Risk and uncertainty in water resources planning and operation

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ABSTRACT Water resources projects have the following interrelated characteristics: benefit, cost, technology and risk/uncertainty. This paper defines the risks and uncertainties. The complexities of why little has been done to quantify these risks and uncertainties and to translate them into an ongoing practical methodology in decision-making are discussed. The problems are outlined of grouping the many types of risk and uncertainty into a small number of overall or specific risks and uncertainties. The importance is emphasized of reducing all project characteristics by risk/cost trade-offs to a single performance measure. The random variable of the effective benefit/effective cost ratio is presented as such a measure.

INTRODUCTION

If one searched for fundamental aspects of water resources planning and operation for which there has been a lot of talk as of importance and relevance but very little done in real terms of methodology of decision making and impacts in practice, one of these aspects would definitely be the treatment of risks and uncertainties. A review of regulatory and advisory activities on these topics within the USA governmental agencies and councils in the last 10 years will support
this statement. The genuine concern and apprehension have characterized water resources activities of public and private sectors in the USA in recent years from the standpoints of how to incorporate the effects of risks and uncertainties into various aspects of decision making in planning and operation (US Water Resources Council, 1983; report of the US Comptroller General, 1978; regulation series, US Corps of Engineers, 1975; plan formulation, US Bureau of Reclamation, 1977; US General Accounting Office, 1978; US Federal Register, 1973; etc.). Other studies have underlined both the importance and difficulties of treating risks and uncertainties in decision making (Mercer & Morgan, 1975; Taylor et al., 1979, Goicoechea et al., 1981). The book Risk/Benefit Analysis in Water Resources Planning and Management (Haimes, 1980), with 20 papers and panel discussion represents in many aspects a state-of-the-art on the subject as of 1980.

Two conventional economic performance measures used in the evaluation of water resources projects are the benefit/cost ratio and the exceedance of benefit over cost. They are computed by using the expected annual benefit and the expected annual cost. These two simple measures were considered sufficient in the era of rapid economic growth, with the "growth of economy" or the "survival of society" conceived as being at stake. When a society reaches an advanced level of development, with a high standard of living, requests are made to increase the quality of life. So, the expected benefit/cost ratio, or the net benefit, seem no longer adequate for selection of water projects.

The expectation of high quality of life, keen competition for limited investment funds, and wide public participation in complex decision-making processes, further require new approaches to design, evaluation and selection of water projects. This new trend in developed countries is especially concerned with finding the appropriate risks and uncertainties related to decisions, and their incorporation into the basic characteristics of a project, namely along with benefit, cost and selection of technology.

The present trends in water resources will likely lead to the following innovations in the most advanced planning and operation of water resources systems in the immediate future:

(a) Introduction of factors that significantly affect the decision-making process, particularly:

(i) selection of appropriate technology and the corresponding institutional framework, and
(ii) identification of risks and uncertainties that are inherent to water projects, and their introduction into the decision making.

(b) Consideration of benefit and cost not as constants but as random variables; and

(c) Development of methods of trade-offs between the basic four project characteristics of benefit, cost, technology, and risk and uncertainty.

DEFINITIONS OF RISK AND UNCERTAINTY

A very large number of random variables are involved in any decision
related to a complex project. They cover water supply, water demand, physical variables of the environment, technologies used, quality of materials and construction, and many other aspects that are subject to chance variations. Since any project is a part of the economic and social environment, it is affected by many chance factors. Projections into the future and assessments of all the factors that will influence the performance of a project, are also subject to high chance variations and uncertainties.

Three terms are often related to random variables of water systems: risk, reliability, and uncertainty, that should always be clearly defined. In this paper, risk is defined as the exceedance or non-exceedance probability of a decision value of the critical random variable. However, the economic risk may be also conceived as the product of the above probability and the consequence (value, damage, loss) due to the occurrence of an adverse event. For example, the probability 0.001 (1 in 1000) of a flood exceeding the critical design flood next year means a well defined physical risk. The product 0.001 x 3 x 10^5 = 3 x 10^5 is defined as the next year prorated damage, as the economic risk.

Reliability in design of a project may be defined as the difference between one and the risk probability, or otherwise. In the above example of the first definition of risk, the reliability (assurance) is 0.999 (one minus the risk).

Definitions of uncertainty are much less uniform than definitions of risk and reliability. In some of the US governmental documents (such as US Water Resources Council 1980, 1983) uncertainty is defined as related to non-quantifiable phenomena, while risk is defined as related to quantifiable random variables. For instance, the projection of population growth may be considered a non-repetitive event, difficult to forecast or quantify; therefore it is the part of uncertainty. However, the annual precipitation of a future year as repetitive can be quantified, so it is the part of the risk.

This example of definition of uncertainty shows a high arbitrariness, as the result of the concepts of "repetitive" and "non-repetitive" variables, or "quantifiable" and "non-quantifiable" variables. In fact, no strict difference exists between the annual change of population and annual precipitation, since both are repetitive and quantifiable. The basic difference is that the annual precipitation is a stationary stochastic process, at least for some time to come until the climate significantly changes (and can be well estimated in case of sufficient data), while the annual increment in population is rather a non-stationary stochastic process (with large errors in its estimation). The reason is that population may grow for some time, then stagnate, restart to grow, start to decrease, etc., which will be difficult to conceive as a stationary process, accurate in estimation for relatively long horizons of time.

Any random variable, either in nature or related to human activities, once identified and clearly defined, should be subject to a particular level of quantification by measurements or data collection. This quantification will range between zero and 100%. However, the two range extremes (0 and 100%) are rarely attainable in practice. It becomes difficult to divide a continuous range of quantification power only into their two extremes. Therefore, it is difficult to accept a definition of uncertainty in terms of either
repetitiveness or power of quantification. True risk always refers to the unknown probability of occurrence of random variables. This true value exists in nature regardless whether there are enough data to estimate it with a prescribed degree of reliability. In this context, uncertainty becomes closely related to the unknown risk, so that uncertainty should be defined rather as the lack of knowledge on the risk.

If nothing is known on a random variable, no guess or no assumption could lead to anything substantial in decision making; it can only confuse the issues by speculating on what might be or might not be in the unknown nature of things. There is a large risk that completely unquantifiable random variables, when used in decision making, may lead to a substantial increase of underlying risks.

Uncertainties are not only related to random, but also to deterministic variables, as the lack of knowledge. In essence, there are three types of uncertainties: (a) model uncertainty (or descriptive uncertainty, Rowe, 1977); (b) parameter uncertainty (or measurement uncertainty, Rowe, 1977); and (c) natural uncertainty (climatic changes, economic changes, even social and environmental changes).

PROJECT CHARACTERISTICS

The basic project characteristics are benefit, cost, technology and risk, as shown in Fig.1; they are conceived as mutually interactive. It means that it is not feasible in a strict analysis to appreciably change any one of the four without changing the other three. It is postulated here that the other project characteristics may be incorporated into one or more of the above four characteristics by the appropriate methods of analysis.

In the final count, the decision-making process in water projects is basically affected by: (a) identification and quantification of benefits and costs, both conceived as random variables; (b) selection of "appropriate technology"; and (c) identification of all types and sources of risks and uncertainties, and their quantification for decision-making process. Methods for finding reliable relations between the above four basic characteristics of water resources projects are advancing very slowly at present. The elementary, simple and constant number, conceived in the form of the benefit/cost ratio, is a unique and basic performance measure of water project feasibility. However, it should be supplemented by the other, also realistic measures of project performance, if further progress is to be made in the quantitative decision making in water resources planning and opera-
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To explain why the four interrelated characteristics of project performance have been difficult to integrate into a practical methodology, complexities of risks and uncertainties are first reviewed. The complex relations of Fig.1 are likely the major reasons that this practical methodology is still not available.

DIFFICULTIES OF TREATMENT OF RISKS AND UNCERTAINTIES

Many factors are responsible for the lack of appropriate methods of incorporating risks and uncertainties into the decision-making processes, but particularly:

(a) Rigorous definitions for risks and uncertainties do not often meet the practical standpoints, either because they are not relevant to the decision making, or they cannot be easily quantified.

(b) Identification of all types and sources of risks and uncertainties that affect planning, operation and survival of water resources projects, are usually missing in most analyses, since a systematic, exhaustive methodology for identifying types and sources has never been reliably compiled and published.

(c) Classification of risks and uncertainties by criteria useful in solving risk-related water resources problems, either is lacking or has not been exhaustively compiled.

(d) Quantification of risks and uncertainties has challenged the best professionals, and still is very difficult to do for most of their types and sources.

(e) Rigorous and careful analysis of the potential use, or misuse, of subjective probability in quantification or application of risks and uncertainties has rarely been successfully undertaken.

(f) Development of suitable methods for combining risks into a composite overall risk, for a subsystem or the entire water resources system, still awaits progress in practical implementation.

(g) Development of new and advanced application of existing methods for the quantitative evaluation of total uncertainty of a subsystem or system, as a composite uncertainty of all the types of uncertainties involved, seem to be so complex that it defies a simple synthesis.

(h) Development of practical interpretation of confidence limits, drawn around the critical design parameters or values of variables involved, that represent the effects of uncertainties, as well as the evaluation of their decision-making procedures, has little progressed in practical terms.

(i) Effects of risks and uncertainties on the selection of appropriate technologies for water projects, especially by the analysis of their fatal flaws, need progress before an applied procedure was developed.

(j) Studies of various quantitative relations between project risks/uncertainties and project benefits/costs, have received basic attention only recently.

(k) Reliable methods of determining the probability distribution functions, appropriate for description of random variables of benefits and costs, still have to be developed by a systematic collection of data and an appropriate synthesis.

(l) Methods for trade-offs between the benefit/cost ratio and
the risk, or in general of risks, benefits costs and technologies, are only in their initial phase of development.

Development of decision-making processes for water projects, which are based on the above concepts and methods, that integrate benefits, costs, and technologies with risks and uncertainties, seems to continue to defy professionals, basically because of a lack of systematic experiments on pilot projects and collection of appropriate data banks.

TYPES AND SOURCES OF RISKS AND UNCERTAINTIES IN WATER RESOURCES PROJECTS

A large number of types and sources of risks and uncertainties occur both in nature and in technical, economic and social environments of water projects. Figure 2 conveys schematically the fact that a project is subject to several types of risks and uncertainties. These types and sources relate to structures, associated subsystems, social, environmental, and economic makeup of affected area, etc. For instance, mechanisms of failure vary greatly from structure to structure. Further facts that affect system performance and that ought to be somehow accounted for in the planning phase, are: project age, physical decay, eventual death and retirement, as well as the practice of adding new structures to old ones. Over the years, substantial information was gathered on system performance during the "growing" and "middle" years of the project life. The matter of decay, death and retirement have been well spotlighted only in recent years, with the design of overhaul and replacement alternatives. The reasons are evident. Many water resources structures and systems, initiated or built in the industrial age 80-120 years ago or even earlier, have already passed not only their economic lives, but have deteriorated or even passed their relatively safe physical lives. Their lives are being extended expensively by the palliative measures, with their physical endurance subject to continuously increasing risks.

The types of risks and uncertainties of Fig.2 are basically four: physical-environmental, technological, socio-economic, and that of human performance. It is sufficient to review the major sources of risks in Fig.2 under these four types to conclude that the most difficult assessments of the overall risks and uncertainties are those cases for which several types and many sources of risks are simultaneously interwoven or superimposed.

Consideration of risks and uncertainties in decision-making process are depicted in Fig.3. They call not only for identification of all types and sources of risks and uncertainties, but also the development of benefit-cost-risk trade-off relations. Risk and uncertainty have both a real and a perceived aspect. These two aspects may have a distinct analogue in the dichotomy of "existent" and "imaginary", with the term "perceived" not necessarily synonymous with "imaginary".

The four project characteristics (benefit, cost, technology and risk), translated into the proper measures of project performance can be used either in a multi-criteria decision making (which is difficult and less reliable), or they can be reduced to only one.
measure, say the ratio of the effective benefit (benefit adjusted for technology and risk/uncertainty characteristics) to the effective cost (cost adjusted also for these two characteristics). Since the benefit and cost are random variables, and as the risk, uncertainty and technology do not change this property, the effective benefit/cost ratio is also a random variable.

AGGREGATED AND SPECIFIC RISKS FOR HIGH LEVEL DECISION MAKING

Regardless of types and sources of risks and uncertainties, the high
level decision-making process requires a reduced number of aggregated and specific risks. From the point of view of a top decision maker, the three risks, that may be mutually independent or dependent, are attractive for final decisions:

(a) Aggregated risks and uncertainties that describe the overall physical safety either of a system of individual structures, or of each of their major components;

(b) Aggregated risk and uncertainty that tell whether all the components of the system would or would not perform as planned or designed, so that real benefits and costs would depart from the assessed ones; and

(c) Aggregated risks and uncertainties for the project not to meet benefit or cost figures in the overall project performance (say, a much different B/C than that on which the decision to build the project was made).

Apart from the overall aggregated risks and uncertainties, many decision makers are interested in specific risks. For purposes of aggregating risks and uncertainties in computing these specific
risks and uncertainties of a subsystem or system, all the specific risks and uncertainties may be sorted into classes. The disaster-type specific risks (floods, storms, landslides, earthquakes, and other natural hazard events) are the aggregated risks of all natural disasters. Group of foundation random variables will produce the aggregated specific risk of performance of foundations. The analysis of economic or social factors should lead to the specific groups of random variables, which in their aggregate would produce the overall specific economic risk of not meeting the benefit, or exceeding the cost. Another group of random variables would lead in the aggregate to an overall social risk and uncertainty of the project, especially from an environmental impact viewpoint.

Objectives of developing and operating water resources systems is to satisfy the well-designed purposes and constraints (in water supply, flood control, hydropower, irrigation, navigation, recreation, water waste management, sediment control, low flow augmentation, fish and wildlife enhancement, etc.). It is of interest to individual purposes to identify their overall specific risks and uncertainties, because significant differences in risk and uncertainty may exist among these purposes in a complex water resources system.

The classification of risks should not be conceived as a goal in itself. It should be only a systematic approach for an overall estimation of risks and uncertainties through the affiliated groups of random variables, of very complex sources of risks and uncertainties. The entire set of interrelations, internal to the project and external between the project and the environment, can then serve to design both, the aggregated or overall specific risks of a project or a water resources system.

QUANTIFICATION OF RISKS AND UNCERTAINTIES

The most difficult problem faced by planners is the quantification of risks and uncertainties. It is considered accomplished when the appropriate probability distributions are estimated for key random variables that underline risks and are subject to high uncertainties in estimation of risk properties.

The quantification of risks and uncertainties should usually cover:

(a) identification of sources of risks and uncertainties specific to benefit, cost and physical safety of structures of individual purposes of a water system;

(b) derivation of probability distributions of risk variables, by the objective probability approaches, with all quantifiable uncertainties found in this derivation;

(c) find how sensitive are the overall values of risk and uncertainties to their sources;

(d) convoluting the components of risks and uncertainties into the overall aggregated or specific risks and uncertainties;

(e) analysis of the risks and uncertainties for the cases of catastrophic structural failures, with the corresponding costs and losses of benefits; and

(f) finding the way to aggregate the risks and uncertainties of
diverse sources, especially those of hydrologic, hydraulic, geophysical, structural, socio-economic and human performance types.

Uncertainty may be considered partially quantified when the confidence limits to any decision-affecting variable value can be estimated. Uncertainties basically cover the potential errors in the selection of probability functions and the estimation of their parameters in quantification of risk variables.

Two basic approaches to be used in quantification are:
(a) Search through the literature for reliable selection of probability distribution functions and reliable methods for estimation of parameters of random variables involved, which means finding the risks and the confidence limits to specific values of the risk-related random variables, as uncertainties in quantitative statements (Taylor et al., 1979).
(b) For specific cases, not previously well covered in the literature, carry the development, by special approaches to quantification, with the corresponding computation of risks and uncertainties.

SUBJECTIVE APPROACH TO RISKS AND UNCERTAINTIES
The danger always exists that subjective probability methods that are "thrown out of the probability house through the door" by using the objective criteria, may "come back through leaking windows". They do come back in various concepts of subjective probability for the use in water resources decision making at present.

The problem of subjective probabilities in risk analysis, in the sense that a planner, designer or consultant assigns subjective values to risks, or calls them uncertainties, say by intuition, "experience", or just by guessing, is a dangerous endeavour. Its real consequence is to avoid complex problems of quantification.

The subjective approach "if-then" may be sometimes acceptable to planners. This means if the probability is such, then the project risk or uncertainty will be such and such. This "if-then" approach may be a kind of camouflage, that hides the danger of using the subjective probabilities.

Modern probability theory has made tremendous efforts to develop methods of determining probabilities as objectively as feasible. Simply, if two statisticians compute risks and uncertainties by using these methods, the results would be close. If subjective probabilities are used, the results are usually far apart. Polling 50 economists on their projection of the next year inflation rate is an example of these subjective probabilities. They are determined from frequencies based on the 50 "intuitive" answers. Often there are cases when all 50 answers are far away from the next year figure, regardless of many objective factors that may help that projection.

AGGREGATED RISKS AND UNCERTAINTIES
Aggregated risks may be produced for a subsystem or a system of
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Water structures. For a dam as the subsystem, the reasonable question to ask is what is the probability that the dam would break next year? Let us assume that a rough computation shows that it is 1 in 10,000. This risk depends on many factors. One has to take into account all random variables which produce that risk, as one approach, or use the number of broken dams of a given type in a time period (say 10 years), and compare it with the number of existing dams, to assess that probability, as another alternative. Similarly, if the benefit-cost ratio is studied, the risk that it will be less than unity during the next 50 years may be evaluated as an aggregated, overall economic risk of the system.

A characteristic of any water resources project or system is the large number of sources of risk and uncertainty, distributed throughout the system, as well as inherent to planning, design, construction, operation and maintenance of a project. It is difficult to identify all their sources, effects, keep track of them through entire planning process, especially to assess the cumulative impacts on system performance, adjacent communities, and surrounding ecologies.

Existing analytical tools, accumulated experience, and structural technology are relatively effective in dealing with the first-order accuracy of estimates. For instance, given hydrological records on streamflow and specifications on downstream draft, it is relatively simple to determine storage requirements and risks. It is far more complex to obtain the second, third and higher-order accuracies, as would be required in the assessment of the cumulative impact of hydrological environment and human performance on the integrity of a system. Simply and categorically stated, the state-of-the-art does not provide tools to arrive at an overall reliability built into a system (and to state precisely: the modes of failure, the sequence of events leading to failure, and their probabilities of occurrence, in the sequence of events known as the concatenation). The dictionary defines "concatenation" as a series of interconnected things or events. Its use is appropriate for dependent events. A good theory of concentrated events in water resources systems would provide the framework for benefit-cost-risk assessments and their trade-offs.

Similarly as for the aggregated risk, all the errors and missing information that make uncertainty may be combined into an aggregated uncertainty. As an example, assume that the assessment of the risk for a dam to break next year is 1 in 10,000. Then, the confidence limits of say 1 in 200 and 1 in 500,000 can be conceived as representing the overall uncertainty in this risk assessment. Methods are needed, however, to determine how to proceed from individual uncertainties to an overall aggregated uncertainty.

Once uncertainty is assessed by finding the confidence limits (or confidence bounds) for a risk statement, these limits need the practical interpretations. For instance, in the case of the lower limit being considered as the true value, the use of the risk may represent an overdesign, while the case of the upper limit may mean an underdesign, or vice versa. When these limits can be determined, the planner needs special methods of interpretation in order to introduce these confidence limits into the decision-making process.
EFFECTS OF RISK AND UNCERTAINTIES ON SELECTION OF TECHNOLOGIES

The selection of most appropriate technologies for water resources projects in the planning stage is heavily influenced by risks and uncertainties, inherent to each technology. The history of many nuclear power plants in the last 10 years is the best example of how risks and uncertainties may affect the selected technologies, and through them the other performance measures in planning and design. Another example is the selection of the dam type. In selecting an arch or gravity concrete dam instead of a rockfill or earth dam, the risk of dam destruction by overtopping water is significantly decreased. Technologies to be selected by taking into account risks and uncertainties may vary in large ranges (from 3-4 redundant back-ups in the key nuclear power plant subsystems, to simple unique subsystems of an old technique in hydraulic engineering).

Risk-cost trade-offs exist for a given technology. Figure 4 depicts a general scheme of the cost of a technology vs. the risk associated in construction and operation of a project. As project cost increases, a given structure can be made safer by constructing the redundant subsystems, or using more expensive but better materials, or design structures for extremely high but low probability loads, etc. The point along the curve that represents an "optimum" and desirable design may be difficult to decide upon. It is particularly difficult when two or more decision makers are involved. In this plot, for instance, a "utility curve" is identified for the general public (decision maker A), and another "utility curve" for the water resources agency (decision maker B) conducting a project study. A utility curve is often called "indifference curve" because the decision maker associates the same utility (e.g. value) to any point along that curve. Therefore, it is the indifference in choosing one point over another. Points a, b, and c on the indifference curve A in Fig.4 represent the pairs of project
costs and risks, with higher risks for lower costs.

A decision maker might be willing to accept any of the three points, if they are technically feasible, e.g. they correspond to points on, or are close to, the technology curve. Point d is the contact of the utility and hypothesized or quantified technology curves. This may be considered as the optimum design point to a water resources agency. The location of decision-makers' utility curves in relation to the technology curve may vary highly from project to project, and from technology to technology. A compromise can be worked out among the decision makers for a single "preferred-optimum design point". This point usually falls along the "compromise frontier". When more than two decision makers exist, points d and e can be thought of as representing the two most differing preferences. However, this logical analysis may be only a hypothetical one in case of difficulties in producing the reliable utility and technology curves of Fig.4.

EFFECTS OF RISKS AND UNCERTAINTIES ON BENEFITS AND COSTS

There may be one-to-one relationship between the benefit/cost and the risk/uncertainty, once the selection of technology is made. Changing the risk usually changes both the benefit and cost. A search for relations of risk/uncertainty to benefit/cost justifies and/or enables the design of their aggregated project performance measures, because they permit a trade-off between risks/uncertainties and benefits/costs. If these important links are not found, statements on risks and uncertainties parallel statements on benefits and costs, as the two independent sets of performance measures. The decision maker is thus put in the position to intuitively compare risks and uncertainties with benefits and costs. It is much more objective when decisions are made after the trade-off.

Consider again Fig.4. Once a design point in Fig.4 is agreed upon, its associated cost C can be used to intersect the desired technology curve in Fig.5, which yields the benefit B. There are two major points to be stressed about the content of Fig.5. Given a technology, say T, all the points in the shaded area represent those conditions for which the B/C ratio will be equal to or greater than 1.0. Also, as technology is improved, it may be possible to obtain additional benefits for the same cost, as would be the case with points b and c. A level of technology can be thought of as the aggregate capability of specified sets of structural vs. non-structural project components; it also may reflect the degree of accuracy of forecasts of water supply and water demand.

Figures 4 and 5 can be combined to give the B/C ratio as a function of the risk inherent in a design, as shown in Fig.6. This function would have a range where it is convex and continuous. There are other possible shapes that address both the design-inherent risk and the perceived uncertainty.

In summary, the analysis of risks and uncertainties have two effects on project benefits and costs: (a) they make the benefit/cost ratio a random variable; and (b) they permit a trade-off between the benefit/cost ratio and the risk/uncertainty estimates.
FIG. 5 Benefit-cost-technology relationships.

FIG. 6 Benefit/cost ratio vs. risk.

PROBABILITY DISTRIBUTION FUNCTIONS FOR DESCRIPTIONS OF BENEFITS AND COSTS

The study of versatile sources of randomness in benefits and costs, and investigation of deviations of realized benefits and costs from their expected values in the planning stages of a project, eventually would lead to inferences on what kind of probability distribution functions are applicable to benefit, to cost and indirectly to their functions either of the benefit/cost ratio or the difference between the benefit and the cost (Goicochea et al., 1981; Taylor et al., 1979; Mercer & Morgan, 1975). The estimation of the standard deviation of probability distribution of the expected benefit/cost ratio about its expected value is crucial, with both parameters needed in the evaluation of a project. By introducing randomness into the benefit/cost ratio (at least by its variance or standard deviation) and by stating the probabilities
for the potential ranges in which the benefits, costs or their ratios may occur during the life of a project, a new dimension will be added to the entire decision-making process.

TREATMENT OF BENEFIT/COST RATIO AS A RANDOM VARIABLE

Once the benefit and cost are determined for a project as the two random variables, with their probability distributions estimated or inferred, the problem becomes one of finding the probability distribution of the benefit/cost ratio, and its parameters estimated. The confidence limits, assigned to the expected benefit/cost ratio enable their application in the decision-making process. The introduction of randomness into this performance measure, previously conceived as the constant benefit/cost ratio, will require many efforts before a working methodology is developed and accepted by planners and decision makers as realistic and practical.

The progress of science and technology of water resources has been mainly in replacing "intuition" or "sound judgement" by quantification of complex problems, as new technology becomes available. Whether the time has arrived for doing this progress in the benefit, cost, risk and technology relations at present, is a question of the overall assessment of the problems and complexities involved.

TRADE-OFF BETWEEN BENEFIT/COST RATIO AND RISK/UNCERTAINTY

Many examples are needed in trade-offs of risks, uncertainties, benefits and costs, before practical procedures are developed that will show in quantitative terms how a change in the risk can be exchanged by the changes in benefits and costs. A change of the risk is paralleled by either an increase or decrease in the benefit/cost ratio.

The variations of the benefit/cost ratio can be obtained by the two basic approaches:

(a) by an a priori approach, with inputs and outputs of the system simulated in the form of a set of samples of given size, with a method of their forecasts and operational decision makings, taking into account the resulting sampling variations in benefit and cost due to variability of all the economic factors involved in their computations; and

(b) by an a posteriori approach, in studying the benefit/cost ratios of projects that have been in operation for the sufficient times, and comparing the realized ratios with the expected ratios from the planning stage.

Each approach will require long systematic studies. Their success will depend on many factors, and the availability of appropriate and accurate data on various variables. It should be then expected that relations could be established between the parameters (at least the mean and standard deviation) of the probability distributions of benefit/cost ratio and the various levels of the overall aggregated or specific risks and uncertainties.
CONCLUSIONS

As expected, the analysis of risks and uncertainties in water resources decision making is a study of very complex problems, if they are realistically approached. Therefore, it is understandable that no methodology has yet been developed that would satisfy a large majority of planners, designers, operators and general decision makers. The only ongoing viable techniques of risk and uncertainty analysis are related to very specific problems, like food risk, dam failure risk, reservoir yield risk, etc. The procedures for determining the overall aggregated risks and uncertainties, especially those that require the aggregation of many types and sources of risks and uncertainties, still elude the modern analytical solutions of sufficient accuracies.

ACKNOWLEDGEMENT The research on stochastic water storage processes, leading to this paper, is sponsored by the US National Science Foundation, Grant CEE-79-16817. This support is gratefully acknowledged.

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