

THE ECONOMICS OF LANDSLIDE MITIGATION STRATEGIES:
PUBLIC VERSUS PRIVATE DECISIONS

by

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(ABSTRACT)

The economic rationale for public intervention in decisions regarding landslide hazard mitigation was examined through a cost-benefit analysis. A study area in Cincinnati, Ohio was used to test whether a public agency decision rule is suboptimal to a private decision rule in maximizing net benefits from landslide mitigation.

A 1985 U.S. Geological Survey (U.S.G.S.) report on landslide mitigation in Cincinnati, Ohio formed the basis for the cost-benefit analysis. Expected gross benefits from mitigation were determined by multiplying the probability of a landslide by an estimate of the property damages. A landslide probability model developed by the U.S.G.S. was tested against data for a study area in Pittsburgh, Pennsylvania. A Spearman rank correlation test, comparing actual and predicted landslide occurrence, indicated that the model is a good predictor and could be used to predict landslides in other areas of similar

geology. Due to the poor quality of data on actual landslide damages, a regression equation was estimated to predict the actual damages resulting from a landslide in the Cincinnati study area.

A cost-benefit analysis was performed for the Cincinnati study area using three different approaches to measuring property damages. The results of the analysis support the hypothesis. In the most extreme case, annualized net benefits from mitigation are equal to \$2.1 million under the private decision rule compared with only \$1.6 million under the public agency decision rule.

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I. Introduction

A. Central Hypothesis.

The burden of responsibility for reducing losses from landslides in the United States has fallen to local government agencies and to individuals, largely due to the absence of a national program.¹ The economic rationale for public intervention in private decisions regarding hazard mitigation is often claimed to be ignorance on the part of individuals as to the magnitude or probability of the hazard.² If individuals were knowledgeable about landslide risk and possible losses, it would not be necessary for public agencies to intervene in decisions regarding mitigation.

The present study undertakes to analyze whether a public agency decision rule is suboptimal to an individual decision rule in maximizing net benefits from landslide mitigation. From an economic standpoint, the efficient or optimal level of hazard mitigation is that level where an

¹ National Research Council, Commission on Engineering and Technical Systems, Committee on Ground Failure Hazards, Reducing Losses from Landsliding in the United States (Washington, D.C.: National Academy Press, 1985), 1.

² Jerome W. Milliman and R. Blaine Roberts, "Economic Issues in Formulating Policy for Earthquake Hazard Mitigation," Policy Studies Review 4, no. 4 (May 1985): 646-647.

increase in mitigation costs is exactly equal to the resulting increase in benefits (losses avoided).³ Any other level of hazard mitigation is suboptimal. In the context of the current analysis, expected benefits (expected value of property at risk) are equal to the probability of a landslide occurrence multiplied by an estimate of the property value. By comparing the costs of mitigation, under various decision rules, with the resulting benefits from mitigation, the maximum net benefits can be determined.

In an attempt to minimize damages resulting from landslides, local government agencies can impose public safety rules that compel individuals to engage in mitigation activities. Among the reasons why public intervention in decisions regarding landslide mitigation may be suboptimal are: (1) public agencies apply broad rules which may not be beneficial to each individual; (2) public agencies may be ignorant of the correct landslide loss function (i.e. property losses); (3) transaction costs associated with implementing a public agency rule may be large.

The first argument is that a cost-effective public agency mitigation rule can result in either over-protection

³ Ibid., 647-648.

or under-protection in certain areas. A public agency rule which requires individuals to mitigate against landslides when it is not cost-effective for them to do so results in some areas being over-protected. On the other hand, a public agency rule which does not compel individuals to mitigate against landslides when it would be cost-effective for them to do so results in some areas being under-protected.

The second argument is that public agencies may actually be misinformed about property losses resulting from landslides, due to incomplete and inaccurate records on this data.⁴ This will result in a misspecification of the expected benefits (losses avoided) and the choice of an incorrect mitigation rule. Once again, individuals may find themselves mitigating when it is not efficient for them to do so.

The final argument against public intervention is that the costs involved in implementing a public agency rule are an additional cost to society. If these costs are large, implementation of a public agency rule may not be desirable.

⁴ Ibid., 651.

B. Economic Framework.⁵

Individual economic choice under conditions of uncertainty can be analyzed by use of the expected utility framework. In attempting to determine levels of landslide risk, an individual will endeavor to maximize the sum of expected utility by,⁶

$$E(U) = (1-P) U(W) + P U(W-L)$$

where, E(U) = expected utility;
 P = annual probability of a landslide;
 (1-P) = annual probability of no landslide;
 W = initial level of wealth;
 U(W) = utility function of wealth for an individual;
 L = property losses resulting from a landslide;
 U(W-L) = utility function of wealth minus property losses, for an individual.

An individual faces two possible outcomes: (1) a landslide will occur, with the probability = P; (2) a landslide will not occur, with probability = 1-P. The term P U(W-L)

⁵ This section is based in part on the "Economic Framework" section of Richard L. Bernknopf, David S. Brookshire, Russell H. Campbell, Carl D. Shapiro and Robert W. Fleming, "The Economics of Landslide Mitigation Strategies in Cincinnati, Ohio: A Methodology for Benefit-Cost Analysis," Chapter D in Feasibility of a Nationwide Program for the Identification and Delineation of Hazards from Mud Flows and Other Landslides, open-file report, U.S. Geological Survey, 85-276D (Reston, Virginia: U.S. Geological Survey, 1985), D-9.

⁶ Based on Hal R. Varian, Microeconomic Analysis (New York: W. W. Norton & Company, 1984), 156.

represents the expected utility (or expected loss of utility) if a landslide does occur, whereas the term $(1-P) U(W)$ represents the expected utility if a landslide does not occur. Note that the risk of death due to a landslide has been omitted here since there is a low expectation of a risk of landslide-related death in the Cincinnati area.⁷ Consequently, in this framework, if a landslide does occur, it will have the sole effect of reducing an individual's wealth by the amount of the property losses.

Assuming that mitigation activities are effective in decreasing the risk of property loss, an individual's willingness to pay for mitigation, thereby avoiding or reducing the risk of property loss, can be measured by,⁸

$$dW/dC = P (-dL/dC)$$

where C = landslide mitigation costs. Assuming that some mitigation measures are more effective than others, this

⁷ Richard L. Bernknopf, David S. Brookshire, Russell H. Campbell, Carl D. Shapiro and Robert W. Fleming, "The Economics of Landslide Mitigation Strategies in Cincinnati, Ohio: A Methodology for Benefit-Cost Analysis," Chapter D in Feasibility of a Nationwide Program for the Identification and Delineation of Hazards from Mud Flows and Other Landslides, open-file report, U.S. Geological Survey, 85-276D (Reston, Virginia: U.S. Geological Survey, 1985), D-9.

⁸ Ibid.

equation states the relationship between a change in an individual's wealth due to a change in mitigation costs. Specifically, the term $P (-dL/dC)$ represents the amount an individual would be willing to pay at the margin to avoid landslide damages to property.⁹ In this case, the change in wealth is simply reflected in the change in property losses resulting from a change in mitigation costs.

1. Maximizing Expected Net Benefits Under Individual Choice.

In attempting to maximize net benefits from landslide mitigation, an individual who is risk neutral will undertake mitigation activities if the resulting net benefits are greater than zero. That is, an individual will mitigate if,

$$P (S_i) L_i - \gamma K_i > 0$$

where, $P (S_i)$ = annual probability of a landslide occurrence in a 100-meter cell, which is a function of the slope in cell i ;

L_i = property value in cell i (losses avoided);

K_i = mitigation costs in cell i .

γ = annualizing factor for one-time mitigation costs.

Expected annual net benefits from mitigation will be maximized for an individual according to,

$$E (NB) = (P (S_i) L_i - \gamma K_i)$$

⁹ Varian, Microeconomic Analysis, 264.

where, E (NB) = expected net benefits of mitigation.
 Maximized expected annual net benefits from mitigation under individual choice for a community can be determined by summing the above equation for all individuals in the community.

$$E (NB) = \sum_i (P (S_i) L_i - y K_i)$$

2. Maximizing Expected Net Benefits Under Public Agency Rule.

A public agency will choose a strategy for landslide mitigation based upon regional topographic information, such as slope or shear strength data. The best strategy for mitigation for a community will be the slope or shear strength rule which maximizes net benefits. Specifically, determination of the appropriate slope or shear strength rule will be based upon maximizing expected net benefits from mitigation, for those cells where mitigation is undertaken, according to,¹⁰

$$\text{MAX } E(NB) = \sum_{i \in Q_j} (P (S_i) L_i - y K_i)$$

where, Q_j = cells where slope or shear strength rule is satisfied and therefore mitigation is undertaken: $AS_i \geq AS_r$
 or $SS_i \leq SS_r$;

AS_i = average slope in cell i;

AS_r = average slope rule;

SS_i = soil shear strength in cell i;

SS_r = soil shear strength rule;

y = annualizing factor for one-time mitigation

¹⁰ Adapted from Bernknopf, "The Economics of Landslide Mitigation Strategies," D-10.

costs;
 $P(S_i)$ = annual probability of a landslide
 occurrence in cell i ;
 L_i = property value in cell i ;
 K_i = mitigation costs in cell i .

By testing various values for slope and shear strength, the optimal public agency mitigation rule can be ascertained.

3. Comparison of Expected Net Benefits From Mitigation Under Public Agency Rule and Under Individual Choice.

The framework described so far has depicted both mitigation costs and property value as being variable for each cell. However, if the assumption is made that they are both constant, the expected net benefits from mitigation will be the same under both private and public agency decision rules. This can be shown through a simple example.

First, assume that the region under consideration can be divided into 100-meter cells for which we have information on the probability of a landslide, the average natural slope, the property value and the costs of mitigation. Property value and mitigation costs are assumed constant in each cell and are as follows:

Property value = \$5,000
 Mitigation costs = \$450

Information for four 100-meter cells on the probability of a landslide and the average slope is:

	<u>Probability of a Landslide</u>	<u>Average Slope</u>
Cell Number 1	1%	1°
Cell Number 2	20%	6°
Cell Number 3	10%	4°
Cell Number 4	40%	12°

An individual will mitigate if net benefits are greater than zero.

	<u>Net Benefits From Mitigation Under Individual Choice</u>
Cell Number 1	\$(400)
Cell Number 2	\$ 550
Cell Number 3	\$ 50
Cell Number 4	\$1,550

Under individual economic choice, mitigation activities would be undertaken in cell numbers 2, 3 and 4 with net benefits for the community equal to \$2,150.

A public agency will mitigate according to the slope rule which maximizes expected net benefits. By analyzing various slope rules, the optimal strategy can be determined.

<u>Public Agency Slope Rule</u>	<u>Cell No. 1</u>	<u>Cell No. 2</u>	<u>Cell No. 3</u>	<u>Cell No. 4</u>	<u>Cumulative Net Benefits</u>
S ≥ 12				\$1,550	\$1,550
S ≥ 6		\$550		\$1,550	\$2,100
S ≥ 4		\$550	\$50	\$1,550	\$2,150
S ≥ 1	\$(400)	\$550	\$50	\$1,550	\$1,750

Net benefits to the community are maximized under the slope rule $S \geq 4$ resulting in net benefits of \$2,150. Again, mitigation activities are undertaken in cell numbers 2, 3 and 4.

Obviously, the assumption that the property value and mitigation costs are the same in every cell is unrealistic.

Suppose for example that the property value and mitigation costs vary for each cell as follows:

	<u>Property Value</u>	<u>Mitigation Cost</u>	<u>Average Slope</u>
Cell Number 1	\$6,000	\$55	1°
Cell Number 2	\$2,000	\$850	6°
Cell Number 3	\$8,000	\$350	4°
Cell Number 4	\$4,000	\$1,500	12°

Under individual choice, the net benefits from mitigation for each cell are:

	<u>Net Benefits</u>
Cell Number 1	\$5
Cell Number 2	\$(450)
Cell Number 3	\$450
Cell Number 4	\$100

Mitigation activities will be undertaken in cell numbers 1, 3 and 4, and net benefits to the community are equal to \$555.

The optimal strategy for the public agency can be identified by,

<u>Public Agency Slope Rule</u>	<u>Cell No. 1</u>	<u>Cell No. 2</u>	<u>Cell No. 3</u>	<u>Cell No. 4</u>	<u>Cumulative Net Benefits</u>
$S \geq 12$				\$100	\$100
$S \geq 6$		\$(450)		\$100	\$(350)
$S \geq 4$		\$(450)	\$450	\$100	\$100
$S \geq 1$	\$5	\$(450)	\$450	\$100	\$105

Cumulative net benefits are maximized under the slope rule $S \geq 1$, where mitigation is undertaken in every cell and net benefits are equal to \$105.

It is clear that when the property value and/or mitigation costs vary, the public decision rule can be suboptimal to the individual decision rule. In this

example, cumulative net benefits to the community are much smaller under the public agency rule due to the fact that mitigation is being undertaken in cell number 2 where net benefits from mitigation are negative. This decision to mitigate in cell number 2 is clearly wrong and highlights the problem resulting from public intervention in private decisions regarding hazard mitigation.

Of course, by changing the numbers in the example, different results could be obtained. It could be shown that in some instances the public agency rule will be equivalent in result to the individual rule. In fact, the public agency and individual decisions will always coincide when their decisions depend only upon the slope in each cell, since it is known from geology that $P(S_i)$ is concave with respect to the slope. This was the case in the first example. Their decisions could also coincide if expected gross benefits, $P_i L_i$ increase as the slope S_i increases. This is a sufficient but not necessary condition for the two decisions to coincide.¹¹ In general, a sufficient condition for the two decisions to coincide is when $P(S_i) L_i - K_i$ is a concave function of the slope S_i . When L_i and K_i are constant, then the sufficient condition is

¹¹ An example in which $P_i L_i$ is not concave with respect to the slope S_i can still result in the public and private decisions coinciding.

satisfied.

The public agency is essentially trying to maximize expected net benefits under a constraint, while the individual is trying to maximize expected net benefits free from any constraint. As could be shown graphically, "a constrained maximum can be expected to have a lower value than the free maximum, although, by coincidence, the two maxima may happen to have the same value. But the constrained maximum can never exceed the free maximum."¹²

¹² Alpha C. Chiang, Fundamental Methods of Mathematical Economics, 3d ed. (New York: McGraw-Hill, Inc., 1984), 371.

II. Background

A. Landslides, need for mitigation and approaches to reducing long-term losses.

Landslides are a persistent problem in the United States, occurring in every state. They are considered to be "an economically significant natural hazard in more than half the states,"¹³ with the Rocky Mountain, Pacific Coast and Appalachian regions suffering the greatest damage. The areas of the Appalachian plateau that are most prone to landslides are southwestern Pennsylvania, southeastern Ohio and northern West Virginia.

Economic losses from landslides in the United States are between \$1 and \$2 billion per year.¹⁴ Of this amount, damages of over \$4 million per year occur in Allegheny County, Pennsylvania and over \$5.2 million per year occur in Hamilton County, Ohio.¹⁵ Economic losses from landslides are continuing to increase, largely as a result of increased construction activities on landslide-prone

¹³ National Research Council, Reducing Losses from Landsliding, 1.

¹⁴ Ibid.

¹⁵ Ibid., 9-10.

terrain. Hillslopes are being reconfigured and equilibrium conditions are being disrupted as man reconfigures the landscape.¹⁶

Losses resulting from landslides can be classified as either direct or indirect costs. Direct costs are a result of actual physical damage to buildings or property, and include the cost of repair, replacement or maintenance. Indirect costs encompass everything else, and include reduced real estate values, loss of tax revenues, loss of productive agricultural or forest land, loss of tourism, losses from litigation, losses of productivity due to injury or death, and mitigation costs aimed at preventing or reducing future landslide damage.¹⁷

Since landslides are to an extent both predictable and preventable, losses from landslides can be reduced. The main approaches to reducing long-term losses from landslides are: (1) avoidance; (2) design, building and grading codes; (3) landslide control and stabilization;

¹⁶ Ibid., 7.

¹⁷ Ibid., 9; Robert L. Schuster and Robert W. Fleming, "Economic Losses and Fatalities Due to Landslides," Bulletin of the Association of Engineering Geologists 23, no. 1 (1986): 12; Roy C. Sidle, Andrew J. Pearce and Colin L. O'Loughlin, Hillslope Stability and Land Use, Water Resources Monograph Series 11 (Washington, D.C.: American Geophysical Union, 1985), 5.

and (4) insurance.¹⁸ The first approach involves adoption of land-use control regulations by local governments in order to restrict development in landslide-prone areas. The second approach refers to regulation by local government agencies of construction activities which might increase the risk of a landslide. The third approach, which is the most commonly used method in the United States, relies on engineering and structural control methods, such as excavation and filling techniques, drainage methods and restraining structures (i.e. retaining walls, piles and caissons).¹⁹ The fourth approach, insurance, is aimed at redistributing the costs of landslides by spreading the losses over a larger population. This method does not result in a reduction in losses unless the insurance includes specific requirements for site selection and construction techniques.²⁰

One major problem with landslide insurance is its general unavailability. According to the National Research

¹⁸ National Research Council, Reducing Losses from Landsliding, 14-15.

¹⁹ Roy C. Sidle, Hillslope Stability, 5.

²⁰ Robert L. Schuster and Robert W. Fleming, "Economic Losses and Fatalities Due to Landslides," 26.

Council,²¹

(t)he history of landslide insurance in the United States indicates that the private sector is relatively uninterested at present in offering this coverage. This reluctance to provide landslide insurance is long-standing. Several highly publicized instances of landsliding,..., have contributed to this reluctance.

Since the areas of high landslide risk are generally known, and are not uniformly distributed, it is difficult for insurance agencies to "spread the risk" over a larger number of property owners. This problem is not unique to landslide insurance; indeed, it is common to many forms of hazard insurance. An analagous situation is that of flood insurance where,

(f)lood insurance covering fixed-location properties in areas subject to recurrent floods cannot feasibly be written because of the virtual certainty of loss, its catastrophic nature, and the reluctance or inability of the public to pay the premium charge required to make the insurance self-sustaining.²²

With the exception of the National Flood Insurance Program, which provides coverage for mudslides (water-caused landslides), insurance for landslides is practically

²¹ National Research Council, Reducing Losses from Landsliding, 24.

²² William J. Kockelman, "Some Techniques for Reducing Landslide Hazards," Bulletin of the Association of Engineering Geologists 23, no. 1 (1986): 39.

nonexistent in the United States today.²³

B. Cincinnati Study Prepared by the U.S. Geological Survey.

The underlying motivation to explore whether public agency rules are suboptimal to individual economic choice in maximizing net benefits from landslide mitigation arose out of a report prepared by the U.S. Geological Survey (U.S.G.S.), "The Economics of Landslide Mitigation Strategies in Cincinnati, Ohio: A Methodology for Benefit-Cost Analysis," open-file report 85-276D, Chapter D, Feasibility of a Nationwide Program for the Identification and Delineation of Hazards from Mud Flows and Other Landslides, 1985, prepared in cooperation with the Federal Emergency Management Agency.

In this study, a cost-benefit analysis was performed to determine the optimum landslide mitigation rule for a public agency. A statistical probability model was developed, using a logit transformation, to predict the probability of a landslide occurrence in 100-meter cell areas in Hamilton County (Cincinnati), Ohio. The resulting landslide probabilities were then combined with property value estimates to determine the expected value of property at risk (i.e. expected benefits). Costs of mitigation were

²³ National Research Council, Reducing Losses from Landsliding, 3.

based on an engineering solution (grading) to landslide hazard, and alternative mitigation rules were selected based on regional topographic and geologic information (i.e. slope and shear strength). Expected net benefits were then calculated for alternative hypothetical mitigation rules in order to identify the mitigation rule which would yield the highest positive net benefits to the community.

The U.S.G.S. study focuses on strategies for community mitigation of landslides, and is ultimately interested in measuring the value of regional physical science information used in determining cost-effective landslide mitigation rules. This paper proposes to go a step further, by comparing strategies for community mitigation with strategies for individual mitigation. The central hypothesis of this paper is that in evaluating the efficient or optimal level of landslide hazard mitigation, strategies for community mitigation may differ from strategies for individual mitigation.

III. Description of Model

In attempting to test the hypothesis that a public agency mitigation rule may be suboptimal to an individual mitigation rule, the following steps were taken. First, the model developed by the U.S. Geological Survey for the Cincinnati study area was tested against data for another study area (Pittsburgh, Pennsylvania) in the Appalachian plateau. This was done for two reasons: (1) to determine if the U.S.G.S. model can be used to predict landslides in other areas of similar geology; (2) to lend confidence to the predictive abilities of the Cincinnati logit equation. A Spearman rank correlation was used to perform the test.

Next, an attempt was made to improve the U.S.G.S. model for Cincinnati by using actual landslide damage estimates in place of property value estimates in determining expected gross benefits. A regression equation was developed to estimate property damages resulting from a landslide.

Finally, a cost-benefit analysis was performed for both individual and public agency decision rules to determine the maximum net benefits from landslide mitigation.

A. Simplifying Assumptions/Variations from the U.S.G.S. Study.

In the context of the current analysis, it was

necessary to make the following assumptions:²⁴

- (1) The probability of a landslide occurrence in a 100-meter cell area is constant over time;
- (2) Mitigation costs are based on a mitigation strategy of landslide control and stabilization. Specifically, an engineering control method relying on grading activities following the guidelines set forth by the International Conference of Building Officials in Chapter 70 of the Uniform Building Code (1979) was used by the U.S.G.S. to determine the cost of excavation and fill for various hillslopes.
- (3) If a mitigation activity is undertaken, it is assumed to be 100 percent effective in preventing a landslide.
- (4) If a mitigation activity is undertaken, only an initial investment cost is required.

It is important to note that the results presented in this paper cannot be directly compared with the results presented in the U.S.G.S. study due to the following variations:

- (1) Property damages resulting from a landslide are analyzed under three different scenarios:
 - (a) Landslide damages = property value. This is the same assumption used in the U.S.G.S. study. Essentially, this implies that if a landslide occurs, the property becomes a complete loss.
 - (b) Landslide damages = $3.6 * \text{property value}^{0.65}$. This equation was obtained from a regression analysis which estimated actual landslide damages in each 100-meter cell in the Cincinnati study area.

²⁴ Based on Bernknopf, "The Economics of Landslide Mitigation Strategies," D-5 and D-6.

(c) Landslide damages = 0.5 * property value. This equation was chosen as a compromise between the two previous scenarios, and is analyzed merely for purposes of comparison.

(2) The results from the present cost-benefit analysis are in 1984 dollars, whereas the U.S.G.S. results are in 1980 dollars.

(3) A smaller sample was used in the present study due to the fact that cells with no structures in them were eliminated from the sample.

(4) The public agency decision rule which identifies cells where mitigation is required has been redefined: average slopes greater than or equal to the average slope rule or soil shear strengths less than or equal to the soil shear strength rule.

(5) Although the costs of excavation and fill were estimated by the U.S.G.S. for various hillslopes, the actual mitigation cost used in their study was a constant \$151 per cell. The mitigation costs used in the present paper were taken directly from the estimates prepared by the U.S.G.S. and vary for each cell depending upon the slope. Specifically, mitigation costs increase for cells with steeper slopes.

B. U.S.G.S. Cincinnati Logit Equation.

In the U.S. Geological Survey report on Cincinnati, a regression equation was developed to estimate the probability of a landslide occurrence, using the variables given in Table 1. A study area in Hamilton County (Cincinnati), Ohio was selected and information was gathered for 14,255 100-meter cells. A logit model with Maximum Likelihood Estimation (MLE) was used to estimate the probability of a landslide occurrence in a specific cell. The resulting logit equation took the following

Table 1. -- Variables Used in the U.S.G.S. Cincinnati Study

Variable	Description
SLD	Landslide occurrence
D	Hillside stability index
MST	Maximum natural slope tangent
AST	Average natural slope tangent
SS	Soil shear strength tangent
NH	New home construction
NR	New road construction
UP	Construction activity downslope

Source: Richard L. Bernknopf, David S. Brookshire, Russell H. Campbell, Carl D. Shapiro and Robert W. Fleming, "The Economics of Landslide Mitigation Strategies in Cincinnati, Ohio: A Methodology for Benefit-Cost Analysis," Chapter D in Feasibility of a Nationwide Program for the Identification and Delineation of Hazards from Mud Flows and Other Landslides, open-file report, U.S. Geological Survey, 85-276D (Reston, Virginia: U.S. Geological Survey, 1985), D-7a.

form,²⁵

$\ln (P/(1-P)) = - 0.23 - 1.45 \ln D + 0.72 \ln MST + 0.77 NR$
 where D = hillside stability index, MST = tangent of
 maximum natural slope, and NR = new road construction.

Note that the hillside stability index, which is defined by
 the U.S.G.S. as "a measure of mechanical stability for
 slope materials in a cell,"²⁶ represents the ratio of the
 soil shear strength tangent to the average natural slope
 tangent.

In an attempt to lend confidence to the logit equation
 generated by the U.S.G.S. for Cincinnati and in an attempt
 to test if this equation can be used for predicting
 landslides in other areas of similar geology, the
 Cincinnati logit equation was applied to regional geologic
 and topographic data for a study area in Pittsburgh,
 Pennsylvania. In order to perform this test of the
 Cincinnati logit equation, information was gathered for the
 Braddock 7.5-minute quadrangle in Pittsburgh on maximum and
 average natural slope, soil shear strength, and new road

²⁵ Bernknopf, "The Economics of Landslide Mitigation
 Strategies," D-8a.

²⁶ Ibid., D-7a.

construction.²⁷

The information was coded and entered into the computer for a total of 14,965 100-meter cells for the Braddock quadrangle. A SAS program was written to combine all of the data sets, calculate the soil shear strength tangent for each cell,²⁸ and calculate the probability of a landslide occurrence based on the coefficients determined from the Cincinnati study. Note that the final number of cells in the sample was 13,080 after eliminating cells where (1) the average or maximum natural slope tangent was equal to zero or (2) it was not possible to estimate the soil shear strength tangent.²⁹

C. Spearman Rank Correlation.

Once the probability of a landslide occurrence in each 100-meter cell was calculated, the Spearman rank correlation was used to compare the predictions generated using the Cincinnati logit equation with actual landslide occurrence data for the Braddock quadrangle taken from a

²⁷ See the Technical Appendix for a description of how the information for each variable was obtained.

²⁸ This variable had to be estimated. See the Technical Appendix for a more detailed discussion.

²⁹ Refer to the Technical Appendix.

U.S.G.S. "Landslide Susceptibility Map."³⁰ Of the eight categories of landslide susceptibility shown on the map, four categories were selected for comparison.³¹ These categories, described in more detail in the Technical Appendix, were (1) recent landslides; (2) debris slides; (3) slopes with conspicuous soil creep and (4) relatively stable ground.

To perform the Spearman rank correlation test, it was necessary to assign "ranks" to both the map data and the prediction data. The four categories from the map were first assigned an index number based on knowledge of their susceptibility to a landslide. There were a total of six index numbers assigned, due to the fact that some cells contained more than one category of landslide susceptibility. Table 2 shows the index number assigned to each category or combination of categories analyzed. Since there were some cells that contained none of the four categories or combinations of categories, the sample was reduced to 14,599 cells. After matching this data set with

³⁰ William E. Davies, "Landslide Susceptibility Map of the Braddock 7 1/2^o Quadrangle, Allegheny County and Vicinity, Pennsylvania," open-file map, U.S. Geological Survey, 74-273 (1974), scale 1:24,000.

³¹ The remaining categories were not used because not enough was known about these categories to be able to differentiate them and assign a rank.

Table 2. -- Landslide Index Numbers Assigned to Map Categories

Category	Landslide Index
Recent Landslide	5.0
Debris Slide and Slopes with Soil Creep	4.0
Debris Slide	3.0
Slopes with Soil Creep	3.0
Debris Slide, Slopes with Soil Creep, and Relatively Stable Ground	2.5
Slopes with Soil Creep and Relatively Stable Ground	2.0
Relatively Stable Ground	1.0

the data set used to generate the predictions of landslide occurrence, the sample was further reduced to 12,761 100-meter cells.

In order to assign a "rank" to the map data for each cell, the data set first had to be sorted by index number. Since there were a large number of observations but relatively few index numbers, a systematic ranking of each cell would result in an extensive number of tied ranks. The standard procedure in this situation is to "assign the tied observations the mean of the ranks which they jointly occupy."³² Table 3 shows the ranks assigned to each cell based on the calculated mean of the ranks for the tied observations.

The procedure for assigning ranks to the prediction data was as follows. First, the data set was sorted according to the calculated probabilities. Second, the data set was divided into the same six groups of observation numbers used for the map data and the same ranks calculated from the map data were assigned to each cell. For example, group 1 consisted of observations 1 through 5,843 and all cells in this group were assigned the rank 2,922.

³² John E. Freund and Ronald E. Walpole, Mathematical Statistics (Englewood Cliffs, New Jersey: Prentice-Hall, Inc., 1980), 493.

Table 3. -- Ranks Assigned to Map Data

Observation Number	Index Number	Rank
1 - 5,843	1.0	2,922.0
5,844 - 10,627	2.0	8,235.5
10,628 - 10,662	2.5	10,645.0
10,663 - 12,534	3.0	11,598.5
12,535 - 12,575	4.0	12,555.0
12,576 - 12,761	5.0	12,668.5

Once the ranks were assigned to both the prediction data and the map data, the two data sets were merged on the basis of the row and column number associated with each particular cell. The prediction data and map data could now easily be compared and a pair of rankings could be obtained for each cell.

The Spearman rank correlation coefficient was used to determine how accurately the predictions of landslide occurrence estimate the actual landslide occurrence. The Spearman coefficient, p , is known to fall in the range $-1 \leq p \leq 1$. A Spearman coefficient equal to 1 indicates complete concordance between the two sets of rankings, whereas a Spearman coefficient equal to -1 indicates complete discordance. A coefficient of 0 indicates that there is no association at all between the two sets of rankings.

Due to the extensive number of tied ranks, it was necessary to use a variation of the standard equation for the Spearman coefficient which includes a correction term for tied ranks. The Spearman rank correlation coefficient was found by using the following equation,³³

$$p = \left[\frac{6 \sum R_j^2}{k^3 - k} - \frac{6(k+1)}{k-1} \right] \frac{2}{\sum T_i} - 1$$

³³ Ray Meddis, Statistics Using Ranks: A Unified Approach (New York, N.Y.: B. Blackwell, 1984), 273-278.

where R_j = rank sum for each pair of ranks; k = number of observations; and T_i = correction term for ties. The correction term for ties was calculated from,

$$T_i = 1 - \frac{\sum (t_i^3 - t_i)}{(k^3 - k)}$$

$$\sum T_i = T_1 + T_2 + T_3 + T_4 + T_5 + T_6$$

where t_i = number of tied observations for each rank. Note that the standard equation for the Spearman coefficient is based on taking the difference between each pair of ranks, whereas the version used here takes the sum of each pair of ranks.

D. Improvements to the U.S.G.S. Cincinnati Model.

In the U.S.G.S. study on Cincinnati, the expected gross benefit (or expected value of property at risk) in a 100-meter cell from landslide mitigation was defined as the probability of a landslide in a cell multiplied by an estimate of the property value in that cell.³⁴ This definition, however, will generally overstate the expected gross benefit since it implies that when a landslide occurs the entire property in a cell will be lost.

Striving to improve the U.S.G.S. model for Cincinnati, a regression equation was developed to estimate the property damages which would result from a landslide in

³⁴ Bernknopf, "The Economics of Landslide Mitigation Strategies," D-9.

each 100-meter cell in the Cincinnati study area. Although never used in the U.S.G.S. study, data on actual landslide damages in the Cincinnati study area were compiled by Paul Beauchemin of the U.S.G.S. This information, together with the U.S.G.S. computer file containing all of the data used in the Cincinnati study, was used in the regression analysis. Table 4 lists the variables used and the expected sign of the coefficients.

Information on the actual damage amount, the year it occurred, and whether the damage occurred to a single or multiple residential structure was manually coded and entered into the computer for a total of 183 cells. The data, which cover a time period from 1970 to 1979, were inflated to 1984 dollars.

The computer file containing the data used in the U.S.G.S. Cincinnati study listed 451 cells which had at least one landslide occurrence in the ten-year period between 1970 and 1979. This data was also inflated to 1984 dollars. After combining these two data sets and deleting all cells where (1) the property value was equal to zero or (2) the property value was less than the damage amount, a total of 136 cells were left in the sample.

Stepwise regressions were run on the computer using SAS to determine whether there was a relationship between actual property damages resulting from a landslide

Table 4. -- Variables Used in the Property Damage Regression

Variable	Description	Expected Sign of Coefficient
ln DAM	Dependent variable: log of actual landslide damages in a 100-meter cell.	N/A
ln V	Independent variable: log of property value in a 100-meter cell.	+
ln A	Independent variable: log of average natural slope in a 100-meter cell.	+
ln M	Independent variable: log of maximum natural slope in a 100-meter cell.	+
ln S	Independent variable: log of soil shear strength tangent in a 100-meter cell.	-
ln D	Independent variable: log of hillside stability index in a 100-meter cell. /1/	+ or -
ln N	Independent variable: log of hillside stability index in a 100-meter cell. /2/	+ or -
D ₁	Dummy variable: new road construction in a 100-meter cell * ln S.	+ or -
D ₂	Dummy variable: multiple residential building in a 100-meter cell * ln V.	+
D ₃	Dummy variable: new road construction in a 100-meter cell * ln D.	+ or -
D ₄	Dummy variable: new road construction in a 100-meter cell * ln N.	+ or -
NRD	Dummy variable: new road construction in a 100-meter cell.	+
MULTIPLE	Dummy variable: multiple residential building in a 100-meter cell.	+

N/A -- Not applicable.

/1/ Equal to the ratio of the soil shear strength tangent in a cell to the average natural slope tangent in a cell.

/2/ Equal to the ratio of the soil shear strength tangent in a cell to the maximum natural slope tangent in a cell.

(dependent variable) and the various independent and dummy variables listed in Table 4. Using a log transformation, the following models yielded the best results:

$$(1) \quad \ln \text{ DAM} = C + a \ln V + b \ln A + c \ln S + d \text{ NRD} + e D_1 + f D_2 + g \text{ MULTIPLE}$$

$$(2) \quad \ln \text{ DAM} = C + a \ln V + b \ln M + c \ln S + d \text{ NRD} + e D_1 + f D_2 + g \text{ MULTIPLE}$$

$$(3) \quad \ln \text{ DAM} = C + a \ln V + b \ln D + c \text{ NRD} + d D_3 + e D_2 + f \text{ MULTIPLE}$$

$$(4) \quad \ln \text{ DAM} = C + a \ln V + b \ln N + c \text{ NRD} + d D_4 + e D_2 + f \text{ MULTIPLE}$$

The results from each of these models are discussed in Chapter IV.

E. Net Benefit Analysis: Cincinnati.

The U.S.G.S. Cincinnati study focused on determining a public agency decision rule for mitigation which would yield the maximum positive net benefits to the community. The present paper maintains that a public agency decision rule can be suboptimal to an individual decision rule in maximizing net benefits from landslide mitigation. This hypothesis can be tested for the Cincinnati study area by performing a cost-benefit analysis under both the public agency and individual decision rules.

The expected gross benefit from landslide mitigation in a cell (or expected value of property at risk) as defined in the U.S.G.S. study is equal to the probability of a landslide occurrence in a cell multiplied by the

property value in that cell. The current analysis will focus on and compare the results of three different definitions of expected gross benefit, based on three different approaches to measuring the property value at risk. The property value or landslide loss functions analyzed are:

- (1) $\text{Landslide Loss} = 3.6 * \text{property value}^{0.65};$
- (2) $\text{Landslide Loss} = \text{property value};$
- (3) $\text{Landslide Loss} = 0.5 * \text{property value}.$

The first equation is the result of the property damage regression analysis performed on the Cincinnati data. This equation will estimate the fraction of the property value at risk and will result in a smaller expected property loss than the method used in the U.S.G.S. study.

The second equation is the same one used in the U.S.G.S. study. It is based on the assumption that if a landslide occurs in a cell, all of the residential buildings in that cell become a complete loss.³⁵

The third equation is included for analysis purposes to represent a compromise between the two extremes. It was chosen arbitrarily, but with the idea that the "true" landslide loss function may actually be closer to this

³⁵ Ibid., D-5.

equation than either of the other equations.

In addition, it is interesting to analyze a situation where a public agency is misinformed about the correct equation for expected losses. The following two scenarios are also briefly analyzed:

(1) Landslide Loss = $3.6 * \text{property value}^{0.65}$, but the public agency mitigates according to Landslide Loss = property value;

(2) Landslide Loss = $3.6 * \text{property value}^{0.65}$, but the public agency mitigates according to Landslide Loss = $0.5 * \text{property value}$.

Under the first scenario, the "true" landslide loss function is the equation generated from the property damage regression analysis. However, the public agency believes that landslide losses in a cell will be equal to the property value in that cell and mitigates accordingly. The second scenario is identical to the first except that the public agency mitigates according to the landslide loss function where losses are equal to one-half the property value.

The costs of mitigation in a cell were measured by the U.S.G.S. on the basis of an engineering solution (grading) for landslide mitigation.³⁶ The guidelines for cut-and-fill requirements set forth in Chapter 70 of the Uniform Building Code formed the basis for the U.S.G.S.

³⁶ Ibid.

calculations.³⁷ The costs of mitigation under this approach for a residential structure are "a function of the volume of earth that must be excavated, placed, and compacted, and increases with increasing slope."³⁸ Table 5 shows the 1984 dollar equivalents of the average cost of excavation and fill per lot for each hillslope range calculated by the U.S.G.S.³⁹ For the present study, this information on mitigation costs per lot was multiplied by the number of structures in a cell and by a real annual discount rate of 10 percent to arrive at the costs of mitigation per cell.

Once the expected benefits from mitigation are known for each cell, they can be compared with the costs of mitigation for each cell to determine the expected net benefits from mitigation. For the public agency, expected net benefits are maximized by identifying the optimum decision rule. This is the rule which will yield the maximum cumulative net benefits to the community, based on mitigating only in those cells identified by the decision

³⁷ Ibid., D-11.

³⁸ Ibid.

³⁹ For more detailed information on how these figures were calculated, refer to Bernknopf, "The Economics of Landslide Mitigation Strategies," D-11b.

Table 5. -- Estimate of Mitigation Costs per Lot Based on Engineering Solution

Hillslope /1/ ----- (degrees)	Average Cost of Excavation and Fill /2/ ----- (1984 dollars)
0 < AS ≤ 3	\$161
3 < AS ≤ 6	\$521
6 < AS ≤ 8	\$977
8 < AS ≤ 11	\$1,581
11 < AS ≤ 14	\$2,404
14 < AS ≤ 17	\$3,606
17 < AS ≤ 19	\$5,527
19 < AS ≤ 22	\$9,331
22 < AS ≤ 24	\$18,972
AS > 24	\$26,003

/1/ Based on average natural slope, AS.

/2/ Converted from 1980 dollars to 1984 dollars by multiplying by the ratio of the 1984 to 1980 implicit price deflator for gross private domestic investment (residential fixed investment) equal to 255.9/218.5. This information was taken from the Economic Report of the President, Transmitted to Congress February 1985 (Washington, D.C.: U.S. Government Printing Office, 1985), 236.

rule. For the individual, expected net benefits in a cell are maximized when the expected benefits in a cell (expected losses avoided) exceed the costs of mitigation in that cell.

A SAS program was written to calculate the net benefits from mitigation under both public agency and individual decision rules. Net benefits were calculated under all the possible combinations of public agency decision rules for each of the three expected benefit scenarios and for the two scenarios where the public agency is misinformed about the "true" landslide loss function. For the individual decision rule, net benefits were calculated only for the three expected benefit scenarios. The U.S.G.S. computer data file for the Cincinnati study area containing information on 14,255 100-meter cells was used to perform the calculations.

Note that all cells where there were no structures were deleted from the sample. In addition, it should be pointed out that with respect to the calculation of expected benefits, the probability of a landslide occurrence in a cell was based on data covering a ten-year time period. Therefore, in order to obtain an annual probability the figures were divided by ten. Note that under the individual decision rule, all cells where the calculated net benefits were less than or equal to zero

were deleted from the sample. The resulting optimum public agency and individual decision rules under each of the expected benefit scenarios discussed previously are given in Chapter IV.

IV. Results and Analysis

A. Spearman Rank Correlation.

A statistics exercise using the Spearman rank correlation was undertaken to test the performance of the Cincinnati logit equation. Under this method, the relationship between actual landslide occurrence and predictions of landslide occurrence (generated using the Cincinnati logit equation) for a study area in Pittsburgh was measured by ranking the values of each variable in order of size and computing the correlation coefficient between the two sets of ranks.

The Spearman rank correlation coefficient, p , was calculated according to the equation,

$$p = \left[\frac{6 \sum R_j^2}{k^3 - k} - \frac{6(k+1)}{k-1} \right] \frac{2}{\sum T_i} - 1$$

which includes a correction term for tied ranks. The resulting Spearman coefficient was $p = 0.43$. This positive coefficient implies that there is a positive association between actual landslide occurrence and the predictions of landslide occurrence. This can be further evaluated by calculating,

$$z = \sqrt{(p^2(k-1))}$$

and consulting the normal distribution tables. The relevant critical values for selected percentiles from the

normal distribution tables are,⁴⁰

	<u>10%</u>	<u>5%</u>	<u>2.5%</u>	<u>1%</u>	<u>0.1%</u>
$z \geq$	1.282	1.645	1.960	2.326	3.090

Since $Z = 48.57$, it can be concluded that the correlation is statistically significant at all of the levels presented above. Figure 1 shows the cells in the Braddock quadrangle where the rankings of actual landslide occurrence matched the rankings of the predictions of landslide occurrence.

Since the Spearman rank correlation test showed a strong positive association between actual landslide occurrence in Pittsburgh and the predictions of landslide occurrence in Pittsburgh (based on the Cincinnati logit equation), it can be concluded that (1) the Cincinnati logit equation is a useful tool which can reasonably be applied to other areas of similar geology to predict landslides and (2) the Cincinnati logit equation as specified in the U.S.G.S. study is a good predictor of landslide occurrence.

B. Property Damage Regression.

The poor quality of data on actual landslide damages is a serious research problem which makes it difficult to evaluate mitigation policy. In the U.S.G.S. study, this

⁴⁰ Taken from John Neter, William Wasserman and G.A. Whitmore, Applied Statistics (Boston, Massachusetts: Allyn and Bacon, Inc., 1978), 692.



Fig. 1. Comparison of Actual Landslide Occurrence with Predictions of Landslide Occurrence; Braddock Quadrangle, Pennsylvania.

problem was solved by assuming that once a residential building had been damaged from a landslide, it became a complete loss, since further damage would not be prevented. An alternative solution to this problem is to estimate a regression equation to predict the actual damages resulting from a landslide.

Using information on the Cincinnati study area, stepwise regressions were performed to determine whether there was a relationship between actual property damages caused by a landslide and property values, slope, soil shear strength, hillside stability index and several dummy variables. Using a log transformation, four models were identified which yielded the best results:

- (1) $\ln \text{DAM} = C + a \ln V + b \ln A + c \ln S + d \text{NRD} + e D_1 + f D_2 + g \text{MULTIPLE};$
- (2) $\ln \text{DAM} = C + a \ln V + b \ln M + c \ln S + d \text{NRD} + e D_1 + f D_2 + g \text{MULTIPLE};$
- (3) $\ln \text{DAM} = C + a \ln V + b \ln D + c \text{NRD} + d D_3 + e D_2 + f \text{MULTIPLE};$
- (4) $\ln \text{DAM} = C + a \ln V + b \ln N + c \text{NRD} + d D_4 + e D_2 + f \text{MULTIPLE}.$

Table 6 shows the results from each of the four models when all variables are included in the regression and when only variables significant at the 15 percent level are included in the regression.

The results of the regression analysis show that all of the regressors have their expected signs except $\ln S$,

Table 6. -- Property Damage Regression Results

Model	Intercept	ln V	ln A	ln H	ln S	ln D	ln M	D ₁	D ₂	D ₃	D ₄	NRD	MULTIPLE	R ²	SSE	F-Statistic	
Model 1: All Variables Included /1/:																	
Coefficient	0.30	0.72	0.11		0.13			-0.30	-1.71				0.06	20.93	0.19	323.87	4.34
Standard Error		0.15	0.28		0.33			1.77	0.74				1.88	8.96			
F-Statistic		22.48	0.16		0.16			0.03	5.33				0.00	5.45			
Only Variables Significant At the 15% Level Are Included /2/:																	
Coefficient	1.28	0.65												0.15	341.85	23.05	
Standard Error		0.14															
F-Statistic		23.05															
Model 2: All Variables Included /1/:																	
Coefficient	0.23	0.71		0.13	0.13			-0.26	-1.70				0.10	20.88	0.19	323.86	4.34
Standard Error		0.15		0.31	0.33			1.77	0.74				1.89	8.99			
F-Statistic		22.67		0.16	0.15			0.02	5.32				0.00	5.44			
Only Variables Significant At the 15% Level Are Included /2/:																	
Coefficient	1.28	0.65												0.15	341.85	23.05	
Standard Error		0.14															
F-Statistic		23.05															
Model 3: All Variables Included /1/:																	
Coefficient	0.62	0.70				-0.01			-1.60	0.26			0.09	19.57	0.19	324.45	5.05
Standard Error		0.15				0.19			0.77	1.16			1.21	9.36			
F-Statistic		22.38				0.01			4.26	0.05			0.01	4.38			
Only Variables Significant At the 15% Level Are Included /2/:																	
Coefficient	1.28	0.65												0.15	341.85	23.05	
Standard Error		0.14															
F-Statistic		23.05															
Model 4: All Variables Included /1/:																	
Coefficient	0.61	0.70					-0.01		-1.63		0.13	0.25	19.97	0.19	324.54	5.04	
Standard Error		0.15					0.21		0.77		1.01	0.83	9.34				
F-Statistic		22.54					0.00		4.45		0.02	0.09	4.57				
Only Variables Significant At the 15% Level Are Included /2/:																	
Coefficient	1.28	0.65												0.15	341.85	23.05	
Standard Error		0.14															
F-Statistic		23.05															

/1/ This is the first step in the "backward-elimination" technique.
 /2/ This is the final step using the "stepwise" method.

which is positive, and the dummy variable D_2 , which is negative. One would have expected to find low soil shear strength values associated with large landslide damages. However, it is possible that either (1) the sample is too small (the sample consists of 136 cells out of a total of 451 which had at least one landslide occurrence in the ten-year period 1970-1979) or (2) the quality and accuracy of the damage data is poor so that this relationship cannot accurately be measured. The most likely explanation is that the logic of expecting the sign of the coefficient to be negative was flawed, since a low shear strength value is consistent with a high probability of a landslide occurrence, but this does not necessarily imply high landslide damages.

The dummy variable D_2 is a combination of the dummy variable MULTIPLE and the variable $\ln V$, which are both positive. The role of the dummy variable MULTIPLE is to shift the intercept by the amount of its coefficient. The cross-product dummy variable D_2 was included in order to capture shifts in the slope of the regression between landslide damage and property value. The wrong sign of the coefficient of the variable D_2 may be due to multicollinearity, since this variable was included in the same model with both the variables $\ln V$ and MULTIPLE.

Although stepwise regression is useful in sorting out

the relative importance of regressors, there are some significant liabilities to using this method of regression. For example, a regressor which is omitted because it fails a test of statistical significance may result in biasing the remaining regression coefficients.⁴¹ Also, the order in which variables are introduced into the model may affect the outcome with respect to which variables are most important in explaining the dependent variable.⁴²

With these liabilities in mind, a moderate significance level of 15 percent was chosen for the significance test which determines whether a variable should be entered into the model.⁴³ Note that under all four models, the only variable which passes the 15 percent significance test is $\ln V$, the log of the property value.⁴⁴

⁴¹ Ronald J. Wonnacott and Thomas H. Wonnacott, Econometrics, 2d ed. (New York: John Wiley & Sons, 1979), 181-183.

⁴² Ibid.

⁴³ Using a moderate significance level in the range of 10 percent to 25 percent should guard against estimating more parameters than can be reliably estimated with the given sample size.

⁴⁴ Based on the stepwise technique employed using SAS, variables are added one by one to the model as long as the calculated F-statistic is significant at the 0.15 level. However, after a variable is added, all the variables in the model are reanalyzed and any variable which has an F-statistic which is not significant at the 0.15 level necessary to remain in the model is deleted.

The calculated F-value is 23.05 which is greater than the critical value of $F_{.001}(1,135) = 10.8$. The resulting regression equation is,

$$\ln \text{DAM} = 1.28 + 0.65 \ln V$$

which can be written in exponential form as,

$$\text{DAM} = e^{1.28} v^{0.65}$$

$$\text{DAM} = 3.6 * v^{0.65}$$

This equation states the relationship between actual landslide damages (dependent variable) and property values (independent variable). Using this equation to estimate landslide damages in a 100-meter cell will result in a smaller expected gross benefit from mitigation than that calculated in the U.S.G.S. study.

It is important to point out that the low R^2 value of 0.15 and the large SSE value indicate that only a small portion of the variation is explained by the independent variable $\ln V$. This may imply that this regression equation is not a good equation for predicting landslide damages due to a large amount of random or unexplained variation.

The results shown in Table 6 indicate that when all of

The process ends when none of the variables excluded from the model has an F-statistic significant at the entry level of 0.15 and all of the variables included in the model are significant at the 0.15 level necessary to remain in the model.

the variables are included in the model the dummy variable MULTIPLE and the cross-product dummy variable D_2 are both statistically significant at the 0.01 level. On this basis, one might argue that these two variables should be included in the final regression equation. However, it would be incorrect to include them for the following reason. The dummy variable MULTIPLE reflects information on the type of building that was damaged (i.e. a single family home versus an apartment building). The positive coefficient indicates that larger damages are associated with apartment buildings than with single family homes. The problem lies in the limitations of the data for the Cincinnati study area, since it is not possible to differentiate between the type of structure that will be damaged by a landslide. If information were available to distinguish between the types of structures in a cell, then these two variables should arguably be included in the equation.

C. Results from Cost-Benefit Analysis.

The approach to landslide mitigation chosen by a public agency or by an individual will be dependent upon their (1) knowledge of landslide probability or risk; (2) knowledge of costs that would be incurred as a result of mitigation activities; and (3) knowledge of property damage estimates. Once this information is known, expected

net benefits from mitigation can be calculated and the optimum decision rule can be identified.

A cost-benefit analysis was performed for the Cincinnati study area to test the hypothesis that a public agency decision rule may be suboptimal to an individual decision rule in maximizing net benefits from landslide mitigation. The results shown in Tables 7, 8 and 9 reflect three different approaches to measuring property damages or property value at risk. The first approach, landslide loss = $3.6 * \text{property value}^{0.65}$, is based on the results from the property damage regression discussed in the previous section. The third approach, landslide loss = property value, was used in the U.S.G.S. study. The second approach, landslide loss = $0.5 * \text{property value}$, was chosen for comparison purposes and is based on the assumption that the first approach may actually understate landslide losses while the third approach probably overstates landslide losses.

Table 7 shows the optimum decision rules under each of the three scenarios; Table 8 shows the number of cells requiring mitigation; Table 9 shows the annualized net benefits from mitigation for both individual and public agency decision rules under the three approaches of measuring property damages. As noted in Chapter I, an individual will mitigate as long as there are positive net

Table 7. -- Optimum Decision Rules to Identify Cells Where Mitigation is Required

Landslide Loss Function	Individual Decision Rule	Public Agency Decision Rule
LSLOSS = 3.6 * VALUE ^{0.65}	net benefit > 0	no mitigation
LSLOSS = 0.5 * VALUE	net benefit > 0	AS ≥ 26 or SS ≤ 0.25
LSLOSS = VALUE	net benefit > 0	AS ≥ 26 or SS ≤ 0.49

NOTE: LSLOSS -- Landslide losses in a 100-meter cell;
 VALUE -- Property value estimates in a 100-meter cell.

Table 8. -- Number of 100-meter Cells Requiring Mitigation

Landslide Loss Function	Under Individual Decision Rule	Under Public Agency Decision Rule
LSLOSS = 3.6 * VALUE ^{0.65}	7	0
LSLOSS = 0.5 * VALUE	1,374	696
LSLOSS = VALUE	4,390	4,067

NOTE: LSLOSS -- Landslide losses in a 100-meter cell;
 VALUE -- Property value estimates in a 100-meter cell.

Table 9. -- Annualized Net Benefits (1984 Dollars) /1/

Landslide Loss Function	Under Individual Decision Rule	Under Public Agency Decision Rule
LSLOSS = 3.6 * VALUE ^{0.65}	\$54.00	--
LSLOSS = 0.5 * VALUE	\$443,483.88	\$97,200.52
LSLOSS = VALUE	\$2,071,999.59	\$1,615,197.42

NOTE: LSLOSS -- Landslide losses in a 100-meter cell;
 VALUE -- Property value estimate in a 100-meter cell.

/1/ Using a real discount rate of 10 percent annually.

benefits from mitigation. Consequently, the individual decision rule under each of the three approaches is the same. Figure 2 shows the cells in the Cincinnati study area where mitigation would occur under the individual decision rule when landslide losses are equal to one-half the property value. Figure 3 shows the same thing for the situation where landslide losses are equal to the property value.

For the public agency, the optimum decision rule will be the slope or shear strength rule which maximizes cumulative net benefits from mitigation. Under the first scenario, where landslide loss = $3.6 * \text{property value}^{0.65}$, no mitigation at all will take place under the public agency rule, since there are no positive cumulative net benefits from mitigating. Under the second scenario, the public agency rule which maximizes net benefits requires mitigation in 696 cells that contain average slopes greater than or equal to 26° or soil shear strengths less than or equal to 0.25. Annualized net benefits from mitigation under this approach are equal to \$97 thousand, compared with \$443 thousand under the individual decision rule. Figure 4 shows the cells where mitigation would occur using the public agency rule under this approach. Under the third scenario, mitigation is required in 4,067 cells that contain average slopes greater than or equal to 26° or soil

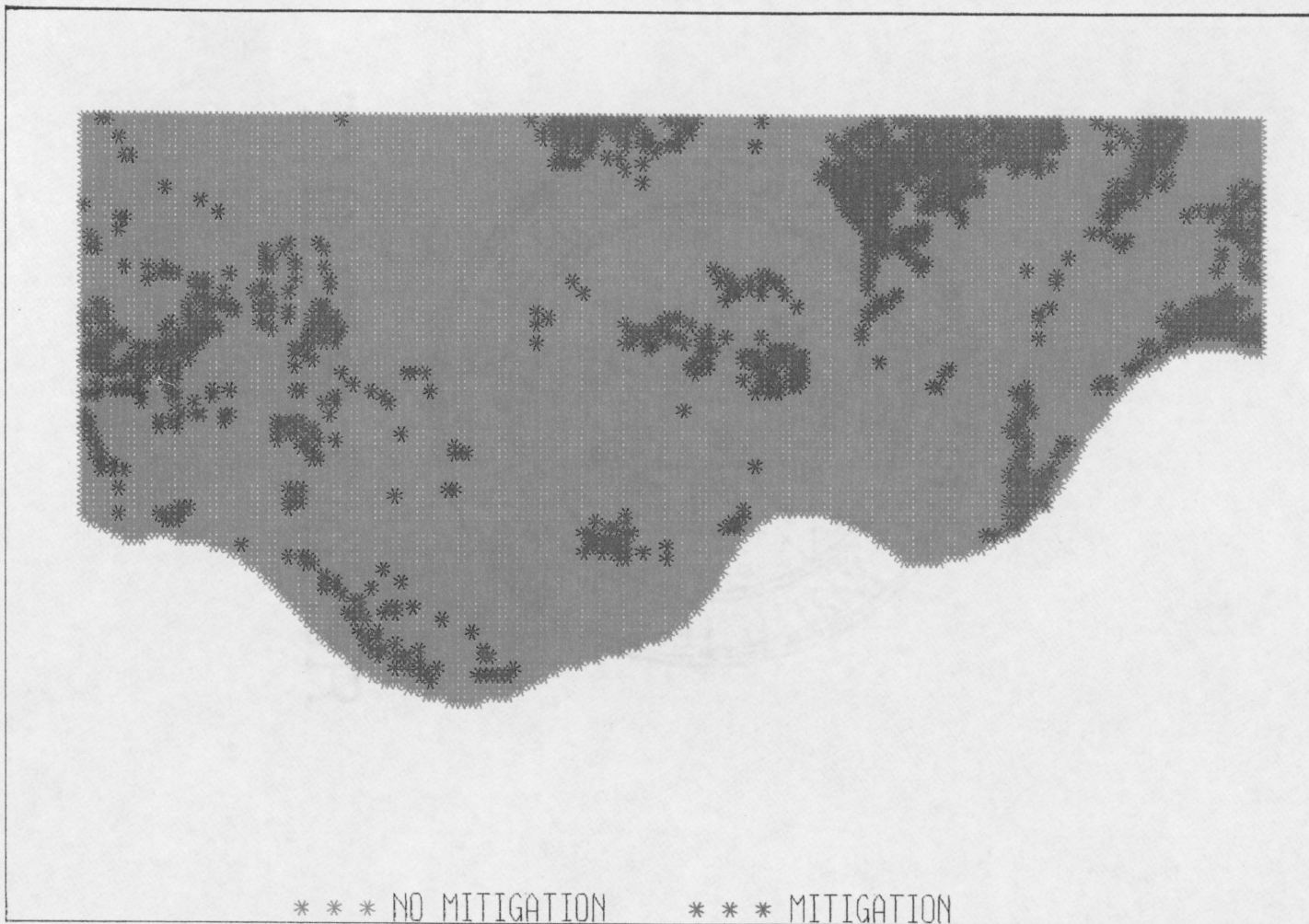


Fig. 2. Private Optimization in the Cincinnati Study Area: Landslide Loss = 1/2 Property Value.

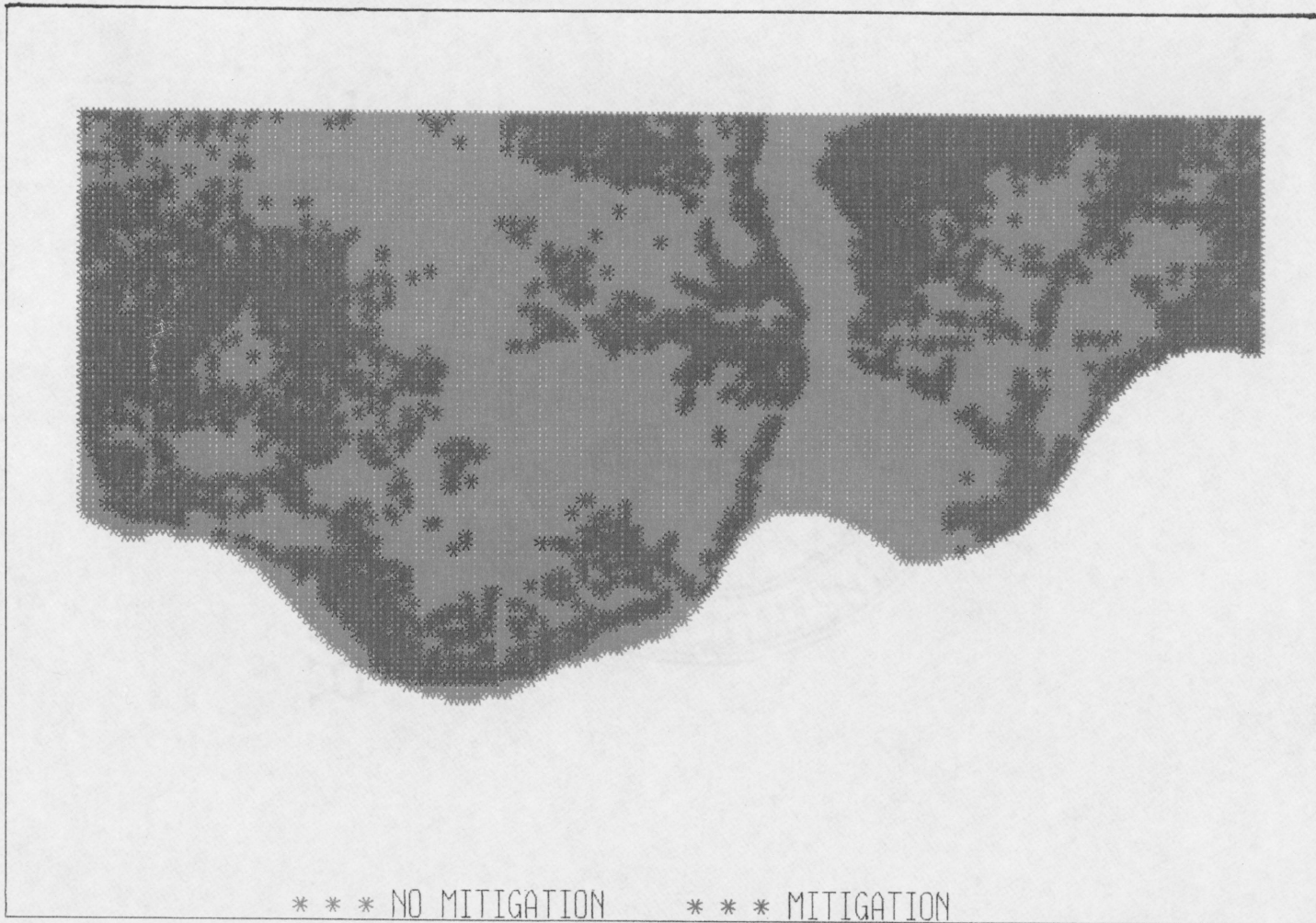


Fig. 3. Private Optimization in the Cincinnati Study Area; Landslide Loss = Property Value.

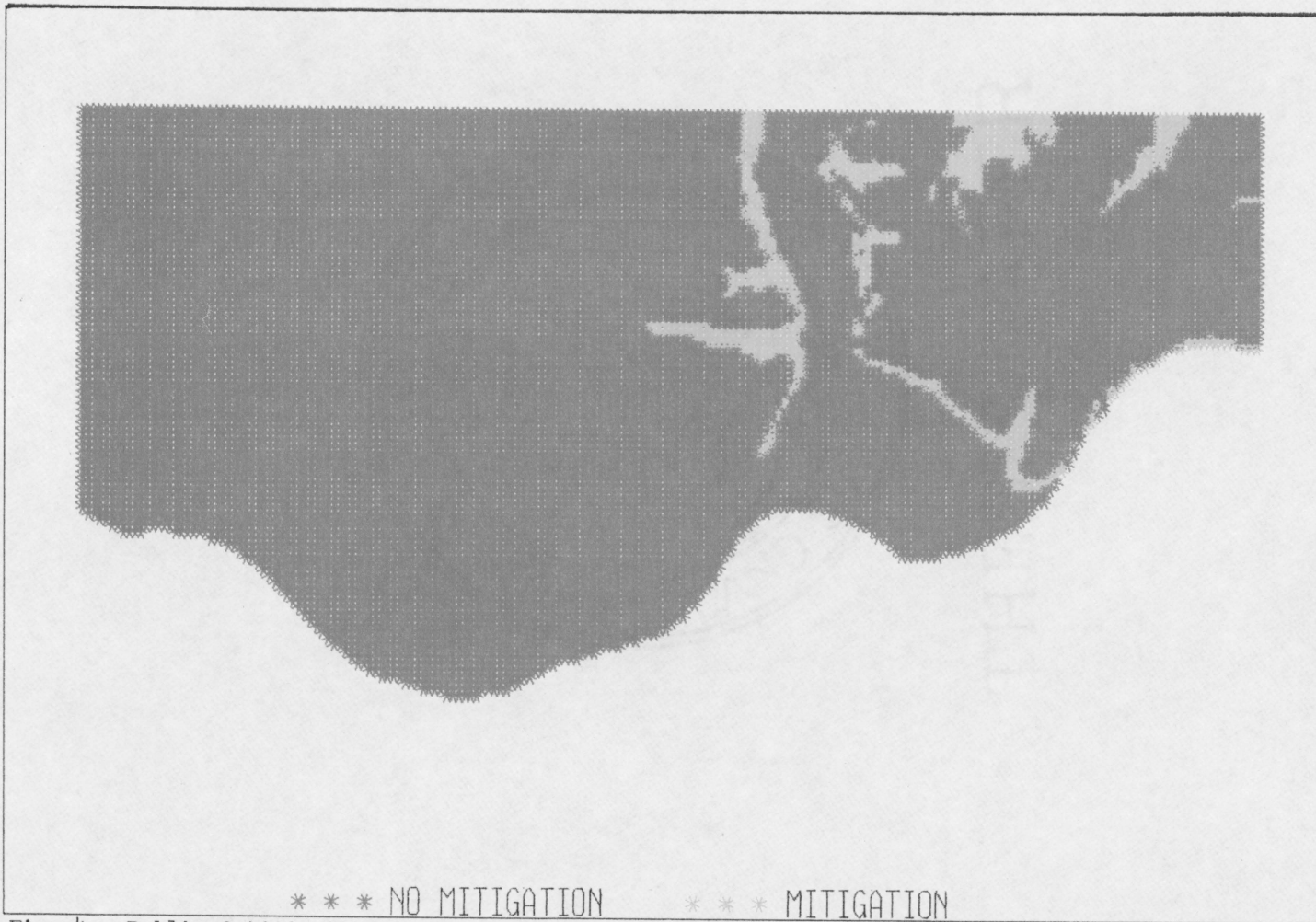


Fig. 4. Public Optimization in the Cincinnati Study Area: Landslide Loss = 1/2 Property Value.

shear strengths less than or equal to 0.49. Annualized net benefits from mitigation are \$1.6 million. Figure 5 shows the cells in which mitigation would occur using the public agency decision rule under this approach. It is clear that the results obtained are highly sensitive to the measurement of landslide losses.

A comparison of the results under individual choice with the results under the public agency decision rule support the hypothesis that a public agency rule may be suboptimal. Under all three scenarios, the number of 100-meter cells requiring mitigation and the resulting annualized net benefits are larger under individual choice than under the public agency decision rule. In the most extreme case, where landslide losses in a cell are assumed to be equal to the property value in that cell, annualized net benefits from mitigation under the individual decision rule are equal to \$2.1 million, compared with \$1.6 million under the public agency decision rule.

Tables 10 and 11 show a more detailed breakout of the net benefit results. Specifically, the results presented here highlight the differences between the individual and public agency decision rules. The number of cells requiring mitigation and the resulting annualized net benefits are shown for cells requiring (1) mitigation under only the individual decision rule (mitigation would

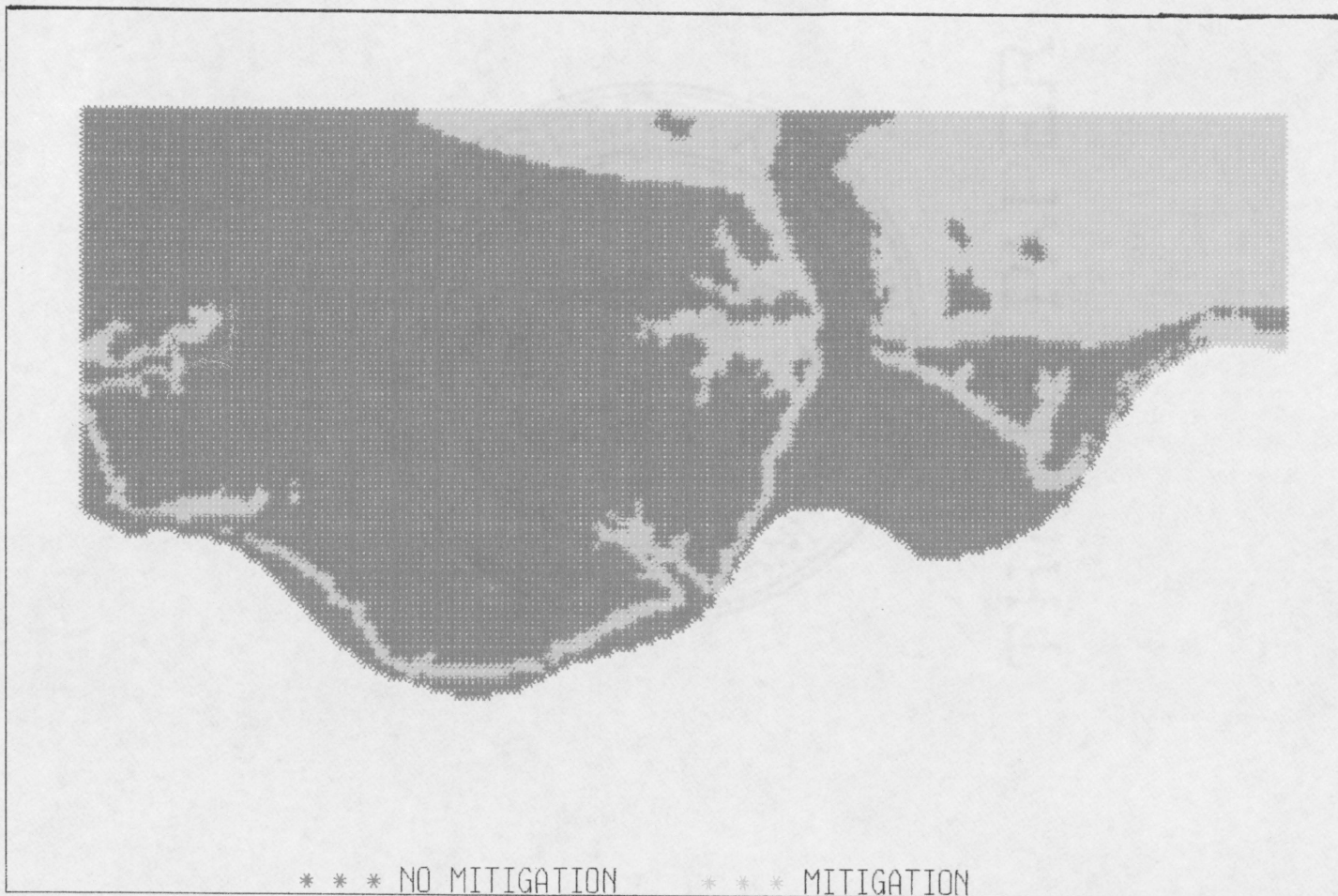


Fig. 5. Public Optimization in the Cincinnati Study Area: Landslide Loss = Property Value.

Table 10. -- Detailed Breakout of the Number of Cells Requiring Mitigation

Landslide Loss Function	Under Individual Decision Rule Only	Under Public Agency Decision Rule Only	Under Both Decision Rules Only	No Mitigation
----- LSLOSS = $3.6 * \text{VALUE}^{0.65}$	7	0	0	14,248
LSLOSS = $0.5 * \text{VALUE}$	1,041	363	333	12,518
LSLOSS = VALUE	1,907	1,584	2,483	8,281
LSLOSS = $3.6 * \text{VALUE}^{0.65}$, but public agency mitigates according to LSLOSS = VALUE	--	4,060	7	10,188
LSLOSS = $3.6 * \text{VALUE}^{0.65}$, but public agency mitigates according to LSLOSS = $0.5 * \text{VALUE}$	--	689	7	13,559

NOTE: LSLOSS -- Landslide losses in a 100-meter cell;
VALUE -- Property value estimate in a 100-meter cell.

-- Not applicable.

Table 11. -- Detailed Breakout of Annualized Net Benefits (1984 Dollars) /1/

Landslide Loss Function	Under Individual Decision Rule Only	Under Public Agency Decision Rule Only	Under Both Decision Rules Only
----- LSLOSS = 3.6 * VALUE ^{0.65}	\$54	\$0	\$0
LSLOSS = 0.5 * VALUE	\$269,078	(\$77,205)	\$174,405
LSLOSS = VALUE	\$195,432	(\$261,370)	\$1,876,567
LSLOSS = 3.6 * VALUE ^{0.65} , but public agency mitigates according to LSLOSS = VALUE	--	(\$2,109,920)	\$54
LSLOSS = 3.6 * VALUE ^{0.65} , but public agency mitigates according to LSLOSS = 0.5 * VALUE	--	(\$387,826)	\$54

NOTE: LSLOSS -- Landslide losses in a 100-meter cell;
VALUE -- Property value estimate in a 100-meter cell.

-- Not applicable.

/1/ Using a real discount rate of 10 percent annually.

not take place in these cells under the public agency decision rule); (2) mitigation under only the public agency decision rule (mitigation would not take place in these cells under the individual decision rule); (3) mitigation under only the individual and public agency decision rules (this excludes cells in which mitigation is required under only the individual decision rule or only the public agency rule); and (4) no mitigation (Table 10 only). Figures 6 and 7 show the number of cells requiring mitigation for each of these categories under the second and third scenarios, respectively. Tables 10 and 11 also incorporate the results from the two scenarios presented in Chapter III, Section E relating to a public agency being misinformed with respect to the "true" landslide loss function.

It is clear from these results that the public agency decision rule results in mitigation in some cells where the annualized net benefits are negative. Specifically, when landslide losses in a cell are assumed to be equal to the property value in that cell, the public agency decision rule $AS \geq 26^\circ$ or $SS \leq 0.49$ requires mitigation in 1,584 cells where net benefits are negative. The decision to mitigate in these cells when it is not cost-effective to do so is clearly wrong. In fact, there are 1,907 cells with positive annualized net benefits of \$195 thousand in which

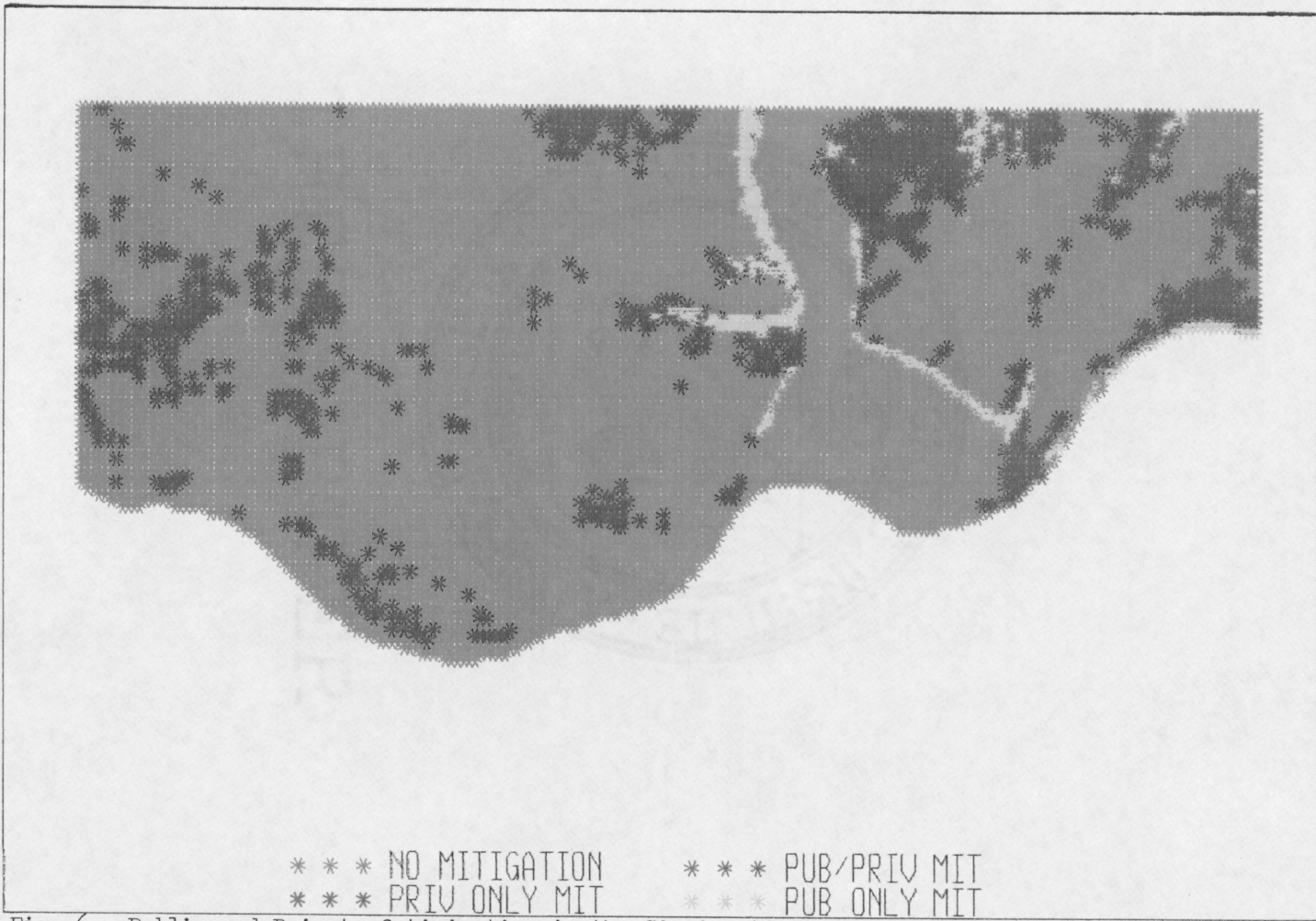


Fig. 6. Public and Private Optimization in the Cincinnati Study Area: Landslide Loss = 1/2 Property Value.



Fig. 7. Public and Private Optimization in the Cincinnati Study Area: Landslide Loss = Property Value.

mitigation occurs only under the individual decision rule. This is a situation in which the public agency is simply misinformed.

The two scenarios which depict a public agency rule requiring mitigation on the basis of an incorrect measurement of landslide damages represent situations where mitigation is undertaken when it is not cost-effective to mitigate. Specifically, under the first scenario where the public agency believes $LSLOSS = 3.6 * VALUE^{0.65}$ is the correct measurement, there are a total of 4,067 cells where mitigation is undertaken, when in fact 4,060 of these cells have negative net benefits. Clearly the correct specification of landslide damages is crucial to determining and evaluating optimal decision rules for mitigation.

In conclusion, the economic rationale for public intervention in decisions regarding hazard mitigation has seldom been questioned.⁴⁵ The results presented in this paper show that public agency decision rules can be suboptimal to individual decision rules in maximizing net benefits from landslide mitigation. Public agencies apply broad rules which are at best only systematically

⁴⁵ Jerome W. Milliman and R. Blaine Roberts, "Economic Issues in Formulating Policy for Earthquake Hazard Mitigation," 645.

selective. Disseminating information on landslide damage, susceptibility and hazard-reduction techniques and costs to individual property owners for them to make decisions regarding mitigation may be a better role for the public agency.

V. Technical Appendix

A. Pittsburgh Data for Probability Equation.

1. Landslide Occurrence Data.

The area selected for study was the Braddock 7.5-minute quadrangle in Allegheny County, Pennsylvania. Data for this area on landslide occurrence was taken from a U.S. Geological Survey "Landslide Susceptibility Map,"⁴⁶ which shows eight different categories relating to landslide susceptibility in the Braddock quadrangle. These eight categories were manually coded and entered into the computer for all 14,965 100-meter cells in the Braddock quadrangle. The categories are:⁴⁷

(1) Recent landslides -- Dominantly earth slumps and earth flows; historically recorded or characterized by fresh scars.

(2) Debris slides -- Slides in steep narrow valleys; primarily rock, soil and vegetation debris.

(3) Prehistoric landslides -- Dominantly earth slumps and earth flows characterized by hummocky topography and slump benches; relatively stable in natural state but can be reactivated by excavation, loading and changes in ground and surface water conditions. Includes some probable recent landslides not covered by records examined.

⁴⁶ William E. Davies, "Landslide Susceptibility Map of the Braddock 7 1/2^o Quadrangle, Allegheny County and Vicinity, Pennsylvania," open-file map, U.S. Geological Survey, 74-273 (1974), scale 1:24,000.

⁴⁷ Descriptions of categories are taken directly from the "Landslide Susceptibility Map."

(4) Slopes with conspicuous soil creep -- Clayey soils, generally less than 5 ft. thick, commonly underlain by weathered shale; characterized by shallow, slow but distinct downslope movement that can be greatly accelerated by overloading from fills or structures.

(5) Outcrop area of thick "red beds" and associated rocks -- Rock weathers rapidly on exposure; weathered rock and related soil commonly result in soil creep and landslides; cuts and fills in "red beds" generally not stable.

(6) Relatively stable ground -- Most slopes have little susceptibility to landsliding unless extensively modified by man; slight soil creep common on undisturbed slope.

(7) Steep slopes susceptible to rockfall -- Dominantly thick-bedded sandstone and limestone, 1 to over 10 ft. thick; subordinate flaggy sandy shale and interbedded shale; highly fractured and locally undercut by weathering of shale; in steep natural and cut slopes and cliffs, 15 to over 150 ft. high.

(8) Man-made fill -- Heterogeneous soil and rock material; variable susceptibility to slope failure depending on nature of materials, foundation conditions, design and construction. Fills in older urbanized areas mapped only where associated with recent landslides.

Note that this map was based on 1973 aerial photographs, field reconnaissance, 1973-74, soil surveys by the U.S. Department of Agriculture, Soil Conservation Service, and existing geologic data.

A 100-meter grid on a scale of 1:24,000 was placed over the map in order to code the information and was positioned according to the Universal Transverse Mercator (UTM) grid ticks of 596,000 latitude and 4,470,000

longitude.

2. Maximum and Average Natural Slope Data.

Information on maximum and average natural slope was calculated for each cell from filtered digital elevation data. A digital elevation model (DEM) tape, which contains "digital records of terrain elevations for ground positions at regularly spaced intervals,"⁴⁸ was obtained for the Braddock 7.5-minute quadrangle from the U.S. Geological Survey. A "level 1" DEM tape contains basically raw elevation data, whereas a "level 2" tape has been filtered (i.e. smoothed for consistency and edited to remove random errors). For this study, a "level 2" DEM tape was used.

The program for calculating maximum and average natural slope from the filtered DEM tape for each 100-meter cell was developed by Robert Claire and Vincent Caruso of the U.S. Geological Survey, for use in the Cincinnati study. This program was subsequently revised by William Watson of the U.S.G.S. for use in the present study. The UTM coordinates used as the starting point in the program for calculating maximum and average natural slope were latitude = 595,300 and longitude = 4,469,700 for the southwest corner of the Braddock quadrangle.

⁴⁸ U.S. Department of the Interior, U.S. Geological Survey, National Cartographic Information Center, National Mapping Program, "U.S. GeoData, Digital Elevation Models," information sheet.

Calculations were performed for a total of 15,228 100-meter cells, resulting in a slightly larger data set than the 14,965 100-meter cells contained in the Braddock quadrangle.

3. Soil Shear Strength Data.

Information on soil shear strength for 100-meter cells in the Braddock quadrangle was not readily available, and had to be estimated. Soil maps for Allegheny County and Westmoreland County in Pennsylvania were obtained from the U.S. Department of Agriculture, Soil Conservation Service.⁴⁹ These soil maps were on different map sheets which had to be assembled in order to obtain a complete soil map for the Braddock quadrangle. The following map sheets were assembled from Allegheny County: 36-38, 46-48, 56-58, 64-66 and 71-73. For Westmoreland County, only map sheet number 38 was used. The resulting soil map was on a scale of 1:15,840. In order to convert this information to a scale of 1:24,000 an overlay grid was made to particular

⁴⁹ U.S. Department of Agriculture, Soil Conservation Service, in cooperation with Pennsylvania State University, College of Agriculture, and Pennsylvania Department of Environmental Resources, State Conservation Commission, Soil Survey of Allegheny County, Pennsylvania, issued August 1981; U.S. Department of Agriculture, Soil Conservation Service, in cooperation with Pennsylvania State University, College of Agriculture and Agricultural Experiment Station, and Pennsylvania Department of Agriculture, State Soil and Water Conservation Commission, Soil Survey, Westmoreland County, Pennsylvania, issued November 1968.

specifications (each cell = 0.24921 square inches). Once this process was completed, the information on soil type for each 100-meter cell was manually coded and entered into the computer. Note that all of the soil types present in a particular cell were coded along with an estimate of the percentage of the cell which contained each soil type. A total of 14,965 100-meter cells were coded with information on 58 different soil types.

One of the engineering soil classification systems most commonly used in classifying samples of soil is the system adopted by the American Association of State Highway and Transportation Officials (AASHTO). Under this system, soils are classified on the basis of properties that affect their use in highway construction and maintenance. Soils are grouped according to grain-size distribution, liquid limit and plasticity index, and are ultimately divided into one of seven groups. The first group, A-1, contains "gravelly soils of high bearing strength, or the best soils for subgrade (foundation)."⁵⁰ In the last group, A-7, are "clay soils that have low strength when wet and that are the poorest soils for subgrade."⁵¹

⁵⁰ U.S. Department of Agriculture, Soil Survey of Allegheny County, Pennsylvania, 37.

⁵¹ Ibid.

Randy Jibson of the U.S.G.S. performed a regression analysis to estimate the effective residual friction angle (shear strength) of a soil type, in degrees. The independent variables included in the regression were AASHTO (maximum AASHTO "A" value) and clay (maximum percent clay content of the soil). The resulting regression equation was,

$$O_R = 34.44 - 0.79 (\text{AASHTO}) - 0.11 (\text{Clay})$$

where O_R = the effective residual friction angle (shear strength), in degrees.

This equation, together with information on AASHTO and clay for each soil type in the Braddock quadrangle,⁵² was used to calculate the effective residual friction angle of a soil type. This information was entered into the computer, and an estimate for the soil shear strength tangent in a cell was then calculated by the computer by matching up the soil type for each cell with the effective residual friction angle and calculating the tangent.

If there was more than one soil type in a cell, then a weighted average of the soil shear strength tangents was taken, based on the percentage of the cell which contained each soil type. Note that there were some soil types which had to be deleted from the sample because (1) their

52 Ibid., Table 2.

properties were too variable to be estimated or (2) there were two or more soil types in one soil mapping unit. A total of seven soil types had to be omitted from the sample. After eliminating cells which fell in a river, creek or quarry, and after eliminating cells where it was not possible to estimate a soil shear strength tangent, there were a total of 13,198 100-meter cells left in the sample.

4. New Road Construction Data.

Information on new road construction in the Braddock quadrangle was based on a comparison of two topographic maps by the U.S. Geological Survey, one photorevised in 1969 and the other photorevised in 1979.⁵³ The new roads were manually highlighted on the 1979 photorevised map, and a 100-meter grid on a scale of 1:24,000 was placed over the map in order to code the information. A total of 510 cells in the Braddock quadrangle had new road construction between 1969 and 1979.

B. Cincinnati Model: Actual Landslide Damage Data.

The Cincinnati study area analyzed by the U.S. Geological Survey was comprised of portions of six

⁵³ State of Pennsylvania, Department of Internal Affairs, Topographic and Geologic Survey, "Braddock Quadrangle, Pennsylvania, 7.5 Minute Series (Topographic)," photorevised 1969 and photorevised 1979 (Reston, Virginia: U.S. Geological Survey, 1969 and 1979), scale 1:24,000.

different 7.5-minute quadrangles: Newport, Covington, Burlington, Cincinnati West, Addyston and Cincinnati East. Information on estimates of actual landslide damages in the Cincinnati study area over the ten-year period 1970-1979 were compiled by Paul Beauchemin of the U.S.G.S. Out of a total of 223 landslides investigated estimates were obtained for 174 landslides, many of which had affected more than one cell. Of these, eight landslides were omitted from the sample because they were the result of a failure to a man-made fill and another 32 landslides were omitted from the sample because they affected only public property.

The topographic maps for the relevant quadrangles in the Cincinnati study area used by the U.S.G.S. in their study were obtained and used to match up the damage estimates with the actual landslides. All landslide occurrences between 1970 and 1979 had been marked on the topographic maps and labelled with a number. The study area had been marked and divided into blocks slightly smaller than one-square inch.

The information on damage estimates had been compiled according to the landslide number and the identifying block number used on the topographic maps. The damage estimates were matched up to specific landslides on the map and a 100-meter grid was placed over the map to identify the

specific 100-meter cells for which landslide damage estimates had been obtained. This 100-meter grid was the same one used by the U.S.G.S. and had been marked to indicate the cells where a landslide had occurred.

The information collected by Paul Beauchemin consisted of a description of the location of the landslide, an estimate of the damage, a categorization of whether the damage occurred to an apartment building or a single family home, whether it was private or public property and in some cases an approximate date was given when the damage occurred. This information was manually coded and entered into the computer on the basis of the associated row and column number for each 100-meter cell. Out of a total of 451 100-meter cells which had at least one landslide occurrence in the ten-year period 1970-1979, information on damage estimates was coded for 183 cells.

Of these 183 cells, only 73 cells had an approximate date given when the damage occurred. In order to convert all of the damage estimates to a 1984 dollar basis, it was necessary to adjust them by multiplying by the ratio of the 1984 implicit price deflator for gross private domestic investment (residential fixed investment) to the implicit price deflator for the year in question.⁵⁴ For the cells

⁵⁴ Taken from the Economic Report of the President, Transmitted to the Congress February 1985 (Washington, D.C.: U.S. Government Printing Office, 1985), 236.

where no information had been obtained regarding the date of the damage, it was assumed that they had occurred in the middle of the ten-year time period and were adjusted to 1984 dollars as described above, using an average of the implicit price deflators for 1976 and 1977. Once this was accomplished for all 183 cells, this information was used along with information from the U.S.G.S. computer file to perform the stepwise regressions.

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