GUIDELINES FOR SUSTAINABLE DEVELOPMENT OF WATER RESOURCES

J.M. Jordaan
Pr. Eng., Pretoria, South Africa

E. Wetzel
Consultant, Heldervue, South Africa

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Contents

Summary

The theme writing on *Hydraulic Structures and Data Acquisition Systems* deals with theme-related conceptual and structural considerations with regard to sustainability in the development of water resources. These concepts include the planning of water supply systems, the management of water projects, the design of hydraulic structural components, and the preservation of the environment. Criteria for sustainability are given, such as strategic planning, demand, and performance management. Problems with modeling, dealing with crisis situations, and avoiding structural and system failures are emphasized. A number of examples are given in this article.

An ethic of awareness, concern, and caution is encouraged in the interest of avoiding serious mistakes, irreversible changes, obsolescence, and technological failures. Two appendixes are included concerning the environmental impact of large dams and water projects.

1. Introduction: Conceptual Considerations

Before structuring the sustainable development of water resources, it is necessary to examine certain concepts and their interrelationships. Only thereafter can one confidently address future considerations about the hardware and structural aspects of a water supply development project.

1.1. Global Sustainability of Human Civilizations

One obtains two contradictory impressions when considering the development of human civilizations with regard to sustainability. One is *negative* in that it predicts, according to Plate, that the ultimate downfall of human civilizations under the cumulative effects of a population increase, resources depletion, and degradation of the environment is imminent and almost unavoidable. The other impression is *positive*, and the evidence seems to support it: life expectancy increases almost everywhere instead of decreasing, and increasing costs of basic foods and raw materials are not apparent.

According to the Dublin Statement at the ICWE Conference, there must be a greater recognition of the interdependence of all peoples and of their place in the natural world. One cannot merely consider a water supply project to be the particular solution at one place for a certain community. It must be seen as a small part of the global wholeness of water and people. Such considerations as those regarding environmental issues are both locally and globally tied together.

Statistics clearly show that global resources are deteriorating. On the increase are energy consumption; pollution of air, soil, and water; emission of greenhouse gases affecting *global warming*, *rising of sea level*, and ozone imbalance; and also, alarmingly so and seemingly in spite of the above, human population growth rate. Something must therefore be done on a large scale to avert the possible self-generated environmental crisis humanity seems to have created.

Brundtland states the implication that sustainability is an all-important issue; humanity has the ability to make development sustainable, to meet the needs of the present without compromising the ability of future generations to meet their own needs. Sustainability does imply limitations imposed by the present state of technology and social organization on environmental resources and by the ability of the biosphere to absorb the effect of human activities.

1.2. Sustainable Project Planning Incentives

Incentives also exist in water resources project planning, where according to COWAR: Substantial savings in operation cost and in return on invested capital are obtainable by efficient use of water and by management strategies that strive to guarantee that water is available to meet changing societal needs under changing supply conditions.

As stated by Bruce, *first*, development must not damage or destroy the basic life support systems of our planet Earth, the air, the water, the soil, and the biological systems. *Second*, development must be economically sustainable to provide a continuous flow of goods derived from the Earth's natural resources, and *third*, it requires sustainable social systems at international, national, and family levels to ensure the equitable distribution of the benefits of the goods and services produced and of sustained life supporting systems.

1.3. Water Resources

Sustainability is important in water resources development and becomes an important factor in the continuous development of societies.

Efficient, economical water usage is a prerequisite for development in many sectors of society, and its misuse poses serious and growing threats to sustainable development and protection of the environment. Human health and welfare, food security, industrial development, and ecosystems on which they depend are all at risk unless water and land resources are managed more effectively than they have been in the past, according to the Dublin Statement of the ICWE.

1.4. Hydraulic Structures

Sustainability is important in hydraulic structures and water supply systems within the above broader concept of water (and land) resources.

Criteria of sustainability must be applied to all kinds of water resource systems ranging from local systems, such as the water supply of a village from a local well or spring, to vast multistructure and multipurpose systems such as systems of large dams that are built to control floods, generate power, irrigate thousands of hectares of land, and that affect more than one nation. Society broadens the demands on water resources planners, engineers, and managers beyond traditional techniques and skills. Research and development are the necessary tools to meet these criteria as stated by Plate (see Appendix 1. Environmental Impact of Large Dams).

2. Design Concepts and Challenges

The implication of these challenges on the concepts for designing, operating, and maintaining water resources and water projects and what needs to be considered for global sustainability is seen to be by Plate as follows:

- A water resource system should be aimed at redistributing the available water of a region in space and time to meet the needs of society.
- Sustainability implies new criteria for all stages of water resources development: planning, designing, operating, and maintaining.

Also important is the environmental impact of large water projects (see *Appendix 2. Environmental Impact of Large Water Projects*).

3. Important Criteria for Sustainability

The following are the principal criteria affecting sustainability of water supply projects:

- Water resource systems are integral parts of the social system, and their interactions with society and environment need expert attention.
- Systems have to be well adapted to the local living conditions and environment and be flexible to future changes in demand or purpose.
- Systems must be resilient, amenable to lasting indefinitely, and restorable if destroyed by rare events.
- Changes such as fluctuations in the demand and supply of water, deterioration, and obsolescence should be anticipated and catered to.
- The above considerations regarding the impact on nature and society in the face of change from present conditions shifts the responsibility on communities for sound generation of water supply systems, from basic design to operation and maintenance.

4. Planning

Key elements such as dams, tunnels, and conveyances, may, to meet long-term objectives, be constrained by the availability of water inflows and the size of the reservoir.

4.1. Stages of Planning

Water resource system planning generally has four stages:

- Preliminary initiation
- Data assembly
- Project alternative selection
- Feasibility of a final project

The planning process proceeds in this orderly fashion until the final project is selected and adopted by the political powers (together with considerations of possible constraints or benefits from other plans).

4.2. Sustainability Criteria in Planning

Long-term use considerations will determine whether a dam in its initial form and in its projected lifetime would continue to comply with present and future societal needs. It might require raising, its usefulness might change, or it could become obsolete. Sustainability requires that during the planning and design stage, potential changes in the use of the water resource system meet changing societal needs. It is unlikely that a dam can be removed when no longer needed, therefore the decision to build it must be carefully taken; it is easy to postpone but impossible to revert, once taken and implemented, to the original condition. The loss of a dam, because of its collapse in a natural disaster, enemy action, or its own frailty, can likewise have serious consequences on the economic sustainability of a civilization, as stated by Plate.

4.3. Adjustment to Changes

Land use might change, society might change, e.g., from a rural to an urban predominance (as in ancient times it changed from nomadic to settled societies). Future generations must still be in a position to augment the source of water supply, and the design and operation of water systems must be adjusted accordingly; therefore:

- Sustainability implies that adjustments of a water supply system to a foreseeable change in land use and societal economic fabric can be made without necessitating expensive constructions or that provisions can be made for accommodating potential changes.
- Regarding global climate changes, foreseen by some but discarded by others, the issue is how stable the water resource is at the local level and how long might it take for a climate change effect to become influential. A precautionary principle is promoted: any disturbance of an inadequately understood system as complex as the Earth system should be avoided.

4.4. Reliability of Yield

A reservoir, to be sustainable, must be able to serve its purpose indefinitely on an assurance basis having a reliability of a yield nearly 100% of the time. Its safe yield depends on a sustained water supply derived from a fluctuating runoff. An understanding of its hydrology is important in assessing the reliability of a storage reservoir.

Because of the randomness, i.e. stochastic nature, of the hydrological processes, there are rare times in which a reservoir supply system may fail temporarily. Such situations should be met with emergency plans. Examples of these could be restrictions on water use or changing of operating rules. Other measures may also be considered to be prudent in the face of foreseeable water shortages. Sustainability means that supply shortages should be met with minimum impact on society.

4.5. Design Life

Design lives of key large structures must not be too short. Even if a design life of 50 years sounds long, replacement needed at the end of the service life of a structure could be taking a heavy toll from other much needed investments.

In designing reservoirs for arid regions, this fallacy is apparent in the case of storage loss due to accumulated sediment, as at San-Men-Xia Dam on the Yellow River in China. This reservoir lost more than 30% of its design capacity in the first 10 years of its operation. Loss of reservoir storage because of sediment has led to disrupted lifestyles in certain arid countries, where change from dry-land farming to irrigation had to be reversed.

Not only did the irrigation systems that subsequently failed create a debt load, but also the difficulties of having to revert to ancestral lifestyles added cost complications. These lifestyles were already forgotten during the time water from the (now abandoned) reservoir was still abundant. True sustainable development needs a reservoir that is so designed and operated that its active storage capacity is never prejudiced. This might imply the periodic raising of a dam to restore reservoir capacity reduced by sedimentation and hence would place future cost burdens on the present or the next generation.

4.6. Environmental and Social Changes

The environment itself might change; desertification or other climate change might occur and reduce the water yield from a catchment area.

Other claims on the water might detrimentally affect both the quantity and quality of available water. These may be caused by upstream developments on the river system, neighboring countries' demands on shared water resources, or the pollution of a main arterial river.

A reasonable margin of safety, flexibility, and room for expansion or development should therefore be included in the planning of any large-scale water supply project and its infrastructure.

5. Structural Considerations in the Sustainable Development of Water Resources

Not only should water supply projects in their entirety be sustainable, but also their structural components and elements, i.e. the dams, reservoirs, conveyances, and infrastructure, should be so created as to be individually sustainable.

5.1. Structural Design: Concepts and Principles for Sustainable Hydraulic Structures

The following considerations apply to the design of sustainable hydraulic structures: *sustainability, stochastic design, modeling difficulties,* and *structural integrity.*

- *Sustainability.* The concept of sustainability of a water resource development includes the design of structures, which with proper maintenance should last indefinitely or which if destroyed cause only a manageable disruption of living conditions.
- *Stochastic Design.* Design procedures should provide for any uncertainty in the variables, which enters from input uncertainties to design criteria. For hydraulic structure design in the water resources context, one has the following main sequence of criteria to satisfy, individually and collectively.
    - *Hydrology:* **D**ata must be adequate, well understood, and the information stochastically modeled.
    - *Hydraulics:* Methodology must be sound, adequate to deal with the spatial and temporal variables.
    - *Hydraulic structures:* Components must be designed to resist all loads, be permanent, maintainable, and cost effective.
    - *Environment: S*ystems must comply with the social order, be economical, and natural environment friendly, in perpetuity.

  There is a model as proposed by Duckstein for such a stochastic design scenario, based on mathematical principles.

- *Modeling Difficulties.* However, the difficulty of all models is that they never represent the *whole* of the physical world, and all models are an abstraction only of *some* aspects of a physical problem, which combines with many other aspects to form the physical reality of a water resources development.
  To this may be added: a *model* or a *theory* is only as good as the *assumptions* made; and in hydraulic or hydrologic modeling the future is linked to the past and to the present through a chaotic disorder/order process that is unpredictable because there are many equally probable outcomes out of many possibilities.
  Stochastic hydrology is applied in attempts to overcome this by considering many s cenarios in parallel, then designing for the worst of these on a so-called risk analysis basis. In one model, the design is schematically based on procedures, with due regard to the uncertainty of the design variables.
- *Structural Integrity.* In this model, a chain of events from *uncertain* hydrology, through *predictable* hydraulic behavior, to *exact* structural design, leads to a designed structure capable of resisting loads for *nearly* all likelihoods. This is based on a probabilistic modeling technique comprising an input/transfer-function/output process at all stages. Stochastic design, such as the above, however, unfortunately results in the presumption that a perfectly safe structure can never be built, which is not a viable proposition.

The structure will no longer serve its purpose if failure occurs under the combination of an extremely unlikely, but nevertheless not discountable, series of events. The water resources supply system depends on the functioning of this structure and all other structural components. Hence it will also fail to serve its purpose, unless an alternative recourse can be taken.

This implies that there has to be some built-in redundancy in the system. For example, the failure of a dam or of a pumping station transferring water might be mitigated by having recourse to a standby underground water supply system, which is held in reserve.

5.2. Structural Failure Scenarios

It may be difficult to persuade designers of the necessity of incorporating *failure* into the design considerations. Incorporating the *risk* of failure in the concept of sustainability is essential, and managers have to allow for such risks. Zero probability of failure would not (on account of cost or nonattainability) be an economical design consideration for any water resource system or component. Sustainability means knowing how to manage risk should the failure event occur and preparing to minimize the consequences.

5.3. Examples of Structural and System Failures

A few examples of structural failures, their causes, and consequences of system failure are given below.

- *Vaiont Reservoir* in Italy failed in 1961 due to a landslide nearly filling the reservoir. Although the dam itself survived, a village below the dam with its population of more than 2000 was totally wiped out by the flood. Subsequently, the project had to be abandoned—the reason being the loss of storage in the reservoir due to the slide material.
- *Gove, Matala, and Calueque Dams* in Angola were sabotaged by terrorists in the 1970s. As a result, the economy of a neighboring water resource-sharing territory, the present Namibia, was seriously set back. This territory, jointly with Angola and with the help of a third country, South Africa, had created these essential storage facilities for border-river hydropower production.

The Ruacana Falls power project on the Kunene River depended on these three reservoirs. It still survives, but at reduced capacity, and had to be augmented by importing thermal power by transmission line from South Africa. Hydroelectric power development on the Kunene River at Epupa Falls farther downstream is being investigated.

- *The Cabora-Bassa Hydroelectric Project* in Mozambique was sabotaged by terrorist attacks on the transfer power lines in the 1960s. Although the dam and powerhouse were unscathed, the project was nonfunctional for some 30 years. After political stability was again established, it was reactivated. In the meantime, part of the power need was met by increasing the thermal power capability.
- *The Zoeknog Dam* in South Africa failed during its first filling due to a construction fault. It was designed to support a new economic venture, coffee production, in a regional development project. Reconstruction of the dam was found to be uneconomical and the project was abandoned, thus sinking the coffee venture, too.

6. Technological Precautions

Technological advances take place continuously. Systems should not depend on obsolete techniques of the past. The vogue of the present often becomes the outmoded relic in the future. It should therefore be the aim of every designer and producer of a water supply system to guard against dysfunction on account of technological barriers.

On the other hand, technological advances may just prolong the life or restitute an almost defunct project. A process of retrofitting has come to the rescue of many hydraulic structures on the verge of being abandoned. More information about natural forces and hazards has nowadays come to hand that can readily be analyzed by high-speed computers to the benefit of humanity. This could prolong the life of structures and sustain the components of life-supporting water supply projects.

Technologies must be used in a sustainable water resource system to prevent natural events from becoming natural disasters. Large disasters cause large economic losses, and they may disrupt social structures and thus impair development for years, or even generations.

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Bibliography

Bruce J.P. (1992). *Meteorology and Hydrology for Sustainable Development,* WMO Pub. No. 769. Geneva, Switzerland: Secretariat of the WMO.

Brundtland G.H. et al. (1987). *Our Common Future,* 400 pp. World Council on the Environment. Oxford, UK: Oxford University Press. [An answer to the Club of Rome report *The Limits to Growth.*]

Duckstein L. and Plate E.J. (1988). Reliability-based Design Concepts in Hydraulic Engineering. *Water Resources Bulletin* ***24***, 234–245.

ICWE Dublin (1992). *Keynote Papers* No. 9 (R. Koudstaal et al.) and No. 10 (E.J. Plate). Dublin: University College. [Prospects for sustainable development. The *Dublin Statement* was concluded with at the ICWE Conference.]

Jordaan J.M., Plate E.J., Prins J.E. and Veltrop J.A. (1993). *Water in Our Common Future,* 150 pp. Paris: UNESCO, Committee on Water Research (COWAR). [Supplement to the Brundtland Report, *Our Common Future*, including water resource sustainability scenarios.]

Plate E.J. (1995). *Sustainable Development of Water Resources: A Challenge to Science and Engineering.* Water Resources Seminar, I.A.H.R. Congress, Tokyo, Japan. [Several statements in this article came from this source.]

Biographical Sketches

J.M. Jordaan is a retired professor of civil engineering and professional engineer in civil engineering hydraulics. He graduated from the University of the Witwatersrand (B.Sc. Eng.) and obtained the degrees M.S. (Wisconsin), Civil Engineer (MIT), and Sc.D. (MIT). He has lectured at the Universities of Hawaii, Delaware, and Pretoria.
His professional career included hydraulic and coastal engineering research with the Council for Scientific and Industrial Research in Pretoria, South Africa, and the US Naval Civil Engineering Laboratory, Port Hueneme California, US.
He specialized in hydraulic engineering practice for a period of 28 years with the Department of Water Affairs in South Africa and Namibia and was active as technical assessor for the proposed Misicuni Multiple-Purpose Hydroelectric and Water Project, Cochabamba, Bolivia, South America.

Erna Wetzel was born and raised in Pretoria, South Africa, where she obtained her B.A. degree in 1983 at the University of Pretoria. She worked for the Department of Water Affairs for five years as public relations officer, being responsible for, *inter alia,* the department's monthly magazine, *Water,* as well as assisting the theme editor with the text of volume *Large Dams and Water Systems in South Africa,* a publication of the South African National Committee on Large Dams (1994). She also assisted the theme editor with assembling and reviewing textual material for the theme of Hydraulic Structures and Water Data Acquisition Systems in this encyclopedia. After moving to Cape Town, South Africa, she continued working for the same department.

Ms. Wetzel is currently assigned to the Public Relations Division of the South African National Life Insurance Company (SANLAM) in their head office in Bellville, South Africa.