Metrics for Sustainable Water Use

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Abstract

In order to advance water resources research and practice that addresses sustainability concerns, this paper identifies and explores the use of a few metrics for water use sustainability. Examples include the ratio of water withdrawal to total supply, the percentage of income spent on water and sanitation, the incidence of waterborne disease, and indices related to a managed system's ability to cope with extreme events. The spatial and temporal scales over which these metrics can be calculated using available data are assessed, and additional data requirements are identified. Some of the challenges faced in predicting future values of these sustainability metrics are also discussed, along with research needs to improve predictability and adaptability.

Introduction

There has been increasing concern over the fate of the earth's resources and the ability of humankind to live in a sustainable way with the interconnected web of existence. It is being realized that humans cannot use natural resources without impacting the ability of future generations to enjoy the same quality of life. Not only is this true for non-renewable resources such as fossil fuels, but also for renewable resources such as air and water. For instance, the atmosphere's ability to assimilate the increased production of carbon dioxide and other greenhouse gases has become a global concern.

Though freshwater resources are abundant on a global level, regional water scarcity and its effects on human health, ecological integrity, and socioeconomic development are becoming increasingly documented. The specter of climate change, combined with population growth and urbanization, threatens to exacerbate existing water crises, possibly leading to mass migration or international conflict over trans-boundary water resources. On a local level, the lack of improved sanitation facilities and protected water supplies adversely affects the health and livelihood of millions of people worldwide.

This paper defines and explores the use of a few simple metrics for water use sustainability. Following a general discussion of sustainability metrics, examples of metrics for sustainable water resources will be presented. The spatial and temporal scales over which these metrics can be calculated using available hydrologic and socioeconomic data will then be assessed, and additional data requirements will be identified. Some of the challenges faced in predicting future values of these sustainability metrics will also be outlined, along with research needs to improve predictability and adaptability.

Review of Sustainability Metrics

Sustainable water use requires the definition of sustainability metrics that encompass key issues and are quantifiable, because only what is measured can be managed and improved (Farrell and Hart, 1998). Figure 1 illustrates that the selection of any sustainability metrics should include consideration of issues related to economics, society, and the environment, or what has become known as the social and economic *triple bottom line* (e.g., Mihelcic et al., 2003). Examples of indicators related to each of these sets of issues are, respectively, the economic value of goods or services produced, wealth distribution across society, and the volumes of wastes generated and measures of their impacts on ecosystems.

Figure 1. Issues that should be included in selection of sustainability metrics (Mihelcic et al., 2003).

Sustainability indices that are relevant to water resources planning and management have been proposed by several groups. The State of the Lakes Ecosystem Conference (SOLEC) has defined more than 80 indicators of ecosystem health, human health, and society for the Great Lakes region (Bertram and Stadler-Salt, 2000). The Lake Superior Binational Forum determined a smaller set of socioeconomic indicators, divided into five categories: (1) reinvestment in natural capital (e.g., sustainable forestry and fisheries), (2) quality of human life, (3) resource consumption, (4) public awareness of the capacity of sustainability, and (5) economic vitality (Bradof et al., 2000). The International Institute for Sustainable Development (www.iisd.org) has devised indicators of progress towards sustainable development. Some of these indicators, such as measures of water quality, are similar to those developed for the Great Lakes. However, many of the sustainable development indicators are more applicable at the local level (rather than regional) and are specific to issues faced in the developing world. For instance, the indicators include measures of the transfer of knowledge and skills, as well as community solidarity and morale. Finally, the Delft Hydraulics Laboratory proposed a procedure to quantify contributions to sustainable development, based on the weighting of various criteria indices (Baan, 1994; ASCE, 1998). The five main criteria are as follows: (1) socio-economic aspects and impacts on growth; (2) use of natural resources and discharge of wastes; (3) enhancement and conservation of natural resources; (4) public health, safety, and well-being; (5) flexibility and sustainability of infrastructure works.

Inherently, sustainability indices cannot be static entities, but must provide a measure of both current and future conditions. Focusing on future conditions, Pezzey (1992) identified three objectives: efficiency, survivability, and sustainability. An “efficient” decision or alternative is one that maximizes the net present value of current and future benefits. Due to discounting of future benefits, this alternative may best satisfy current needs, but may not always assume a survivable or sustainable future. An alternative decision may be considered “survivable” if it provides no less than a minimum level of societal benefits in each future period. Finally, a “sustainable” alternative is one that meets the current needs and assures continuously increasing societal benefits in each future period. Thus, a sustainable alternative may not be efficient in the short term, but it will be survivable and will likely provide greater benefits in the future than an efficient alternative.

For a renewable resource such as water, one must consider natural variations and the duration of each period for which sustainability is evaluated. Furthermore, the critical duration of each period may change in the future. For instance, some recent climate studies suggest that longer durations of hydrologic extremes may occur in the future. To address issues related to temporal variability, Hashimoto et al. (1982) defined the criteria of reliability, resilience, and vulnerability to evaluate water resources systems. Reliability is defined as the probability that system benefits or performance will be within an acceptable range (e.g., water demands met sufficiently). Resilience is a measure of the speed of recovery from an unsatisfactory condition. Vulnerability is a measure of the extent or severity of the unsatisfactory condition. Simulation is typically used to produce time series of these indices, which may then be divided into time periods and summarized using statistical measures (ASCE, 1998).

Since predicting the distant future with a high degree of certainty is not possible, some have argued that it is important to maintain system reversibility and robustness so that future generations can adapt to changing conditions. One measure of irreversibility is entropy, or the reduction of future options (e.g., Ruth, 1993; Nachtnebel, 1996). A statistical measure of robustness is the variance in possible future benefits (e.g., Fiering, 1982). As Fiering and Matalas (1990) explained, it is important to design systems that are adaptable to a range of "wait and see" strategies, with some efficiency sacrificed for the sake of adaptability and robustness. Watkins and McKinney (1997, 1999) showed how to embody this notion in water resources optimization models in order to generate robust alternatives—alternatives that would perform well under a range of future conditions.

Evaluation of Water Use Metrics

In this section we propose and subsequently evaluate a few simple metrics for water use sustainability in light of other proposed sustainability metrics, such as those discussed above. We also consider the availability and accuracy of data needed to estimate current and future values of these metrics. The metrics are primarily selected for the purpose of discussion, and are in no way meant to be comprehensive or even representative of issues that should be considered in water resources planning. However, they are selected to show examples of metrics that consider social, economic, and environmental issues.

The simple metrics we propose are the following:

1. Relative water demand, or the ratio of water withdrawal or consumption to total water availability;
2. Percentage of income spent on water and sanitation services;
3. Incidence of waterborne disease; and
4. Robustness of a system (e.g., a reservoir) in providing a specified amount of water.

Social concerns are considered primarily in the third metric. Environmental concerns are considered, at least indirectly, in the first metric, as the greater percentage of water that is diverted from its natural course, the greater the environmental impact. Environmental concerns may also be addressed in the fourth metric if part of the water allocation is for environmental purposes (such as in-stream flow maintenance). Economic issues are addressed most directly by the second metric, although the third and fourth metrics may also address economic issues indirectly. For instance, health care costs or lost wages may be inferred from the third metric, which is also an indicator of economic development, and the economic benefits of water use may be directly related to the fourth metric.

The first metric—relative water demand—was considered by Vörösmarty et al. (2000) in assessing the adequacy of the world's freshwater resources under potential climate change and population growth scenarios. They defined relative water demand to be the ratio of water withdrawal or use to the surface and subsurface (shallow aquifer) runoff, accumulated as river discharge. They also defined a relative water stress threshold value of 0.4, meaning that regions with water demands greater than 40% of river discharge are experiencing severe water scarcity. While their study certainly provided an interesting and insightful perspective on global freshwater resources, there are several limitations that may hinder useful application on a local or regional scale. First, relative water demand was calculated on a mean annual basis only, which ignores the effects of hydrologic variability. Second, water withdrawals were defined at 30-minute grid resolution (longitude by latitude), linked to a digital river network and corresponding discharge estimates, and compared to country-level data. This degree of spatial resolution is probably adequate for many regional assessments, but may not be accurate at local scales, especially since water withdrawals were not specified by watershed. Third, by considering only river discharge in water availability estimates, they ignore the contribution of groundwater resources, which are significant throughout the world and especially in rural areas dependent on groundwater for irrigation.

Improving upon the analysis of Vörösmarty et al. (2000) for local and regional sustainability assessments is possible, though by no means trivial. Hydrologic variability could be incorporated by analysis of historical discharge data, which may be limited in a particular watershed. Linking water withdrawals or water use to individual watersheds, perhaps delineated using digital elevation data, would improve the accuracy at the local or regional level. Including estimates of groundwater availability (e.g., sustained groundwater yield) would also improve accuracy at the local and regional levels, although a complication is that surface watersheds and groundwater aquifers do not necessarily share geographical boundaries. The relative water stress threshold value may also be varied on a case by case basis, depending on the environmental impacts of water withdrawal and consumption. In any case, to evaluate the effect of hydrologic variability, an averaging period and one or more summary statistics for the relative water demand index would need to be defined.

Next, we consider the second metric—percentage of income spent on water and sanitation services—as a measure of water system sustainability. This metric may obviously be considered a measure of economic welfare, since the income not spent on water and sanitation may be invested or used to purchase other goods and services. However, particularly in the developing world, it may also be considered an indirect measure of social and environmental costs. For instance, numerous studies (e.g., Whittington et al., 1993) have shown that household income is a strong determinant of willingness to pay for water and sanitation services. However, underestimation of willingness to pay (say, for household taps) may result in water supply systems with limited numbers of public taps and relatively few house connections, which may allow private water vendors to generate substantial monopoly rents, thereby increasing household expenditures on water and contributing to an inequitable distribution of wealth (Lovei and Whittington, 1993). Furthermore, in the absence of public planning and oversight, these private vendors may acquire water at high environmental costs.

In industrialized countries, economic and census data are available to estimate the percentage of income spent by various sectors of society on water and sanitation. In developing countries, local surveys may need to acquire accurate information, especially since households may seek private sector alternatives (i.e., vendors) to meet their water needs despite the presence of a public water system. Whittington et al. (1993) and others have found that contingent valuation surveys can be done successfully in developing countries, and that reliable information can be obtained on household demand for different water and sanitation technologies.

Our third proposed metric—incidence of waterborne disease—is a direct measure of human health impacts and is likely to be strongly dependent on water and sanitation technologies, thus providing a measure of economic development as well. Globally, water- and excreta-related diseases are estimated to be responsible for the loss of 93 million disability-adjusted life years, which amounts to billions of dollars in lost wages each year (Mara, 1999). Close spatial relationships have been observed between poverty levels, access to clean water, and infant diarrhea (Dasgupta, 2003). The World Health Organization claims that more than half of Africa's economic shortfall can be explained by disease burden, demography, and geography (WHO, 2001). Clearly, good population health is critical in reducing poverty and providing for economic growth and development.

On a local level, it may be difficult to obtain accurate data on the incidence of waterborne disease, as well as to evaluate the health impacts of alternative water system designs. Health statistics readily available from the World Health Organization are typically aggregated by country and year, and may be based on surveys conducted at irregular time intervals. In some cases, enteric diseases may be reported, which include both waterborne diseases and food contamination. There are potential inaccuracies related to spatial aggregation of the data, and annual aggregation overlooks seasonal variations which may be important (Becker, 1981; Arar, 1998). Finally, although it is generally assumed that improvements in water quality will lead to a reduction in incidence of disease, studies have provided mixed evidence to support this assumption. Of 12 studies reviewed by Esrey and Habicht (1986), only 9 showed positive impacts from improved water quality. Several studies using E. coli bacteria as an indicator of water quality have found no statistical evidence of a link with health risks (Strauss, 2001; Cifuentes, 2002). McConnell et al. (2001) found no consistent change in gastrointestinal-related fecal specimens despite improvements in water quality.

Our final proposed sustainability index—robustness—is an example of an index related to a managed system's ability to cope with hydrologic variability. Here, we define a robust system as one that performs optimally, or nearly so, under a wide range of conditions. Typically, simulation based on historical hydrologic data and current or predicted water demands can be used to evaluate a system's robustness (e.g., Fiering, 1982; Hashimoto et al., 1982). However, this approach assumes that historical hydrology is representative of variability in future conditions, and also that water demand is predicted accurately. The validity of this assumption may be limited by relatively short data records and by uncertainty in future climate. Nonetheless, in addressing sustainability issues, it seems prudent to consider both past variability and expected future conditions. To this end, Curriero et al. (2001) analyzed the link between extreme precipitation and waterborne disease outbreaks in the United States, motivated by concern that climate change will lead to more extreme hydrologic events. Vörösmarty et al. (2000) used general circulation models to generate climate change scenarios used in the estimation of future relative water demand values.

One limitation of using simulation modeling alone to evaluate system robustness is that it may be difficult to model system adaptability, or the "wait and see" decisions that will affect system performance. For this purpose, a robust optimization model may be needed (Watkins and McKinney, 1997). If formulated properly, such a model can generate "here and now" decisions that will perform well under a range of conditions, as well as model the adaptability of the "wait and see" decisions in the future. Though optimization models typically seek efficient solutions, perhaps overlooking sustainable solutions, recent methods have been devised to accommodate sustainability considerations in optimization models for water resources planning (Cai et al., 2002).

Concluding Thoughts

As discussed in Mihelcic et al. (2003), developing sustainable solutions to engineering problems such as water resources management include at least three important steps. First, societal needs must be understood and translated into proposed engineering solutions. Second, the long-term consequences of these engineering solutions must be explained to society. Third, the next generation of scientists and engineers must be educated to acquire both the depth and breadth of skills necessary to develop and use integrative analysis methods to identify and design sustainable systems.

There are numerous research challenges and opportunities in the field of sustainable water resources planning and management. It is clear that water conservation and efficient water system operation alone are not sufficient to achieve sustainability, because even these efficient systems can exceed the sustainable yield of a region or lead to other socially unacceptable outcomes. Some key questions that must be answered are as follows:

- How much and what types of human activity can a region handle without resulting in undesirable impacts?
- What attributes of the human, industrial and the natural world does society wish to preserve for future generations?

- What are the expected effects of present and planned activities in water conservation, water management, and sustainability on the long-term attributes of a region?
- What incentives (e.g., water rate structures, water markets), policies, or education/information programs can private and public entities develop to drive or motivate the development of the industrial and human environments that achieve the desired goals?
- How can stakeholders evaluate numerous sustainability metrics, their uncertainties, and the tradeoffs between them?

A critical aspect of sustainable water management will be to understand the flow of information that supports and motivates decisions that ultimately control water use and the consequent system sustainability.

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