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Using Bayesian networks (BNs) for mapping stakeholders behaviors in integrated water resource management with a focus on irrigated agriculture in Al Batinah region of Oman

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ABSTRACT

The problems of water resource management and its interaction with society have to be tackled from an integrated perspective taking into account the interdependence of environmental, political, social and economic factors. The conventional approaches being currently used, to study water resources management (WRM), lack to reflect the mutual relationship between water resources and societies. However, varieties for approaches to developing models of complex systems are available. Bayesian networks (BNs), is an approach, which can integrate data and knowledge of different types and from different sources in which, causal links join the variables. A BN is a type of decision support system based on a probability theory that implements Bayes' rule. This work is focusing on the case of Al-Batinah coastal plain in Oman where lots of small-scaled farms practice agriculture. There is no control over the water amounts abstracted from the coastal aquifer. Therefore, the coastal aquifer is at risk due to seawater intrusion. Since groundwater replenishment is limited, the region is facing a problem of water deficit, which also influences the sustainability of agricultural production. Based on a social survey conducted regarding the Al Batinah case, the existing situation generates conflicts between different stakeholders (SHs) which have different interests regarding water availability, sustainable aquifer management, and profitable agricultural production. Therefore, the development of appropriate management strategies for a transition towards a stable and sustainable future hydrosystem states is required. This work aims to evaluate the implementation potential of several management interventions and their combinations by analysing behaviors and opinions of relevant SHs (farmers and decision makers) in the region. This should support decision makers (DMs) in taking more informed decisions. Data were collected through a social survey. Differences were examined statistically between opinions of farmers and decision makers regarding potential interventions.

Additionally, the approach of BN was used for mapping stakeholders' behaviors and to show the strength of a relationship between dependent and predictor variables. The findings suggest that BNs provided an enhanced understanding of the presence and strength of causal relationships. The hypothesis for most of the variables, in the structure of the network, worked logically. Moreover, it is possible to determine the implementation potential of management interventions regarding their acceptance, and additionally, triggers can be identified to increase this potential. Nevertheless, management interventions should also be evaluated regarding economic and environmental criteria.

Keywords: Decision support system (DSS); Stakeholder; Potential interventions; Bayesian Network; Oman

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1. Introduction

In the field of WRM, the decision is surrounded by multiple actors (Simonovic & Fahmy, 1999), with contradicting interests and vision about the potential management options. In addition to that, the number of alternatives might be very high and the selection of a suitable one with the satisfaction of most of the stakeholders needs many efforts. Therefore a sustainable WRM is essential, to ensures the integration of social, economic, and environmental issues into all stages of WRM (Sun et al., 2016). This should be done with the consideration of the associated uncertainties of water resources. In this regard, many decision systems have been built to help users to understand uncertainty issues in water resources. However, for a decision process in areas with high demand to succeed, an integrated water resources management (IWRM) approach is recommended. This should allow the assessing of different management policies and interventions. Moreover, it should include the application of a participatory approach which allows the participation of the relevant stakeholders in a system. The environmental decision makers need to be supported with a good decision support system (DSS) to help them to take more informed decisions.

This work is focusing on a real management problem of the coastal agricultural region in South Al Batinah plain in the northern Oman where lots of small-scaled farms practice agriculture. There is no control on the amounts abstracted from the aquifers. The wells' owners pump as much groundwater as they want, from the main aquifer along the coast, without any restriction (Al-Shaqsi, 2004). Therefore, the coastal aquifers are at risk due to seawater intrusion and the region is facing a problem of water deficit, which also influences the sustainability of the agricultural production.

The work aims to evaluate the implementation potential of several management interventions and their combinations by analyzing behaviors and opinions together with the responses of relevant SHs in the region. Data and results were obtained for several types of stakeholders, for example, water professionals, farmers from the study area and decision makers of different organizations and ministries by using either face to face interviews or distribution of questionnaires. Among others, they have been asked regarding several management interventions such as water quotas, subsidise, crop pattern changes, modern irrigation systems which reveal in partly contradicting opinions between stakeholders.

Data were analysed statistically by using the SPSS (Statistical Package for Social Science) software package. This included using Independent Sample T-test, which allows comparing the means for two different groups to find out whether the difference between group means is statistically significant. Additionally, the approach of BN was used for mapping stakeholders' behaviors and to show the strength of a relationship between dependent and predictor variables. The results of the social survey and BN application allow evaluating management interventions from the social perspective. It is possible to determine the implementation potential of management interventions regarding their acceptance and additionally triggers can be identified to increase this potential.

2. Background – the study area

The Sultanate of Oman is an arid country and relies on groundwater as a source of fresh water, typically in shallow alluvial unconfined aquifers (Stoery, 1995). Agriculture is the leading consumer of groundwater, around 53%, of total cultivated areas in the country, is concentrated in Al Batinah (MAF, 2005) mainly because this region is characterised of soils that are more fertile and easier access to water, in the form of groundwater, compared with other administrative areas in the country. As a result, the groundwater abstraction exceeds the rate of recharge which affects the social and economic situation of farmers as well as the environment. The imbalance between the abstraction rates (ca. 120 Mm^3/y), and recharge rates (ca. 50 Mm^3/y) led to a dramatic decline in groundwater levels accompanied with saltwater intrusion into the coastal aquifer of the region. Agriculture is also facing challenges in Al Batinah. The study done by MRMWR in 2011 (MRMEW, 2011), reported that the land area effected by salinity above 10,000 μS/cm, in Al Batinah, has increased with time since the year 1995 by 14,500 fd. Several agricultural lands of the coastal areas have become unsuitable for cultivation (MAF, 2011) and some farms have become abandoned (Zekri et al., 2010). This is a typical example of a social dilemma (common-pool resources dilemma). The groundwater aquifer is a common source for the farmers to irrigate their farms but farmers are only focusing on their individual profit and immediate satisfaction rather than behave in larger societal best or long-term interests.

The main part of interest for the work, consists of two; Wadi catchments; wadi Bani Kharus and wadi Ma'awil (Fig. 1). The study area comprises two Wilayat (villages) Al Musana'a and 'Barka' where the farms are located near the coast line and the aquifer is affected by the salinity intrusion. Several interventions (e.g., construction of groundwater recharge dams, a ban on construction of new wells without permission) are practiced by the government to maintain the groundwater aquifer. However, the situation is getting worse and may require more effective management interventions which may range between the extremes of stopping all agriculture activities to recover the local aquifer system, and producing as much as possible as long as water and soil are available (Subagadis et al, 2014).

2.1. Common approaches in supporting the decision-making process in IWRM

Varieties of approaches to develop models of complex systems are available. Following are some of the common known integrated approaches in supporting decision making processes in water resource management;

- *Coupled component models*: employed when integrating different components of hydrological, economic, social and environmental processes (Grundmann et al., 2013).
- *Bayesian Networks (BNs)*: employed for management and decision-making applications in which stakeholder participation and uncertainty is a key consideration (Ticehurst et al., 2011).
- *Multiple criteria decision analysis*: This is a type of an integrated modeling approach for prioritizing or scoring

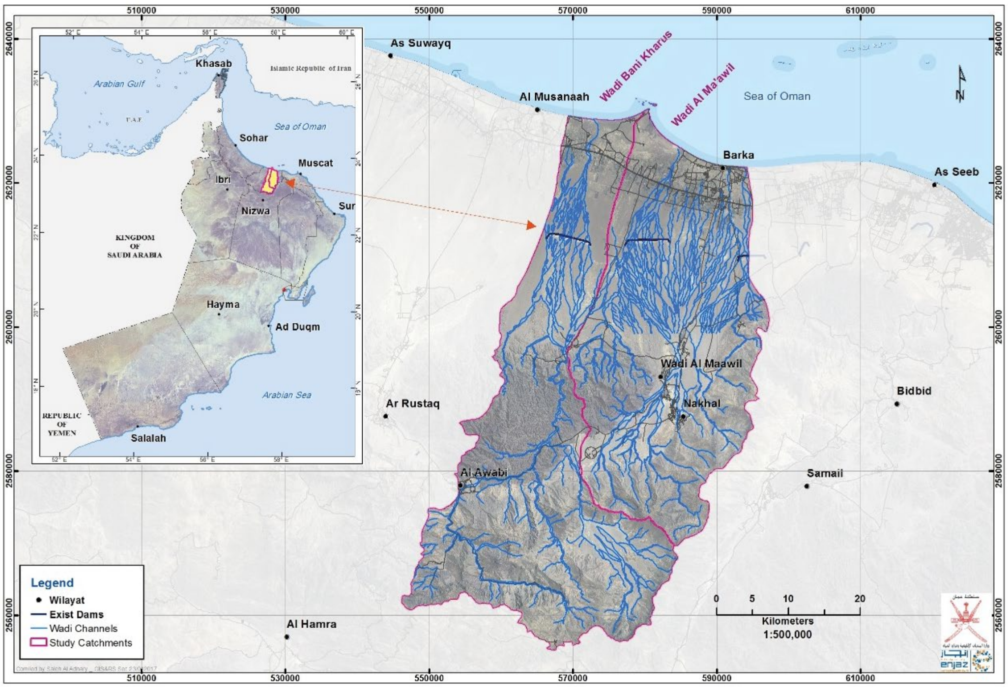

Fig. 1. Location of Wadi Bani Kharus and Wadi Ma'awil – Map provided by MRMWR (2017).

the overall performance of decision options against multiple criteria or objectives (Afshar et al., 2011).

- *System dynamics*: these are dynamic system models which are used to study the dynamics, feedbacks and evolving interaction in a system over time (Akbar et al., 2013).
- *Agent-based models and knowledge-based models*: These are simulation models partly driven by increasing demand from decision makers to provide support for understanding the potential implications of decisions in complex management systems (Rounsevell et al., 2014).

Subagadis (2015) argued that BNs are the most appropriate for modeling complex systems under uncertainty. Castelletti and Soncini-Sessa (2007) developed an integrated model of a water reservoir network by using a BN structure coupling to a hydrological model. BNs were used to describe, in a probabilistic way, the behavior of farmers within an irrigation district in response to some planning actions. Ticehurst et al. (2011) presented findings from a study done to explore the benefits of combining BNs with conventional statistical analysis. BNs were used with conventional statistical analysis to examine landholders' adoption of conservation practices for Wimmera region in Australia.

2.2. Summary

Models are highly used in the field of water resources. However, BN model applications have not been widely used in studies related to agriculture irrigated by groundwater in coastal areas, which are affected by saline water intrusion. Although such types of models are helpful in extending knowledge, they require additional efforts. Moreover, they have not been used, so often, in exploring the influence of social factors on the adoption of management options related to water resources in those particular regions. In Oman, no social research studies have been done associated with behavior analysis of both decision makers (DMs) and farmers in the field of IWRM with a focus on irrigated agriculture. Moreover, modeling approaches, applied as decision support tools, have not been introduced yet in such fields. The work introduced through this paper intends to explain the dilemma of limitation in successes of the already applied solutions concerning the behavior of the stakeholders. It outlines how IWRM can encompass social issues. It elaborates ways for prediction and estimation of the implementation potential of selected interventions by analyzing opinions and responses of the relevant stakeholders. It is an attempt to bring closer the views of the stakeholders to achieve the goal of accepting the proposed interventions gradually.

3. Methodology

3.1. Data, information and knowledge collection

Data, information and knowledge were collected by performing a social survey, and questionnaires were designed to collect data from different groups of SH's.

The information collected for this work is a combination of environmental, social and economic data. Following are the type of information which was decided to be collected for the study purposes:

- Information related to water availability and water quality
- Farm size, irrigation sources and irrigation methods
- Information related to opinions of farmers and DMs

- Information related to knowledge about water and agricultural management
- Information related to training and subsidies
- Information related to suitable interventions and stakeholders participation in water management

3.1.1. List of interventions for agriculture and water management

The primary goal, for the management interventions, is that groundwater levels are to be stabilized in conjunction with maintaining the social and economic interests of the relevant SH's. Based on this idea, a list of interventions was constructed and included in the questionnaires.

The list of the intervention was constructed based on different sources;

- Literature review (some were used in similar studies, not only in Oman, but also in different other regions).
- Some of them were suggestions from expert consultation through the project meetings.
- Some of them are results of an analysis of a pre-test survey

The general specifications of the management options and interventions either focus on water demand-side measures (e.g., an implementation of water quotas and subsidies) to reduce water consumption and use the resources more efficiently, or on water resources side measures (e.g., climate conditions and artificial recharge) to increase the availability of water.

3.2. Data analysis

Data analysis was performed in different ways; statistically by applying descriptive statistics, cross tabulation and independent samples *t*-test. Descriptive statistics such as frequencies, means, medians, standard deviation (SD), correlation and percentages are used to analyse the answers of particular questions. Both, data collection and data analysis are performed in order to explore if the impacts can be quantified. Then all this is followed by the modeling part. This is an advanced step, to explore if models can be used to reproduce the relations in the data, and for allowing future forecast. In other words, to forecast how the different groups of stakeholders will behave with changing conditions.

3.2.1. Modeling

The modeling part includes two different analysis:

- *Discriminant analysis (DA)*, which is performed to identify the drivers influencing farmers' opinions regarding different intervention measures.
- *Bayesian network (BN)*, which are techniques used to represent a probabilistic dependency model. They are graphical models for reasoning under uncertainty in a domain (Ticehurst et al., 2011).

For the purpose of this paper, we will focus more on the analysis procedure and results of the BNs modeling part.

Bayesian networks (BNs) are one of the techniques used to represent a probabilistic dependency model. They are graphical models for reasoning under uncertainty in a domain (Ticehurst et al., 2011). Each BN consists of nodes and arcs, but there is another hidden part which is a set of local conditional probability distributions. The two parts together can represent the joint probability distribution of a domain and explain or show the cause and effect between the variables and outcomes throughout the network. Therefore, the basic idea of BNs is Probabilistic reasoning.

The network was developed by using GeNIe (Graphical Network Interface) software[1], which is a development environment for building decision networks. It was constructed manually, based on experts' opinions on factors that are believed to be affecting farmers' decision regarding implementation of specific interventions. Variables included representing the economic situation, water resource situation, knowledge situation and trust or confidence situation of the community.

The BN was developed by following eight major steps:

Step 1: Define the focus issue

The selected intervention to be the intervention analysed through the network.

Step 2: Develop an influence diagram (manual step of determination of the variables and conditions)

Variables and links were assigned and a proposed BN map was developed.

Step 3: Review influence diagram (validation of the structure of the BN)

During a pre-test survey, performed in earlier steps of the work, an example of the proposed BN was distributed to the water experts and decision makers from water-related organizations in Oman who participated in the pre-test survey.

Step 4: Define states for the framework variables (assignment of conditional probabilities to input/output variables and learning of conditional probability table for the manual variables)

Data were used to develop a spreadsheet (generate data file in GeNIe) containing data and information for each variable in the network. Then the relationships between variables were quantified by conditional probability distributions.

After that, the data in the spreadsheet were merged with the network. The full network (Fig. 2) then consists of the three main elements:

1. The nods which are the variables that represent the factors relevant to the implementation of a particular intervention measure:
    - The input variables (green in color)
    - The intermediate variables (blue in color)

1. (http://genie.sis.pitt.edu/)

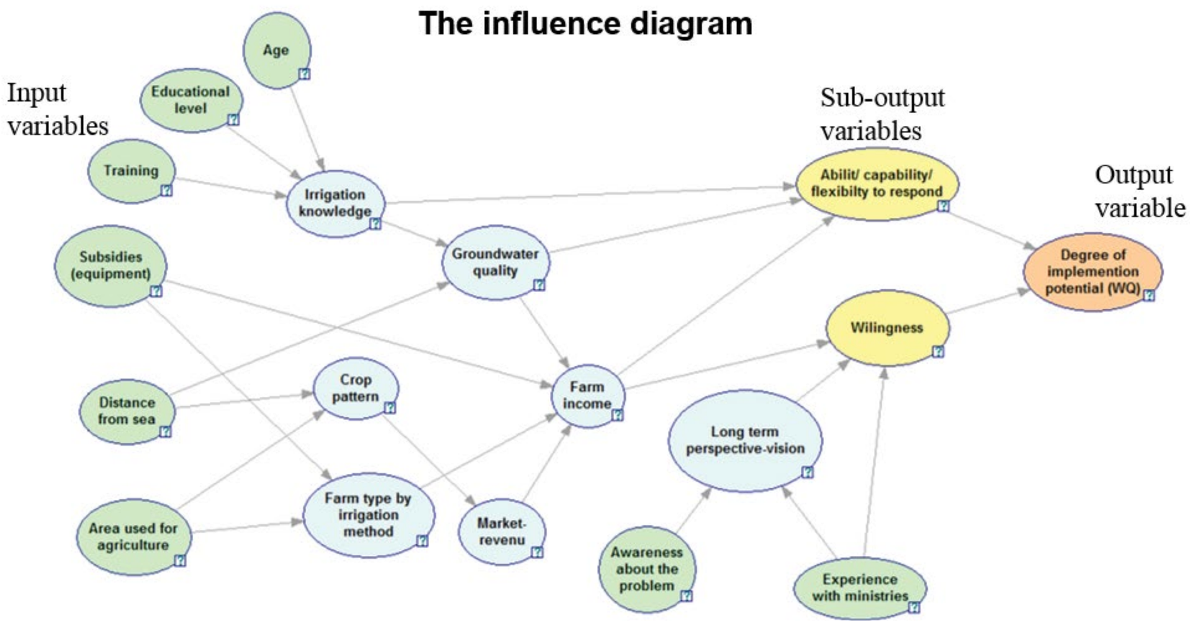

Fig. 2. Suggested influence diagram for the Batinah case.

- The sub-output variables (yellow in color)
- The output variable (orange in color).

2. The arcs (the arrows) which represent the relationships between the variables that quantify the links between them.
3. The CPTs, which are used to calculate the states of the variables. A CPT is attached to each variable. This table is representing the relationship between the node (variable) and its parents based on a prior information or knowledge and experience. The table should include all the possible combinations between the values of the node of interest and values of its parents' nodes.

The first two elements can be seen from the BN diagram, while the third element is hidden behind.

Steps 5 and 6: Validation of the variables and links between variables (Performance of the BN)

Running of the method should allow investigating the linkage and feedbacks between hydrological and socio-economic interactions for the management problem of Al Batinah. The first simulation was run to evaluate if the network represents the current situation and the outputs (re-production) are similar to the ones obtained by statistical analysis. The results obtained from the first simulation are compared with the statistical results obtained from analysing the intervention table. This is how the performance of the network was validated.

Steps 7 and 8: Sensitivity analysis – monitor and observe

Afterward, the model is used for further simulation to investigate the effects of the selected variables on the implementation and acceptance of interventions (Hypothesis: Identify how the network should behave if some adjustments are made to some variable).

A sensitivity analysis was performed to create a set of scenarios. Those scenarios were then used to determine how changes in one variable(s) will impact the target variable. For example; if an update is made on one variable (say crop pattern), other variables in the BN might change probabilities after the update. This enables to check whether the output results of other variables in the BN make sense and are justifiable and realistic after the update of a particular variable. Then the variables, play a role in farmers' opinions can be ranked according to the level of influence on the target variables.

4. Results and discussion

The study population consisted of 131 respondents, combining 64 farmers from the study area, 12 water professionals from different research centers, and 55 water experts from different water and agriculture-related organizations (e.g., groundwater, agricultural water use, WRM and planning, surface and sub-surface hydrology, climate change, environment protection, and others) in Oman. Since the group of water professionals was too small and for analysis purposes, water professionals were combined with the group of water experts to be treated as one group. The survey covered at least 80% of the total number of farmers included in a list of the registered farms, provided earlier by the Ministry of Agriculture and Fisheries.

4.1. Modeling

For the validation of the structure of the BN, water quota was considered to be the intervention to be tested through the network. The reason is that there is a high variation in opinions regarding water quotas implementation within the group of farmers. The variables (Table 1) to be included in the network were decided based on knowledge obtained through the description and evaluation of the

Table 1
Assumptions behind the variables used in the structure of the Baysian Network model (BN)

Variable	Definition – the idea	Impacts on	Assumption	Data available or not (A/N)
Degree of implementation potential of water quotas	Water quota is defined to be, the allocation of the resources in an equitable way. Implementation of water quotas to the groundwater used for irrigation in the study area is essential to control the problem of water shortage and saline intrusion in the coastal aquifer. The idea is to test the degree of implementation potential through evaluating variables affecting behaviors and opinions of different stakeholders.	N/A	N/A	A
Ability/capability/ flexibility to respond	Ability and capability of the stakeholders In the matter of money.	1) degree of implementation potential	According to the factors influencing farmer's capability, to accept or reject the idea.	A
Willingness/attitude	This is to test the level of willingness of accepting or rejecting the idea.	1) degree of implementation potential	Increase the level of acceptance	A
Farm income/month	Net income from the farm (O.R/month)	1) ability/capability/ flexibility to respond 2) Willingness	If there is an income from the farm, it means more money is available for the adoption of better management activities.	A
Market- revenue	Farm production sold (percentage)	1) farm income/month	Increasing monthly income from the farm production	A
Ground water quality/ salinity range	Recorded salinity range for the ground water in the farm	1) ability/capability/ flexibility to respond 2) farm income/ month	Good water quality helps the farmer to increase the cultivated area and produce more products.	A
Crop pattern	Type of cultivated crops in the farms (trees, forage & clover, vegetables)	1) marketing	Deciding the percentage of total farm production sold and make a profit.	A
Irrigation knowledge	If farmers have good irrigation skills	1) farm classification 2) ability/capability/ flexibility to respond	This should allow farmers to manage their farms in a good way and adopt new irrigation methods. Also, farmers become more likely to respond	A
Farm type	Classified by irrigation method used	1) farm income/month	A modern farm with new irrigation techniques is more likely to have more income compared to a traditional one.	A

The area used for agriculture	Percentage of the area used for agriculture on the farm.	1) crop pattern 2) farm type (by irrigation method)	Effects the type of cultivated crops and type of irrigation methods to be used.	A
Distance from sea	Distance between the farm and the coastline.	1)groundwater quality/ salinity range 2) crop pattern	Near to the sea, more water salinity problems.	A
Subsidies	Government support (equipment). Farmers will be able to have new irrigation equipment in their farms and upgrade their farms from being traditional to modern ones.	1) farm type (by irrigation method) 2) farm income/month	Reduction in water used for agriculture	A
Training	Training and education in different aspects of water & agricultural management	1) irrigation Knowledge	1) By training, farmers can gain more information on farm and water management; then their irrigation skills will improve.	A
Educational level	Respondent's educational level	1) irrigation knowledge	A good education helps to introduce new technologies in irrigation.	A
Age	Age of the Respondents	1) irrigation knowledge	long experience in water management and farming will impact the irrigation knowledge	A
Long-term perspective	The vision and perspectives of the respondent about future alternatives	1) willingness	A respondent with a long-term vision for the situation will be more willing to respond.	A
Experience with ministries	The level of trust between farmers and governmental water and agricultural organizations.	1) long-term perspective 2) willingness	Experience with Ministries: representing the level of trust between farmers and governmental water and agricultural organizations. Availability of good cooperation with water and agriculture organizations, farmers, are more likely to respond. The more the farmers trust these organizations, the more willing to support optimization.	A
Awareness about the problem	Awareness of the respondent about water management, limitation of resources and the environmental problems.	1) long-term perspective	A farmer with a good knowledge of the situation will be able to evaluate what is best for the future.	A

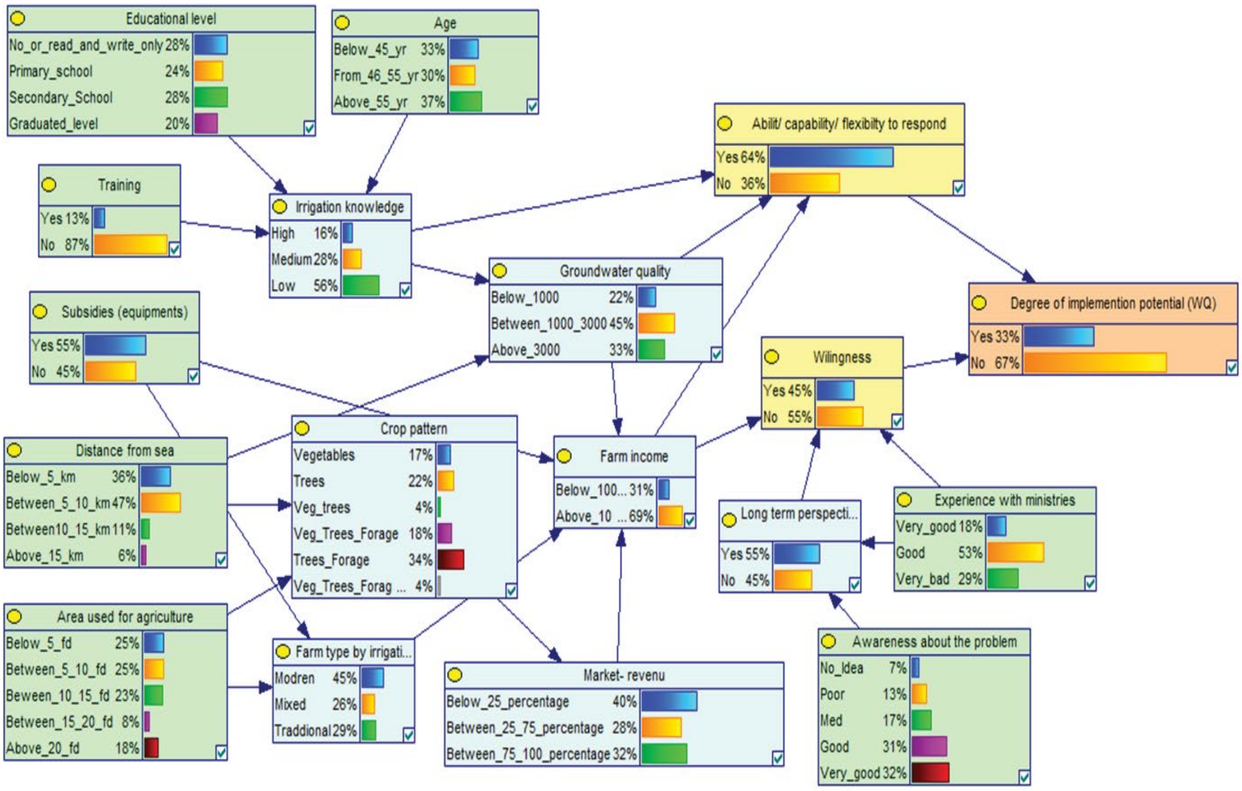

Fig. 3. Structure of the BN (implementation of water quotas).

problem, the statistical results and by using expert opinions. The stakeholders (decision makers and scientists) through meetings and workshops reviewed the structure of the BN.

The data initiated in the network were directly formed from the answers of the responses to the survey questions. Almost all the collected data and information were useful and applicable even the qualitative ones. The missing data were very few in the data set, so the interpolation option was used to fill the gaps in the spreadsheet.

The statistical approaches were used to identify the key variables influencing farmers' willingness and capability to change. These were represented as nodes in the BN and described using states relevant to the survey responses. An initial representation of the causality links between the key factors was developed. Then the BN was automatically learnt from the dataset. The algorithm used was clustering, which is the default algorithm of the software, and according to literature, for example (Jongsawat et al., 2008), it should be sufficient for most applications. The software used in this study (GeNIe) automatically normalises any values entered. Each variable is assigned with its CPT. The BN structure and results of the first round simulation are presented in Fig. 3.

The results obtained through the validation step indicated that the reproduction by using BN was performing well and other simulation can be carried out by making some adjustment to the network.

During the sensitivity analysis, an increase/decrease in the probabilities of some parent nodes (input nodes) was made to explore the result in the effect of relative increase/decrease on the output nodes' probabilities. As an example of the results, we will illustrate in the following figure (Fig. 4) the impacts of "training" and "subsidies"[2]:

The probabilities of "training" and "subsidies" were increased to 100% for the 'Yes' state and decreased to 0% for the 'No' state. The results showed that the node "training" is not influencing the target output node "degree of implementation potential" and regarded as having a less influencing effect on the sub-output node "ability/capability/flexibility to respond".

Moreover, the node "subsidies" is not influencing any of the output nodes. It has a slight impact on the node "farm income" and "farm-type by irrigation method." The increase in the probability of "farm-type by irrigation method" changed from 45% for 'modern' to 48%. Also, the "farm income" which is 'above 1000 Omani reals' increased from 69% to 71%.

Six rounds of simulations were carried out, and the preliminary results from the BN model showed that:

- The hypothesis for most of the variables worked logically.
- The impacts of the input variables on the implementation potential of water quota (the output variable) were limited.
- Some variables (e.g., subsidies from the government) might be related to the adoption of water quota.

2. The adjusted variables are surrounded by blue circles and the influenced variables are surrounded by red circles.

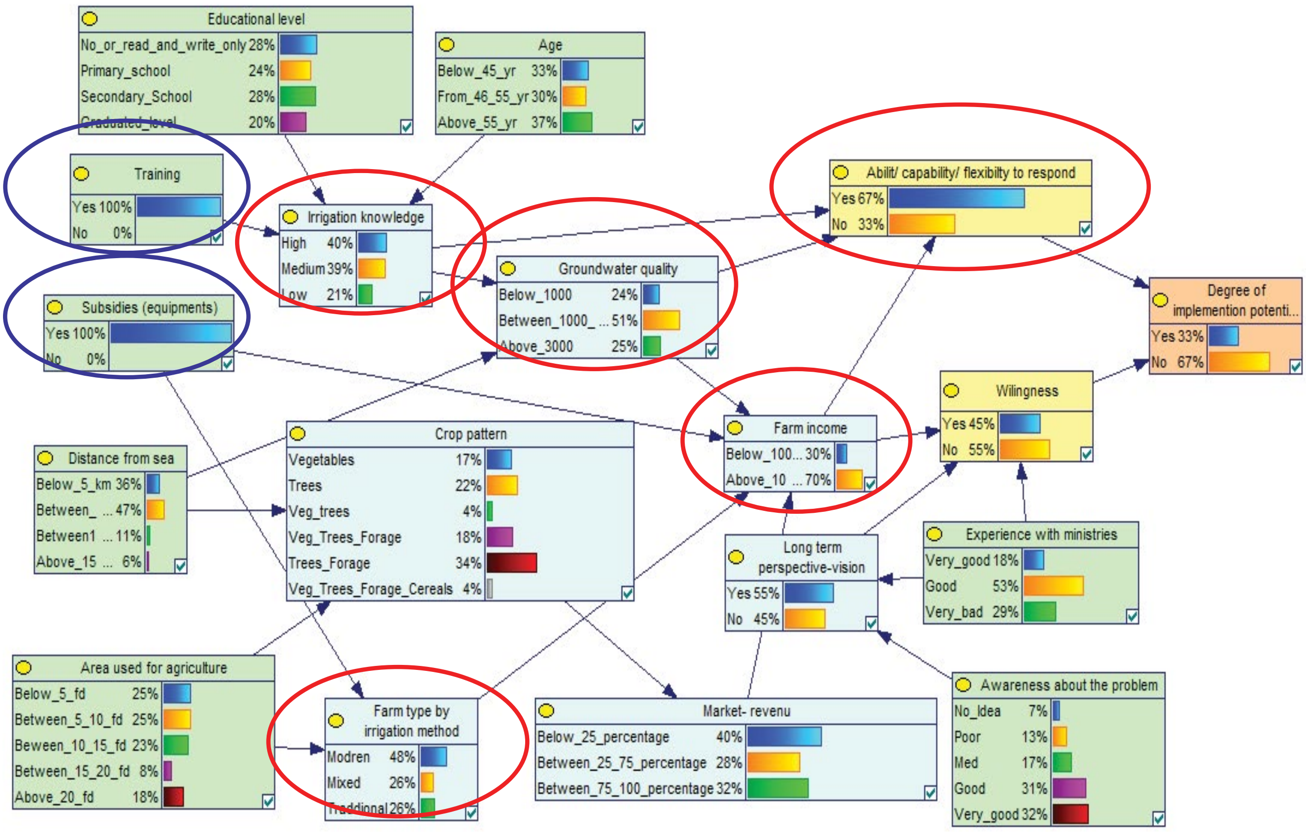

Fig. 4. Impacts of "training" and "subsidies" on the output variables.

- The variables, which are very close to the variable of interest, have more influence than those variables which are far away from the output or the variable of interest.

It was also noticed that, if the BN is too big, there are no much effects on the output. The reasons might be that some variables are misplaced[3] , or the sample size might be too small, and improvement of the database set is needed. This spots the light on the importance of the care which should be taken while developing such a network in order to construct the best model from the data. In this regard, Neil et al. (2000) argued that although tools are available to construct large BN, there are no guidelines on building those networks.

5. Conclusion and outlook

BNs are one type of techniques of using computer technology for dealing with probabilities to integrate data, experience, knowledge, and information along with their uncertainties from different sources. They provide a useful tool for inferring hypotheses from the available information by transmitting probabilistic information from the data to various hypotheses (Suermondt, 1992).

The application of the BN approach, in this study, is a matter of transfer the statistical results to an explanation model. The scenarios should form the basis to increase the acceptance of different interventions. Therefore, the network can be used as a DSS enabling DM's to identify what is possible to be implemented from the social point of view.

In this work, the future forecasting ability was quite limited by the structure of the BN. The evidence were very low (not so clear) and the limitation was high. BNs are complex and sometimes consist of too many connections and relationships, dependency and CPT are not strong enough, or even the sample size is not enough. The level of missing data also has a significant impact on the results of a BN. Therefore, the improvement of the database (extension of the survey) is a potential future task. Moreover, another BN model can be developed with different connections and relationships. But one should be aware that if there are major changes, over time, in the structure of the institutions, then the BN cannot deal with such evolution of the behavior. It is hard to understand the behaviors of people; the techniques used can be limited to the type of data available, characteristics of the selected region, sample size. In this work, the implementation of cost and law and regulations issues was not considered. Therefore, additional research, taking into consideration those issues, is required. Finally, for the case of South Al Batinah, both groups agreed that the water situation is at risk. However, there are difficulties in implementing the intervention, and it is not easy to

3 There might be more than one possible structure of the BN for the problem we are trying to solve.

predict which one is the most suitable with a good chance to be implemented from the social point of view.

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