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Bayesian network application in socio-economic and ecological effects analysis in watershed management

Ali Afzali[1], Karim Solaimani*[1], Shafagh Rastgar[2], Amirreza Keshtkar[3]

[1] Department of Watershed Management, Sari Agricultural Sciences and Natural Resources University, Sari, Mazandaran, Iran. Email: k.solaimani@Sanru.ac.ir
[2] Department of Rangeland Managment, Sari Agricultural Sciences and Natural Resources University, Sari, Mazandaran, Iran.
[3] International Desert Research Center (IDRC), University of Tehran, Karaj, Alborz, Iran.

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ABSTRACT

Natural resource management using appropriate management tools, is one of the critical issues in the watershed, especially in arid and semi-arid areas, land management and its associated resources will create a balance between economic and social needs and the sustainability of biological ecosystems. The present study, with the aim of watershed management and controlling sedimentation rates, evaluated socio-economic effects in the Damghan Rud watershed. The study area with an area of 5.66314 ha is located in Semnan Province. By choosing four economic and social activity variables, along with rangeland vegetation cover, were identified management options for the Damghan Rud basin. Based on the regional conditions and study objectives, four economic and social parameters the presence of surplus livestock, reliance of watershed residents on rangeland, Literacy of watershed residents' level, and their participation percentage in water and soil resource conservation were determined as effective options for rangelands vegetation cover in the region. The sediment production rate at the output site of the selected basin at the Astana hydrometric station was investigated in the statistical period of 1995-96 to 2015-16, then by using the frequency distribution diagram of observational sediment, determined its classes. Then, with the implementation of the model were calculated the probabilities associated with each variable, and were evaluated the possible effects of the implementation of managerial options on the middle and target variables. The results showed that the option of reducing the reliance of watershed residents on rangelands to the minimum level led to a 15.3% increase in vegetation cover, a 5.5% reduction in river flow rate, and a 3.6% decrease in sediment production rate. Furthermore, the results showed that the Bayesian network models had a high capability and ability to express various dimensions of the issue and handle uncertainties within the system, and making them suitable tools for watershed resources management.

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1. Introduction

Given the limitations of water resources in nature, the non-uniform spatial and temporal distribution of water resources, the increase in pollution and destruction of natural resources, as well as the increase in population, growth, and development of urban communities, and agricultural and industrial activities, is inevitable proper planning and management (Ahmadi *et al*., 2008). Estimating the amount of runoff and sediment production in a watershed due to the lack of measurement stations and sediment in all watersheds is an inevitable matter for planning soil and watershed conservation plans. River sediment simulation and evaluation are also important and practical issues in water resources management. In most natural rivers, the majority of sediments are transported suspended (Feiz Nia *et al.*, 2002. Arab khedri, 2021).

In recent years, due to decreased rainfall, the occurrence of drought phenomena, and as well as changes in rainfall regime from snow to rain in the Damghan Rud watershed, consequently the decline in agricultural prosperity on one hand, and the presence of surplus livestock and double pressure on the region's rangelands, resulting increasing the reliance of watershed residents on rangelands to meet their needs on the other hand, causing excessive exploitation and double pressure on rangelands and thus increasing soil erosion and sediment production (Ghaffari *et al.,* 2014). This phenomenon has led to the destruction of vital resources of the rangeland ecosystem, including soil, water, and vegetation cover, and the entry of sediment into the Shahid Shahcheraghi Dam reservoir, resulting in the loss of useful volume of the dam reservoir (Anonymous, 1991)

In recent decades, the use of models in understanding hydrological processes, management, and planning of watersheds has received significant attention from researchers, in this regard, (Dehghani *et al.,* 2009) compared the estimation of suspended sediment load in two methods of rating curve and neural network in the Doogh River of Golestan province. They used the desired flow rate, the flow rate of the previous day, and the hydrograph state (in terms of ascending or descending branches) as inputs and the suspended sediment load flow rate as the output parameter. The results showed that the neural network provides a more accurate estimation of the suspended sediment load compared to the rating curve. (Hosseinpour *et al.,* 2014) investigated the flow rate of suspended sediment in the Ahar Chai River using meta-exploration methods and concluded that the genetic programming model is the best model for estimating suspended sediment in the studied river. (Agarwal *et al.,* 2006) used artificial neural networks with a backpropagation algorithm to estimate daily, weekly, ten-day, and monthly flow rates and sediment loads and compared the results with observational values. The results showed that artificial neural networks have high accuracy in modeling streamflow-sediment. (Prathams *et al.*, 2018) used Bayesian network modeling to evaluate the indirect effects of hydrology-based forest management. The results showed that hydrology-based forest management had a very positive, as more water was available due to reduced harvesting, resulting in increased evaporation, transpiration soil water content, and a slight increase in deep infiltration, and conversely, surface runoff was significantly reduced.

(Lee *et al.,* 2023) presented a new Bayesian modeling framework for better planning of optimal executive actions, by integrating process-based domain modeling and Bayesian optimization algorithms to reveal the impact of multiple uncertainties. The results showed that identified priority areas of executive actions accounted for approximately 80% of the entire watershed, while also leading to over 15% reduction in pollutant loads. Analysis of multiple sources of uncertainty showed that precipitation was the most influential source of uncertainty in the effectiveness of optimal executive actions. Several studies have proven the usefulness of Bayesian networks in utilizing and combining expert knowledge and experimental data for modeling and transforming qualitative data into quantitative models (Smith *et al.,* 2007;

Bashari *et al.*, 2009; Johnson *et al.*, 2010). Bayesian modeling method has been applied in various fields where the available data is highly uncertain, such as ecosystem management (McNay *et al.*, 2006; Nyberg *et al.*, 2006; Howes *et al.*, 2010; Mdadgar *et al.*, 2014; Sperotto *et al.*, 2019; Li *et al.*, 2023).

The purpose of this study was to employ a Bayesian network model in watershed resource management in arid and semi-arid regions and evaluate and identify effective options for reducing sedimentation rates in the Damghan-Rud basin.

2. Materials and methods

2.1. Study area

The Damghan Roud watershed has an area of 56314 ha, it is located between 53°58' to 54°28' longitude and 36°16' to 36°30' latitude. Figure 3-1 illustrates the location of this watershed in the country and Semnan province. The maximum and minimum elevations of the study area are 3780 and 1449 meters, respectively. The average annual rainfall is equivalent to 238 millimeters, and the average slope of the watershed is 30%. The soils in the Damghan-Rud watershed are mostly non-profile evolution and most of them have sedimentary and igneous maternal materials (Natural Resources and Watershed Management Department of Semnan, 2016).

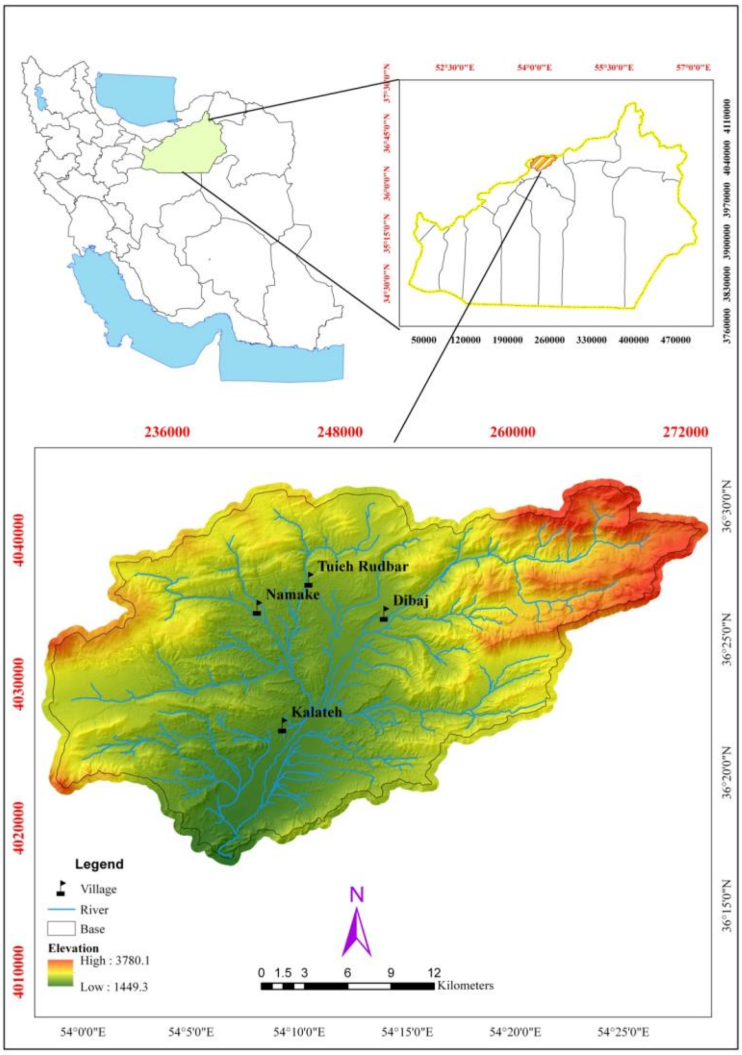

Fig. 1. Location of the Damghan-Rud watershed in the country and Semnan province

2.2. Bayesian networks

A Bayesian network is a probabilistic graphical model that represents a set of variables and the probabilities associated with each of them. It is a direct and non-cyclic graph where nodes are issue variables. The structure of a Bayesian network is essentially a graphical representation of the interactions of variables that need to be patterned and in addition to indicating the quality of the relationship between these variables, which numerically uses their joint probability distribution. This method is based on conditional probability calculations (Bayes' theorem), which shows the following equation of Bayes' relationship (Akhonipourhosseini *et al.*, 2017).

$$P(a/b) = \frac{P(b/a) * P(a)}{P(b)} \tag{1}$$

The conditional probability of event $p(b/a)$, b probability of event occurring *P*(b), a probability of event occurring *P*(a) in which it is. Each network a has a conditional probability of event $p(b/a)$, and a is conditional that the event is b. Bayesian consists of three main components: a set of nodes, a set of clauses, and a set of probabilities. In general, nodes are either parents or children. A child node can be produced by multiple parent nodes, nodes that are preceded by another node in the graph are defined by conditional probability distribution. Otherwise, they are represented by their initial probabilities. The probabilities associated with the lowest part of the Bayesian network are obtained through the law of total probability, while the probabilities associated with higher parts of the network are calculated based on Bayes' theorem. More details about Bayesian networks can be found in various sources (Kuikka and Vari, 1997; Keshtkar *et al.,* 2013; AkhoniPourhosseini and Asadi, 2017).

2.3. Bayesian network model of the Damghan Rud watershed

Considering the existing problems in the Damghan Rud watershed, a Bayesian network model for watershed resources management of the Damghan Rud watershed has been designed with the aim of determining the factors affecting the sedimentation rate and selecting an appropriate management option to reduce the sedimentation basin at the output location in the study area (Astaneh station). The influential and manageable variables include rangeland vegetation cover, social variables (literacy level and participation rate of stakeholders), and economic variables (livestock overpopulation and income dependency ratio on rangeland) to reduce the amount of production sediment under various conditions. The design of this initial network has actually been done as a source for analyzing the subsequent statistics and information and redefining and aggregating network probabilities (Figure 2).

2.4. Model sensitivity analysis

Model evaluation and sensitivity analysis have been conducted by entering information and the occurrence of new events, as well as quantifying the sensitivity analysis. In this regard, has been investigated the change in posterior probability distributions under different conditions and concerning various variables. Quantifying the network sensitivity analysis using methods to measure the amount of irregularity and the mutual effect (dependency and independence) of various model variables. In this way, the variables affecting the target variable (sedimentation rate) test and variable with maximum irregularity and dependency were determined and have been determined in the following variables affecting this variable. This process continues until the end of the network in the influential path and branch and ultimately determines the external variable effect.

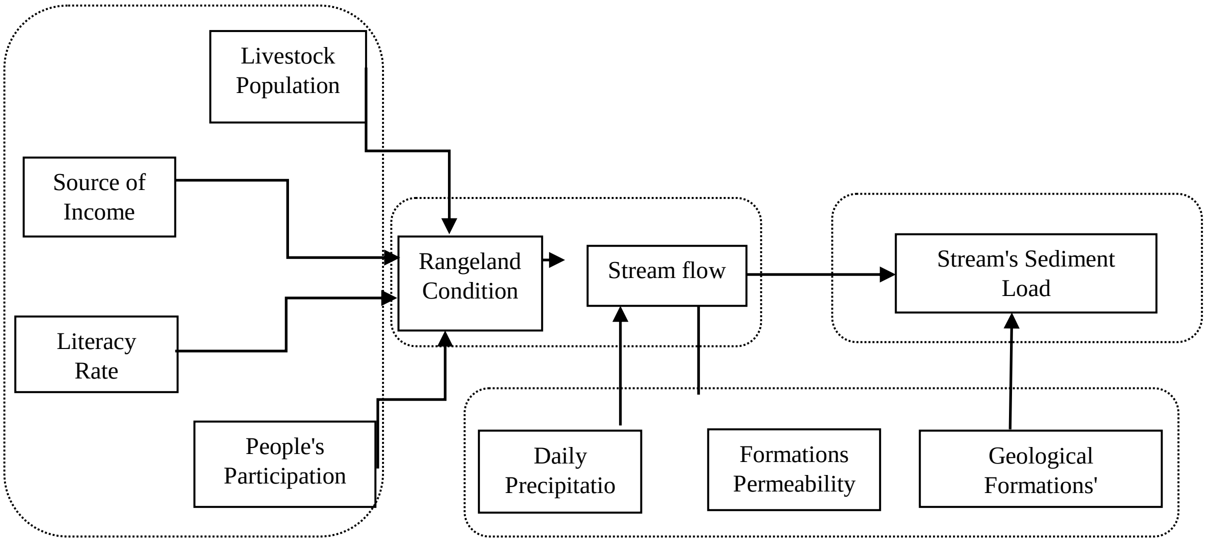

Fig. 2. Conceptual model of the Damghan Rud watershed

3. Results

3.1. Economic and Social

The results showed that the options of surplus livestock and income reliance of watershed residents on rangeland, in the economic sector, and the options of literacy level, level of knowledge, and participation level of watershed residents in the preservation of water and soil resources in the region, in the social sector, are among the most influential factors in improving sediment production rates in the Damghan Rud watershed (Table 1).

Table 1. Probability percentage of sediment production rate after applying economic-social management options

Option	Description	Sediment rate		
		Low	Medium	High
1	Present	42.3	30.5	27.3
2	livestock overpopulation	41.6	30.7	27.6
3	Non livestock overpopulation	44.1	29.8	26.1
4	income dependency ratio on rangeland -Low	45.9	29.1	25.0
5	income dependency ratio on rangeland -Medium	43.9	29.9	26.2
6	income dependency ratio on rangeland -High	40.2	31.3	28.5
7	Literacy-Low	41.1	30.9	28.0
8	Literacy-Medium	42.8	30.3	26.9
9	Literacy-High	43.9	29.9	26.2
10	Participation-Low	41.1	30.9	27.9
11	Participation-High	44.6	29.6	25.8

The option of low reliance of watershed residents on rangeland percentage in low states, with a change probability percentage of 3.6%, 4.1%, and 2.2% respectively for low, moderate, and high states, cause reduced sediment production rate and the option of management of watershed residents' participation, in the high state with a probability change percentage of 2.3%, 9.0%, and 4.1% for low, moderate, and high states, respectively, was observed to be effective in reducing sediment production rate.

3.2. Ecological

The results showed that the 24-hour rainfall variable and the sensitivity of geological formations to erosion, in low and erosion-resistant conditions, respectively, had the greatest positive impact on reducing sediment production rate, with a reduction percentage of 1.8% and 3.0%. The permeability of geological formations, in low and moderate conditions, had the greatest negative impact, with a reduction percentage of 4.6%, on the sediment production rate, meaning that it increased the sediment production rate in the Damghan Rud watershed.

Table 2. Probability percentage of sediment production rate in different states of ecological options

Option	Description	Sediment Rate		
		Low	Medium	High
1	Present	42.3	30.5	27.2
2	Daily Rain-Low	44.1	29.9	26.0
3	Daily Rain-High	40.4	31.1	28.5
4	Formation Permeability-Poor	37.7	31.4	30.9
5	Formation Permeability-Medium	37.7	31.4	30.9
6	Formation Permeability-Good	42.6	30.4	27.0
7	Resistant geological formation	43.6	30.4	27.0
8	Erodible geological formation	33.3	33.3	33.3

3.3. Sensitivity analysis of the economic and social subsets

The results of the analysis (Tables 3 and 4) showed that the maximum percentage of probability of changes in sediment conditions in the economic variables basin, which include the number of permissible livestock and the reliance of watershed residents on rangeland, were the most influential variables, in the moderate state, reliance of watershed residents on rangeland, with a 2.2% reduction in sediment production rate, was the superior option, after that takes priority by the absence of surplus livestock with a 1.2% reduction in sediment production rate. In the social variables, watershed residents' participation in the protection of water and soil resources, in the high state, reduced the sediment production rate by 8.1%, and the literacy of watershed residents, in the high state, also had the next most effective option with a 6.0% reduction in sediment production rate. The option reliance of watershed residents on rangeland, in the moderate state, reduced the river flow by 3.6%, and the absence of surplus livestock also reduced the river flow by 1.9%. Regarding the social parameters, watershed residents' participation in the protection of water and soil resources, in the high state, reduced the river flow by 9.2%, and the literacy of watershed residents, in the high state, reduced the river flow by 9.0%.

Table 3. Sensitivity analysis of sediment rate to economic variables

Probability distribution	Sedimentation rate			livestock overpopulation		income dependency ratio on rangeland		
	Low	Medium	High	Available	Non Available	Low	Medium	High
prior	42.3	30.5	27.2	72.4	27.6	16.7	26.7	56.7
posterior	100.0	00.0	00.0	71.2	28.8	17.3	28.9	53.8
posterior	00.0	100.0	00.0	73.0	27.0	16.3	25.4	58.2
back	00.0	00.0	100.0	73.5	26.5	16.1	24.5	59.4

Table 4. Sensitivity analysis of sediment rate to social variables

Probability distribution	Sedimentation rate			Literacy level of watershed residents			Participation of watershed people	
	Low	Medium	High	Low	Medium	High	Available	Non Available
prior	42.3	30.5	27.2	40.0	43.3	16.7	65.5	34.5
posterior	100.0	00.0	00.0	38.8	43.9	17.3	63.7	36.3
posterior	00.0	100.0	00.0	40.6	43.1	16.3	66.5	33.5
posterior	00.0	00.0	100.0	41.1	42.8	16.1	67.3	32.7

3.4. Sensitivity Analysis

The results of the sensitivity analysis of the model showed that the variable reliance of watershed residents on economic variables and the percentage of watershed residents' participation in the protection of water and soil resources in the Damghan Rud Basin, had the highest probability of influencing the sedimentation rate with maximum irregularity percentages of 172.0% and 0.66% respectively (Table 5).

Table 5. Sensitivity analysis of sedimentation rate to economic variables

Variable	Covariance	Entropy percent
Discharge	3.606E+0.009	31.700
Rangeland Condition	4.697E+0.008	4.130
Income	1.954E+0.007	0.172
Precipitation	9.626E+0.006	0.084
Erodibility	9.195E+0.006	0.080
Participation	7.531E+0.006	0.066
Permeability	7.225E+0.006	0.063
Livestock OP	3.435E+0.006	0.030
Literacy	2.431E+0.006	0.021

Social capital can be defined as a set of networks, norms, values, and understandings that facilitate cooperation within and between groups for mutual benefits (Woolcock & Narayan, 2001). Since social capital is a function of production and is considered a fundamental and influential component of income, economy, growth, and development, it can be used as a variable to improve the environment and social capital development (Renani & Deliri, 2010).

In the Damghan Rud Basin, there are 1,350 surplus livestock units. Two states, the presence and absence of surplus livestock, have been considered in the model. The absence of a surplus livestock option leads to a 3.7% increase in rangeland vegetation cover. Another economic variable examined in the basin is the reliance of watershed residents on rangelands, in the Damghan Rud Basin, 35% of the residents rely on agriculture and livestock farming for income, while 25% of the residents rely 100% on traditional animal husbandry and, as a result, rangelands. This study considers three states: low, moderate, and high. The highest percentage of change, with a 15.3% increase in vegetation cover, is related to the option of reliance of watershed residents on rangeland in the lowest state.

Increasing the literacy level of local communities enhances their capacity and ability to adopt the necessary technology and knowledge for better management of water resources, cultivation methods, agricultural production, and livestock. Additionally, increased production and, consequently, increased income as an important resource that empowers individuals to engage in criticism, debate, and greater participation (Glaser, 2001; Uphoff & Vachani, 2002; Narejo *et al.*, 2012). Literacy of watershed residents in the high state with a 6.7% change rate is one of the most effective management options for increasing vegetation cover in the Damghan Rud watershed. Another social variable in the Damghan Rud watershed is the participation rate of watershed residents in the protection of water and soil resources in the basin. The participation of stakeholders who have a complete understanding and sufficient knowledge of rural economic planning and land use is one of the significant benefits of knowledge production in this regard, and there is a close relationship between the justification, a complete understanding of stakeholders and shareholders, and the management of a basin, this mutual interaction is essential for achieving sustainable success (Philpott *et al.*, 2012). The participation rate of watershed residents in the protection of water and soil resources in the Damghan Rud watershed is divided into two categories: low and high. The high participation option ranks second among the influential variables with a 9.5% increase in vegetation cover.

4. Conclusion

In summary, through the analysis of the research results, the following conclusions can be drawn, although the management activity of restoring and rehabilitating rangeland vegetation cover has been one of the most effective options for reducing erosion and sediment production and has been the most suitable and effective management option for managing the water resources of the Damghan Rud watershed and improving water and soil conservation in the region, it alone has not had a significant impact on improving and reducing the sedimentation production rate in the region. Therefore, it was not possible to introduce a single activity to solve the problem of managing the water resources of the Damghan Rud watershed. However, Bayesian networks are capable of representing the consequences of management options, and with the help of this approach, users will be able to reach conclusions and final judgments by better understanding the processes of the watershed system and balancing the different results obtained from the implementation of management scenarios.

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