represent them. If we cannot forecast their objectives and needs, we should assume that future generations will have values and needs similar to ours, and use conservative projections of the means which will be at their disposal."

The Scientific Committee on Water Research (SCOWAR) of the International Council of Scientific Unions* prepared a report on trends and needs in water resources research (SCOWAR, 1998). They considered the scientific issues to which existing interdisciplinary knowledge and mechanisms were insufficient. Sustainable reservoir development and operation was among the eight selected topics and it was stressed that physical sustainability, environmental concerns and efficient and sound operation and maintenance were the key areas for further research.

2.2. SUSTAINABLE DEVELOPMENT AND MANAGEMENT IN THE RESERVOIR CONTEXT

2.2.1 Introduction

Sustainable water resources management is, from the methodological viewpoint, a generalization of the notion of integrated water management which has been known as a concept for decades. However, it requires a clear commitment to broader objectives explicitly including ecological conservation and intra- and inter-generational equity issues. As a result, it calls for new instruments, such as demand management which has not been seriously exercised in the past. Management of water demand, using pricing mechanisms and other regulatory measures is a key instrument for sustainable freshwater resources management as proposed in Agenda 21, Chapter 18 (UNCED, 1992). They are important everywhere in the world including the countries where supply increase is mandatory for water resources management. Without a coherent demand management policy, supply tends to create more demand and inefficient use. Chapter 3 will discuss the details of various means of demand management as non-reservoir options.

Sustainable water resources management may require a change of administrative system from an orientation towards supply to the development of management-oriented organizations. It may require a new allocation of administrative power endorsed by new legislation. The administration itself may need to be reorganized to achieve the objectives of sustainable development.

Sustainable reservoir management is a subset of sustainable water resources management and requires every notion of integrated management, multiple objectives, risk and uncertainty matters, systems approach and the like which should eventually be translated into workable criteria. Sections

* Now called the International Council for Science.
2.2.2 Integrated water resources management

Integrated water resources management basically requires consideration of the system design and operation at basin scale. The considerations should include:

- integrated hydrological control of water and material transport;
- land use and vegetation management;
- upstream and downstream economic integrity; and
- collection and dissemination of hydrometeorological information.

**Basinwide integration** A river basin is the natural physical unit within which any water resources management works are interrelated and dependent on each other. Flood control, water use, sediment control and many other reservoir functions affect hydrological, socio-economic and environmental conditions of the basin from the headwaters to the estuary. Upstream versus downstream conflicts in socio-cultural and economic matters require large regional scale management and mutual understanding. The upstream basin management controls the water quantity, quality and sediment inflow into the reservoir. Reservoirs may impact on sedimentation, water quality, groundwater levels, river bed erosion, estuary retreat and marine culture, condition of navigable water, scenic, cultural and recreation values and many others. The water use downstream, its withdrawal and discharge, affects water level, infiltration, evaporation, and water quality. All these factors should be considered and coordinated from the planning stage throughout the whole lifetime of a reservoir as mutually dependent with integrated basin-scale hydrological and environmental cycles.

Reservoir sedimentation is a key factor for controlling the physical sustainability of a reservoir. In order to control sediments to and from reservoirs, bypass (compensation) channels, release gates, sediment check-dams upstream and other elements of infrastructure may be needed. Compensation channels are especially useful to curb deepening the river bed...
downstream arising from erosion. Although the average reservoir lifetime is not very short (cf. Section 1.3.3), there are many reservoirs that may be filled by sediments in a few decades. It is obvious that the basin management upstream is the most fundamental remedy for sediment control in the long run. There are examples of reservoirs, such as the Meiktila Reservoir in Burma constructed nearly two millennia ago, which was sustainable for a long time as laws introduced a severe penalty for removing a tree in the drainage basin of the tributary to the lake. Once the regulations became less onerous, accelerated sedimentation of reservoirs began. Evapotranspiration losses are important indices of reservoir sustainability. Human successes in suppressing evaporation are virtually non-existent. This means that evaporation from a reservoir should be given due consideration at the planning stage. Reservoirs with large inundated areas are not desirable not only due to the loss of much land, severe disturbances in ecosystems and the need for substantial relocation of people, but also because of the high water losses by evaporation, especially in arid and semiarid regions of the world. Evapotranspiration problems extend to the upstream catchment. As an example, the Bhumibol Reservoir in Thailand, built in 1964 with a capacity of 13.5 billion m$^3$, has experienced a decrease of reservoir inflow since its completion. Some claim that the effect of climate change has been responsible but the major reason is believed to be the expansion of irrigation and other major uses of water in the upstream catchment, that is developments which, in fact, caused an increase of evapotranspiration upstream.

An example of integrated urban water management is a combination of artificial infiltration of urban rainfall underground and to cisterns in houses, which contributes to flood control, low flow augmentation and water supply, considerably reducing the dependency of urban areas on upstream reservoirs. More detail is provided in Section 3.2.

**Information integration** The integrated perspective also embraces the use of meteorological forecasts which can improve reservoir operation. If meteorological forecasts are used in an effective way, the same reservoirs may function better, satisfying more needs and thus possibly offsetting a part of new developmental needs. The techniques used for measurement of hydrometeorological variables, such as satellites, radar, automated and telemetered observation networks; and data transmission and processing techniques, have progressed rapidly. Together with the scientific advancement in hydrometeorology to obtain knowledge about physical processes, the advanced observations render complex numerical models operational. These may yield accurate forecasts. Yet, in general, reservoir operation is not taking sufficient advantage of advanced technology. This may be partly because reservoir operation is so sensitive to human society that even a small error creates an unacceptable impact on users and
Sustainability and reservoirs accordingly the existing forecasting accuracy is still below the acceptable level. The other reason being that reservoir operators do not fully realize the benefit that may be obtained with the available level of forecasting accuracy. Section 4.2.2 shows an example by Takeuchi & Sivaarthitkul (1995) of how the introduction of accurate forecasts virtually expands the capacity of a reservoir and offsets some developmental needs for new reservoirs.

Integrated water resources management necessarily increases the number of system components to be jointly considered and the amount of data to be collected, stored, analysed and used. The necessary information typically includes hydrometeorological records, past operational experiences, GIS with various layers, such as topography, land use, social, physical, chemical, administrative and other components. Integrated water management is possible only with the aid of an advanced computer system with an adequate knowledge base and a capable inference engine to update, process, analyse and utilize the available information. Computer graphics and man machine dialogue devices are useful for the development/creation of public awareness in water resources planning and management.

Artificial intelligence and other computer-aided decision support systems lend themselves particularly well to applications in the field of reservoir operation (Simonovic, 1996a,b). One of the reasons is the complexity of integrated management. However, in addition, reservoirs are often located in remote mountainous areas with difficult access. They are therefore difficult to maintain, in particular in winter, during heavy rain or snowfalls and during natural hazards such as floods. At the same time, the amount of accumulated past data is very high and growing fast. The proper use of these data is essential for improved management of water resources. Thus, both in reservoir operation and design, the introduction of automated decision support systems is anticipated. However, its introduction is currently being cautiously received in field operation offices.

From the reliability and robustness viewpoints, it should be noted that dependence on computer knowledge base and decision support systems, coupled with automated remote controls, can be quite risky. If electricity goes off, if machines malfunction, if unwelcome surprises appear and so forth, human ability to control automated systems is very limited, as evidenced in examples of aircraft crashes and disasters in nuclear power stations. There are many efforts to get around such problems and to pre-program for such emergency cases within the system. Indeed, a cautious approach to artificial intelligence systems is justified until truly intelligent robots with self-learning, self-thinking and risk-conscious minds become available. Human ability to control emergency cases such as gate operation of reservoirs should always be permitted and appropriate arrangements (including training) made. Under such circumstances, integrated large systems should be subdivided into manageable sizes.
2.2.3 Notion of multiple objectives

Water resources planning and management for maximization of net economic benefits is no longer sufficient. The introduction of the principles of sustainability expands the range of issues that must be incorporated in the objectives of water resources planning. The main modifications are required to account for:

- non-economic objectives (example: requirement of no net loss of ecosystem productivity);
- needs of future generations;
- distribution of costs and benefits;
- balancing inequalities (within, and between, generations);
- increase in efficiency; and
- avoidance or minimization of irreversible effects.

Sustainability places a significant weight on replacing single objective optimization with a multi-objective analysis where a set of trade-offs (non-dominated, noninferior, compromise, Pareto optimal solutions) can be identified. Selection of the best compromise solution is a political decision. Trade-offs are an inherent part of the consensus reaching process. Simonovic (1989) has shown that the idea of replacing the best compromise solution with the most robust solution is an appropriate one to be used in the multi-objective analysis for sustainable development of water resources.

**Necessary institutional setting** In order to render integrated water resource management possible, it is most important to establish an institutional setting that can allow various policies to be implemented. Integrated water resource management includes basinwide multi-objective management, optimal allocation of water with economic and environmental evaluation, the use of demand management with pricing mechanisms and regulatory measures, the development of alternative sources of water supply including waste-water reuse and water recycling, water conservation through improved water-use efficiency, water-saving and effluent control. Many of these measures could be implemented within the current administrative and institutional structure. But in practice they would all need a drastic modification and rearrangement of current administrative sectoring, regulations, water rights etc. to make the multi-sectoral approach possible. As regards reservoir operation, the allocation of water rights set separately for each reservoir is an obstacle to utilizing available water in an efficient way and to managing the water resources in an integrated manner at the basin scale. Joint operation of a set of reservoirs makes it possible to benefit from coordination. Even during severe droughts, enforcement of a temporary transfer from less urgent agricultural
water use to more urgent municipal water use is not easy. Still more problematic is the introduction of new demands such as environmental use. The reliability and robustness required can never be achieved within rigid administrative constraints, sectionalism and regulations. The opportunity cost of administrative rigidity is very high creating inefficient water use, difficulty for risk management and extra demand for reservoir development.

Sustainable development requires improvement in efficiency of use of environmental, economic, manpower, time and other resources. Efficient use of existing reservoirs should precede any new reservoir construction since creating a new major element of infrastructure is expensive, affects people and the environment and also uses the irreversible dam site resources. There must be a great possibility of increasing efficiency in flood control, water supply, etc. by improvement of operation of existing reservoirs, integrated with such measures as predictions of hydrometeorological phenomena as well as demand patterns and socio-economic preferences. The rational allocation of water rights according to realistic priorities, i.e. earmarking more water to the most urgent need, is of utmost importance. Optimality is a difficult concept in a multi-objective scheme but it can be colloquially stated as efficient and rational water use without critical institutional constraints.

Notion of equity and democracy One other aspect of sustainability considerations of reservoirs is the notion of equity, which refers to other passengers of the spacecraft Earth at the present time and in future generations. Intra-generational equity requires consideration of a range of issues belonging to the realm of social systems, organizational levels, institutional arrangements and public participation, which can be collectively called human dimensions of sustainable reservoir development. In particular, one should be cognisant of:

- respect of the opinions of reservoir site communities;
- care for involuntarily displaced people;
- benefits to the poor, the weak, the illiterate;
- fairness between upstream and downstream residents; and
- democratic and collective process for decision making and conflict resolutions.

A decision on the construction of a reservoir requires a broad consultation. People affected by the project need to be given the opportunity to express their opinion which, in turn, should be seriously taken into account in the decision-making process. The process of mass displacement needs to be considered with due concern in order to at least maintain the living standard of the involuntarily displaced people. Simple monetary compensation is not an adequate solution for those people who may have never before managed a
large amount of money in their lives. They need to be taken care of until their new life is stabilized. Socio-economic fairness in upstream and downstream development is one of the most important issues in any basin, where water quantity and quality are the limited resources to be shared for development.

Public participation, including that of women, young people, indigenous people and local communities is essential to sustainable reservoir development. As mentioned in equity considerations above, this is the basic condition for equity criteria to be satisfied. It also plays other important roles. It is a challenging issue to identify how the current political movement of regionalization and the overall weakening of government intervention affects such needs of governmental coordination and where the new leadership in achieving integrated water resource management comes from. It may be pointed out that a strong government usually has strong sectionalism, which creates the need for coordination whilst acting as a barrier to coordination. Regionalization and the weakening of central government would weaken sectionalism and, as a result, create a more flexible basis for integrated basinwide management. As for the source of new leadership for integrated management in a regionalized weak government, public awareness and citizen participation would play an important role. Information disclosure (e.g. via various computer-aided decision support systems) would be indispensable in allowing the public to have a correct understanding of alternative courses of action and their consequences and to reach wise judgements.

A democratic institutional structure is an important prerequisite for sustainable development. Planning of non-sustainable schemes is frequently developed behind locked doors, and the concentration of uncontrolled power allows the few to close the door to the many and gives birth to the monument-building syndrome. Increased public involvement will create more forethought in the decision-making process and there is a reason to expect a more fair allocation of benefits and costs. Pursuing sustainable development of water resources will require major changes in both substantive and procedural policies. The diverse policy questions raised include:

- How should the methods and processes of impact assessment and planning be used?
- What should be the role of the market as opposed to direct regulatory mechanisms?
- What should be the role of public and interest groups in the management of the resource?
- How much should be invested in managing the resource and how should this be financed?

It is difficult to specifically consider the notion of inter-generational equity in reservoir design and planning. Its most concrete aspects are:
• conservation of nature, ecological systems and cultural heritage;
• dam safety;
• quality of reservoir water;
• sediment control;
• rehabilitation; and
• reversibility.

Most of them are important for the contemporary generation, too. However, dams are expected to serve not only for the present but also for a long time into the future. Rehabilitation programmes for existing reservoirs may improve their sustainability (cf. Section 4.3.2). Other aspects of inter-generational equity listed above are also discussed in this section.

A release from a reservoir which is close to the natural flow pattern of the hydrological variability including floods and droughts may be considered beneficial from the viewpoint of natural habitats of aquatic fauna and flora. This would surely help the conservation of nature, possibly at the expense of the economic use of water. The balance between economic use and the environmental use of water is shaped by the people. For example, after many years of discussion, it was decided to release water from the Glen Canyon Dam in Colorado in order to create artificial floods. It was not an easy decision to take. The hydropower loss by this operation is not marginal although the water is recaptured again downstream by the Hoover Dam.

Consideration of hydropower When analysing hydropower development, impacts on sustainability of the use of energy (production, urbanization etc.) should also be included. Electricity rates have frequently been found to be inefficient and serving to subsidize industrial activities that have significant impacts on the overall sustainability (Goodland et al., 1992). These authors recommend that hydropower development should not be considered unless:
• the price of electricity has reached the long-term marginal cost;
• most energy conservation and efficiency measures are substantially in place;
• all economically perverse subsidies and other incentives have been rescinded; and
• rehabilitation, re-development and expansion of existing sites have already been accomplished.

Agreeing with the principle of this approach one could note that the process of reservoir planning takes a long time. Typically, it is based on a projection of energy demand some time into the future. Suppose that there are still reserves
in energy conservation, yet even full implementation of these reserves, whose efficiency is highly uncertain, may still be insufficient for meeting future energy demands. The search for reserves in energy conservation is to be encouraged. Brazil has probably saved more than US$ 1 billion in new generation capacity because of recent major improvements in the electricity tariff structure.

A proposed dam should have a high rate of power production per area inundated. The acceptable efficiency of the use of the area should depend on the value of the ecosystems and production systems. Goodland et al. (1992) suggest that if the ecosystem to be flooded is an intact primary tropical forest, then the acceptable ratio should be set higher, e.g. to 100 kW ha\(^{-1}\). In the case of impounded agricultural areas or degraded lands, the acceptable ratio could be respectively lower. However, it does not seem possible to devise general guidelines for acceptable limits in quantitative terms.

Thompson (1994) compared two hydroelectric projects of different sizes—a mini-hydro and a micro-hydro in the Himalayas. The smaller scheme compared favourably to the bigger one in terms of its sustainability: people with tiny incomes seem to look sufficiently well after a microscale hydropower station. Thompson (1994) advanced the hypothesis that improving sustainability and enhancing resilience are very close to each other. Synghal (1994) sketched how a small, community-owned reservoir system may contribute to sustainable development by triggering community welfare (activating initiative, assuring water supply, increasing agricultural production, livestock, fuel and timber, improving family and community income, advancing education, health and recreation infrastructures). The reservoir in question, increased the availability of gainful employment in the locality without the need for the population to migrate to a city. It is easy to see that the case presented by Synghal (1994) can be conveniently described by a number of indicators of sustainable development included in Section 2.1.3 describing social, economic, environmental and institutional indicators of sustainable development. In the same reference, Synghal (1994) compared a system of 34 small reservoirs giving comparable benefits at a total cost of one third of that for a project with a single large reservoir.

2.2.4 Risk- and uncertainty-related considerations

Dam safety is partly an efficiency issue in the economic sense and partly an inter-generational equity issue. A reservoir must be safe and serve as long as possible. Takahasi (1990) considered several cases of dam failure: the South Fork Dam, Pennsylvania (of height about 22 m (72 ft) and length about 284 m (931 ft), completed in 1852) broke in 1889. The dam burst, triggered by the blockage of the spillway by trees etc., resulted in a major disaster with a substantial loss of human life (2209 people killed in Johnstown). The
Malpasset Dam, France (arch dam, height 66.5 m, dam length 222 m, storage capacity 50 million m$^3$, completed in 1959) broke in 1959 due to rock movement on the bank of the dam on the first occasion that full capacity was reached. The Teton Dam, Columbia River, USA (earth-fill dam, height 93 m, dam length 930 m, storage capacity 356 million m$^3$, completed 1975) broke in 1976 initiated by piping flow on the bank during the first filling, before water storage reached the full capacity. In the case of the Viant Dam, Italy (arch dam, height 262 m, dam length 190 m, storage capacity 169 million m$^3$, completed 1961), a volume of 300 million m$^3$ of earth from a landslide after heavy rain in 1963 created overtopping of 30 million m$^3$ of water, which killed 2125 people and destroyed 595 houses downstream. These are clear cases of unsustainable reservoir design. Increasingly risk-averse societies wish to reduce the probability of rare, yet highly serious, disastrous events. They are willing to pay increasing costs for securing safety.

Sustainable management of water resources necessitates consideration of longer time scales over which various anticipated and unexpected uncertainties may occur. Nobody knows with certainty the degree of population growth, urbanization, industrialization, climate change, societal preferences and value system changes, and technological innovation over the longer term, say, half a century. And it is precisely changes in these processes that strongly influence the hydrology, objectives, constraints, evaluation criteria, operational domain and many other conditions under which water resource systems must operate. There currently exists no firm design methods to incorporate such uncertainties or to increase the ability of the system to adjust to new conditions, to accommodate the unexpected, and perhaps there never will be.

Expanded spatial boundaries, lengthened time scales, comprehensive multi-objective analysis and other issues related to sustainable water management are placing immense demands on science. A number of questions raised by the sustainable development perspective of water resources reveal major deficiencies in the knowledge of the behaviour of a wide range of natural and human systems under consideration. Recognizing the fact that many of these deficiencies cannot be eliminated in the short term, makes it evident that risk and uncertainty are inherent concepts related to sustainable water management.

It is common to study various predictions and scenarios. They are meaningful when the probability and conditions of occurrence of each scenario are, to some extent, scientifically identifiable and the decision can be made on such probabilities. In reality, however, the probability of occurrence of each realization is too uncertain to be relied upon. Scenario analyses are therefore useful for selecting policy alternatives for the relatively short and known future. In reservoir management these scenarios are not so much concerned with the physical design, except for the design in stages with the possibility of add-ons, but rather the operation and management that reservoirs can cope with and adapt for unknown future conditions. Some increase in resilience and
robustness in reservoirs can be assured, in physical terms, if the following conditions for distributed systems are fulfilled:

- many small reservoirs rather than a single giant one;
- many alternative water sources and storage facilities; and
- water transfer and exchange lines and networks.

However, the major sources of resiliency and robustness reside in managerial flexibility in reservoir use. Water allocation, integrated operation with other reservoirs and sources, demand management policy and other reservoir use policies all help to make the physical reservoir capable of meeting unknown or crisis situations.

Flexibility means the requirement to meet changing constraints and changing quality criteria, and accounting for side effects which were not considered at the design stage. This criterion is especially important for sustainable development in the context of a longer time scale to be considered and a wide spectrum of possible future uncertainties to be managed. Flexibility is not necessarily the adaptability of a system to meet two or more scenarios, but rather the adaptability to meet unexpected occurrences. Flexibility is a notion, germane to resiliency and robustness, which relates to the time necessary to adjust to the unexpected occurrence and the degree of surprise to which a system can be adjusted. One can distinguish physically-based flexibility and managerial flexibility. The physical flexibility of a dam is not very high, except for add-on flexibility. However, as a reservoir can serve many purposes in many ways, the managerial flexibility can render the storage useful or useless, with a range of intermediate levels.

Sustainable water resources planning and management include, by definition, long-term consequences in the analysis. This implies examining not only the longer term consequences of proposed developments but also the possibilities of modifying or even reversing the consequences of past commitments. It is especially difficult for government plans to be modified. A dam construction process may sometimes take more than three decades including planning, authorization, residents’ agreement, financing, land acquisition and construction, while societal needs and the economic situation may change in both directions. The dam may even become no longer necessary before completion of the infrastructure. In most countries, it is very difficult to modify or to cancel past commitments of the government. For sustainable reservoir development, however, a flexible decision-making process adjustable to such changes is indispensable.

Physical reversibility is difficult, but there are some examples, as in the case of Elwha (see Section 1.3.4), coming into the picture now. Since dam sites are limited, reversible dam construction, if ever possible, is a rational way to ensure sustainable river use. The technology required for dam removal may not be very simple. But it would be a matter of cost and
economic justification rather than a technological challenge. Any very large
dam that contains huge amounts of sediment would take decades to remove
and little justification is likely under normal circumstances. Small dams
would have more chance. If reversibility is included as a managerial option
for reservoirs, the original plan has to include the cost of removal and the
financial means have to be identified from an early stage. In this sense, one
has to consider the life cycle of a dam, in the context of environmental
impacts and economy.

2.2.5 Systems view

Reservoir analysis, design, planning and operation are difficult and complex
problems. They require expertise from numerous fields like engineering,
economics, physics, chemistry, biology and zoology. No one can be expert on
every subject. But when we turn to experts for help, they often seem confused
and isolated, arguing with each other and looking only at those pieces of a
reservoir problem that happen to fit their own particular specialities.

Systems thinking (often called systems approach, systems view etc.) and
its practical application known as “systems analysis” have been recognized as
essential tools for reservoir analysis. Probably the most important
contributions of systems thinking as it applies to reservoirs are (a) provision of
a way of tackling those big, complicated, real-world reservoir problems which
do not fit neatly into various specialities and (b) provision of a way for
decision makers and the general public to get a clear picture of how reservoirs
and their environment work.

The systems approach is a discipline for seeing entities. It is a framework
for seeing interrelationships rather than things and seeing patterns rather than
static snapshots. It is a set of general principles. It is also a set of specific tools
and techniques.

We live and work within social systems. Our research is exposing the
structure of nature’s systems. Our technology has produced complex physical
systems. But even so the principles governing the behaviour of systems are not
widely understood. A systems approach is needed now more than ever before
because we are becoming overwhelmed by complexity. Probably, for the first
time in history, human kind has the capacity to create much more information
than anyone can absorb, to foster far greater interdependency than anyone can
manage, and to accelerate change far faster than anyone’s ability to keep pace.

Problems related to reservoirs (Section 1.4) are examples of system
breakdowns. Complexity can easily undermine confidence and responsibility.
Systems thinking is one cure for this type of helplessness. It allows us to see
the structure that underlines complex situations. Through proper
implementation of a systems approach to reservoir analyses we can expect:
• To understand reservoirs and their interactions with the surrounding environment much more easily. The basic rules of how reservoirs work apply to other kinds of system (social, political, economic, ecological, physical) and vice versa.

• A systems approach to help us identify "high leverage points" in the reservoir systems where the effective strategies for influencing them will have a greater chance of success.

2.2.6 Sustainability criteria for possible use in reservoir analysis

In order to describe in more detail the behaviour of water resource systems, with regard to sustainability, performance indices (PI) are used, classified as resilience, vulnerability, grade of service, availability, quality of service etc. In addition to performance indices, figures of merit (FM) are also used for the analyses of system behaviour. They are defined as functions of performance indices. Some attempts are made to measure sustainability using different FMs. One idea views sustainability as a combination of high resiliency and low vulnerability (Duckstein & Parent, 1994). Another idea involves identifying a new FM as a weighted statistical index to directly describe sustainability (Loucks, 1997). Yet another concept used to assess planning decisions in terms of sustainability includes entropy (McMahon & Mrozek, 1997).

Most criteria for sustainable decision-making are not yet in operation. Environmental integrity, for example, is difficult to define in an operational form. Inter-generational equity is difficult to comprehend except as a combination of more measurable terms such as reversibility, resiliency or robustness. Unlike the above concepts, economic efficiency is better understood and is commonly applied.

Four practical criteria developed for sustainable water resources decision-making with potential application to reservoir developments: fairness, reversibility, risk and consensus are recommended by Simonovic et al. (1997) and Bender & Simonovic (1997). The sustainability definition emphasizes the integral treatment of three subsystems: economic, social and ecological. In general, developmental decision-making related to reservoirs becomes progressively more complex with the growing recognition of the comprehensive linkages between the natural (ecological), economic and human (socio-political, inter-temporal) subsystems to be considered. The selection of inter-temporal fairness, reversibility, risk and consensus as sustainable decision-making criteria is an attempt at addressing some of these issues.

**Fairness** Fairness or equity, is an important consideration in the selection of large-scale reservoir project alternatives. Consideration of the fairness of
impacts of a reservoir project is important both to ensure the maintenance of social well-being and to secure project acceptance by affected stakeholders. The fairness of a distributive situation can be quantified using a variety of distance-based approaches which result in both intra-temporal and inter-temporal fairness measures (Lence et al., 1997).

The distance-based measures (Lence et al., 1997) are grouped according to whether they are essentially measures of proportionality, quality or need. A set of required principles and characteristics for distance-based distributive fairness measures are necessary and these can be extended for inter-temporal consideration. General formulations are developed for intra-temporal fairness and inter-temporal fairness. Overall fairness may be interpreted as a combination of equity, equality, and need-based fairness objectives. The overall fairness of a reservoir alternative can be used in the process of selecting project alternatives for implementation.

**Reversibility** Reversibility is viewed as a measure of the degree to which the aggregated set of anticipated and unanticipated impacts of a reservoir can be mitigated (Fanai & Burn, 1997). Reservoir projects that are highly reversible should allow the users of the affected system to continue their normal use. A high degree of reversibility requires the imposition of the least amount of disturbance to the natural environment. The reversal of adverse effects is often not technically feasible, but mitigation plans, or the provision of substitute resources, can help to reduce the negative effects.

The reversibility framework developed by Fanai & Burn (1997) considers all alternatives of the reservoir project of interest and determines the degree of reversibility associated with each project alternative. An alternative that is more reversible is superior to alternatives that have a lesser degree of reversibility. The framework for measuring reversibility involves several tasks. These tasks include: (a) identifying and categorizing impacts; (b) classifying the impacts, if necessary; (c) specifying units of measure for the purpose of quantifying each impact; (d) specifying weights for each impact; and (e) applying a formula to obtain indices of reversibility. The framework results in measures of reversibility that can be used as a part of the evaluation and selection of reservoir alternatives.

**Risk** Risk exists when there is the possibility of negative social, environmental or economic impacts associated with a reservoir. Risk can be defined as the product of the magnitude of a negative consequence and the probability of occurrence of that consequence (Simonovic, 1997a). Risk can be estimated using combinations of historical and empirical data, heuristic knowledge and cultural perceptions. A composite measure of risk is influenced by the weighting that is given to the various components of the risk measure.

Kroeger & Simonovic (1997) have developed an algorithm for the evaluation of risk that can be used in the process of selecting reservoir
project alternatives. The intent of the risk measure is to involve project stakeholders in the process of quantifying the risks associated with each project alternative. The algorithm for quantifying the risk measure includes the following steps: (a) identifying the risks that are relevant for the analysis; (b) estimating the probability of each of the risks occurring for each alternative; (c) calculating the risk magnitude for each risk for each stakeholder group; (d) estimating the risk separately for each alternative and each stakeholder group; (e) comparing the alternatives by combining the risk estimates from the stakeholders; and (f) analysing the future joint estimates of risk.

Consensus Consensus, as the concept for promoting sustainability in reservoir analyses is a criterion quite unlike the others described previously (Bender & Simonovic, 1997). Consensus has no units of measurement. It is measured in a brief moment of time, but may implicitly consider future events and uncertainties. Consensus is a high level criterion, dependent on value judgements which may in turn depend on lower level indicators derived from facts concerning problem characteristics. The definition for consensus in Webster’s Dictionary is “a general agreement in opinion”. It relies on a qualitative and subjective opinion, and the qualifying condition is a general agreement. How well do they need to agree? There may not be an adequate answer to this question, but a consensus approach may indicate more than just when to stop an exploration of alternatives.

If consensus leads to sustainability, what is consensus sustainability in an operational form? The following definition for consensus as it relates to sustainability is suggested: “Consensus is an equitable compromise which is robust with regard to (a) reservoir management uncertainties, and (b) stakeholder perspectives”. Reservoir management uncertainties include data uncertainty, model uncertainties, and technological uncertainties. Stakeholder perspectives are related to the value systems. This definition is not yet operational, but its constituent parts might be manageable. There are some assumptions which also need to be made. It is assumed that the appropriate stakeholders have been included in the decision-making process. By stakeholder, we refer to interested parties which may be impacted in some way by any decision that is made (a political choice). The second major assumption is that all stakeholders voluntarily cooperate in the decision-making process.

The decision-making process for a reservoir involves the creation of alternative choices (in the design and operations framework) that appear to satisfy developmental criteria, and are financially feasible and institutionally acceptable. The addition of four new criteria to be used in decision-making is placing much greater weight on replacing single-criterion optimization with multi-criteria analysis. Sustainable reservoir decision making is subject to four major sources of complexity regarding the application of multi-criteria
analysis: (a) addition of sustainability criteria to the payoff table; (b) quantification of different criteria; (c) obtaining preferences from decision-makers regarding the different criteria; and (d) avoiding overlap between different criteria. These problems are being addressed in current research efforts. Meanwhile, this publication provides an alternative practical approach, the checklist, which serves as a vehicle for considering some of the points relevant to reservoir sustainability.

2.2.7 Rationale of the checklist for sustainable reservoir development and management

The aspects discussed in Section 2.2 are transformed into a checklist to be examined in various steps of reservoir planning, design, construction and operation. It is a collection of concrete actions to be taken during those steps. Although the list itself is presented in Chapter 6 as part of the conclusion of this report, the present section provides the rationale behind it. It is hoped that the checklist will serve as a guideline for implementation of the concept of sustainable reservoir development and management.

A sustainable reservoir is a reservoir designed and managed in accordance with the principle of sustainability. It is designed and managed as an integral part of the holistic system of society, land, air and water. The checklist was prepared based on the following rationale:

(1) Existing reservoirs are fully utilized.
Existing reservoirs, as well as those under construction or authorized to be constructed, are used or will be used efficiently, integrated with other physical and managerial components of water resource systems. Efficient use of existing reservoirs can offset or postpone the need for new reservoir construction or reduce their necessary size. Efficiency of reservoir operation may be enhanced, among others, by such means as conjunctive use with alternative sources, lengthening the life of a reservoir by sediment control, use of hydrometeorological forecasts and priority and flexible allocation of water rights among users.

(2) Alternatives are exhaustively examined.
The option of constructing a reservoir should be considered together with many other alternative ways, managerial or physical, that can equally attain the objectives to be achieved. This should include, as extensively described in Chapter 3, economic incentives, legal arrangements, modification and restructuring of existing water resource systems, use of other existing as well as new sources, efficient water distribution and use and many other demand management methods.
(3) Selection of a reservoir option should be made under the sustainability criteria.
A reservoir option has to be selected under the sustainability criteria, as discussed in the previous sections of Chapter 2, specifically considering future generations, ecological soundness, fairness to the indigenous people, robust performance, sedimentation and other long-term consequences, in addition to economic efficiency, reliability and structural safety.

(4) Reservoir size is determined using the least marginal environmental impact rule.
If the reservoir option is selected, the size should not exceed the level where the marginal socio-environmental impact is the least among all other alternatives that can provide the same level of satisfaction in objectives. There is no reason to increase a reservoir size if alternative means can provide the same objective with less negative impacts. This is the procedural means to ensure sustainable reservoir design, explained in detail in Section 4.3.4.

(5) Democratic decision-making process is followed.
The decision-making process on reservoir development should be open to all the indigenous people, affected people, interest groups and other public with full information disclosure related to the plan and be carried out in a democratic way at all levels of decision making. In the event that a reservoir is built, the life of the people involuntarily displaced should be taken care of until they and their community regain their existing vitality and viability.

(6) Mitigation measures are fully taken.
If reservoirs are built, construction, inundation and operation should be planned and implemented, by using all feasible mitigation measures, to minimize the negative environmental impacts and ensure the quickest recovery of the damaged ecological system.

(7) Reservoir is post audited over the full life cycle of its existence.
The reservoir should be developed and managed considering its full life cycle from the planning stage to the time when it is filled by sediments. The environmental situation, sedimentation and the reservoir’s use and impacts in the whole basin should be continuously audited and proper measures and modification have to be taken to make it function properly over its total lifetime.

(8) Systematic approach.
New technology and tools are emerging everyday. Various data are
acquired and are accumulating. A systems approach provides the greatest possibility to use these available resources for reservoirs so that they perform better with higher efficiency and reliability and to make the decision-making procedure more democratic.

REFERENCES


