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# Floodplain Planning with Risk-based Optimization

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**Abstract**
Economical integration of permanent and emergency flood control options is a long-standing problem in water resources planning and management. A two-stage linear programming formulation of this problem is proposed and demonstrated which provides an explicit economic basis for developing integrated floodplain management plans. The approach minimizes the expected value of flood damages and costs, given a flow or stage frequency distribution. A variety of permanent and emergency floodplain management options can be examined in the method, and interactive effects of options on flood damage reduction can be represented. The approach is demonstrated and discussed for a hypothetical example. Limitations of the method in terms of forecast uncertainty and concave additive damage function forms also are discussed, along with extensions for addressing these more difficult situations.

## INTRODUCTION

The effectiveness of floodplain management options has long been recognized, and such options have come to be considered integral with classical structural options for addressing flood control problems (USACE 1976; White 1945; Wood, et al. 1985; Lind 1967). But integrated floodplain planning with probabilistic flood descriptions remains a problem.

The most common economic framework for floodplain management is minimization of expected annual damages and flood management expenses (structural and non-structural flood control options) (WRC 1983; Goodman 1984). This form of probabilistic benefit-cost analysis largely has replaced older forms of economic analysis performed by examining only a particular design flood, such as a flood of record or an estimated 100-year event. Recently, more probabilistic approaches have become common, considering the damages that would result from a full range of probability-weighted flood events (Davis, et al., 1972; USACE 1996) and for long-term dynamic floodplain planning (Olsen, et al. 2000). This has improved the application of benefit-cost analysis for flood control problems, although considerable work remains to be done.

Within this newer form of analysis, a great deal of research has been devoted to the assignment of probabilities to the range of flood event discharges and flood stages (Cunnane 1978; USACE 1996). The assignment of probabilities in an expected damage evaluation framework has received considerable attention (Arnell 1989; Beard 1997; Goldman 1997; Stedinger 1997). Much of this controversy remains unresolved. The estimation of damages associated with inundation to a given stage/elevation also has received considerable attention (USACE 1988).

The problem examined here is to identify the optimal mix of floodplain management options within a probabilistic framework. Some earlier optimization of floodplain management has been done on this using enumeration (James 1967), recursive linear programming (Day 1970), linear programming (Bailas and Loucks 1978), dynamic programming (Morin, et al., 1989), and branch-and-bound techniques (Ford and Oto 1989). The approach developed below applies two-stage linear programming to find the minimum expected value cost of responding to a given flood flow or stage frequency distribution. The approach is analogous to the use of two-stage linear programming for estimating the willingness to pay to avoid a probability distribution of water shortages (Lund 1995) and developing minimum expected value cost plans for responding to a probability distribution of water shortages (Wilchfort and Lund 1997). This optimization approach should be useful for risk-based flood and floodplain management evaluation and design.

## MATHEMATICAL PROGRAM FORMULATION

Given a probability distribution of inundation flows or stages for a floodplain, what non-structural floodplain management options should be undertaken? And, what is the economic value of a changed set of probabilistic inundation levels, as might arise from the operation of a system of levees, reservoirs, and channel improvements?

### General Formulation

Let $D(\vec{X}_P, \vec{X}_E(s), s)$ be the damages in a floodplain resulting from water stage s, given a set of permanent floodplain management actions $\vec{X}_P$ (e.g., flood walls, raising foundations, and changing land use) and emergency flood response actions $\vec{X}_E(s)$, (e.g., evacuations and levee sandbagging). Let there also be an implementation cost to each of these management actions, $c_{Pi}$ and $c_{Ejs}$, respectively (annualized in the case of permanent actions). The overall economic objective of managing the floodplain (assuming loss of life can be neglected) is then the expected value of the sum of these costs and damages, with the average taken using the stage-probability distribution p(s),

(1) $$z_1 = \sum_{i=1}^{m} c_{Pi}(X_{Pi}) + \int_0^{\infty} p(s)\left[\sum_{j=1}^{n} c_{Ej}(X_{Ej}(s), s) + D(\vec{X}_P, \vec{X}_E(s), s)\right] ds,$$

for m permanent floodplain management options and n emergency options. Expected value decisions are appropriate for decisions which are small relative to the accounting stance of the decision maker, in this case a nation, state, or large region (Arrow and Lindh 1970).

Where costs and damages are linear (or convex and piecewise linear), this objective function becomes suitable for a two-stage linear program, if the stage-probability function is discretized. This then becomes:

(2) $$z_2 = \sum_{i=1}^{m} c_{Pi} X_{Pi} + \sum_{s=1}^{q} p_s \left[\sum_{j=1}^{n} c_{Ejs} X_{Ejs} + D_s\right],$$

with residual flood damages being defined for each flood event s as:

(3) $$D_s = D(\vec{X}_P, \vec{X}_{Es}, s), \ \forall \text{ s}$$

or if linearized,

(4) $$D_s = d_s - \vec{b}_{Ps}^{T} \vec{X}_P - \vec{b}_{Es}^{T} \vec{X}_{Es}, \ \forall \text{ s}$$

where $d_s$ is the damage without any floodplain management actions and $\vec{b}_{Ps}$ and $\vec{b}_{Es}$ are vectors of unit damage-reduction effectiveness for each management measure X for each stage level s. These unit effectiveness measures can be defined as:

(5) $$b_{Pis} = \frac{\partial D(s)}{\partial X_{Pi}} \quad \text{and} \quad b_{Ejs} = \frac{\partial D(s)}{\partial X_{Ejs}}.$$

**Assumptions**

The following assumptions and definitions are made. In this formulation, parameters are lower case variables and decision variables are upper case.

1. An unbiased probability distribution of inundation flows or stages ($p_s$) is available for the floodplain.
2. A range of permanent floodplain management options is available for properties in the floodplain and their costs are known. Such options could include raising foundation elevations, installing flood walls, stocking sand-bags, installing a flood warning system, changing land use, etc. Let these permanent decisions be $X_{Pi}$ and their annualized unit costs be $c_{Pi}$, for option i. While not always linear, convex costs can be piece-wise linearized. An integer-linear program solution might be employed if damages are concave and non-additive.
3. A range of emergency flood response options can be undertaken during a specific flood event, such as evacuation of people and goods, levee watches, placing sand-bags, doing nothing, etc. The costs for these individual options also are known. Let these decisions be $X_{Ejs}$ and their unit implementation costs be $c_{Ejs}$, for option j under event/stage s. These decisions and costs vary with inundation stage s.
4. Estimates of damage are available for different levels of flood inundation if no actions are taken, $d_s$.
5. Estimates of the benefits (damages avoided) if permanent and emergency options were undertaken in the floodplain are available for each inundation stage s ($b_{Pis}$ for permanent measures and $b_{Eis}$ for emergency measures). These benefits also vary by inundation stage s and are also assumed to be additive, although convex avoided damages can be represented using piece-wise linearization and non-additive damages avoided can often be represented with additional constraints or integer linear programming.

**Two-Stage Linear Program Objective Function**

The overall objective is to minimize the sum of expected annual damages and annualized expected flood response costs of floodplain management. Increases in permanent and emergency flood responses will reduce flood damages, but there will come a point where additional flood mitigation actions will no longer be economical. The expected annualized cost equation for a combination of implemented floodplain options and resulting flood event damages is:

(6) $$\text{Min } z_2 = \sum_{i=1}^{m} c_{Pi} X_{Pi} + \sum_{s=1}^{q} p_s \left( \sum_{j=1}^{n} c_{Ejs} X_{Ejs} + D_s \right)$$

where $D_s$ is the damage resulting from a managed event size (flow or stage) s.

Given a set of structural flood control options (implemented outside of the floodplain damage area) that provide a probability distribution of event sizes, $p_s$, the floodplain management objective should be to minimize expected annual damages plus expected annual flood control costs.

**Constraints**

The minimization of total expected cost is limited by several types of constraints.

*Flood damage calculation.* Overall damage reduction is assumed to be the sum of incremental damage reductions arising from implementation of management options, as in Equation 7. Floodplain damage for each flood event ($D_s$) is calculated to prevent the impossible situation of reductions in damages exceeding base-case damages, $d_s$. The constraints distinguish calculated damages for each event ($CD_s$) from corrected damages ($D_s$) which cannot be negative.

(7) $$d_s - \sum_{i=1}^{m} b_{Pis} X_{Pi} - \sum_{j=1}^{n} b_{Ejs} X_{Ejs} = CD_s,\ \forall\ s$$

(8) $$D_s >= CD_s,\ \forall\ s$$

(9) $$D_s >= 0,\ \forall\ s$$

*Limits on option implementation.* There are limits on each decision variable (the X's), representing the limits of implementation for each option. Usually,

(10) $$X_{Pi} <= 1,\ \forall\ i,\ X_{Ejs} <= 1,\ \forall\ j,s.$$

Sometimes, particular options can only be implemented either completely or not at all, or in integer values. For example, floodplain evacuation typically is implemented in discrete stages. This can be accommodated using a limited number of integer variables in the formulation, Integer $X_{Pi}$.

*Interaction of implemented options.* To make the formulation more realistic, the interaction of floodplain management options can be specified in constraints, allowing representation of some forms of non-additive costs and damage reduction. This has been done for some similar water-supply applications (Lund 1995). Cases where implementing a permanent option i precludes implementing an emergency option j during event s can be represented by the following constraint,

(11) $$X_{Pi} + X_{Ejs} \leq 1,\ \forall\ j,\ s \text{ precluded by implementing } i.$$

Such a case might be where a particular land use control precludes the relevance or benefits of evacuation measures. Conversely, where a particular emergency option j for an event s requires prior establishment of a particular permanent option i, the following constraint can be used,

(12) $$X_{Pi} - X_{Ejs} \geq 0,\ \forall\ j,\ s \text{ requiring implementation of } i.$$

This might be the case where the closure of a floodwall gate (an emergency option) would require prior construction of a floodwall (a permanent option). In such a case, the permanent option might confer no flood damage reduction benefits without implementation of the emergency option during flooding episodes.

**Numerical Solution**

The complete formulation is a two-stage linear or integer-linear program. This form of problem often can be solved with common spreadsheet software. Larger problems can be solved by readily available commercial linear program solvers. The examples below are solved using spreadsheet linear program solvers.

**ILLUSTRATIVE EXAMPLES**

Consider a floodplain management problem where several permanent and emergency options can be implemented. The optimal mix of these options is likely to vary with the flood frequency distribution for the floodplain arising from different structural flood control options, such as levees of different heights or upstream reservoirs of different capacities or operations. Illustrative examples are presented which illustrate how a two-stage linear program can be used to 1) identify an economical mix of permanent and emergency floodplain management options and 2) derive an expected economic value for modification of flood frequencies through structural actions, such as levees or upstream reservoirs.

**Integration of Floodplain Management Options**

What is an economically desirable mix of permanent and emergency floodplain management options, given a probability distribution of flood stages, $p_s$? Consider the following problem, with tables from an illustrative spreadsheet model. Table 1 represents the current annual probability and "no-action" damage associated with five different peak flow events, and also contains a modified flow frequency distribution used in the second example.

Table 2 represents the permanent floodplain management options available. These include the raising of structures in the floodplain, adoption of a flood warning system, and construction of sacrificial first floors for buildings in the floodplain. These permanent options are distinguished by the need to implement them well before the onset of flooding for them to be effective. Each permanent floodplain management option has an associated unit of implementation, unit annualized cost, limit of maximum implementation, and unit independent reduction of flood damage for each flood event (peak flood flow). Table 2, coming from the model spreadsheet, also includes least-cost permanent decisions for this problem, in bold, and the total annualized cost of implementing permanent options, in the last row.

Table 3 presents emergency floodplain management options, those that respond directly to particular peak flow events. Each option has units of implementation, unit annual cost per implemented year, a limit on implementation, and an independent unit damage reduction per event. All items in Table 3 are fixed parameter values. Table 4 presents for each event size, the least-cost decisions for emergency options (in bold), their total cost per event, and their expected value costs as well as the total expected value cost of emergency option implementation ($/year).

Table 5 contains the calculated damages (Equations 7) and corrected damages (Equations 8 and 9) for each flood peak event, along with the expected value of these damages, and the total expected value of economic losses. Total expected value of economic losses per event is the expected value of flood damage plus the expected value of emergency option costs (from Table 4). Table 5 also includes rows summing the expected annual value of emergency losses, restating the annualized cost of permanent options, and the overall expected value of floodplain costs and losses, in the last row. Of these items, only the corrected damages, in bold, are decision variables, as constrained by Equations 8 and 9.

These spreadsheet tables, with the formulae behind them, embody the two-stage linear program described in equations above. When solved, they indicate that the minimum total annualized expected value cost of the first set of flood frequencies in Table 1 is $210,750/year. Beyond this, the solution indicates that of the permanent management options, only some raising of structures is justified economically. Among the emergency response options, each option is employed for different flood events.

**Economic Value of Changing Flood Frequency Through Structural Actions**

Often several structural flood control actions are being considered, such as selection of a levee height or changes in upstream reservoir operations, in conjunction with non-structural flood control. Economically, the problem is to estimate whether the reduction in flooding costs from a higher levee, considering reasonable use of floodplain management options, exceeds the cost of the levee or other structural action.

Structural flood control actions mostly affect flood damages by changing the flood or stage frequency distribution in the floodplain. In the formulation above, this amounts to changing the probability distributions for different flood events $p_s$. Changing this flood probability distribution has some net benefit or cost that can be estimated from the two-stage linear program employed above. The mathematical program is solved for the base case and for the case of the proposed structural flood control action. The difference between these two objective function values is the floodplain benefit of the change in event probabilities.

Consider where a change in levee heights or operation of an upstream reservoir changes the probabilities of flooding from the third column of Table 1 to those as modified in the fourth column. What is the economic value of this change in flood frequency for this floodplain? More specifically, what is the change in the overall annualized economic cost of responding to probabilistic flooding for this area?

With the new annual flood frequencies, the least expected-value annual cost from the floodplain linear program is $125,800. Thus, the new less flood-prone annual flood frequencies reduce the expected value cost of flooding for the floodplain by $210,750 - $125,800 = $84,950/year. The cost is lower because with the lower frequency of flooding, permanent floodplain options are neither implemented nor optimal, and emergency floodplain options are employed less frequently. Given a 5% real discount rate and a very long project life, the maximum present value cost economically justifiable for a structural or operational change that provides this change in flood frequency would be $84,950/0.05 = $1,699,000.

## SENSITIVITY ANALYSIS

Some of the sensitivity analysis from standard linear program solution software is useful in interpreting these results for practical problems.

a. The reduced cost and range of decision variable costs for which the basis remains unchanged. This information is produced directly from most linear program solution software. This information must be interpreted slightly differently for permanent options ($X_{Pi}$) than emergency options ($X_{Ejs}$). For permanent floodplain options unimplemented in the solution, corresponding reduced cost and range of basis values are estimates of how much the cost of that particular permanent option would have to be reduced before it would be economical to employ it in the floodplain. For example, the cost of converting buildings to have sacrificial first floors would have to decrease from $40/sq. ft. to about $6.40/sq. ft. before this option would be implemented at all. For permanent options implemented in the solution, the corresponding range of basis values are estimates of how much higher these costs could be before they would no longer be economical for the floodplain. For example, if the cost of raising structures increased from \$10/cu. yd. to \$18/cu yd, this option would no longer be implemented. However, if this cost were reduced to \$7.50/cu yd, then additional raising of structures would be suggested.

The range of basis values for emergency response options ($X_{Ejs}$) represent the range of costs for these options under which they would remain implemented (or not) economically, except that these values are weighted by the probability of each event $p_s$. These values must be divided by the corresponding $p_s$ to yield the changes in cost at which an unimplemented option becomes economically attractive or an implemented option becomes unattractive. For example, sandbagging levees is very effective for 5-6,000 cfs floods, with an allowable unit cost increase of \$12,200 (in expected value terms); however, this must be divided by the annual probability of this event, p = 0.11, to give the true event unit cost of \$110,909, the unit cost increase in sandbagging for this event that would result in less sandbagging being optimal for this event. The usefulness of these numbers for emergency response decision making is severely restricted by their being specific to an individual flood event s.

b. Range of basis for constraints. Estimates of no-action damages often are subject to some error. Range of basis values for each damage event calculation constraint (Equations 7 and 8) indicate the degree to which no-action flood damages $d_s$ would have to increase or decrease before changing the mix of alternatives suggested by the linear program.

c. Perhaps the most useful form of sensitivity analysis for this problem is simply re-running the optimization model for different cost, probability, and effectiveness scenarios. The model is easy and quick to solve.

**LIMITATIONS AND EXTENSIONS**

The proposed approach has several limitations. First, the implementation of emergency options presumes very good (ideally perfect) forecasting of flood events. Emergency flood-response options are not implemented futilely or without necessity because the stage forecast for each flooding episode is assumed to be perfect. Significantly imperfect flood forecasts might be represented by conditional probabilities and a third stage might be added to the linear program. The resulting linearized objective function would be

$$z_3 = \sum_{i=1}^{m} c_{Pi} X_{Pi} + \sum_{s=1}^{q} p_s \left[ \sum_{j=1}^{n} c_{Ejs} X_{Ejs} + \sum_{s_2=1}^{q} p(s_2 \mid s) D_{s_2|s} \right], \quad (13)$$

and primary constraints

$$D_{s_2|s} = d_{s_2} - \vec{b}^T_{P_{s2}} \overrightarrow{X}_P - \vec{b}^T_{E_{s2}} \overrightarrow{X}_{Es}, \ \forall \text{ s, } s_2 \quad (14)$$

where s is the forecast flood stage, $s_2$ is the actual flood stage, and $p(s_2|s)$ is the probability of flood stage $s_2$ occurring if flood stage s is forecast. Damage reduction parameters are also modified for the occurrence of the actual flood stage $s_2$, rather than the forecast flood stage s. Expansion to a three-stage linear program greatly expands the computational and calibration effort needed for the model, requiring solution for $m + qn + q^2$ decision variables and at least $q^2$ constraints and calibration for at least $2m + q(1+2n) + q^2$ parameters. Calibration of the additional parameters for a three-stage model would require estimates of conditional flow probabilities for flood forecasts, perhaps not an easy estimation.

Second, reductions in damage arising from implementation of permanent and emergency options are assumed to be additive. This will often not be strictly the case. Constraint Equations 7, 8, and 9 provide this additive model, limited to positive damages. Some interactions of options, restricting additivity, can be handled as described above in Equations 11 and 12. Other major limitations and concerns would be for the estimation of flood frequencies, damage costs, and flood option effectiveness and interactions. Nevertheless, most of these data must already be estimated for current analysis methods.

The method proposed here seeks to optimize a mix of fixed floodplain management options for a fixed flood frequency distribution. Other methods have been proposed to examine the long-term dynamics of flood management decisions, allowing examination of how flood management decisions might change in the aftermath of different flood events (Olsen, et al. 2000). However, particularly for examining mixtures of flood management options, these dynamic methods would require a great deal more computational effort than the static model proposed here. Nevertheless, such dynamic methods can provide useful planning information, particularly in the aftermath of major events and for examining optimal staging of flood management investments over time (as economic and/or climate changes occur).

## CONCLUSION

A method is proposed for economically and explicitly integrating a wide variety of permanent and emergency flood control measures for floodplain management, given a probabilistic description of flood probabilities ($p_s$). The results of the method include an explicit economic valuation of the cost of flooding and an economically-based plan for management of floodplain property. The method can also be used comparatively to evaluate the economic value of changes in flood frequencies that might result from levee or upstream actions.

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## REFERENCES

Arnell, N. (1989), "Expected Annual Damages and Uncertainties in Flood Frequency Estimation," *Journal of Water Resources Planning and Management*, ASCE, Vol. 115, No. 1, January, pp. 94-107.

Arrow, K.J. and R.C. Lind (1970), "Uncertainty and the evaluation of public investment decisions," *American Economic Review*, Vol. 60.

Beard, L.R. (1997), "Estimating Flood Frequency and Average Annual Damage," *Journal of Water Resources Planning and Management*, ASCE, Vol. 123, No. 2, March/April, pp. 84-89.

Bialas, W.F. and D.P. Loucks (1978), "Nonstructural Floodplain Planning," *Water Resources Research*, Vol. 14, No. 1, February, pp. 67-74.

Brown, J.P. (1972), *The Economic Effects of Floods: Investigation of a Stochastic Model of Rational Investment Behavior in the Face of Floods*, Lecture Notes in Economics and Mathematical Systems, Vol. 70, Springer-Verlag, New York, NY, 87 pp.

Cunnane, C. (1978), "Unbiased Plotting Positions - A Review," *Journal of Hydrology*, Vol. 37, pp. 205-222.

Davis, D.R., C.C. Kisiel, and L. Duckstein (1972), "Bayesian Decision Theory Applied to Design in Hydrology," *Water Resources Research*, Vol. 8, No. 1, February, pp. 33-41.

Day, J.C. (1970), "A Recursive Programming Model for Nonstructural Flood Damage *Water Resources Research,* Vol. 4, No. 5, pp. 1262-1271.

Ford, D.T. and A. Oto (1989), "Floodplain-management plan enumeration," *Journal of Water Resources Planning and Management*, ASCE, Vol. 115, No. 4, pp. 472-485.

Goldman, D. (1997), "Estimating Expected Annual Damage for Levee Retrofits," *Journal of Water Resources Planning and Management*, ASCE, Vol. 123, No. 2, March/April, pp. 89-94.

Goodman, A.S. (1984), *Principles of Water Resources Planning*, Prentice-Hall, Englewood Cliffs, NJ.

James, L.D. (1967), "Economic Analysis of Alternative Flood Control Measures," *Water Resources Research*, Vol. 3, No. 2, pp. 333-343.

Lind, R.C. (1967), "Flood Control Alternatives and the Economics of Flood Protection," *Water Resources Research*, Vol. 3, No. 2, pp. 345-357.

Lund, J.R. (1995), "Derived Estimation of Willingness-to-Pay to Avoid Probabilistic Shortage," *Water Resources Research*, Vol. 31, No. 5, May, pp. 1367-1372.

Morin, T.L., W.L. Meier, and K.S. Nagaraj (1989), "Dynamic Programming for Flood Control Planning: The optimal mix of adjustments to flood," in A.O. Esogbue (ed.), *Dynamic Programming for Optimal Water Resources Systems Analysis*, Prentice-Hall, Englewood Cliffs, NJ, pp. 286-306.

Olsen, J.R., P.A. Beling and, J.H. Lambert (2000), "Dynamic Models for Floodplain *Journal of Water Resources Planning and Management*, Volume 126, No. 3, May/June, pp. 167-175.

Stedinger, J.R. (1997), "Expected Probability and Annual Damage Estimators," *Journal of Water Resources Planning and Management*, ASCE, Vol. 123, No. 2, March/April, pp. 125-135.

USACE (1976), *Proceedings of a Seminar on Nonstructural Flood Plain Management Measures*, Hydrologic Engineering Center, US Army Corps of Engineers, Davis, CA.

USACE (1988), National Economic Development Procedures Manual – Urban Flood Damage, IWR Report 88-R-2, Institute for Water Resources, U.S. Army Corps of Engineers, Alexandria, VA.

USACE (1996), *Risk-based Analysis for Flood Damage Reduction Studies*, Engineer Manual EM 1110-2-1619, August, U.S. Army Corps of Engineers, Washington, D.C.

U.S. Water Resources Council (WRC) (1983), *Economic and Environmental Principles and Guidelines for Water and Related Land Resources Implementation Studies*, March 10, 1983.

White, G.F. (1945), *Human Adjustment to Floods: A Geographical Approach to the Flood Problem in the United States*, University of Chicago, Chicago, IL.

Wilchfort, O. and J.R. Lund (1997), "Shortage Management Modeling for Urban Water Supply Systems," *Journal of Water Resources Planning and Management*, ASCE, Vol. 123, No. 4, July/August.

Wood, D.W., T.C. Gooch, P.M. Pronovost, and D.C. Noonan (1985), "Development of *Journal of Water Resources Planning and Management*, ASCE, Vol. 111, No. 4, October, pp. 417-433.

Table 1: Event Damages with No Action and Current and Modified Event Probabilities

| Peak Flow cfs | Event Damage with No Action ($ millions) | Current Annual Probability | Modified Annual Probability |
|---|---|---|---|
| < 5,000 | 0.0 | 0.80 | 0.90 |
| 5-6,000 | 2.1 | 0.11 | 0.05 |
| 6-8,000 | 3.0 | 0.06 | 0.03 |
| 8-10,000 | 4.2 | 0.02 | 0.015 |
| 10,000+ | 6.0 | 0.01 | 0.005 |

Table 2: Permanent Floodplain Management Option Characteristics

| Characteristic | Raising Structures | Warning system | Sacrificial First Floors |
|---|---|---|---|
| Unit of implementation | yd3 of fill | $ invested | Building sq. feet |
| Unit cost | $10 | $1 | $40 |
| Limit of implementation | 1,000,000 | $200,000 | 200,000 |
| Unit damage reduction per event: | | | |
| <5,000 cfs | 0 | 0 | 0 |
| 5-6,000 cfs | $200 | $3 | $100 |
| 6-8,000 cfs | $90 | $4 | $60 |
| 8-10,000 cfs | $70 | $6 | $50 |
| 10,000 + cfs | $10 | $10 | $20 |
| Optimal Implementation | **500** | **0** | **0** |
| Total Annualized Cost of Permanent Options: | | | $5,000 |

Table 3: Emergency Floodplain Management Option Characteristics

| | Evacuation | Sandbagging of levees | Heightened levee monitoring |
|---|---|---|---|
| Unit of implementation | 0 or 1 | ft. | $spent |
| Unit cost | $100,000 | $30,000 | $1 |
| Limit of implementation | 1 | 2 | $20,000 |
| Unit damage reduction per event: | | | |
| <5,000 cfs | 0 | 0 | 0 |
| 5-6,000 cfs | $200,000 | $1,000,000 | $2 |
| 6-8,000 cfs | $300,000 | $800,000 | $1 |
| 8-10,000 cfs | $500,000 | 0 | 0 |
| 10,000 + cfs | $1,000,000 | 0 | 0 |

Table 4: Emergency Option Implementation for Each Event

| Event | Evacuation (Binary Integer) | Sandbagging of levees | Heightened levee monitoring | Total Emergency Option Cost | EV of Emergency Option Cost |
|---|---|---|---|---|---|
| <5,000 cfs | **0** | **0** | **0** | $0 | $0 |
| 5-6,000 cfs | **0** | **2** | **0** | $60,000 | $6,600 |
| 6-8,000 cfs | **1** | **2** | **20000** | $180,000 | $10,800 |
| 8-10,000 cfs | **1** | **0** | **0** | $100,000 | $2,000 |
| 10,000 + cfs | **1** | **0** | **0** | $100,000 | $1,000 |
| Total Expected Value of Emergency Option Costs: | | | | | $20,400 |

Table 5: Total Damage with Option Implementation

| Event | Calculated Damage | Correct Damage | EV Damage | Total EV Economic Loss |
|---|---|---|---|---|
| <5,000 cfs | $0 | **$0** | $0 | $0 |
| 5-6,000 cfs | $0 | **$0** | $0 | $6,600 |
| 6-8,000 cfs | $1,035,000 | **$1,035,000** | $62,100 | $72,900 |
| 8-10,000 cfs | $3,665,000 | **$3,665,000** | $73,300 | $75,300 |
| 10,000 + cfs | $4,995,000 | **$4,995,000** | $49,950 | $50,950 |
| Total EV Emergency Damages and Costs: | | | | $205,750 |
| Total Annualized Cost of Suggested Permanent Options: | | | | $5,000 |
| Total Cost of Responding to Flood Frequency Distribution: | | | | $210,750 |

**Appendix A – Notation**

$b_{Ejs}$ = unit damage reduction benefits for emergency options with flood event s
$b_{Es}$ = vector of unit damage reduction benefits for emergency options with flood event s
$b_{Pis}$ = unit damage reduction benefits for permanent options with flood event s
$b_{Ps}$ = vector of unit damage reduction benefits for permanent options with flood event s
$CD_s$ = corrected flood damage with flood event s
$c_{Ejs}$ = cost of emergency decision j under flood stage s, as a function $c_{Ejs}()$ or unit cost
$c_{pi}$ = cost of permanent decision i, as a function $c_{pi}(.)$ or unit cost
$D_s$ = flood damage with flood event s
$d_s$ = no-action flood damage with flood event s
m = number of permanent floodplain management options
n = number of emergency floodplain management options
$p(s_2|s)$ = probability of flood event $s_2$ actually occurring if flood event s is forecast
$p_s$ = probability of flood event s
q = number of flood events considered
s = flood event index
s = forecast flood stage
$\vec{X}_E(s)$ = vector of emergency floodplain management decisions, contingent on forecast stage s
$X_{Ejs}$ = implementation decision for emergency floodplain management decision j with event s
$\vec{X}_P$ = vector of permanent floodplain management decisions
$X_{Pi}$ = implementation decision for permanent floodplain management option i
$z_1$ = generalized two-stage expected value cost objective
$z_2$ = linear two-stage expected value cost objective
$z_3$ = linearized expected value objective with imperfect flood forecasts