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# SYSTEM MODELLING FOR FLOOD CONTROL DECISIONS

by

D.K. Robinson and D.T. Howell

## S U M M A R Y

The problem of deciding on the best combination of flood control measures and the best level of flood control for any given situation is dealt with in terms of the identification of objectives and the establishment of quantitative criteria or measures of performance for those objectives.

The measures of performance are evaluated from a system model made up of components to simulate rainfall, the runoff from a catchment, the behavior of a flood plain and the generation of flood loss. A brief numerical example is given.

D.K. Robinson, N.S.W. Department of Public Works
D.T. Howell, The University of New South Wales

## 1. INTRODUCTION

The making of flood control decisions requires the comparison of alternative methods of reducing flood loss and the determination of appropriate levels of flood mitigation. Comparisons may be made on the basis of measures of performance, which demand the use of models which can yield estimates of the losses due to floods. The development of such a model will be described and related to decision criteria.

## 2. NATURE OF THE PROBLEM

The problem confronting the designer of a flood control scheme is to determine the optimal scale of a variety of measures so as to realise certain predetermined objectives to the greatest extent possible. It then has to be decided whether the performance of the scheme warrants the expenditure of the scarce resources necessary for its implementation. To carry out these tasks it is necessary to establish the characteristics of the process which leads to flood losses and to determine the effects of flood losses. The objectives of design must be established and a method of measuring the performance of a scheme in relation to the objectives developed. The decision maker can then compare alternatives and make decisions in terms of this quantitative measure.

The flow of a river varies from time to time largely in a random manner. A river is usually confined to a narrow water course, but such a river occasionally breaks out to inundate the surrounding floodplain. The flood plain, formed by the deposition of silt, is often valuable for agricultural production. Flood plains have locational advantages that have lead to considerable development of other activities on them. It is a sound economic proposition to develop floodplains if the benefits obtained are greater than the total costs incurred.

Flood control measures are intended to lower the costs of floodplain use. This cost lowering may be achieved in two ways. First, if the losses for a certain activity exceed the benefits, the activity may be removed from the floodplain and another activity substituted, e.g. frequently flooded houses may be replaced with parklands. Second, the control of flooding so as to lower losses is often achieved with engineering structures.

A catchment may be modified in a number of ways, such as by clearing forests or replanting them with exotics, by improving river channels, by rerouting rivers and by building dams. A floodplain may be modified by building levees, excavating floodways, controlling the flooding of storage areas and by improving drainage. The loss potential of the floodplain may be modified by substituting different activities for those already there, by banning some activities and by modifying present activities to minimise damage.

The problem is to decide to what extent, if any, all or any of these measures should be implemented in any given situation. It is necessary to be able to incorporate the effects of any of them in a measure of performance.

## 3. NATURE OF THE FLOOD LOSS PROCESS

Floods cause damage and interrupt activities.

The inundation of a floodplain occurs when rainfall on a catchment is at a sufficiently high rate for a sufficiently long period for runoff collected in tributary streams and led into main streams to give rates of flow in excess of what can be carried by the streams at bank full stage. This inundation may interrupt economic activities such as dairying, may destroy crops, building and various public utilities and interfere with ordinary living.

In examining the flood loss process, with the aim of reducing losses, it is necessary to trace the generation of floods back to a source that cannot be modified by man (at least for the present). That source is rainfall. The flood process may be conveniently divided into four processes: rainfall, flow across the catchment into the various river channels, flow out of the various channels onto the flood plain and flood loss generation.

If rainfall is considered to be a statistically stationary process, it can be considered a suitable foundation on which to base the analysis.

## 4. OBJECTIVES OF FLOOD CONTROL

To design a flood control scheme rationally it is necessary to evaluate its objectives and then measure the performance of the scheme with respect to these objectives. The following objectives are often of great importance in the evaluation of flood control measures.

(a) National Economic Growth

It is convenient to consider the contribution to national economic growth of flood control schemes in terms of the minimisation of some of the cost of capital works and the cost of the residual flood damage. These costs may be readily measured in dollars, in terms of the market value of goods and services, and are conveniently expressed as long term average or expected annual costs.

(b) Variability Reduction Objective

The variability of flooding is of great importance to the floodplain user. If the pattern of flooding is very predictable, e.g., that caused by spring snow melt, it is possible to budget for it accurately. However, if it is irregular, this cannot be done, and a larger sum must be set aside to cover randomly occurring losses. Variability may be measured in terms of the standard deviation of the flood loss distribution.

Dorfman (1) has given an account of a method suggested by H.A. Thomas, Jr., which can be used to account for both the mean and variance of flood loss when comparing two different schemes. This procedure is realistic but arbitrary. It involves the setting up at the beginning of the economic life of the project of an interest-bearing contingency fund to cover the cost of failure. This fund is used to make up the difference between the cost of flooding in a particular year and the mean cost of flooding, be that difference positive or negative. The initial value of the fund is selected so that there is a certain arbitrarily chosen probability of its being exhausted. The value of the cost of variability, as given by Thomas, for a normal distribution of losses is stated below.

$$U = \frac{V\alpha\ \sigma}{\sqrt{2r}}$$

where $U$ = the cost of uncertainty, a "bank" set up at the beginning of the economic life carrying interest ($)

$V\alpha$ = a normal variate with $\alpha$% chance of being exceeded

$\alpha$ = the chance of the failure of the bank

$\sigma$ = standard deviation of annual flood losses ($)

$r$ = annual interest rate

This value may be readily combined with the total economic cost of flooding as defined by the national economic objective to give a picture of the cost of flooding to the flood plain users.

(c) Social Well-Being Objective

Another important reason for the construction of flood mitigation measures is to reduce the interference to activities caused by floods. These activities may be associated with economic pursuits such as earning a living or with others such as the convenience of one's mode of life. One appropriate measure of this objective is the mean number of days individuals are evacuated per annum. The most appropriate measure would need to be evaluated in each particular instance.

(d) Environmental Quality Objective

It is necessary to evaluate the impact of flood control works on the environment. In some instances this may be beneficial and in others detrimental. An example of a beneficial change would be the replacement of run-down, frequently inundated houses with parkland (which, incidentally, would offer less resistance to flood flows). A detrimental change may be associated with a change in the ecology of a certain area after the improvement of drainage. The appropriate unit will be decided by the characteristics of the particular scheme but could, for example, be acres of parkland created or acres of ecologically important swamp lands changed.

(e) Regional Economic Objective

A flood control scheme may be constructed to stimulate a particular region at the possible expense of the economy as a whole. This could be done for political or social reasons. The appropriate unit by which to measure this change is dollars but difficulty is currently found in quantification because of the scarcity of regional statistics in Australia.

## 5. QUANTITATIVE CRITERIA FOR FLOOD CONTROL OBJECTIVES

A variety of different quantitative criteria depending on the objectives of design may be established.

For the comparatively simple case of a national economic efficiency objective the decision criterion could be to minimise the total of the average annual cost of flood mitigation measures and the average annual value of flood losses. This can be alternatively stated as to maximise the excess of average annual flood mitigation benefits over the average annual cost of flood mitigation measures.

All criteria involve the determination of both benefits and costs. Costs of flood mitigation schemes are comparatively easy to estimate. Their benefits require the setting up of a model to estimate flood losses.

## 6. MODEL FOR PERFORMANCE ESTIMATION

A model is required to estimate the performance of the proposed scheme with respect to the various objectives considered important. The basic requirements of the model are that it is capable of describing the effects of possible prototype modification (to catchment, floodplain and loss processes) in both time and space, that it generate the flood loss distribution and other parameters required for objective performance estimation, and that it be computationally efficient. To do this it will be necessary to describe the various physical components of the flood loss process. Monte Carlo simulation is a modelling technique that satisfies these various requirements.

A suggested model formulation will be discussed in some detail. The model is broken down into four components to describe the flood loss process: rainfall simulator, catchment simulator, floodplain simulator, and flood loss simulator. In this discussion, the term performance statistics will be taken to mean a quantitative estimation of all the parameters required to measure performance in relation to an objective.

The rainfall simulator uses the statistics derived from historic rainfall data to generate periods of synthetic rainfall corresponding to a selected economic life of the project. Each period of rain is analysed and the resulting performance statistics are calculated and collated. The results of a number of periods are combined to define the performance of the scheme. A fifty-year economic life and the generation of daily rainfall is suggested.

Even when there are no catchment modifications it is often better to simulate rainfall events than flood events because the statistical parameters describing rainfall may be more accurately determined. The sampling errors associated with estimating the rain fall distribution are less because of the greater number of events occurring in the same time period. Also in many instances rainfall records have been kept for a greater number of years than accurate flood records.

The synthetic rainfall is examined day by day in the catchment simulator. When flood-producing rains are detected, the corresponding flood is determined and routed through the catchment. The characteristics of the flood required to calculate the flow across the floodplain are determined and passed to the floodplain simulator.

The floodplain is divided into a number of small areas where the flood parameters may be regarded as homogeneous. The flood flow across the floodplain is simulated and the flood parameters in each of the homogeneous areas calculated.

From the flood parameters in each area the values of the performance statistics for the various activities in it are calculated. The total values from the flood are then found by summing the values for each area. The parameter values are recorded for collation at the end of this simulation run and the examination of the daily rainfall values is recommenced.

The results of each flood are collated and the process is repeated to generate frequency distributions of the performance statistics. This method of model operation allows for the temporal adjustment of factors; the various models describing the process may be modified as the rainfall trace is examined day by day. The component models selected should be those that most aptly describe the process given the various constraints.

The effect of introducing flood mitigation measures may be determined by firstly modifying the model to describe the change and then generating a new set of performance statistics.

## 7. COMPONENTS OF MODEL FOR PERFORMANCE ESTIMATION

The model structure described in the preceding section can accommodate a variety of component models for particular parts of the process. The range of available models is large, and a few are listed. Rainfall simulation models have been dealt with by Wiser (2), Pattison (3) and Cornish (4). Catchment simulation models have been put forward by Crawford and Linsley (5) and Cordery (6). Floodplain simulation models have been suggested by Bell (7) and McDonald (8). Flood loss simulation has been dealt with by Bhavnagri and Bugliarello (9), James (10) and Robinson (11).

## 8. NUMERICAL EXAMPLE OF EVALUATION OF FLOOD LOSSES

The model described herein has been used to evaluate the performance with respect to a national economic efficiency and an income variability objective for the Macleay Valley on the mid-north coast of New South Wales. The valley has a catchment area of 4,400 square miles (11,400 square kilometres) and a damage prone floodplain of 156 square miles (400 square kilometres). The floodplain is predominantly used for beef and dairy cattle husbandry with small areas of maize being grown on the high natural levees. There is one town and a few villages subject to damage. The valley has a history of flooding. The longest flood to date occurred in 1949 and had a peak discharge of 500,000 cubic feet per second (14,000 cubic metres per second) which caused damage of many millions of dollars.

The model developed to describe the valley will be discussed component by component.

The rainfall simulator uses an urn type model developed by Cornish (4). In the model the historic rainfall pattern is analysed and divided into single dry days, single wet days and periods of consecutive wet days. Rain is generated by random selection from these three divisions and in accordance with the probability of their occcurrence and then by random selection of events within each division. Each event is successively recorded until the required period of rain is generated.

In the catchment simulator the daily rainfall is examined day by day with the use of an antecedent precipitation index - initial loss model as proposed by Cordery (6) to determine if initial loss is satisfied. If it is, rainfall excess is calculated with a $\phi$-index to estimate continuing losses and is routed through the catchment to the floodplains by means of a unitgraph. The loss caused by the flood is first calculated before the examination of the rainfall is recommenced.

The floodplain is divided into a number of small areas that may be regarded as homogeneous and the flood parameters of which may adequately be described by a unique set of values. The floodplain falls into eight distinct drainage basins. Each of these was further divided into sixteen one foot contours to form 224 sub-areas. The hydrograph was routed through the floodplain using a correlation model and the values of the following parameters were determined for each sub area: time of the year, depth and duration of inundation.

Flood loss models were developed to describe the loss to the beef and dairy industries, maize growing, towns and various utilities in terms of the three flood parameters. Further details are given by Robinson (11). The flood loss for each area is calculated and summed to give the total damage.

At the end of each simulation run the results from each flood are collated and the average annual flood loss is calculated. A number of different simulation runs are conducted to generate the average annual flood loss distribution.

The effect of varying the scale of a typical flood control structure was investigated using a fixed geometry storage reservoir placed between the catchment and floodplain components. The capacity of the reservoir was varied and the effect on the mean and the standard deviation of flood loss was determined. The value of the standard deviation was used to calculate the

variability cost for a 5% chance of failure and a 6% per annum interest rate. The results of the study are shown in the table below.

SUMMARY OF PERFORMANCE OF FLOOD CONTROL RESERVOIRS OF DIFFERENT CAPACITY

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| A | Reservoir capacity (thousands of acre feet *) | | 0 | 125 | 250 | 500 | 750 | 1,000 |
| B | Average annual flood loss | ($) | 382,000 | 184,000 | 140,000 | 81,500 | 39,200 | 18,600 |
| C | Standard deviation of annual flood loss | ($) | 72,000 | 38,000 | 46,000 | 28,000 | 22,000 | 16,000 |
| D | Equivalent uniform annual cost of variability (Thomas uncertainty fund x capital recovery factor for 50 years at 6% p.a.) | ($) | 160,000 | 94,000 | 85,000 | 70,000 | 51,000 | 33,000 |
| E | Average annual benefits from flood control reservoir (By subtraction in row B) | ($) | 0 | 198,000 | 242,000 | 300,500 | 342,800 | 363,400 |

* One thousand acre feet = 1.25 million cubic metres

The evaluation of a decision criterion could be completed with the inclusion of the costs of reservoirs of different capacity.

## 9. CONCLUSION

A model with features of the sort developed herein offers a reasonable method for the assessment of the performance of different flood control schemes. Appropriate decisions may be made if such a model is used to evaluate a quantitative decision criterion appropriate to the objective or objectives of the decision maker. The model may readily be modified to make quantitative estimates for a variety of objectives. It may also be modified to give results to varying degrees of accuracy.

## 10. REFERENCES

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