Environment, Development and Sustainability (2005) 7: 453–464
DOI 10.1007/s10668-004-3309-7

PHYSICAL AND ECONOMIC SUSTAINABILITY OF WATER: NEW APPROACH USING THE CASE OF THE BIG LOST RIVER, IDAHO

AHMED SAID[1,*], DAVID K. STEVENS[2] and GERALD SEHLKE[3]
[1]*Department of Civil and Environmental Engineering, University of South Florida, Tampa, FL, USA;*
[2] *Civil and Environmental Engineering Department, Utah State University, Logan, UT, USA;*
[3] *Integrated Environmental Analysis Department, Idaho National Engineering and Environmental Laboratory, Idaho Falls, Idaho, USA*
*(*author for correspondence, e-mail: asaid@eng.usf.edu; fax: 1-813-974-5838; tel.: 1-813-974-5902)*

(Received 11 February 2004; accepted 14 September 2004)

Abstract. A new approach for evaluating water sustainability is introduced by comparing physical and economic sustainability. To achieve physical sustainability, water should be available in sufficient quantity and of good quality and used efficiently. The economic sustainability can be achieved by balancing between costs and values of water. The objectives of this study were to estimate the physical and economic sustainability of surface water in the Big Lost River, south–central Idaho. The study used a Bayesian network by building a graphical diagram of nodes representing all significant variables related with the sustainability, such as water demand, water quality, and the different costs and values of water. The study showed that the likelihood of the physical sustainability is less than that of the economic sustainability, which is attributed to the scarcity of water in the Big Lost River.

Key words: Bayesian network, water cost, water quality, water sustainability, water use, water value

1. Introduction

Sustainable activities meet the needs of the present generation without endangering the ability of future generations to meet their needs. Sustainability stipulates that future generations should be left at least no worse off than current generations. Sustainability has environmental or physical, and economic requirements (Wilson and Tyrchniewicz, 1995). From a water resources management perspective, environmental sustainability stipulates that physical resources should be maintained while economic sustainability stipulates that cost and value of water must be balanced. Ideal economic sustainability requires that the value and the cost should balance each other; full cost must equal the sustainable value in use.

The gap between cost and value clearly indicates the lack of economically sustainable use (Rogers et al., 1997). Most irrigation pricing is area-based,

Readers should send their comments on this paper to: BhaskarNath@aol.com within 3 months of publication of this issue.

leading to low water use efficiency especially in surface irrigation systems. In this case, the value-in-use is much lower than the full economic cost, which includes the opportunity costs of water used in irrigation, implying that there may be concerns with economic sustainability.

To achieve water sustainability, water should be used efficiently and there should not be gaps between the values and costs of water. In addition, water quality is very important as it may limit the beneficial uses of water. In order to get the stakeholder involved, water quality evaluation should take into account its economic impact.

In this study, physical sustainability of water will be handled without regard to the cost or other economic criteria of water. On the other hand, economic sustainability will be evaluated according to the criteria stated by Rogers et al. (1997). Nevertheless, physical and economic sustainability can be expressed as strong or weak or even non-existant. A new approach is developed by comparing these two measures. If the resources are physically and economically sustainable, the result is a strong sustainability. On the other hand, if the physical sustainability is strong while the resources are economically unsustainable, the result is a weak sustainability that can be strengthened by adjusting the costs and values of the resources. However, if both are low there is no sustainability. Scarcity exists if there is a low physical sustainability while the resources are economically sustainable.

In terms of surface water resources, sustainability stipulates that the use of water resources should not exceed the renewable annual supply. The total amount of water entering, leaving and being stored in the system must be conserved, in other words to consume the flow and not the capital resource.

The objective of this study was to estimate the physical and economic sustainability of surface water in the Big Lost River Watershed, in south–central Idaho and evaluate the whole situation by comparing physical sustainability with the economic sustainability.

2. Big Lost River

The Big Lost River Watershed is about 3885 km^2 and is the largest tributary basin to the Snake River plain (Bennett, 1990) (Figure 1). Mackay Dam, the only artificial storage in the basin, was completed in 1923, and it is the major artificial water control on the Big Lost River. Water resources in the Big Lost River will be described in the following sections.

2.1. Precipitation

The mean altitude of the valley is about 1830 m and average precipitation is about 300 mm/yr. Figure 2 shows the GIS data that present precipita-

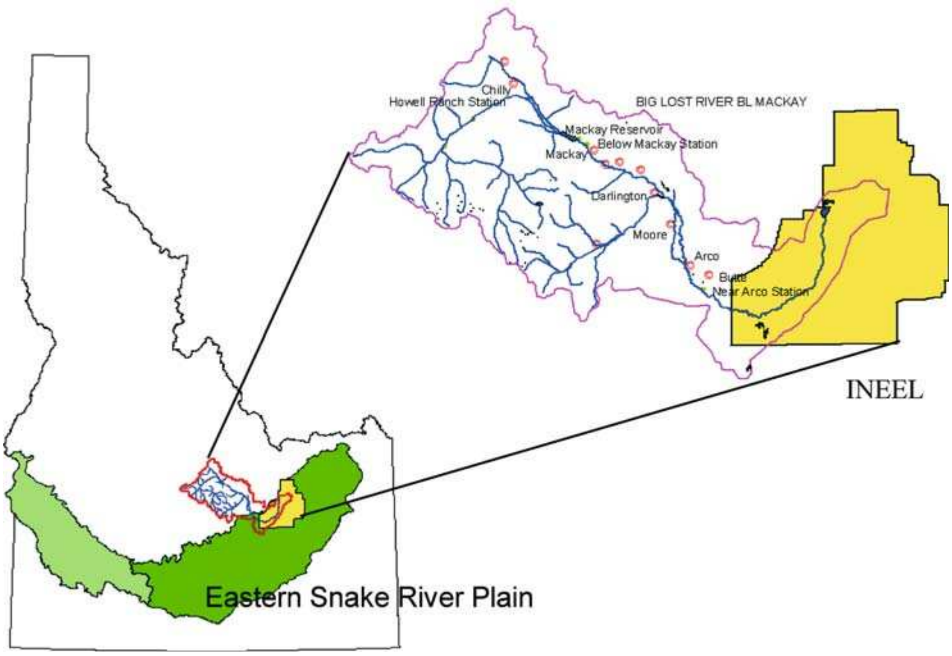
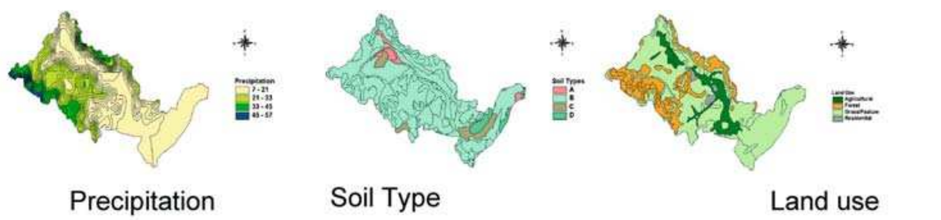


Figure 1. Big Lost River location.



High	0.54
Low	0.46

A: Not erodible	0.05
B: Semi-erodible	0.81
C: Erodible	0.05
D: Very erodible	0.09

Agriculture	0.16
Forest	0.31
Grass/Pasture	0.49
Residential	0.04

Figure 2. Precipitation, soil types, and land use for the Big Lost River Watershed.

tion, soil type, and land use. Precipitation is fairly evenly distributed throughout the year (Mundorff et al., 1964). The average annual flow of the Big Lost River at the gaging station below Mackay Dam is 0.26 km^3 from a drainage area of 2710 m^2. An additional 0.08 km^3 comes to the river as the average annual flow from tributaries between Mackay and

Moore cities, making a total average annual supply of about 0.36 km^3. The probability of getting high precipitation is 0.54, while that of getting low is 0.46. A summary of water yield upstream from selected points is shown in Table I (Crosthwaite et al., 1970).

If there were no seepage loss and the consumption of water on the 10,117 ha of irrigated lands in this area is taken as 0.05 km^3 annually, the average annual flow of the river at Moore should be about 0.28 km^3. However, the average annual flow at Moore is only 0.15 km^3. Hence, it is inferred that approximately 0.12 km^3 annually moved to ground water past Moore (Mundorff et al., 1964).

2.2. Water Quality

According to the USDA-SCS, sediment from eroding croplands is the largest non-point source pollutant in Idaho's surface water. Consequently, erosion has been chosen in this study to represent water quality in the Big Lost River Watershed. Erosion is affected by rainfall and snowmelt, how prone soil is to erosion, land slope, and soil cover. Land use can also affect water quality as shown in Table II and III shows the areas and water requirements for different crops. The land has a slope of 0.54 steep and 0.46 flat.

TABLE I. Water budget in the Big Lost River watershed.

Sub-watershed	Water Yield (m^3/s)	Surface Water (m^3/s)	Ground Water (m^3/s)	Evapotranspiration (m^3/s)
Above Howell Ranch	9.8	8.8	1	–
Above Mackay Narrows	12.8	9.2	2.1	1.4
Above Arco	18.4	2.1	12	4.2

TABLE II. Total nitrogen and total phosphorus for different land use.

Weighted average (kg/ha/year)	Agricultural	Grass	Residential	Forest
Total nitrogen	4.53	0.432	2.62	0.288
Total phosphorus	0.749	0.006	0.821	0.004

TABLE III. Number of hectares cultivated by different crops in the Big Lost River watershed.

County	Barley	Alfalfa	Grass	Potato	Oats	Wheat
Butte	15461	24420	6314	1870	323	9255
Custer	1728	6258	3665	146	667	10
Total	17189	30678	9979	2016	990	9265
Water Requirements (m^3/hectare)	5100	7000	6500	5000	5500	5250

2.3. Surface Water Values

For surface water, the values are calculated as net value from direct use, indirect use, return flow, and non-use values. The value of water in irrigated agriculture can be derived as the Net Value of Output (NVO) attributed to the use of water for irrigating crops (Rogers et al., 1997). As a result of the interviews with the Big Lost River farmers, the average value of output with irrigation in the Big Lost Watershed is estimated at \$2500/hectare per year, while the gross value of output without irrigation is estimated at only \$1250/hectare. Thus, irrigation increases the gross value of output by about \$500/acre. However, the average cost of inputs, including the cost of irrigation, fertilizers, and labor, is \$1500/hectare. This gives \$500/hectare as the net value of crop output, providing a net of 7 cents as the value of output per cubic meter of water as shown in Table IV. This is close to the study performed by Moore and Willey (1991) where they found that the value of water in irrigation of food grain is about 5 and 30 cents/m^3 for irrigation of vegetables. The value for environmental purposes is 20 cents/m^3. The estimates of irrigation requirements for the Big Lost Watershed are: 7000 m^3/hectare for alfalfa and 5100 m^3/hectare for barley as shown earlier in Table III.

Return flow is the flow that is reused by irrigation as surface or ground water flow. The average water delivered in the irrigation ditches is about 0.13 km^3. From this amount, 0.07 km^3 are being lost through seepage from different irrigation ditches and Big Lost River channel. A part of the return flows in the Big Lost Watershed go to a sink of ground water while the rest recharges the ground water. On average, net benefits from return flows are 50% of the net value of output in agriculture, based on the volume of the recharge. This gives an estimate of 3.5 cents/m^3.

While irrigation provides water for agriculture, it can also be used for indirect uses as in the case of livestock. There are no empirical studies that quantify the additional value of these benefits in the Big Lost Watershed. In the shortage of such data for the Big Lost Watershed, an estimate of 1 cent/m^3 is used for additional benefits to the value of water diverted for irrigation.

The estimated total economic value of water diverted to irrigated agriculture is estimated at 11.5 cents/m^3, based on the sum of the three mentioned components.

TABLE IV. The net value of a cubic meter of water in the Big Lost River watershed.

	Value of output with irrigation	Value of output without irrigation	Residual values/costs
Gross Value of Output (\$/hectare/yr)	2500	1250	1000
Cost of cultivation (\$/hectare/yr)	1500	750	750
Net value of output (\$/hectare/yr)	1000	500	500
Estimated water input (m^3/hectare/yr)	7000	0	7000
Net value of output (cents/m^3)			7

2.4. Surface Water Costs

There are three different costs for water in the Big Lost River Watershed: user cost, opportunity cost, and externalities cost. The externalities occur when one user influences the quantity and quality of water available to another user. Ignoring important environmental externalities introduces a potential for resource misallocation and can accentuate ecosystem sustainability and distributional or social equity problems (Matthews et al., 2001). However, due to shortage of data and previous studies, using local expert judgments, this cost is estimated at 1 cents/m^3.

User cost is the cost for operating and maintenance of Mackay Dam and irrigation ditches and marginal cost. The marginal cost is the cost of producing one more unit of water. In the Big Lost River, the marginal cost is due to water scarcity and senior water rights in the basin. The Water Master charges 1590 cents/m^3/year (45 cents/cfs/year). These charges include operation and maintenance. Using the appropriate conversion, user cost is estimated to be 5 cents/m^3.

The opportunity cost depends on costs of transferring the water among potential users. Location and the costs of transfer should be taken into account. In the Big Lost River Watershed, irrigation is the predominant use of water; therefore, the opportunity cost would be low. The opportunity cost can be estimated on the basis of the weighted average volume of the value-in-use in recreation. Assuming that the irrigation water could be transferred to recreation (in-stream-use), the opportunity cost for about 65% of the water used in irrigation would be zero. By estimates of value-in-use in recreation, the opportunity cost of irrigation is estimated as 4.5 cents/m^3. It is assumed that 50,000 m^3 of water could be transferred with little costs since the main channel of the Big Lost River can be used for that after maintaining some segments to reduce infiltration.

3. Method

The basis of the Bayesian approach is to provide a mathematical rule explaining how existing beliefs should be changed in the light of new evidence. In other words, it allows combining new data with existing knowledge or experience. In this study, a Bayesian network was implemented because it has many advantages as shown below. Bayesian networks use inductive reasoning to determine the causes based on observed effects. They became interactive algorithms for decision making to find optimal decisions, control systems, or plans. These networks use Bayes' theorem that can be described as follows (Kwon, 1978): If we have A_j as possible causes of event B and have prior probabilities $P(A_j)$ (the probabilities assigned prior to performing the process and observing outcome B), and we know $P(\mathrm{B}|A_j)$ but our primary interest is to revise them or get $P(A_j|\mathrm{B})$, then:

$$P(A_j|B) = \frac{p(A_j) \times p(B|A_j)}{\sum_{i=1}^{n} p(A_i) \times p(B|A_i)} \tag{1}$$

The prior probabilities or belief about the likelihood of A $P(A_j)$ are called also the absolute probabilities and they can take any probability form, including subjective assessment concerning the existing state of nature. Posterior or revised probabilities $P(A_j|\mathrm{B})$ are post-experiment conditional probabilities assigned to the possible causes A given that B has occurred. Both the prior and the posterior probabilities are independent for each parameter group; therefore, we can compute them separately.

A Bayesian network consists of the set of variables of interest represented by nodes, as well as a set of probabilistic relationships among the variables represented by arcs. These relationships can be quantified using subjective assessment, such as combined knowledge engineering and statistical induction, historical data, models, and expert judgment.

Bayesian networks use probability to quantify uncertainty about the unknown parameters and they also allow easy updating of prediction when observations of model variables are made. The resulting estimates can be updated without rebuilding the whole representation. If we start with the initial value for each node, these initial parameters are used as prior information. The posterior probability is a function of the prior probability and is calculated as the ration of the joint probability [the nominator of Equation 1) to the marginal probability (the denominator of equation (1)]. This allows updating a network using new data. Bayesian networks allow to find $P(A = a|\mathrm{B} = b)$, where A_j is the query variable, and B the set of evidence variables. This capability is important when applied to a natural system in which additional monitoring is likely to occur concurrent with the modeling effort (Borsuk and Reckhow, 2000).

Figure 3 shows an example of a Bayesian network that has three nodes representing variables and two links representing the relationships between them. In this example, water use can be either efficient or inefficient and population can be either high or low. Therefore, water demand is affected by these variables and would be high or low according to the status of the affecting variables. In addition to the previous studies that used Bayesian networks to address environmental problems that were mentioned in the first example of stakeholder participation, the following are studies centered on the costs and values of water.

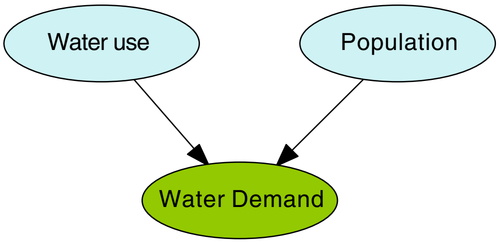


Figure 3. A Bayesian network representing the domain of the water demand.

3.1. Physical Sustainability

Physical sustainability can be handled in a more complicated way but same concept using a Bayesian network by building a graphical diagram of nodes representing all significant variables related with the sustainability, such as water demand, water quality, and the different costs and values of water. Using the information from Figure 2, which was shown earlier, a Bayesian network, can be drawn as shown in Figure 4.

3.2. Economic Sustainability

The economic sustainability is mainly the relation of costs and values of water (Figure 5). The values should balance the costs or an economic sustainability issue should be addressed. Using the information mentioned above about the study area and some expert knowledge from the Big Lost River Watershed stakeholders, the conditional probability tables (CPTs) can be populated. Table 5 shows the CPTs for values and costs of surface water.

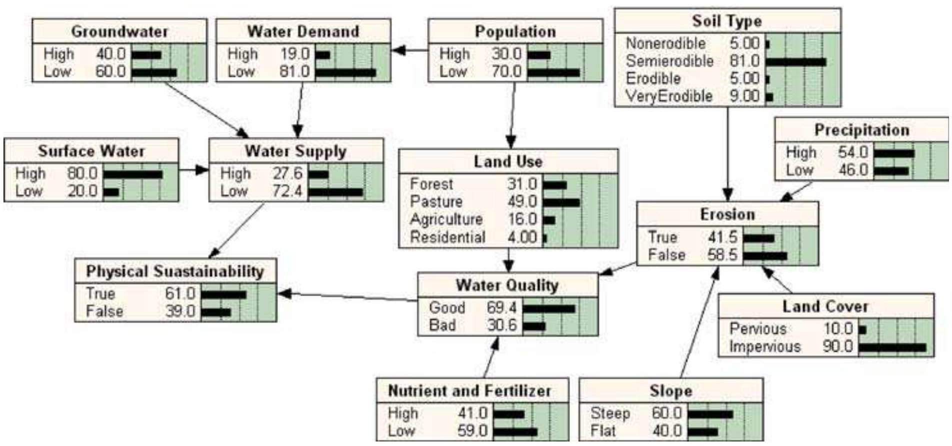


Figure 4. Physical sustainability representation.

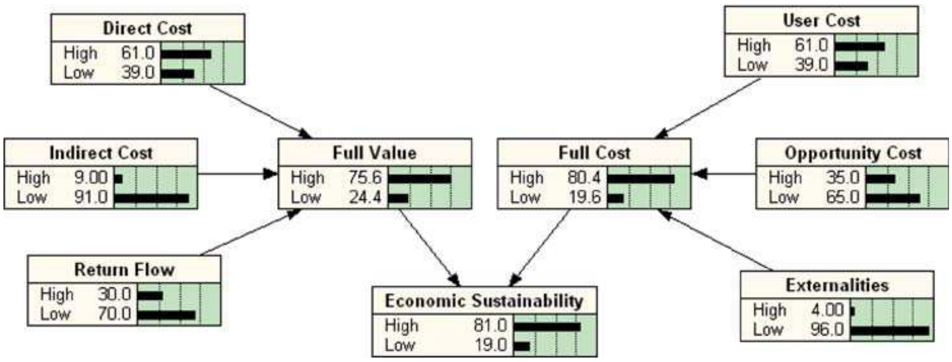


Figure 5. Economic sustainability representation.

TABLE V. Values and costs of water in cents/m^3.

Water value		Water cost	
Direct use	0.61	Operational & Maintenance Cost	0.11
Indirect use	0.09	Marginal Cost	0.42
Return flow	0.30	Opportunity Cost	0.47

4. Results

As for the Bayesian network, nodes, arcs, and CPTs are constructed and considering the common fact that observational data for parameterization of the models in general are almost always woefully inadequate for the task, the gap is filled with judgmental parameter selection (Reckhow and Chapra, 1999). The software model HUGIN Runtime (HUGIN Expert Systems, 2000) was used to generate the posterior predictive distributions, which represents the current estimate of the value of the response variable, taking into account both the uncertainty about the parameters and the uncertainty that remains when the parameters are known (Lee, 1989). The complete probability tables and the results are shown in Figures 4 and 5. The water quality has occurrence probability of 75% good and water demand is 67% high and water supply satisfies 54% of the demand.

Water resources in the Big Lost River are 61% physically sustainable, which indicates that water resources are unreliable resources for watershed development. The economic sustainability is 82%, which means it is higher than the physical sustainability and means scarcity of the resources. Physical sustainability can be improved by augmentation that include reducing erosion and conducting ground water remediation, implementing TMDLs, changing land cover, adapting water conservation schemes, integrating surface and ground water management, and reducing flow alteration.

Some important observations are possible from these results. First, there is some room to improve the physical sustainability and have the same economic advantage. In other words, if physical sustainability is increased from 61 to 82%, this will make the farmers and the investors in the water sector in general enjoy the lower cost of the water. Above that level, any increase of physical sustainability will be accompanied with an increase in the water cost.

Another remarkable point is that an increase in the population in the study area, which is already low compared to the past, will not be beneficial unless the physical sustainability is increased. However, if the economic sustainability is higher than the physical sustainability, the resources are economically sustainable and the cost is relatively small relative to the value of water. Therefore, the problem is physical due to scarcity of the resources. If the economic sustainability is lower than the physical sustainability, the problem is economic sustainability, which can be solved by adjusting the cost or value of water.

5. Discussion

There are two requirements to achieve full sustainability: economic and physical. Gray (1991) stated that two general views prevail concerning sustainability in agriculture: consumers' view and producers' view. Consumers view sustainability in terms of its capacity to provide an abundance of quality food. Producers view sustainability as an income generating activity with economic and social value. The producers' concern is with maintaining a net return from the sale of agricultural products. In economic terms, consumers assess sustainability in terms of maintaining a level of consumer surplus in the consumption of food over time. On the other hand, in economic terms, producers regard sustainability as the maintenance of a producer surplus or economic rent (a return to factors used in production) over time. Gray (1991) argues that sustainability may be measured in terms of the flow of income from agricultural production. He also notes that society regards sustainability in terms of all the costs and benefits of production. Particular issues that are raised when measuring sustainability are: the discount rate, private *versus* social costs (negative externalities), nonmarket benefits (positive externalities), economic flexibility, and income/risk preferences. In addition to maintaining a producer surplus, there is the need to sustain farm families.

Physical sustainability of water deals with its uses. Zentner (1981) illustrated it with reference to the soil resource. He noted that since the soil resource used in agriculture is largely privately owned, producers could be expected to organize their activities in a manner that maximizes their private benefits. On the other hand, society wants to maximize the social benefits. There is a common interest in conserving the soil since failure to do so increases the marginal costs of production and reduces the future streams of private and social benefits.

Rogers et al. (1997) stated that the gap between the value and costs implies a problem with sustainability. This statement can be applied for economic sustainability. Economic sustainability concerns matching costs and values of water to be used by different sectors. Briscoe (1996) noted that economic development and environmental sustainability in many countries depend on considering water as a scarce resource, and using economic principles for its management. He indicated that financial sustainability of irrigation systems is important for operation and maintenance reasons.

There are some other definitions for strong and weak sustainability. For example, Tietenberg (2000) relates them to preservation of capital stock. Strong sustainability exists when natural resources are considered as the only capital stock. On the other hand, weak sustainability exists when physical capital is counted as a part of capital stock that should not decline. Strong sustainability, therefore, includes environmental or physical sustainability. We understand from the last definition that sustainability can be strong or can be weak and, as these are two limits, sustainability can take intermediate values between these two limits. However, unlike the last definition, the comparison of physical and economic sustainability determines the sustainability situation. The new approach determines the strong sustainability of water as the combination between strong physical and strong economic sustainability. In fact, this is not the case in the Big Lost River where the physical sustainability is weak.

6. Conclusions

The study used a Bayesian network to evaluate two measures of sustainability in the Big Lost River in south–central Idaho. Bayesian networks can be used to support watershed management, such as to evaluate sustainability of water use in any watershed especially those that have sparse water quality data by incorporating available data, results of model simulations and by incorporating the knowledge of experts. The basic advantage of this tool is that the resulting estimation can be updated in case of changes or new observations and data received.

The results showed that the water resources in the Big Lost River are 61% sustainable, which means that water resources are not reliable sources for watershed development. There are also some opportunities to enhance surface water physical sustainability through increasing management capacity, such as increasing water supply using water conservation schemes, improving water quality by implementing TMDLs, changing land cover, and reducing erosion. Evaluating the local economic effects on sustainability showed that water resources in the Big Lost River are economically sustainable. However, it can be a little higher by increasing the values through cultivating higher value crops. However, the physical sustainability is lower than the economic sustainability and according to the new approach; this is attributed to the scarcity of water.

References

Bennett, C.M: 1990, *Stream Flow Losses and Ground Water Level Changes Along the Big Lost River at the Idaho National Engineering Laboratory, Idaho*, *Water-Resour. Invest. Rep. 90-4067*, U.S. Geol. Surv., Boise, Idaho, 47 pp.

Briscoe, J: 1996, *Water as an Economic Good: The Idea and What it Means in Practice*. Paper presented at World Congress of the International Commission on Irrigation and Drainage, Cairo.

Committee on Valuing Ground Water: 1997, *Valuing Ground Water: Economic Concepts and Approaches*, National Academy Press, National Res. Council, 204 pp.

Crosthwaite, E.G., Thomas, C.A. and Dyer, K.L.: 1970, *Water Resources in the Big Lost River Basin, South-Central Idaho*. Open File Rep., U.S. Geol. Surv., Boise, Idaho, 109 pp.

Gray, R.: 1991, Economic Measures of Sustainability,' *Canadian Journal of Agricultural Economics*, **39**(4), 627–635.

HUGIN Expert Systems, HUGIN software, 2000, available at: http://www.hugin.dk/.

Kwon, I.: 1978, *Statistical Decision Theory with Business and Economic Applications: A Bayesian approach, Modern Decision Analysis Series*, Mason/Charter Publishing, New York, 278 pp.

Lee, P.M.: 1989, *Bayesian Statistics: An Introduction*, Oxford University Press, New York.

Matthews, O.P., Brookshire, D.B. and Campana, M.E.: 2001, *The Economic Value of Water: Results of Workshop in Caracas, Venezuela*, Publ. No. WR–4, Water Resour. Program, Univ. of New Mexico, Albuquerque, N.M. 26 pp.

Moore, D., and Willey, Z.: 1991, 'Water in the American west: institutional evolution and environmental restoration in the 21st Century. Univ. of Colo'., *Law Review* **62**(4), 775–825.

Mundorff, M.J., Crosthwaite, E.G., and Kilburn, C.: 1964, *Ground Water for Irrigation in the Snake River Basin in Idaho*, Water-Supply Pap. 1654, U.S. Geol. Surv., Washington D.C., 224 pp.

Reckhow, K.H., and Chapra, S.C.: 1999, 'Modeling excessive nutrient loading in the environment', *Environmental Pollution* 100, 197–207.

Rogers, P., Bhatia, R., and Huber, A.: 1997, Water as a social and economic good: how to put the principle into practice, available at: http://members.tripod.com/~jzjz/ watroger.html.

Tietenberg, T.: 2000, *Environmental and Resource Economics*, 5th edn., Addison-Wesley, New York City, New York.

Wilson, A., and Tyrchniewicz, A.: 1995, *Agriculture and Sustainable Development: Policy Analysis on the Great Plains*, International Institute for Sustainable Development (IISD), Winnipeg, Manitoba, Can., 118 pp.

Zentner, R.: 1981, *Economics of Soil Conservation in Western Canada*, Res. Branch, Agric. Can. Res. Station, Swift Current, Saskatchewan, Sask., Can.