A Multicriteria Approach to Risk Analysis
Part I: Framework

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Abstract

Risk identification consists of defining the hazard, loss-causing event E, probability P(E) of that event, perception Pe(E,P(E)) and consequences C(Pe) of that perception. Risk identification is followed by risk management, whose purpose is to mitigate the risks, for example by reducing P(E) or C(Pe) and providing suitable risk communication to the population at risk. Since managing risk has a financial cost, that cost should be traded off with risk severity or frequency - hence a bi-objective model is naturally called for. Furthermore, several risks may exist, thus a risk-risk tradeoff constitutes a multicriterion decision (MCDA) procedure as shown in part I of this paper. These points are illustrated using hydrologic examples in part II.

1 Introduction

In this paper, it is shown that the risk management process is basically of a multicriterion nature, for risk mitigation or avoidence decisions have to be traded off with either the cost of those actions or else, other types of risk. For example, when deciding upon release volume from a reservoir, the risk of overtopping in the case of an incoming flood must be traded off with the risk of shortage that may occur if the release is too large and a drought occurs. As pointed out in [1], this release decision may be modelled as a game against nature: the notion of risk thus involves a bet or lottery.

In the next section, a definition of risk is given, comprising two phases: risk characterisation and risk management. The ensuing material describes a systems approach and then, a multicriterion analysis.

2 Steps of Risk Analysis

2.1 Risk Characterisation

Broadly speaking, risk may be defined as the following set of 7 elements:

$$R = \{H, E, P(E), C(E), \Pi(P(E), C(E)), D(\cdot)\} \quad (1)$$

Where:

H	a hazard set, say high rainfall on moist watershed
E	an event such as a flood
P(E)	the probability of E
C(E)	the consequence of E; a loss due to inundation
Π (P(E),C(E))	the perception of the consequence
D()	a decision procedure for risk management - for example a mitigation action on C(E) or a physical action on P(E).

The first four sets correspond to risk identification and the last two, to risk management. The result of risk identification is summarised as in risk characterisation, combining probability and consequences, for example:

"What is the minimum reliability of a given reservoir yield under predicted drought"

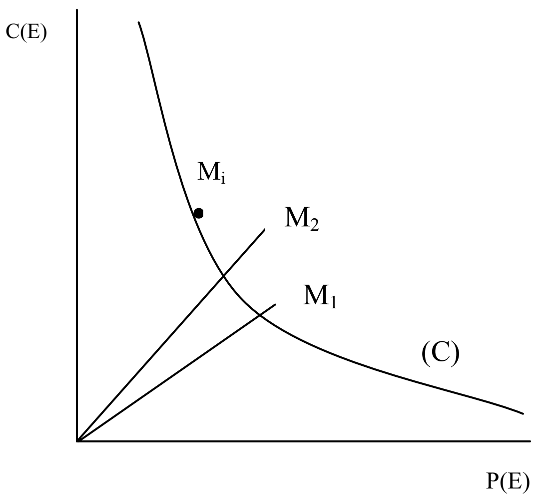

Figure 1. Trade-off between C(E) and P(E).

The consequences C(E) of an event may be monetary but difficult to estimate, or non-monetary: such as social disruption or deterioration of aesthetic functions or destruction of biodiversity. The perception Π(P(E),C(E)) is different for varying individuals or social groups. Thus, consequence can be everything and probability nothing or vice versa. Before communicating risk to people at risk, their perception of risk must be assessed, and addressed also. We are now facing a trade-off between C(E) and P(E), as sketched in figure 1.

This type of curve has been used to characterise and compare natural disasters: floods, dam breaks, fires, earthquakes. If one considers C(E) and P(E) as two criteria to be minimised, then we have a bi-objective problem with the typical feature that improving (here decreasing) one of the criteria necessarily determinates (also decreases) the other one. In fact, using composite programming to find an operating point M, one is lead to minimise measure of distance between ideal point O and the curve (C). This measure is the L_p norm:

$$L_p = \left\{ W_p \left| P(E) \right|^p + W_c \left(C(E) \right)^p \right\}^{1/p} \qquad (2)$$

P is the balancing factor
- if P = 1, there is perfect compensation between the two objectives, the solution point is M_1,
- if P = 2, a high value of either P or C is precluded,
- if P = infinity,

$$\begin{gathered} L_p = \max\left(W_p P(E), W_c C(E) \right) \\ W_p + W_c = 1 \end{gathered} \qquad (3)$$

there is a balance between P and C, solution point M_i. Taking equal weights $W_p = W_c = 0.5$ and P= 2 yields the Euclidean distance and solution point M_2.

2.2 Risk management

Whether for a design or an operation problem, one strives to reduce risk including occurrence of E and consequences C(E). Constructing flood central dams usually reduces P(E) and taking flood central measures decrease C(E): zoning, constructing dikes, reinforcing levees, creating recharge areas or wetlands. To compare alternative plans, a set of criteria should be defined, corresponding to objectives of the system, typically:
- ensure water supply (minimise water shortages)
- central flood damages- and water quality
- consider ecology and environmental factors
- minimise costs.

Criteria are usually risk-related, such as reliability, vulnerability, resilience. A pay-off matrix of alternatives versus criteria can thus be constructed. MCDA techniques are there applied to rank the alternatives in the matrix. Among the trade-offs are cost versus risk, or risk-risk.

Risk-cost trade off
The decision maker should trade off the cost of protection against an event E, which may be measures as, in a decision-theoretic formulation, the expected damage.
Risk-risk trade off
Sometimes protections against one type of risk may forget another risk.

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 follows.

3.1 Benefit-cost and Benefit-risk Analysis

Benefit-cost analysis is a method of evaluating the net value/benefit (or worth) of a project by computing and examining the ratio (or difference) of the monetary benefits derived from the project and the monetary costs associated with the project. The term benefit-risk emphasizes that actual dollars, say for construction, may be compared to expected dollars, say for risk avoided. These techniques have been developed since the sixties. Benefit cost analysis ". . . forces those responsible to quantify costs and benefits as far as possible," a point that can be made of all of the approaches discussed in this section. Benefit-cost analysis has the very valuable by-product of causing questions to be asked which would otherwise not have been raised. Further discussion of benefit-cost may be found in [2]. An extension of benefit-cost analysis is risk-cost which means developing a trade-off between risk and the cost of protection against that risk (flood risk for example).
One of the major problems with benefit-cost analysis is the complete absence of an a priori structure for handling a given problem: There is bound to be a certain degree of arbitrariness in initiating such a study. Since the necessary mathematical structure must be formulated in advance, subjective biases are often placed (perhaps unknowingly) into the framework. Consequently, a certain amount of arbitrariness is inherent in answering several fundamental questions : which costs and which benefits should be included how should they be evaluated, who pays and to whom do benefits accrue?

3.2 Bayesian decision theory

It has been observed that investment requires justification, justification is prediction, prediction embodies uncertainty, uncertainty is reduced by information, getting information requires an investment, investment requires justification, etc. ad circulum. Decision theory is able to break this cycle.

The value of additional data is defined as the reduction of opportunity loss less the full cost of obtaining the data including lost benefits. The basic premise is that data are of pragmatic value only if they may lead to a change of decision or action. The focus is not on the model parameters or the forecasts but on the decision to be made from the information generated by the model. The decision problem is rather trivial if the parameters and model are truly known. A common pratice in hydrology is to use point estimates without assessing the consequences of their uncertainty on the decision process. However, the presented framework allows for parameter uncertainty while assuming that the chosen model from which the parameters arise is correct. Extensions of this theory to uncertainty in models are possible. The above formalism has been computationally developed for a simple reservoir design problem, a bridge pier design problem, a flood levee design problem [3] and exceptional floods of a French river [4].

The risk may be considered as a measure of effectiveness of the CE approach as described in part II. BDT thus adds another quantitative dimension to a CE analysis because the expected economic value of additional data may be computed.

To date, BDT has only been developed for a single objective or loss function representing, allegedly, the decision maker's preferences. Literature within and outside the water resource field has recognized that optimizing a single objective function is not necessarily equivalent to following those preferences which usually reflect multiple objectives. There may be a considerable difference between the numerical value of an objective function and the worth to the decision maker of that number : we will therefore examine techniques for multiobjective decision making. We begin with a mathematical programming technique because it represents one of the oldest and most popular type of multiobjective approach.

3.3 Sequential Multi-objective Problem Solving

[5] presents an updated classification scheme for multiobjective problems. He distinguishes between aggregation models, interactive search models, partial order models and uncertainty reduction models. Of these groups, the interactive models seem to take the most cognizance of the observation that a decision maker's preferences are not equivalent to an optimized single objective function. These models actively include the decision maker in the search for a solution to the decision situation and so this individual's preference function may remain implicit within himself. The principal advantages of the interactive search techniques are:

1. No explicit weighting of the goals is required a priori. Explicit weighting seems to prejudge the future and tends to usurp the prerogatives of the decision maker to change his mind.
2. It allows the decision maker to revise preferences dynamically as available alternatives are offered.
3. It permits the final choice to reflect the preference structure of the decision maker as an individual.
4. It actively generates feasible alternatives rather than being restricted to a set of known feasible alternatives.

This last feature is exploited further in the genetic-type of algorithm developed by [6] called ESEMOPS for "evolutionary sequential multiobjective problem solving" (Evolutionary SEMOPS). It may be interesting to describe SEMOPS because it represents one of the first attempts to apply interactive multi-objective mathematical programming to water resource systems and has contributed to tracing an avenue of development of the interactive programming approach.

For solving multiobjective problems, [7] present an interactive technique that is characterized by continuous policy variables, nonlinear constraints, and nonlinear criterion functions. The underlying philosophy, motivated by the Gestalt school of psychology, is that in a perceptual sense, the problem and its solution cannot be separated from the environment or context in which the problem exists. Because the decision maker is an integral part of his environment, he must be part of the solution of the problem. It is next assumed that there are no "optimal" answers, but only "satisfactory" alternatives, in part because of the insensitivity of our preferences within certain. ranges of acceptances. Psychological research suggests that an individual can assimilate a maximum of 7 plus or minus 2 goals in a decision problem and that he operates upon them in some sort of serial manner as he searches for a satisfactory alternative. This point has been investigated further in the multicriterion literature. Using the above assumptions, [7] developed the algorithm SEMOPS. Each cycle consists of two subsequent phases : optimization and evaluation. After each cycle the decision maker can define a new direction of search or terminate the algorithm. In reality, SEMOPS is only an information-generating device; the decision maker still must make the choice among the alternatives. [7] demonstrate SEMOPS with a hypothetic case study of water quality management. Both deterministic and probabilistic aspects of the example have been explored.

Although many interactive programming techniques with user-friendly software have been developed since the studies just mentioned, relatively few real-life water resources systems have been designed or operated using these approaches.

3.4 Cost-effectiveness

Although about 30 years have past since CE was developed, it is felt that there are major benefits in applying it to prefeasibility studies nowadays. Strictly speaking, it should be noted that CE is a systems design methodology that should be preceded by a problem definition phase. CE is now described because for a long time, it had not been applied water or natural resource management, in contrast with benefit-cost analysis which exhibits a broad range of applications.

The CE method seeks to find significant differences in the costs or resource requirements of the available alternatives for approaching one or more goals while also examining the beneficial effects. Thus, CE compares alternative systems with each having a chance to meet a set of goals which, especially for water resources systems development, can and should include social goals, sustainability being the most important one. The CE approach can be schematized into ten steps (part II).

3.5 Operations Research

Operations research which deals with both simulation and optimization is the study of management tools whose description may be found in many standard texts are. Some of the tools developed are applied to water resources problems by [8] who also present an economic analysis of water resources systems. All these operations research techniques add their special and important insights to the growing fabric of understanding of the role of systems approaches to water resource management, as do physical, chemical, sociological or ecological models. We consider these models as elements in the decision process; but these models are not necessarily the primary tools in the decision process. The human element is usually predominant in terms of cultural features, public institutions, legal elements and changing preferences. It is thus important to include such social and human factors criteria. Note that design by operations research deals mostly with single objective problems, which is typically a net benefit index; furthermore, most models require full quantification.

3.6 Modern System Theoretic and Artificial Intelligence Methods

In roughly the past 20 years, several emerging techniques that may be grouped under the above title have been applied to an increasing extent to water resources systems analysis. These techniques include:

a) algebraic system modeling;
   i) polyhedral dynamics (Q-Analysis),
   ii) bifurcation, catastrophe and chaos,
   iii) finite state, discrete state and cellular automata theory.
b) Soft system modeling,
   i) artificial neural nets,
   ii) neuro-fuzzy modeling,
   iii) rough sets
c) System optimization approach,
   i) neuro-dynamic programming,
   ii) fuzzy and neuro-fuzzy control.

Since a detailed exploration of each of these methods is beyond the scope and space limitation of this article, the reader is invited to examine some of the bibliographic references provided below.

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