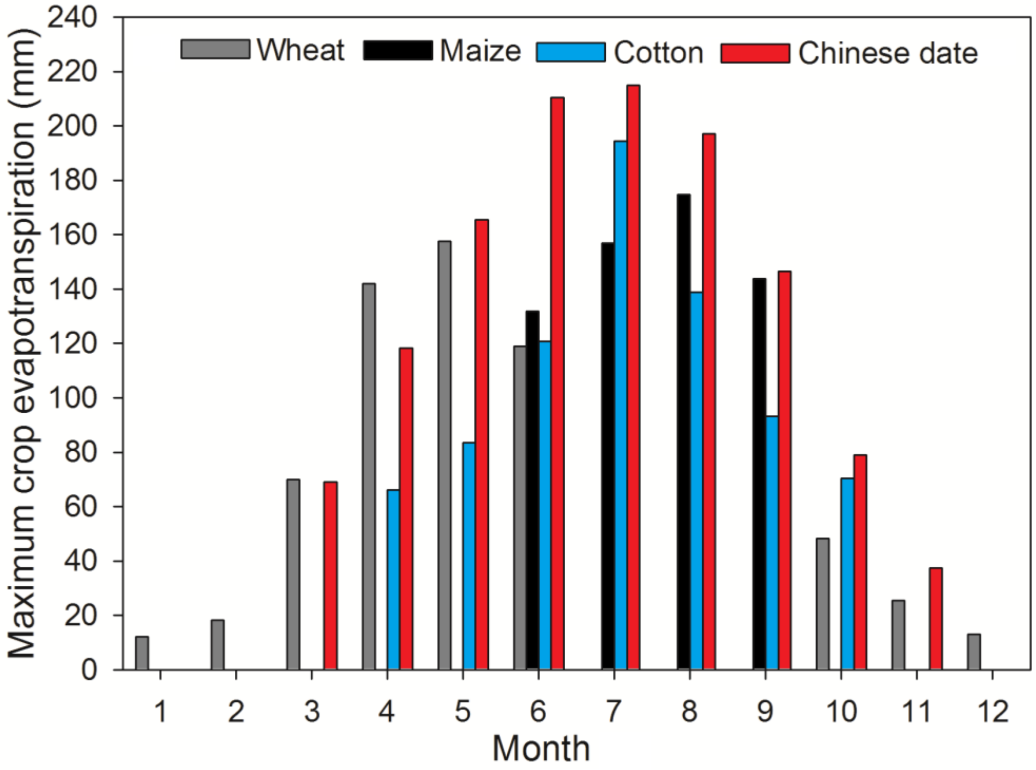
Wheat
Maize
Cotton
Chinese date
Maximum crop evapotranspiration (mm)
240
220
200
180
160
140
120
100
80
60
40
20
0
1
2
3
4
5
6
7
8
9
10
11
12
Month

Fig. 4


Level 1
Critical environmental flow
Available water supply
Irrigation regime
Water saving engineering
Level 2
Agricultural water shortage (wheat)
Agricultural water shortage (maize)
Agricultural water shortage (cotton)
Agricultural water shortage (Chinese date)
Level 3
Production reduction (wheat)
Production reduction (maize)
Procuction reduction (cotton)
Production reduction (Chinese date)
Maize price
Cotton price
Economic losses for wheat
Economic losses for maize
Economic losses for cotton
Economic losses for Chinese date
Wheat price
Chinese date price
Level 4
Total economic losses
Level 5

Fig. 5

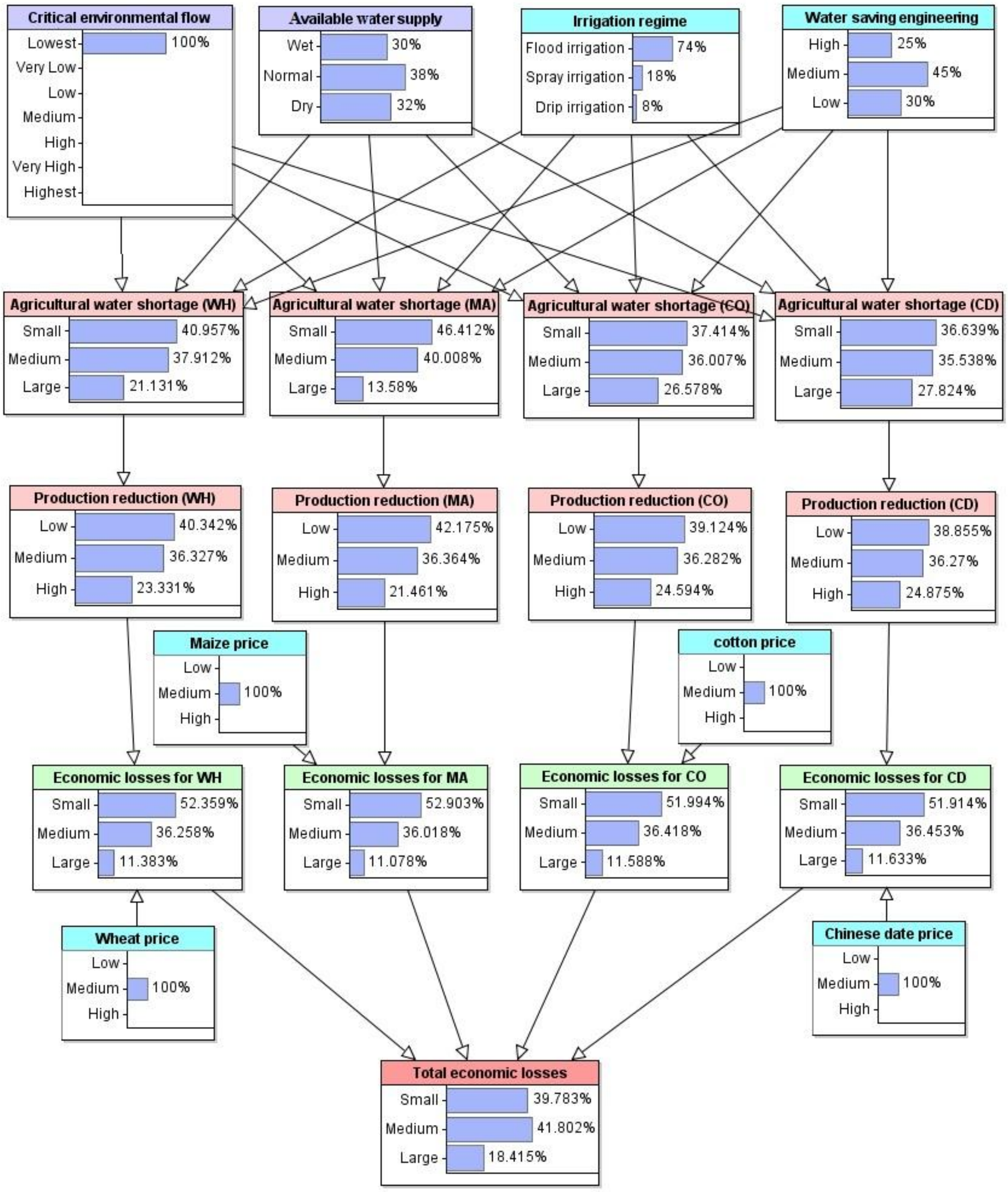
Critical environmental flow
Lowest 100%
Very Low
Low
Medium
High
Very High
Highest
Available water supply
Wet 30%
Normal 38%
Dry 32%
Irrigation regime
Flood irrigation 74%
Spray irrigation 18%
Drip irrigation 8%
Water saving engineering
High 25%
Medium 45%
Low 30%
Agricultural water shortage (WH)
Small 40.957%
Medium 37.912%
Large 21.131%
Agricultural water shortage (MA)
Small 46.412%
Medium 40.008%
Large 13.58%
Agricultural water shortage (CO)
Small 37.414%
Medium 36.007%
Large 26.578%
Agricultural water shortage (CD)
Small 36.639%
Medium 35.538%
Large 27.824%
Production reduction (WH)
Low 40.342%
Medium 36.327%
High 23.331%
Production reduction (MA)
Low 42.175%
Medium 36.364%
High 21.461%
Production reduction (CO)
Low 39.124%
Medium 36.282%
High 24.594%
Production reduction (CD)
Low 38.855%
Medium 36.27%
High 24.875%
Maize price
Low
Medium 100%
High
cotton price
Low
Medium 100%
High
Economic losses for WH
Small 52.359%
Medium 36.258%
Large 11.383%
Economic losses for MA
Small 52.903%
Medium 36.018%
Large 11.078%
Economic losses for CO
Small 51.994%
Medium 36.418%
Large 11.588%
Economic losses for CD
Small 51.914%
Medium 36.453%
Large 11.633%
Wheat price
Low
Medium 100%
High
Chinese date price
Low
Medium 100%
High
Total economic losses
Small 39.783%
Medium 41.802%
Large 18.415%

Fig. 6

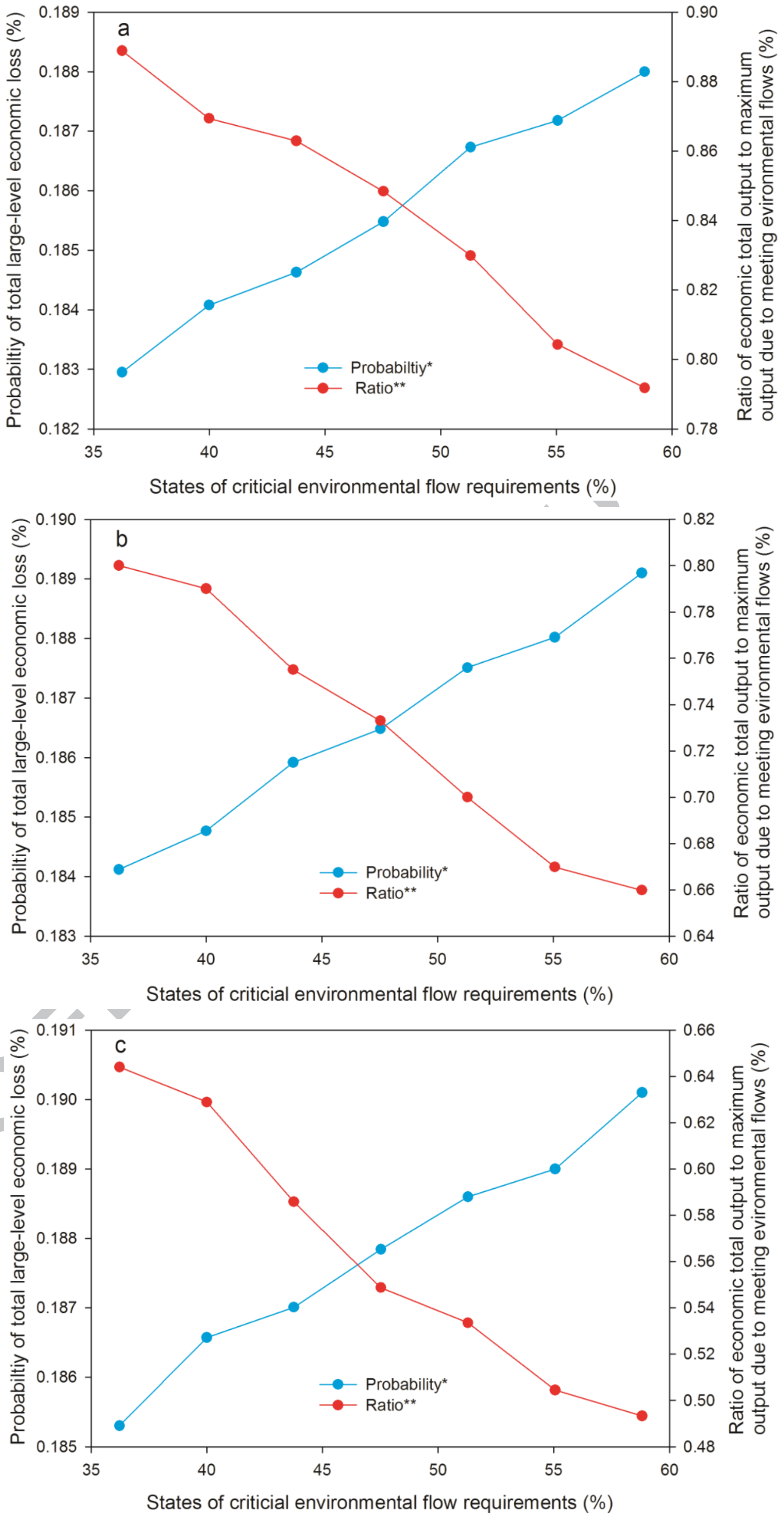
a
Probabiltiy of total large-level economic loss (%)
0.189
0.188
0.187
0.186
0.185
0.184
0.183
0.182
Ratio of economic total output to maximum output due to meeting evironmental flows (%)
0.90
0.88
0.86
0.84
0.82
0.80
0.78
Probabiltiy*
Ratio**
35
40
45
50
55
60
States of criticial environmental flow requirements (%)
b
Probabiltiy of total large-level economic loss (%)
0.190
0.189
0.188
0.187
0.186
0.185
0.184
0.183
Ratio of economic total output to maximum output due to meeting evironmental flows (%)
0.82
0.80
0.78
0.76
0.74
0.72
0.70
0.68
0.66
0.64
Probability*
Ratio**
35
40
45
50
55
60
States of criticial environmental flow requirements (%)
c
Probabiltiy of total large-level economic loss (%)
0.191
0.190
0.189
0.188
0.187
0.186
0.185
Ratio of economic total output to maximum output due to meeting evironmental flows (%)
0.66
0.64
0.62
0.60
0.58
0.56
0.54
0.52
0.50
0.48
Probability*
Ratio**
35
40
45
50
55
60
States of criticial environmental flow requirements (%)

Fig. 7

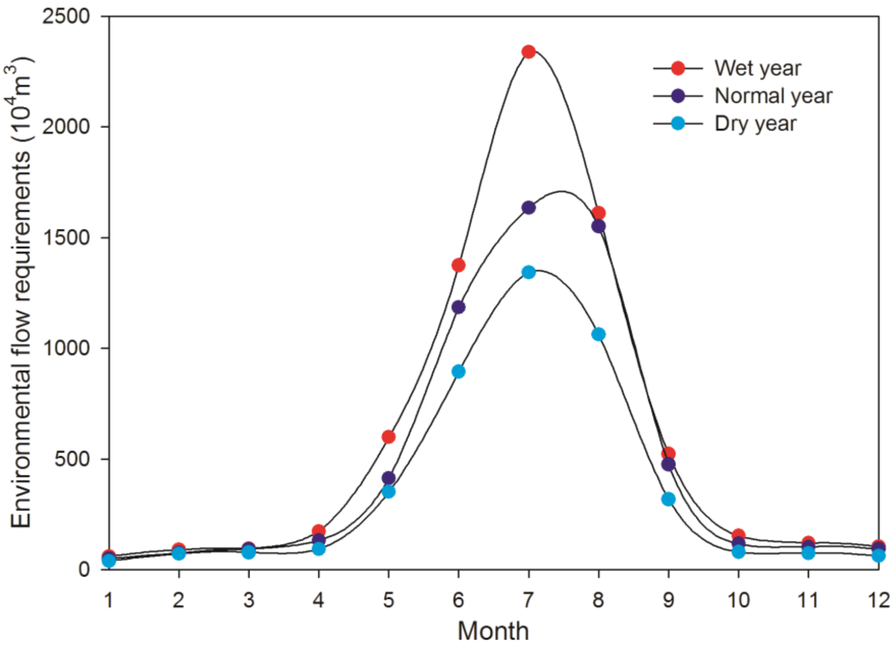
2500
2000
1500
1000
500
0
Environmental flow requirements ($10^4 m^3$)
1
2
3
4
5
6
7
8
9
10
11
12
Month
Wet year
Normal year
Dry year

Fig. 8

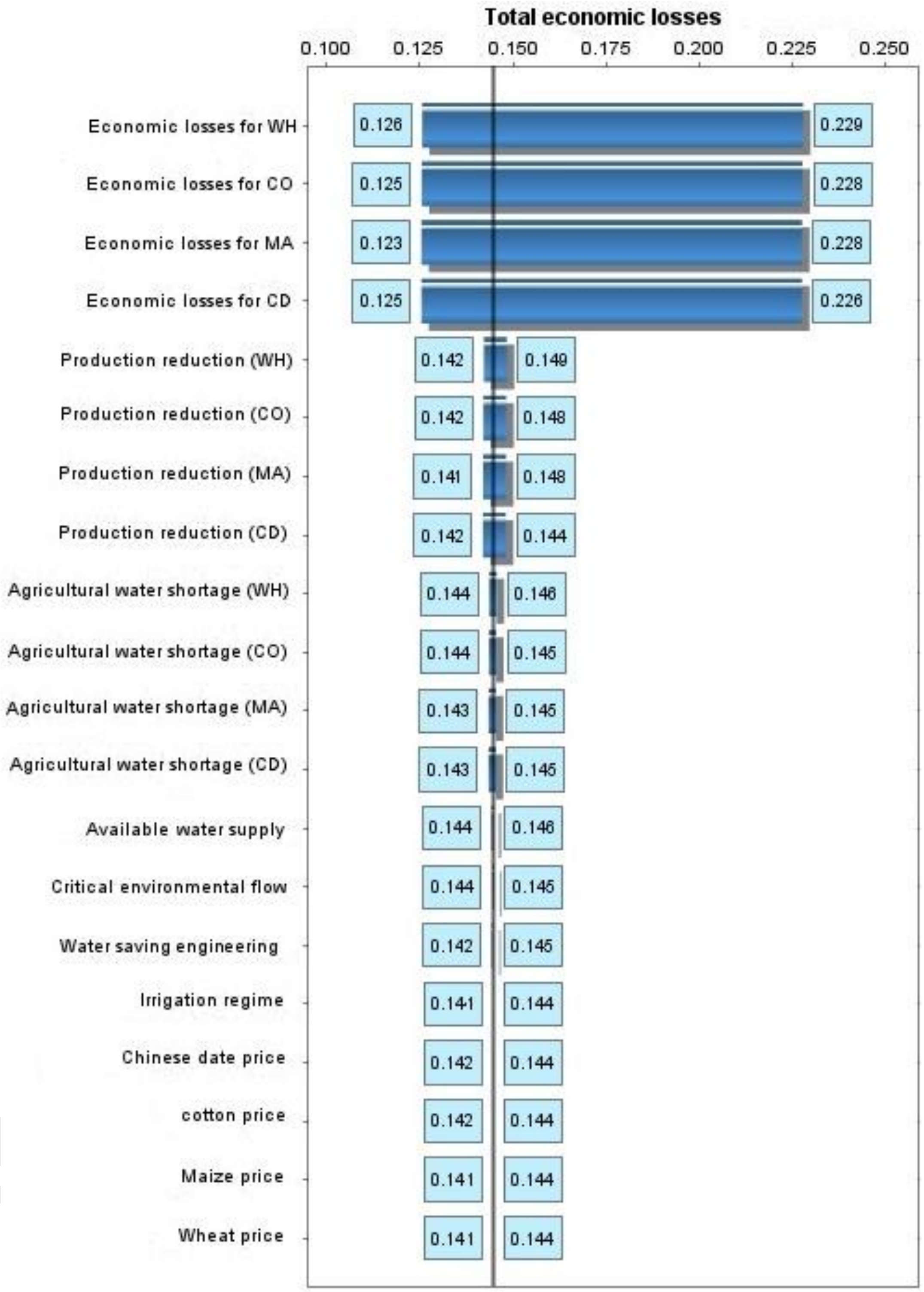
Total economic losses
0.100
0.125
0.150
0.175
0.200
0.225
0.250
Economic losses for WH
0.126
0.229
Economic losses for CO
0.125
0.228
Economic losses for MA
0.123
0.228
Economic losses for CD
0.125
0.226
Production reduction (WH)
0.142
0.149
Production reduction (CO)
0.142
0.148
Production reduction (MA)
0.141
0.148
Production reduction (CD)
0.142
0.144
Agricultural water shortage (WH)
0.144
0.146
Agricultural water shortage (CO)
0.144
0.145
Agricultural water shortage (MA)
0.143
0.145
Agricultural water shortage (CD)
0.143
0.145
Available water supply
0.144
0.146
Critical environmental flow
0.144
0.145
Water saving engineering
0.142
0.145
Irrigation regime
0.141
0.144
Chinese date price
0.142
0.144
cotton price
0.142
0.144
Maize price
0.141
0.144
Wheat price
0.141
0.144

Fig. 9

Highlights

- We propose a decision-making framework for model environmental flows in the oasis areas.
- The decision-making framework mitigates the water-use conflict between agricultural and natural oasis ecosystems.
- A Bayesian network approach is developed to model environmental flow decision-making.
- Bayesian network provides a powerful tool to model and evaluate the water management and decision through incorporating agri-economic factors into eco-environmental assessments.