A Multicriteria Approach to Risk Analysis

Part II: Application

Pieter van Gelder
Faculty of Civil Engineering and Geosciences
Delft University of Technology,
Delft, the Netherlands

Lucien Duckstein & Eric Parent
Ecole Nationale du Genié Rural des eaux et des Forêts (ENGREF)
Laboratoire Gestion du Risque En Science de l'Eau (GRESE)
France

Abstract

Following the framework of part I of this paper, the steps of a Cost-Effectiveness (CE) approach with an an application to Water Resources Systems are presented.

1 Steps in the Cost-Effectiveness approach

Step 1. Formulation of goals

Very often the weak point of many projects is the lack of clearly defined goals. Consider for example the sole goal of flood control that may be understandable in a river basin such as the Brahmaputra in India where the flood problem is of preponderant dimensions. Shouldn't, however, other goals be listed as well, in case flood protection measures lead to some undesirable environmental effects? A comprehensive definition of goals may lead to the consideration of flood protection measures that are not always put forth by engineering firms, such as zoning, insurance, or other solutions. The formulation of goals is certainly subject to uncertainty, which may be called "model uncertainty". Indeed goal uncertainty may be of a strategic nature - environmental factors may not have been listed as goals earlier but may become important by the time the project is implemented. At any rate, environmental goals may be treated either as primary constraints to development, or as parallel to engineering and economic factors.

Step 2. Identify system specifications corresponding to goals

Specifications should be defined in order to quantify or at least characterize goals and constraints. The absence of well defined goals causes difficulties in listing an organized set of specifications that are meaningful to river basin development. For example, if the type of goal, i.e., national versus regional, and the related project purposes, i.e., industrial versus agricultural, have not been clearly stated at the beginning of the planning process, then confusing specifications are bound to result. On the other hand, single goal and/or single purpose projects may follow a standard procedure to define specifications, as presented in the next section, which is not to say that such a task is necessarily simple. In. general, engineering specifications cause no particular difficulty; Further, economic specifications are usually assumed to be given which may be a simplification of reality. Water "demand" is, to a great extent, a self-fulfilling prophecy. Also, it may be quite difficult to give precise specifications for social and environmental factors. Most papers do mention "social demands" or "social vulnerability" but there are no generally agreed upon ways to express these. In the end, one may resort to specifying indices such as the number of hectares to be irrigated, or the population at risk under a p% flood .

Step 3. Establish evaluation criteria or measures of effectiveness relating system capabilities to specifications

Most studies include an economic criterion, either explicitly or implicitly. Such a criterion fraught with various uncertainties may include several sub-criteria: present value, internal rate of return, cash flow, foreign exchange necessary, or, simply, net benefit. Clearly, economics constitutes an implicit constraint, but it would be appropriate to state this, so that one may consider the trade-off between reducing one kind of uncertainty versus reducing another one. As far as data are concerned, perhaps the greatest merit of the aforementioned Bayesian (BDT) approach is to provide an economic measure of the value of perfect information and of sample data.

It is important to establish a correspondence between specifications that reflect goals, and criteria that express how close the performance of a given system approaches the specifications. Thus, in a problem of irrigation development, specifications include:

numerical criteria, such as	*and non-numerical one*
costs, benefits,	reliability of the system,
decline of water table,	environmental quality,
salt loading into water bodies, especially aquifers	farmer participation,
employment	political acceptance.

To understand fully what is meant by a criterion, one may consider answering questions such as the following ones.

- What is the benefit of better accuracy of a reservoir inflow prediction?
- What is the value (in units to be defined) of 100 hectares of land added to an existing 1200 hectares recreational park?
- In other words, what is the benefit of reducing the various uncertainties in terms other than purely economic measures such as statistical or environmental?

Here again, suitable performance indices and figures of merit may provide an answer or at least a procedure to reach an answer. For some projects, such a detailed analysis may not be relevant but then how does one select the relevant features?

Step 4. Select a fixed-cost or fixed-effectiveness approach

A fixed-cost approach corresponds to a budget or resource limit: for a given amount of resources, identify the alternative system that provides the best values of effectiveness criteria. On the other hand, one may seek the least-cost alternative to reach certain water quality performance indices or to satisfy water supply figures of merit such as low risk and high sustainability, which would constitute a fixed effectiveness approach. Using both of these perspectives one after the other sheds light on the structure of a water resources system. The most common practice is to select a fixed-cost approach, yet, it appears that little explicit consideration has been given to this step 4 in the literature.

Step 5. Develop alternative systems for attaining the desired goals

In the discrete decision framework of the CE approach, one can construct a wide spectrum of distinct set of actions, that may be called "structurally" distinct, in the sense that they have completely different structures (one large dam versus three small ones) as opposed to "marginally" different alternative actions or decisions (a 78 m versus an 80 m maximum pool level).

A set of alternative decisions may be constructed in a "combinatorial" manner by taking a mix of pure actions. A more modern technique to construct alternatives is the generic programming one, in which only good alternatives produce offsprings which in turn are retained only if they are satisfactory. One should be careful, however, to avoid that the generation of alternatives becomes an end in itself: it should remain only one step of analysis.

Finally, it is often desirable to make a continuous problem discrete, which means that every point in the decision (or objective function) space constitutes an alternative action. Note that alternative actions should be defined only after specifications and criteria have been set. This is to avoid biasing the evaluation of actions toward "pet projects". On the other hand, for an ex-post study, respecting this ordering of the steps is not very important, because not much can be done about the past of an existing system. Most modern systems analysis methods point out that it is essential to consider distinct alternative designs to reach a given set of goals.

Step 6. Determine capabilities of alternative systems

In this step, statistical, operations research, decision-theoretic, artificial intelligence and general scientific methods may be of use. To illustrate this broad statement, consider the following:

- statistics can be used to estimate parameters and the structural reliability
- operations research which includes simulation provides both stochastic process results (queuing) and optimization schemes based on quantified performance indices and figures of merit;
- artificial intelligence methods help handle either large amount of input-output data or a sparse amount thereof (for example using fuzzy regression);
- general scientific methods are necessary to describe the hydrologic and socio-economic processes which determine for example supply and demand elements.

The outcome of this step is a vector of criterion values for each alternative action.

Step 7. Generate an array of systems versus criteria

In a sense, this array is the core of the CE approach and even that of most discrete multicriterion methods. The construction of the CE array emphasizes an essential feature of a coherent analysis of alternative systems, namely, that all those must be evaluated in terms of the same criteria. If this is not the case, then one has to return to the previous steps: the CE approach should be performed with several feedbacks.

Step 8. Analyze and compare merits of alternative actions

A multicriterion approach is now applied. It is preferable to use more than one type and then compare the results, say the rank ordering of alternatives. If the rankings are similar, it means that the order thus obtained is robust (and that techniques utilized are consistent). If there are large differences, one should investigate the reasons.

Step 9. Sensitivity analysis

A good system design procedure should include cycling or feedback loops. In terms of the simple system model presented. at the beginning of the report, the output z(t) is used as an input at time $t' \geqq t + 1$.

Step 10. Report the assumptions and analysis underlying the previous steps

This last step of the proposed cost-effectiveness methodology, which consists in reporting and documenting the rationale, assumptions, and analysis followed in the first nine steps, should be an integral part of any water resources system design. Following the performance of a system in order to learn from past mistakes can be done only with proper documentation. In fact, system design should include a so-called test plan which specifies how one will verify that the system performs as it is designed to perform. The CE approach has several merits. First, the approach is applicable to compare structurally different alternatives. Goals or objectives must be defined. This is contrary to benefit-cost analysis wherein it is generally accepted that the exceedence of benefits over costs is a measure of national income objectives. Further, the most crucial step in the CE approach is that alternatives in resources development have to be sought and compared on the basis of several criteria.

2 Application to Water Resources Systems

2.1 Introduction

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 and risks 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 and risk 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, and environmental objectives, constraints and impacts.

2.2 System Definitions

The first task in this section 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 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 or 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? At this point, a model-based mathematical system model similar to the one introduced in [1] 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 s(t) of the system; 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. 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 human factors: water demand and consumption, reclamation, institutional arrangements, population, local, regional and national economy, aesthetics, legal and political factors. Furthermore, as explained in [1], the state 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)). 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, or the expected number of lives saved by a flood warning system. 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)). 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 CE approach. The CE methodology was first defined in a systematic form by [2].

2.3 Classification of Decision and Planning 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. Just 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 2 or 3 elements; furthermore, a stochastic state transition function F 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.

2.4 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, say 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, such as figures of merit, while purposes should be included into the system description itself (function F). Although it is easier to design multipurpose projects than multi-objective river basin systems, the objectives of planning, 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 more than 150 years ago. 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).

2.5 Uncertainties

It is important to recognize that several types of uncertainties may be present so as to be able to cope properly with them - otherwise poor planning may occur.

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 become primary goals later. Finally, the uncertainty in the consequences of international agreements, which may involve not only water quality but also political, and financial ones, should be taken into account

3 Conclusions

Although more complete prescriptions for systems design exist than the cost-effectiveness format followed here, it is suggested that water resources systems development prefeasibility studies should begin as developed herein.

The following points have fundamental bearing in water resources systems analysis:

a) the system elements should be well defined,
b) goals or objectives of various nature (social, economic, environmental) should be clearly stated and preferably distinguished from purposes,
c) risk management is inherently a multi-criterion process,
d) specifications may be given in probabilistic or fuzzy logic terms so that the various types of uncertainties may be traded off in the analysis,
e) distinct alternative sets of actions should be considered and numerous tools may be applied to determine their effects on system behavior,
f) multicriterion schemes may be used to rank the alternative systems,
g) difficulties in the analysis may appear if any one of the CE steps is by-passed,
h) feedback should be present in project definition, design, and implementation.

References

1. Duckstein L. A systems framework for risk and reliability applied to hydrologic design and operation. In: Benedini M, Andah K and Harboe R (eds), Water Resources Management: Modern Decision Techniques, pp 29-57, Balkema, Rotterdam, 1992
2. Kazanowski A. D. A Standardized Approach to Cost-Effectiveness Evaluations. In: English, JM (ed), Cost-effectiveness: the Economic Evaluation of Engineering Systems, pp. 113-115, John Wiley and Sons Inc., New York, 1968