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University of Arizona

Technical Reports on
Natural Resource Systems

Collaborative Effort Between:

Hydrology and Water Resources
Systems and Industrial Engineering

The University of Arizona
Tucson, Arizona 85721

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FORWARD

This report is the culmination of a number of research projects: the first, started in 1973, was on the topic of the "Worth of Hydrologic Data for Short Term Forecasts." This research showed that the sole use of statistical measures of forecast error and its change due to the aquisition of additional data was not sufficient to evaluate the worth of the data. The need for a holistic approach that would consider the purpose of the forecasts and would utilize a broad framework including economic and social factors, among others, was indicated. The thrust of the research was then changed to the "Evaluation of Flood Forecasting-Response Systems." A systems approach was formulated which considered the response system and its components as well as the forecasting system and its components. The worth of a flood forecast-response system is considered to be the expected annual reduction in flood damage due to the use of the system.

The theoretical construct of an evaluation methodology using the systems approach was accomplished (Sniedovich et al., 1975); however, it was based on a number of simplifying assumptions such as the issuance of only one forecast. In the current contract, the research effort concentrated on developing a mathematical model for the flood forecast-response system that would reflect the sequential nature of both the forecasting process and the resultant decisions made by the floodplain dweller to determine the level of mitigating action to be taken. Based on this model, an evaluation methodology was developed, one which enables the quantitative economic evaluation of the flood forecast-response system for specific communities of interest. A previous report (Krzysztofowicz, et al., 1978) describes in detail the structure of the model, the required input data, and the calculations necessary for the evaluation. A complete computer package for the evaluation calculations and the implementation of the evaluation methodology, along with a manual explaining the programs were included in this report. An evaluation of the flood forecast-response systems in Milton, Pennsylvania, was carried out to illustrate the theory developed and to provide an example of the use of the computer package.

This report presents further studies accomplished during the period January 16 - December 31, 1978, for the second modification of Contract 6-35229: "Evaluation of Flood Forecasting-Response Systems."

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ABSTRACT

A system model and computational methodology have been developed which evaluate the worth of flood forecast-response systems in reducing the economic damage caused by floods. The efficiencies of the forecast system, the response system, and the overall system may be individually obtained and compared.

In this report the case study of Milton, Pennsylvania, was extended and further case studies were performed including a large residential section of Victoria, Texas, and all the residences in Columbus, Mississippi. These locations show better forecast and response efficiencies than obtained for Milton, Pennsylvania. The difference is attributed to longer forecast lead times at Columbus and Victoria. Sensitivity analyses were run at all three locations. These show the effects of many system factors, such as the time required to produce, disseminate and respond to a forecast, on the efficiency of the system. The forecast efficiency improves significantly as these times are reduced. Further analysis of the response system based on human factors involved has led to the development of a simulation model of the process by which the floodplain dweller determines the appropriate response to a flood warning. Investigation of ways to extend the methodology to evaluate regions lacking the detailed data used for the case studies has indicated more problems than answers. Extrapolation based on overall system efficiency related to published regional and national flood damage estimates was used to provide an approximate value of the flood forecast-response system for two regions and for the nation.

A listing of simplicities and approximations which make computations tractable but which may affect accuracy is given. Finally, an evaluation of the work accomplished for this project and suggestions for the constructive use of the flood forecast-response system model and computational procedures is given.

CHAPTER 1

INTRODUCTION

1.1. Overview of the Study

A methodology has been developed which determines the worth and efficiency of a Flood Forecast-Response (FFR) system and of its forecasting and response components (Krzysztofowicz, et al., 1978). The methodology has great potential for the design and evaluation of FFR systems; the calculated efficiencies can be used to indicate whether the forecasting or the response component most needs improvement. The incremental worth of proposed system improvement can be used in cost-benefit studies of the proposed improvement.

This methodology, developed at the University of Arizona, is the first which uses a quantitative system model to evaluate a flood forecast-response system. Elements explicitly and quantitatively considered by the methodology include 1) the sequential stochastic nature of the forecast, 2) the factors affecting the response of the floodplain dweller, and 3) the effectiveness of measures taken to mitigate the flood damage.

The previous report for this project (Krzysztofowicz, et al., 1978) includes, in detail:

1. the theoretical structure of the systems model,
2. the computational procedures,
3. a listing of the information requirements,
4. methods for obtaining the required information from the data available,

5. an analysis of the human factors involved in determining the flood-plain dweller's response to flood forecasts and a method for calculating the level of such response,
6. computer programs to implement the computational procedures,
7. a case study of Milton, Pennsylvania.

The previous report was mainly concerned with the development of the systems model and the computational methods. The case study was principally used to verify the model and the computational procedures.

In this report the emphasis is on the use of these concepts and procedures to analyse FFR systems. The case studies were extended to include Victoria, Texas, and Columbus, Mississippi. Beside basic evaluations of the FFR systems for these communities, detailed sensitivity analyses of the factors determining the effectiveness of the FFR system for these communities were made. These analyses indicate that the quantified systems approach is a powerful tool in the study of FFR systems.

In addition to the case studies and sensitivity analyses:

1. a simulation model of the mechanism of the human response to flood warning was developed,
2. a study of means to extend the methodology to larger regions was accomplished, and
3. refinements in the theory were introduced.

The body of the report begins with a review of the concepts used in the systems model, the information needed and the computational procedures. Next, the evaluation of the FFR systems of Milton, Pennsylvania, Victoria, Texas, and Columbus, Mississippi, is presented followed by sensitivity analyses. Of special interest is the study of the factors affecting forecast efficiency. The simulation model of the response mechanism of the floodplain dweller is given next. The regionalization studies follow. The discussion section starts with a listing of the critical assumptions and simplifications made in the system model and computational procedures. This listing introduces an evaluation of the results of this research project and a comparison with other methods for evaluating FFR systems. The discussion leads to the conclusions.

1.2. Systems Model and Computational Methodology

1.2.1. Systems Model

The model of the *flood forecast-response* system is composed of the *forecasting system* and the *response system*; see Figure 1-1. The first component of forecasting system is the hydrometric system, which provides data to the forecasting model, which is the second component. The third component is the dissemination system which transmits the forecasts to the floodplain dweller. In the response system the first component is a decision model by which the floodplain dweller determines the level of response to the forecast. This response activates the protective system and protective action is taken.

For this project, the model developed has a level of detail which includes the essential aspects of the FFR system and yet is computationally tractable. The basic concept involved is that the *state* of the system changes sequentially during the forecast-response process. This change is determined by a stochastic state transition function called the *law of motion* and by the response *strategy* of the floodplain dweller. The values of the (vector valued) state of the system attained during a flood

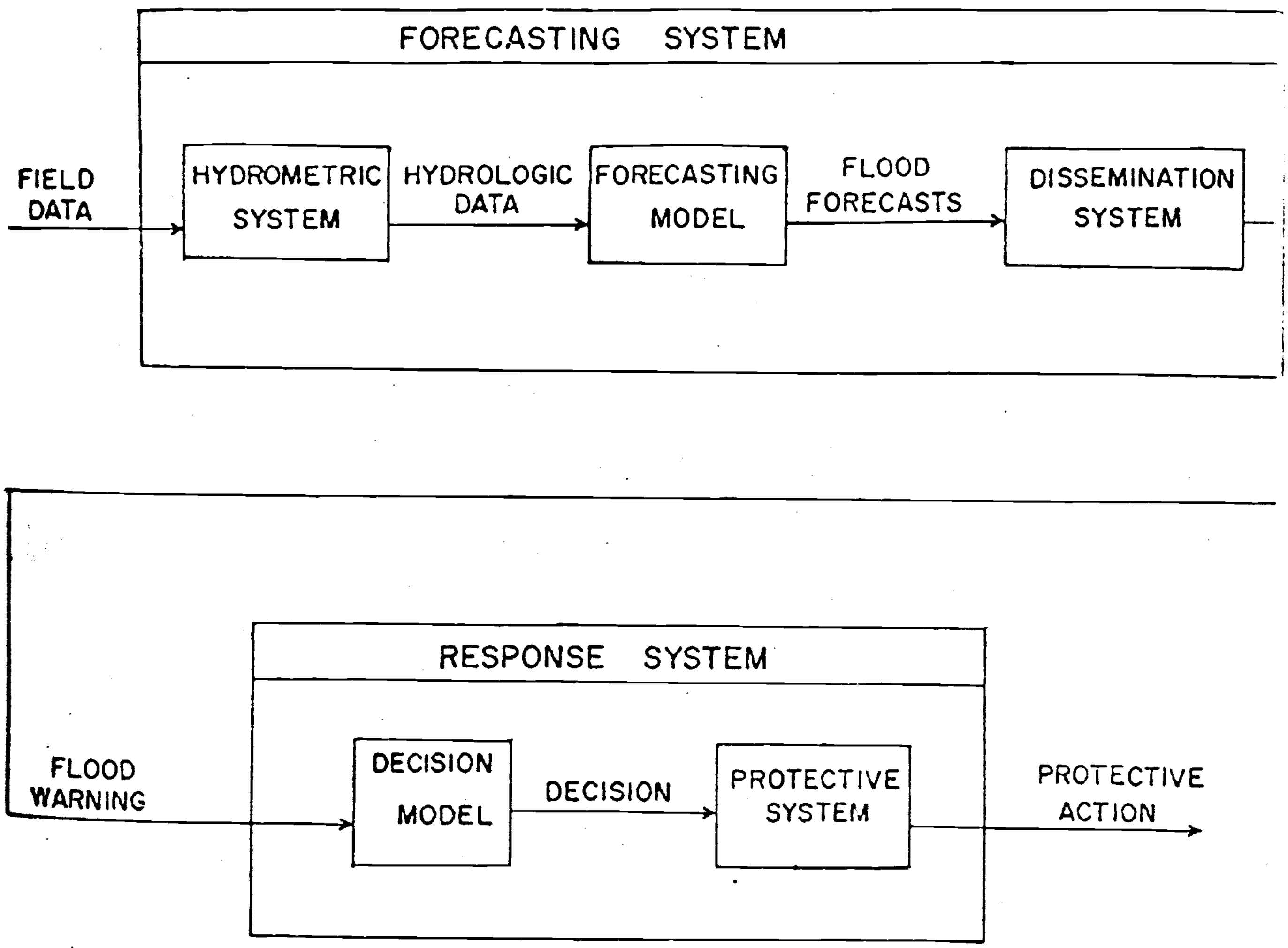


Figure 1-1. Flood Forecast-Response System

event determine the net flood loss, which is calculated by the *loss function*. Use of this model and the associated computational methodology enables the calculation of the average annual reduction in flood damage to be expected by the use of the FFR system. In addition the efficiency of the forecast system, the efficiency of the response system, and the overall system efficiency may be obtained.

1.2.2. FFR Process

A definition and derivation of a model of the FFR process is given in the previous report (Krzysztofowicz, et al., 1978). In Appendix A of the present report the model's definition is rewritten with a more compact notation. The model is presented in an intuitively functional manner in this section. It may be viewed as a simulation model of a flood event.

The state of the system is defined for each of the forecasts in a flood event. The receipt of a forecast is a decision time for the floodplain dweller. At this time the floodplain dweller knows the value of three out of the four elements of the state space: α, the degree of response already achieved in response to earlier forecasts: i, the current flood level, and h, the currently forecast flood crest. The fourth element in the state space, w, which is unknown to the floodplain dweller, indicates whether there will be an additional forecast. If there is no additional forecast there is a final state space valuation of h; in this instance h is the actual flood crest.

At each decision time the state of the system changes. The sequence of values for the current flood level, i, the forecast flood crest, h, and the forecast indicator, w, is determined by a law of motion. The new value for the degree of response, α, achieved by the floodplain dweller is based on the response strategy of the floodplain dweller. The law of motion may be viewed as a stochastic simulation of crest forecasts and river stages. Similarly the response strategy is a simulation of the output from the floodplain dweller's decision model.

For this project the law of motion was obtained for each community by analysing forecast verification reports supplied by River Forecast Centers. The computation of the law of motion for Milton, Pennsylvania, is illustrated in Chapter 5 of the previous report (Krzysztofowicz, et al., 1978). To analyse other than the present forecasting systems having a verification record, a law of motion would have to be developed based on the characteristics of the system rather than on its record. The response strategies used in the evaluation calculations will be described later in this chapter.

Losses in the FFR model come from both the cost of responding to a forecast and from the damage caused by the flood waters. These losses depend on the structure being considered, on the response achieved before flooding and on the level of inundation.

Structures in the floodplain were classified into seven types. For each type, functions were developed describing the costs of response, the value of response, the damage due to flooding and the limiting response rate. Each of these functions is a unit function, that is the value of the function is expressed as a fraction of the maximum flood damage to the structure.

The model of the FFR process and the evaluation measures derived from it are based on one decision maker and one structure in the floodplain. The use of the unit function concept enables the extension of the evaluation methodology to all structures in the floodplain in a reach of river with similar characteristics. In a reach the value of the FFR system is the sum of the value of the system to each decision maker and structure in the reach. The computations are made tractable because the unit function concept allows all structures having similar physical and flood exposure characteristics to be lumped for purposes of calculation.

1.2.3. Decision Process

The state variable, α, representing the degree of response already achieved on receipt of forecast number k, is determined by the level of response decided upon by the floodplain dweller on receipt of forecast number k-1 and the time available to implement this decision. A new forecast with the attendant need for a new decision serves to limit the time available for response to the previous forecast.

The response strategy is a delineation of the response decisions at all decision times for all values of the state vector. For evaluating the FFR system two types of response strategies are used: an optimal strategy and the strategy actually used by the floodplain dweller.

The optimal strategy is the strategy that produces the least expected loss due to flooding. The expected loss associated with a specified strategy is calculated by determining the loss to be obtained for all possible sequences of state variables during a flood event and weighting these losses by the probability of each sequence occurring. The strategy that produces the least expected loss is found by stochastic dynamic programming.

The actual strategy is an approximation to the strategy actually used by the floodplain dweller. Two approaches to the problem of determining the actual strategy were taken. In the *pure* strategy it is assumed that the floodplain dweller makes no response until a crest is forecast that would cause flooding of the floodplain dweller's structure, in which case the decision to undertake a maximum response is made. If the time to actual flooding is shorter than the time required to make a full response, the pure strategy is not the best strategy. In contrast, the optimal strategy often involves making small responses even if the forecast does not indicate flooding of the structure.

A *human factors* strategy is an actual strategy which simulates the response of the floodplain dweller in more detail than the pure strategy. This strategy cannot be empirically validated at present because the detailed data required are not available. In this model, a response is made when the decision maker is sufficiently sure of flooding. Such assurance depends on the floodplain dweller's experience with flooding while a member of the community, and on the sequence of forecasts during the flood event. Mathematically, assurance is measured as subjective probability and is based on a learning model with Bayesian updating. Details are given in Chapter 3 of the previous report (Krzysztofowicz, et al., 1978). The summary of the human factors model is given in Appendix B of this report.

Fitting the mathematical human factors model involves estimation of parameters associated with learning and with Bayesian probability updating. The choice of these parameters is explained in the previous report (Krzysztofowicz, et al., 1978; pp. 312-317) and is believed to be reasonable.

Validation of this model would require a substantial amount of actual response data from floodplain dwellers subject to different histories of loss and having lived for different periods on the floodplain. Such data is presently not available. The most useful next step was considered to be to interrelate the characteristics of the warnings and of the decision maker by simulating the actual decision process rather than persuing a mathematical abstraction of it. This new model, developed in the third chapter of this report, cannot at present be used to provide an actual strategy for the FFR system evaluation, but it provides a method for exploring the effects of demographic, social and warning variables on response.

1.2.4. Measures of Effectiveness

The computational procedures are designed to calculate the expected annual flood losses for a structure or a community. Six measures of effectiveness have been developed which allow the performance of the overall FFR system, the forecast system and the response system to be evaluated and compared.

The *potential value*, PV, of the FFR system is defined as maximum expected annual reduction in flood losses that may be obtained by the use of a FFR system. It is the difference of the expected annual loss with no response and the expected annual loss based on an optimal response to a perfect forecast with a large lead time.

The *optimal value*, OV, of a FFR system is the difference between the expected annual loss with no response and the expected annual loss using an optimal response to the actual forecast situation, as defined by the law of motion.

The *actual value*, AV, of the FFR system is the difference between the expected annual loss with no response and the expected annual loss using the floodplain dweller's actual response to the actual forecast situation.

From the potential, optimal and actual values of the FFR system, efficiencies may be obtained for the forecast system, the response system and the overall FFR system. The *forecast efficiency*, EF, is the quotient obtained by dividing the optimal value by the potential value:

$$EF = OV/PV,$$

the *response efficiency*, EF, is the quotient obtained by dividing the actual value by the optimal value:

$$ER = AV/OV,$$

and the *overall efficiency*, EO, is the quotient obtained dividing the actual value by the potential value:

$$EO = AV/PV.$$

Seven computer programs have been developed for the calculations required. These can be used in a wide variety of situations. They are listed in Volume 2 of the previous report (Krzysztofowicz, et al., 1978). A manual for their use is given in Chapter 7, Volume 1, of that report. The programs are quite flexible: in addition to the evaluation, the detailed response strategy may be obtained, and for a community, matrices may be obtained showing the distribution of potential, optimal and actual values throughout the community, classfied according to structural type and location in the floodplain.

In the next chapter the precepts developed in this chapter are used to evaluate and analyse the FFR systems of three communities.

CHAPTER 2

CASE STUDIES

2.1. Overview

Three communities were analysed: Milton, Pennsylvania; Victoria, Texas; and Columbus, Mississippi. Evaluations were made for individual structures within the community and for the complete community as far as data would allow. In addition, sensitivity analyses were run on many factors affecting the evaluations so as to provide insight into the FFR system.

Flood verification records were provided for each community from the district River Forecast Center. A complete inventory of the structures in Milton was obtained from the Corps of Engineers, Baltimore district. Inventories for Columbus and Victoria were provided by Day and Lee (1978).

The three communities have quite different economic, geographic and flooding characteristics. Only low lying areas, mainly of residential character, are flooded in Victoria. The evaluation for Victoria is actually for the Green Addition, the area in which most of the flood damage occurs. At this point the difference between the 10 year flood stage and the 100 year flood stage is less than one foot. Columbus was the largest community evaluated. The Tombigbee River drops 10 feet as it traverses Columbus. Since the procedure for evaluating a river reach assumes homogeneous conditions, Columbus was broken into five segments for the evaluation of the whole community. Due to the difficulty in obtaining the information required about commercial and industrial structures in Columbus, the community evaluation is of residences only. Milton is the smallest of the three communities. It is located on the West Branch of the Susquehanna River. For this community the forecasts listed on the verification reports are 6 hours apart; for Columbus and Victoria the forecasts are 24 hours apart. The structural inventory furnished by the Corps of Engineers allowed all structures in Milton to be considered in the community evaluation.

Some of the salient charactersitics of the FFR system for these communities are listed in Table 2-1. A complete specification of the parameters of the forecasting system for each community is listed in Appendix C. The computer printout for the complete law of motion for Milton is reproduced on pp. 244-302 of the original report (Krzysztofowicz, et al., 1978). For all three communities the law of motion was verified by using it to simulate the distribution of peak annual floods. The correspondence to the historical record was satisfactory in all cases (see pp. 303-306 of the original report for the Milton verification).

2.2. Evaluations

Values and efficiencies are shown for Milton in Table 2-2, Victoria in Table 2-3 and Columbus in Table 2-4. Each table contains an evaluation for an individual structure as well as an overall community evaluation as described in the previous section. Two actual strategies are considered, the pure strategy and the human factors strategy. Table 2-5 gives a community evaluation in Milton for residences alone.

	Milton	Victoria	Columbus
rification records	1959-1975	1965-1976	1955-1973
nge of actual ad times hrs.	5-12	5-37	22-71
nge of ocessing times hrs.	2.7-3.5	2.1-4.0	1.1-5.7
me between recasts hrs.	6	24	24
fference between 10 ar and 100 year flood ft.	8.7	0.8	11.9
pulation	8,000	24,000	53,000

ocessing time is the difference between the time the forecast was made and e time the observations upon which the forecasts was based were made.

tual lead time is the time between the issuance of the last increasing recast and the arrival of the flood crest.

Table 2-1

Some Characteristics of Evaluated Communities

Structure(s)	Residence #221	AFC plant	all of Milton
Elevation above flood stage, ft.	12	6	0-21
Maximum possible damage, $	46,900	3,500,000	48,599,580
Expected annual loss, $			
perfect forecast and response	333	94,968	874,688
no response	467	175,106	1,541,249
optimal strategy	419	158,839	1,404,766
actual strategy			
pure	504	205,841	1,788,478
human factors	466	168,990	1,495,367
Performance, $			
potential value	134	80,138	666,561
optimal value	48	16,267	136,483
actual value			
pure	-37	-30,735	-247,229
human factors	1	6,116	45,881
Efficiency			
forecasting system	.36	.20	.20
response			
pure	-.77	-1.89	-1.81
human factors	.021	.38	.34
overall			
pure	-.28	-.38	-.37
human factors	.007	.076	.069

Table 2-2

Evaluation of Milton, Pennsylvania,

Flood Forecast-Response System

Structure(s)	Residence #23	all of Green Addition
Elevation above flood stage, ft.	11	0-13
Maximum possible damage, $	35,000	1,396,860
Expected annual loss, $		
perfect forecast and response	1346	50,085
no response	1722	63,853
optimal strategy	1527	57,201
actual strategy		
pure	1697	62,918
human factors	1722	63,850
Performance, $		
potential value	376	13,768
optimal value	195	6,652
actual value		
pure	25	935
human factors	0	3
Efficiency		
forecasting system	0.52	0.48
response		
pure	.13	.14
human factors	0.00	.0005
overall		
pure	.067	.068
human factors	0.00	.0002

Table 2-3

Evaluation of Victoria, Texas,

Flood Forecast-Response System

Structure(s)	Residence 61 reach 2	all residences
Elevation above flood stage, ft.	10	0-16
Maximum possible damage, $	75,400	22,127,620
Expected annual loss, $		
perfect forecast and response	3,350	382,850
no response	4,816	531,560
optimal strategy	3,887	441,170
actual strategy		
pure	4,349	505,310
human factors	4,812	530,890
Performance, $		
potential value	1,466	148,710
optimal value	929	90,390
actual value		
pure	467	26,250
human factors	4	670
Efficiency		
forecasting system	0.63	0.61
response		
pure	.50	.29
human factors	.004	.007
overall		
pure	.32	.18
human factors	.002	.004

Table 2-4

Structure(s)	
Elevation above flood stage, ft.	0-21
Maximum possible damage, $	21,383,815
Expected annual loss, $	
perfect forecast and response	169,204
no response	239,777
optimal strategy	215,853
actual strategy	
human factors	238,997
Performance, $	
potential value	70,573
optimal value	23,924
actual value	
human factors	780
Efficiency	
forecasting system	0.34
response	
human factors	.033
overall	
human factors	.011

Table 2-5

Evaluation of All Residences in Milton

of flood events per year. This number varies with the length of record used. Based on the verification reports, for Milton, Victoria and Columbus, the expected number of flood per year used in the calculations for each community is 0.529, 2.667 and 1.368 respectively. Milton has received considerably more flooding in the years covered by the verification reports than in the prior years. Therefore the computed valuations for Milton are adjusted down by 64% to reflect the longer record (from 1889) of peak annual flows available at Harrisburg, Pennsylvania.

Such an adjustment has not been used in the valuations of Victoria and Columbus. Partial duration series should be used in these cases, and consideration made of physical changes in the rivers upstream of the communities. Information is not available for this type of adjustment, so results for Victoria and Columbus are based on flood verification reports only. Note that while an adjustment made in the annual number of flood events affects the average annual value of the FFR system , it does not affect the efficiencies of the system.

The results presented in this section evaluate the actual FFR systems of these three communities as well as they could be modelled. In the next section changes are made in certain aspects of the systems in order to obtain insight into the factors effecting the value and efficiency of FFR systems.

2.3. Sensitivity Analyses

The overall efficiencies of the FFR systems for the three communities are not high. Many factors are involved. Sensitivity runs were made to examine the effect of varying some of these factors. Among the factors examined were the lead time of the last forecast, the processing time for forecasts, the time and cost required for response, the response strategy used and the type of structure and its location in the floodplain.

For each community the effect of extending the lead time of the last forecast and reducing the processing time is shown in Tables 2-6, 2-7 and 2-8. The effect of these changes is to increase the floodplain dweller's consumer time, the time available in which to respond. The efficiencies of the FFR system increased slightly.

Large increases in efficiency result when drastic changes are made in the response system. Tables 2-9, 2-10 and 2-11 show the efficiencies for the three communities when the cost of response is zero and when the rate of response is instantaneous. Large increases in efficiency resulted.

Efficiencies differ considerably for structures in the same community depending on type of structure and its location in the floodplain. In Figure 2-1, the forecast efficiency and the response efficiencies for the pure response and the human factors response are plotted against location in the floodplain as measured in feet above flood stage for a Columbus, Mississippi, residence. Sensitivity analysis results also vary with location, as measured by height above flood stage, in the floodplain. Table 2-12 shows how the efficiencies for a residence and an industry in Milton change with location and with changes in the forecast and response system.

Structure(s) and	Lead Time Change	Processing Time Change	Residence on step 4	ACF plant	Milton
elevation above flood stage			6	6	
			Efficiencies		
forecasting system	0	0	.26	.20	.20
response (human factors)			.025	.37	.33
overall			.007	.076	.070
forecasting system	+6	0	.30	.22	.22
response (human factors)			.032	.44	.38
overall			.010	.095	.084
forecasting system	0	-2	.33	.24	.26
response (human factors)			.031	.53	.44
Overall			.010	.13	.11

Table 2-6

The Effect of Decreasing Processing Time

and Increasing Lead Time for Milton

Structure(s) and	Lead Time Change	Processing Time Change	Residence	Green Addition
elevation above flood stage			11	0-13
			Efficiencies	
forecasting system	0	0	.52	.48
response pure			.13	.14
overall			.07	.07
forecasting system	+6	0	.54	.53
response pure			.14	.14
overall			.08	.08
forecasting system	0	-2	.54	.54
response pure			.15	.16
Overall			.08	.08

Table 2-7

The Effect of Decreasing Processing Time

for Victoria

Structure(s) and	Lead Time Change	Processing Time Change	Residence	All Residences
elevation above flood stage			10	0-16
			Efficiencies	
forecasting system	0	0	.63	.61
response pure			.50	.29
overall			.31	.18
forecasting system	0	-2	.65	.62
response pure			.56	.33
Overall			.37	.20

Table 2-8

The Effect of Decreasing Processing Time

for Columbus

Structure(s) and	Cost of response	Rate of response	Residence	ACF plant	Milton
elevation above flood stage			6	6	
			Efficiencies		
forecasting system	actual	actual	.26	.20	.20
response					
human factors			.025	.37	.33
pure			-1.00		
overall					
human factors			.007	.076	.070
pure			-.28		
forecasting system	zero	actual	.32	.30	.31
response					
human factors			.02	.48	.46
pure			.22	.55	
overall					
human factors			.007	.14	.15
pure			.07	.16	
forecasting system	actual	instantaneous	.93	.86	.82
response					
human factors			.40	.90	.86
pure			.99	.99	
Overall					
human factors			.37	.75	.71
pure			.92	.83	

Table 2-9

The Effect of Changes in the Rate of Response

and the Cost of Response for Milton

Structure(s) and	Cost of response	Rate of response	Residence	Green Addition
elevation above flood stage			11	0-13
			Efficiencies	
forecasting system	actual	actual	.52	.48
response				
human factors			0	.001
pure			.13	.14
overall				
human factors			.07	.000
pure			0	.07
forecasting system	zero	actual	.95	.95
response				
human factors			.000	.000
pure			.10	.10
overall				
human factors			.000	.000
pure			.09	.10
forecasting system	actual	instantaneous	.59	.59
response				
human factors			.001	.001
pure			.27	.27
Overall				
human factors			.000	.000
pure			.16	.16

Table 2-10

The Effect of Changes in the Rate of Response

and the Cost of Response for Victoria

Structure(s) and	Cost of response	Rate of Response	Residence	All residences
elevation above flood stage			12	
			Efficiencies	
forecasting system	actual	actual	.63	.61
response				
human factors			.004	.007
pure			.50	.29
overall				
human factors			.002	.004
pure			.32	.18
forecasting system	zero	actual	.92	.95
response				
human factors			.002	.004
pure			.42	.21
overall				
human factors			.002	.004
pure			.38	.20
forecasting system	actual	instantaneous	.71	.66
response				
human factors			.003	.007
pure			.67	.41
Overall				
human factors			.002	.005
pure			.48	.27

Table 2-11

The Effect of Changes in the Rate of Response

and the Cost of Response for Columbus

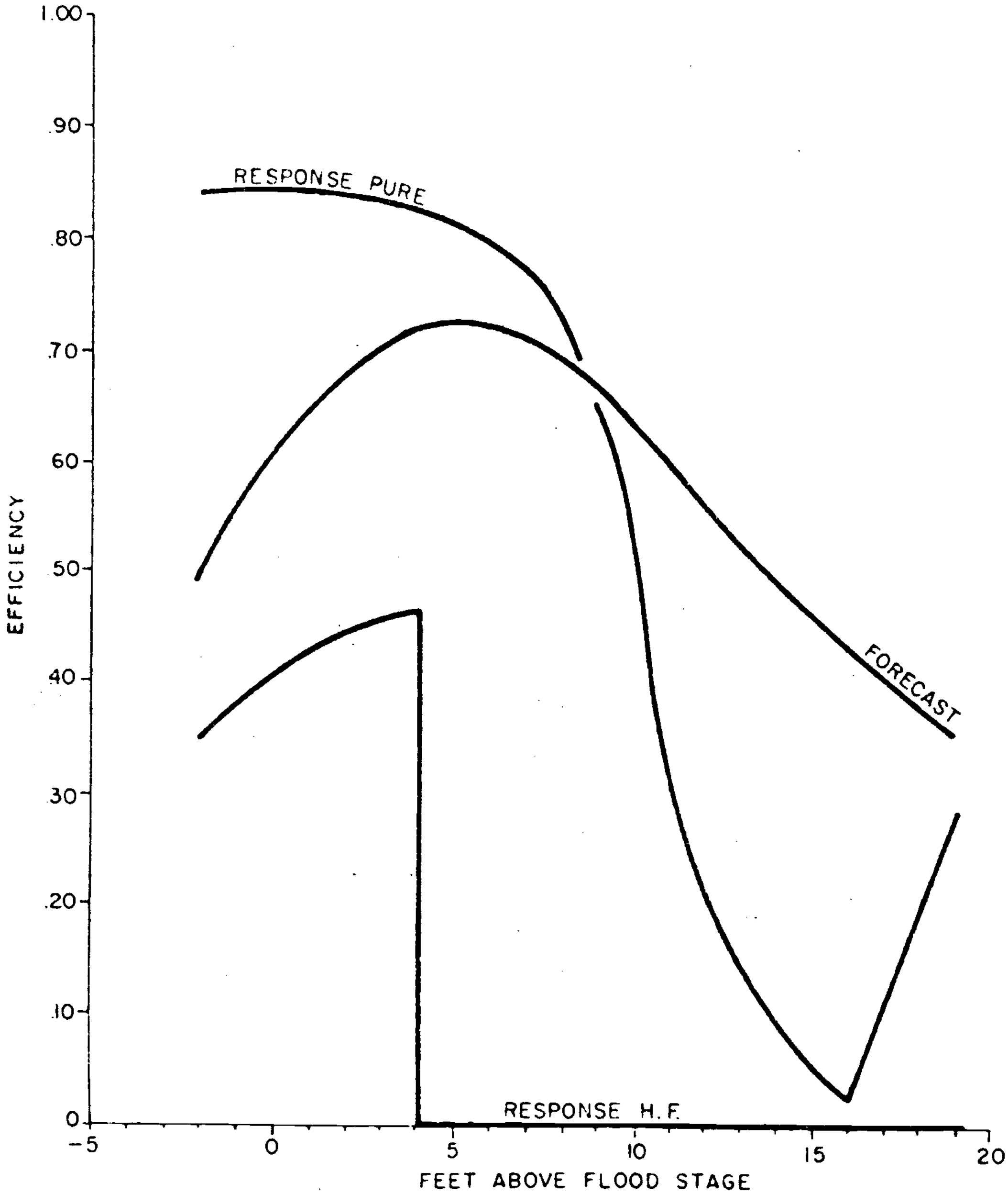


Figure 2-1

Efficiency vs Location of Residence above Flood Stage, Columbus; Human Factors and Pure Strategies

	Industry					Residence			
processing time	actual	actual	actual	-2	-2	actual	actual	actual	actual
rate of response	actual	actual	instantaneous	actual	actual	actual	actual	instantaneous	instantaneous
Height above flood stage	EF	ER	ER	EF	ER	EF	ER	ER	EF
0	.14	.71	.99	.19	.79	.07	.90	.99	.89
3	.19	.61	.96	.23	.72	.17	.13	.63	.96
6	.20	.38	.90	.24	.53	.26	.02	.40	.93
9	.17	.37	.91	.20	.58	.33	.03	.51	.89
12	.13	.30	.97	.19	.52	.36	.01	.27	.80
15	.09	-.06	.85	.15	.38	.37	.06	.53	.75
18	.04	-.03	0	.05	-.02	.29	0	0	.54

Table 2-12

Forecast Efficiency, EF, and Response Efficiency, ER as a Function of Location above Flood Stage for a Residence and an Industry in Milton.

Efficiencies are Also Shown for Instantaneous Response and for Processing Time Reduced 2 Hours. Human Factors Strategy Used.

Changes in the forecasting system, in general, produced smaller changes in efficiencies than did changes in the response system. Different response strategies may produce change in the response efficiency but, by definition they can not change the forecast efficiency. However, changes in other parameters of the response system such as cost of response or the time required to complete damage mitigating measures produce changes in both the response and forecast efficiencies. While this is expected from the definition of the efficiencies, it raises the question of whether the forecasting efficiency, as defined, is truly descriptive of the forecast system.

2.4. Forecast Efficiency

For the entire community of Milton the forecast efficiency was 0.20. Sensitivity analysis showed that improvements in some parameters of the forecasting system did not produce much increase in the forecasting efficiency but that changes in the parameters of the response system caused dramatic improvement in the forecast efficiency. Victoria and Columbus have overall forecast efficiencies of 0.48 and 0.61, respectively. Changes in the forecast system parameters produced proportionally less change in forecast efficiency than did like changes for Milton. The parameter change in the response system which increased the forecast efficiency the most for Victoria and Columbus, produced the smallest change in the forecast efficiency for Milton and vice versa. In this section a detailed look will be taken at these results and it will be argued that the forecast efficiency is indeed an accurate measure of the effectiveness of the forecast system, when viewed in the context of the complete FFR system in which it is embedded.

The forecast efficiency is defined as the optimal value of the FFR system divided by the potential value of the system. The optimal value is the maximum expected reduction in flood loss that can be achieved with information provided by the actual forecast system, while the potential value is the maximum expected reduction in flood damage that can be achieved with optimal response to a perfect forecast system. A perfect forecast system would provide perfect forecasts sufficiently in advance of the flood to allow all mitigating actions to be taken and completed.

The optimal value of the FFR system depends on parameters in the response system as well as on parameters of the forecasting system. If time is not available to implement mitigating actions, an accurate forecast will have a low efficiency. If time to complete mitigating actions is available, and if the cost of such action is small compared to the possible benefits, the optimal strategy will call for the mitigating actions to be taken, whether the forecasts are accurate or not. In that case a FFR system will have a relatively high forecast efficiency, whether the forecasts are intrinsically accurate or not. Conversely an intrinsically accurate forecasting system will have a relatively low efficiency if time is not available to complete mitigating activities, regardless of the cost of response.

On the other hand, if the cost of response is not low, an intrinsically inaccurate forecast will not have a very high forecast efficiency regardless of the time available to respond. Of course the efficiencies are affected by other factors also, but the considerations above can explain the differing efficiencies for Milton as compared with Victoria and Columbus.

All three communities have the same parameters in the response system. Table 2-1 shows some characteristics of the forecast system for these communities; Appendix C gives the details of the forecast parameters. The main differences are that Milton receives forecasts at 6 hour intervals while Columbus and Victoria receive them every 24 hours and that for Milton the time between the last forecast and the crest is shorter, on the average, than it is for Victoria or Columbus.

For an industrial structure, it takes 120 hours to achieve the maximum mitigating response although 60% effectiveness may be achieved after 24 hours (Krzysztofowicz, et al., 1978, p. 172). In Milton, residences have a higher forecasting efficiency than industrial structures at the same location, as the maximum mitigating response may be achieved in 24 hours. Figure 2-2 shows the changes in forecast efficiency for an industry in Milton with changes in cost of response and the time needed for maximum response. Figure 2-3 shows changes in forecast efficiency, response efficiency, and overall efficiency with changes in time needed to attain maximum response for a residence in Columbus. Similar sensitivity analyses for the response efficiencies of the industry in Milton are shown in Figure 2-4, and for a residence in Milton at the same location in the floodplain in Figure 2-5.

The apparent anomalies in the forecast efficiencies may now be explained. The forecast efficiency is lower in Milton than in Columbus or Victoria because there is less time available to complete response activities in Milton. When the cost of response is reduced, there is a bigger improvement in forecast efficiency in Victoria and Columbus than for Milton because there is time to take the additional mitigating action the optimal strategy calls for. On the other hand when the time required to reach maximum

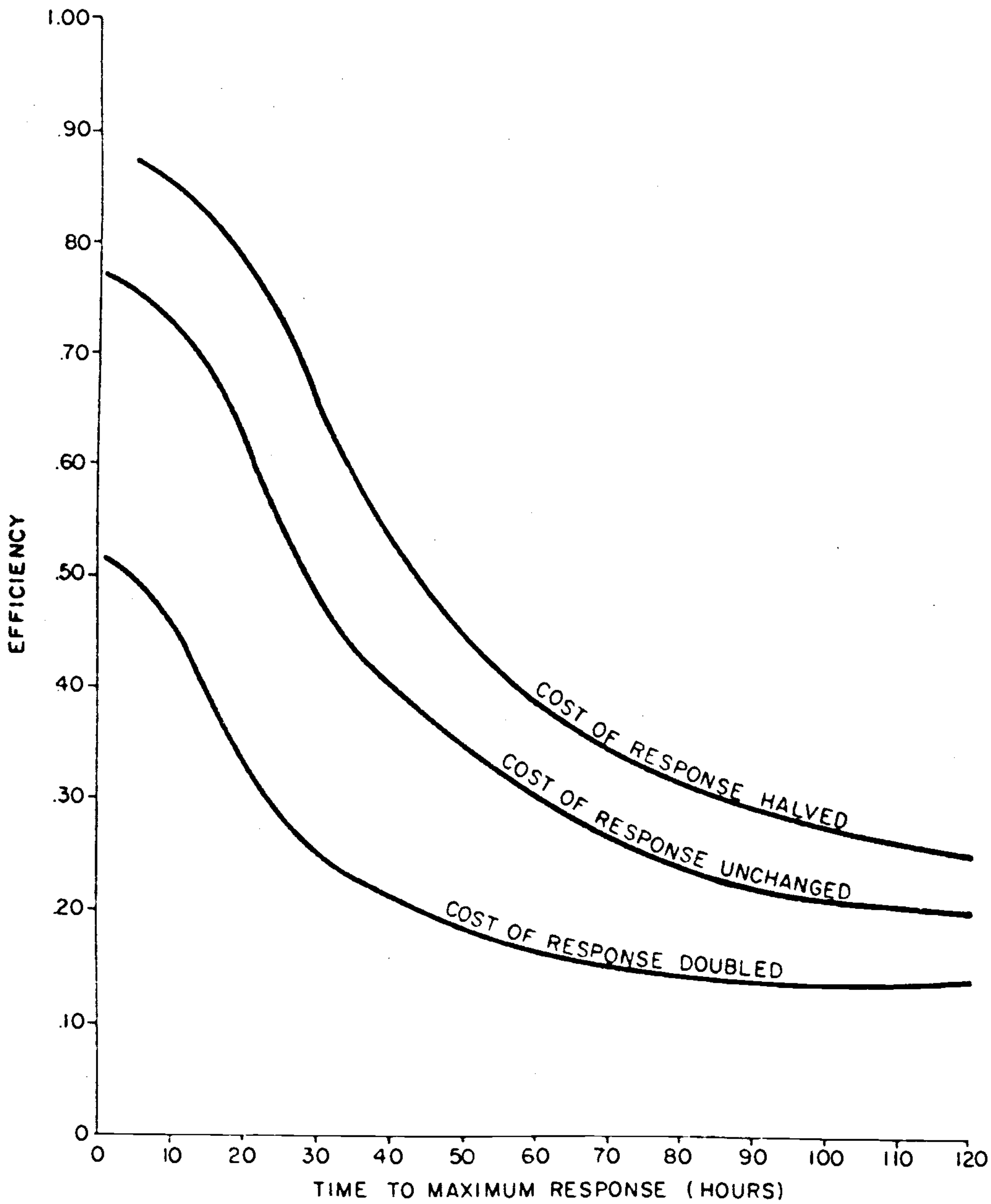


Figure 2-2

The Effect of Time to Maximum Response and Cost of Response on Forecast Efficiency, ACF Plant in Milton; Pure Strategy.

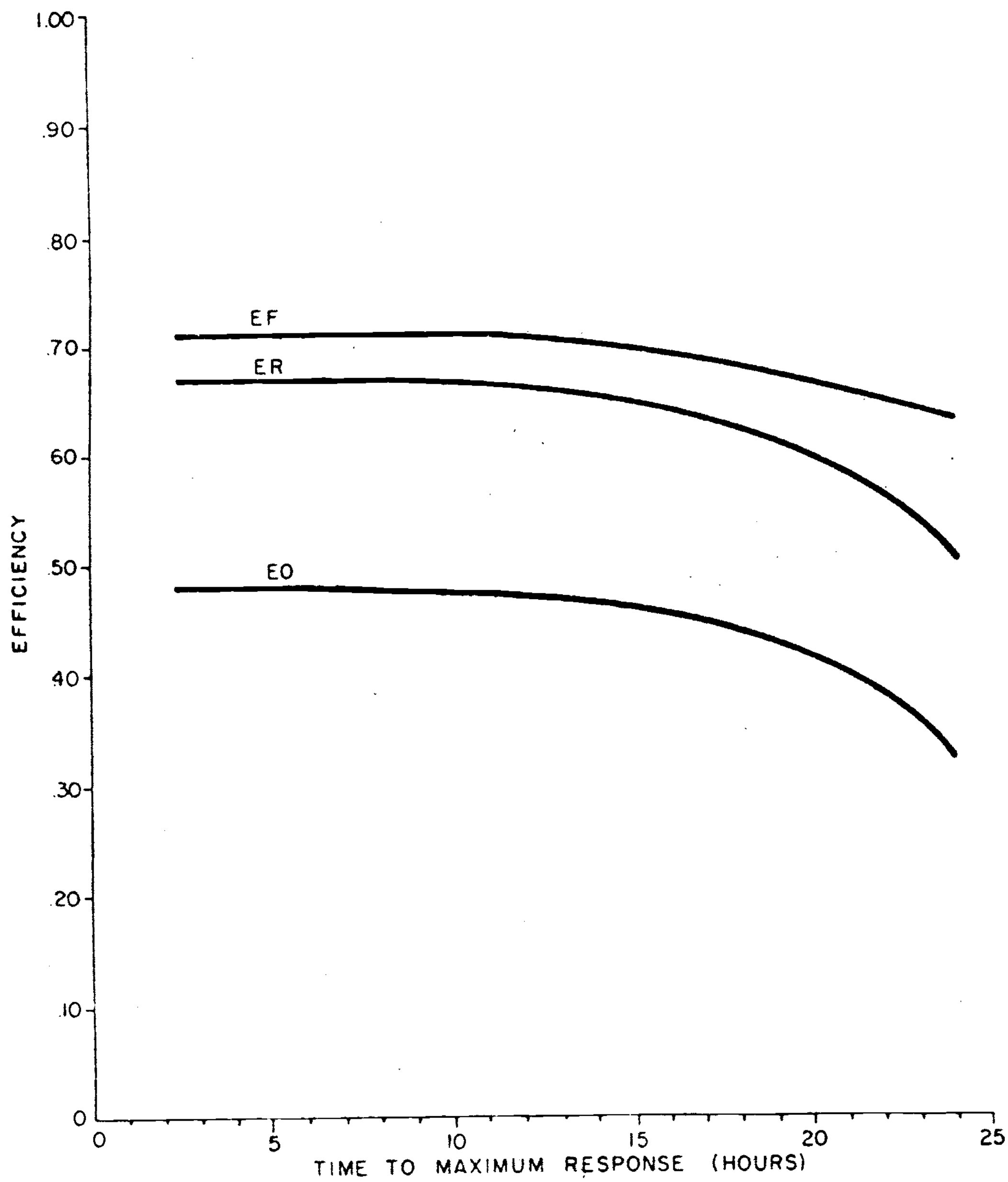


Figure 2-3

The Effect of Time to Maximum Response on Forecast Efficiency, EF, Response Efficiency, ER, and Overall Efficiency, EO, for Residence 61 in Columbus: Pure Strategy.

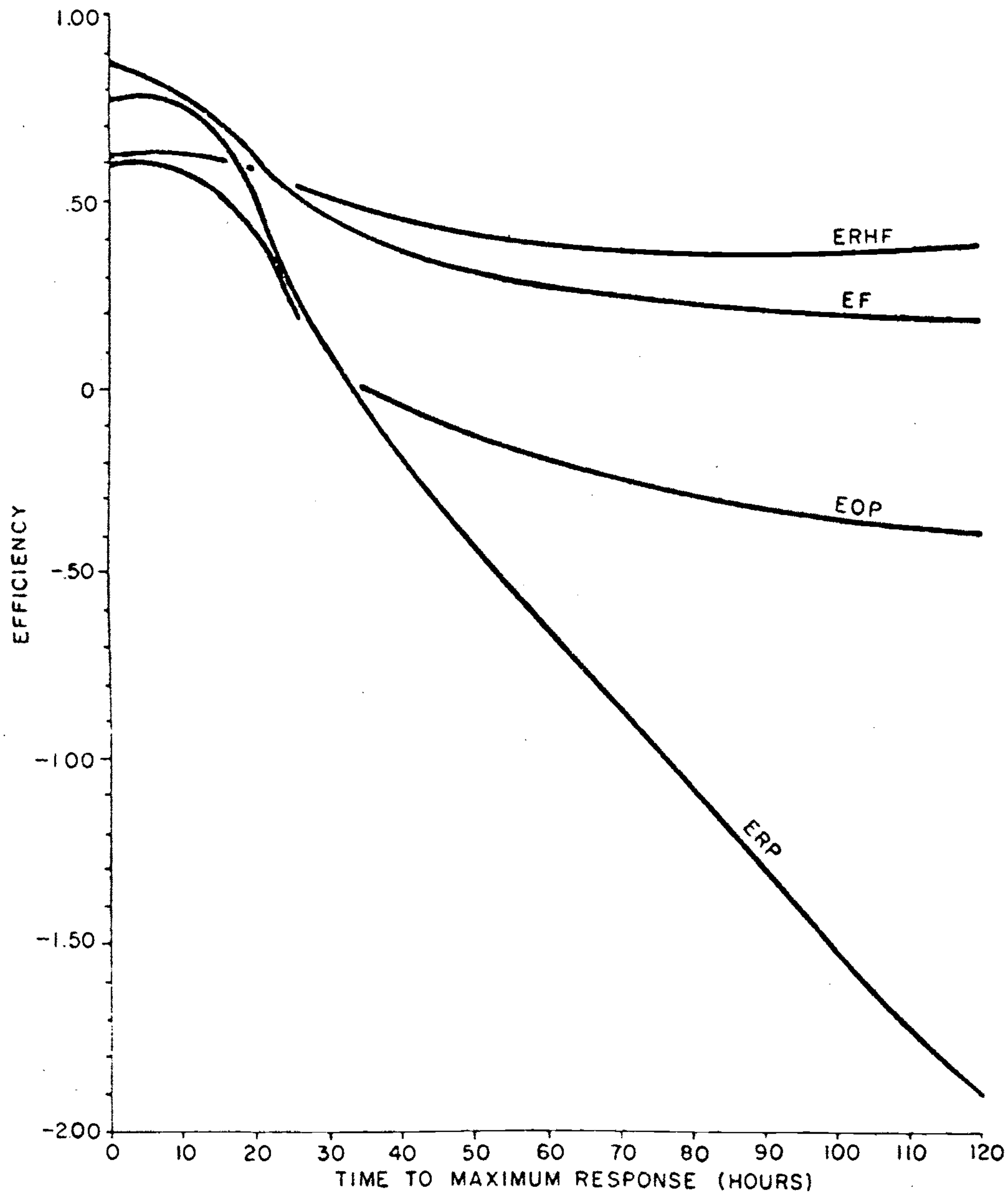


Figure 2-4

The Effect of Time to Maximum Response on Forecast Efficiency, EF, Response Efficiency, Pure Strategy, ERP, Response Efficiency, Human Factors Strategy, ERHF, and Overall Efficiency, Pure Strategy, EOP, Industry in Milton.

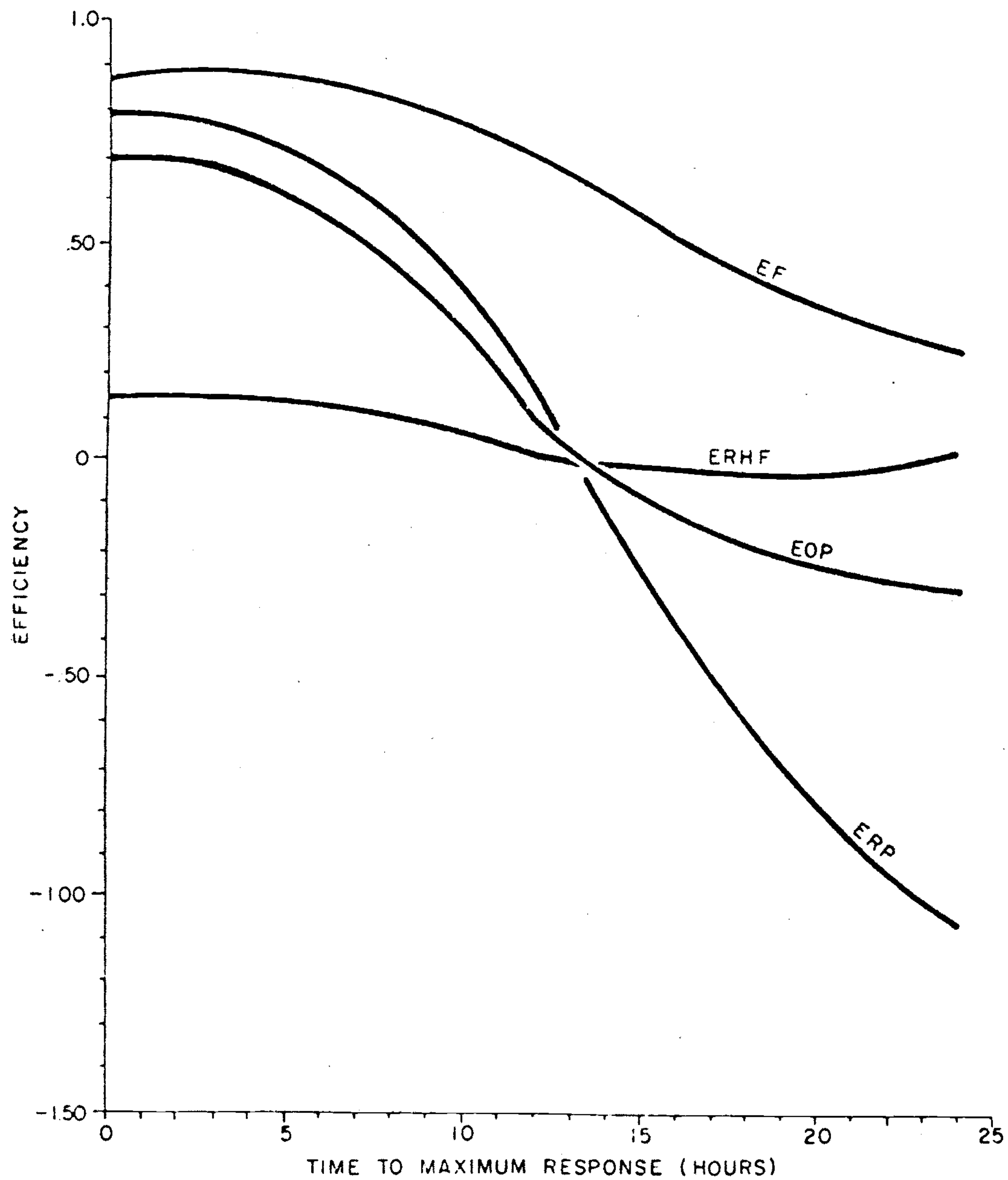


Figure 2-5

The Effect of Time to Maximum Response on Forecast Efficiency, EF, Response Efficiency, Pure Strategy, ERP, Response Efficiency, Human Factors Strategy, ERHF, and Overall Efficiency, Pure Strategy, EOP, Residence in Milton.

response is lowered, the forecast efficiency for Milton increases more than for Columbus or Victoria because Milton floodplain residents normally have less time to react than those in Columbus or Victoria. For the same reason the forecast efficiency at Milton shows more increase when the lead time is increased and the processing time reduced than do the forecast efficiencies at Victoria and Columbus. Figures 2-2 through 2-5 imply that for mitigation activities which can be completed in a relatively short period of time, the forecast efficiencies of all three communities are comparable, though Milton's is the best.

The forecast efficiency, as defined in this report, measures the effectiveness of the forecast system in meeting the needs of floodplain dwellers who use the forecast. Different structures at varying points within the floodplain of a community can have different forecast efficiencies. Forecast efficiency can be changed by changes in either the forecast system or the response system. Using the methodology presented in this report can give insight to the workings of an FFR system. Using this methodology to compare forecasts of two systems at different locations should be approached cautiously. Drastically reducing the time of response for similar structures may allow a gross comparison. The power of the methodology however lies in

CHAPTER 3

HUMAN FACTORS SIMULATION MODEL

3.1. Introduction

The mathematical human factors model described in the previous report (Krzysztofowicz, et al., 1978) was designed specifically for inclusion in the model of the flood forecast-response system. It does not involve most of the characteristics of warnings that can be affected by decisions nor most of the characteristics of the population that affect its response. It is the purpose of the present simulation model to relate a broader spectrum of warning and population characteristics to the level of response and to resulting damage reduction.

The data requirement to place such a model on a firm foundation is much greater than for the more abstract mathematical evaluation model, and verification of the components of the model would require much more detailed research. The advantages of a simulation model in relating specific system characteristics to behavior are paid for in the uncertainty that must be allowed for in its predictions--however it may still be revealing of system interrelationships even if assumed values are inaccurate.

The theoretical viewpoint taken is a combination of the views of Janis and Mann (1977) on human decisions in difficult choice situations and of Kates (1970) on human adjustment to flood hazard. Because of the central importance of sequences of revised and timely flood warnings in the present research, the simulation model has been developed in a dynamic form suitable to a sequence of inputs and decisions.

The model is in the form of a computer program along with an annotated and referenced list of model variables (Appendix D). The present chapter consists of a discussion of the basis for the model, an outline of its structure, and a detailed description of how each component works.

3.2. Theoretical Background

Starting with his dissertation in 1942, White has developed a verbal descriptive model of adjustment to natural hazard. This model has been developed by him (White, 1961) and by Kates (1970) and others. It relies heavily on Simon's (1957) concept of bounded rationality and describes a process whereby the decision maker (DM) rationally uses his own, possibly faulty, perceptions to decide upon an appropriate response to the hazard. The model describes a process of adjustment that takes place over a time spanning a number of hazard events. Kates' model is diagrammed in Figure 3-1.

Kates introduces it by saying (Kates, 1970, p. 16):

> The presence of a natural hazard encourages human action to minimize its threat and mitigate its effects. For any individual managerial unit the decision process is a complex but interesting one, and it has been a focus of hazard research for many years.
>
> A model of decision-making applicable both to the choice of resource and natural hazard adjustment has been developed. This model by White (1961) is heavily influenced by the work of Simon (1957) particularly in the notions of "bounded rationality" and "satisficing." The work also parallels the complex model of resource use developed by Firey (1960).
>
> Over the years, variants of this approach have been tested in different hazard and resource use situations. Two emphases can be found in this work: to develop a sharper, more predictive decision-making model and to incorporate individual personality characteristics into it.

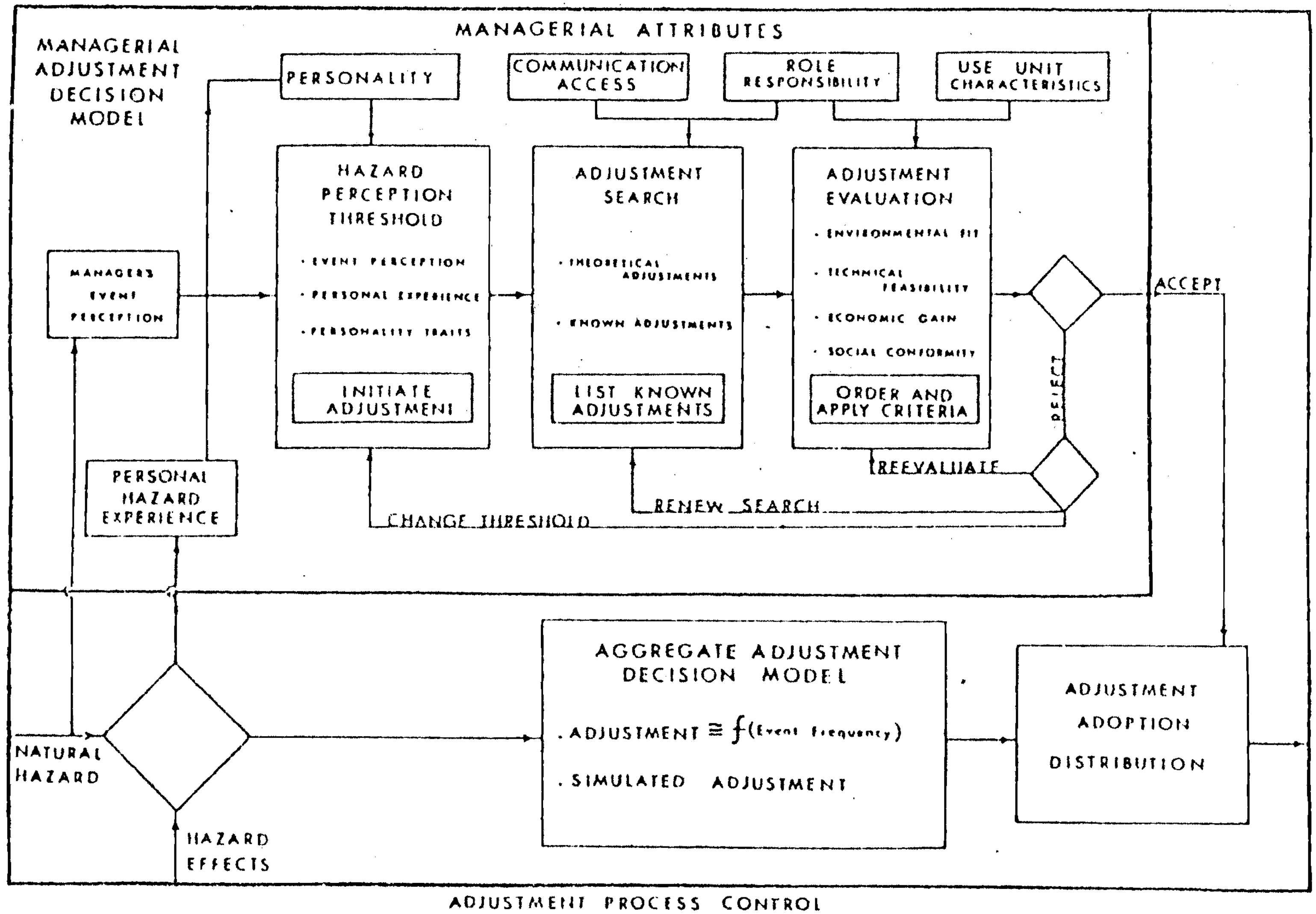


Figure 3-1. Kates' Model

The sub-model presented in Figure 3-1, then, is really the current state of our decision making theory strung together in an operative sequence.

Also over a period of many years, Janis has been developing a model of the psychological response to risk, and, in particular, to challenging situations that require decisions about whether and how to respond. The present form of this model is based on extensive data taken in a large variety of contexts, and it purports to be of quite general applicability. The model from Janis and Mann (1977) is diagrammed in Figure 3-2. It consists of three sequential parts: 1) evaluation of the risk of not responding, 2) evaluation of the risk of responding, and 3) selection of a response. If the risk of not responding is acceptable, the DM does not act but awaits developments. If the risk of not responding is unacceptable and that of responding is acceptable, the DM responds. This assumes he has a potential response. If he does not and there is time, he searches for a better response.

A somewhat more complete representation of the model (from Janis and Mann, 1977) is shown in Figure 3-3. An important aspect of the model is that it predicts psychological states that are indicative of the kinds of responses to flood hazard that have been found in field research, e.g., refusal to acknowledge a hazard or preserverence in an ineffective response.

It should be noted that neither Kates nor the Janis-Mann model explicitly allow for the decision process to be iterated in a period prior to the event, as would be the case if there were a sequence of flood warnings. A synthesis of these two models that takes account of the sequential nature of flood warnings is shown in Figure 3-4. It explicitly incorporates the

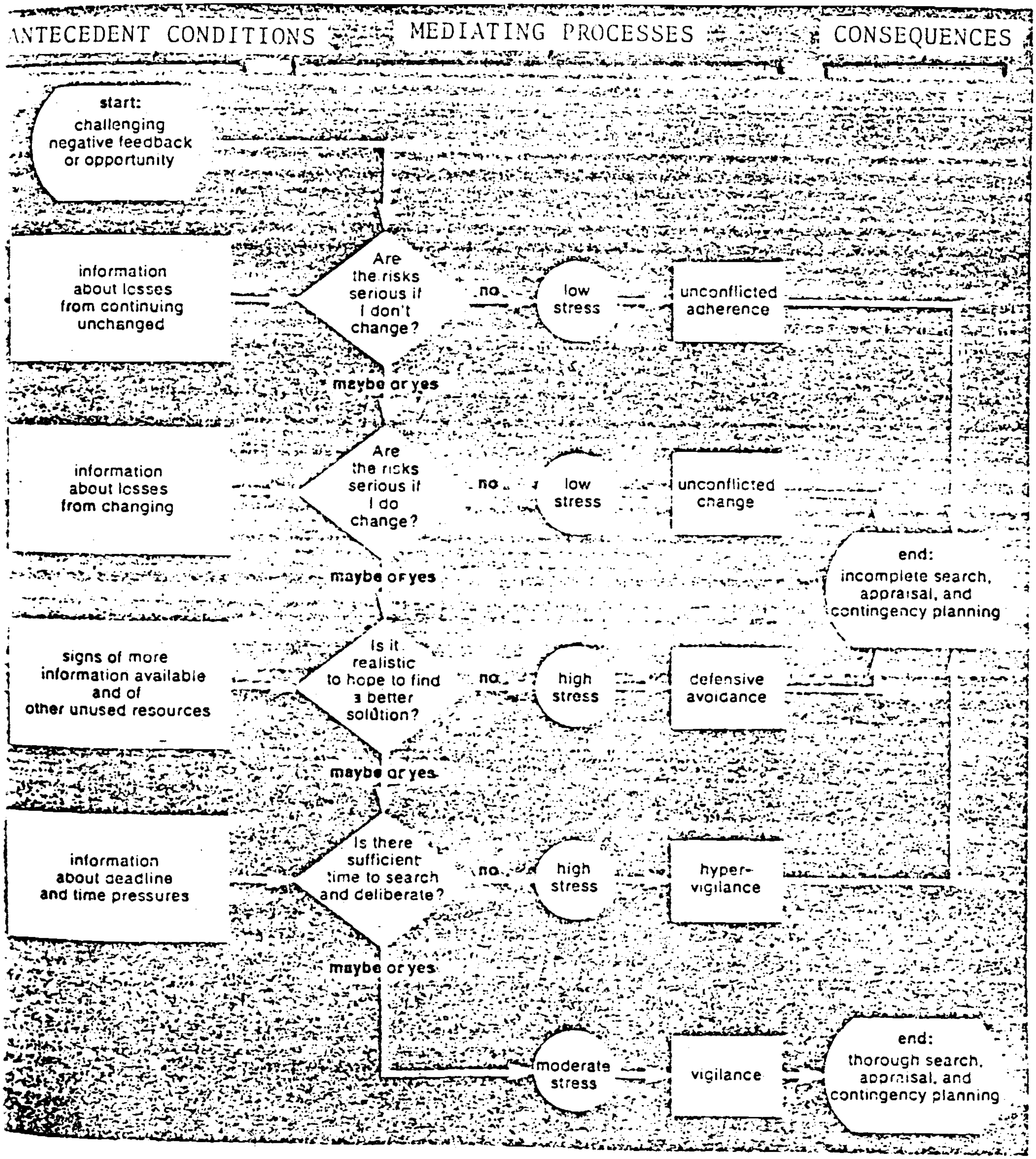
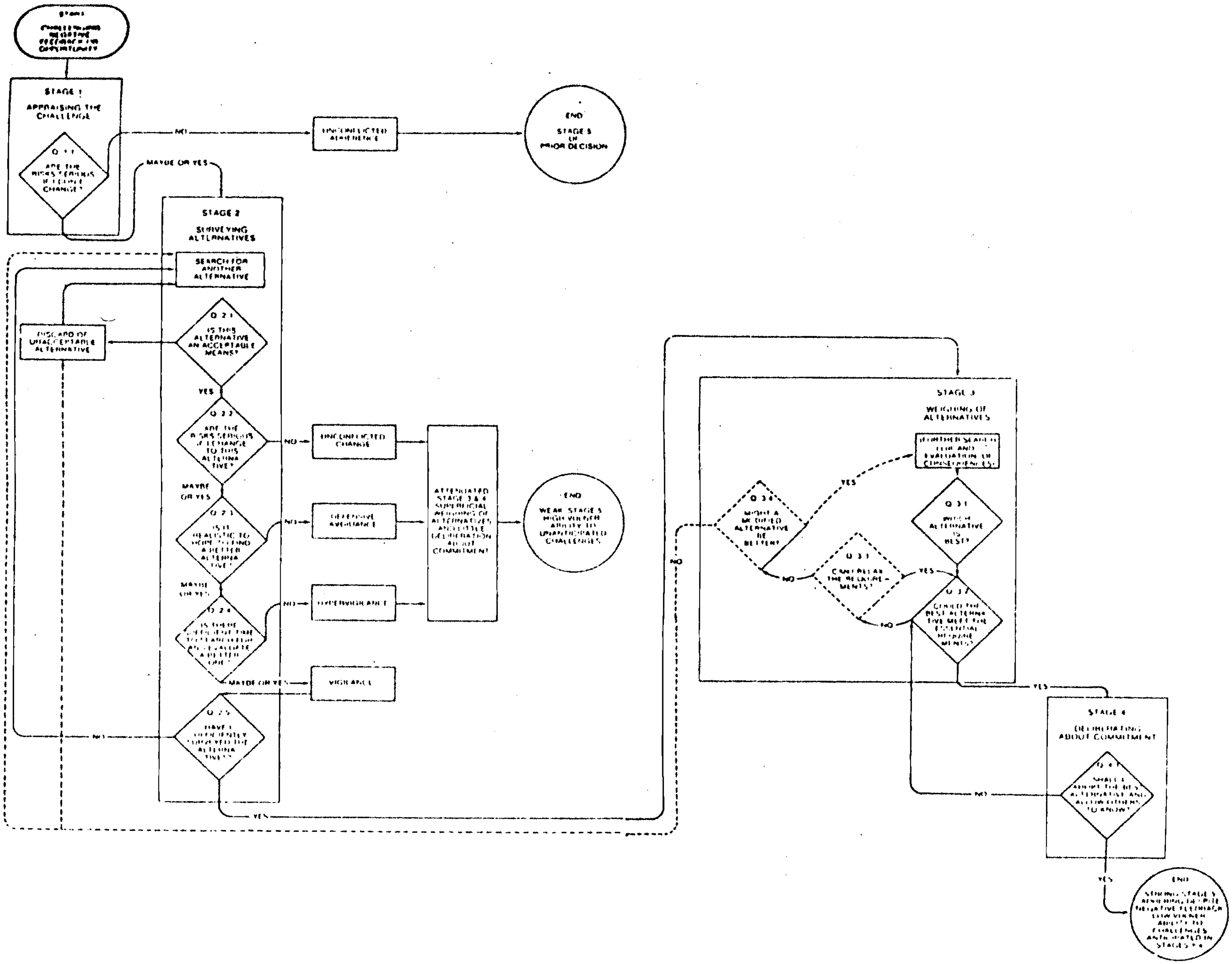


Figure 3-2. Janis and Mann's Model


STAGE 1
APPRAISING THE CHALLENGE
NO
MAYBE OR YES
END
STAGE 5
PRIOR DECISION
STAGE 2
SURVEYING ALTERNATIVES
SEARCH FOR ANOTHER ALTERNATIVE
Q 2.1
IS THIS ALTERNATIVE AN ACCEPTABLE MEANS?
YES
MAYBE OR YES
MAYBE OR YES
VIGILANCE
ATTENUATED STAGE 3 & 4
END
WEAK STAGE 5
STAGE 3
WEIGHING OF ALTERNATIVES
STAGE 4
ABOUT COMMITMENT
END

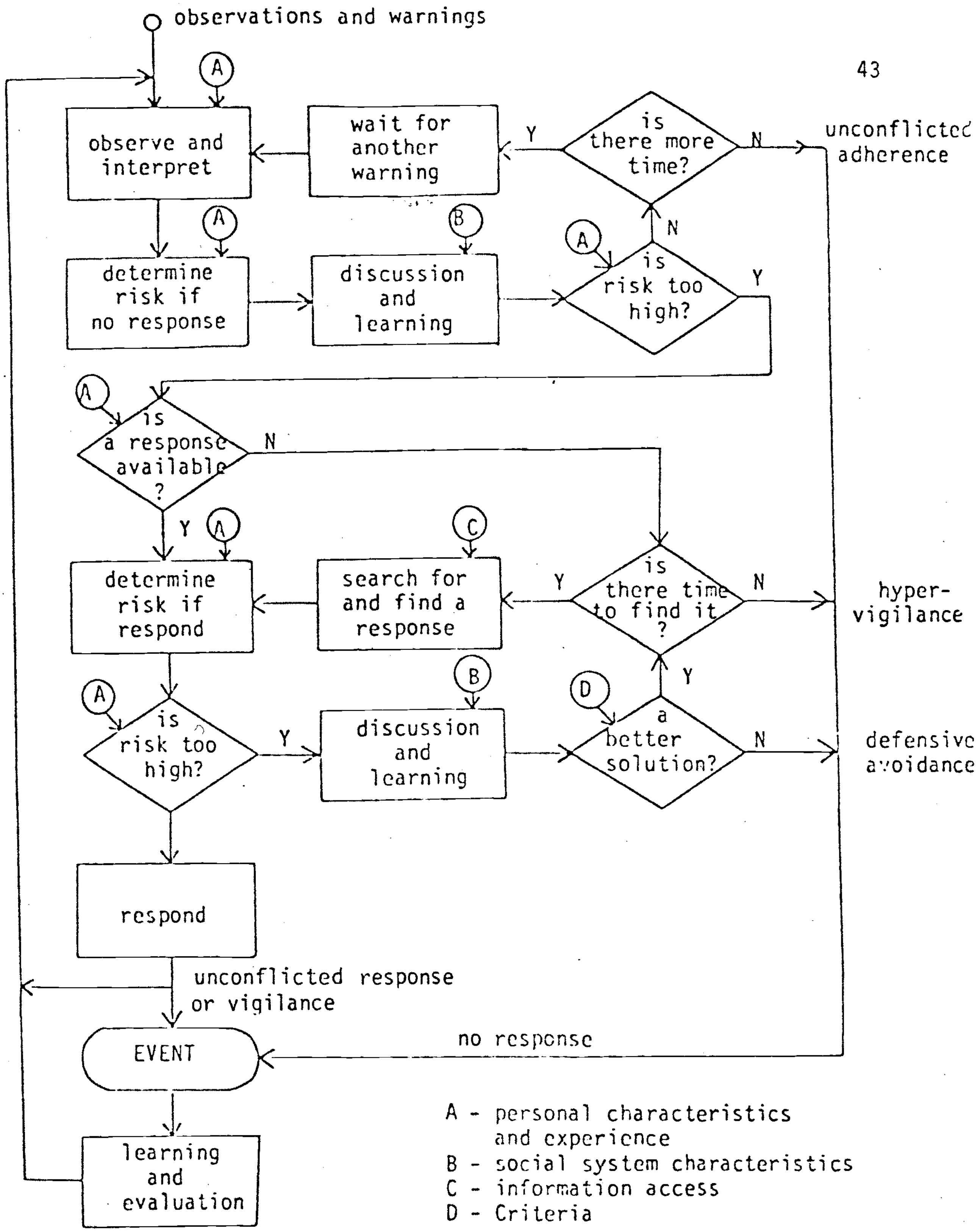


Figure 3-4. General Simulation Model

fact that the DM obtains information from his peers and either revises or confirms his opinions in discussion with them. This feature of exposure of one's opinions to the opinions of others and revision on the basis of the extent of agreement has been important in sociological simulations for some years (Gullahorn and Gullahorn, 1963), and is in agreement with field studies which show that people's perceptions of hazard warning depend on their immediate social context or reference group (McLuckie, 1973).

3.3. Simulation Model Structure

The present simulation model was developed from the general sequential decision model of Figure 3-4. A preliminary version of the simulation model was presented in the previous report (Krzysztofowicz, et al., 1978), but that version has been entirely reworked on the basis of a systematic survey of the relevant variables affecting response. The new model consists of three major sections: 1) warning reception, 2) warning interpretation, 3) response.

1. Warning Reception

Obviously the decision maker cannot begin protective measures until he is warned about the threat. The delay in communication may be a significant factor in terms of the amount of damage averted before the flood arrives at the DM's level. The previous human response model did not consider this link between the warning system and the threatened population.

2. Warning Interpretation

Reception of a flood warning by a decision maker does not directly provoke a response. Many individual characteristics have an effect on the interpretation of and belief in a given warning message. The degree to which features in the physical environment and actions of other people in the area support or discount the warning has an effect on the DM's estimate of the threat.

3. Response

Once the DM has dealt with the uncertainties concerning the threat he has another task--to choose one of a variety of responses. Each has costs associated with it as well as damage aversion promise.

The model is diagrammed in Figure 3-5 and the variables that are used are defined, and references to their nature and importance are given in Appendix D.

3.4. Operation of the Model

The model is driven by an ordered set of warning vectors that represent the sequence of warnings for a flood event. Each warning vector in the set represents the warning information broadcast through the media for the current model time interval. Each vector contains the following information:

1. Predicted crest height
2. Predicted time to flood stage
3. Predicted time until crest
4. Communication mode (personal or media)
5. Media saturation of warning messages

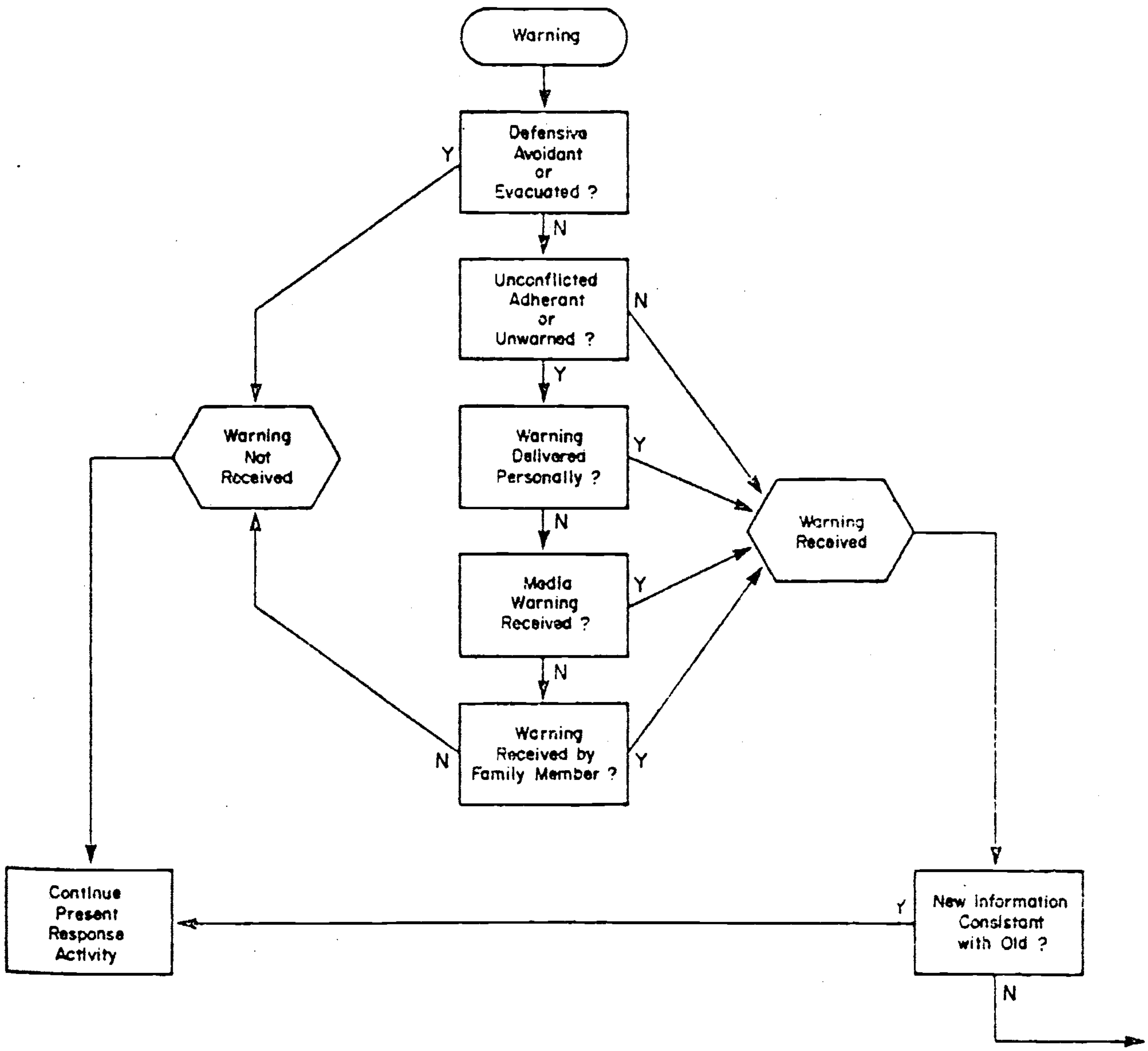


Figure 3-5. Model Diagram

a. Warning Reception

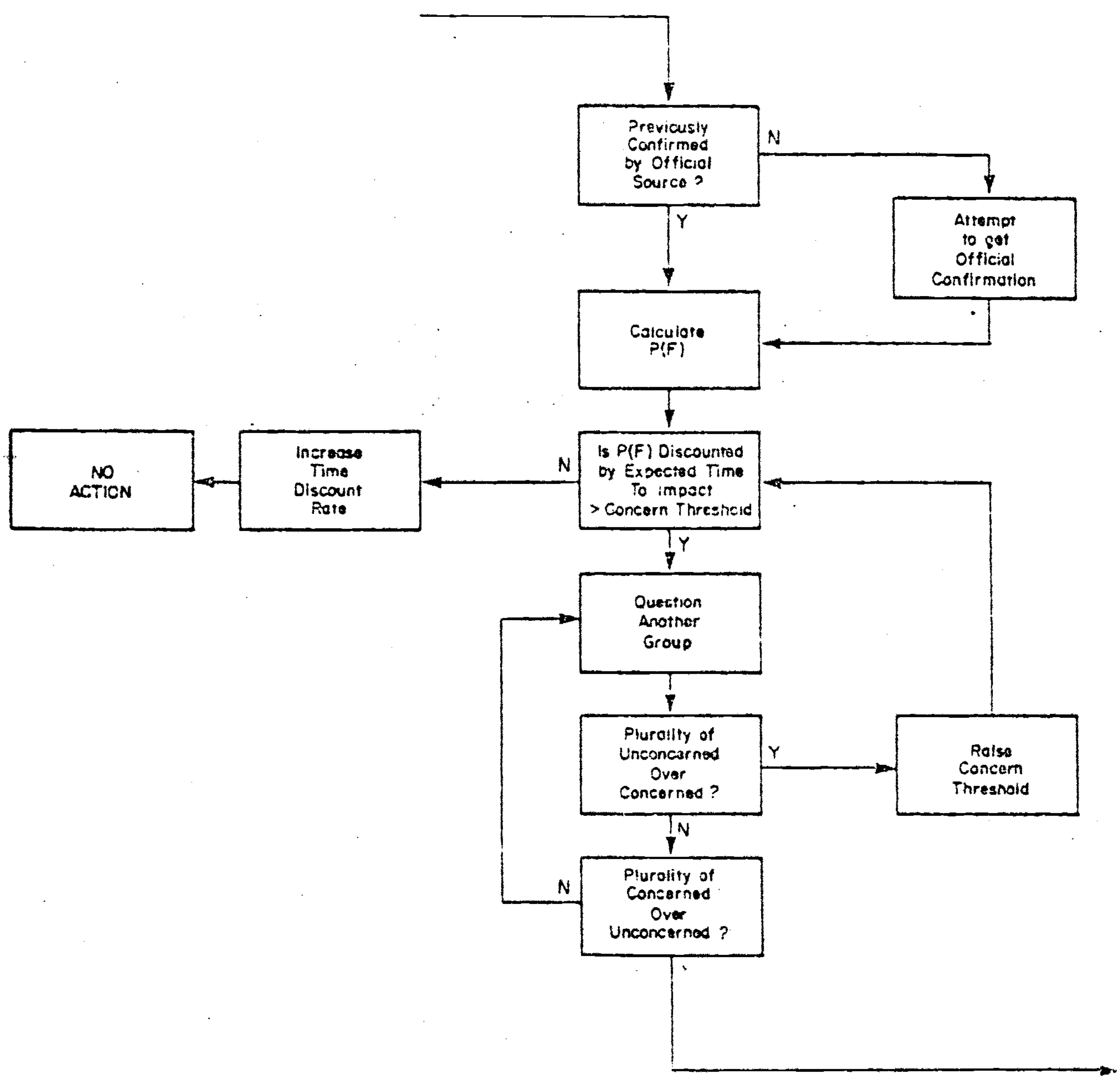


Figure 3-5. Model Structure

b. Warning Interpretation

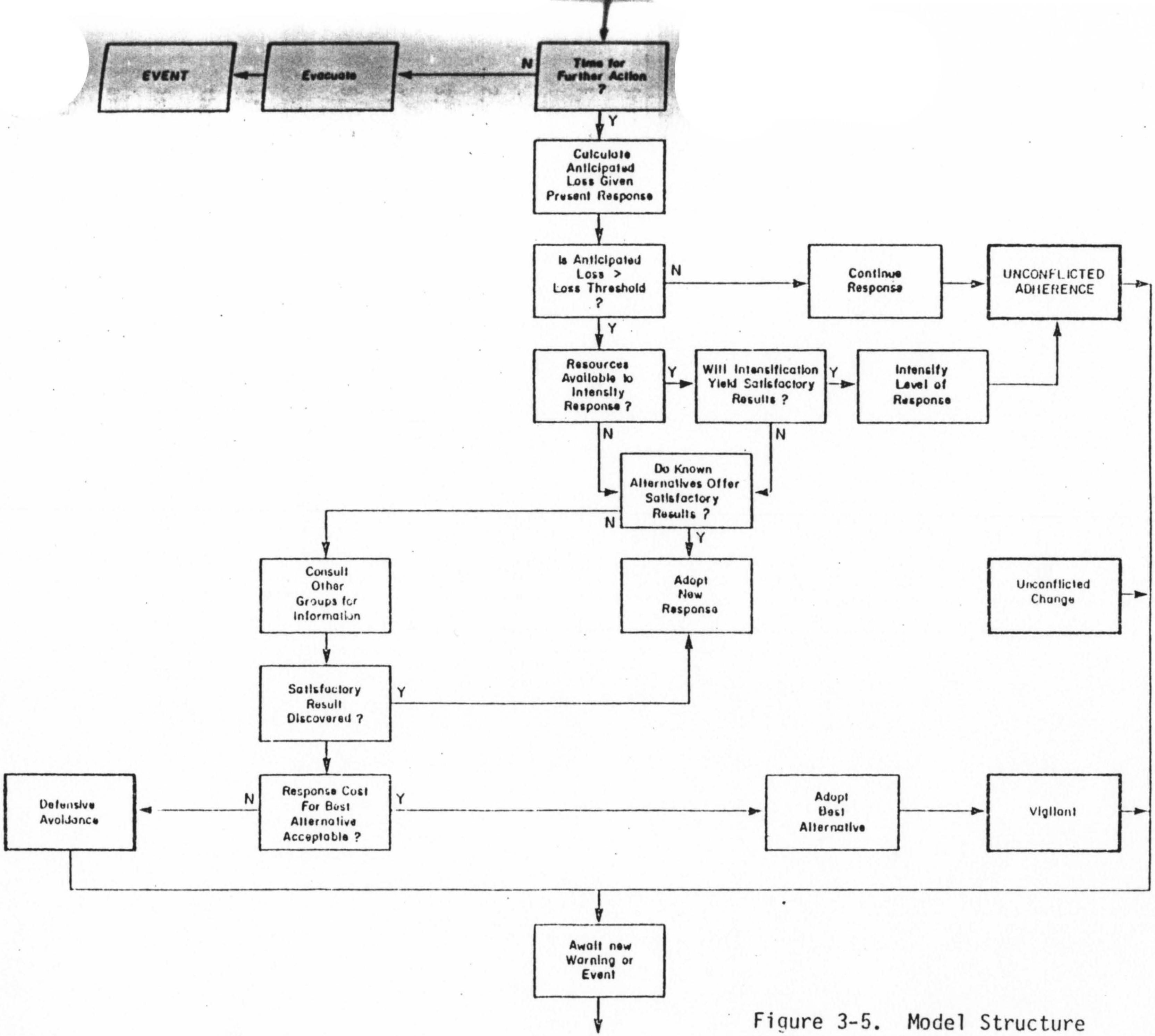


Figure 3-5. Model Structure

6. Informativeness
7. Time of day
8. Magnitude of environmental cues
9. Consistency with prior vectors

The warning reception segment considers each individual in a family. If any member of the family receives the warning it is assumed that he will communicate the message to all the other members. The reception section is the only one where each individual has autonomy. The warning interpretation and response strategy sections deal with family group characteristics, not individual characteristics.

When deciding whether or not a warning is received the following information is used:

1. The individual's state of stress as characterized by the Janis-Mann model, and his state of warning or evacuation
2. The time of day
3. The manner in which the information is communicated
4. Media saturation of warning
5. The individual's sleep pattern, inferred from the individual's work shift.

If the individual has evacuated or is in a state of defensive avoidance, then the model assumes that the message is not received. If the individual is in a state of vigilance, then message reception is automatic. There are three remaining stress states that the individual may be in: unconflicted adherance to his previous behavior, hypervigilant (i.e., panic) and unwarned. Each of the five states will be discussed in greater detail later.

If the individual is hypervigilant, then the model assumes that he will take no further rational actions that result in property savings. He is effectively classified as evacuated.

If the individual is either unwarned or in a state of unconflicted adherance, then whether or not he receives the warning depends upon the communication mode of the warning. If the warning is personally delivered by the authorities, then it is received. If the message is delivered via TV or radio, then reception is a probabilistic matter. The model for determining the number of messages that a person will receive in a given time period follows an exponential distribution with parameter related to the media saturation of the message. This model is widely used in media simulations.

When a warning is received, it is interpreted by the family group. Each family member assesses the risk and the weighted opinion of each contributes to the resultant group decision. This group decision is expressed as a single value--the estimated probability of the flood inflicting material damage on the home and possessions. There are several factors considered in arriving at this value.

One important factor influencing the assessment is whether or not the warning message has been confirmed by an official source. A message personally delivered by authorities carries inherent confirmation. A message delivered through the media or an unofficial source carries no such implicit confirmation. People tend not to believe unusual information, and many will not take measures without confirmation.

There is a section of the model devoted to confirmation to decide who will attempt confirmation and who will succeed in obtaining it. Whether confirmation is attempted or not is dependent upon the following:

1. Previous confirmation
2. Previous experience with floods
3. Proximity to the river
4. Perceived certainty in warning message
5. Communication mode (mentioned above)

If an individual has confirmed an earlier warning for the present flood event, then the model assumes that there will be no further attempts at confirmation, even if the warning message changes considerably.

Individuals who have prior experience with floods, as indicated by their prior subjective probability of being affected by a flood at their location, are more likely to seek official confirmation than those with no experience. It also assumed that those closest to the river are more prone to seek confirmation than those at a distance.

The final factor that has an effect on confirmation is the perceived certainty of the warning message. Perceived certainty is undoubtedly affected by many variables, however in the model it is an exogenous element in the warning vector. In other words, perceived certainty is assumed to be a direct function of the certainty expressed in the warning.

If a family decides to confirm, it may not be able to reach an official source. Communication channels have limited capacity, so the probability of achieving confirmation is inversely proportional to the number of people trying for confirmation.

Confirmation by an official source is but one factor comprising the group's assessment of risk. The other factors included in the model are:

1. Number of warnings received
2. Environmental cues
3. Previous flood experience
4. Warning communication mode
5. Information content of warning
6. Predicted crest height
7. Socio-economic status
8. Organizational membership
9. Urban/rural location
10. Role conflicts
11. Consistency of warnings in warning sequence
12. Confirmation/nonconfirmation by official source
13. Age of principal decision maker(s)
14. Sex
15. Proximity to flood source

There is not enough information in the literature to identify the relationships between each of these factors and the individual's belief that the flood will have a material effect on him. Because of this, the model assumes a weighted average summation of a measure of the magnitude of each factor, except for proximity. A resultant value of belief in the threat is calculated for each contributing group member and these values are again weighted according to each member's "voting power" and summed to get the overall group belief value. This group value is then multiplied by the inverse of the group's proximity to the flood source. Proximity is used rather than height on the floodplain because there is considerable evidence that most families are aware of the former, but not the latter. This means that someone near a river will feel more threatened, even though he is at a higher elevation, than someone farther from the river.

Once a group's belief strength has been calculated a test is made to determine whether or not that belief strength is higher than a threshold value. If it is not, then the group will take no action. The comparison between belief level and the threshold value is affected by the lead time before the event. An event predicted for the relatively distant future is less threatening than one predicted for the more immediate future. This phenomenon is modeled by applying a "discount" to belief, the magnitude of which is proportional to the length of the inferred interval between the predicted time of flood stage, or the present if flood stage has been reached, and when the individual thinks he will be affected. The inference is based on his proximity to the river and on the predicted time of cresting. Those closest to the source expect damage shortly after flood stage is reached. Those more distant who believe they will be affected believe that the distance from the source buys them more time. This scheme can be made to model reality more accurately by assigning a proximity value that is also affected by height--either with respect to the floodplain or local terrain. For simplicity, this is an exogenous transformation, not an internal transformation.

If the group's discounted measure of belief or concern (belief is assumed to be directly related to concern) is above a threshold, then it is still possible that the group will not take action. Few people have the confidence in their own judgment to choose a course of action that others in the same circumstances are not taking. The next section of the model allows for interaction between different groups. This is the only portion of the model where groups interact. The interaction scheme is a simple one. The group is considered a concerned group if it reaches this section of the model. The group randomly selects other groups to inquire whether or not they are concerned. One of two things must happen for the group to stop taking samples. The first possibility results in the group deciding upon a course of action to limit damage to its property. This occurs when, including itself, it finds a plurality of two for concerned groups over groups that are not concerned. For example, if the first group that is interrogated is a concerned group, then (counting the inquiring group) there are two concerned and zero unconcerned, leaving a plurality of two of concerned over unconcerned. The other alternative is a plurality of two of unconcerned over concerned. The simplest path to this state is to interrogate three consecutive unconcerned groups. Three unconcerned is a plurality of two over one concerned. If this occurs, then it is assumed that the group will feel that it gets concerned too easily. The concern threshold is raised and their time-discounted concern level is compared to the new higher concern threshold and either the threshold is not exceeded and no action is taken, or the threshold is again exceeded (indicating great concern) and the interrogation of other groups is repeated.

The interrogation step is only avoided by those groups who do not exceed the threshold and groups in a state of defensive avoidance. It is assumed that all members of a group share a common stress state.

At this point all concerned groups enter the third section of the model where a response is adopted or changed.

The model is cycled in three hour time increments. If the perceived time until impact is less than three hours, no further action is taken and the group is considered evacuated.

If there appears to be time for further action, then an estimate of anticipated loss given the present belief and response is calculated. The anticipated loss estimate is based on the following information:

1. Proximity (distance from the river)
2. Crest height (predicted)
3. Value of home
4. Percentage of potential loss that is avertable
5. Response strategy
6. Time to impact
7. Response intensity

The details of the calculation are set out in Table 3-1. Anticipated loss is basically potential damage given anticipated crest height minus the loss that is averted, given response strategy. The potential damage given a crest height is the unit damage function times the value of the home. The level of the house is estimated from its proximity. The anticipated loss that is averted given a response strategy is a function of the particular response, the response intensity, and the time it can be carried out.

TABLE 3-1

RESPONSE QUANTITIES AND RELATIONSHIPS

A person's anticipated loss is given by the following formula:

Anticipated Loss = \$ of damage caused by predicted crest height if no response made

- \$ of damage averted by response strategy

+ \$ of cost of response strategy

\$ of damage given crest height and no response =

[(Maximum damage (\$) from "infinite" flood height) x (Predicted Crest (ft) Proximity (perceived ft)) x (% of maximum loss/foot of water in home (ft^{-1}))]

\$ of cost of carrying out response strategies =

$$\sum_{\text{Responses used}} [(\text{cost/MH } (\$/\text{hr})) \times (\text{MH of work for this response (hr)})]$$

\$ of damage averted by response strategy =

1) 0 if crest height is greater than protected height*

2) Tabled values of (\$ of savings/MH) x (MH) for each response

where: $\$ \text{ of savings/MH} = \frac{\text{Damage averted}}{\text{Damage avertable}} \times \text{Damage avertable}$,

MH = Intensity (MH/hr) x Time spent responding (hr),

for response strategies with finite protection height, the protection height for a given response is from tabled values of (feet of protection/MH) x (MH).

Response intensity is measured as the number of standard man-hours of work that the group expends per clock hour on its response. Intensity is limited by the group size, its age and sex composition, and it is determined by the group's expectations of loss; it will work hard enough, if it can achieve a satisfactory reduction of anticipated loss, but not harder unless its anticipation of loss changes. Potential damage is assumed to be a linear function of water level with respect to the dwelling (crest height-proximity) times value of the dwelling. The amount expected to be averted is the amount already averted plus a table function for each type of response that gives percentage of percentage of avertable loss averted given man-hours of work. Man-hours of work is calculated as man-hours/hr (response intensity) times time to impact (hrs).

This resultant anticipated loss is compared with a loss threshold. If the anticipated loss is less than the threshold, the present response strategy is kept for this time period and the stress state is set to unconflicted adherence. If the anticipated loss is greater than the threshold value, then the family group will estimate whether it is possible to increase the intensity of the response (increase the value of MH/hr). Each individual in the group has a potential maximum fraction of the standard man-hour of work that he or she is capable of delivering in an hour. This value is a function of sex and age. If it is possible to pull the anticipated loss below the threshold by increasing the number of man-hours/hour expended by the group without exceeding that group's limit, then the group will simply intensify its response to the necessary level.

If intensification of the response will not yield satisfactory results, the group will search for a different type of response. If a known alternative response offers a satisfactory anticipated loss without violating the group's Man-hour/hour constraint, then that new response will be adopted.

If no known alternatives offer a satisfactory expected loss, then other groups are consulted for ideas.

The simulation of this process does not actually involve the other groups in the simulated population. A random number is generated to determine whether or not the group finds a better response. If the group finds a better response and it is satisfactory, then the response is adopted.

If there is still no satisfactory response at this point, then the cost of responding for the best response is considered. That response cost is explained below. If that cost is less than a threshold for the best (though unsatisfactory) solution, then that solution is adopted. If not, the other productive alternatives are considered. If one with an acceptable cost is found (acceptable cost being a response cost less than the expected savings realized by that response) it is adopted. If no such response is found, the group becomes defensive-avoidant and will not respond until impact, i.e., can be considered as having evacuated.

If a response if found that shows hope for a net savings, it will be adopted. The group will be moved to a vigilant state which leaves it open for change if a still better solution can be found.

The response array is set up in the following manner. A vector of different response strategies comprises one dimension of the array. The elements of the vector are:

1. No response or evacuation
2. Movement of items to higher elevation on ground story
3. Movement of items to higher story (not allowed in single story dwelling)
4. Movement of items to another location
5. Sandbagging
6. Movement of residence to another location (allowed only for mobile home)
7. Speical alternative one
8. Special alternative two

The second dimension of the array is a scale of Man-hours of labor. The table gives three pieces of information as a function of Man-hours and response type. These are percentage of maximum avertable damage averted, cost in dollars of responding and protected height. Averted damage is equal to 0 if protected height is less than crest height, since for certain strategies (sandbagging, moving things to a higher level in home) a flood that exceeds the protected height (height of sandbags or height to which valuables are moved) will cause approximately the same damage as if no protective measures were taken. For response strategies that are safe for arbitrarily high floods (evacuating goods to higher ground) the protected height is set to infinity. Flood height is no longer a factor in averted damage, though it is a factor still in \$ of damage given crest height. The cost of response is the final factor in the calculation of expected loss given present strategy. If a more comprehensive response is adopted after some damage has been averted, the damage already averted is logged and the new strategy does not result in additional savings until it exceeds the logged level. The costs, however, are cumulative.

For example, a mobile home owner who moves items off the floodplain for two hours and then sandbags for ten hours and then decides to have his entire unit moved to higher ground really accomplishes nothing in terms of savings by having moved and sandbagged. The cost of response for all three strategies is cumulative, however.

It is necessary to specify the characteristics of a particular strategy for the following reasons:

1. Cost of response is a definite limiting factor--the expense of moving a mobile home is high enough that it should not be undertaken if cheaper methods can accomplish the same savings;
2. Man-hours is similarly important for obvious reasons. Different families can be expected to chose different strategies under identical circumstances because of differing limits of response intensity on each. A family comprised of an elderly couple can manage fewer Man-hours/hour than can a middle-aged couple with four teen-aged sons!

3.5. Simulation Program

As of this writing, the program for the simulation model is not yet running in a satisfactory manner and needs further debugging. Work will continue at least until the program is in operating condition and until it can be evaluated. At that time a brief addendum to this report will be made and copies of the program and instructions for its use may be obtained from the authors of this report.

3.6. Validation and Parameter Estimation

The simulation model developed above has a substantial amount of "face validity", i.e., it is plausible in structure and it coincides in many respects with current psychological theory. However, it by no means reflects all the factors that are known to be relevant to decisions such as ones that a floodplain dweller would make. The problem with validation of such models is "model uncertainty," the fact that relatively small changes in the structure of the many component parts of the model may have as much effect on the response as changes in parameters. In effect, the model has a very large number of parameters with large ranges of possible values. Alternatively, one could characterize such models as predicting a large number of intervening variables in addition to the amount of protective response. Each of the components of the model is a model, in its own right, of a component activity. On this view, the simulation consists, in effect, of a large number of models all of which need to be validated and need to have parameters estimated for them. Either way, the problem of relating the model to actual data is formidable if one requires that the model accurately reflect the processes that take place prior to the floodplain dweller's actions and also predict the amount of protective activity. However, the purpose of the simulation model is seen more as providing a means for exploring the possible effects of particular variables and for improving understanding than as a predictive device for obtaining the "actual strategy" to be used in the FFR system evaluation.

CHAPTER 4

REGIONAL AND NATIONAL MODELS

4.1 Introduction

An improvement in the forecasting system would affect many structures in many communities. To do a cost-benefit analysis for a change in the forecasting system, the benefit to all structures affected by that change has to be ascertained. The systems model and the computing methodology presented in this report give the value of the FFR system for a single structure and, by an extension of the computing methodology, give the evaluation of relatively homogeneous river reaches.

In this chapter an approach to regional and national evaluation of FFR system is developed. Basically it is a regional model that is needed as the national evaluation is the sum of regional evaluations. A regional FFR system evaluation could be obtained by evaluating each river reach within the region by the methodology given previously. For most communities, some of the information needed for the evaluation calculations is not available. Most often the community's structural inventory is not available. Flood verification reports of sufficient length to develop a law of motion for forecast and actual river stages may not be available. On the other hand, some of the required information is easily available. The response strategy can be simulated by the use of the pure strategy or the human factors strategy. For calculating flood cost and losses, the unit function concept enables an easy transfer of this information to regional evaluation. However, even if all the required information were available, an evaluation of a regional FFR system, based on a reach evaluation of every forecast point in the region, would require prohibitively large amounts of effort to abstract from the data, the information needed for input to the computer programs. In addition large amounts of computing time would be consumed.

The objective of the regional analysis research was to develop a regional evaluation methodology which would not have large personel or computing requirements.

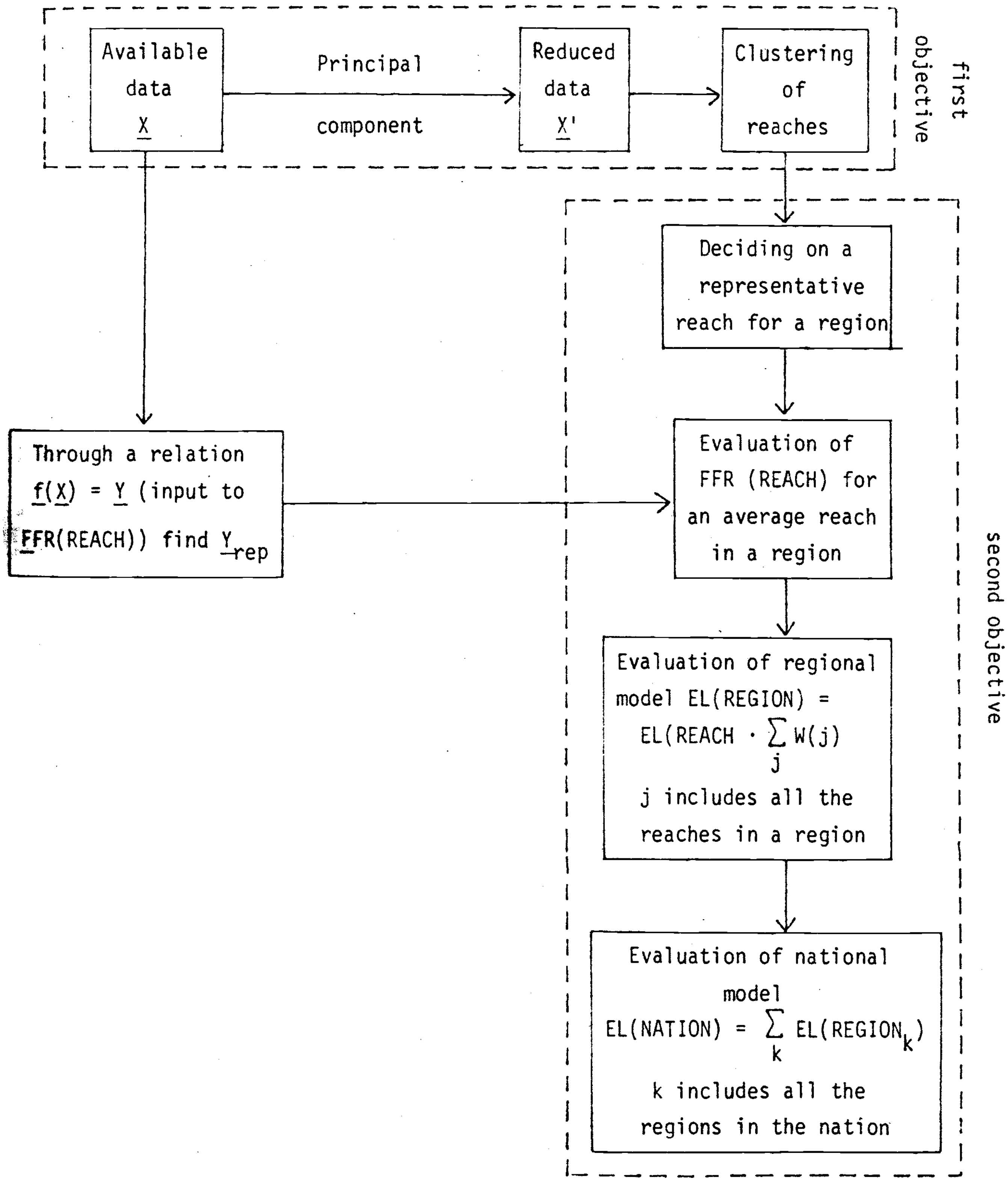
4.2 Regional Model

There are two main facets in the approach to a regional model: 1) obtaining regions consisting of river reaches which are roughly similar with respect to the input parameters of the reach model, and 2) obtaining estimates of the input parameters needed for the reach evaluation calculation from available data. If a region of similar reaches, contiguous or non-contiguous, can be obtained along with estimates of input parameters, then an evaluation of the region can be obtained from the reach model.

The conceptual model used is shown in Figure 4-1 (Hosne-Sanaye, 1978). Analysis is based on data available describing many river reaches. This data is used to cluster the reaches into one or more regions with similar characteristics. The clustering may be intuitive or mathematical. By using hydrologic and geographic transformations, estimates of the information needed as inputs for the evaluation of a reach are obtained. A representative reach in the region is then evaluated. The regional evaluation is obtained by multiplying the evaluation of the representative reach by a scaling factor. The scaling factor is the sum of weighting ratios for each

FIGURE 4-1

A SCHEMATIC DIAGRAM FOR REGIONAL ANALYSIS



reach. These ratios are an estimate of each reach's contribution to the evaluation in comparison with the representative reach's contribution.

Perhaps the easiest way to cluster reaches into similar regions is by intuitive grouping. Geographically adjacent reaches are clustered. If the clustering is based on moderately sized river basins, the reaches in the region may have similar hydrologic and geographic characteristics. Dissimilar charactersitics of the reaches may have to be transformed to maintain the similarity between reaches. The effect of the required transformations would be compensated for in the weighting ratio of the reach. Intuitive clustering is exemplified by the use of WRC regions and aggregated subareas (ASA) by the U.S. Water Resources Council (1976) for estimating annual flood damages in the United States.

Although the intuitive method fo clustering is straightforward it has disadvantages. Truly homogeneous regions will be small. There may be redundancy; non adjacent, but similar regions, will not be grouped together for analysis. The necessary transformations and concomitant weighting ratio adjustments for obtaining larger "homogeneous" regions may not be obvious and can require much time and effort before suitable ones are found.

A statistical clustering approach can be used to construct regions having similar characteristics. The river reaches comprising these regions need not be geographically adjacent.

4.3. Clustering

A cluster analysis technique divides a finite set of elements into smaller subsets according to some specified criterion (Anderberg, 1973). For clustering technique, the following conditions should be satisfied:

1. The number of subsets is less than the number of elements in the original set.
2. Individuals assigned to the same cluster are similar, yet individuals from different clusters are different (not similar).
3. The terms similarity and difference should be defined in a quantitative manner. Usually a distance function is used for this problem (e.g., Euclidean norm).
4. A solution of the cluster problem is usually to determine a partitioning that satisfies some optimality criterion (optimization of an objective function).

For application of a cluster analysis technique to a problem, the cluster variables, similarity measures and a clustering criterion should be specified.

Three types of information are required for an evaluation of a reach: hydrologic, economic and response strategy. Use of the unit function concept for economic damages and use of the pure or human response strategy gives similarity for these informational needs across all reaches. But reaches will vary in hydrologic characteristics and in flood loss characteristics. The USGS National Water Data Exchange (NAWDEX) can provide detailed hydrologic data for a great many U.S. communities. However, data on flood loss characteristics of communities is not easily obtained nor is it centrally located.

Generalized data on the location of various types of structures located on floodplains throughout the United States has been developed by Friedman and Bocaccino (1972), Friedman and Roy (1966) and most recently by Wiggins (1976). Acceptance of this generalized data eases the regionalization information requirements with respect to flood loss characteristics. However, this data is not purported to represent specific river reaches; comparison with Columbus, Mississippi, showed wide variations in the distribution of residential structures. If the statistically clustered reaches form large enough regions, perhaps the variations will "average out."

Cluster analyses were run on the river reaches of the 19 U.S. communities listed in Table 4-1. Twenty seven variables were used to describe the hydrology of the reach, Table 4-2. First, all variables were transformed to mean zero and variance one. Then a two stage clustering technique was used; preliminary clusters were formed by the "Quick" method and then adjusted by the "K-means" method (Anderberg, 1973). The clusters obtained are not unique and are dependent on many parameters such as thresholds for acceptance into a cluster and the variables used to characterize the reaches. Clusters were obtained based on four sets of variables: 1) all 27, Table 4-3a, 2) all 27 except longitude and latitude, Table 4-3b, 3) a subset consisting of drainage area, channel slope, main channel length, latitude and longitude of drainage basin centroid, mean annual precipitation and flood stage, Table 4-4 and 4) seven linear combinations explaining the most variance in the variables as determined by principle components analysis, Table 4-5. The clustering is shown in Tables 4-3a, b; 4-4 and 4-5. Some of the larger clusters are mostly from one geographic area, others are spread geographically.

TABLE 4-1

LIST OF THE CITIES WHOSE DATA WERE USED IN THE CASE STUDY

City	State	River
Augusta	Georgia	Savannah
Macon	Georgia	Okmulgee
Rome	Georiga	Alabama
Freeport	Illinois	Mississippi
Iowa City	Iowa	Iowa
Iola	Kansas	Arkansas
Amory	Mississippi	Tombigbee
Columbus	Mississippi	Tombigbee
Fulton	Mississippe	Tombigbee
Chillicothe	Ohio	Ohio
Albany	Oregon	Williamette
Salem	Oregon	Williamette
Harrisburg	Pennsylvania	Susquehanna
Lewisburg	Pennsylvania	West branch Susquehanna
Renova	Pennsylvania	Susquehanna
Sunbury	Pennsylvania	Susquehanna
Williamsport	Pennsylvania	West branch Susquehanna
Columbia	Tennessee	Duck
Victoria	Texas	Guadalupe

TABLE 4-2

LIST OF VARIABLES USED IN THE CASE STUDY

Variable	Description
CONTDA	Contributing drainage area.
FLD STGE	Flood stage in feet.
I24,2	2-year recurrence interval 24-hour precipitation in inches.
LAT GAGE	Latitude of centroid of basin in degrees.
LENGTH	Main channel length to drainage divide in miles.
LNG GAGE	Longitude of centroid of basin in degrees.
M7,2	2-year recurrence interval 7-day minimum flow in cfs.
M7,10	10-year recurrence interval 7-day minimum flow in cfs.
M7,20	20-year recurrence interval 7-day minimum flow in cfs.
P1,25	
P2	2-year recurrence interval peak flood in cfs.
P5	5-year recurrence interval peak flood in cfs.
P10	10-year recurrence interval peak flood in cfs.
P25	25-year recurrence interval peak flood in cfs.
P100	100-year recurrence interval peak flood in cfs.
PRECIP	Mean annual precipitation in inches.
Q1-Q9 Q10-Q12	Qi = mean monthly discharge in cfs. for ith month of year.
SD1-SD9	SDi = standard deviation of monthly discharge in cfs. for ith month of year.
SDA	Standard deviation of mean annual discharge in cfs.
SKEWPK	
SLOPE	Main channel slope between 85% and 10% length points in feet per mile.
V7,2	2-year recurrence interval 7-day discharge in cfs.
V7,10	10-year recurrence interval 7-day discharge in cfs.
V7,50	50-year recurrence interval 7-day discharge in cfs.
WRC SKEW	

TABLE 4-3a

CLUSTER REGIONS USING ALL VARIABLES

Cluster number	Member city	State	River
I.	Albany	Oregon	Williamette
II.	Rome Macon Amory Columbus Columbia	Georgia Georgia Mississippi Mississippi Tennessee	Okmulgee Okmulgee Tombigbee Tombigbee Duck
III.	Salem	Oregon	Williamette
IV.	Freeport Iowa City Iola Chillicothe Victoria	Illinois Iowa Kansas Ohio Texas	Mississippi Iowa Arkansas Ohio Guadalupe
V.	Augusta	Georgia	Savannah
VI.	Lewisburg Renova Williamsport	Pennsylvania Pennsylvania Pennsylvania	West branch Susquehanna Susquehanna West branch Susquehanna
VII.	Sunbury	Pennsylvania	Susquehanna
VIII.	Harrisburg	Pennsylvania	Susquehanna

TABLE 4-3b

CLUSTER REGIONS USING ALL VARIABLES EXCEPT LONGITUDE AND LATITUDE

Cluster number	Member city	State	River
I.	Albany	Oregon	Williamette
II.	Amory Fulton Columbus Macon Rome Freeport Iowa City Iola Chillicothe Victoria	Mississippi Mississippi Mississippi Georgia Georgia Illinois Iowa Kansas Illinois Texas	Tombigbee Tombigbee Tombigbee Okmulgee Okmalgee Mississippi Iowa Arkansas Ohio Guadalupe
III.	Salem	Oregon	Williamette
IV.	Renova Williamsport Lewisburg	Pennsylvania Pennsylvania Pennsylvania	West branch Susquehanna Susquehanna West branch Susquehanna
V.	Augusta	Georgia	Savannah
VI.	Sunbury	Pennsylvania	Susquehanna
VII.	Harrisburg	Pennsylvania	Susquehanna

TABLE 4-4

CLUSTERING REGIONS USING REDUCED SET OF VARIABLES

Cluster number	Member city	River
I.	Amory Fulton	Tombigbee Tombigbee
II.	Harrisburg Sunbury	Susquehanna Susquehanna
III.	Augusta Lewisburg Williamsport	Savannah West branch Susquehanna West branch Susquehanna
IV.	Columbia Columbus Macon Rome	Duck Tombigbee Okmulgee Okmulgee
V.	Salem	Williamette
VI.	Albany	Williamette
VII.	Victoria	Guadalupe
VIII.	Chillicothe Freeport Iola Iowa City Renova	Ohio Mississippi Arkansas Iowa Susquehanna

TABLE 4-5

CLUSTERED REGIONS WHEN PRINCIPAL COMPONENTS DETERMINED VARIABLES

Cluster number	Member city	State	River
I.	Renova	Pennsylvania	Susquehanna
II.	Harrisburg Sunbury	Pennsylvania Pennsylvania	Susquehanna Susquehanna
III.	Williamsport	Pennsylvania	West branch Susquehanna
IV.	Augusta	Georgia	Savannah
V.	Macon Freeport Amory Chillicothe	Georgia Illinois Mississippi Ohio	Okumgee Mississippi Tombigbee Ohio
VI.	Salem	Oregon	Williamette
VII.	Albany	Oregon	Williamette
VIII.	Victoria	Texas	Guadalupe
IX.	Iowa City Iola Lewisburg	Iowa Kansas Pennsylvania	Iowa Arkansas West branch Susquehanna
X.	Rome Columbus Fulton Columbia	Georgia Mississippi Mississippi Tennessee	Alabama Tombigbee Tombigbee Duck

The community closest to the cluster center is taken as the representative reach for the region. This reach is evaluated by use of the reach model. This value is denoted FFR (REACH). The regional evaluation may be obtained once the weighting ratios are known:

$$FFR(REGION) = FFR(REACH)\sum W_i.$$

The weighting ratios, W_i, should reflect the non-similar loss characteristics of the reaches, specifically the magnitude of the flood loss. Lacking flood damage information, Tables 2-8 and 2-13 of the Wiggins (1976) report provide estimates of residential commercial and industrial structures exposed to floods of different recurrence intervals, for cities of different populations. These may be used to estimate weighting ratios.

For example, cluster X in Table 4-5 consists of Rome, Georgia; Columbus, Mississippi; Fulton, Mississippi and Columbia, Tennessee. An evaluation for this region may be made based on the evaluation of Columbus.

Weighting ratios were calculated, Table 4-6, based on the expected number of residences flooded annually as calculated from data in Wiggins (Table 2-8, 1976). The scaling factor as determined from the sum of the ratios is 2.12. Since the actual value of the FFR system for residential Columbus is $26,250, (see Table 2-4), the actual value of the FFR system for the residences in the region consisting of Rome, Columbus, Fulton and Columbia is that amount multiplied by 2.12: $55,650.

Further refinement of this regional methodology, such as interpolating between the categories in the Wiggins data, etc., is needed. However, validation of this method of regional analysis is necessary before it could be used on a broad scale. It has not been shown that clustering

	Population Catagory		Location in Flood Plain Catagory and Probability of Flooding A .35	B .15	C .07	D .03	E .015	F .01	Expected Number Flooded Annually	Weight-ing ratio
Columbus	51,000	B	230	255	340	417	459	1701	179	1.00
Rome	31,000	C	140	161	214	262	289	1070	112	.63
Columbia	21,000	D	82	91	122	149	164	608	64	.36
Fulton	3,000	F	31	35	47	57	63	233	24	.13
										2.12

TABLE 4-6

Weighting Ratios for the Region Consisting of Columbus, Rome, Columbia and Fulton, Based on Number of Residential Structures in the Flood Plain. Data from Wiggins (Table 2-8, 1976).

based on hydrologic variables, that are commonly available, will provide regions that consist of reaches having similarity in the parameters directly relevant to the value of the reach's FFR system. Nor has it been shown that the scaling factor and weighting ratios can be satisfactorily obtained from generalized data.

In the clustering method of regionalization the evaluation of one community is extrapolated to a regional evaluation. Both the flood loss characteristics, and the flood hydrology as expressed by the law of motion, are extrapolated. This method requires a structural inventory for the community which is in the center of the cluster, which may not be available. It would seem desirable to develop a regionalization methodology which would not rely so heavily on the flood loss inventory for a single community, but would use available information on the flood losses of the whole region.

4.4 Regionalization by ASA

In its nationwide flood damage report for the "Second National Water Assessment" the U.S. Water Resources Council (1976) divides the country into regions and aggregated subareas (ASA) for the purposes of estimating flood damages. The ASA are large, but small enough to be considered regions having some similar characteristics. In Appendix B of the Second National Water Assessment, estimated flood damages for the U.S. are given by WRC region, of which there are 21, and by ASA, of which there are 106. Flood damage estimates are given for 1975 and estimated in constant dollars for 1985 and 2000. For each ASA flood damages are given for upstream locations (drainage area less than 400 square miles) and downsteam locations (drainage area greater than 400 square miles). Flood damages are further classified as urban, non-urban (agriculture) and non-urban (other).

In this section a regional evaluation method is developed for evaluating the FFR system of an ASA whose objective is the reduction of urban economic damage to structures. It is assumed the downstream urban flood damage estimated by the WRC for the ASA is equivalent to the expected annual losses with no response (LNR) in the terminology of this report. The potential value, optimal value and actual value of the FFR system for the region is determined by extrapolation from the results of the analysis obtained for the representative reach in the region. This extrapolation is based on the assumption that the forecast efficiency, response efficiency, overall efficiency and the ratio of the potential value of the expected annual loss with no response, is constant for all reaches throughout the region.

Let W be the ratio of the potential value to the loss with no response, for a known reach in the region:

$$W = \frac{PV(REACH)}{LNR(REACH)}$$

Then: $PV(REGION) = W \cdot LNR(REGION)$. Having the potential value of the FFR system for the regin enables the calculation of the optimal value, OV, and actual value, AV, of the FFR system for the region, as the known values of the forecast efficiency, EF, the overall efficiency, EO, of the reach are assumed to hold for the region. The values are calculated as follows:

$$OV(REGION) = EF \cdot PV(REGION)$$
$$= EF \cdot W \cdot LNR(REGION),$$

$$AV(REGION) = EA \cdot PV(REGION)$$
$$= EO \cdot W \cdot LNR(REGION).$$

The information required for regionalization by ASA is the WRC estimate of the annual flood loss in the ASA and a valuation of the FFR system for a representative reach in the ASA. The analysis of Milton, Pennsylvania and of Columbus, Mississippi is used to provied a valuation of the two ASA's in which they are located.

Milton is located in ASA 204, which includes many tributaries of the Susquehana in eastern Pennsylvania and southwestern New York. The regional evaluation of ASA 204 is shown in Table 4-7. The evaluation for the Community of Milton is shown in Chapter, Table 2-2.

Is ASA 204 a homogenous region? In the example of cluster analysis five cities in the Susquehana River basin were included. The upstream communities of Lewisburg, Renova and Williamsport are in one cluster in Table 4-3, while the downstream cities of Sunburg and Harrisburg are in other clusters. If this difference in classification implies different characteristics in the law of motion between the upstream and downstream cities, ASA 204 would have to be subdivided for regional analysis. Day's (1970) work, discussed in Chapter 5, shows the upstream and downstream cities have different characteristics.

Columbus is located in ASA 308, which consists mainly of the Tombigbee River Basin. The regional evaluation is shown in Table 4-8. It is based on the evaluation of the residential structures in Columbus, Chapter 2, Milton

Annual loss, no response	$1,541,249
Potential Value	666,561
W = PV/LNR	0.432
Forecast efficiency	0.200
Overall efficiency	0.069

ASA 204 downstream urban losses

Regional valuation	$3,244,000
potential value	1,401,408
optimal value	280,281
actual value	96,700

TABLE 4-7

Regional Evaluation of ASA 204 Based on Evaluation of Milton Using Human Factors Response Strategy.

Columbus (residential only)

Annual loss, no response	$531,560
Potential Value	148,720
W = PV/LNR	0.28
Forecast efficiency	0.61
Overall efficiency	0.18

ASA 308 downstream urban losses

Regional valuation	$657,000
potential value	184,000
optimal value	112,000
actual value	33,120

TABLE 4-8

Regional Evaluation of ASA 308 Based on Evaluation of Columbus Using Pure Response Strategy.

Table 2-4. The extrapolation to the region is for all structures in the region. Basing the regional extrapolation on a potential value ratio obtained by evaluating residential structures only, produces lower values as the ratio of potential value to loss with no response is lowest for residential structures.

One basic assumption in ASA regional analysis is that the reported urban downstream damage represents damage that could be reduced by utilization of presently available forecasts. If the assumption does not hold, the regional valuations will be inflated.

The second basic assumption is that the potential value ratio and the efficiencies in the urban river reaches are constant throughout the region, or that they in some sense "average out." Without doing complete evaluations on many river reaches in the region this assumption is difficult to check. Figure 4-2 shows the actual efficiency of the FFR system for a residence as a function of the structure's height above flood stage for three communities along the Tombigbee River: Columbus, Gainsville and Demopolis. Columbus and Demopolis may be considered similar in a broad sense. Gainsville does not fit but should not cause much error in the regional analysis as it is quite a small town.

There are no structural inventories available for Gainsville and Demopolis. Forecast verification reports were available. These reports contained the information required for construction of the law of motion for these communities. If desired, an evaluation of the river reach for these communities could be approximated by using the generalized distribution of structures contained in the Wiggins report (1976).

Regional analysis is not limited to ASA's; any region having similar flood hydrology and flood loss characteristics may be evaluated. The

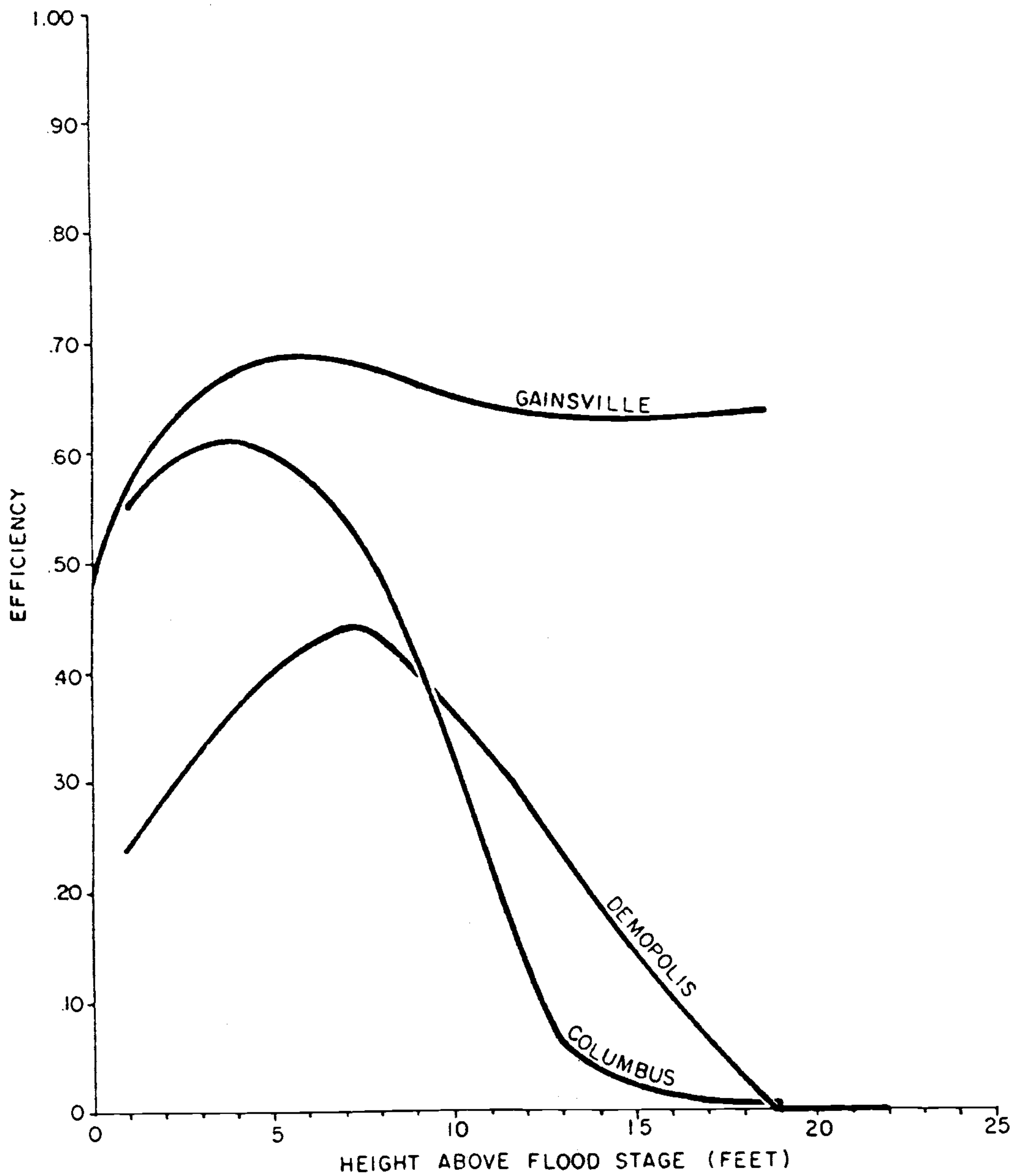


Figure 4-2

Overall Efficiency vs Height Above Flood Stage for Gainsville, Demopolis and Columbus Residences, Pure Response expected annual flood losses for the region must be known. One representive community in the region must have its FFR system evaluated to provide the potential value ratio and the efficiencies. If no structural inventories are available for a community, it may be estimated from the Wiggins (1976) data based on the community's population.

4.5 National Evaluation

If the United States can be divided into relatively homogeneous regions, and these regions evaluated; the potential value, optimal value and actual value of the FFR system for the nation is the sum of the regional values. If the component regions were ASA's, over 100 regional and community evaluations would be required. This could be accomplished providing forecast verification reports were available for at least one representative community in each region. Considerable effort would be required for these evaluations.

To obtain an indication of what an analysis of the national FFR would look like, a "quick and dirty" calculation was made, Table 4-9. The United States was considered to be a region and Milton and Columbus were considered to be representative communities in the "region." Quick and dirty actual values of the national FFR system were calculated to be $17,000,000 based on Milton and $28,000,000 based on Columbus (residences only).

In the regional evaluation of the ASA's, the assumption was made that the annual down stream urban flood losses as reported in the WRC's Second National Water Assessment (1976), were equivalent to what is termed in this project as annual loss with no response. Referring to

Representative Community	Milton	Columbus
W = PV/LNR	0.43	0.28
Forecast efficiency	0.20	0.61
Overall efficiency	.069	0.18
USA downstream urban losses	$557,000,000	$557,000,000
Evaluation		
potential value	239,000,000	156,000,000
optimal value	48,000,000	95,000,000
actual value	17,000,000	28,000,000

TABLE 4-9

A "Quick and Dirty" National Evaluation, Using the Regional Methodology With Milton and Columbus as Representative Communities

Table 4-7, it can be seen that the ratio of annual flood losses with no response in Milton to the annual urban downstream losses for the ASA in which it is contained is 0.48. The ratio of the annual residential flood losses in Columbus to the annual urban downstream losses (of all types) for the ASA in which it is contained is 0.81. These values seem to be too high.

Most likely the flood damage reported in the WRC assessment is not equivalent to the loss with no response. Mitigating action in response to flood forecasts is taken which reduces the reported flood damage. If that is the case, the potential value ratios used in the regional evaluation examples are low and the regional evaluations are low. If, however, the high ratio is caused by error in the evaluation of Milton or Columbus, the error would not carry over to the regional evaluation due to the use of ratios in the analysis.

4.6. Summary

A methodology has been developed for regional analysis of FFR systems based on the determination on regions that are relatively homogeneous with respect to flood hydrology and flood loss characteristics. Inputs to the regional evaluation model are obtained from a representative reach in the region. The regional evaluation is obtained from the evaluation of the representative reach multiplied by a scaling factor.

Variability of flood hydrology and of flood loss characteristics within the region would reduce the accuracy of the regional evaluation. Large amounts of error would also result if the representative community were not representative of the region. If it could be developed, a representative law of motion, based on regional parameters, would reduce the error for regional analysis.

CHAPTER 5

DISCUSSION AND CONCLUSIONS

5.1. Background

Flood losses over the past 50 years show a trend towards a decreasing loss in terms of human life, but increasing economic losses. Recently there has been more emphasis on the use of non-structural measures to slow or halt the increase in economic losses. Flood forecasting, warning systems and emergency plans are among the non-structural measures listed in the Water Resources Council's flood damage report (1976). While the emphasis in the report is on floodplain regulation ("Perhaps two-thirds of the potential reduction from non-structural measures could be realized from regulation."), the report states that "Forecast and warning systems need to be improved." Flood forecasting systems have a place in the mix of non-structural measures, although that place may be hard to locate due to the difficulty in evaluating the effectiveness of FFR systems in comparison with other non-structural measures.

It has been shown in this report, and by others (Day, 1970; Day and Lee, 1976) that mitigating action taken by the floodplain dweller to reduce flood losses is cost effective. Day (1970) states that the net benefits of flood forecasts to the floodplain dweller in the Susquehanna River Basin substantially exceed the cost of providing the forecasts. However, there is a recognition that the full potential of the flood forecast-response system for reducing economic flood losses is not being realized and that the system could be improved.

Flood forecasting is but a preliminary action in a sequence of actions whose purpose is to reduce flood damage. Communication of the forecast to the floodplain dweller and proper response are also necessary actions in this sequence, if flood damage is to be reduced. It has been recognized, implicitly or explicitly, that analysis of FFR systems is best accomplished from a system's viewpoint that encompasses all the stages in the sequence of actions leading to a reduction of flood damage. From the systems viewpoint, the overall FFR system is evaluated on how well it accomplishes its objective of reducing flood damage.

An FFR system whose objective is to reduce economic losses due to flooding will be evaluated differently than one whose objective is to reduce the loss of life due to flooding. Different questions will be asked, different factors will be important. The authors believe that the FFR systems model described in this report, and the accompanying computational methodology, contain the factors necessary to evaluate FFR systems whose purpose is to reduce economic flood damage to urban structures. Factors such as the cost of response and the time required to take them are considered. Questions concerning the interplay of these response factors with qualities of the forecast system such as accuracy and lead time can be answered quantitatively in terms of the overall system's objective.

While the model is the most comprehensive of those which the authors are familiar, it is a new concept and does not pretend to consider all facets of urban flooding. Computational requirements alone prevent the inclusion of more detail. Before discussing the implication of the model with reference to its structure and the results of the case studies, it seems best to examine the assumptions inherent in the model and to compare the Milton case study with the evaluation of Milton done by Day (1970).

5.2. Analysis of the Assumptions

All the assumptions behind the operational version of the FFR model that has been implemented for the communities in Pennsylvania, Texas and Mississippi can be grouped into two sets.

1. *Structural assumptions.* These assumptions had been postulated in the phase of conceptualization of the general FFR model, and they determine the basic structure of the model. Accordingly, these assumptions should be viewed as irreplaceable unless, of course, one would wish to change the entire concept of the model.
2. *Operational assumptions.* These assumptions are imposed on the general FFR model in the phase of implementation, and they serve the dual purpose of (a) making the model operational for the given set of input information available, and (b) reducing the computational complexity and thus the cost of numerical computations. Hence, these assumptions can easily be modified according to the desires of the client.

In the following sections, both sets of assumptions are identified and their implications are discussed.

5.2.1. Structural Assumptions

1. *The forecasting and decision-making are discrete-time processes with a common time index.*

While the assumption of a discrete-time process well reflects the reality as far as the forecasting practice and human decision behavior are concerned, the validity of indexing both processes by the same time index may be questioned. This assumption implies that the DM will make the decisions only at those instants at which he receives the forecast. Although the forecasts provide the major stimulus for making the decisions, in reality the DM may time his or her decisions differently than the NWS times its forecasts.

2. *The floodplain is represented by a finite number of steps.*
Essentially, this assumption has no bearing on the general concept of the model. The number of steps can always be assumed large enough so as to reflect the configuration of the floodplain with any desired accuracy. The only reason for discretization comes about from numerical considerations. At present, it seems infeasible to solve the stochastic FFR decision problem while maintaining the continuity of the state space. Thus, since we have to discretize the state space, we prefer to do it at the stage of the model formulation.

3. *The law of motion.*
The postulated structure of the law of motion was developed on the basis of what the authors believed to be a plausible description of hydrologic reality. The authors have not been able to obtain enough data to empirically validate their presumptions. Moreover, the notorious lack of the data forced further simplifications of the law of motion. Those simplifications are analyzed in the next section.

4. *The loss function.*

There are three major assumptions associated with the loss function:

a) The decision d(k) made at the time t_k will be implemented in the time interval $[t_k, t_{k+1}]$, where t_{k+1} is the next decision time.

b) The cost of implementing d(k) is paid by the DM at the time t_k when the decision is made. This means that even though the DM may not be able to implement the decision d(k) (for instance if he is flooded before the next decision time t_{k+1}), he still will be charged the cost of the intended action.

c) The flood damage is a function of the crest magnitude and the final degree of response achieved.

5. *The human response*

There are four major structural assumptions associated with the human response: a) A threshold on subjective probability of loss governs the decision to act. b) The subjective probability of loss is the result of a prior subjective probability revised, in the correct Bayesian manner but with suboptimal values, on the basis of evidence. c) The prior is determined solely by the past experiences of loss and by their remoteness in time. d) Response consists of a fixed sequence of actions which result in a predetermined reduction of loss as a function of time. The action proceeds until stopped by flood water or completion ($\alpha = 1$).

5.2.2. Operational Assumptions

1. *The lead time of the forecast is constant for the given decision time.*

The most logical way to include the lead time in the model is through the state space. The lead time could then be assumed to be a random variable, which in fact it is. This approach, however, would increase the dimensionality of the state space to five, thus, seriously affecting the economics of the computational solvability of the model, as well as the feasibility of estimating the law of motion from the real data. In the alternative approach, adopted for operational purposes, the lead time enters the model in the form of a set of certainty equivalents computed independently for each decision time.

2. *Transmission times.*

Three assumptions bear on the modeling of the transmission times:

a) It is assumed that the processing time and the dissemination time are indexed by the time parameter of the forecasting process, but otherwise they are fixed characteristics of the forecasting system and the dissemination system, respectively.

b) Between the decision times, the flood hydrograph is interpolated linearly. In order to define the consumer time, the exact timing of the event: {flood level $\geq$ location of the DM} is needed. Inasmuch as the ordinates of the hydrograph are modeled as a discrete-time random process, the ordinates between the process times ought to be found by an interpolation. Any interpolating procedure can be used. For the present case studies, linear interpolation has been assumed.

c) The final degree of response is equal to the degree of response achieved up to the instant at which the flood reaches the location step of the given establishment. In actuality it may happen that the establishment is flooded initially to a relatively low level so that further evacuation could be accomplished before the flood crest arrives. This is not permitted in the present model. Once the step is flooded, further action cannot take place on this step.

3. *The law of motion.*

The complexity of the law of motion which is multivariate, conditional, and dynamic, as well as shortage of real data from which the elements of the law of motion could be estimated, uniquivocally forced the authors to make further simplifying assumptions about the structure of the flood forecasting process. These assumptions can be categorized as follows:

a) Monotonicity assumptions (the current flood level is monotonically increasing function of time, and the forecasted flood crest is greater than the current flood level).

b) Independence assumptions concerning the relationship between the state variables of the process (current flood level, forecasted flood crest, forecast indicator).

c) Probability model assumption (choice of the multinomial family of distributions).

These assumptions have been motivated in the previous report (Krzysztofowicz, et al., 1978). More quantitative evaluation of the validity of the proposed simplified law of motion, beyond a simple goodness of fit test, cannot be done at present because no alternatives are available. Modeling the law of motion by means of parametric distributions presents a research problem in itself. Virtually nothing has been done in this area of hydrology. Perhaps this is because the proposed concept for modeling flood forecast-response processes is the first one that fosters the need for describing sequential flood forecasts and actual flood stages in probabilistic terms.

4. *Loss function.*

To obtain an operational representation for the loss function, the concept of unit damage and unit cost functions has been assumed. This concept offers an enormous advantage in both increasing the computational efficiency of the dynamic programming algorithm and in reducing the amount of information needed from a field survey for estimation of the loss function. Although there has been some criticism concerning the unit function concept, the analysis performed by the authors of the damage functions from various sources including the Corps of Engineers (Krzysztofowicz, et al., 1978, pp. 159-188), concluded with results favorable to the concept. Furthermore, considering that damage estimates are subject to large errors whose magnitude and direction are not known, the unit function approach does not seem to be inferior to other damage assessment techniques.

Human response.

The operational assumptions for the human response model are of two types: a) Modifications to the model for computational reasons and b) choice of specific values of the model parameters. a) although the determination of the subjective probability of loss is considered as a sequential Bayesian revision of a prior, it is calculated at each forecast from the prior and from the current forecast height and current water level because of the dynamic programming formulation. Additionally, no attempt was made to relate the threshold and the subjective probability revision parameters to the previous loss history. b) The values chosen for the parameters were obtained in an entirely *ad hoc* manner. They are onces which were considered plausible by the investigators, did not violate known laboratory results, and which resulted in plausible model behavior. It is not clear how one could objectively estimate values of such parameters without a very large amount of quantitative data about actual flood response behavior.

5.3. Comparison of FFR Model with Day's Approach

The construction and calibration of the FFR system model were discussed in the prior report (Krzysztofowicz, et al., 1978). The structural and operational assumptions were presented in the previous section. As the computational algorithms were developed and calibrated for specific case studies, they were checked wherever possible. Loss functions were compared with those in the literature (Krzysztofowicz, et al., 1978, pp. 161-166). The stage frequency curve developed from the historic record was compared with one obtained by computer simulation using the law of motion (Krzysztofowicz, et al., 1978, p. 306). For both comparisons, the correspondence was close but not exact.

Day (1970) did a quantitative flood warning benefit evaluation for urban residences in the Susquehanna River Basin. Included is a detailed study of Milton. Both Day's study of Milton and the case study described in this report used a structural inventory developed by the Baltimore District, U.S. Corp of Engineers. A comparison between Day's results and those obtained from the FFR model is shown in Table 5-1. Difficulties

Day		FFR Model	
Flood damages, no warning	$33,000	Flood damages, no response	$240,000
Net benefits, max. practical evaluation	9,500	potential value	71,000
$\frac{\text{Net. Ben. MPE}}{\text{Flood dam, NW}}$	0.288	$\frac{\text{potential value}}{\text{Flood dam, NR}}$	0.296
		optimal value	24,000
net benefits, limited warning time	7,000	actual value	780

TABLE 5-1

A Comparison of Day's (1970) Evaluation for Milton with the FFR Model's Evaluation (from Table 2-5).

arise in the comparison because different measures of effectiveness are used in the two evaluations. Three comparable measures and one contrasting measure are shown.

It is believed that Day's measurements of flood damages with no warning and net benefits with maximum practical evaluation represent the same quantities as the FFR model's flood damage with no response and potential value, respectively. Table 5-1 shows that the ratio of Day's measures is almost equal to the equivalent ratio of FFR measures. However, the magnitude of the FFR measures is 8 times that of Day's. Three factors, estimated to have about equal weight, are believed to account for this difference. The first is inflation. In this report the value of residential structures used in the flood loss calculations (Krzysztofowicz, et al., 1978, p. 202) is twice that used by Day (1970, p. 7). The second factor is the change in the stage-frequency relationship occasioned by the floods occurring in 1972 and 1975. Hurricaine Agnes in 1972 produced the largest flood of record at Milton. The third factor is the simplifications and approximations needed to keep the computational algorithms tractable. The stage frequency curve developed for Milton from the law of motion shows exceedance probabilities 50% higher, than computed from the historical record, for those levels in the floodplain where the most housing is located.

Further equivalent comparisons with Day's evaluation are not possible as he did not specifically consider the accuracy of the sequence of forecasts. Day has no equivalent to the FFR model's optimal value. A lower net benefit recorded by Day was for limited warning time evacuation rather than for maximum practical evaluation. This net benefit was nine times greater than the actual value of the system as calculated by the FFR model's calculations consider the accuracy of the forecasts and Day's calculations do not.

Using data provided by the Corps of Engineers for 116 reaches in the Susquehanna River Basin, Day(1970) used simulation to accomplish a regional evaluation. Two of his results are of special interest to the regionalization studies of this report. The ratio of net benefits with maximum practical evacuation to flood damages with no warning does vary throughout the basin, from about 0.24 to 0.36; the average being 0.25, which is lower than the ratio for Milton. He also documents other differences between upstream and downstream locations. These results further indicate that the regionalization method using ASA's, as outlined in Chapter 4, produces rough estimates.

5.4. Comparison of FFR Model with MFLT Method

At this point a comparison of the FFR evaluation technique with that of mean forecast lead time (MFLT) as developed by Sittner (1977) is instructive. Both techniques consider the sequence of flood forecasts and the rising limb of the hydrograph. Fundamentally MFLT is a reach measurement while FFR is developed for one structure and one decision maker. MFLT is a verification measure while the FFR evaluation concerns expected (future) performance. MFLT does not consider the behavior of the floodplain dweller, while the FFR model may consider many types of human response to flood warning, although the use of the pure strategy in the FFR model gives equivalent timing to that of the MFLT model.

The time available to respond to the forecast is central to both methods. MFLT averages this time over the sequence of flood forecasts.

The FFR model averages the net economic benefits to be expected by using the lead time to take mitigating actions. Effectively no value is given by the FFR systems model for lead time in excess of that needed to make a full response. The FFR evaluation treats under and over estimation of the crest in the same manner, the net benefits, if any, of responding to the forecast are calculated and go into the average. The FFR model can evaluate a reach; it does so by adding the evaluations obtained for the individual structures.

Basically however, the FFR model is individual situation oriented. Two identical structures located at the same level in the floodplain would receive different evaluations using the FFR system model, if the cost or time required for responding to the same flood forecast were different.

MFLT does not have decision theoretic components. Otherwise, the philosophies of these two methodologies for the evaluation of working FFR systems are quite similar, but the measures used for the evaluations differ markedly. Yet, it would not require too much change in the program calculating the actual value of the FFR system to obtain expected MFLT.

5.5. Discussion

A system model and an associated computer package has been developed to evaluate flood forecast-response systems in terms of their ability to reduce flood damage to urban structures. Quantitative evaluations are made of the expected annual reduction in dollar amount of flood losses as well as of the efficiency of the forecast system, the response system and the overall system. Evaluation of FFR system for communities and region are a composite of individual evaluations of separate systems. In a river reach these separate FFR systems have individual response systems but share the forecast system. As a result the forecast efficiency as well as the response efficiency may vary greatly from structure to structure in a community. The forecast efficiency is a measure of the ability of the forecast system to meet the needs of the response system for accurate and timely information, rather than an intrinsic measure of the timeliness and accuracy of the forecasts. This is illustrated in the case studies and sensitivity analyses presented in Chapter 2. Tables 2-6 through 2-11 show the effect of changes in the parameters of the forecast and response system on the forecast and response efficiencies. It has been noted that there is a different pattern of change in Milton as compared to Columbus, most likely due to the different lead times for these communities. Figures 2-3 through 2-5 show the increase in forecast and response efficiencies as the time required to complete response action decreases. Figure 2-2 shows how the cost of response effects the forecast efficiency. There is a point beyond which decreasing the time necessary to complete the response activities is no longer beneficial. This point decreases as the cost of response increases. It may be surmised that as the time to respond decreases the forecast efficiency is limited by the cost of response and the accuracy of the forecast. This limiting value of the forecast efficiency might be considered the intrinsic value of the forecast accuracy for the structure under consideration.

Comparison of Tables 2-9 and 2-11 show a residence in Milton to have a lower forecast efficiency than a residence in Columbus, reflecting the shorter forecast lead time in Milton. The limiting forecast efficiency, or intrinsic forecast efficiency, as shown in Tables 2-9 and 2-11, however is 0.20 higher for Milton than for Columbus. Perhaps this is accounted for by more frequent forecasts in Milton.

Figure 2-1 shows that response efficiencies generally drop for structures higher in the floodplain. Forecast efficiencies make much less change. Table 2-12 shows the effect of changes in the forecast and response efficiencies as a function of step height for several values of the parameters of the forecast and response systems. Of special interest is the change in response efficiency when the time required to process a forecast is reduced by two hours. The response efficiency is substantially increased, with the largest increase occurring in the higher levels of the floodplain. At the same time the forecast efficiency shows proportionately less increase. The power of the FFR systems model is illustrated by examining the implications of this seeming paradox.

The response efficiency is defined as the expected annual reduction in flood damage accomplished by the response strategy actually in use, divided by the expected annual reduction in flood damage that would be accomplished by using the best possible response strategy. In terminology of this report the response efficiency is the actual value divided by the optimal value. The forecast efficiency is defined as the expected annual reduction in flood damage that could be accomplished by using the best possible response strategy divided by the expected annual reduction in expected annual flood damage that could be accomplished by using the best possible response strategy in conjunction with perfect forecasts. In the terminology of this report, forecast efficiency is the optimal value divided by the potential value. Since the choice of response strategy only affects the actual value, a change in response strategy can affect the response efficiency but not the forecast efficiency. In the example above, sensitivity analysis showed that if the industry in Milton was located 9 feet above flood stage, Table 2-12, this 2 hour reduction in the processing time of forecast would provide up to 3 times as much improvement in the response efficiency as it would in the forecast efficiency. An equivalent or better increase in response efficiency could be had by improvement in the response strategy alone. Essentially the improvement in the forecast system enables the actual strategy being used to do better, but providing the forecast a little earlier does not improve the value of a system using the best possible response strategy nearly as much.

This result is specific for the case analysed and cannot be generalized on the basis of the data presently available. It is a reasonable conjecture, though based on the limited data and information available, that the result may hold in cases where both the forecast and response efficiencies are low. Why would this be?

An optimal strategy for the prevention of economic loss is often anticipatory due to the time required to take mitigating action. Since the (potential) benefit cost ratio of the early increments of responsive action is high, the gamble of making incremental anticipatory responses to flood forecasts pays off in the reduction of economic flood loss. Table 5-2 shows the effect of an anticipating, and a delaying, response to flood forecasts for a residence in Columbus. Even with relatively high forecast and response efficiencies, as is the case in Columbus, anticipation is

Height Above Flood Stage Actual	Perceived	Variation in Strategy	Actual Value
10	7	anticipating	$674
10	10	none	467
10	13	delaying	4

TABLE 5-2

The Effect of Differing Strategies on Actual Value of FFR System for a Residence in Columbus, Using Pure Strategy.

beneficial. An optimal response strategy uses the historical record of floods and forecasts as the basis for anticipation. Receiving a forecast 2 hours earlier than usual may not then be very beneficial if the response strategy is accurately anticipating the future forecasts.

The case studies and sensitivity analyses show that as the cost of response increases and the time available for response decreases, the overall efficiency and actual value of an FFR system whose objective is to reduce economic loss to urban structures, drops and may be negative. This is the case for the industry in Milton as shown in Figure 2-4. Pure response strategy, that is only responding if the forecast indicates inundation, is no longer satisfactory. However, the positive value of the forecast efficiency indicates that the use of a more sophisticated response strategy would increase the actual value of the FFR system in this situation.

The results shown in Table 5-2 may also be used to show the effect of misperception of a structure's location in the floodplain on the value of the FFR system. If a floodplain dweller who uses a pure strategy acts as if the structure were located three feet below its actual location the actual value of the FFR is increased. If the location of the structure is assumed three feet higher than it actually is, the actual value of the FFR system drops almost to zero.

Computational requirements for evaluation are large. An evaluation of Milton, once all the parameters have been determined, takes about 1200 seconds on the CDC 6400. Efforts to reduce the time required were not successful. The accuracy required for differentiating between some parameter changes made as part of the sensitivity analyses presented in Chapter 2 required changes that added to computation time. Longer forecast verification records and quantitative field data on the response to flood forecasts are needed for more accurate evaluations. Additional accuracy could be obtained by a more detailed use of the data presently available by considering more structural categories and by using more steps in the floodplain. Computation time would be adversely affected if more catagories and steps were used.

Information about flood losses is deficient for all types of non-residential structures. If non-residential structures are concentrated lower in the floodplain than residential structures, this lack of information could be serious. In Milton, see Tables 2-2 and 2-5, 55% of the maximum possible flood damage occurs to non-residential structures. But 90% of the potential value of the FFR system is accounted for by the non-residential structures. An additional factor explaining this difference is that a larger proportion of flood damage can be reduced by mitigating response in the case of industrial and commerical structures than for residential structures (Krzysztofowicz, et al., 1978, pp. 194-196). Of course, in order to realize this reduction, time for response must be available and it must be used in the best possible manner. Large commerical and industrial organizations are more likely to be able to devise and utilize efficient response strategies than individuals. The study of FFR systems for large commercial and industrial organizations seems to offer large potential for reducing economic flood damage.

Each structure in a river reach has its own response system but shares the forecast system. Structures having substantially different response characteristics may need forecast systems with different characteristics.

For a single forecast situation it has been shown (Sniedovich, et al., 1975; Sniedovich and Davis, 1977) that a forecast system having a long lead time but less accuracy may be of more value in reducing economic flood losses than a forecast system with more accuracy and less lead time. Since industries require more time to complete mitigating actions than other structural categories, the study of alternate forecast systems for industrial users is recommended. Such a study would be specially warranted for those industries using forecasts having a short lead time such as those in Milton.

Complete region and national FFR systems evaluation could be made if the data and resources to analyse them were available. A methodology to provide approximate regional evaluations was given in Chapter 4. Considering the difficulties in estimating regional flood losses (Goddard, 1973; Wiggins, 1976) judicious use of the region methodology for evaluating changes in regional characteristics of FFR systems seems warranted.

In examining the results of the case studies presented in Chapter 2 of this report it should be kept in mind that the low efficiencies are due in large part to the cost and time required for response. The sensitivity analyses showed that as the cost and time required are reduced, the efficiency rises. While the overall efficiency for a residence in Milton is low, or even negative when an unsuitable response strategy is used, the overall efficiency for a motor home, which could be evacuated quickly and at low cost, would be quite high.

In evaluating an FFR system, the characteristics and the objectives of the system must be examined and considered. When the objective is reducing economic losses, the FFR systems model and associated computational methodology has been designed to include the characteristics essential to evaluation while retaining computational tractability. It can be successfully used in the analysis of real world flood forecast-response systems.

5.6. Conclusions

1. The evaluation of flood forecast-response (FFR) systems whose objective is the reduction of economic damage due to flooding must consider the characteristics of the forecast system and of the response systems that determine whether that objective can be achieved.
2. A systems model was developed to evaluate such FFR systems which take into consideration the stochastic and sequential nature of the forecasts; and the cost of and the time required to respond as well as the strategy used in responding to the forecasts. The value of the system is obtained as well as the efficiencies of the forecast and response systems by the use of an associated computational methodology. In addition a learning model and a simulation model of human response to flood forecasts were developed.
3. For FFR systems whose objective is to reduce economic.flood losses, forecast efficiency is a measure of the ability of the forecast system to meet the needs of the response system. Response efficiency is a measure of the ability of the response system to make use of the information provided by the forecast system. The actual value of an FFR

system is the reduction in the annual flood loss to be expected by use of the system.

4. Case studies were made of Milton, Pennsylvania; Columbus, Mississippi and Victoria, Texas. The FFR system for individual structures as well as for the community were evaluated. Forecast efficiencies ranged from 20% to 63%, response efficiencies from below zero to 50%. Extensive sensitivity analyses of the contrasting communities of Columbus and Milton were made. The effect and interaction of many characteristics of the forecast and response systems on the efficiency of the overall system was illustrated and some causes of low efficiencies delineated. The potential for improving the effectiveness of FFR systems in reducing economic flood damage is greatest where: i) the forecasts provide short lead times, ii) the cost of and the time required for response is high, and iii) response is not initiated until the forecasts indicate inundation.

Quantitative field data on action taken to mitigate economic losses in response to flood forecasts is needed. Overall the data base for evaluating FFR systems in their role of reducing economic flood losses is poor, especially for commercial and industrial structures. Indications are that commercial and industrial structures have the most potential for reducing economic flood losses.

APPENDIX A

STOCHASTIC MODEL OF A FLOOD FORECAST-RESPONSE PROCESS

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SYNOPSIS

A stochastic model of a *Flood Forecast-Response* (FFR) process has been developed. The purpose of this model is to provide a means for quantitative evaluation of effectiveness of FFR systems in reducing flood damage. The FFR system is decomposed conceptually into the forecasting system and response system. The sequence of forecasts of the flood crest and the actual river stages are described by means of a Markov process. The floodplain dweller's response to the sequence of forecasts is formulated as a random duration, multistage, discrete-space decision process under uncertainty. A set of measures of effectiveness for evaluating the performance of the FFR system is proposed. Results of a case study are presented.

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INTRODUCTION

A stochastic model of a *Flood Forecast-Response* (abbreviated henceforth FFR) process has been developed. The purpose of this model is to provide a means for quantitative evaluation of the effectiveness of FFR systems in reducing flood damage.

In general, the FFR process can be described as follows. The forecasting service collects data which are used to provide flood forecasts (i.e. forecasts of the flood crest). These forecasts are communicated to various public and private organizations which disseminate them to potential users threatened by the oncoming flood. The *floodplain dweller* is the *decision maker* (DM) who must then make a decision about an action aimed at reducing his potential loss due to flooding. Inasmuch as the flood forecasts may not be perfect, the floodplain dweller must act *under uncertainty*, i.e., his decision process ought to consider all the probabilistic events: {Given the forecasted flood crest is h, the actual flood crest will be hh}.

The FFR process has been conceptualized in the form of a system shown in Figure 1. This system is composed of two subsystems: (1) the *forecasting system* which includes the hydrometric system, forecasting model, and dissemination system, and (2) the *response system* which includes the decision-making process followed by protective actions taken by the floodplain dweller. The efficiency of the FFR system is determined by a number of interrelated factors such as: structure and reliability of the hydrometric network, performance of the forecasting model (i.e. timeliness and accuracy of the generated forecasts), speed and reliability of the dissemination process, decision behavior of the floodplain dweller, and stochastic nature of the actual flood process. Admittedly, the complexity of the factors involved is enormous. This research effort has been aimed at developing a model which would include the essential aspects of the FFR process and yet be computationally tractable.

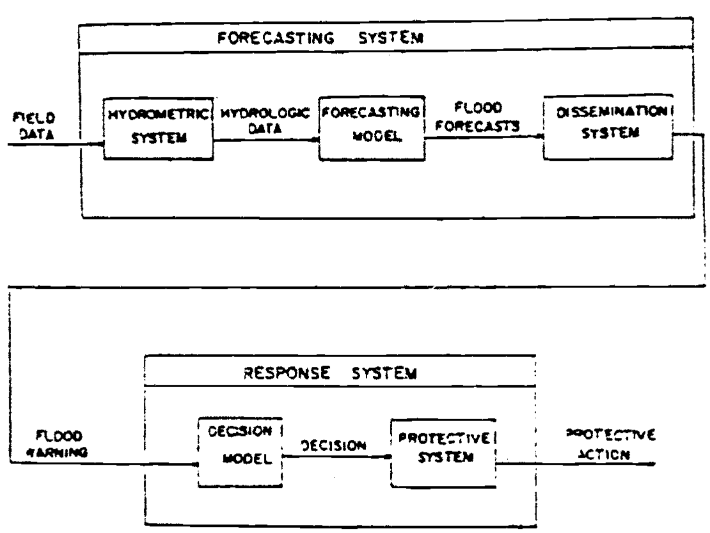

Figure 1. Flood forecast-response system

In a previous study, Sniedovich and Davis (1977) developed a decision theoretic system framework for evaluating a FFR system with respect to an individual DM when only one forecast is issued for the entire flood event. The present study recognizes the sequential nature of the FFR process. The sequence of forecasts of the flood crest and the actual river stages are described by means of a Markov process. The DM's response to the sequence of forecasts is formulated as a random duration, multistage, discrete-space decision process under uncertainty. The model presented herein is formulated for a single DM. Its extension to a group of DMs (e.g. a community) has been formulated in Krzysztofowicz et al. (1978).

The paper begins with a general mathematical formulation of the FFR process. This is followed by development of the measures of effectiveness which provide a means for quantitative evaluation of performance of a FFR system. The subsequent section is devoted to detailed modeling of some of the model components. Finally, the results of a case study are presented to demonstrate the potential of the model. In addition, sensitivity analyses are performed to illustrate that the model can provide answers to a variety of problems that are paramount to efficient design as well as operation of FFR systems.

MODEL OF FFR PROCESS

The FFR process is formulated as a random duration, multistage, discrete-space decision process under uncertainty. The basic references to the theory of such processes are Yakowitz (1969), Hinderer (1970), and Bertsekas (1976).

Definition 1. The *set of decision times*, K, is an initial segment of the set of positive integers:

$$K = \{k : k = 1,2,\ldots,KN\}.$$

It is assumed that the sequence of decisions matches the sequence of forecasts. Hence, KN is the maximum number of forecasts expected with a positive probability, or

$$KN = \min\{j : P[(\#\text{ of forecasts}) > j] = 0,\ j = 1,2,\ldots\}.$$

The real time interval, Δt, between any two decision times is not necessarily constant.

Definition 2. The *state space*, Ω, is a Cartesian product of sets:

$$A = \{\alpha : \alpha \in [0,1]\},$$

$$I = \{i : i = 1,2,\ldots,IN\},$$

$$H = \{h : h = 1,2,\ldots,IN\},$$

$$W = \{w : w = 0,1\}.$$

Accordingly,

$$\Omega = \{x : x = (\alpha,i,h,w)\}$$

where

α - the degree of response already achieved (due to the decision already made),

i - the current flood level,

h - the forecasted flood crest, or the actual flood crest following the last forecast (for clarity, the actual flood crest will be denoted by hh; theoretically, h and hh are assumed to be the same state variable),

$$w \text{ - forecast indicator} = \begin{cases} 0, & \text{no more forecasts will be issued,} \\ 1, & \text{at least one more forecast will be issued.} \end{cases}$$

Conceptually, the floodplain is discretized into IN steps. Both $i\varepsilon I$ and $h\varepsilon H$ correspond to the steps of the floodplain. The degree of response α is a cardinal measure of the DM's response defined arbitrarily on the closed interval of real numbers [0,1]. We shall speak of:

no response	if	$\alpha = 0$,
partial response	if	$0 < \alpha < 1$,
full response	if	$\alpha = 1$.

At any time $k\varepsilon K$, information known perfectly to the DM is the value of (α,i,h), whereas w is known only through its probability distribution. The state $x = (\alpha,i,h,w)$ represents, therefore, partially imperfect information.

Definition 3. The *decision set*, D, is a set-valued mapping defined on ΩxK, the set of state-time pairs:

$$D = \{D(x,k): x\varepsilon\Omega,\ k\varepsilon K\}$$

where D(x,k) is the set of admissible decisions available to the DM at decision time $k\varepsilon K$ when the state of the system is $x\varepsilon\Omega$. An element d of D is a degree of response. Hence, $D(x,k) \subset A$ for every $x\varepsilon\Omega$, $k\varepsilon K$.

Definition 4. A *law of motion*, Φ, is a family of conditional probability distributions defined on Ω of the form:

$$\Phi = \{P[\cdot|x,k]: x\varepsilon\Omega,\ k\varepsilon K\}$$

where $P[x'|x,k]$ is the conditional probability of the state of the system x' at decision time k+1 given that at decision time k the state of the system is x.

In the present model, we restrict our attention to the following particular form of the law of motion:

$$P[x'|x,k] = \begin{cases} P[i(k+1),h(k+1)|i(k),h(k),k] & \text{if } w(k) = 1 \\ P[hh(k)|i(k),h(k),k] & \text{if } w(k) = 0 \end{cases}$$

where the value of w(k) is determined according to the probability

$P[w(k)|k]$, for all $k \varepsilon K$.

The law of motion reads: (a) If at least one more forecast beyond the decision time k will be issued, i.e. w(k) = 1, then $P[x'|x,k]$ is the probability that at decision time k+1 the actual flood level will be i(k+1) and the forecast issued will indicate crest h(k+1) given that at decision time k the current flood level is i(k) and the forecasted flood crest is h(k). (b) If no more forecasts beyond decision time k will be issued, i.e. w(k) = 0, then $P[x'|x,k]$ is the probability that the actual flood crest will be hh(k) given that at the decision time k the current flood level is i(k) and the forecasted flood crest is h(k). (c) $P[w(k)|k]$ is the probability of the forecast indicator w(k) being one or zero at the decision time k.

It has to be made clear that the law of motion described above bears the following two assumptions: (a) The forecast indicator variable, w, is independent of the remaining coordinates of the state vector x. (b) The sequence {w(k)} forms a Markov chain of order zero.

Definition 5. A *trajectory*, $\bar{x}$, is a sequence of states indexed by $k \varepsilon \{1,2,\ldots,KN,KN+1\}$. The following notation will be used:

$\bar{x}_k$ - the sequence of states for decision times not less than k,

x(k) - the state of the system at the kth decision time.

Definition 6. A *policy*, $\bar{d}$, is a sequence of decisions indexed by $k \varepsilon K$. The following notation will be used:

$\bar{d}_k$ - the sequence of decisions for decision times not less than k,

d(k) - the decision made at the kth decision time.

Since at each decision time k the DM may choose a decision d from a set of decisions available D(x,k), depending on the state of the system x at that time, his response may be expressed as a function defined on the state and decision times sets with values in the decision set.

Definition 7. A (response) *strategy*, S, is a function defined on $\Omega x K$ with values in D. S(x,k) is the decision made at decision time k when the state of the system is x. A set of *feasible strategies* is $\sigma = \{S: S(x,k) \varepsilon D(x,k), x \varepsilon \Omega, k \varepsilon K\}$.

Definition 8. A *loss function*, L, is a real valued function defined on the triple $(\bar{x}_k, \bar{d}_k, k)$, where $k \varepsilon K$, and $\bar{x}_k$ and $\bar{d}_k$ are, respectively, a trajectory and a policy whose domains are restricted to times not less than k. For brevity, notation $L(\bar{x},\bar{d},k)$ will be used.

It is assumed that the loss function is separable, viz., that it admits the representation:

$$L(\overline{x},\overline{d},k) = \sum_{n=k}^{KN} L(x(n),x(n+1),d(n),n).$$

Specifically, the following structure of the loss function is postulated:

$$L(x(k),x(k+1),d(k),k) = \begin{cases} L_1(\alpha(k),d(k),k) & \text{if } w(k)=1, \quad k=1,\dots,KN-1. \\ L_0(\alpha(k),hh(k),\alpha(k+1),d(k),k) & \text{if } w(k)=0, \quad k\varepsilon K. \end{cases}$$

L_1 represents the cost of implementing d(k) given the degree of response already achieved α(k). Note the implicit assumption that the decision d(k) is implemented in the time interval $[t_k, t_{k+1}]$. L_0 represents: (a) the cost of implementing d(k) given the degree of response already achieved α(k), *plus* (b) the damage caused by the flood crest hh(k) given the final degree of response α(k+1). It is assumed that the cost of response is monotonic increasing function of α, and the flood damage is monotonic decreasing function of α.

Definition 9. A *flood forecast-response process* (FFR process) is a quintuple (Ω,K,D,Φ,L).

Theorem 1. *In the FFR process the expected loss* E[L(x,S,k)] *associated with a strategy* Sεσ *and an initial state-time* (x,k) *is a uniquely determined quantity and may be obtained from the following algorithm:*

(a) For k = KN *and every* xεΩ, *set* d = S(x,KN) *and compute*

$$V(x,KN) = E[L(x,x',d,KN)].$$

(b) For every k < KN *and every* xεΩ, *set* d = S(x,k) *and compute*

$$V(x,k) = E[L(x,x',d,k) + V(x',k+1)].$$

Finally, set

$$E[L(x,S,k)] = V(x,k).$$

The decision behavior of the floodplain dweller may be characterized by the response strategy. Three types of strategies are identified:

Definition 10. An *optimal strategy* is a strategy S*εσ such that

$$E[L(x,S^*,k)] = \min_{S\varepsilon\sigma} E[L(x,S,k)] \text{ all } x\varepsilon\Omega,\ k\varepsilon K.$$

The set of all optimal strategies will be denoted by σ*.

Definition 11. An *actual strategy* is a strategy S^aεσ used actually by the DM. By definition

$$E[L(x,S^*,k)] \le E[L(x,S^a,k)].$$

The set of all actual strategies will be denoted by σ^a.

Definition 12. A *pure strategy* of the DM located on the step m is a strategy S′εσ, satisfying for all xεΩ and kεK the following condition:

$$S^p(x,k) = \begin{cases} 0 & \text{if } k < \min\{t:h(t) \geq m,\ t\varepsilon K\} \\ \max\{d:d\varepsilon D(x,k)\} & \text{if } k \geq \min\{t:h(t) \geq m,\ t\varepsilon K\}. \end{cases}$$

Most of the works in flood forecasting evaluation consider solely pure response, assuming $K = \{1\}$, and $\max\{d:d\varepsilon D(x,1)\} = 1$.

S^p is completely specified by the definition. S^a is expected to be generated by a human response model described elsewhere (Krzysztofowicz et al., 1978). Construction of S^* is shown below.

Theorem 2. *In the FFR process, an optimal strategy* S^* *may be constructed by the dynamic programming algorithm as follows:*

(a) $S^*(\alpha,i,h,KN) = d^*$, *where for any state* (α,i,h), d^* *is a solution to the equation*

$$V(\alpha,i,h,KN) = \min_{d\varepsilon D(x,KN)} \sum_{hh\varepsilon H} L_0(\alpha,hh,\alpha',d,KN)\cdot P[hh|i,h,KN],$$

(b) $S^*(\alpha,i,h,k) = d^*$, $k < KN$, *where for any state-time* (α,i,h,k), d^* *is a solution to the recursive equation*

$$V(\alpha,i,h,k) = \min_{d\varepsilon D(x,k)} \{ \sum_{\substack{i'\varepsilon I \\ h'\varepsilon H}} (L_1(\alpha,d,k) + V(\alpha',i',h',k+1))\cdot$$

$$P[i',h'|i,h,k]\cdot P[w=1|k] + \sum_{hh\varepsilon H} L_0(\alpha,hh,\alpha',d,k)\cdot$$

$$P[hh|i,h,k]\cdot P[w=0|k]\}.$$

The expected loss associated with the initial state-time (x,k) *and the strategy* S^* *is*

$$E[L(x,S^*,k)] = V(\alpha,i,h,k).$$

As has been shown above, the optimal strategy S^* is a function defined on the variable (α,i,h,k). Clearly, at the decision time k, the optimal decision d^* is chosen according to the degree of response already achieved α, the actual flood level i, and the forecast of the flood crest h.

Definition 13. An *initial condition* is a probability distribution $\Phi_0 = \{P[x(k_0)]:x(k_0)\varepsilon\Omega\}$ of the initial state $x(k_0)\varepsilon\Omega$ at a specified initial decision time $k_0\varepsilon K$. For short-hand we shall denote $x(k_0) = x_0$.

Given a strategy S, the expected loss *per one flood event* is defined by $E[V(x_0,k_0)]$. Very often economic analysis is conducted in terms of annual losses.

Definition 14. The *expected annual loss*, EL, associated with a strategy S is defined as

$$EL = E[V(x_0,k_0)]\cdot E[N]$$

where $E[N]$ is the expected number of flood events per year. In order to determine Φ_0 and $E[N]$, a precise definition of a flood event is needed.

Definition 15. A *flood*, F, is an occasion on which at least one forecast of the flood crest would be issued by a given forecasting system. It is assumed that the forecasting system has a well defined set of rules which determine initiation of the forecasting process from hydrometeorological conditions on each occasion in a consistent manner.

MEASURES OF EFFECTIVENESS

Measures of effectiveness are to relate the system performance to accomplishment of goals. It seems desirable to distinguish between the performance of the forecast-response system as a whole and the performance of its major components, namely forecasting system and response system. In this way, the relative effectiveness of various improvements in the one component may be compared with the alternatives of improving the other component. The measures of effectiveness described herein have been first proposed in Sniedovich and Davis (1977).

Although part of the flood damage may be reduced by implementation of a response strategy, even with a perfect forecasting system (no errors in the forecasts and large lead-time) and an optimal response strategy ($S^*\varepsilon\sigma^*$) some damage will still occur. There is an upper bound to the preventable damage.

Definition 16. *Potential value*, PV, of the FFR system.

Assume: (1) a perfect forecasting system which at the decision time $k_0 = 1$ predicts the actual value of the flood crest with an "infinite" lead time,

(2) an optimal response of the DM who at $k_0 = 1$ chooses an optimal strategy $S^{**}\varepsilon\sigma$.

Then the potential value of the FFR system is defined as

$$PV = EL^0 - EL^{**}$$

where EL^0 denotes the expected annual loss with "no response" from the DM, and EL^{**} is the expected annual loss under strategy S^{**}. For the specific type of the loss function introduced in Definition 8, we have

$$PV = \underset{hh}{E}[L_0(0,hh,0,0,1)]\cdot E[N] - \underset{hh}{E}[\min_{d\varepsilon D(x,1)} L_0(0,hh,d,d,1)]\cdot E[N].$$

By definition, PV is an upper bound of the damage reduction one may expect in a given FFR system.

Forecasts are seldom perfect. Sequential forecasting is employed to reduce the uncertainty of long lead-time forecasts. Remaining uncertainty and sequential inflow of information must be accounted for by an optimal response strategy.

Definition 17. *Optimal value*, OV, of the FFR system.

Assume: (1) a forecasting system having law of motion Φ,

(2) an optimal response $S^* \epsilon \sigma^*$ of the DM to the sequence of forecasts generated by Φ.

Then the optimal value of the FFR system is given by

$$OV = EL^0 - EL^*$$

where EL^* is the expected annual loss under strategy S^*. The difference between PV and OV is that OV accounts for the uncertainty in the forecasts (quantified in terms of Φ). Thus, OV represents the optimal value of the forecast information in a given FFR system.

Since often (if not always) the actual response strategy is not optimal, the actual value of the forecast information in a given FFR system is less than OV.

Definition 18. *Actual value*, AV, of the FFR system.

Assume: (1) a forecasting system having law of motion Φ,

(2) an actual response strategy $S^a \epsilon \sigma$ is used by the DM.

Then the actual value at the FFR system is defined as

$$AV = EL^0 - EL^a$$

where EL^a denotes the expected annual loss incurred by the DM under strategy S^a. AV may be viewed as a measure of the performance of the overall FFR system since it is computed with the actual law of motion, Φ, and the actual response strategy, S^a.

In order to present the effectiveness of both the forecasting and the response systems, as well as the effectiveness of the overall forecast-response system, the following measures are defined.

Definition 19. The *performance*, PE, of the FFR system is defined by the vector:

$$PE = \{PV, OV, AV\}.$$

Definition 20. The *efficiency*, EC, of the FFR system is defined by the vector:

$$EC = \{EF, ER, EO\},$$

with

$$EF = OV/PV; \quad ER = AV/OV; \quad EO = AV/PV,$$

where EF is the efficiency of the forecasting system, ER is the efficiency of the response system, and EO is the overall efficiency. The following relations hold:

(1) $AV \leq OV \leq PV$,

(2) $EO \leq EF$; $EO \leq ER$; $0 \leq EF, ER, EO \leq 1$,

(3) $EO = EF \cdot ER$.

While PE is designed for evaluating alternative FFR *systems*, EC should be used for evaluating the *components* of a given system. Together, PE and EC provide a basis for making decisions concerning allocation of resources to activities involved in a FFR system.

DETAILED MODELING

The formulated FFR model provides a general framework within which many aspects of the forecast-response processes can be studied. In the phase of implementation, further detailed modeling and/or specification of the model components are needed. In this section, we show the modeling of some of the components which was done for the case study by the authors.

Lead Time

An important fact, ignored so far, is the timing of the flood crest. Precisely, the flood crest is defined by a two-tuple (h,ξ) on the product space HxT, where $h \varepsilon H$ is the crest magnitude, and $\xi \varepsilon T$ is the time of occurrence. Let t_k be the *time of origin* of the forecast ($\equiv$ time of making the observations upon which the forecast is based). Suppose that a forecast originating at the decision time $k \varepsilon K$ (real time $t_k \varepsilon T$) is $(h(k),\xi_k,k)$.

Definition 21. The *lead time*, $\lambda \varepsilon \Lambda$, of the forecast originated at k is defined by the relation

$$\lambda(k) = \xi_k - t_k, \qquad \text{for } \xi_k \geq t_k, \qquad k \varepsilon K.$$

If $w(k) = 1$, then the forecast (h,ξ,k) will be followed by at least one more forecast. If $w(k) = 0$, then the forecast (h,ξ,k) is the last one, and it may be verified by the actual flood crest (hh,ξ',k) with the *actual lead time*

$$\lambda'(k) = \xi'_k - t_k, \qquad \text{for } \xi'_k \geq t_k, \qquad k \varepsilon K.$$

The most logical way to include the lead time in the model is through the state space. However, this would increase the dimensionality of the state space to five, thus, seriously affecting the economics of the computational solvability of the model. An alternative approach adapted herein is based on a certainty equivalent (naive feedback).

Definition 22. The *average actual lead time*, LT(k), of the forecast h(k), for $w(k) = 0$, $k \varepsilon K$, is given by

$$LT(k) = E[\lambda'(k)] \qquad \text{for all } k \varepsilon K.$$

The use of LT in the model will be shown in the definition of the consumer time.

Transmission Times

Definition 23. *Processing time*, *PT*, is the length of a closed time interval defined on the set of decision times K by the relation

$$PT(k) = t'_k - t_k, \qquad k \varepsilon K$$

where t_k is the time of the forecast origin, and t'_k is the time of issuing the forecast by the forecaster. Physically, the processing time

rates the time needed for data acquisition and the time needed for
t preparation.

ion 24. *Dissemination time, DT*, is the length of a closed time
l defined on the set of decision times K by the relation

$$(k) = t''_k - t'_k, \qquad k \in K$$

t'_k is the time of issuing the forecast by the forecaster, and t''_k is
e of receiving the forecast by the DM.

the above development, {PT(k)} and {DT(k)} are fixed characteris-
the forecasting system and the dissemination system, respectively.
e DM's viewpoint, there is a need for defining one more element
e shall call consumer time. It is the actual net time available
DM located on m for implementing the decision d(k), when the states
system at k and k+1 are x(k) and x(k+1), respectively.

tion 25. *Consumer time, CT*, is the length of a closed time interval
d on $\Omega \times K$ for a DM located on $m \in I$ such that

$$T(x(k), x(k+1), k, m) = \max \{0, \text{"value"}\},$$

value" specified as follows:

state		"value"
$w(k) = 1$	$i(k+1) < m$	$\Delta t(k)$
	$i(k+1) \geq m$	$\beta \Delta t(k) - PT(k) - DT(k)$
$w(k) = 0$	$hh(k) < m$	∞
	$hh(k) \geq m$	$\beta LT(k) - PT(k) - DT(k)$

a real valued function defined on Ω for location m with values in
. It accounts for timing of the event $\{i \geq m\}$. Inasmuch as hh(k),
and i(k+1) are random variables, the consumer time, CT, is also a
n variable.

on Mechanism

tion 26. *The decision constraint function* is a real-valued mapping
m $[0, \infty)$ into A such that for any $t \in [0, \infty)$, dd(t) is the maximum degree
sponse which can be achieved in the time interval $[0, t]$. Accordingly,
decision time k, the degree of response already achieved is $\alpha(k)$,
e consumer time is CT(k), then the maximum degree of response,
), that can be achieved at k+1, is constrained by

$$\alpha(k) \leq \alpha(k+1) \leq dd[dd^{-1}(\alpha(k)) + CT(k)].$$

The following decision mechanism, incorporating the consumer time, CT, is assumed. At the decision time k, the DM chooses d(k), and the cost of response is computed from $\alpha(k)$ and d(k). However, $\alpha(k+1)$ does not necessarily equal d(k) since the actual net time available for implementation of d(k) (i.e., the consumer time, CT(k)) is a random variable. Hence, the degree of response $\alpha(k+1)$ actually achieved at time k+1 is determined by the relation

$$\alpha(k+1) = \min\{d(k), dd[dd^{-1}(\alpha(k)) + CT(k)]\}.$$

Loss Function

Two real-valued, stationary functions are assumed to exist:

a) *Cost function*, $LC(\alpha)$, specifying the cost of response of degree α,

b) *Stage-damage-response function*, $LD(\alpha,hh,m)$, specifying the damage caused to the establishment located on step m by the actual flood crest hh, given the final degree of response α.

Now the loss function, L, can be written in terms of the LC and LD as follows:

$$L_1(\alpha,d) = LC(d) - LC(\alpha) \qquad \text{for } w = 1$$

$$L_0(\alpha,hh,\alpha',d) = LC(d) - LC(\alpha) + LD(\alpha',hh,m) \qquad \text{for } w = 0$$

where $\alpha' = \alpha(k+1)$ is the final degree of response.

A proposed form of LD and LC will now be developed. Let $\{y(m): m = 1, \ldots, IN\}$ be a set of step elevations above an arbitrary level and z denote the depth of flooding measured from the first floor level. For an establishment located on m, the following relation holds:

$$z(hh,m) = y(hh) - y(m), \qquad hh \geq m,\ hh \in H.$$

Define

MD - *maximum possible damage* to the establishment due to flood of any magnitude with no response, $\alpha = 0.0$,

MR(z) - *unit reduction function* expressing the reducible fraction of MD induced by full response, $\alpha = 1.0$, when the depth of flooding is z,

$\delta(z)$ - *unit damage function* (Bhavnagri and Bugliarello, 1965),

$\gamma(\alpha)$ - *unit cost function*, $\alpha \in A$.

Assuming now that, for a given establishment, the functions LC and LD are linear transformations of the appropriate unit functions, it is a simple matter to verify that

$$LC(\alpha) = MD\gamma(\alpha),$$

$$LD(\alpha,hh,m) = MD[1-\alpha MR(hh,m)]\delta(hh,m).$$

As shown in Krzysztofowicz et al. (1978), the above approach offers an enormous advantage in both increasing the computational efficiency of the dynamic programming algorithm and in reducing the amount of information needed from a field survey for estimation of the loss function.

CASE STUDY

The model of the FFR process has been developed under an assumption that the response subsystem is a single DM. If the response subsystem consists of a group of DMs, then the performance, PE, of the FFR system can be obtained by summing up the performances obtained for individual DMs. Inasmuch as for a large community such an approach would require prohibitive amount of computations (e.g., solving a stochastic dynamic programming problem for each DM), a version of the FFR model, which, under certain additional assumptions, is computationally efficient for even very large communities, has been developed and is documented elsewhere (Krzysztofowicz et al., 1978).

The case study reported herein was done for Milton, a community with population of about 8,000, located on the West Branch of the Susquehanna River in northeastern Pennsylvania. Flood data were provided by the River Forecast Center at Harrisburg. An inventory of structures was obtained from Baltimore district of the Corps of Engineers. Information regarding the dissemination of forecasts was given by the Susquehanna River Basin Commission. The actual response strategy was simulated from a mathematical model of human response to flood warnings. This model was developed by Ferrell and Schmidt (see Krzysztofowicz et al., 1978).

An example of the evaluation results is presented in Table 1 for three DMs: (1) a large residence containing two stories, a basement, and high quality furnishings, and located 12 feet above the flood stage in the 50-year floodplain, (2) the ACF plant, located 6 feet above the flood stage in the 17-year floodplain, and (3) the whole town of Milton.

One of the most important features of the FFR model is perhaps its capability to quantitatively evaluate the effectiveness of a change in any of the components of the FFR system. As an example, we analyzed the effects of increased lead time, LT, and reduced processing time, PT. The results of this analysis are given in Table 2. Another sensitivity analysis is illustrated in Figure 2. The ACF Plant, located actually on step 4 of the floodplain, was "moved" up and down, and the FFR system was evaluated for each location of the plant. Figure 2 shows the efficiency across the steps of the floodplain. It has to be pointed out that for each location of the plant, the actual response strategy was computed as if the DM's experience with floods corresponded to the frequency of floodings for this particular step. Inasmuch as a DM on a high step has relatively small experience, he acts somewhat reluctantly; hence, the efficiency drops for high levels. In addition, the effect of decreasing PT by two hours was evaluated, again, as a function of steps.

More sophisticated changes in both hydrologic and human components of the system, which can be investigated by means of the FFR model, include, for instance, usage of radar observations in preparation of the forecasts, usage of quantitative precipitation forecasts, and increased community preparedness for floods.

Table 1. Results of Evaluation of FFR System in Milton, Pennsylvania

Structure(s)		Residence	ACF Plant	All Milton
Elev. above flood stage [ft]		12	6	0-21
Max. possible damage, MD [$]		46,900	3,500,000	48,599,580
EXPECTED ANNUAL LOSS [$]				
	EL^0	472	176,842	1,541,249
	EL**	336	95,910	883,363
	EL*	424	160,415	1,404,766
	EL^a	471	170,699	1,510,198
PERFORMANCE [$]				
potential value,	PV	136	80,932	657,886
optimal value,	OV	48	16,427	136,483
actual value,	AV	1	6,143	31,051
EFFICIENCY				
forecasting system,	EF	.353	.203	.207
response system,	ER	.021	.374	.228
overall,	EO	.007	.076	.047

Table 2. The Effects of Changes in Lead and Processing Times for FFR System in Milton, Pennsylvania

Change in[1] Lead Time, LT	Change in[1] Processing Time, PT	Efficiency \ Structure	Residence	ACF Plant	All Milton
0	0	EF	.353	.203	.207
		ER	.021	.374	.228
		EO	.007	.076	.047
+6	0	EF	.410	.220	.220
		ER	.024	.440	.380
		EO	.010	.097	.084
0	-2	EF	.440	.240	.200
		ER	.025	.560	.560
		EO	.011	.134	.112

[1] Actual lead time is 5-13 hrs and actual processing time is 2.5-3.5 hrs.

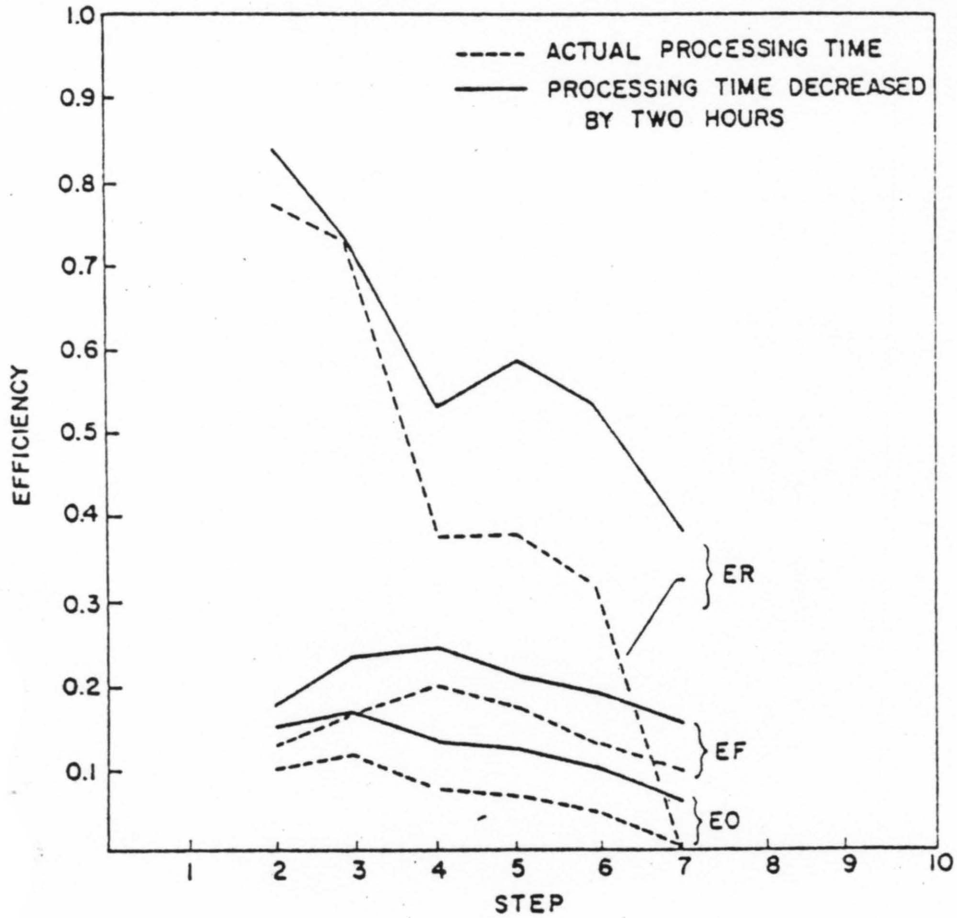

Figure 2. Efficiency as a function of the location in the floodplain for the ACF Plant, Milton, Pennsylvania

SUMMARY

A comprehensive systems model of the whole flood forecast-response process has been developed. It enables the quantitative evaluation of flood forecast-response systems in reducing urban property damage. This model represents a significant advance in evaluation methodology due to its explicit recognition of the following features: (1) the sequential nature of flood forecasts and the responses to them, (2) the simultaneous consideration of the performance of the forecasting model, the speed of the dissemination process, the decision behavior of the floodplain dweller, the type and location of the structures in the floodplain, and the stochastic nature of the actual flood process.

ACKNOWLEDGEMENTS

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APPENDIX B

SUMMARY OF THE HUMAN FACTORS LEARNING MODEL

This appendix summarizes the human factors learning model. All response strategies labelled human factors were calculated on the basis of this model. The appendix was taken from the original report (Krzysztofowicz, et al., 1978, pp. 19-24).

The human factors mathematical model for response to warnings assumes that the decision maker (DM) begins to respond when he is sufficiently sure that a flood will reach his property. His degree of certainty that this will happen is represented by a subjective probability, the value of which depends on his past experience with floods and losses and on the warnings he receives. When his subjective probability exceeds a threshold, he takes a characteristic course of action that will result in savings should he be flooded. The amount of savings he can accomplish is limited by the time available to him, and he stops his protective action if the flood reaches his property, or if the crest occurs below it. Following a flood incident, the decision maker learns from that experience. The specific features of this are described below.

It is assumed that when the decision maker arrives on the floodplain his subjective probability of a flood $p(F)$ and of a loss given a flood $p(L|F)$ are both essentially zero. The DM revises his subjective probability of a flood $p(F)$ toward the historical value for his area, to an extent dependent on his willingness to learn, whenever a flood occurs. Between floods the probability decays exponentially toward zero. The tendency to be concerned about flooding right after floods and for that concern to diminish in time has been widely reported in the literature.

Similarly the subjective probability of a loss given a flood, $p(L|F)$ is revised toward the experienced frequency with each loss, again to a degree dependent on the willingness to learn. And it too decays between losses.

Figure B-1 shows the model's output for the time course of the subjective probabilities of a flood and of a loss given a flood for a DM who began residing on the Milton, Pennsylvania floodplain (at level $m = 4$) in 1940 in time for that year's flood. The initial zero probabilities are quickly modified toward their historical values, but a long period without loss, such as that before Agnes, produces a very low prior probability of loss.

The DM's subjective probability of a loss at any time a warning has not been given is assumed to be $p(F)p(L|F) = p(F,1)$. This would be indicative of the DM's willingness to take precautions prior to a flood, seek insurance or abatement projects, or learn how better to protect his property.

When a warning is issued, it is assumed that the DM revises his prior probability, the current value of $p(L|F)$, to obtain a posterior value. The model for revision is the prescriptive Bayesian model in which the posterior odds are obtained by multiplying the prior odds by the likelihood ratio for the data (i.e., for the set of warnings received) with the modification that a subjective likelihood ratio is used, one which is closer to unity than the correct "historical" value. This means that the DM's revision is "conservative," i.e., he changes his opinion less than the warnings actually warrant.

Figure B-2 shows the revisions of the prior from Figure B-1 that the model indicates would have occurred during the warning sequences of the

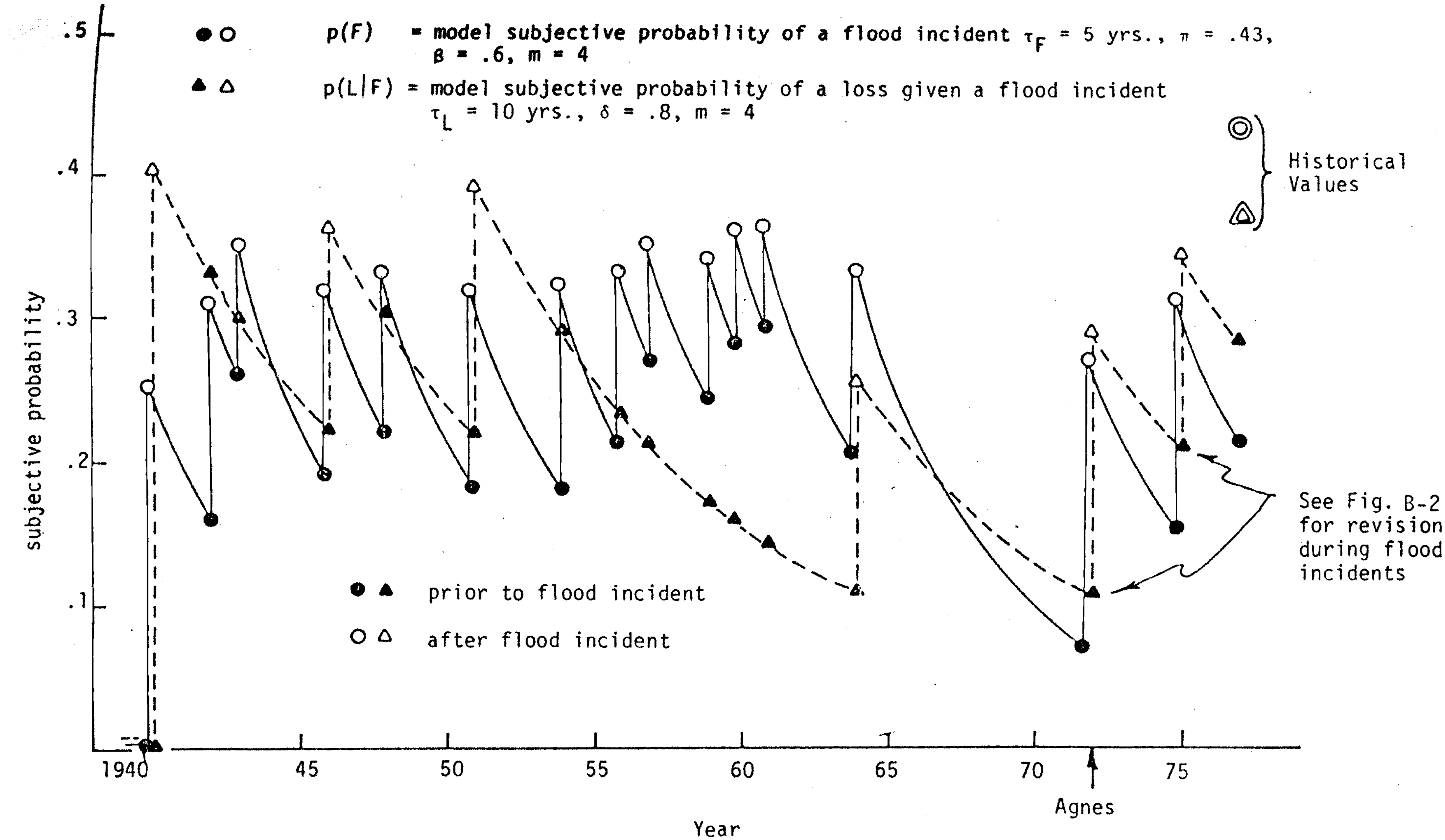

Figure B-1. Subjective uncertainty for floods and flood losses for Milton, Pennsylvania for a resident on level 4 who moved there in 1940

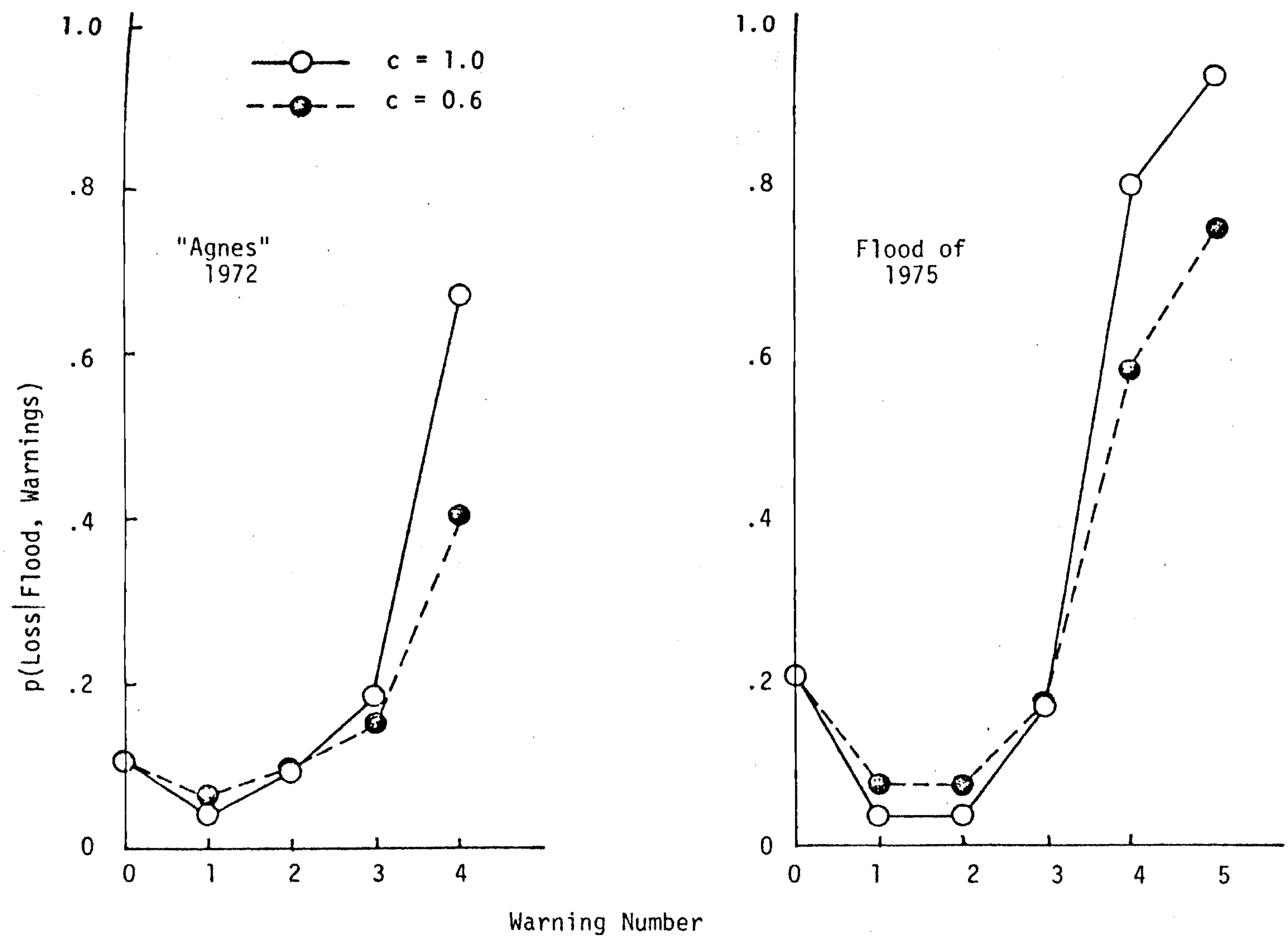

Figure B-2. Predicted revision of prior as the result of floodwarnings. Priors from Figure B-1. C is the exponent to which the likelihood ratio is raised to represent discounting the warning.

floods of 1972 (Agnes) and 1975. The likelihood ratios were calculated from the entire historical record for Milton from 1940. It is particularly interesting to note that the early predictions, being for low crests, result in downward revision of the prior--i.e., the DM is led to believe that he is less likely to suffer a loss than he previously thought. Since early forecasts for small floods are also for low crests and since most floods do not cause a loss for the DM on level 4, this is correct behavior on his part.

When the revised prior probability of a loss exceeds a threshold value characteristic of the individual DM, he then takes protective action. The model does not define the nature of the protective action, except that it assumes a fixed sequence such that the proportion of possible protection achieved is a function of the time spent working at it. Certain major protective efforts, such as complete evacuation of goods, will not be undertaken unless there is even greater subjective certainty that a loss will occur, and the model assumes successively higher thresholds for actions such as these.

Following a flood incident and its outcome of loss or no loss, the DM revises his probabilities of flood and of loss. In addition, he could be expected to modify either his threshold for action or his degree of belief in the warnings he receives, or both if there had been discrepancies among his revised probability, the warnings given and the actual outcome. If he suffered a loss but had a low revised probability of loss in spite of warnings he would be more inclined to believe warnings next time, and to act sooner. If there were no loss, but he had taken protective action on the basis of a high probability of loss he would be less likely to believe the warnings. If the DM learns, as a result of the flood or at any time, how better to protect his property, the change in his knowledge is reflected in a suitable change in the function describing the amount of protection he can achieve with time.

APPENDIX C

PARAMETERS FOR THE FFR SYSTEM

```
***********
          *
NOTATION  *
          *
***********
```

AN	=	NUMBER OF DISCRETE POINTS IN DECISION SPACE
IN	=	NUMBER OF STEPS IN THE FLOOD PLAIN
KN	=	MAXIMUM NUMBER OF FORECASTS
RN	=	NUMBER OF STRUCTURAL CATEGORIES
K	=	DECISION TIME
DET(K)	=	TIME INTERVAL BETWEEN DECISION TIMES
PT(K)	=	PROCESSING TIME
DT(K)	=	DISSEMINATION TIME
LT(K)	=	AVERAGE ACTUAL LEAD TIME
PW(W,K)	=	PROBABILITY OF W(K)
EN	=	EXPECTED NUMBER OF FLOODS PER YEAR
I	=	CURRENT FLOOD LEVEL
H	=	FORECASTED FLOOD CREST
Y(M)	=	ELEVATION OF A STEP
PHH(H)	=	PROBABILITY OF ACTUAL CREST
PC(I,H)	=	INITIAL CONDITION
M	=	LOCATION STEP
R	=	STRUCTURAL CATEGORY
DMN	=	NUMBER OF DECISION MAKERS IN THE REACH
MDR	=	MAXIMUM POSSIBLE DAMAGE FOR THE REACH IN DOLLARS
E(M,R)	=	DISTRIBUTION PARTITIONING MDR

```
************************
*                      *
* FORECASTING SYSTEM   *
*                      *
************************

AN        =     11
IN        =      9
N         =      8
N         =      7

          =     1      2      3      4      5      6      7      8

DET(K)    =    6.0    6.0    6.0    6.0    6.0    6.0    6.0    6.0
T(K)      =    3.5    3.4    3.3    3.2    3.1    2.9    2.8    2.7
T(K)      =    1.0    1.0    1.0    1.0    1.0    1.0    1.0    1.0
LT(K)     =    5.0    6.0    7.0    8.0    9.0   10.0   11.0   12.0

PW(1,K)   =   .960   .830   .710   .580   .460   .330   .210   .080
PW(0,K)   =   .040   .170   .290   .420   .540   .670   .790   .920

EN        =   .529

M,H       =     1      2      3      4      5      6      7      8      9

I(M)      =   16.0   19.0   22.0   25.0   28.0   31.0   34.0   37.0   40.0
PHH(M)    =   .106   .128   .170   .167   .159   .126   .084   .044   .016

FO(I,M)   =

               M

               1      2      3      4      5      6      7      8      9

   I      1   .194   .284   .253   .138   .046   .009  0.000  0.000  0.000
          2  0.000   .034   .028   .015  0.000  0.000  0.000  0.000  0.000
          3  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000
          4  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000
          5  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000
          6  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000
          7  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000
          8  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000
          9  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000
```

Milton

```
**********************
*                    *
* FORECASTING SYSTEM *
*                    *
**********************
```

:N	=	11									
'N	=	9									
N	=	10									
:N	=	2									
.	=	1	2	3	4	5	6	7	8	9	10
ET(K)	=	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0
FT(K)	=	5.7	5.2	4.7	4.1	3.6	3.1	2.6	2.1	1.6	1.1
CT(K)	=	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
LT(K)	=	71.0	65.5	60.0	54.5	49.0	43.5	38.0	33.0	27.5	22.0
PW(1,K)	=	.985	.650	.420	.285	.190	.125	.080	.055	.035	.025
PW(0,K)	=	.015	.350	.580	.715	.810	.875	.920	.945	.965	.975
:N	=	1.368									
M	=	1	2	3	4	5	6	7	8	9	
F(M)	=	24.0	27.0	30.0	33.0	36.0	39.0	42.0	45.0	48.0	
PMM(M)	=	.113	.174	.192	.201	.148	.104	.050	.016	.003	

PC(I,H) =

H

	1	2	3	4	5	6	7	8	9
1	.130	.228	.270	.215	.115	.042	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
3	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
6	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
7	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Columbus

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*************************
*                       *
* FORECASTING SYSTEM    *
*                       *
*************************
```

IN	=	11								
:N	=	9								
[illegible]	=	8								
[illegible]	=	2								
[illegible]	=	1	2	3	4	5	6	7	8	
LET(K)	=	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	
?T(K)	=	4.0	3.7	3.5	3.2	2.9	2.6	2.4	2.1	
DI(K)	=	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
LT(K)	=	37.0	32.5	28.0	23.3	18.7	14.1	9.5	5.0	
P(1,K)	=	1.000	.750	.390	.200	.100	.050	.030	.010	
P(0,K)	=	0.000	.250	.610	.800	.900	.950	.970	.990	
EN	=	2.667								
[illegible]	=	1	2	3	4	5	6	7	8	9
(P)	=	16.0	20.0	22.0	24.0	26.0	28.0	30.0	32.0	34.0
PHH(K)	=	.004	.028	.068	.171	.227	.223	.163	.073	.023

PG(I,P) =

P

	1	2	3	4	5	6	7	8	9
1	.051	.106	.158	.167	.124	.066	.028	.007	0.000
2	0.000	.052	.072	.070	.049	.024	.008	0.000	0.000
3	0.000	0.000	.009	.008	.005	0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
6	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
7	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Victoria

APPENDIX D

HUMAN FACTORS/RESPONSE SIMULATION VARIABLES: RELATIONSHIPS AND REFERENCES

I. WARNING VARIABLES

Warning variables are listed under Group Variable (15) Belief in Flood Threat

II. INDIVIDUAL VARIABLES

SEX

Individual variable (1) exogenous

Belief -- Women are more likely to believe warning than men
(Mack and Baker, 1961; Drabek, 1969)

Response -- Women at the extreme of adaptive-maladaptive spectrum
(Mack and Baker, 1961)
More anxious to evacuate than men
(Moore, et al., 1963:125)

AGE

Individual variable (2) exogenous

Belief -- Inversely related to age, the older the less believing
(Friedsam, 1961, 1962; Mack and Baker, 1961)

Response -- Inversely related, less likely for the old than the young to act
(Friedsam, 1962; Moore, et al., 1963)

NIGHT SHIFT/DAY SHIFT

Individual variable (3) exogenous

Related to warning reception through time of day of warning message

= -1 night shift 0000 - 0700

= +1 day shift 0700 - 2400

ROLE CONFLICT, SOCIO-ECONOMIC STATUS, URBAN/RURAL, ORGANIZATIONAL MEMBERSHIP

Individual variable (4) exogenous

Organizational Membership is related to belief--people belonging to large, complex organizations are more likely to believe warnings (Mack and Baker, 1961; Moore et al., 1963)

Urban/Rural - related to belief--small town residents less likely to believe than urbanites (Mack and Baker, 1961)

Socio-Economic Status - related to belief--tendency for low or high education levels to disregard formal meaning of warning (Mack and Baker, 1961)

Role Conflict - related to belief through response--conflict hampers response and lowers belief through cognitive dissonance elimination (Fogelman, 1958; Thompson and Hawkes, 1962; Bates, et al., 1963; Moore, et al., 1963)

PAST EXPERIENCE

Individual variable (5), Group variable (14) exogenous

Confirmation -- People with previous disaster experience are more likely to go through organizational channels for confirmation than inexperienced people

Related to confirmation (Mack and Baker, 1961)

Belief -- P(f) (post warning) related to belief (Wallace, 1956; Demerath, 1957; Williams, 1957; Fritz, 1961; Mack and Baker, 1961; Drabek and Boggs, 1968; University of Oklahoma Research Institute, 1953)

Response -- P(F) as above, related to response (Menninger, 1952; Killian, 1956; Fritz and Williams, 1957)

PERCENT OF GROUP VOTE

Individual variable (6) exogenous

Used to translate measure of individual belief into Group Variable 15

The head of the household has the largest voting share. Spouse and older children have decreasing share.

PRIOR PROBABILITY OF FLOOD

Group Variable (14) exogenous (but calculated)

Individual Variable (5) exogenous (but calculated)

$$P_n(F|t_n) = \beta\pi + (1-\beta)\ P_{n-1}(F|t_{n-1})\ \exp\ [-(t_n-t_{n-1})\ \gamma_F]$$

Source: Mathematical model from previous report

III. GROUP VARIABLES

NUMBER IN GROUP

Group variable (1) exogenous

Indirectly important in determining the maximum response intensity

Used mainly to keep track of group boundaries when deciding with individual calculations

WARNED/UNWARNED

Group variable (2) exogenous

If state is Defensive Avoidance/Evacuated

or Message conveyed through media

and if random number is less than e^{-ALPHA}

where ALPHA = Media Saturation $\times \begin{cases} +1 \text{ if time of day 0700-2300} \\ -1 \text{ if time of day 2300-0700} \end{cases}$

$\times \begin{cases} +1 \text{ if night shift} \\ -1 \text{ if day shift} \end{cases}$

Then message is not recieved--otherwise message is received

Note: If time of day and shift do not correspond (i.e., worker is asleep) then--ALPHA is positive and the random number has to be less than e^{-ALPHA}, $0 \leq RN \leq 1$. If they correspond, then exponential distribution is determining.

NUMBER OF WARNINGS RECEIVED (NWR)

Group variable (3) endogenous

Counter based on the number of different warnings received by a group. Recall that if one member of a group receives a warning all members are considered warned. This counter is incremented only if the current warning contains different information from that of the previous warning.

Number of warnings received incremented if warning (K) ≠ warning (K-1).

Confirmation [inversely related to attempt to confirm] (Drabek 1969).

Belief -- Belief increases as NWR increases--direct relationship (Fritz, 1961; Drabek and Boggs, 1968; Drabek, 1969).

CONFIRMED/NOT CONFIRMED

Group variable (4) endogenous

= 1 if official confirmation received once

= -1 if confirmation never received

Computed as weighted average of communication mode, prior prob. and proximity to source.

Communication mode--people warned via media more likely to confirm than those warned by other mechanisms (Drabek, 1969; Drabek and Stephenson, 1971).

Prior prob--related to prior experience: people with prior experience are more likely to seek official confirmation than those without experience (Mack and Baker, 1961).

Proximity--the closer to the source of threat the greater the number of information sources sought (Diggory, 1956).

STATE

Group variable (5) endogenous Source (Janis and Mann, 1976)

Evacuated/Hypervigilance--Evacuation occurs when time to impact will occur within current cycle. Hypervigilance occurs when danger is imminent and all sources of escape have disappeared. Hypervigilance is not used in the model since it is not differentiable from evacuation and has no effect on savings.

Defensive Avoidance--Occurs when expected loss is greater than loss threshold and all response costs exceed their respective savings.

Unconflicted Change--Occurs when present response strategy leads to an expected loss greater than threshold but known alternative offers loss less than threshold. Alternate is adopted.

Unconflicted Adherence--is really the default state and results when the present strategy is not changed in present cycle; for example, a state of unconflicted change at cycle K-1 is changed to unconflicted adherence at cycle K if the response strategy at cycle K is the same as the strategy at cycle K-1.

Warned for first time--is the temporary state held for the period of time between receiving the first warning and adopting the first response strategy.

Vigilance--occurs when no response yields a loss less than threshold but a response is found that yields a response cost less than the savings expected for that response.

CONCERN/UNCONCERN

Group variable (6) endogenous

This variable is a flag with value:

1 if present belief level is greater than concern threshold

-1 if present belief level is less than concern threshold

0 if the group has not been warned - no opinion

RESPONSE INTENSITY

Group variable (7) endogenous

The rate of Man Hours of Labor/hour being expended by the group. The rate is the value that does not exceed the maximum possible value of MH/hr that allows the response strategy to realize adequate savings so that the expected loss is less than the loss threshold. If this is not possible, then there is no satisfactory solution and a less than satisfactory solution is adopted as well as a state of vigilance. In this case, intensity is set to its maximum value.

PROXIMITY TO THE RIVER

Group parameter (8) exogenous

Confirmation -- Closer to target area, higher word-of-mouth communication, the larger the number of sources

Related to confirmation (Diggory, 1956)

In terms of number of sources used for confirmation, proximity inversely related to confirmation.

Belief -- Greater the proximity to the threatened area, smaller the tendency to overestimate threat magnitude

Directly related to belief (Diggory, 1956)

Response -- Closer to impact, greater likelihood of taking adaptive behavior

Directly related (Diggory, 1956; Danzig, 1958)

Proximity is basically a measure of horizontal distance, although vertical "height" of the house with respect to local elevation is the significant factor in flooding. It is assumed that the resident knows only the former but assumes it to be exactly correlated with the latter.

CONCERN THRESHOLD

Group variable (9) endogenous

The value of this variable is affected by the groups with other groups. If the group is "concerned", i.e., their value exceeds the concern threshold, but they find a plurality of who are unconcerned, then the concern threshold is raised.

ACCUMULATED MAN HOURS FOR PRESENT RESPONSE

Group variable (10) endogenous

This variable is incremented by 3 x Response Intensity for states of unconflicted adherences on each cycle. Any other state will reset the value to zero and then increment by 3 x Response Intensity.

VALUE OF THREATENED PROPERTY

Group variable (11) exogenous

This is the dollar value of the maximum loss that could occur from flood damage.

PERCENT OF MAXIMUM LOSS THAT CAN BE AVERTED

Group variable (12) exogenous

This quantity is equal to $\frac{\text{Dollar value of damage that can be averted}}{\text{Dollar value of maximum flood damage}}$

MAXIMUM POSSIBLE MAN HOURS/HOUR FOR GROUP

Group variable (13)

This variable is the upper limit for Response Intensity

$$\text{Max MH/hr} = \sum_{i=1}^{\text{Group size}} \text{sex}(i) \times \text{age}(i)$$

$$\text{sex}(i) = 1-\alpha \text{ for males} \qquad \text{age}(i) = 1 \text{ if } 15 < \text{age} < 40$$

$$= \alpha \text{ for females} \qquad = 0.5 \text{ if } 11 < \text{age} < 14 \text{ or } 41 < \text{age} < 55$$

$$= 0 \text{ if } 56 < \text{age} < 11$$

PRIOR BELIEF IN FLOOD THREAT

Group variable (14) exogenous

For more information see individual variable (5)--individual prior belief.

This group variable is the weighted average of individual priors. The weights are individual variable (6) - percent of voting strength.

$$\text{Prior Group Belief} = \sum_{i=1}^{\text{Group size}} \text{\% of vote } (i) \times \text{Individual Prior}$$

BELIEF IN FLOOD THREAT

Group variable (15) endogenous

This value is the weighted sum of the following variables multiplied by crest height x proximity. Note: GV = Group Variable

WV = Warning Variable

GV(3) = number of warnings received; belief increases as the number of warnings received increases (Fritz, 1961; Drabek and Boggs, 1968; Drabek, 1969)

WV(warning variable)(3) = environmental cues; belief increases to the extent that changes in the environment support the belief (Williams, 1956; Mack and Baker, 1961)

GV(14) = prior belief; experience related to belief (proportional) (University of Oklahoma Research Institute, 1953; Instituut voor Sociaal Onderzoek van Het Nederlandse Volk Amsterdam, 1955; Wallace, 1956; Demerath, 1957; Williams, 1957; Fritz, 1961; Mack and Baker, 1961; Drabek and Boggs, 1968)

WV(6) = communication mode; official sources that deliver message personally carry more authority than media messages (Clifford, 1956; Moore et al., 1963)

WV(7) = information content; accuracy and informativeness of warnings increase belief (University of Oklahoma Research Institute, 1953; Clifford, 1956; Demerath, 1957; Fritz, 1957; Goldstein, 1960; Schatzman, 1960; Mack and Baker, 1961; Withey, 1962)

WV(8) = crest height; crest height predictions are assessed with respect to proximity to estimate the chance of the flood affecting the group

IV(4) = socioeconomic status, role conflict, urban/rural, organizational membership; the weighted (by voting percentage) average of the conglomerate of these factors is part of the weighted sum for belief

Socioeconomic status and organizational membership; high and low education levels are more disbelieving. Organizational membership increases belief (Mack and Baker, 1961; Moore et al., 1963)

Urban/Rural; small town inhabitants are less believing than city dwellers (Mack and Baker, 1961)

Confirmation GV(4); confirmation increases belief (Mack and Baker, 1961; Danzig et al., 1958; Withey, 1962; Drabek and Boggs, 1968; Drabek, 1969; Drabek and Stephenson, 1971)

Age of principal decision makers IV(2); the older the individual, the less likely he is to believe the warning (Friedsam, 1961; Friedsam, 1962; Mack and Baker, 1961)

Sex IV(1); women are more likely to believe warnings than men (Mack and Baker, 1961; Drabek, 1969)

Proximity GV(8); the closer to the threat source the more accurate the danger estimate (Diggory, 1956)

EXPECTED LOSS

Group variable (16) endogenous

Expected Loss (given response strategy) = Maximum loss - loss averted + cost of response

Maximum loss = exogenous group variable (11)

Cost of response = sum of table values of exogenous array of response costs

Loss averted = (crest height - proximity) x (Maximum Loss) - [Response Table Savings (Accumulated) x (Maximum Loss)]

Accumulated man hours is the index for the response table

	Man-Hours					
	3	6	9	12	15	. . .
Response A	5%	10%	20%	22%		

For example, for Response A, if six man hours were accumulated, the loss averted would be

[(crest height - proximity) - (.10)] x maximum loss (dollars)

If 12 man hours had been logged, then the formula would be

[(CH - P) - (.22)] maximum loss (dollars)

PERCENT OF LOSS AVERTED

Group variable (17)

$$= \frac{\text{dollar value of loss (actual)}}{\text{dollar value of loss with no response}}$$

$$= \frac{\text{crest height} - \text{proximity} \times \text{maximum possible damage} - \text{response table} \;\; \text{man hours} + \text{response cost}}{\text{crest height} - \text{proximity} \times \text{maximum possible damage}}$$

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