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Application of Bayesian networks for sustainability assessment in catchment modeling and management (Case study: The Hablehrood river catchment)

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ABSTRACT

Catchment management is a process which increases the sustainable development and management of all catchment resources in order to maximize the balance among socioeconomic welfare and the sustainability of vital ecosystems. The increase of anthropogenic activities within river catchments causes degradation and serious problems for stakeholders and managers, particularly in arid and semi-arid regions. Although there are many techniques for solving these problems, it is not easy for catchment managers to apply them. An integrated Bayesian network model framework was applied to evaluate the sustainability of a semi-arid river catchment located in the Iranian Central Plateau river basin encompassing 32.6 km^2 area on the Hablehrood river catchment, located in the northern part of the Iranian Central Plateau river basin. The research illustrated the assessment of the relevant management problems, the model framework, and the techniques applied to extract input data. Results for the study area implementation and a suggestion for management are described and discussed.

1. Introduction

Catchment management tries to solve catchment issues based on sustainable development. Among these issues, degradation of water quality has become the critical limit of catchment development in many catchments of the world including the arid and semi-arid catchments of the Iranian Central Plateau river basin. Hence, one of the main objectives of catchment management is to find solutions in order to protect and restore water quality. It is necessary to have the stakeholders' participation to obtain an integrated catchment management plan that includes water quality and quantity objectives. Combining the needs and objectives of decision-makers and stakeholders is the main advantage of using integrated catchment management.

Generally, the most widely discussed themes in catchment modeling and management include uncertainty. The past decades have shown an increasingly significant interest in probabilistic assessment, risk analysis, and related subjects and methods (Varis, 1997). Probabilistic assessment and risk analysis methods are widely used.

Recently, the utilization of graphical models, such as Bayesian networks (BNs), has grown rapidly in natural resources modeling and management under uncertainty and integrated water and catchment management.

Many authors have used BNs to better understand and model many complicated problems in such fields as medicine and artificial intelligence (Charniak, 1991; Pearl, 1988; Heckerman et al., 1995; Jensen, 1996). BNs have been applied to various ecological problems (Kuikka et al., 1999; Borsuk et al., 2002; Little et al., 2004; Prato, 2005; McCann et al., 2007; Pollino et al., 2007; Aalders, 2008; Bashari et al., 2009; Liedloff et al., 2009; Mesbah et al., 2009; Reckhow, 2010). Applications of BNs in water resources include groundwater management (Martin de Santa Olalla et al., 2007; Henriksen et al., 2007; Farmani et al., 2009; Malekmohammadi et al., 2009), irrigation and farming system modeling (Batchelor and Cain, 1999), and by Varis and Kuikka (1997) to study the effect of climate change on surface waters. BNs were applied by Borsuk et al. (2001, 2004), Hamilton et al. (2007), Johnson et al. (2009) and Alameddine et al. (2010) to investigate the eutrophication of various water bodies. Some studies reviewed applications of BNs in integrated natural resources management and catchment

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modeling (Ames et al., 2005; Bromley et al., 2005; Sadoddin et al., 2005; Khadam and Kaluarachchi, 2006; Said, 2006; Zobrist and Reichert, 2006; Castelletti and Soncini-Sessa, 2007a; Davies, 2007; Dorner et al., 2007; Ticehurst et al., 2007; Barton et al., 2008; Fox and Papanicolaou, 2008; Kragt, 2009; Kragt et al., 2009; Stewart-Koster et al., 2010; Merritt et al., 2010; Holzkämper et al., 2012). The objective of this paper was to apply Bayesian network modeling to assess the sustainability of social, economic, and ecological conditions within a semi-arid catchment. In particular, we present how management action costs can be coupled with these conceptual models to recognize the most cost-effective management action and select the best management plans to improve river water quality using Bayesian networks.

1.1. Bayesian networks

BNs (also called belief networks or causal probabilistic networks) include a set of nodes (variables) and causal links. BNs are used to conceptualize and simulate a system which consists of uncertain consequences through incomplete understanding or insufficient knowledge of a system (Pearl, 1988). BNs consist of a graphical model and a fundamental probabilistic structure; the graphical model represents the most significant variables in the system and causal links between the nodes. The causal links between nodes are explained using conditional probability tables (CPTs). The empirical data, various models, and expert technical inputs (when measured data are not accessible) are information sources to produce CPTs (Pearl, 1988; Jensen, 1996). There are a number of benefits with BNs such as integrating different types of variables and data within a single framework, describing uncertainty, and the ability to be updated when new information and knowledge become available (Castelletti and Soncini-Sessa, 2007b; Cinar and Kayakutlu, 2010). They are also applicable as a tool to assist decision-making in natural resources management, where issues are complicated and data are insufficient and uncertain. The framework of Bayesian networks and their applications in participatory modeling can be found in other studies (Borsuk et al., 2004; Castelletti and Soncini-Sessa, 2007b; Jensen, 2001).

We used BNs because their applications are comparable to other integrative models as an effective tool to integrate social, economic, physical, and ecological variables. In this paper, we present a case study of the application of BNs in catchment modeling and management.

2. Materials and methods

2.1. Study area

The Hablehrood river catchment (HRC) (35° 13′ to 35° 57′ N, 51° 39′ to 53° 8′ E) is located in northwestern Semnan and northeastern Tehran provinces, on the northern part of the Iranian Central Plateau river basin, with a total surface area of approximately 32.6 km^2 (Fig. 1). The mean annual precipitation and air temperature of this river catchment are 318 mm and 7.8 °C, respectively. The Hablehrood river, which originates from the Alborz Mountains, flows north to south and is bound by mountains except at its outlet (at the location of Bonkooh hydrometric station), where it empties into the Garmsar Plain. The catchment area is dominated by degraded rangelands; intense salinity outbreaks occur in the southern parts of the catchment. This maximum salt load is observed at the Bonkooh hydrometric station. The Hablehrood river supplies water for the municipal consumption of the city of Garmsar which has a population of over 84,000, for industry, and for farmlands on the Garmsar Plain (about 5.2 km^2).

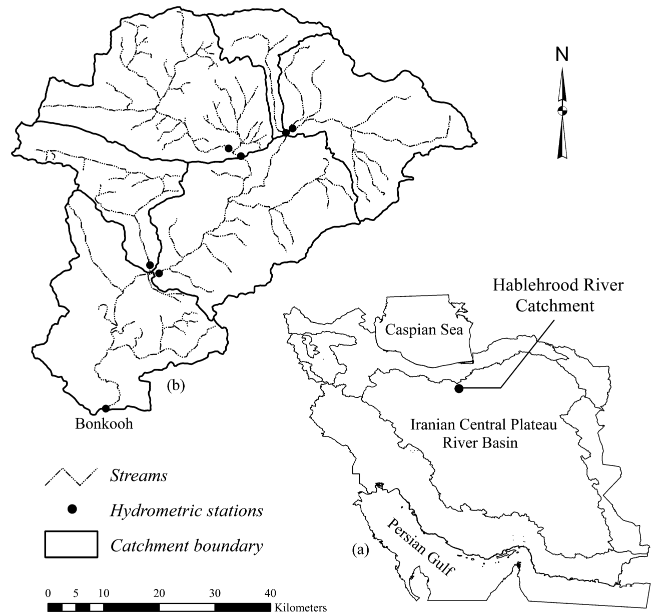

Fig. 1. (a) Geographical location of the study area in Iranian Central Plateau river basin; (b) map of the Hablehrood river catchment.

The Hablehrood river catchment has significant natural, social, and economic value, such as medicinal plant species like *Ferula* sp., natural rangelands, water resources for the city of Garmsar, and irrigation. The most effective factors on the Hablehrood river catchment's sustainability are overgrazing, intensive farming on the Garmsar Plain, and urban development due to population growth in the city of Garmsar. Managers need the appropriate tools to analyze the consequences of management actions in order to balance human activities with environmental issues and improve water quality. BNs were chosen as a practical approach to analyze these interactions.

2.2. Model development process

A Bayesian decision network was developed to analyze the consequences of suggested management plans on the sustainability of the Hablehrood river catchment. In the first step of the model construction, we reviewed previous implemented management actions, studies, and other scientific articles to better understanding the limitations, problems, and the needs of stakeholders and communities involved (Ames et al., 2005; Carmona et al., 2009; Sadoddin et al., 2005; Schwilch et al., 2012; Ticehurst et al., 2007; WNRMO, 1998). An initial review assisted in determining a preliminary BN structure and possible management actions.

2.3. Model structure description

The preliminary BN framework was presented and discussed with local community leaders and the Watershed and Natural Resources Management Office (WNRMO), which is responsible for the sustainability of the Hablehrood river catchment. This helped to refine and improve the preliminary BN framework. A simplified version of the improved BN model is shown in Fig. 2. For example, river water quality is shown as a single node in Fig. 2, but the original model structure contains three separate nodes, including; Total Dissolved Solids (TDS), Electrical Conductivity (EC) and Sodium Absorption Ratio (SAR). The current model includes 19 nodes and 29 links. The models' nodes and their states are described in Tables 1 and 2.