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Quantifying trends in system sustainability

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Abstract This paper focuses on the measurement of the relative sustainability of renewable water resource systems. Being able to quantify sustainability makes it possible to compare alternative plans and policies, and to include sustainability as one of the multiple objectives to be considered when making decisions regarding the design and operation of these systems. Commonly used measures of reliability, resilience and vulnerability, based on subjective judgements concerning what is acceptable or unacceptable with respect to multiple system performance indicators, are combined into an index and used as a measure of changes in relative system sustainability over time.

Quantification des tendances de la durabilité des systèmes

Résumé Le sujet de cet article est la définition et la quantification du potentiel de développement durable des ressources en eau renouvelables. Cette quantification permet la comparaison de différentes politiques et options de planification. La capacité d'un système à se développer durablement est un des multiples critères qui doivent être pris en compte lors des prises de décision concernant la planification et le fonctionnement d'un tel système. Un index combinant la fiabilité, la résilience et la vulnérabilité du sytème, estimées selon des critères subjectifs prenant en compte ce qui est ou n'est pas acceptable en fonction de multiples indicateurs de performance du système, peut être utilisé pour apprécier les variations du potentiel de durabilité d'un système au cours du temps.

INTRODUCTION

Ever since the concept of sustainability, as expressed in the Brundtland Commission's report *Our Common Future* (WCED, 1987), was introduced, professionals from many disciplines have been trying to define and measure it. This has turned out to be more difficult than expected. Nevertheless, this paper proposes an approach for doing that, i.e. for defining relative sustainability in a manner that can help address better some of the many issues and challenges that accompany the Commission's concept of sustainability. This approach should allow one to measure or quantify, at least relatively, the extent to which sustainability is being, or may be, achieved. Such measures are needed in order to evaluate development alternatives and monitor water resource systems, and indeed the economy, the environment and social systems to see if they are becoming increasingly sustainable.

This paper focuses on the relative sustainability of renewable water resource systems. This limited focus on water permits a redefinition of sustainability in a way that makes it easier to quantify sustainability and include it as one of the multiple objectives to be achieved, or at least considered, when making decisions regarding the design and operation of water resource systems. Commonly used measures of reliability, resilience and vulnerability, based on subjective judgements concerning

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what is acceptable or unacceptable with respect to multiple system performance indicators, can be used as measures of changes in relative sustainability over time associated with particular systems and their management.

SUSTAINABILITY—SOME ISSUES AND CHALLENGES

The word sustainability has assumed a variety of meanings. While it can imply different things to different people, it always includes a consideration of the future. The Brundtland Commission (WCED, 1987) was concerned about how actions today will affect, "...the ability of future generations to meet their needs." Their notion of sustainability commands this generation not to take actions aimed at meeting its current needs that would limit or constrain the ability of future generations to meet their needs. Because there are disagreements on just what this definition or statement suggests should be done (or indeed how one today can know what the needs of future generations will be), there are also disagreements on just how the sustainability of any system, including water resource systems, can or should be achieved.

Should one enhance the welfare of future generations by preserving or enhancing the current state of natural environmental resources and ecological systems? If so, over what space scales? What is to be done about non-renewable resources, e.g. the water that exists in many deep groundwater aquifers, which are not being replenished by nature? The concept of the preservation of non-renewable resources now and in the future would imply that those resources should never be consumed. If permanent preservation seems unreasonable, then how much of a non-renewable resource should be consumed, and when?

If sustainability applies only to human living conditions and standards, as some argue, then perhaps some of today's stock of natural resources should be consumed. The amount consumed today could be used to increase the current standard of living, improve technology, enhance knowledge, create a greater degree of social stability and harmony, and contribute to the general culture. All of this might provide future generations with an improved technology and knowledge base that would enable them to increase further their standard of living using even less natural, environmental and ecological resources. Of course, it is impossible to know whether this substitution of natural resources for other capital, intellectual and social resources will happen—or even if it does happen whether it would necessarily lead to higher levels of sustainable development, eventually. Professionals, together with the public, can only guess and act accordingly.

Thus the debate over the definition of sustainability is among those who differ over just what it is that should be sustained and just how to do it. Without question, determining who in this debate has the better vision of what should be sustained and how one can reach a path of effective and efficient sustainable development will continue to be a challenge. But this challenge need not delay the attempts in trying to achieve a more sustainable water resources infrastructure and its operation.

An explicit consideration of the needs or desires of future generations may require giving up some of what could be consumed and enjoyed in this generation. How should trade-offs among current immediate "needs" and those of future generations be made? A standard economic approach to making these intergenerational trade-offs involves the discounting of future benefits, costs and losses. This type of analysis requires converting all future benefits, costs and losses to equivalent present day values to account for inflation and the time-value of money. Simply put, most people are willing to pay more for something today than for the promise that the same will be given to them at some specified date in the future. Money available today can be invested and earn interest over time. As a consequence, investments increase in value over time. Their future values, when discounted to the present (using a specific discount (interest) rate) will be what they would appear to be worth today.

Since future economic benefits, costs and losses and future non-economic statistical or risk-based measures of performance, when discounted (at a rate greater than 0) to the present time, decrease in amount or significance, any impact in the future will be weighted less than the same impact occurring at the present time. Consider then the result of such a procedure if the supply of a supporting environmental resource is limiting, such as the quality of the soil of an irrigation area or the assimilative capacity of a water body. Should decisions today allow this resource to be diminished in the future just because that future loss, when discounted to today's values, is nil? Most would argue that the concept of discounting is valid. But they would generally agree that discounting should be applied with safeguards where the integrity of life-supporting resources such as fertile soils, potable water, clean air, biodiversity and other environmental and ecological systems are concerned.

Then how can any safeguards or constraints on the traditional benefit-cost analysis be applied, and by whom, to ensure that those who live and consume today will adequately consider the needs and desires of those who follow in the future? How can one possibly know what those future needs and desires will be? To what extent do people understand what impacts their actions today might even be having on people living fifty or a hundred years from now?

Resource economists have been saying over the past century why it is so difficult to manage and use the environmental resources today in a way that will benefit everyone today, let alone that it might be of benefit to those in the distant future. Any study of recent history also shows how difficult it has been for governments to modify either a free-market system or a centrally-planned and controlled economy (by means of taxes and subsidies or by laws and regulations) in attempts to ensure any sustainable use of common property environmental resources. But these difficulties should not be excuses for ignoring sustainability issues. Rather, those who are involved in natural resources management need to work to ensure that the public and those who make decisions are aware of the temporal as well as spatial sustainability impacts and trade-offs associated with those decisions.

When considering trade-offs of natural, capital and social resources that affect the welfare of humans and other living organisms over time, one must also address the question of spatial scale and resource mobility. As previously asked, should each square kilometre of land be sustainable? Should each watershed or country or province or state be sustainable? Might some large regions (e.g. the Aral Sea and its basin) be sacrificed in order to enhance the economic survival of a larger region or country?

Opportunities for resource transfers and trade-offs and for the achievement of sustainability are generally greater the larger the space scale. And yet, concern only with the sustainability of larger regions may overlook the unique attributes of particular local economies, environments, ecosystems and possible limits on ecosystem adaptation, resource substitution and human health.

Given these and no doubt many other questions and issues, it is evident why there has been so much difficulty achieving a consensus on just what is meant or implied by sustainability or sustainable development. Most will probably agree that sustainability involves an explicit focus on at least maintaining if not increasing the quality of life of all individuals over time. Sustainability also addresses the challenge of developing regional economies that can ensure a desired and equitable standard of living for all the inhabitants and their descendants. It is not sure how this will be done, or even if it can be done. It will, without question, require some truly interdisciplinary research over a considerable period of time to address and answer many of these questions and issues.

For water resource managers, this concept of sustainability is a challenge to develop and use better methods for considering explicitly the possible needs and expectations of future generations along with the present one. Better methods must be developed and used for identifying development paths that keep more options open for future populations to meet their, and their descendants', needs and expectations. Finally one must create better ways of identifying and quantifying the amounts and distribution of benefits and costs (however many ways they might be measured) when considering trade-offs in resource use and consumption among current and future generations as well as over different populations within a given generation.

The issue of intergenerational equity is central to the concept of sustainability. Intergenerational equity requires that each generation manage its resources in ways to ensure that future generations can meet their demands for goods and services, at economic and environmental costs consistent with maintaining or even increasing *per capita* welfare through time. However, how does one know that future generations will value environmental resources as at present? Conditions for sustainability will vary for specific regions, and these differences will increase as the area of the region decreases. Mobility of populations and resources also affect sustainability. It is important, then, to consider the spatial or regional dimensions of sustainability, and the institutional conditions and arrangements which determine the relationships among regions.

Irrespective of the definitions used, a number of questions remain:

- should resource use and population be controlled?
- are resource limits critical?
- can technology be improved fast enough to eliminate a possible crisis caused by resource degradation if not depletion?
- what is the appropriate spatial scale for examining these questions?
- resource substitution and spatial mobility of resources and people need to be considered. Does one permit the devastation of certain regions in favour of others?
- the same question as the last can be asked with respect to time scales.
- over what periods should one expect or permit decreases in overall welfare due to, for example, fluctuations in renewable resource supplies?
- just what is irreversible?

Clearly there is no general agreement on exactly how to answer these questions. But they are important when trying to define sustainability precisely (Pezzey, 1992). However defined, nevertheless, sustainability involves the notion of trade-offs over time. How to identify these trade-offs and their implications today is the essence of the debate taking place regarding sustainable development.

DEFINING WATER RESOURCE SYSTEM SUSTAINABILITY

Sustainable development can be defined in terms of resource use, including water resource use (UN, 1991). Under this definition an alternative development policy might be considered sustainable if positive net benefits derived from natural resources (including water supplies) can be maintained in the future. However, there are difficulties in measuring net benefit for some resource uses. For example, how does one evaluate the benefits of wetlands, fisheries, water quality for recreation, ecosystem rehabilitation and preservation, etc.?

Goodland *et al.* (1991) view sustainable development as a relationship between changing human economic systems and larger, but normally slower-changing, ecological systems. In this relationship human life can continue indefinitely and flourish, and the supporting ecosystem and environmental quality can be maintained and improved. Sustainable development, then, is one in which there is an improvement in the quality of life without necessarily causing an increase in the quantity of resources consumed. But the idea of sustainable growth, i.e. the ability to get quantitatively bigger, continually, is an impossibility. Sustainable development, i.e. to improve qualitatively and continually, on the other hand, may be possible.

Economists and ecologists differ somewhat in their definitions of sustainable development. Much of this debate revolves around the concept of social capital. Should one be focusing on the preservation or enhancement of natural resources or should one be looking at the entire mix of resources (the environment, human knowledge, manmade capital, etc.) that comprise what is called social capital. It also revolves around the general problem of understanding which elements of social capital future generations are likely to value the most.

Sustainable development has also been defined in terms of financial viability. To be financially sustainable, all costs associated with a water resources development policy should be recovered. The service provided by a water development project must be able to pay for the project. In fact, the revenues should exceed the costs, and thereby provide for the improvement and maintenance of the project. An indication of the financial sustainability of a project paid for by a development bank could be the ability of that project to continue to deliver service or welfare after the initial funding has been spent.

Falkenmark (1988) focuses on the role water plays in sustainable development. She identifies various conditions for sustainability. Soil permeability and water retention capacity have to be secured to allow rainfall to infiltrate and be used in the production of biomass on a large enough scale for self-sufficiency. Drinkable water has to be available. There has to be enough water to permit general hygiene. Fish and other aquatic biomass have to be preserved and remain edible.

It is clear that there is no clear nor commonly accepted definition of sustainability, even when focusing on the single topic of water. As professionals involved in water resources planning and management, is it possible to come to some agreement on how to define sustainability of water resource systems, and then how to measure the extent to which the systems are sustainable? Probably not, since even this much more narrow focus on water resource systems is still incredibly broad. But one can certainly become involved in a debate over how it might be best done. This paper offers a proposed method, based on measures of risk and uncertainty.

Before discussing such risk-based measures of sustainability it may be useful to try to define a little more precisely what sustainability means with respect to water resource systems—a definition that encompasses all the concepts just discussed and that still focuses on the central point of the Brundtland Commission (WCED, 1987) definition—a concern for the future. First of all the word "needs" in the Brundtland Commission's definition is bothersome. Even if one could define present water resource "needs", let alone those of future generations, one may not be able to meet them, at least at reasonable or acceptable economic and social costs. Hence, the following proposed definition:

Sustainable water resource systems are those designed and managed to contribute fully to the objectives of society, now and in the future, while maintaining their ecological, environmental and hydrological integrity.

Is it to be wished that decisions and actions in this generation be viewed favourably by future generations? Will future generations find fault with actions decided in this generation that may affect what they can do and enjoy in their generation? If one placed all current preferences on future generations, one might define as sustainable those actions that minimize the *regret* of future generations. Clearly there are current interests and desires too, and indeed there may be trade-offs between those interests and desires *vs* what is thought that future generations might wish to be done now for them. These issues and trade-offs must be debated. Decisions will be made at the political level. There is no scientific theory to help identify which trade-offs, if any, are optimum.

Sustainability is more of a social goal than a scientific concept. It implies an ethic. Public value judgements must be made about which demands and wants should be satisfied today and what changes should be made to ensure a legacy for the future. Different individuals have different points of view, and it is the combined wisdom of everyone's expressed opinions that will shape what society may consider sustainable.

MEASURING SUSTAINABILITY OF WATER RESOURCE SYSTEMS

This section focuses on the quantification of sustainability. While the focus is on quantification, mathematical or technical languages alone are not sufficient to measure sustainability fully. Sustainability involves other aspects that deserve intensive discussion, and it requires a willingness to go beyond the scope of what may be quantifiable or measurable. But unless one can measure or describe in precise terms what is to be achieved, it becomes rather difficult (if not impossible) to determine how effectively one is doing what is wished, even in comparing alternative plans and policies with respect to their relative sustainability.

Efficiency, survivability and sustainability

To begin a discussion concerning how one might measure and include sustainability in planning models, it is perhaps useful first to distinguish among several planning objectives that focus on future conditions. These objectives are called efficiency, survivability and sustainability (after Pezzey, 1992).

To compare these three objectives, assume there is some way one can convert the impacts of whatever decisions are made into a common metric (unit of measure) called welfare. Each possible decision that could be made today, denoted by a different value of the index k, will result in a time series of net welfare values, $W(k, y)$, for each period y from now on into the future. Assume there is a minimum level of welfare needed for survival, $W_{\min}$.

A decision k is efficient if it maximizes the present value of current and all future net welfare values. Using a discount rate of r per period, an *efficiency* objective involves a search for the alternative k that will maximize:

$$\sum_y W(k, y)/(1 + r)^y \qquad (1)$$

Clearly as the discount rate r increases, the welfare values, $W(k, y)$, obtained now will contribute more to the present value of total welfare than will the same welfare values obtained sometime in the distant future. In other words, as the discount or interest rate r increases, what happens in the future becomes less and less important to those living today. This objective, while best satisfying present or current demands, may not always assure a survivable or sustainable future.

Efficiency involves the notion of discounting. There is a time value of assets. Those who need and could benefit from the use of a given resource today are likely to be willing to pay more for it today than for the promise of having it some time in the future. Yet high discount or interest rates tend to discourage the long term management of natural resources and the protection of long term environmental assets. Low discount rates, however, may favour investment in projects which are less likely to survive economically, and which are less likely to invest in environmental protection and the technology needed for efficient resource use and recycling. Thus, the relationship between interest rates, resource conservation and sustainable development is ambiguous (Norgaard & Howarth, 1991).

An alternative decision k can be considered *survivable* if in each period y (on into the future) the net welfare, $W(k, y)$, is no less than the minimum required for survival, $W_{\min}$. Hence if:

$$W(k, y) \geq W_{\min} \qquad (2)$$

then alternative k is survivable for all periods y.

A survivable alternative, and there may be many, is not necessarily efficient (in the normal sense) nor even sustainable.

Next, consider an alternative development path that is sustainable. Here an alternative is considered as sustainable if it assures that the average (over some time period that accounts for the variations in natural water supplies—e.g. floods and droughts) welfare of future generations is no less than the corresponding average welfare available to previous generations. Welfare could involve or include opportunities for resource development and use. A *sustainable* alternative k assures that there are no long term decreases in the level of welfare of future generations. In other words, if:

$$W(k, y+1) \geq W(k, y) \tag{3}$$

for all periods y, the alternative k is sustainable.

Equivalently, a sustainable alternative k is one that assures a non-negative change in welfare:

$$\mathrm{d}W(k, y)/\mathrm{d}y \geq 0 \tag{4}$$

in each period y. There may be many development paths that meet these sustainability conditions.

The duration of each period y must be such that natural variations in a resource, like water, are averaged out over the period. Results of recent climate change studies suggest these periods may have to be longer than what past historical precipitation and streamflow records would suggest due to the increased likelihood of more frequent and longer periods of extremes.

Any constraints on resource use for sustainability reasons must also be judged based on their impacts on economic efficiency and externality conditions (Toman & Crosson, 1991). Before setting them, resource managers must understand how sustainability constraints could affect development paths and policies, especially in regions where substitution among multiple resources is possible but affected by uncertainty and endogenous technical change.

Figure 1 illustrates various development paths of net welfare that represent examples of efficient, survivable and/or sustainable development. These development paths are only examples. While not illustrated, it might be possible in some situations

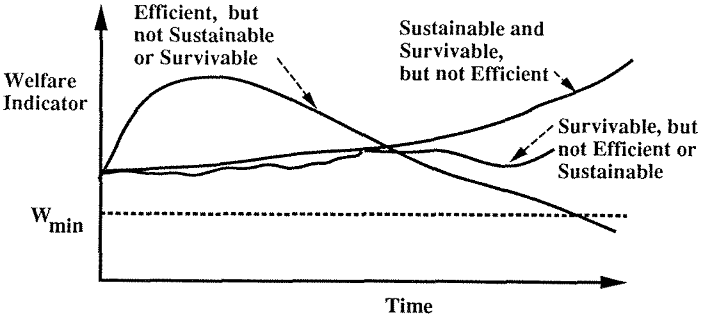


Fig. 1 Plots of social welfare (or other quality-of-life indicator) resulting from three alternative development scenarios over time.

to identify a development path that is efficient, survivable and sustainable at the same time. In most cases, however, some trade-offs are required among these three development objectives.

Weighted criteria indices

The Delft Hydraulics Laboratory in The Netherlands has proposed a procedure that can be used to measure or quantify the extent to which projects may contribute to sustainable development (Baan, 1994). This procedure consists of a check list, the responses to which are very subjective. Five main criteria have been identified. Each of the five criteria is subsequently divided into four sub-criteria.

The five main criteria and their respective sub-criteria are:

Socio-economic aspects and impacts on growth, resilience and stability

- effects on income distribution
- effects on cultural heritage
- feasibility in socio-economic structure

The use of natural and environmental resources including raw materials and discharge of wastes within the carrying capacity of natural systems

- raw materials and energy
- waste discharges (closing material cycles)
- use of natural resources (water)
- effects on resilience and vulnerability of nature

Enhancement and conservation of natural and environmental resources, and the improvement of the carrying capacity of natural and environmental resources

- water conservation
- accretion of land or coast
- improvement and conservation of soil fertility
- nature development and conservation of natural values

Public health, safety and well-being

- effects on public health
- effects on safety (risks)
- effects on annoyance/hindrance (smell, dust, noise, crowding)
- effects on living and working conditions

Flexibility and sustainability of infrastructure works, management opportunities for multifunctional use, and opportunities to adapt to changing circumstances

- opportunities for a phased development
- opportunities for multifunctional use and management and to respond to changing conditions
- sustainable quality of structures (corrosion, wear)

- opportunities for rehabilitation of the original situation (autonomous regeneration, active reconstruction and restoration)

Each sub-criterion is given equal weighting. The sum of numerical values given to each sub-criterion is a sustainability index. The higher the index value the greater the contribution of a project to sustainable development. Users of this index must then decide, based on the index value, whether to accept, reject or urge the potential client to modify the project.

Weighted statistical indices

Alternatively, sustainability indices can be defined as separate or weighted combinations of reliability, resilience and vulnerability measures of various economic, environmental, ecological and social criteria. To do this it is first necessary to identify the appropriate economic, environmental, ecological and social criteria to be included in the overall measure of relative sustainability. These criteria must be able to be expressed quantitatively or at least linguistically (such as "poor", "good" and "excellent") and be determined from time-series of water resource system variables (such as flow, velocity, water surface elevation, hydropower production or consumption, etc.).

Criteria that can be expressed in monetary units can be considered economic criteria. This might, for example, include the present value of the economic costs and benefits derived from hydropower, irrigation, industry and navigation. Economic criteria usually include distribution as well as efficiency components. Who pays and who benefits is as (if not often more) important as how much the payments or benefits are or will be.

Environmental criteria may include pollutant and other biological and chemical constituent concentrations in the water as well as various hydraulic and geomorphologic descriptors at designated sites of the water resource system. Ecological criteria could include the extent and depth of water in specified wetlands, the diversity of plant and animal species in specified flood plains, and the integrity or continuity of natural ecosystems that can support habitats suitable for various aquatic (including fish) species. Social criteria may include the frequency and severity of floods and droughts that cause hardship or dislocation costs not easily expressed in monetary units and the security of water supplies for domestic use. They might also include descriptors of recreational opportunities provided by the rivers, lakes and reservoirs, their operation or regulation and the relative quality or attractiveness of the scenery provided for those living next to or using the water resource system.

Once the water resource system is simulated using hydrological inputs representative of what one believes could occur in the future, the time series values of these system performance criteria can be derived. These time series values themselves can be examined in any comparison of alternative water resource system designs and/or operating policies. Alternatively, they can be summarized using the statistical measures of reliability, resilience and vulnerability. The relative sustainability of the system with respect to each of these criteria is higher the greater the reliability and resilience, and the smaller the vulnerability. There are often trade-offs between these three statistical measures of performance.

To illustrate this procedure, consider any selected criterion called C. Its time series of values from a simulation study are denoted as C_t, where the simulated time periods t extend to some future time T. To define reliability one must identify the ranges of values of this criterion that are considered satisfactory, and hence the ranges of values considered unsatisfactory. Of course these ranges may change over time. Note that those ranges of these criterion values that are considered satisfactory, and hence those ranges of values considered unsatisfactory, are determined by the analysts or planners. These ranges are subjective. They are based on human judgement or human goals, not scientific theory. In some cases they may be based on well-defined standards, but standards will not have been predefined or published for most system performance criteria.

Figure 2 illustrates a possible time series plot of simulated future values of C_t along with the designated range of values considered satisfactory. In this example the satisfactory values of C_t are within some upper and lower limits. Values of C_t above the upper limit, UC_t, or below the lower limit, LC_t, are considered unsatisfactory. Each criterion will have its own unique ranges of satisfactory and unsatisfactory values. Once these data are defined, it is possible to compute associated reliability, resilience

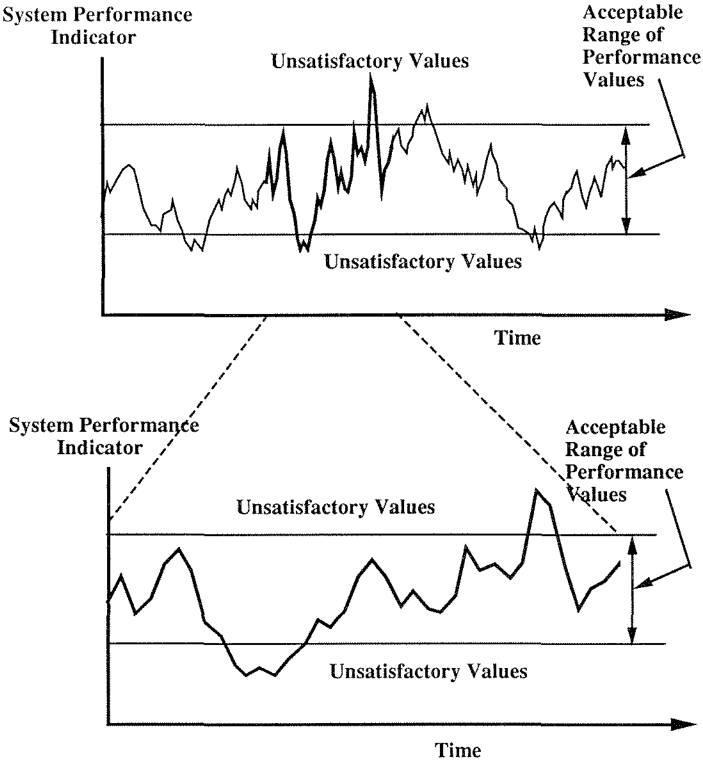
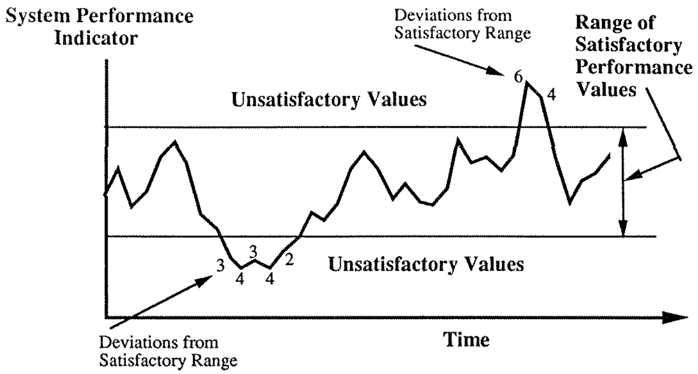


Fig. 2 A portion of the time series of values of a system performance indicator derived from a predictive simulation model.



Reliability: $\frac{\text{Number of Satisfactory Values}}{\text{Total Number of Values}} = \frac{31}{38} = 0.82$

Resilience: Number of Times a Satisfactory Value Follows an Unsatisfactory Value / Number of Unsatisfactory Values

= 2 / 7 = 0.29

Vulnerability:

Extent: 6 with conditional probability of exceedence of 0 / 7 = 0.0
4 with conditional probability of exceedence of 1 / 7 = 0.14
3 with conditional probability of exceedence of 3 / 7 = 0.43
2 with conditional probability of exceedence of 6 / 7 = 0.86

Expected Extent given Unsatisfactory values = (3+4+3+4+2+6+4) / 7 = 2.7

Duration: 5 with conditional probability of exceedence of 0.0
2 with conditional probability of exceedence of 0.5

Expected Duration given Unsatisfactory values = (5 + 2) / 2 = 3.5

Fig. 3 Deriving measures of reliability, resilience and vulnerability from the time series data shown in Fig. 2.

and vulnerability statistics for successive portions of this time series, as illustrated in Fig. 3 and as defined below:

$$\text{Reliability of } C = \frac{\text{number of satisfactory } C_t \text{ values}}{\text{total number of simulated periods } T} \tag{5}$$

$$\text{Resilience of } C = \frac{\text{number of times satisfactory } C_t \text{ follows unsatisfactory } C_t}{\text{number of unsatisfactory } C_t \text{ values}} \tag{6}$$

Reliability is the probability that any particular C_t value will be within the satisfactory range of values. Resilience is an indicator of the speed of recovery from an unsatisfactory condition. It is the probability that a satisfactory C_{t+1} value follows an unsatisfactory C_t value.

Vulnerability is a statistical measure of the extent or duration of failure, should a failure (i.e. an unsatisfactory value) occur. The extent of a failure is the amount a value C_t exceeds the upper limit, UC_t, of the satisfactory values or the amount that value falls short of the lower limit, LC_t, of the satisfactory values, whichever is greater. It is the maximum of $[0, LC_t - C_t, C_t - UC_t]$.

The extent of failure of any criterion C can be defined in a number of ways. It can be based on the extent of failure of individual unsatisfactory values or the cumulative extent of failure of a continuous series of unsatisfactory values. In the latter case, each individual extent of failure is added together for the duration of each continuous failure sequence.

Since there can be many values of these individual or cumulative extents of failure for any set of simulations, a histogram or probability distribution of these values can be defined. Thus "extent-vulnerability" can be defined as:

Individual extent-vulnerability (p) of C =
maximum extent of individual failure of criterion C occurring with probability p, or that may be exceeded with probability $1 - p$ (7)

Cumulative extent-vulnerability (p) of C =
maximum extent of cumulative failure of criterion C occurring with probability p, or that may be exceeded with probability $1 - p$ (8)

Extent-vulnerability can also be defined based on the expected or maximum observed individual or cumulative extent of failure. The conditional expected extent of failure indicator can be defined as:

Conditional expected extent-vulnerability of C =
Σ_t individual (or continuous cumulative) extents of failure of C_t / number of individual (or continuous series of) failure events (9)

The sum of equation (9) is over all individual or continuous sequences of failure events. Continuous sequences include those of only one period in duration. The unconditional expected extent-vulnerability of C is defined using the above equation except that the denominator is replaced by the total number of simulation time periods T.

The maximum simulated individual extent of failure can be defined as:

Maximum extent-vulnerability of $C = \max[0, LC_t - C_t, C_t - UC_t]$ (10)

For some criteria, for example droughts, the duration as well as the individual and cumulative extents of failure may be important. A histogram or probability distribution of the durations (number of time periods) of failure events can be constructed following any one or multiple simulations. From this histogram or probability distribution, duration-vulnerability measures for each criterion C can be defined:

Duration-vulnerability (p) of C =
maximum duration (number of time periods) of a continuous series of failure events for criterion C occurring with probability p or that may be exceeded with probability $1 - p$ (11)

Expected duration-vulnerability of C =
total number of periods t having failures of C_t / number of continuous series of failure events (12)

The number of continuous sequences of failures for criterion C includes events which last for only one period.

Once these statistical reliability, resilience and vulnerability measures of the time-series values are defined, as appropriate for each economic, ecological, environmental and social indicator or criterion, they can be applied to predicted criteria values over groups of years on into the future. This produces time series of reliability, resilience and vulnerability data for each criteria. If over time these statistical measures are improving, i.e. the reliabilities and resiliences are increasing, and the vulnerabilities are decreasing, the system being studied is getting increasingly sustainable. Often, however, one will find the predicted reliabilities, resiliences and vulnerabilities of some criteria improving, and for other criteria they may be worsening. Or for any given criterion, some of these statistical measures may be improving, and others worsening. This will force one to give relative weights to each measure of each criterion.

One of the better ways to present and examine and compare the values of all these measures for all relevant criteria is through the use of a scorecard. A scorecard is a matrix that presents the values of each of these measures for each of the criteria associated with each alternative system. Table 1 illustrates such a scorecard that uses actual values of the criteria that are not assumed to vary over time. Table 2 is a scorecard of statistical measures of these criteria that vary over time. One can see the increasing or decreasing predicted values over each of the five 10-year periods examined in the study on which this scorecard was based.

The scorecard in Table 2 shows that some alternatives are predicted to be better with respect to some criteria, and other alternatives are predicted to be better with respect to other criteria. In these situations, which are common, the multi-objective decision making process will involve making trade-offs among incommensurate objectives. In some cases this negotiation or decision-making process can be facilitated by attempting to rank each of the alternatives, taking into account each of the criteria. One such approach is through the use of sustainability indices.

Table 1 Example scorecard showing average annual values of various criteria for alternative regional development alternatives.

Impacts	Alternative policies and components:			
	Agricultural irrigation pumps drainage	Industrial water storage groundwater use	Environmental water recreation treatment tax on water use	Mixed water storage treatment canal transport
Annual investment costs	**300**	400	*700*	*700*
Annual econ. benefits	**1200**	700	*100*	1000
Agricultural production	**800**	150	*50*	600
Drinking water cost	*1.4*	**0.90**	1.20	1.10
Pollution index at site A	150	*220*	**30**	70
Power production	200	**1200**	*50*	800
Fisheries production	70	*20*	**80**	40
Flood protection (%)	**99**	98	*96*	**99**

Best; *worst*.
Units of each impact are defined elsewhere.

Table 2 Example scorecard showing average annual values and trends in reliability, resilience and relative vulnerability of various criteria values for alternative regional development alternatives.

Impacts	Alternative policies and components: Agricultural irrigation pumps drainage	 Industrial water storage groundwater use	 Environmental water recreation treatment tax on water use	 Mixed water storage treatment canal transport
Annual investment costs	**300**	400	*700*	*700*
Reliability trends	0.89–0.93	0.85–0.89	0.82–0.84	0.74–0.78
Resilience trends	0.77–0.76	0.78–0.80	0.67–0.75	0.74–0.78
1-Rel. *vulnerability:*				
extent trends	0.84–0.91	0.75–0.77	0.66–0.72	0.78–0.83
duration trends	0.91–0.96	0.92–0.90	0.89–0.87	0.90–0.92
Overall product	**0.52–0.62**	0.46–0.49	*0.32–0.39*	0.46–0.53
Annual econ. benefits	**1200**	700	*100*	1000
Reliability trends	0.83–0.88	0.82–0.85	0.82–0.88	0.78–0.89
Resilience trends	0.71–0.81	0.76–0.83	0.77–0.79	0.84–0.88
1-Rel. vulnerability:				
extent trends	0.94–0.91	0.79–0.76	0.76–0.77	0.88–0.89
duration trends	0.91–0.86	0.90–0.93	0.85–0.88	0.93–0.96
Overall product	0.50–0.56	0.44–0.50	*0.41–0.47*	**0.54–0.67**
Agricultural production	**800**	150	*50*	**600**
Reliability trends	0.92–0.94	0.65–0.60	0.72–0.77	0.78–0.79
Resilience trends	0.71–0.75	0.72–0.76	0.85–0.90	0.76–0.77
1-Rel. *vulnerability:*				
extent trends	0.88–0.93	0.62–0.67	0.86–0.92	0.88–0.84
duration trends	0.93–0.86	0.71–0.75	0.89–0.85	0.90–0.95
Overall product	**0.53–0.56**	*0.21–0.23*	0.47–0.54	0.47–0.49
Drinking water cost	*1.40*	**0.90**	1.20	1.10
Reliability trends	0.83–0.85	0.88–0.89	0.82–0.86	0.85–0.91
Resilience trends	0.81–0.80	0.88–0.85	0.77–0.78	0.78–0.88
1-Rel. vulnerability:				
extent trends	0.84–0.93	0.85–0.87	0.86–0.92	0.88–0.93
duration trends	0.92–0.95	0.82–0.90	0.89–0.88	0.90–0.91
Overall product	0.52–0.60	0.54–0.59	*0.48–0.54*	**0.53–0.68**
Pollution index at site A	150	*220*	**30**	70
Reliability trends	0.79–0.83	0.75–0.79	0.92–0.94	0.78–0.83
Resilience trends	0.73–0.77	0.76–0.80	0.97–0.95	0.90–0.92
1-Rel. *vulnerability:*				
extent trends	0.74–0.81	0.71–0.73	0.86–0.92	0.88–0.89
duration trends	0.81–0.86	0.82–0.90	0.89–0.94	0.84–0.88
Overall product	0.35–0.45	*0.33–0.42*	**0.68–0.77**	0.52–0.60
Power production	200	**1200**	*50*	800
Reliability trends	0.78–0.80	0.77–0.76	0.67–0.75	0.74–0.83
Resilience trends	0.85–0.89	0.89–0.93	0.82–0.84	0.88–0.92
1-Rel. vulnerability:				
extent trends	0.92–0.90	0.91–0.96	0.89–0.87	0.90–0.89
duration trends	0.75–0.77	0.84–0.91	0.66–0.72	0.78–0.78
Overall product	0.46–0.49	**0.52–0.62**	*0.32–0.39*	0.46–0.53
Fisheries production	70	*20*	**80**	40
Reliability trends	0.82–0.84	0.78–0.83	0.84–0.91	0.92–0.90
Resilience trends	0.68–0.75	0.90–0.92	0.91–0.96	0.75–0.77
1-Rel. *vulnerability:*				
extent trends	0.65–0.72	0.88–0.89	0.89–0.93	0.78–0.80
duration trends	0.89–0.87	0.74–0.78	0.77–0.76	0.85–0.89
Overall product	*0.32–0.39*	0.46–0.53	**0.52–0.62**	0.46–0.49
Flood protection (%)	**99**	98	*96*	**99**
Reliability trends	0.89–0.98	0.95–0.99	0.90–0.92	0.89–0.87
Resilience trends	0.97–0.96	0.78–0.80	0.74–0.83	0.67–0.72
1-Rel. vulnerability:				
extent trends	0.94–0.91	0.85–0.87	0.78–0.78	0.66–0.75
duration trends	0.91–0.92	0.92–0.95	0.88–0.89	0.82–0.84
Overall product	**0.71**	0.58–0.65	0.46–0.53	*0.32–0.39*
Overall Sustainability Index	**0.55–0.56**	*0.44–0.50*	0.46–0.53	0.47–0.55

Best; *worst.*

Units of all criteria are defined elsewhere; relative weights of Sustainability Index were assumed to be equal and sum to 1.

To rank each of the alternatives that are non-dominated (i.e. ones that are not inferior to others with respect to all criteria) the information contained in the scorecards can be combined into a single sustainability index. When defining an index using these statistical measures of reliability, resilience and vulnerability, it is convenient to convert each vulnerability measure into a measure that, like reliability and resilience, ranges from 0 to 1 and in which higher values are preferred over lower values. This can be done in two steps. The first involves identifying the largest vulnerability value for each criterion C among all the alternative systems being compared and then dividing each system's vulnerability measure for the criterion by this maximum value. The result is a relative vulnerability measure, ranging from 0 to 1, for each criterion C. One of these relative vulnerability values for each criterion C will equal 1, namely that associated with the system having the largest vulnerability measure.

$$\text{Relative vulnerability}(C) = \text{vulnerability}(C)/\max \text{ vulnerability}(C) \text{ among all alternatives} \tag{13}$$

This definition of relative vulnerability will apply to each type of vulnerability identified above, and for any specified level of probability, when applicable.

The second step in converting the vulnerability measure to one that is similar to reliability and resilience in that higher values are preferred over lower values is to subtract each relative vulnerability measure from 1.

Once this scaling and conversion have been performed, each statistical measure ranges from 0 to 1 and higher values are preferred over lower values. They can now be combined into a single index for each criterion C. One way of doing this is to form the product of all these statistical measures.

$$\text{Sustainability}(C) = [\text{Reliability}(C)]\,[\text{Resilience}(C)\,]\,[\Pi_v \{1 - \text{relative vulnerability\_}v(C)\}] \tag{14}$$

where relative vulnerability_$v(C)$ is the vth type of relative vulnerability measure being considered for criterion C. The use of multiplication rather than addition in the above index gives added weight to the statistical measure having the lowest value. For example, if any of these measures are 0, it is unlikely any of the other measures are very relevant. A high value of the index can result only if all statistical measures have high values.

The resulting product, the sustainability(C) index, ranges from 0, for its lowest and worst possible value, to 1, at its highest and best possible value. This sustainability index applies to each criterion C for any constant level of probability p, and can be calculated for each alternative system or decision being considered.

To obtain a combined weighted relative sustainability index that considers all criteria, relative weights, W_C, ranging from 0 to 1 and summing to 1, can be defined to reflect the relative importance of each criterion. These relative weights may indeed be dependent on the values of each Sustainability(C) index. Once defined, the relative sustainability of each alternative system being compared is:

$$\text{Relative sustainability} = \Sigma_C\, W_C\, \text{Sustainability}(C) \tag{15}$$

Since each sustainability index and each relative weight W_C ranges from 0 to 1, and the relative weights sum to 1, these relative sustainability indices will also range from 0 to 1. The alternative having the highest value can be considered the most sustainable *with respect to the criteria considered, the values of each criterion that are considered satisfactory and the relative weights.* Every sustainability index value involves the subjective judgements of those participating in the evaluation process. The last row in Table 2 is a relative sustainability index for the 8 criteria listed in that table.

Note what has been done here. A particular proposed or actual water resource system design and management policy is simulated over time. The simulated data include assumptions regarding system design, operation, and hydrological and other inputs and demands that represent a scenario representative of what could occur in the future. Incorporated into that simulation are the variables individual stakeholders consider important and relevant to sustainability. These are called criteria. These criteria could include physical, economic, environmental, ecological and social variables. The time series of each of these criterion values at different locations are produced from the simulation. These time series are divided into sub-periods and statistical measures of reliability, resilience and vulnerability are used to summarize each sub-period's time series of each criterion.

The results can be presented on scorecards, or can be combined into a sustainability index for each of the simulated criterion variables considered important with respect to system sustainability. These individual indices for succeeding time periods can be compared to judge whether sustainability is increasing or decreasing over time.

Now consider some complications. These criterion values are in all likelihood spatially dependent. It is very likely that these relative sustainability indices will vary depending on the site where the time series values are observed and computed. If so, these relative sustainability indices can be computed for various sites for each alternative water resource system being evaluated and compared. Each of these site-specific relative sustainability indices can then be considered using scorecards and other multi-objective analyses methods. Alternatively, one could develop an overall system indicator of reliability, resilience and vulnerability through some averaging scheme.

Another complication occurs if the time series data for any criterion show trends. In such situations some partitioning of time may be appropriate. Any worsening (or improving) situation in the future should not be hidden by including the poorer future (or present) values with the better present (or future) values when calculating these statistical measures. In these cases the relative sustainability indices will be time dependent as well as spatially dependent.

It is important to remember that these relative sustainability indices are all based on subjective assumptions concerning future hydrology, costs, benefits, technology, ecological responses and the like. They are also based on subjectively determined ranges of satisfactory or unsatisfactory values, and on subjectively determined relative weights. Nevertheless, if the range of criteria used is comprehensive and identifies the concerns and goals of everyone now and, one hopes, on into the future, as can best be guessed, this relative sustainability index can be used by itself to identify the preferred design or policy alternative. Otherwise it can be used along with other criteria in a multi-objective analysis.

These is no guarantee that analyses such as these, performed by different groups and/or at different times, will end up with the same conclusions.

Once again, change is ever present, and until someone convincingly provides a scientific definition of sustainability, one that does not involve human judgements, it is very possible different groups and different generations will have different views of just what is sustainable. Using methods such as the ones just proposed, however, does force one to look into the future as best as is possible, to evaluate the multiple physical, economic, environmental, ecological and social impacts of what one may wish to do now for individuals living in the present generation and for those living in future generations. It also ensures that that information is available in some summarized form in front of everyone involved during the entire decision making process.

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