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Flood Damage Mitigation: A Review of Structural and Nonstructural Measures and Alternative Decision Frameworks

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Literature from diverse sources such as public expenditure economics, management science, geography, agriculture, and engineering reveals a wide range of decision frameworks for deriving flood mitigation strategies. These different types of decision frameworks are reviewed in this paper. The aim is to provide an understanding of these frameworks, along with their relative adequacies and inadequacies. Such an understanding reveals the directions along which the formulation of a more adequate framework should proceed. However, the formulation of a given decision framework is influenced by the types of economic benefits associated with the flood mitigation measures considered in that framework. Hence the various flood mitigation measures are reviewed, prior to the various decision frameworks.

1. INTRODUCTION

The objective of this paper is to review the wide range of decision frameworks which are employed in the formulation of flood mitigation strategies. Such a review warrants an understanding of the various flood mitigation measures and their economic significance. Hence the paper commences with a review of the various flood mitigation measures in section 2. This is followed by a review of the various decision frameworks in section 3. The final section deals with a comparative evaluation of these frameworks.

The commonly adopted measures of flood mitigation are classified into structural and nonstructural varieties. This classification is shown in Figure 1. Similarly, the decision frameworks could be classified into those dealing with (1) structural measures alone, (2) nonstructural measures alone, and (3) structural and nonstructural measures.

A detailed classification of these frameworks is presented in Figure 2 (see section 3). This classification enables a comprehensive comparison of the various decision frameworks. Such a comparison brings forth the relative adequacies and inadequacies of these frameworks and sheds light on how a more adequate framework can be formulated.

2. REVIEW OF FLOOD MITIGATION MEASURES

The basic aim perceived by most floodplain communities is to minimize flood losses and thereby maximize the gains that could accrue through utilization of the beneficial features of floodplains.

Following *Renshaw* [1961], flood losses may be classified into three categories. They are (1) direct income losses involving damage to property on the flood plain; (2) indirect income losses such as business interruptions, price rises, depletion of inventories, and unemployment of resources; and (3) intangible losses such as the costs of dislocations in family life and rehabilitation. At any one time, these losses cannot be predicted with certainty. Hence flood losses are often assumed to be a random variable with a given distribution. The mean of this distribution, namely the expected value of flood losses, is assumed to be the losses due to flooding during a given time period. Thus the adoption of flood mitigation creates benefits by reducing the expected value of flood losses.

However, the floodplain residents also take the risk of incurring losses other than those defined by the mean of the distribution [*Arnold*, 1975; *Burton et al.*, 1975; *Disaster Research Group*, 1961; *Kates*, 1962; *White*, 1975]. *Kaul* [1976], *Kaul and Willis* [1975], and *Lind* [1967] describe the risk taken by the floodplain residents in terms of the dispersion of losses around the mean. That is, risk taking is measured by the variance of the distribution of flood losses. The use of variance as a measure of risk taking is pervasive in the literature [*Anderson et al.*, 1977; *James and Lee*, 1971; *Kaul*, 1976; *Markowitz*, 1952]. On the other hand, the use of variance for this purpose has been questioned [*Tobin*, 1958]. However, *Markowitz* [1959] demonstrates that if either the utility function to be optimized is quadratic or the joint probability distribution of the uncertain event is multivariate normal, then variance occurs as an adequate measure of risk taking. Following the work of *Arrow* [1965] and *Pratt* [1964], the acceptable condition for using variance is only when the distribution function is multivariate normal; for example, also see *Bawa et al.* [1979].

Despite difficulties in measurement, risk taking is an explicit cost, and that cost is hereinafter referred to as the "cost of risk taking." Further, if the adoption of flood mitigation alters the distribution of flood losses to reduce the expected value of such losses, then the cost of risk taking is reduced as well [*Lind*, 1967].

2.1. *Structural Measures*

The various structural measures prevent inundation of the floodplain in different ways. For example, reservoirs reduce peak flows; levees and flood walls confine the flow within predetermined channels; improvements to channels reduce peak stages; and floodways help divert excess flow. The engineering and hydraulic aspects of structural measures are dealt

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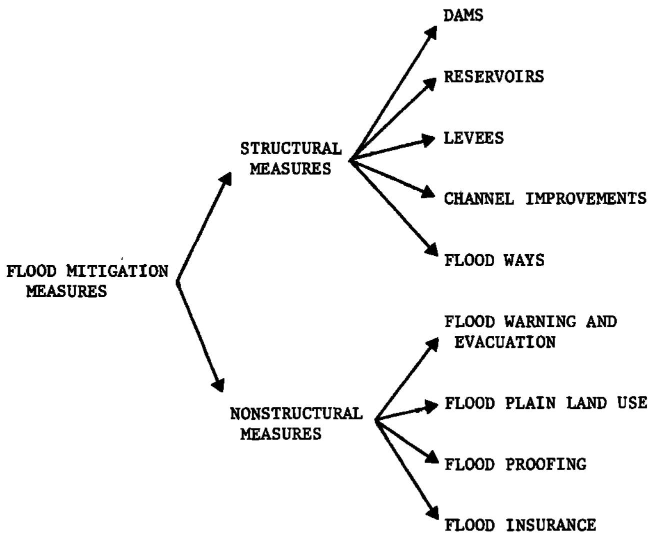

Fig. 1. Classification of flood mitigation measures.

with elsewhere [*Chow*, 1964; *James and Lee*, 1971; *Jarvis*, 1942; *Linsley and Franzini*, 1972]. Suffice it to note that structural measures alter the streamflow of rivers and channels, resulting in the reduction of the frequency and severity of floods. This includes the possible prevention of the more frequent smaller floods which on many floodplains cause a large proportion of flood losses [*Chow*, 1959; *Lind*, 1967]. Hence structural measures alter the distribution function associated with flood losses to reduce both the expected value of flood losses and the cost of risk taking (that is, variance of flood losses).

However, two features of structural measures need to be noted. First, structural measures do not provide complete protection against flooding. They only reduce the expected value of flood losses and cost of risk taking. Hence some residual flood losses and risk persist after the adoption of structural measures.

The second feature is that structural measures can often create a false sense of security [*Krutilla*, 1966; *White*, 1964]. The belief that the probability of flooding has been reduced could lead to an intensive development of the floodplain. Consequently, the expected value of flood losses may tend to increase. Such has often been the case, especially in urban floodplains [*Krutilla*, 1966; *U.S. Water Resources Council*, 1972; *White*, 1975]. *Brown* [1972] uses a simple conceptual framework pertaining to floodplain investment to demonstrate (1) how high income-generating enterprises will be attracted to the floodplain following the adoption of structural measures and (2) how consequently the expected value of flood losses and the cost of risk taking will increase.

The consensus among several authors [*Brown*, 1972; *James*, 1967; *James and Lee*, 1971; *Lind*, 1967; *White*, 1975] is that the adoption of structural measures alone could lead to suboptimal development of the floodplain. Therefore the need to regulate floodplain development along with the adoption of structural measures is explicit. Such regulation may be achieved through certain nonstructural measures such as floodplain land use planning.

2.2. *Nonstructural Measures*

2.2.1. *Floodplain land use planning.* Floodplain land use planning involves the derivation of a pattern of development on the floodplain in order to reduce the expected value of flood losses and the cost of risk taking. Such planning involves an analysis of the various land use options on the floodplain. This analysis is often facilitated by the classification of the floodplain into various zones based on the frequency and severity of flooding. In fact, in the literature [*James and Lee*, 1971; *White*, 1975] the term floodplain zoning is often used interchangeably with floodplain land use planning. The various land use options are defined by the location of economic enterprises in the various zones of the floodplain. Some of these enterprises may be more vulnerable to flood losses than others. The pattern of development derived from the analysis of land use options may either (1) prohibit these more vulnerable enterprises from the floodplain or (2) locate them in less hazard prone zones. In the event of all land use options being vulnerable to flood hazards, the pattern of development may dictate the preservation of some or all zones (that is, the zones to be left intact without any development). Hence floodplain land use planning performs the role of regulating the pattern of development on the floodplain.

Brown [1972], *Krutilla* [1966], and *Lind* [1967] provide arguments against floodplain land use planning. For example, *Lind* [1967] states that the expected value of flood losses which may be decreased by zoning will be at the cost of forgoing certain uses which could earn greater expected net returns on the floodplain than elsewhere. On the other hand, *Kates* [1962] and *White* [1964] indicate that some of those seeking employment on the floodplain either are ignorant of flood hazards or assure themselves of assistance from the state in the event of a disaster. Ignorance can be combated by education, and unwarranted charity by collective will. Strictly speaking, education and public determination to resist the meeting of private costs are also flood mitigation measures [*Kunreuther*, 1976]. Contrarily, *Brown* [1972] and *Lind* [1967] argue that even better, and less costly, might be a program of mandatory flood insurance. However, difficulties exist in implementing such a program [*James and Lee*, 1971; *Koch*, 1957; *Neville*, 1957]. A further case against zoning stems from (1) imperfections in knowledge that zoning authorities may have [*Brown*, 1972] and (2) scope for inflexibility and corruption inherent in resource allocation by regulation.

Implicit in the arguments against floodplain zoning is concern about the denial of freedom of choice in land use. However, the freedom of choice assumed to exist in a perfectly competitive economy coincides with a parallel assumption of perfect knowledge. If floodplain occupants are ignorant of flood hazards, then denial of freedom to use land in certain zones is perhaps appropriate and may even promote the knowledge of flood hazards. This would be particularly so where public education is prohibitively expensive or ineffectual.

The way in which zoning and land use decisions are made is important. If they could be derived through procedures which incorporate rational economic reasoning, then floodplain land use planning could contribute to the maximization of public welfare.

2.2.2. *Flood insurance. Lind* [1967] outlines the nature of the economic benefits created by flood insurance as follows. Assume that an insurance policy covers all economic losses caused by floods at a premium equal to the expected value of flood losses. Within such a context, floodplain occupants need to add this premium to the cost of being on the floodplain. Hence the expected value of flood losses is the same either with or without such a flood insurance policy. Flood insurance does not therefore create benefits by reducing expected value of flood losses. On the other hand, however, the cost of risk taking is eliminated. Hence in the absence of transaction costs, flood insurance creates benefits by removing the cost of risk taking. However, in reality, there are transaction costs associated with any insurance policy. Hence flood insurance will create a benefit only if the amount by which the premium exceeds the expected value of flood losses is less than the cost of risk taking.

Irish and Burton [1973] list the following advantages of flood insurance: (1) making floodplain occupants aware of the risks involved; (2) complementing structural measures by removing residual risks, (3) being relatively less costly than structural measures, and (4) creating environmental advantages by not interfering with nature.

Krutilla [1966] considers flood insurance to be a viable alternative to structural measures because the net effect of flood control (structural measures) legislation in the United States has been to increase flood damage potential even after many millions of dollars were spent. (The flood damage potential increases because structural measures can induce a false sense of security, as shown in section 2.1.) *Brown* [1972] and *Krutilla* [1966] provide further arguments in favor of flood insurance as follows. When flood disasters take place, the community at large steps in to help the disaster victims. Although such community effort is charity, it is also a way of spreading the flood risks. However, this spreading of risk is inequitable because persons not affected by flooding also bear the costs. Flood insurance restores this equity and enables floodplain occupants to meet their own costs.

Lind [1967] notes certain difficulties in implementing a flood insurance program. Most mutual insurance schemes are based on the assumption that losses incurred by the insured individuals are statistically independent. That is, all insured individuals will not incur losses at the same time and hence will not claim compensation at the same time. This, however, is not the case with floodplain occupants. When inundated, all policy holders in the floodplain will claim compensation at the same time. Consequently, a situation could arise where the claims exceed the pooled premium payments. Hence few insurance companies would accept such a risk. In order to avoid risks to insurance companies, *Brown* [1972], *Krutilla* [1966], and *Lind* [1967] argue in favor of mandatory national flood insurance. *Lind* [1967] further advocates government assistance where government absorbs the loss incurred by insurance companies. In such a scheme the insurance industry has to insure against regionally specific losses with the central government. If not, the restoration of equity through flood insurance in terms of cost bearing becomes infeasible. However, the difficulties in enforcing mandatory insurance schemes [*Foster*, 1957; *James and Lee*, 1971; *Koch*, 1957; *Neville*, 1957] and the unwillingness of governments to engage in such schemes [*Neville*, 1957; *U.S. Congress*, 1966] tend to render flood insurance ineffective. In the context of such difficulties, *James and Lee* [1971] argue that insurance premiums could be high enough to discourage any economic development on the floodplain.

On the other hand, *Kunreuther* [1976] reveals that a nonmandatory flood insurance scheme has been unsuccessful in the United States, despite a 90% subsidy from the federal government. This is due to the lack of awareness by individuals with respect to (1) flood losses and their probability of occurrence and (2) availability of insurance and the terms of a policy. Hence *Kunreuther* [1976] suggests the following measures to enhance the adoption of flood insurance: (1) provision of incentives for insurance firms to educate floodplain residents on matters such as flood losses and terms of insurance policies, (2) revision of federal government legislation in terms of liberal disaster relief, and (3) the introduction of requirements by private and public lending organizations that some form of comprehensive disaster insurance is a condition for issuing a mortgage.

White [1975] and *White and Hass* [1975] indicate that decisions pertaining to flood insurance could be made subsequent to decisions on other measures. This is because the adoption of measures other than flood insurance could reduce the expected value of flood losses and the cost of risk taking and so would warrant feasibly low insurance premiums.

2.2.3. *Flood warning systems.* If the occupants of a floodplain can be warned of an imminent flood, then precautionary measures (such as evacuation and erection of temporary damage reduction structures) can be adopted. This means that only a portion of the floodplain property is left exposed to flood hazards. Consequently, the expected value of flood losses is reduced. Since efficient flood warning systems are capable of predicting any level of flooding (including those capable of causing catastrophic losses), the cost of risk taking is also reduced.

A flood warning system is an effective mitigation measure because of the "flood to peak interval," that is, the time interval on the rising limb of a flood hydrograph between flood stage and flood peak [*Chow*, 1964]. Flood peak denotes bank overflow and inundation. In this context, *Scheaffer* [1960] recommends the following classification of floods on the basis of flood to peak interval (FPI): type F floods, where FPI is less than 1 day; type M floods, where FPI ranges from 1 to 3 days; and type S floods, where FPI is greater than 3 days.

The various precautionary measures floodplain occupants could adopt rely on two aspects of a flood warning system. First, the warning can be most useful if a flood prediction includes not only the time of flooding but also the magnitude of flooding. Further, a priori reasoning suggests that the greater the predictive accuracy of flood warning, the greater the value of expected flood losses prevented and the less the cost of risk taking.

The second aspect is the scale of operation of the warning system, namely the radius over which the warning could be received. The benefits to society increase if an expansion of the radius of warning includes additional floodplain communities.

2.2.4. *Flood proofing.* *Scheaffer* [1960] defines flood proofing as a body of adjustments to structures and building contents. These adjustments are designed to reduce flood damages and are classified into three categories, namely, (1) permanent measures which are not contingent on flood warning, such as choice of material less susceptible to flood damage in the construction of buildings and construction of elevated buildings, (2) contingency measures which are implemented after the receipt of warning such as closure of unnecessary openings and sealing of walls to prevent seepage, and (3) emergency measures which are carried out during the flood, such as the use of sand bags. Flood proofing reduces to some extent the expected value of flood losses and the cost of risk taking.

This review of the various flood mitigation measures reveals that (1) the adoption of all flood mitigation measures, except flood insurance, creates economic benefits by reducing both the expected value of flood losses and the cost of risk taking and (2) the adoption of flood insurance creates economic benefits by reducing only the cost of risk taking. The maximization of these economic benefits is the central objective un-

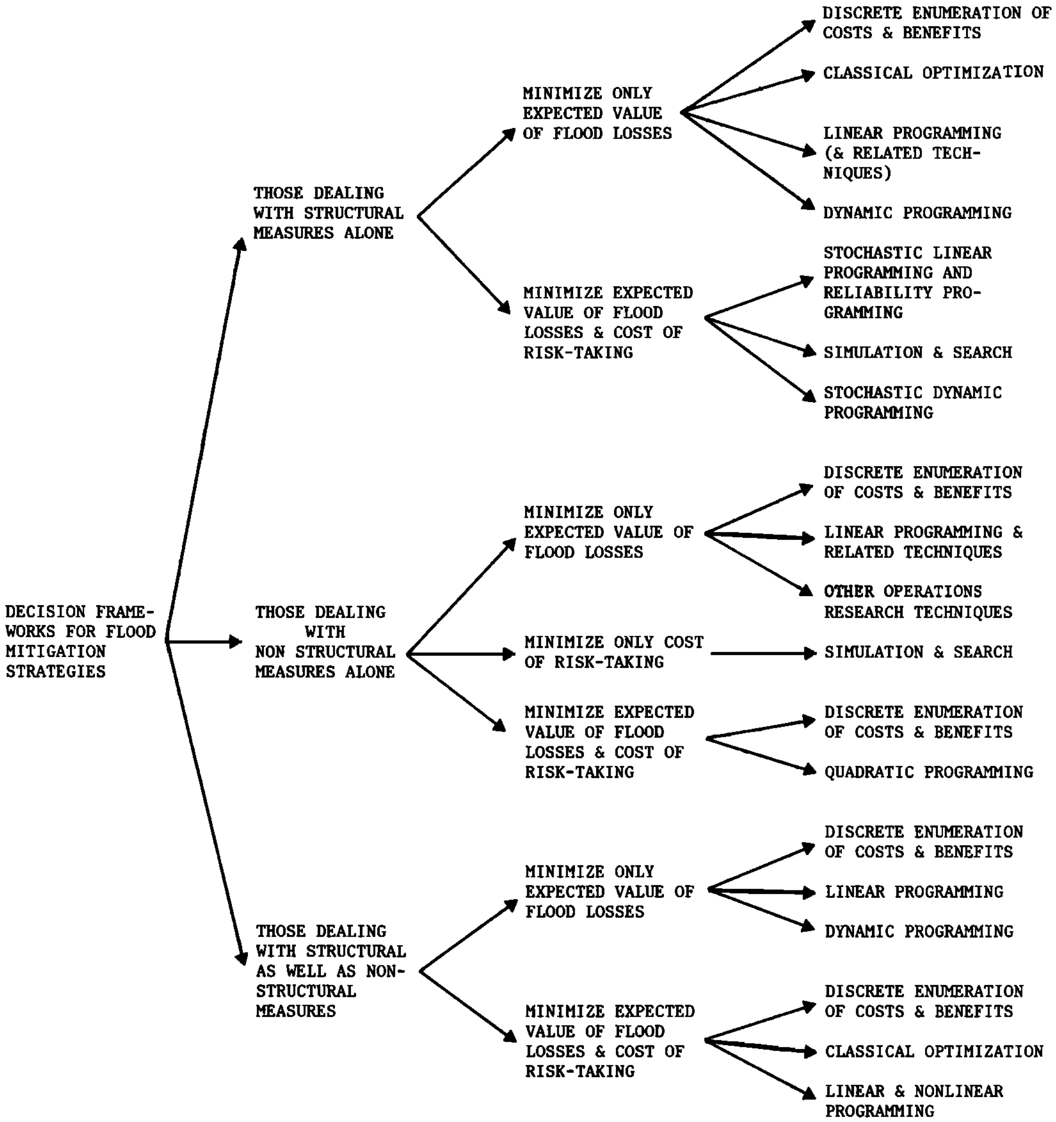

Fig. 2. Overview of decision frameworks for flood mitigation strategies.

derlying the strategies involving the adoption of flood mitigation measures. Such strategies are derived through various decision frameworks as revealed in the literature. These decision frameworks are reviewed in the next section.

3. REVIEW OF THE VARIOUS DECISION FRAMEWORKS USED IN THE DERIVATION OF FLOOD MITIGATION STRATEGIES

The formulation of a flood mitigation policy will involve the elicitation of optimal quantities of the various flood mitigation measures, namely optimal capacities of reservoirs and channels, optimal patterns of land use, optimal magnitude of flood insurance premiums, and optimal investments in flood warning systems and flood proofing. A decision framework permits such elicitation.

The classification, shown in Figure 2, is based on the consideration given in the frameworks to (1) the types of flood mitigation measures, (2) the nature of the economic benefits created by the measures, and (3) the techniques of analysis employed. The review of frameworks follows this classification.

3.1. *Decision Frameworks Dealing With Structural Measures Alone*

The major decision variables encountered in these frameworks are those pertaining to design and management aspects of structural measures. The design aspects include variables such as the capacity of reservoirs and the height of levees. Management aspects include variables such as timing of reservoir inflow discharge.

The various decision frameworks dealing with structural measures may be classified into two broad groups, namely those dealing with the minimization of (1) the expected value of flood losses and (2) the expected value of flood losses along with the cost of risk taking.

Although structural measures inevitably reduce both the expected value of flood losses and the cost of risk taking, the above distinction depends on whether the minimization of the cost of risk taking is explicitly stated as an objective in the decision framework.

3.1.1. *Decision frameworks for structural measures: minimization of expected value of flood losses alone.* The explicit objective of these frameworks is to choose levels of design and/or management variables to minimize the expected total costs of flood mitigation. In this context the expected total costs consist of three components: costs of constructing structural measures, operating costs, and the expected value of flood losses.

This class of decision frameworks could be subdivided into four groups on the basis of the analytical technique employed, namely those based on (1) discrete enumeration of costs and benefits, (2) classical optimization, (3) linear programming and related techniques, and (4) dynamic programming.

Decision frameworks based on discrete enumeration of costs and benefits: The simplest application of this framework is to compute expected total costs in relation to discrete prespecified values of the decision variables. The values of the decision variables which coincide with the lowest total expected costs are chosen. An extension of this procedure is the computation of benefits and costs in relation to prespecified design and management strategies. The most efficient strategy is chosen on the basis of criteria such as net present value, benefit-cost ratio, and internal rate of return. Applications of such a framework are reported by *Dasgupta and Pearce* [1973], *Eckstein* [1958], and the *U.S. Army Corps of Engineers* [1967]. The framework is illustrated using hypothetical examples by *James and Lee* [1971] and *Linsley and Franzini* [1972].

The major deficiency of this framework is that it is based on the evaluation of only a limited number of design and/or management options. Hence the efficient strategy identified in such an evaluation may often not coincide with the true optimum of either a cost function or a net benefit function. In view of the availability of frameworks (to be reviewed subsequently) capable of evaluating an infinite set of design and/or management options, discrete enumeration is useful only as a rough guide.

Decision frameworks based on classical optimization: These frameworks overcome the deficiency of discrete enumeration because a function is optimized. A framework which permits the choice of an optimal extension to existing heights of dikes (levees) is provided by *van Dantzig* [1956]. Because the objective function to be minimized, (namely expected total costs) is unconstrained, the framework merely involves equating the first derivatives of the objective function to zero. However, the choice of an optimal decision depends on the algebraic nature of the objective function and could be difficult in the event of multiple optima.

In the presence of constraints, the framework needs further adaptation. If the constraints are equalities, Lagrangian multipliers need to be adopted. On the other hand, if the constraints are inequalities, the Kuhn-Tucker conditions [*Hadley*, 1968] need to be observed. *Hughes* [1971] demonstrates the use of Lagrangian multipliers in reservoir design and expansion decisions. However, the use of Lagrangian multipliers and Kuhn-Tucker conditions becomes less appealing with complex problems of even moderate dimensionality. This is due to the problem of defining and applying the conditions required for the extremum [*McMillan*, 1975; *Wilde and Beightler*, 1967].

Decision frameworks based on linear programming and related techniques: The regular linear programming model may be used in the choice of an optimal strategy for structural measure as follows. The various design and management options represent the activities. The linear constraints are conjunctive constraints on combinations of design and management options. The constraints implicitly define an infinite set of alternative combinations of design and management options. Linear programming identifies an optimal strategy by selecting the best combination of activities. The suitability of linear programming has been well explored in relation to reservoir design and management. *Colorni and Fronza* [1976] provide the following reasoning for the suitability of linear programming. The typical constraints of any reservoir problem are the continuity equation and a number of restrictions on the range of values that variables such as storage and outflow could take. (For a detailed description of these constraints, see *Chow* [1964].) The linear nature of these constraints may account for a relatively large amount of linear programming applications [*Castle*, 1961; *Dorfman*, 1961; *Lee* 1958; *Maass and Hufschmidt*, 1959; *Maass et al.*, 1962; *Masse*, 1962; *Masse and Gibrat*, 1957; *McKean*, 1958; *Windsor*, 1973].

However, the basic assumptions of linear programming, namely linearity, continuity, convexity, and additivity, could restrict economic and engineering analysis [*Heady and Candler*, 1958; *Windsor*, 1975]. Some extensions of linear programming which involve the relaxation of these restrictions have been applied to the derivation of flood mitigation strategies. Separable programming accommodates various nonlinearities, and its applicability to reservoir decisions has been demonstrated by *Dorfman* [1962]. Integer programming permits the inclusion of nondivisibilities, and its application to optimal reservoir design and management has been demonstrated by *Windsor* [1975].

Decision frameworks based on dynamic programming: An optimal sequence of decisions is usually needed in the event of intertemporal planning over the various flood plain reaches. Dynamic programming identifies such an optimal sequence of decisions.

Expected benefits or flood losses are optimized, in terms of the decision variables, subject to a set of constraints. Often these constraints operate as state variables. That is, the values that decision variables (design and management options) could take are conditioned by the values taken by the state variables. These state variables also serve as linkages between succesive time periods and/or floodplain reaches. The nature of the state variables could depend on the particular structural measures. In the context of reservoir decisions, the state variables are often initial storage, reservoir inflows, and downstream discharge or stage. Apart from the virtues of identifying an optimal sequence of decisions, the attractiveness of dynamic programming is augmented by the fact that additional hypotheses concerning the form of the objective function are not required, as opposed to, for example, the convexity assumptions required to linearize separable programs [*Dorfman*, 1962].

Applications of dynamic programming which minimize the expected value of flood losses to reveal optimal reservoir decisions are given by *Burton et al.* [1963], *Hall and Buras* [1961], *Hall et al.* [1968], and *Lucke* [1976]. The various dynamic programming models developed to analyze irrigation and water supply decisions [*Dudley*, 1972; *Dudley and Burt*, 1972; *Dudley et al.*, 1971*a*, *b*, 1972; *Hall and Howell*, 1963] could also be adapted to provide flood mitigation decisions.

The major difficulty with the application of dynamic programming is the "curse of dimensionality." That is, as *Klemes* [1977] states, the dimensionality of the solution procedure rapidly increases when the interval between values of the state variables decreases and/or the number of state variables increases.

3.1.2. *Decision frameworks for structural measures: mini-*

mization of the expected value of flood losses and the cost of risk taking. In section 2 the cost of risk taking was defined in terms of the dispersion of flood losses around the mean, namely the variance of flood losses. The various decision frameworks considered here do not address such a definition of the cost of risk taking directly. The treatment, however, is indirect through the incorporation of a constraint which deals with the probability that the structural measure will fail. Such constraints are often referred to as reliability constraints or chance constraints. The decision frameworks of this type may be described as taking the following form:

minimize expected total costs = (costs of construction)

+ (operating costs) + (expected value of flood losses)

subject to the various resource and technical constraints, and constraints on the probability of system failure.

Although some of the frameworks of this nature [*Askew*, 1974*a*, *b*] have been developed in the context of water supply decisions, they appear to be adaptable to the context of flood mitigation.

The various frameworks of this category may be further divided into three broad groups, namely those based on (1) stochastic linear programming, (2) simulation and search, and (3) stochastic dynamic programming.

Decision frameworks based on stochastic linear programming: These frameworks follow the logic of chance-constrained linear programming developed by *Charnes and Cooper* [1963]. The design and management options of structural measures (reservoirs) are described as a linear system, and the probability of system failure is a chance or reliability constraint. Optimal levels of design and management options are derived for a given value of reliability.

Applications of this framework in relation to reservoir decisions are reported by *Eisel* [1972], *Houck and Cohon* [1978], *Nayak and Arora* [1971], *ReVelle et al.* [1969], and *Young* [1972]. However, as noted by *Askew* [1974*b*] and *Colorni and Fronza* [1976], a major deficiency of these frameworks is that the reliability of the system (or probability of failure) is determined a priori. If the reliability of the system is to be included as an extra decision variable, then the levels of reliability associated with various levels of design and management options may also be derived. Thus the best choice of risk along with optimal design and management decisions is feasible. *Colorni and Fronza* [1976] achieve this end by adopting an extension of stochastic linear programming, namely reliability programming developed by *Sengupta* [1972]. However, all frameworks based on linear programming lose their appeal when the design and management options of structural measures cannot be described as a linear system.

Decision frameworks based on simulation and search: These frameworks become a useful alternative when the design and management options of structural measures are described as a nonlinear system. Constraints pertaining to the failure of the system limit the range of values the decision variable could take.

Yeh et al. [1970] demonstrate the operation of a mathematical program in conjunction with synthetic hydrology techniques. That is, a mathematical program depicting various design and management options is run in correspondence with a set of generated reservoir inflows. Hence the procedure enables the derivation of a pattern of optimal decisions. *Askew et al.* [1971] demonstrate the use of Monte Carlo techniques in reaching reservoir decisions. However, as *Askew* [1974*d*] points out, although simulation and search are of great value owing to their simplicity and flexibility, the guarantee of a global optimum is absent.

Decision frameworks based on stochastic dynamic programming: The distinguishing attribute of these frameworks is the incorporation of system reliability as a state variable. The relationship between system reliability and decision variables is described as either a continuous or a large number of discrete intervals in the relationship. Hence the need to determine the reliability of the system a priori does not exist. Further, the inclusion of reliability as a state varible restricts the decision variables to a given range of values. The framework is useful in the context of time-sequenced decisions where reliability of structural measures may decrease over time. It is also useful for a sequence of spatial decisions where upstream decisions could affect the reliability of structures downstream. *Askew* [1974*b*] describes such dynamic programs as chance-constrained dynamic programs and demonstrates their application to reservoir decisions. In this application the return function includes a penalty cost for a given level of probable failure. Nevertheless, owing to the curse of dimensionality, a global optimum is restrictd within such frameworks as well.

The major drawback with all the frameworks discussed in this section is that structural measures are considered in isolation. As has been demonstrated in section 2.1, the expected value of flood losses may increase in the event of implementing structural measures alone. Hence the singular optimization of structural measures may not yield a social optimum even when the floodplain is regarded as an independent economic entity; that is, within a context of partial equilibrium.

3.2. *Decision Frameworks for Nonstructural Measures Alone*

The various decision frameworks dealing with nonstructural measures may be classified as those dealing with the minimization of (1) the expected value of flood losses alone, (2) the cost of risk taking alone, and (3) the expected value of flood losses and the cost of risk taking together. The basis for such a classification is similar to the one mentioned above in relation to the frameworks dealing exclusively with structural measures. Although all nonstructural measures, other than flood insurance, are capable of reducing both the expected value of flood losses and the cost of risk taking, the above classification is based on whether or not the decision frameworks explicitly account for the expected value of flood losses and/or the cost of risk taking.

3.2.1. *Decision frameworks for nonstructural measures: minimization of only the expected value of flood losses.* The decision frameworks of this category are used to formulate strategies in terms of floodplain land use, flood warning, and flood proofing. The objective function of these frameworks is either to minimize the expected value of flood losses or to maximize the expected net returns. The frameworks do not account for any properties of the distribution other than the mean.

The decision frameworks of this category could be further classified into three broad groups, namely those based on (1) discrete enumeration of costs and benefits, (2) linear programming or related techniques, and (3) other operations research techniques.

Decision frameworks based on discrete enumeration of costs and benefits: These frameworks are used to evaluate the economic efficiency of either a single nonstructural strategy or a discrete set of strategies. The evaluation of the former involves absolute desirability while the latter involves relative desirability. As indicated before (section 3.1.1), the evaluation of economic efficiency rests on the computation of criteria such as net present value, benefit-cost ratio, and internal rate of return.

Scheaffer [1960] demonstrates the use of benefit-cost ratios for various flood proofing decisions in urban floodplain communities. *Day et al.* [1969] establish the basis for estimating net benefits from a given set of flood warning dissemination programs. *Heatherwick and Quinnel* [1976] estimate benefit-cost ratios of flood warning systems for urban communities on the Brisbane river floodplain. *Baker* [1962] demonstrates the use of benefit-cost ratios in deriving efficient floodplain land use decisions. The deficiencies of such frameworks have been already mentioned in section 3.1.1.

Decision frameworks based on linear programming and related techniques: *Day* [1969] was the first to demonstrate the use of operations research in floodplain land use planning. His framework permits not only the derivation of optimal land use decisions but also optimal flood proofing decisions. The activities are represented by various land uses under different combinations of land type, geographic location, site elevation, and flood proofing. The framework seeks to maximize a stream of expected economic rents subject to various land resource and population constraints. The recursive nature of the framework permits the derivation of optimal decisions, spatially and intertemporally. *Day* [1970, 1973] also reports empirical applications of this framework. A similar application of recursive linear programming, reported by *Smiarowski et al.* [1974], differs slightly from the previous ones by *Day* [1970, 1973] because, in addition to the usual constraints, political and legal constraints are also included.

Linear programming frameworks of this nature become restrictive when the relationships between the various land use and other options are nonlinear. However, the validity of the linearity assumption in the context of land use decisions has been supported by *Day* [1973] and *Hardaker* [1975].

Bialas and Loucks [1978] provide a decision framework for floodplain land use planning based on quadratic programming. The objective function maximizes the difference between expected economic rent and the sum of expected flood losses and the cost of relocation. The constraints are of two types, namely definitional and operational. The definitional constraints include legislation such as zoning laws, and the operational constraints are the usual resource endowments.

The incorporation of zoning laws as constraints in some of the above frameworks [*Bialas and Loucks*, 1978; *Smiarowski et al.* 1974] is perhaps restrictive. This is because it might be desirable for the framework to generate guidelines for such zoning laws rather than incorporate zoning laws determined a priori.

Decision frameworks based on other operations research techniques: *Brown* [1972] and *Brown et al.* [1972] demonstrate a framework based on replacement theory to choose a set of land use decisions which maximize expected economic rent. The framework also permits the elicitation of an optimal replacement strategy for floodplain capital which deteriorates rapidly (in relation to elsewhere) because of floods. However, the framework is theoretical and lacks empirical content. On the other hand, this framework for optimal replacement of floodplain capital may be incorporated into an overall analysis of land use decisions based on mathematical programming.

3.2.2. *Decision frameworks for nonstructural measures: minimization of the cost of risk taking alone.* Flood insurance is the only flood mitigation measure capable of reducing the cost of risk taking exclusively. Hence the frameworks of this category consider only flood insurance.

Most of the literature on flood insurance [*Brown*, 1972; *James and Lee*, 1971; *Krutilla*, 1966; *Lind*, 1967] tends to be conceptual, indicating the relative advantages of flood insurance over other measures of flood mitigation. Only a few attempts [*Karlinger and Attanasi*, 1980; *Loughlin*, 1971; *Schaake and Fiering*, 1967] appear to be reported where a decision framework is utilized to derive an optimal insurance strategy. Of these, one considers flood insurance in conjunction with structural measures [*Loughlin*, 1971] and is hence discussed subsequently in section 3.3.

Schaake and Fiering [1967] demonstrate a decision framework based on simulation where an optimal strategy is sought for a national flood insurance scheme. The optimal strategy dictates optimal magnitudes of variables such as premium rates, discount coefficients, and initial capitalized values. The simulation involves the following sequence of events, namely synthesis of flood flows, estimation of damages caused by such flows, translation of damages into claims, compensation of floodplain losses, collection of insurance premiums by the state from the insurance industry, and the compensation of losses borne by the insurance industry. Thus this framework incorporates the need for government assistance in the event of the insurance industry incurring a loss. It also indicates the scope for developing other frameworks in the context of flood insurance. For example, dynamic programming frameworks may be adopted to derive optimal premium rates, in an intertemporal sense.

Karlinger and Attanasi [1980] also develop a computer simulation model to determine the effects of alternative sources of uncertainty on the willingness to pay for flood insurance. Two types of flood insurance schemes, namely a coinsurance scheme and a fixed coverage scheme, were evaluated. This evaluation is based on the response of the purchasers of flood insurance to flood risks. Such response is monitored in terms of the purchasers' willingness to pay for flood insurance and follows the authors' earlier work [*Attanasi and Karlinger*, 1979]. The flood risks were simulated by assuming that floods are lognormally distributed, and the estimation of willingness to pay was based on a consumer decision model. The analysis of such consumer behavior could provide guidelines for the formulation of an insurance strategy.

3.2.3. *Decision frameworks for nonstructural measures: minimization of the expected value of flood losses and cost of risk taking.* The frameworks discussed in this category account for the mean as well as the variance of the distribution of flood losses. The variance is considered as a proxy for the cost of risk taking. The frameworks of this type reported in the literature may be classified into two broad groups, namely those based on (1) discrete enumeration of costs and benefits and (2) quadratic programming and related procedures.

Decision frameworks based on discrete enumeration of costs and benefits: *Willis and Alkiku* [1974] present a framework for estimating means and variances of net benefits from a discrete set of flood proofing decisions. The objective function may be stated as

$$\text{maximize } W = b_1 E - b_2 V$$

where W is a measure of net benefits, E is expected net benefits, V is variance of net benefits, and b_1 and b_2 are weights which transform expected value and variance to the same dimension. (The role of weights in performing such transformations is described by *Anderson et al.* [1977], *MacCrimmon* [1974], and *Sinden and Worrell* [1979].) The framework permits the elicitation of an *E-V* boundary, namely the trade-off function between expected net benefits and variance of net benefits. Choice of an optimal strategy is possible only if the floodplain community's indifference between expected net benefits and variance of net benefits is known.

However, the same limitations of discrete enumeration mentioned earlier also apply here, namely that the framework permits evaluation of only a limited number of flood proofing alternatives. Besides that, an implicit assumption, which may not always hold, is that the benefits and costs are related linearly to various levels of flood proofing.

Decision frameworks based on quadratic programming and related procedures: *Kaul* [1976] and *Kaul and Willis* [1975] demonstrate a quadratic programming framework for floodplain land use strategies. The objective function is as follows:

maximize (expected rent from land use) $- \lambda$ (variance of rent)

where λ is a risk aversion factor or a weight which transforms the variance term to the same dimension as expected rent. For example, see *Anderson et al.* [1977], *Arrow* [1965], and *Pratt* [1964] for a detailed description of the concept of risk aversion. This appears to be an extension of *Day's* [1973] framework in the sense that activities are represented by various land uses under different combinations of land type, geographic location, and flood proofing. Parametric variation of λ permits the elicitation of the trade-off function between expected rent and variance of rent. If the floodplain community's measure of risk aversion is known, then the optimal land use strategy is defined by a single point on the trade-off function.

A major difficulty of the above and all quadratic programming frameworks concerns the derivation of a variance-covariance matrix as a measure of risk. A further framework developed by *Hazell* [1971] is a linear approximation to quadratic programming and confines the measure of risk to absolute deviations of returns (or costs). The application of such stochastic linear programs has been demonstated for causes of risk other than floods (see, for example, *Anderson et al.* [1977], *Hardaker and Troncoso* [1979], *Hazell and Scandizzo* [1974], and *Wicks and Guise* [1978]). These frameworks could be readily adapted to identify optimal floodplain land use strategies.

However, an inadequacy in all these frameworks is that the physical interrelationships between the various reaches of the floodplain are not accounted for. The quantification and incorporation of such interrelationships is important because upstream decisions may affect downstream decisions and vice versa [*Chow*, 1959, 1964; *Linsley et al.*, 1949].

The major deficiency of all frameworks considered in this section is the omission of structural measures. If structural and nonstructural measures are considered as alternatives to one another, then a framework dealing with both these types of measures is capable of promoting better resource allocation decisions than those discussed in this and the previous section.

3.3. *Decision Frameworks for Both Structural and Nonstructural Measures*

The various decision frameworks of this category may be classified into two further categories, namely those involving the minimization of (1) only the expected value of flood losses and (2) the expected value of flood losses and the cost of risk taking. Again, the basis for such a classification is whether or not the expected value of flood loses and/or the cost of risk taking are explicitly stated in the framework.

3.3.1. *Decision frameworks for both structural and nonstructural measures: minimization of only the expected value of flood losses.* These frameworks may be further classified into three categories, namely those based on (1) discrete enumeration of costs and benefits, (2) linear programming and related techniques, and (3) dynamic programming.

Decision frameworks based on discrete enumeration of costs and benefits: As indicated before (sections 3.2.1, 3.2.2, and 3.2.3), these frameworks permit the selection of either a single strategy or a set of strategies from a group of prespecified strategies through an evaluation of economic efficiency.

James [1965] demonstrates a framework which permits the choice of a strategy on the basis of minimum expected total cost. The components of this total cost are flood damage, cost of structural measures, cost of flood damage, cost of structural measures, cost of flood proofing, and cost of land use planning. The procedure involves a systematic comparison of total costs for a number of discrete combinations of flood mitigation alternatives. Hence the framework is restrictive because only a limited number of alternatives can be evaluated. However, subsequent frameworks by *James* [1967] and *Rachford* [1966], also involving the minimization of total costs, permit the evaluation of a large number of alternatives due to the incorporation of digital computer programs. Nevertheless, the framework is inadequate, because a strategy depicting minimum total costs need not necessarily coincide with that depicting maximum net benefits.

Whipple [1969] attempts to select strategies which combine zoning with structural measures. The aim is to maximize net benefits by choosing a strategy which depicts the largest benefit-cost ratio. A similar framework is also demonstrated by *Brownhall et al.* [1976] and *Folie et al.* [1976]. As indicated before, the major deficiency with such a framework is that alternative strategies need to be prespecified.

Decision frameworks based on linear programming: *Day and Weisz* [1976] and *Weisz and Day* [1974] demonstrate the use of a linear programming framework which incorporates structural measures with floodplain land use options. However, the objective function of the linear program contains only the benefits of land use decisions and not decisions pertaining to structural measures, resulting in a linear programming framework of the type suggested by *Day* [1969, 1970, 1973], discussed earlier in section 3.2.1. This framework generates optimal land use decisions for a set of preselected decisions on structural measures. Hence, despite the evaluation of an infinite set of land use options, a global optimum is not guaranteed, because only a limited number of structural options are considered. Thus the framework degenerates to a form of discrete enumeration.

However, the difficulties involved in incorporating structural and land use measures into a linear programming framework need to be appreciated. While the relationship between benefits and various land use decisions may be linear, that between benefits and various structural decisions may approach a high degree of nonlinearity [*Askew*, 1974*a*; *Ball et al.*, 1978]. In such an event, structural measures and land use decisions cannot be jointly considered, without an algorithm capable of solving highly nonlinear problems. Such algorithms are not readily available.

Decision frameworks based on dynamic programming: Although dynamic programming overcomes, to some extent, the problem of nonlinearity involved in accommodating both structural and nonstructural measures, the framework reported here does not explicitly account for structural measures. *Hopkins et al.* [1978] demonstrate a framework based on dynamic programming that finds the optimal allocation of floodplain land to various uses in various reaches. An attractive feature of this framework is that the hydrologic interrelationships between the various reaches are accounted for. The optimal land use strategy implicitly defines a strategy for structural measures. This is because the decision variable in a given reach is revenue from land use and the state variable is either the volume or stage of river flow into the reach. Thus the optimal pattern of land use is reconcilable with given values of the state variable (volume or stage of flow) in the various reaches. Hence the strategy for structural measures would be to mitigate the volume (or stage) of flow associated with the optimal pattern of land use. However, the return function does not account for the cost of structural measures, and hence the framework does not guarantee a global optimum. In a subsequent dynamic programming framework, *Hopkins et al.* [1981] overcome this inadequacy by explicitly incorporating the costs of the structural alternatives.

3.3.2. *Decision frameworks for structural and nonstructural measures*: *minimization of the expected value of flood losses and the cost of risk taking.* Three frameworks within this category appear in the literature. The first two [*Aislabie*, 1976; *Loughlin*, 1970, 1971] consider flood mitigation strategies involving structural measures and flood insurance, while the third [*Thampapillai*, 1980*a*, *b*] considers flood mitigation strategies involving structural measures and floodplain land use. *Loughlin*'s [1970, 1971] framework belongs to the category of discrete enumeration of costs and benefits, and *Aislabie*'s [1976] framework can be classified as classical optimization. *Thampapillai*'s [1980*a*, *b*] framework is based on linear and nonlinear mathematical programming.

Decision framework based on discrete enumeration of costs and benefits: *Loughlin* [1970, 1971] demonstrates a cost-sharing framework which indicates the reduction that would occur in insurance premiums if the floodplain occupants contribute toward structural measures. This reduction in premiums is proportional to the increased benefits caused by structural measures. Because the reduction in premiums is computed for contributions made to given preselected strategies of structural measures, an optimal mix of insurance and structural measures may not be attained.

Decision framework based on classical optimization: *Aislabie* [1976] also demonstrates a conceptual framework for floodplain occupants (microunits). The framework maximizes a profit function where insurance and structural measures are determined. The optimal decision rule is that structural measures should be substituted for flood insurance until the cost of premiums saved from a marginal investment in structural measures equals the cost of those measures. However, empirical applications of such frameworks could entail problems because defining and applying the conditions required for an extremum could be difficult, even with problems of moderate dimensionality [*McMillan*, 1975]. The framework is perhaps empirically applicable if the dimension of the problem reduces to two decision variables. Such frameworks then tend to be unrealistically simple.

Decision frameworks based on linear and nonlinear programming: *Thampapillai* [1980*a*, *b*] demonstrates frameworks for independent and interdependent floodplain reaches. The distinction between the two sets of frameworks is as follows. In the frameworks for independent reaches, the hydrologic relationships between reaches are ignored, but in the frameworks for interdependent reaches, these relationships are acknowledged. In the case of independence, a two-stage stochastic program is constructed for each reach. The first stage is a geometric programming model where investment in structural methods is optimized. The second stage is a linearly approximated quadratic programming model where expected returns from land use and the cost of risk taking are optimized. The second-stage model follows the formulation by *Hazell* [1971] and is contingent on the solution from the first-stage model.

In the context of interdependence between reaches, interdependence functions are incorporated as constraints into the first-stage model. Any array of solutions is derived for each reach by parameterizing the appropriate interdependence function. These solutions are then used as inputs to a dynamic programing framework to derive an optimal sequence of structural and nonstructural decisions. Although the frameworks are appealing, they rest on a set of restrictive assumptions such as definition of floods in terms of flood heights alone, a "one-way" relationship between structural measures and land use (that is, structural measures influence land use decisions and not the reverse), and linear relationships between flood heights and flood losses.

4. IMPLICATIONS OF THE REVIEW

A condensed and comparative description of the frameworks reviewed in section 3 is provided in Table 1. This comparison reveals the inadequacies contained in these frameworks. However, the comparison, along with the review of flood mitigation measures in section 2, indicates the directions in which the formulation of a more adequate framework may proceed. These two outcomes of the review, namely the inadequacies of frameworks reported in the literature and the directions for the formulation of a more adequate framework, are discussed below.

4.1. *Inadequacies of the Frameworks*

Frameworks dealing with only structural measures are inadequate because they ignore nonstructural measures. Similarly, those dealing with only nonstructural measures are inadequate because they ignore structural measures. Since structural and nonstructural measures can be alternatives to each other, the exclusive consideration of one type of measure generally cannot improve the allocation of floodplain resources. Besides, these inadequacies are aggravated by problems associated with specific frameworks, as shown in Table 1. Hence for optimal decisions, frameworks which incorporate both structural and nonstructural measures appear desirable. However, as shown in section 3.3, such frameworks also possess inadequacies. Thus an important implication of the review is the need to develop future frameworks are free of at least some of the inadequacies mentioned above.

4.2. *Directions in Which Formulation of More Adequate Frameworks May Proceed*

Such directions can be examined by considering first the implications of the review of flood mitigation measures. These implications are important because the nature of formulation of decision frameworks depends on the type of flood mitigation measures considered in that framework.

The review in section 2 reveals that the analysis of flood insurance decisions may be considered as a step subsequent to

TABLE 1. Comparison of Decision Frameworks Used in the Derivation of Flood Mitigation Strategies

Objective of the Framework	Type of Framework	Potentials of the Framework		Problems Associated With the Framework
		Type of Problem Solved	Type of Solution Given	
		Framework Dealing With Only Structural Measures		
Minimize only expected value of flood losses in relation to design and/or management options in strategies pertaining to structural measures	(1) Discrete enumeration of costs and benefits	Making choices within a given set of pre-specified structural strategies	Relative superiority of one or more strategies on design and/or management by economic efficiency criteria	May not provide global optimum. Does not account for cost of risk taking and nonstructural measures.
	(2) Classical optimization	Making choices from an infinite set of structural strategies defined by a mathematical function	One optimal strategy on design and/or management	Not applicable to complex problems. Does not account for cost of risk taking and nonstructural measures.
	(3) Linear programming	Making choices within an infinite set of structural strategies from a set description, where relationships are linear	One optimal strategy on design and/or management	Problems due to basic assumptions of linear programming and related procedures. Does not account for cost of risk taking and non-structural measures.
	(4) Dynamic programming	Making choices within an infinite set of structural strategies from a set description, where relationships need not be linear	One optimal strategy on design and/or management	May not provide global optimum owing to curse of dimensionality. Does not account for cost of risk taking and nonstructural measures.
Minimize expected value of flood losses and cost of risk taking in relation to design and/or management options in strategies pertaining to structural measures	(1) Stochastic linear programming	Making choices within an infinite set of structural strategies from a set description, where relationships are linear and cost of risk taking is determined a priori	One optimal strategy on design and/or management	Problems due to basic assumptions of linear programming. A priori determination of the cost of risk taking. Does not account for nonstructural measures.
	(2) Reliability programming	Making choices within an infinite set of structural strategies from a set description, where relationships are linear but cost of risk taking is an extra decision variable	One optimal strategy on design and/or management and risk	Problems due to basic assumptions of linear programming. Does not account for non-structural measures.
	(3) Simulation and search	Making choices within an infinite set of structural strategies from a set description, where relationships may be nonlinear and cost of risk taking may be an extra decision variable	One optimal strategy on design and/or management and sometimes risk	Global optimum is not guaranteed. Does not account for non-structural measures.
	(4) Stochastic dynamic programming	Making choices within an infinite set of structural strategies from a set description where relationships may be nonlinear and cost of risk taking may be an extra decision variable	One optimal strategy design and/or management and sometimes risk	May not provide global optimum owing to curse of dimensionality. Does not account for non-structural measures.
		Framework Dealing With Only Nonstructural Measures		
Minimize only expected value of flood losses in relation to decisions on floodplain land use and/or flood	(1) Discrete enumeration of costs and benefits	Making choice within a given set of pre-specified nonstructural strategies	Relative superiority of one or more Strategies on flood proofing and/or flood warning and/or flood-plain land use	May not provide global optimum. Does not account for cost of risk taking, other mitigation measures, and relationship between reaches.

TABLE 1. (continued)

Objective of the Framework	Type of Framework	Potentials of the Framework		Problems Associated With the Framework
		Type of Problem Solved	Type of Solution Given	
		Framework Dealing With Only Nonstructural Measures (continued)		
warning and/or flood proofing	(2) Linear programming and related techniques	Making choices within an infinite set of nonstructural (land use) strategies from a set description	One optimal strategy on pattern of land use (spatial and intertemporal)	Problems due to basic assumptions of linear programming. Does not account for cost of risk taking, other mitigation measures, and relationship between reaches.
	(3) Replacement theory	Maing choices within a given set of nonstructural (land use and capital replacement) strategies	Relative superiority of one strategy on land use and capital replacement (spatial and intertemporal)	May not provide global optimum. Does not account for cost of risk taking, other mitigation measures, and relationship between reaches.
Minimize only cost of risk taking through flood insurance	(1) Simulation	Making choices within an infinite set of insurance strategies from a set description of the insurance scheme	One optimal strategy on premiums, discount coefficients, and initial capitalized values	May not provide global optimum. Does not account for other mitigation measures and relationship between reaches.
Minimize expected value of flood losses and cost of risk taking in relation to floodplain land use or flood proofing	(1) Discrete enumeration of costs and benefits	Making choices within a given set of prespecified nonstructural (flood proofing) strategies	Relative superiority of one strategy on flood proofing. Trade-off function between expected value of benefits and risk.	May not provide global optimum. Difficulties in deriving society's preference to determine optimum on the trade-off function. Does not account for other mitigation measures and relationship between reaches.
	(2) Quadratic programming and related techniques	Making choices within an infinite set of nonstructural (land use) strategies from a set description where relationships are quadratic or approximated to linear	One optimal strategy on pattern of land use (spatial and intertemporal). Trade-off function between expected value of benefits and risk.	Elicitation of variance-covariance matrix. Difficulties in determining society's risk aversion factor to determine optimum trade-off function. Does not account for other mitigation measures and relationship between reaches.
		Framework Dealing With Structural and Nonstructural Measures		
Minimize only expected value of flood losses in relation to structural measures and land use and/or flood proofing	(1) Discrete enumeration of costs and benefits	Making choice within a given set of prespecified strategies which combine structural and nonstructural measures	Relative superiority of one or more strategies involving structural measures and flood proofing and/or land use	May not provide global optimum. Does not account for cost of risk taking and relationship between reaches.
	(2) Linear programming	Making choices within an infinite set of land use strategies for prespecified strategies on structural measures	Relative superiority of one strategy on structural measures and land use	May not provide global optimum. Does not account for cost of risk taking and relationship between reaches.
	(3) Dynamic programming	Making choices within an infinite set of strategies combining land use and structural measures	One optimal strategy on pattern of land use implying also level of structural protection	May not provide global optimum. Does not account for cost of risk taking.
Minimize expected value of flood losses and cost of risk taking in relation to structural measures and	(1) Discrete enumeration of costs and benefits	Making choices within a given set of preselected strategies which combine structural measures and flood insurance	Relative superiority of one or more strategies on investment in structural measures and insurance premiums through a cost-sharing formula	May not provide global optimum. Does not account for other mitigation measures and relationship between reaches.

TABLE 1. (continued)

Objective of the Framework	Type of Framework	Potentials of the Framework: Type of Problem Solved	Potentials of the Framework: Type of Solution Given	Problems Associated With the Framework
	Framework Dealing With Structural and Nonstructural Measures (continued)			
flood insurance and/or land use	(2) Classical optimization	Making choices from an infinite set of strategies combining structural mearures and flood insurance defined by a mathematical function	One optimal strategy on investment in structural measures and insurance premiums	Not applicable with complex problems. Does not account for other mitigation measures and relationship between reaches.
	(3) Linear and nonlinear programming	Making choices from an infinite set of strategies combining structual measures and land use	One optimal strategy of investment in structural measures and land use	Assumptions such as structural measures affect land use and not the reverse, and floods defined through only height.

the analysis of decisions pertaining to all other measures of flood mitigation. Such a procedure is suggested to accommodate feasibly low insurance premiums (see section 2.2.2). Besides, as shown by *Day* [1969, 1970] and *Kaul* [1976], flood proofing decisions can be readily incorporated as components of land use decisions (see sections 2.2.1 and 2.2.3). Hence the formulation of a more adequate framework may require the consideration of only structural measures, land use decisions, and flood warning systems.

The type of framework required for a consideration of structural, flood warning, and land use decisions may be approached from an examination of the specific types of frameworks (reviewed in section 3): (1) discrete enumeration of costs and benefits, (2) classical optimization, (3) replacement theory, (4) mathematical programming (involving linear programming, nonlinear programming, and related techniques, (5) dynamic programming, and (6) simulation and search.

With the exception of replacement theory, the above mentioned specific types of frameworks appear in all three broad categories of frameworks (see Table 1). However, as indicated previously (in section 3.2.1), the framework based on replacement theory may be incorporated into other specific frameworks for land use such as mathematical programming. Of the five remaining types of frameworks, discrete enumeration should be disregarded because of its inability to evaluate a large number of flood mitigation strategies. Classical optimization should also be disregarded because of its inability to deal with complex problems. The remaining frameworks, namely mathematical programming (involving linear and nonlinear programming), dynamic programming, and simulation, possess the advantage of permitting the evaluation of an infinite set of flood mitigation strategies, despite shortcomings due to assumptions and problems of dimensionality. The above review also reveals that these three specific types of frameworks are useful for the evaluation of specific flood mitigation measures as listed below:

1. Either dynamic programming or simulation is useful for the evaluation of decisions pertaining to (1) structural measures (if nonlinear programming algorithms capable of dealing with high degrees of nonlinearity are unavailable), (2) land use decisions, and (3) flood warning systems.

2. Linear programming is useful for evaluation of decisions pertaining to floodplain land use and flood proofing if the cost of risk taking is ignored. Quadratic programming or linear approximations to quadratic programming are useful for evaluation of such decisions if the cost of risk taking is accounted for.

Hence the formulation of a more adequate framework may involve the formulation of an overall systems framework which combines the above three specific types of frameworks.

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