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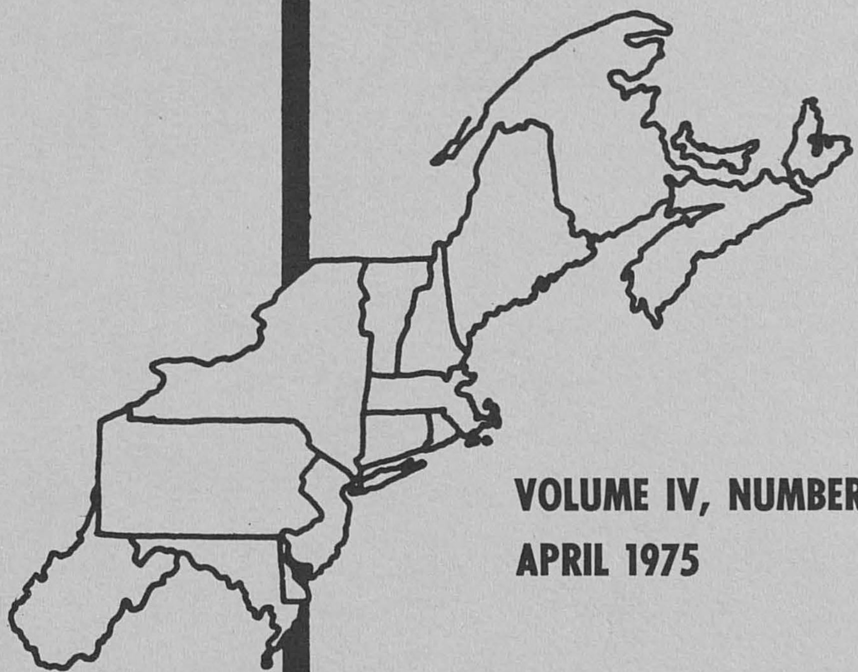

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AN APPLICATION OF A FLOODPLAIN LAND USE DECISION FRAMEWORK WITH ZERO-ONE CONTROLS

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INTRODUCTION

Resource economists and the federal government have shown a growing awareness of the role of non-structural measures (such as floodplain zoning) as an important part of an overall flood damage reduction program. This awareness has come in part with the realization that structural measures often provide a false sense of security to floodplain occupants and, as such, often result in increased flood damages contrary to their intended purpose. To be sure, restrictions prohibiting all development in flood prone areas could eliminate all damages. There are no *a priori* reasons, however, to believe that all uses should be prohibited from all floodplain areas. Through sound land use management practices, some of these areas can, in fact, be put to economic use such that the benefits derived outweigh the costs associated with such development.

The objectives underlying this investigation are: (i) to develop a methodology useful to planners at several levels for efficient floodplain management considering both structural and non-structural measures and (ii) to demonstrate the usefulness of the methodology by applying it to a selected floodplain in the Connecticut River Basin.

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Floodplain Management Methodologies

Only several empirical efforts have been directed at providing a comprehensive methodology for floodplain management. James [1967] made the first such attempt. His approach seeks the least cost combination of flood control measures by systematically comparing totals of measured costs and residual damages for a number of discrete combinations of alternatives defined by kind and designed level of protection.

Day [1970, 1973] provided the first application of operations research methods to the problem of floodplain land use management. His efforts took the form of a recursive linear programming solution to "optimal" land use management of a flood prone area. His framework, however, made no explicit reference to structural measures (other than flood proofing).

Following Day's formulation, Smiarowski, et. al. [1974] applied a mathematical (linear) programming technique to provide (conditional) normative decisions regarding choice of land use alternatives ranging over a 25 year planning horizon for a community on the Connecticut River floodplain.

All of the formulations above are subject to some (in some cases, rather severe) shortcomings, most of which are pointed out by the authors. Each formulation was cast in a deterministic mode and hence the rather important aspects of risk and uncertainty were all but ignored. In addition, the demand for land in various uses was presumed in each case to be price inflexible at least over the relevant range. That is, land values were presumed constant regardless of the quantity developed. The formulations presented here address these and other limitations.

Farmington, Connecticut

The floodplain in Farmington (the selected floodplain for this study) comprises almost 3,000 acres of which approximately 2,176 are undeveloped. Despite the threat of floods, demand for urban development on the floodplain is rather strong. Part of an industrial park is situated on the floodplain and demand for industrial and other land uses remains strong -- in part due to the location of Route 4 and the proximity of adequate public services.

The floodplain was divided into three basic regions on the basis of demand for the various land uses. Each of these three regions is presumed homogeneous with respect to the demand for (and price of) land for the various uses. Each basic region is further subdivided into three risk zones on the basis of flood frequency. These zones provide information regarding the probabilities of a flood occurring in a particular year and suggest the relative flood risk involved. The lowest frequency (risk) zone corresponds to the "maximum flood of record" (1955), the second zone reflects land which is expected to be flooded once every hundred years, and the highest risk zone is land which is flooded, on the average, every fifty years.

Organization

Section 2 below provides in rather general form the decision framework for comprehensive flood damage reduction planning. This includes a discussion of the activities or decision variables, the objective function, and the constraint set. In the final part, some special considerations are treated regarding price flexibilities and the objective function and the treatment of externalities.

Section 3 develops this framework in an integer programming context. The activities, objective function, and the constraints are set out in that order.

Finally, Section 4 sets out the results of the empirical application of the framework to the region described above, and the final section draws some conclusions regarding the usefulness of this public decision framework.

DECISION FRAMEWORK

A general formulation for floodplain management including some special features to be recognized in any given regional application is provided below.

Activities

The control variables (x_{ijt}) denote the portion of a large area of floodplain and non-floodplain land (not necessarily contiguous) i to be devoted to a particular use j in period t (and beyond);

$i = 1, 2, \ldots, I,$
$j = 1, 2, \ldots, J,$
$t = 1, 2, \ldots, T.$

All land in category i is homogeneous with respect to value and expected flood damages in each use j for all t. For simplicity, let us further assume that demands for a particular use j in i are unrelated to demands for the same use j in i'; $i' \varepsilon I$ and $i' \neq i$.

Examples of uses j are: residential, industrial, commercial, agricultural, and open space. The designation of the land to be contained in a particular category i is conditional upon not only the location within the floodplain with respect to flood risk but also upon the relevant factors which account for differences in the derived demand for such land.

Finally, each variable (x_{ijt}) presumes some (optimal) level of flood proofing of structures as well as a given level of structural protection through dams, etc. Willis and Aklilu [1973] provide the methodology for determining the optimal level or amount of flood proofing for a given set of conditions (regarding probabilities of floods of various intensities and market values of structures) such that for any given ijt circumstance, there need be considered only one level of flood proofing. Thus, the flood proofing decisions can be considered as separable. Similarly, each dam (or set of structural measures), in the presence of land use constraints, brings with it an associated benefit in terms of expected damage reductions. These are reflected in the objective function below. Hence, each problem is solved for a particular dam specification, the expected costs of such an undertaking are subtracted from the respective objective function values and the final decisions are made by inspection.

Objective Function

The objective is to select x_{ijt} so as to achieve maximum expected economic rent from the land. The criterion function is expressed, then, as:

$$(2.1) \quad \text{Maximize } Z = Z(x_{ijt}).$$

More specifically, the objective may be rewritten as:

$$(2.1)' \quad \text{Maximize } Z = \sum_{i,j,t} \left(r_{ijt} \sum_{t'=1}^{t} x_{ijt'} \right)$$

where r_{ijt} are measures of economic rent on a per acre basis. The r_{ijt} can be considered as a set of constants (as in Day [1973] and Smiarowski, et. al. [1974]) or as functions of x_{ijt}. The latter approach is more realistic and is adopted in the sections below.

Since we are generally dealing with less than an infinite time horizon (T), we must consider terminal conditions. One means of accomplishing this is to replace the annual rent functions in the terminal period (r_{ijT}) by an inverse demand relationship using expected land price as a proxy variable for the stream of expected economic rents given the conditions on $\sum_{t'} x_{ijt'}$ at T. That is, in the absence of serious market imperfections, the price of land reflects the buyer's expected net returns attributable to the land. This ignores the problems of consumers' surplus and alternative buyers' motives, of course. Support to this measure, however, is given by Day [1973] and Gaffney [1962].

Constraints

The maximization of the objective function (2.1) is subject to a set of physical constraints:

$$(2.2) \quad \sum_{j,t} x_{ijt} \leq b_i, \qquad \forall_i$$

That is, each of these I restraints simply requires that no more land is devoted to uses in category i than is physically available (b_i) in that location.

Other constraints can be added, of course, depending upon the specifics of the community preferences in the floodplain under investigation. Minimum restrictions on open space in certain locations, for example, may be added to reflect alternative (non-efficiency) goals.

Special Features

We focus attention here on several features to be developed more fully in succeeding sections.

Non-linear Objective Function. Since any reasonable representation of the r_{ijt} in the objective function would recognize the likelihood that r_{ijt} are variables which are functions of the decision variables or activities, this representation should appear in the objective functional. Kaul and Willis [1974] provide a quadratic programming approach which presumes the relation between r_{ijt} and $\sum_{t'=1}^{t} x_{ijt'}$ is linear and continuous over the relevant range. The integer programming approach used below views the same relation as a (discontinuous) step function, and homogeneous parcels are further divided into separate variables whose objective function coefficients take on different values. That is, the rent relationship for the i^{th} parcel of land in the j^{th} use in t (conditioned by past decisions) is portrayed where the i^{th} parcel is simply divided into k = 1, 2, ..., K sub-parcels each of which is characterized by a single-valued rent structure.

Externalities. In a larger regional context, the framework provided above, and the variations to follow, permit the internalization of the value of the externality commonly associated with the development of floodplain lands. That is, development along a particular reach of a floodplain may increase damages both above and below the development site. For these individuals, such costs would be considered external and hence would be ignored. In a larger regional context, however, these costs are internal and hence it is important that these frameworks permit the regional decision maker to internalize these costs with respect to the zoning decision.

INTEGER PROGRAMMING APPROACH

In light of some of the limitations suggested earlier, it is worthwhile under some circumstances to replace the rent and price functions by discrete approximations -- treating these in effect as "step functions". This can be implemented by means of zero-one integer programming procedures.

Activities

Under this approach, the basic activities of Section 2 would be modified in two respects. First, the parcels of land in each category 1/ i are divided into K sub-parcels each of which is presumed homogeneous with respect to rent (and demand) for a given use j and period t. Second, the variables (x_{ikjt}) are constrained such that:

$$x_{ikjt} = \begin{cases} 1, & \text{if the } k^{th} \text{ sub-parcel of } i \text{ is devoted to the } j^{th} \text{ use in } t, \\ 0, & \text{otherwise.} \end{cases}$$

Objective Function

Since each category of land area i is presumed homogeneous with respect to demand characteristics, the k = 1, ..., K subareas can be assigned a development sequence arbitrarily. Letting k = 1 be the first part of category i to develop in use j and k = K be the last, we can assign rents (prices) r_{ikjt}, where $r_{ikjt} > r_{ik'jt}$ for $k > k'$. 2/ With this specification, the objective function is:

1/ For present purposes, the categories are defined as follows: i = 1 denotes region 1, 500 year zone; i = 2 denotes region 1, 100 year zone; i = 3 denotes region 1, 50 year zone, ..., i = 9 denotes region 3, 50 year zone.

2/ Note that r_{ikjt} includes the rent from $r_{i,k-m,j,t-m}$. Hence, e.g., for period t, $r_{ikjt} = \sum_{k=1}^{k} \sum_{t=1}^{t} r_{ikjt}$.

(3.1) Maximize $Z = \sum_{ikjt} r_{ikjt} \, x_{ijkt}$.

In this formulation, r_{ikjt} reflects, as before, a negative component equal to expected flood damages, a negative component equal to the costs of flood proofing structures to the selected (dominant) degree of intensity, and the probabilities (and hence costs) of floods remaining if a particular dam is constructed. As before, separate problems are solved for each dam configuration and final decisions are made by inspection.

Constraints

Optimization of (3.1) is subject to a number of restraints. The first set of (binary) constraints is expressed as:

(3.2) $\sum_{jt} x_{ikjt} \leq 1; \qquad \forall_{i,k}$.

This set of IK restraints ensures that the same parcel is neither developed in two or more periods nor used for two or more uses.

A second set of restraints,

(3.3) $\sum_{kjt} x_{ikjt} \leq H_i \qquad \forall_i$

ensures that for each category i, no more land than is available (H_i) is developed. As before, a host of additional constraints can be added to reflect alternative community goals and limitations.

EMPIRICAL RESULTS

The empirical results of several demonstration runs of this framework are set out and interpreted below. For present (illustrative) purposes we have kept the problem reasonably small. The time (planning) horizon was limited to two periods of five year lengths and only six categories3/ were included. The demand and rent functions were divided into three relevant (equal) sections (k = 3). Some results of the applications of the model to the regional situation described above are set out in Tables 1 and 2.4/

3/ The highest flood frequency zone in each region was excluded on the basis of previous analysis, i.e., categories i = 2, 3, 5, 6, 8, and 9 have been included in the analysis.

4/ These formulations presumed risk aversion was absent, no dams would be constructed, and externalities would receive a zero weighting. The results for these models as well as the data for all of the models is available upon request.

Table 1

Land Use Management Decisions (Acres Zoned) by Region, Use, and Period, Assuming 5 and 10 Percent Discount Rates, and Damage Coefficient (a_h) of 0.052*

Region	Land Use Activity (j)	Discount Rate (r)							
		.05				.10			
		Period				Period			
		1		2		1		2	
		100 Yr.	500 Yr.	100 Yr.	500 Yr.	100 Yr.	500 Yr.	100 Yr.	500 Yr.
1	1	-- --	-- --	-- --	-- --	-- --	-- --	-- --	-- --
	2	15.0 (15.0)	69.0 (69.0)	-- --	69.0 --	15.0 (15.0)	69.0 (69.0)	-- --	69.0 (69.0)
	3	-- --	-- --	-- --	-- --	-- --	18.0 --	-- --	-- --
	4	5.0 (5.0)	5.0 (5.0)	5.0 (5.0)	-- (5.0)	5.0 (5.0)	-- (5.0)	5.0 (5.0)	-- --
	5	-- --	-- --	-- --	-- --	-- --	-- --	-- --	-- --
2	1	24.0 --	-- --	24.0 --	-- --	24.0 --	-- --	-- --	-- --
	2	7.0 (7.0)	7.0 (7.0)	-- --	7.0 (7.0)	7.0 (7.0)	7.0 (7.0)	7.0 --	7.0 (7.0)
	3	-- (18.0)	-- (18.0)	-- (18.0)	-- --	-- (18.0)	18.0 (18.0)	-- (18.0)	18.0 --
	4	-- --	-- --	-- --	5.0 --	-- --	-- --	-- --	-- --
	5	-- --	-- --	-- --	-- --	-- --	-- --	-- --	-- --
3	1	42.0 --	-- --	-- --	-- --	-- --	-- --	-- --	-- --
	2	15.0 (15.0)	15.0 (15.0)	-- --	15.0 (15.0)	15.0 (15.0)	15.0 (15.0)	-- --	-- (15.0)
	3	-- (18.0)	-- --	-- --	-- --	-- --	-- --	-- --	-- --
	4	-- (5.0)	5.0 --	5.0 --	-- (5.0)	-- (5.0)	5.0 --	5.0 (5.0)	5.0 (5.0)
	5	-- --	-- --	-- --	-- --	-- --	-- --	-- --	-- --

*Numbers in parentheses indicate decisions assuming flood proofing of structures and contents. Land use activities are denoted as: 1 is single unit dwellings, 2 is apartments, 3 is industrial use, 4 is commercial use, and 5 denotes open space.

Table 2

Land Use Management Decisions (Acres Zoned) by Region, Use, and Period, Assuming 5 and 10 Percent Discount Rates, and Damage Coefficient (a_h) of 0.057*

Region	Land Use Activity (j)	Discount Rate (r)							
		.05				.10			
		Period				Period			
		1		2		1		2	
		100 Yr.	500 Yr.	100 Yr.	500 Yr.	100 Yr.	500 Yr.	100 Yr.	500 Yr.
1	1	--	--	--	--	--	--	--	--
		--	--	--	--	--	--	--	--
	2	15.0	69.0	--	69.0	15.0	69.0	--	69.0
		(15.0)	(69.0)	--	--	(15.0)	(69.0)	(15.0)	--
	3	--	--	--	--	--	--	--	--
		--	--	--	--	--	--	--	--
	4	5.0	5.0	5.0	--	5.0	5.0	5.0	--
		(5.0)	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)	--	(5.0)
	5	--	--	--	--	--	--	--	--
		--	--	--	--	--	--	--	--
2	1	24.0	--	24.0	--	24.0	--	24.0	--
		--	--	--	--	--	--	--	--
	2	7.0	7.0	--	7.0	7.0	7.0	--	7.0
		(7.0)	(7.0)	--	(7.0)	(7.0)	(7.0)	--	(7.0)
	3	--	--	--	--	--	18.0	--	--
		(18.0)	(18.0)	(18.0)	--	(18.0)	(18.0)	(18.0)	--
	4	--	--	--	5.0	--	--	--	--
		--	--	--	--	--	--	--	--
	5	--	--	--	--	--	--	--	--
		--	--	--	--	--	--	--	--
3	1	42.0	--	--	--	--	--	--	--
		--	--	--	--	--	--	--	--
	2	15.0	15.0	--	15.0	15.0	15.0	--	15.0
		(15.0)	(15.0)	(15.0)	--	(15.0)	(15.0)	--	(15.0)
	3	--	--	---	--	--	--	--	--
		(18.0)	--	--	--	--	--	--	--
	4	--	5.0	5.0	--	5.0	--	5.0	5.0
		--	(5.0)	--	(5.0)	(5.0)	--	(5.0)	(5.0)
	5	--	--	--	--	--	--	--	--
		--	--	--	--	--	--	--	--

*Numbers in parentheses indicate decisions assuming flood proofing of structures and contents. Land use activities are denoted as: 1 is single unit dwellings, 2 is apartments, 3 is industrial use, 4 is commercial use, and 5 denotes open space.

Table 1 provides decisions by region, use, and period for alternative discount rates assuming a damage coefficient[5/] of 0.52. The interpretation of the results is straightforward. In period 1, assuming a five percent discount rate, for example, there should be 15 acres in the 100 year zone and 69 acres in the 500 year zone of region one allocated to apartments (with or without flood proofing). In period 2, an additional 69 acres should be put into apartments in the 500 year zone without flood proofing (none with flood proofing).

Table 2 provides similar results for a slightly higher flood damage coefficient. Note the degree of solution insensitivity to small changes in parameters. This is in part due to the levels of indivisibilities present.

CONCLUSIONS

The purpose has been to recognize an area of decision making which is, or can reasonably be, in the realm of at least a quasi-public domain, and which has received remarkably little attention with respect to formal decision frameworks and virtually none in the area of mathematical programming procedures. We have suggested a framework or approach which we feel could provide information for improved decisions. In some regional situations, the variables we designate as controls are not controllable under current institutional arrangements. In these cases, solutions can provide implications (opportunity costs) associated with the maintenance or alteration of these institutional structures. Finally, we demonstrate the applicability of the framework for an existing regional situation.

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5/ For a given flood depth d, the flood damages to a structure bear a constant proportion to its market value M. It is calculated by the relation $D_j = a_h M_j d$, where the constant of proportionality a_h is called the damage coefficient. See Willis and Aklilu [1973].

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