# Water resources development and management for developing countries in the 21st century: revisiting older and newer ideas

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The development and management of water resources involve several important scientific and technical questions, as well as logico-philosophical ones, yet they may strongly depend on economic, social, political and ideological influences. Some of these aspects are briefly examined considering the experiences of the developed countries in the 20th century, but with reference to developing countries in the 21st century.

**Keywords**: water resources development, water resources management, developing countries, soft path, determinism, uncertainty, randomness, stochastics

## 1. Introduction

The development and management of water resources involve several important scientific and technical questions, yet they may strongly depend on economic, social, political and ideological influences. The 20th century was marked with an unprecedented progress in both development and management of water resources in several countries in Europe and North America, as well as in Japan, whose water infrastructures development approached saturation. The situation is not the same in other countries, particularly in Asia, Africa and South America, where the building of infrastructures is only partial or, in some countries, insufficient to non-existent.

Will the developments in these countries in the 21st century benefit from the experiences in the already developed parts of the world and how? The answer to this question is not trivial. In the following sections it is attempted to study some aspects of the question, starting from politico-ideological ones, continuing with logico-philosophical, and ending with scientific and technical.

## 2. Political and ideological influences: Soft path and hard hypocrisy

Societies of the 20th century worldwide adopted a problem-solving approach, in which engineering solutions to real world problems had a prominent position. By modifying the natural environment using engineering means, societies benefited substantially. This allowed increase of the population and its wealth, better quality of life, more hygienic life style and, most importantly, spectacularly increased life expectation. Toward the end of the 20th century, as the infrastructures were completed to a large extent in the developed world, engineering started to lose importance and engineering solutions to existing problems were opposed, while virtual reality games gained the interest of the societies in the developed world. Environmentalism, the now dominant ideological current and social movement, focusing on environmental conservation and improvement, and emphasizing a duty to save the planet from diverse threats, has also determined the social views of water related problems and solutions. Most of these views are regarded “politically correct”, but sometimes this “correctness” may be a euphemism, if not a synonym for irrationality.

Interestingly, this ideology that was developed in the richest countries tried to influence the less developed world. This particularly concerns the dilemmas on water resources development and the questions about the appropriate scale of development in areas of the world not already developed. Certainly, the negative (and the positive) experiences from the already developed areas should be taken into account in exploring the opportunities and directions in less developed areas. However, just applying currently dominant ideological views, developed by people who live in the luxury of advanced (and in effect not questioned) infrastructure, brings in mind a land owner who, after building his villa, inhibits the neighbours to build in their own lands, which he regards as an extension of his garden.

The hypocrisy behind the promotion of this ideology is illustrated by the discussions that dam removal has significant environmental benefits for restoration of aquatic ecosystems and native fisheries. While the discussions are intensifying, what happens in reality diverges. An internet search will gather information from multiple sources that hundreds of dams have already been dismantled in an attempt to restore the health and vitality of rivers. However, more careful examination of specific data or photos of "dams removed" will reveal that these are small and rather old constructions that could be rather called barrages or embankments (with heights from less than a metre to a few metres). Magnifying stories of embankment demolition (necessary due to aging of the constructions), while at the same time keeping the luxury provided by the advanced large-scale infrastructures, has provided a fictitious element of realism of the environmentalist ideology, which may be necessary for its conservation.

This promoted perspective for water management of 21st century has become known by the name 'soft path' (Gleick, 2002, 2003). According to Gleick (2002), the soft path:

> "*by investing in decentralized facilities, efficient technologies and policies, and human capital […] will seek to improve overall productivity rather than to find new sources of supply [and] will deliver water services that are matched to the needs of end users, on both local and community scales*".

This has been promoted as a contrasting alterative to engineering solutions to problems that rely on infrastructure development, which Gleick (2002) calls the hard path and criticizes for:

> "*spawning ecologically damaging, socially intrusive and capital-intensive projects that fail to deliver their promised benefits*".

Interestingly, the groups that discourage building new water projects and promote their soft path, at the same time highlight projections on threats like bigger floods and droughts of greater duration due to climate change, as well as the need for adaptation to climate change. The soft path concept has become popular in several countries and international organizations (Brooks et al., 2009). Thus, it was argued that some "*major shortcomings of conventional water management [are] avoided by using the 'soft path*'" (Wagner, 2008—an UNESCO publication) and that "*the soft path opens new avenues for accessing capital*" (Leflaive, 2008—an OECD publication).

On the other side, in one of the rare instances that the concept was criticized, Stakhiv (2011) found it wholly inadequate for the needs of most of the developing world. An important very recent (July 2013) development is that the World Bank (2013) decided to re-engage in large-scale hydropower infrastructure after having withdrawn from it for the past two decades. The report of the World Bank (2013) highlights the fact that nearly 3/4 of potential hydropower resources in the developing world are yet to be realized, including more than 90% in Sub-Saharan Africa and about 70% in South Asia. The report now recognizes that for many countries, hydropower is the largest source of affordable renewable energy and that reservoir hydropower can pave the way for the later introduction of other forms of renewable energy. Furthermore it recognizes the unique ability of hydropower to instantly offset variability of other parts of the electric power system, as well as the potential for pumped storage to store, for example, wind power during periods of surplus. It is very positive that these unique abilities of hydropower (Koutsoyiannis et al., 2008, 2009;

Koutsoyiannis, 2011) are now understood by the World Bank and this creates hopes that it may be understood by others too. While this strategic change of World Bank has been carefully assessed and reported by some groups (Appleyard, 2013), naturally it disappointed other groups (Bosshard, 2013).

## 3. Philosophical aspects: Certainties and uncertainties, inflation and parsimony, monomeric and holistic approaches

Naturally, infrastructure development has also negative consequences. Perhaps the most adverse one is the implied delusion for elimination of uncertainty. Certainly infrastructure reduces the high variability of the natural processes and enables exploitation of natural resources, including water, in controllable, almost constant, rates that correspond to the human demand rates. However, this does not mean that uncertainty is, or can be, eliminated. If it could, this would have destructive effects as evolution and progress have been made possible because of change and the implied uncertainty. Also, uncertainty makes our world liveable. Were the future predictable without uncertainty, it would also be controllable and this would give an enormous power to an elite of technocrats for whom the future would have no secrets.

Several modern thinkers (Ravetz, 1986; Funtowicz and Ravetz, 1993; Casti, 1994; Rescher, 1995; Peterson, 1998; Chaitin, 2005; Taleb, 2007) point to randomness and uncertainty as intrinsic to science, nature and life. In addition, radical advances in physics, mathematics and natural sciences of the 20th century teach us similar lessons, i.e. (Koutsoyiannis et al., 2009):

(a) The *dynamical systems* theory has shown that uncertainty can emerge even from pure, simple and fully known deterministic (chaotic) dynamics, and cannot be eliminated.
(b) *Quantum theory* has emphasized the intrinsic character of uncertainty and the necessity of probability in the description of nature.
(c) *Statistical physics* used the probabilistic concept of entropy (which is nothing other than a quantified measure of uncertainty defined within the probability theory) to explain fundamental physical laws (most notably the Second Law of Thermodynamics), thus leading to a new understanding of natural behaviours and to powerful predictions of macroscopic phenomena, despite microscopic uncertainty.
(d) Developments in *mathematical logic*, and particularly Gödel's incompleteness theorem, challenged the almightiness of deduction (inference by mathematical proof) thus paving the road to inductive inference, characterized by uncertainty.
(e) Developments in *numerical mathematics* highlighted the effectiveness of stochastic methods in solving even purely deterministic problems, such as numerical integration in high-dimensional spaces (where a Monte Carlo method is more accurate than a classical deterministic method, and thus preferable for numerical integration, in spaces with more than four dimensions) and global optimization of non-convex functions (where stochastic techniques, e.g. evolutionary algorithms or simulated annealing, are in effect the only feasible solution in complex problems that involve many local optima).
(f) Advances in *evolutionary biology* emphasize the importance of stochasticity (e.g. in selection and mutation procedures and in environmental changes) as a driver of evolution.

Despite these advances, the deluded philosophical view pointing to the opposite direction, i.e. to the quest of certainties, which has its roots in the 19th century, dominantly affects science even today. The aspiration of deterministic predictability, based on perfect understanding of natural processes, is still regarded by many as the ultimate goal of science, while uncertainty has been regarded as the enemy of science. The current modelling attempts in all geophysical disciplines seek certainties. Specifically, it is hoped that, by cutting the natural systems into small nearly-homogeneous pieces and by describing the natural processes in each piece using differential equations, it would be possible to perfectly model and predict the system behaviour in detail and without the need of data. The differential equations could be, in principle, solved numerically thanks to the ever increasing power of computers. The prediction horizon has no limits then. In this vein, climate modellers cast routine predictions (albeit calling them projections) for the next hundreds of years, while there is no shortage of publications predicting the climatic state on Earth for the next thousands of years.

However, pragmatism and experience help us see that the more complex a system is, the more unpredictable it becomes. Also, the more detailed an approach is, the more data it needs to calibrate and the less reliable its predictions become. History of science teaches that feasible and convenient macroscopic views can better be achieved using the principle of parsimony, supported by the probability theory (e.g. the law of large numbers as well the principle of maximum entropy and its application is statistical thermophysics) or even by conceptual and systems approaches. Parsimony in process description is paramount and much more powerful, particularly for prediction (Gauch, 2003). There are several examples of complex hydrological systems where simpler and more parsimonious models gave better fits and better predictions than inflationary detailed models (Koutsoyiannis, 2013).

Often, such detailed (at a micro-scale) models for complex systems are in fact detailed only for parts of the system (those ones for which theories allow the detailed description), while for other parts oversimplified models or rough and naïve assumptions are used. Such approaches, which have been called monomeric (from the Greek "μόνος", i.e. "solely" and "μέρος", i.e. "part"), can be misleading because of the uneven treatment of the different system elements. Conversely, when all parts of the studied system are modelled in similar detail and are linked via feedback mechanisms, the approach is called holistic (from the Greek "όλον", which means "whole). A holistic modelling strategy involves model integration for all processes for all system parts (instead of isolation of certain system parts and study thereof as individual entities), parsimonious parameterization and hybrid manual-automatic parameter optimization based on multiple objectives. Clearly, a holistic approach is superior compared to a monomeric one (Nalbantis et al., 2011).

## 4. Technical aspects: Modelling and management of hydrosystems

Time horizons for planning and design of water infrastructures are several decades long. Even in (rational) water management the required time horizon is decade-long because a decision made today may affect the state of the hydrosystem for the next several years. A current widespread practice, encouraged by the climate change Zeitgeist, to use deterministic projections for such horizons (or even for the next centuries) is flawed as it underestimates the natural uncertainty and hence increases the risk (Koutsoyiannis et al., 2007, 2009).

However, proved methodologies exist which can work in complex systems under uncertain conditions and for long time horizons. Such methodologies are consistent with the philosophical principles mentioned in the previous section, i.e. full respect of uncertainty, parsimony and holistic approach, and are in effect based on stochastic simulation. The reasoning to prefer a stochastic approach is summarized as follows:

- In water resources engineering and management decisions are made with reference to the future.
- The future is (and will always be) unknown.
- Methods assuming known future conditions are common but inappropriate.
- Only stochastic approaches offer a scientifically rigorous method to cope with future uncertainty.

In stochastic simulation of input variables, such as rainfall and runoff, it is essential to use models (stochastic processes) consistent with the observed natural behaviour. It is particularly important to ensure consistency with the "trendy" character seen in time series of observations of natural processes. Such behaviour, in which excursions from the statistical mean are high and last long, is ubiquitous in nature and has been known with several names such as long term persistence or Hurst-Kolmogorov dynamics. Methods to generate synthetic series or fields respecting this behaviour in univariate, multivariate or even two-dimensional setting exist (Koutsoyiannis, 2000, 2001, 2002, Koutsoyiannis et al. 2011).

For the simulation of the internal state and the outputs of hydrosystems, as well as the optimization of their design and operation, the following notes could be considered.

- Hydrosystems are nonlinear with respect to their dynamics, operation constraints and objectives. Thus, linear programming methods, despite their fast and accurate algorithms, are inappropriate except for simple sub-problems within water management.
- Water management problems cannot be divided into sequential stages. The overall reliability and performance cannot be assessed unless a global view is acquired. Thus, dynamic programming methods are inappropriate.
- Water control problems may involve many variables. However, a parsimonious representation, in which the number of control variables is kept at a minimum has advantages.
- Typical problems are highly nonconvex in terms of objective functions and constraints, so that numerous local optima appear very often. This renders classical (deterministic) optimization methods useless.
- Uncertainty is always present, albeit often missed to include in modelling.
- Deterministic methods cannot deal with the uncertainty of future conditions (inflows, demands, etc.); even stochastic extensions of these methods (e.g. linear-quadratic-Gaussian control) necessitate drastic oversimplifications that make the obtained results irrelevant to reality.
- Problems may be multiobjective (may involve several performance criteria).

In seeking a general methodological scheme for water management, it can be noticed that, mathematically, water engineering and management problems include two sub-problems:

- An integration problem to find the performance measure of the hydrosystem, $J(\boldsymbol{\mu}, \boldsymbol{\lambda}) := \mathrm{E}[L(\boldsymbol{z}(\underline{\boldsymbol{x}}(\boldsymbol{\mu}, \boldsymbol{\omega}), \boldsymbol{\lambda}))]$. Here $\underline{\boldsymbol{x}}$ denotes the stochastic process of input variables, $\boldsymbol{z}$ denotes output variable, $\boldsymbol{\mu}$, $\boldsymbol{\lambda}$ and $\boldsymbol{\omega}$ denote, respectively, parameters of the hydrological inputs, parameters of the hydrosystem operation, and random components, while E[ ] denotes expectation (which is integration over the feasible space of the random components).
- A constrained optimization problem, in which we seek to determine the hydrosystem operation parameters $\boldsymbol{\lambda}$ (which become the control variables) that optimize the performance $J(\boldsymbol{\mu}, \boldsymbol{\lambda})$.

For both sub-problems the Monte Carlo method offers a feasible and consistent solution, while optimization in the second sub-problem is facilitated if the entire representation is parsimonious, i.e. if the number of control variables is kept at a minimum by involving a suitable system parameterization. The thus shaped general methodological framework is termed parameterization-simulation-optimization (PSO) (Nalbantis and Koutsoyiannis, 1997; Koutsoyiannis and Economou, 2003; Koutsoyiannis et al., 2002, 2003; Efstratiadis et al., 2004). Table 1 provides some key characteristics of the PSO approach (last column) in comparison to classical approaches which are characterized by inconsistences, as listed in the table.

**Table 1: Key characteristics of the PSO approach in comparison to classical approaches.**

| **Classical approach** | **Inconsistency** | **PSO approach** |
|---|---|---|
| Input time series are assumed to be known | Water management is made with reference to the future, which is unknown | The parameters of a stochastic (Monte Carlo) model of inflows are known |
| Control variables are the controlled water fluxes per time step | This results in inflationary modelling which contravenes the principle of parsimony and is meaningless due to the uncertain future | The **parameterization** approach, in which the control variables are the parameters of operation rules, radically reduces dimensionality |
| The system representation is simplified, so that it can be handled by classical methods | Common simplifications (e.g. discretization, avoidance of probabilistic constraints) annuls the optimality of the solutions determined | A faithful system representation and assessment of performance via stochastic **simulation** is possible and not difficult within a Monte Carlo framework |
| Simplified optimization methods, such as linear or dynamic programming, are used | Water management problems are highly nonlinear (except some simple sub-problems); dynamic programming is inappropriate | The nonlinear stochastic **optimization** is a general method that gives results in reasonable computational time |

## 5. Concluding remarks

The plurality of ideas spanning all aspects related to water resources, from politico-ideological to scientific and technical, in principle enable a richness of approaches that can be chosen and adapted to confront the diverse water problems worldwide. On the other hand, the currently dominant ideas may obscure or create confusion about the nature of these problems and the proper solutions, particularly in developing countries. Hopefully, the above discourse can contribute in mitigating this confusion. The general analysis leads to the conclusion that more large-scale water infrastructures (dams, hydropower plans, water supply and irrigation systems) are needed worldwide to meet increased water and food supply needs. In particular, more hydropower plants, preferably reversible (pumped storage) are needed to meet energy needs using the most effective and efficient renewable technology, as well as to meet energy storage needs and to make possible the replacement of fossil-fuel-based energy with renewable (and, hence, highly varying and uncertain) energy.

From a more technical point of view, the approaches to be chosen should recognize the dominance of uncertainty in nature and faithfully model it through stochastic approaches, instead of using unreliable deterministic projections. The stochastic character of approaches should not be limited to the modelling of hydrological inputs but could be expanded to represent the entire function of hydrosystems and the optimization of their design and management.

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