WATER RESOURCES SYSTEMS ANALYSIS

Lucien Duckstein
Ecole Nationale du Génie Rural, des Eaux et des Forêts/Laboratoire de Gestion du Risque en Sciences de l'Eau, Paris, France

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Contents

Summary

Functioning of a river basin is first described in terms of a simple system model, in order to agree on terminology and set the stage for a classification of decision and planning problems. In this classification, a distinction is made between single and multi-period, then multipurpose and multi-goal problems. The possible level and phase of development of a river basin are examined and the types of uncertainties that arise in planning are briefly reviewed.

Basic tools for analyzing water resources systems range from benefit-cost analysis, multi-criterion decision making and programming, cost-effectiveness analysis (CE) to artificial intelligence schemes. It appears that the CE methodology provides a simple yet fairly comprehensive step-by-step approach to water resources management, including ex-post or hindsight studies. Difficulties may emerge as soon as one of the steps of CE is not considered, starting with the failure to define carefully economic, social, and environmental objectives, constraints and impacts.

1. Introduction

The first task in this paper is to attempt to provide a unifying yet simple approach for attacking the complex problems that are encountered when managing water resources systems. There are many methods available and then many levels at which decision problems may be considered. Most approaches follow a common thread. Clearly, before rational decisions may be made, one must first define the problem on hand and at the same time understand how the system operates: how can we build a reservoir or a flood levee without some knowledge of the local hydrology? How can we even design it without knowledge of capital, operation and maintenance funds available and legal constraints that may be applicable during the lifetime of the project? How can we speak of sustainability if the long-range impacts of a project have not been estimated?

At this point, a model-based mathematical system model similar to the one introduced in chapter “Multi-criteria Decision Analysis in Water Resources Management” [by L. Duckstein and A. Tecle] will be sketched briefly, so as to make the necessary multidisciplinary approach manageable. First, define a discrete time scale and then the following five elements:

The first element is the state $\boldsymbol{s(t)}$ of the system; $\boldsymbol{s(t)}$ is a vector of descriptors of the presence and motion of all categories of water, (and related people or goods) at a given sampling interval that includes time t. Note that this interval may be a day, week, month or year. Elements of the state may be represented by an instantaneous reading of a meter or an average taken over the time interval of interest. This state is akin to an inventory listing, including the human factors: water demand and consumption, reclamation, institutional arrangements, population, local, regional and national economy, aesthetics, legal and political factors. Furthermore, as explained in the above mentioned chapter, the state also includes running criteria called performance indices.

The second element is the input $x(t)$ into the system, which is a set of functions and variables that modifies members of the state set. For example, a new international agreement is an input that may change the water quality state variable of a given transboundary river basin At least six broad classes of inputs may be distinguished: deterministic, uncertain (probabilistic) or vague (fuzzy) and, under each of those three categories, passive (non-controllable) and active (controllable). A flood is a passive probabilistic input. A reservoir release is an active deterministic input. Decisions such as subsidy, taxation, determination of a discount rate, flood plain zoning are also active deterministic inputs. Note that the consideration of a comprehensive set of input elements enables one to study the impact on a water resources system of decisions made “outside” of the water sector.

The third element is a function F that determines how the state changes as a consequence of the application of an input. More precisely, the state s(t+1) at time t + 1 is given by the state transition function

$$s(t+1)=F(x(t), s(t)) \quad (1)$$

For example, the human-induced content of nutrient loading into a river, a component of $x(t)$, changes the dissolved oxygen, a component of $s(t)$, to a value of $s(t+1)$. As another example, the input of a safety margin $\Delta H(t)$ added to an existing levee of height (state) $H(t)$ changes the expected flood damage to a lower value. Hydrological studies are necessary for the definition of system state and input.

The fourth element of the analysis framework is the output $z(t)$ of the system; this output may be chosen subjectively. It may simply be an element of the state, an objective function, such as the net benefit due to increasing the height of a levee, the expected number of lives saved by a flood warning system or the number of persons displaced by a dam. In general, the output may include a figure of merit composed of several performance indices.

The fifth element of the analysis framework is the output function G of the system. To obtain output $z(t)$, we define such a function or rule G that calculates or evaluates this output when the state is given:

$$z(t) = G(s(t)) \quad (2)$$

In this formulation, for example, the net benefit or cost of operation z(t) of year t is evaluated as a function of system state $s(t)$. The net present value would be a figure of merit evaluated over the whole lifetime of the system.

Systems may be coupled in series or parallel. A system coupled to itself means feedback. This simplified system description enables us to agree on a common language. The phrase “decision making” refers to the numerous decisions that must be made during the various water resources systems analysis phases. Such decisions include engineering aspects (size of a dam) and social ones (priorities for allocating water). In the remainder of this paper such decision problems are classified, basic approaches to decision making are described and embedded into frameworks designed to aid decision making, especially the so-called cost-effectiveness (CE) approach. The development of the CE methodology was first defined, in a systematic form, by Kazanowski in 1968. Applications are found in the references.

2. Classification of Decision and Planning Problems

2.1 Space-time Aspects of Problems

In real life situations, decisions are rarely taken in one large step: people usually follow a sequential procedure. For example, a plan may be set up to develop a river basin, but then the problem is decomposed into river sections (in space) and development phases (in time); decisions are taken within each section and phase. The problem is then to coordinate those various decisions, whenever a river basin is divided into sections, and an optimum plan should be drawn up jointly for that set. Juxtaposing the sections optima is acknowledged to be a sub-optimal procedure.

Most decision-making models are inherently for a single time period; the introduction of multiple periods creates conceptual and computational difficulties that may be insurmountable. Multiperiod or multi-section optimization may be performed using a dynamic programming approach that is an optimum procedure by definition. However, the method is seriously limited because the state vector ***s(t)*** should not have more than two or three elements; furthermore, a stochastic state transition function F (Eq. (1)) may render computations untractable; also, it is very difficult to use multi-objective decision models sequentially in time. Note that even if gross approximations must be used, it is preferable to seek an optimum for the complete time horizon or total river basin, rather than juxtapose section/local or stage optima calculated separately. This is well illustrated in standard operations research texts.

2.2 Multipurpose versus Multi-goal Problems

It is useful to distinguish between goals or objectives of a development scheme, and purposes of a project. In general, goals or objectives are stated in societal terms: economic efficiency, income distribution, self-sufficiency, social welfare, quality of life, safety, sustainability; while the purposes of a given structure, e.g., a dam, are given in physical (or engineering) terms: power production, navigation, flood control, water supply, irrigation. Thus, a multipurpose reservoir may be planned to satisfy either the single objective of economic efficiency, or the dual objectives of economic efficiency and social welfare. Further, a flood levee, which is a single purpose structure (flood control), may be built to satisfy the goals of economic efficiency, social welfare and safety.

In terms of system description, the attainment of goals is measured by elements of the output vector of Eq. (2), such as figures of merit, while purposes should be included into the system description itself (function F of Eq. (1)). Although it is easier to design multipurpose projects than multi-objective river basin systems, the objectives of planning, especially social ones, should always be clearly stated at the beginning of the process; most modern systems design methodologies, including CE, make this point quite clear.

Water resources system development may be started at various existing levels. Using the example of river basins, at the first level, the river must be trained, that is, elementary flood protection measures must be taken. Along many rivers in the world, this protection work was started in the early nineteenth century. At the second level, more sophisticated measures, such as flood plain zoning may be taken, and flood control reservoirs are built. The third and highest level of development happens when enough multipurpose storage capacity exists for utilization in the dry seasons (or years) of almost all the water available during the wet seasons (or years).

2.3 Uncertainties

It is important to recognize that several types of uncertainties may be present, otherwise poor planning may occur with high social and economic costs. This point is developed further in the Section 3.

In particular, the strategic uncertainties in the social goals should be identified. For example, environmental or sustainability objectives, which may be unimportant at the early stage of development, may later become primary goals. This is particularly true when uncertain consequences of water resources development occur, e.g., some unforeseen downstream erosion problems, or public health problems emerging because of water resources development (e.g., snail and other water-borne diseases in newly irrigated African and Asian regions). Finally, the uncertainty in the consequences of international agreements, which may involve not only water quality and quantity aspects but also political, financial and technical ones, should be taken into account.

3. Basic Approaches

A range of tools has been proposed in recent years to assist in the evaluation and management of water resources. These tools are variously named: benefit-cost, benefit-risk, systems analysis, operations research, simulation, cost-effectiveness, welfare theory or collective utility, multi-criterion approaches, sequential multi-objective problem solving, decision theory which include Bayesian decision theory and artificial intelligence (neural nets, fuzzy logic).

A brief review of some of these tools will now be undertaken.

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Biographical Sketch

Lucien Duckstein was a professor of Systems and Industrial Engineering and also of Hydrology and Water Resources at the University of Arizona Tucson ,USA,from 1962 to 1997.
He has then become a professor emeritus at the same institution and has since returned to his native city, Paris, France, as a professor at ENGREF (French Institute of Agronomy, Water Resources and Forestry).
His research areas cover multiobjective analysis, decision theory, statistical and Bayesian decision theory, fuzzy logic with applications to hydrology and water resources.