# Enhanced Freshwater Inflow to the Chesapeake Bay Through Reservoir System Operation

Stuart S. Schwartz
Water Resource Systems Engineer

Report 86-11b

August 1986

Interstate Commission on the Potomac River Basin
6110 Executive Boulevard, Suite 300
Rockville, Maryland 20852-3903

"A movement in behalf of an improved environment and quality of life is a gift to others and a joy that comes back to you"

Paul W. Eastman 1972

Paul W. Eastman, ICPRB's Executive Director since 1972 died on August 6, 1986. A rare grace and good humor marked his unwavering commitment to excellence and optimistic vision for the future. His great humanity and exemplary professionalism remain as the standard to be satisfied by those who follow him.

## TABLE OF CONTENTS

# ACKNOWLEDGMENTS

This report has benefited from thoughtful and animated discussions with many individuals. Dr. J. Hugh Ellis of the Johns Hopkins University shared his expertise on stochastic optimization and applications to water resource systems. Mr. Richard Olin, Mr. J. Ignatius, and Mr. P. Juhle generously shared their expertise and understanding of flood control operation and hydrometeorologic telemetry. Dr. James A. Smith, Director of the COOP section of ICPRB regularly shared his expertise and insight in hydrologic modeling and water resource management. Dr. Daniel P. Sheer offered stimulating discussion on the potential of randomized reservoir allocation.

The assistance which was received in completing this work is gratefully acknowledged. Responsibility for all assertions, errors and conclusions contained herein lies solely with the author.

This study resulted from the enthusiastic support and steadfast encouragement of original and creative work that was fostered at ICPRB by the late Paul W. Eastman. Those who had the privelege of knowing him are richer for the experience.

# LIST OF FIGURES

# LIST OF TABLES

# EXECUTIVE SUMMARY

During low flow periods in the summer and early fall, freshwater inflow to the Chesapeake Bay and its tributaries may be enhanced through non-structural means by modifying current operating procedures for multiple purpose reservoirs. Low flow enhancement through reservoir operation could provide incremental improvements to water quality and aquatic habitat as well as enhancing recreational opportunities and water supply reliability. This study examined techniques for allocating and operating shared reservoir storage. The emphasis of this study was operating procedures which would allow all authorized project purposes to be satisfied, while providing additional reservoir storage for use during low flow periods.

The feasibility of non-structural enhancement of freshwater inflow to the Chesapeake Bay requires that modified operating procedures preserve, if not enhance, the achievable benefits of each authorized project purpose in a multiple purpose reservoir. Strategic allocation of storage can increase the volumes available for both flood control and enhanced freshwater inflow. Tactical operation of flood control storage ensures that flood protection will not be compromised by sharing reservoir storage. The combination of strategic storage allocation and tactical reservoir operation offers the non-structural tools to realize enhanced benefits for all authorized project purposes in multiple purpose reservoirs.

- In most years up to 12 billion gallons of water supply storage on the North Branch of the Potomac River could be made available to enhance freshwater inflow to the Potomac estuary and the Chesapeake Bay. This storage could be utilized in the late fall without increasing the risk of water supply failure for current levels of municipal water demand.
- Traditional analysis of flood control storage has compared alternate storage volumes based on the expected monetary value of flood damages. For risky situations in which decisions must be made with caution, expected monetary value criteria understate the importance of rare events and can produce inferior results.
- Adjusting storage allocations in response to changing risks throughout the year, can make additional storage available while keeping operating risks at acceptable levels.
- A dynamic, risk based allocation can reliably reallocate water supply storage for flood control during the late fall and winter without significantly reducing the probability of refilling water supply storage by June 1.

- Traditional approaches to multipurpose reservoir management could more accurately be described as managing multipurpose impoundments, behind which a number of single purpose reservoirs are created.

- Reservoir reliability is provided by allocating additional volumes of storage for each authorized project purpose. These incremental volumes of storage are rarely used. The extra storage is allocated to hedge against hydrologic uncertainty.

- Both water supply and flood control risk vary seasonally. Maintaining fixed volumes of storage to hedge against hydrologic risk is equivalent to providing protection against extreme floods in the summer, and extreme droughts during the winter.

- Improved hydrologic forecasting and operating procedures provide a non-structural means to hedge against hydrologic uncertainty, freeing reservoir storage for other purposes.

# Enhanced Freshwater Inflow to the Chesapeake Bay Through Reservoir System Operation

# INTRODUCTION

A diverse set of benefits can result from the construction and operation of a reservoir. Historically these have included flood control and water supply benefits as well as hydropower, irrigation, recreation, water quality, and instream habitat protection. A single reservoir can be operated to serve several of these purposes, thereby increasing the overall benefits of the project. Such operation has become institutionalized in an emphasis on multipurpose reservoirs.

Although multipurpose reservoirs provide a mix of benefits, operationally, they are more accurately described as multipurpose impoundments, behind which a number of single purpose reservoirs are created. The analysis of operations in multipurpose reservoirs has traditionally used separate methodologies, examining the volume allocated for each purpose independently. These volumes are obviously linked through the capacity of the structure itself. The allocation of that total volume is determined in a benefit-cost framework, within the context of the priorities of the authorized project purposes.

This report examines the strategic allocation and tactical operation of flood control storage in multipurpose reservoirs to identify ways in which more efficient operating procedures could make storage available to enhance freshwater inflow to the Chesapeake Bay. Bloomington Reservoir on the North Branch of the Potomac River is examined as an example of the techniques developed in this report.

Section 1 considers two risk based allocation rules which share reservoir storage on an annual basis. In effect the allocation of storage between flood control and water supply is determined as a wager. The results are evaluated on an expected value basis. The use of an expected value criterion to compare storage allocations is also discussed

Section 2 provides a general overview of structural means for modifying flood hydrographs by operating flood control reservoirs. The goal of minimizing the flood peak at damage sites is linked to reservoir operating strategies. Operating rules are characterized as modifying the flood hydrograph through both attenuation of the peak flows, and delay of the entire hydrograph. A parametric operating rule is developed that uses only observations at the reservoir to make hourly flood control releases.

Section 3 describes a model of the North Branch of the Potomac River. A space-time model of thunderstorm precipitation is linked to a hydrologic model of the North Branch to produce multiple site hourly flood hydrographs. The damage reducing impacts of alternate operating rules for Bloomington Reservoir are compared through simulation.

Section 4 extends the parametric operating rule of section 2 to take advantage of telemetered hydrologic data and flood forecasts. An optimizing operating rule is proposed in which the risk of flood damage is balanced against the risk of overtopping the reservoir. Strategic operating targets are linked with tactical release decisions based on current hydrology.

Section 5 introduces a linear deconvolution technique for short term forecasting. The technique uses streamflow observations to estimate effective precipitation. Constrained optimization is used to estimate precipitation on an hourly time step. The method is shown to overcome a major drawback of similar estimation-prediction techniques. An example drawn from the hydrologic literature is used to illustrate the skill with which precipitation can be estimated.

## 1.0 Water Supply and Flood Control Storage Allocations

Integrated reservoir operation can reduce the competition for storage in multipurpose impoundments by actively reallocating storage throughout the year. While flood control storage should be available during the wet season, water supply operation does not require storage to be full during flood season. Water supply operation requires full conservation storage at the beginning of the water supply season - the end of the flood season. If the last flood of the season could be stored to fill water supply storage, there would be no conflict. The source of the conflict is the uncertainty concerning the probability of future runoff. Hedging against this uncertainty is currently accomplished by designating separate storage volumes for water supply, and flood control. Conservation storage is refilled as soon as possible to ensure adequate storage for the following low flow season. This operating strategy is used to hedge against the uncertainty in winter/spring runoff.

One way to represent this uncertainty is to compare the probability of successfully refilling conservation storage by late spring. Figure 1.1 shows the hydrograph for water year 1973. Consider a year in which water supply operations ended in October with a 12 billion gallon drawdown of conservation storage. If refill did not begin until day 92 of the water year (January 1) the hydrograph of water year 1973 would provide refill of conservation storage by day 129 (February 6). The refill of conservation storage could be delayed until day 212 (April 30) for this hydrograph, and still refill conservation storage in time for summer water supply operations. Delaying the refill of conservation storage would make available additional flood control storage during the winter and early spring, without compromising water supply reliability. The prudent operating rules that are followed, refill conservation storage as early in the year as possible in order to hedge against the uncertainty in estimating winter and spring runoff.

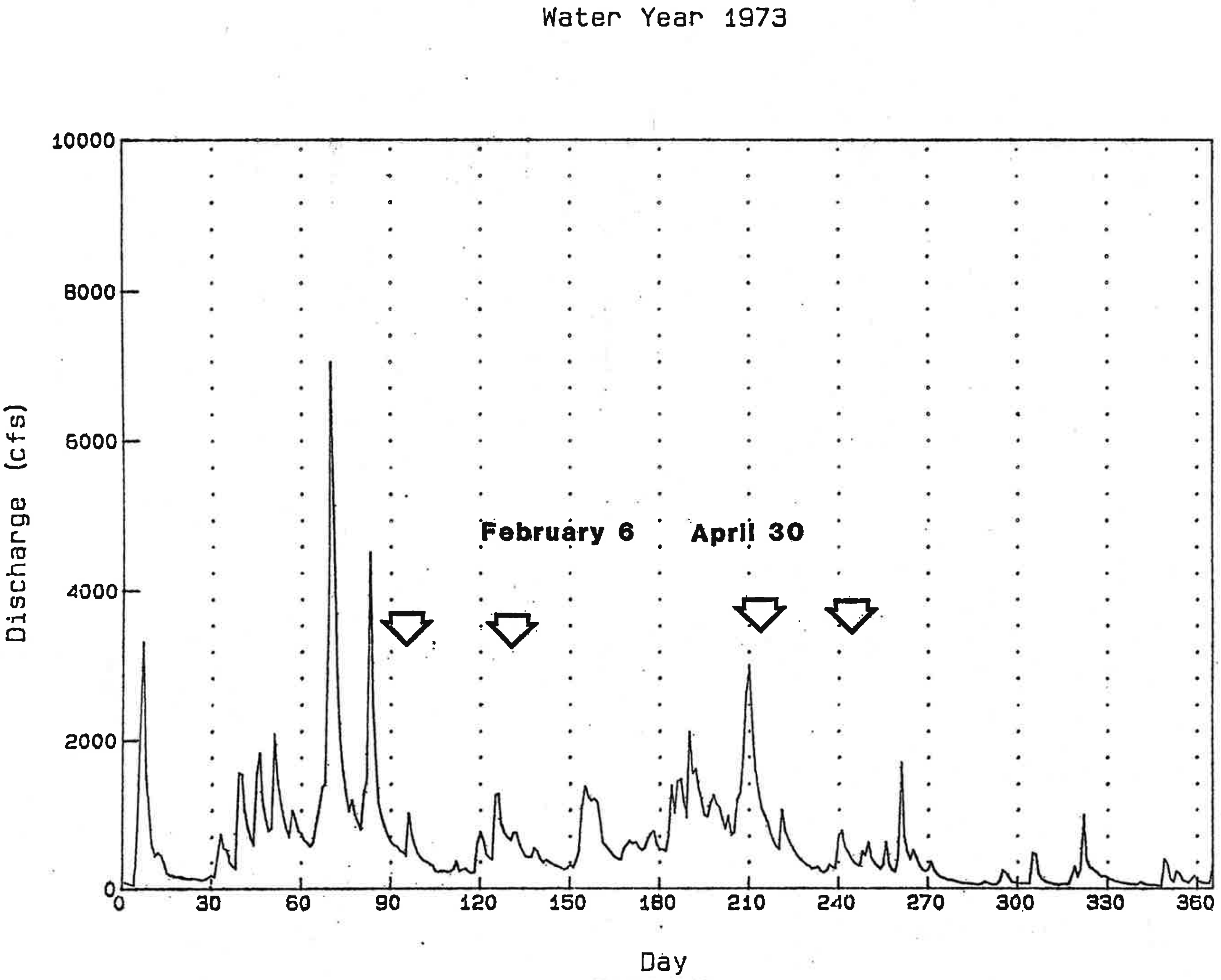

Water Year 1973
Discharge (cfs)
10000
8000
6000
4000
2000
0
Day
0
30
60
90
120
150
180
210
240
270
300
330
360
February 6
April 30

Figure 1.1

The probability of successfully refilling conservation storage will decrease as the water supply season approaches. When this probability is extremely high in the late fall, operations could delay refill or even drawdown conservation storage to provide additional water quality releases and flood control storage. Refill would begin as the probability of refill continued to decline. Figure 1.2 illustrates the decrease in the unconditional probability of cumulative runoff through May, for the USGS gage located at Kitzmiller, Maryland. The cumulative runoff probabilities illustrate the high probability of refilling water supply storage through the fall and winter. A simple dynamic storage allocation could be implemented in which water supply storage was made available for flood control until the probability of refill fell below a predetermined level of reliability. At that time inflow would be stored to refill water supply storage.

A drawdown-refill operating rule explicitly linked to refill probability would allow additional flood control benefits to be realized with an actively managed, pre-specified level of risk to the water supply system. In this way a common volume of reservoir storage would be shared between two authorized project purposes throughout the year.

In contrast to this dynamic storage allocation, most multipurpose operation defines fixed volumes of storage which are allocated and operated for a single purpose. Hydrologic uncertainty is manifested as an incremental allocation of reservoir storage which will only be used in extreme events. The traditional design and operation of single purpose reservoirs formed by a multiple purpose impoundment will incorporate incremental volumes of rarely used storage into each single purpose allocation as a hedge against hydrologic risk.

Allocating storage between flood control and water supply must balance the risk of water supply failure against the risk of flood damage. The probability of a failure as well as the distribution of the magnitudes of these failures must be considered in making operating decisions. Operations must choose between alternative feasible probability distributions of failure and benefits. Analytical methods can quantify and describe the distribution of operating impacts. The choice between feasible distributions of impacts is a value judgement which must be based on preferences between risky alternatives.

UNCONDITIONAL RUNOFF PROBABILITY

North Branch Potomac River at Kitzmiller

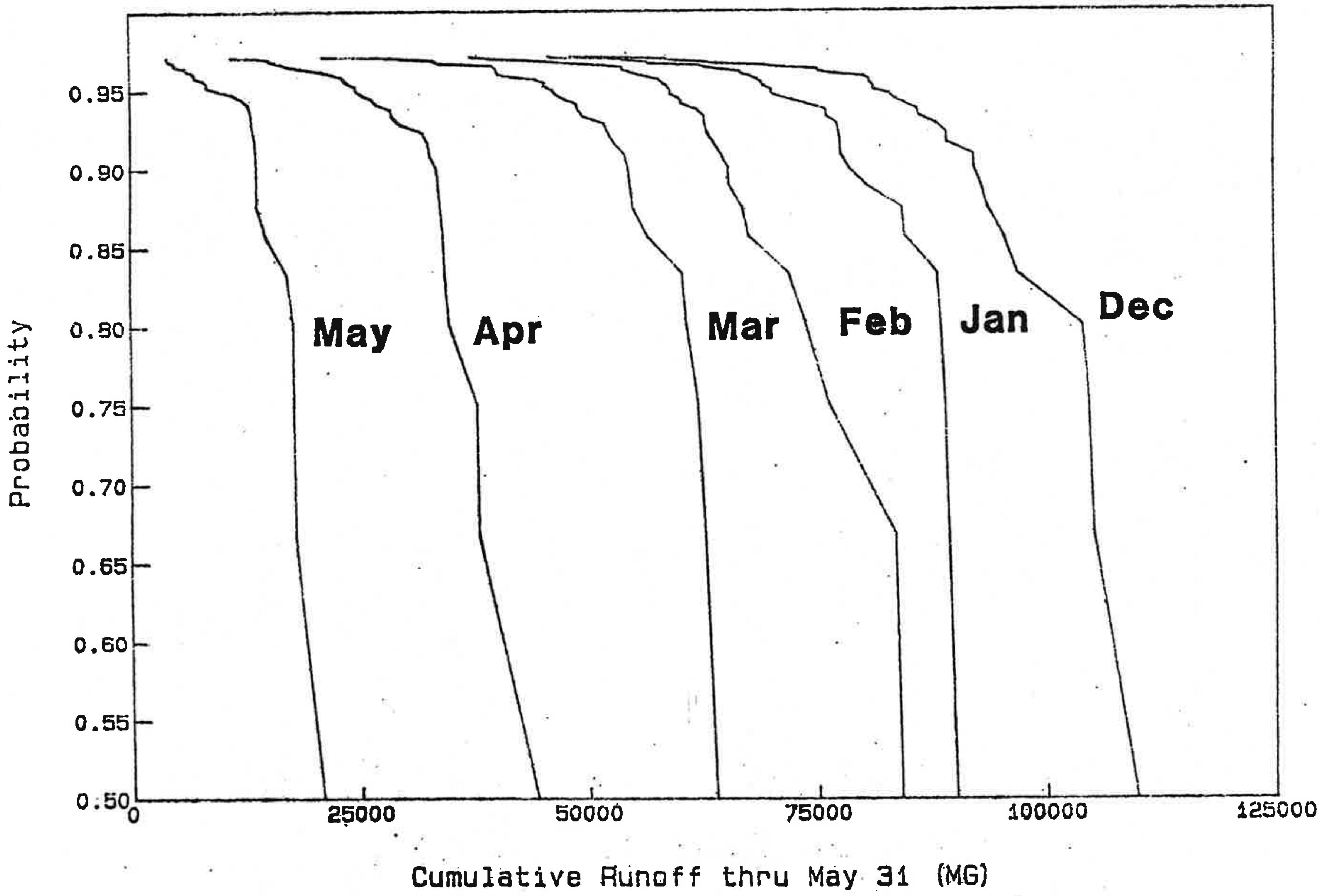


Figure 1.2

### 1.1 Randomized reallocation

In this section, alternative allocations of flood control, and water supply storage are used to illustrate the distinction between the probabilistic impacts of a storage allocation, and the preference for a particular probability density function of these impacts. The former is the result of hydrologic variability and reservoir operation and can be analytically and objectively described. The latter represents the judgements that must be made in choosing between alternative uses of reservoir storage.

In examining a possible reformulation for storage allocation within Bloomington Reservoir on the North Branch of the Potomac River, the U.S. Army Corps of Engineers (COE) developed average annual flood damage estimates for 10 different plans, corresponding to different volumes of flood control storage, and different seasonal patterns of drawdown. The resulting probabilistic impacts of each operational plan were quantified based on the expected monetary value of annual flood damages.

A simple randomized storage allocation rule is proposed to clarify the distinction between the consequences of a particular storage allocation, and the preference for a particular allocation based on attitudes toward risk. For this example we assume that the probability of damaging floods are independent on an annual basis, and that we have no long-term (months) skill in forecasting the occurrence of such floods. Since accurate flood forecasting requires the ability to forecast precipitation, this is reasonable. In contrast to long term flood forecasting, we have considerable forecast skill for low-flow situations which are critical for water supply. Soil moisture conditions developed over winter and spring give us considerable insight into the likelihood of low flows which are dominated by baseflow, not precipitation.

The "operating rule" described here is a simple rule curve. The rule simply specifies the initial elevation of the conservation pool in April. Daily operating rules are not effected by the initial flood pool elevation. The randomized allocation between flood control and water supply simply allows flood control storage to be partially filled in the spring if water supply forecasts suggest a significant probability of below average baseflow. For the 3 years out of 4 in which spring water supply outlooks are favorable, some water supply storage is emptied, providing additional flood protection. Rather than attempting to estimate the probability of storm events, this rule gambles only on the year. In years when flood control storage was reallocated to water supply, the flood risks (in expected damage terms) would be higher. However, as long as the frequency of increased damages is significantly lower than the frequency of reallocations of water supply storage to flood control, the overall expected monetary value of flood damages could be reduced. Using the criterion of expected annual flood damages, the infrequent increases in flood damages would be offset by the more common reduction in flooding created by lowering the elevation of the conservation pool.

Table 1 shows the incremental flood damages resulting from a reduction of the 36,200 acre-foot (AF) flood control pool in Bloomington Reservoir by 25%, 50%, and 75%. Assuming the normal flood control pool was 18,000 AF, the incremental expected annual damages from a reallocation to 27,400 AF and 9,200 AF are shown in Table 1 as -$59,000 and $359,000 respectively. In contrast to a constant flood control volume of 18,000 AF, the randomized allocation increases the volume of flood control storage to 27,400 AF in wet years. In dry years the flood control volume is reduced to 9,200 AF, providing an additional 8,800 AF of water supply storage. If the larger volume of flood control can be made available 9 out of 10 years, the annual expected monetary damages from flooding would be reduced by $17,000 compared to the fixed allocation of 18,000 AF. In addition, for the one year in ten when additional water supply storage was provided from the flood pool, water supply benefits would increase as well.

The randomized allocation rule could work quite well as long as expected monetary value was the sole criterion used to evaluate operations. Using expected monetary damages, randomized reallocation is superior to a fixed allocation of 18,000 AF. The superiority of the randomized allocation rule is independent of the mechanism used to initiate a storage reallocation for a given year. The expected monetary damage criterion implicitly values long-term operating consequences as though infrequent increases in flood damages can be offset by a number of years of incremental damage reduction.

In actual flood control operations this may not be the case. If damages occur (though infrequently) that could have been prevented, it is not at all clear that many years of damage reduction could provide adequate compensation. In the extreme, no amount of damage reduction could compensate for a loss of life.

## 1.2 Preferences Among Distributions of Damages

Operating policies which infrequently allow higher damages than originally planned may produce unacceptable consequences unrelated to expected dollar losses. For example, if flood control is an authorized project purpose for which payment has already been advanced, the benefits must be provided. In addition, assured flood control protection has insurance value, that is typically quite significant even though it is not reflected in flood damage calculations. The economic value of downstream development would be lost if flood protection was not dependably provided.

Table 1

## INCREMENTAL ANNUAL DAMAGES FOR FLOOD CONTROL STORAGE

| Available Flood Control storage (acre-feet) | Incremental damages (dollars) | Incremental damages |
|---|---|---|
| | 36,800 AF | 18,000 AF |
| 27,400 | $49,000 | -$59,000 |
| 18,000 | $108,000 | $0 |
| 9,200 | $467,000 | $359,000 |

## RANDOMIZED REALLOCATION

0.9 * (-$59,000) + 0.1 * ($359,000) = -$17,000

Net reduction of flood damages relative to
fixed allocation of 18,000 AF

Even in an economic damage context, the expected monetary value of damages may be an inadequate criterion to guide operations. Expected monetary damages (EMD) are calculated as the product of the damage associated with a flow and the probability of that flow, summed over all flows.

$$EMD = \sum p(i)\ D(f(i))$$

where:

$f(i)$ = the i-th possible damaging flow

$p(i)$ = the probability of flow $f(i)$ under a particular operation-allocation plan

$D(f(i))$ = the monetary damage caused by flow $f(i)$

The randomized reallocation described above produces a set of damaging flows with different magnitudes and probabilities of occurrence than the current design operations. The basis for proposing such a reallocation is the reduction in the expected monetary value of flood damages. As an illustration, consider a highly simplified comparison of a randomized reallocation rule and a fixed allocation rule. Assume there are only two types of flood situations. The fixed allocation rule results in damages with dollar value $d(1)$ in moderate flow years, which occur with a probability $p(1)$, and dollar damages of $d(2)$ in high flow years, which occur with a probability $p(2)$. The EMD of this fixed allocation would therefore be:

$$EMD(fixed) = p(1)d(1) + p(2)d(2)$$

For comparison, we imagine the randomized allocation can supply enough additional flood control storage so that in years when the additional storage is available, no damages are experienced. In the relatively rare cases in which flood control storage is reallocated to water supply, and flows are high, flood damages are higher and equal to $d(1)+d(2)$ with a probability of $p(3)$, producing expected damages of :

$$EMD(random) = p(3)(d(1)+d(2))$$

For illustration we assume EMD(fixed) = EMD(random). In this example, EMD as a criterion of choice leaves a decision maker indifferent between the two storage allocations. This indifference is unavoidable with an expected value criterion, which tends to equate frequent small events of small magnitude, and larger events which are less common. In flood control operation the large though less frequent flow may well be more important than more common events. Given a choice between two achievable frequency distributions of damaging flows with equal EMD's, a decision maker might well prefer the alternative in which the largest flows are less severe or less likely.

The expected monetary damage criterion is insensitive to any of the characteristics of the probability density function (pdf) of damages other than expected value. Using only the expected value criterion, the randomized reallocation rule can provide equivalent, or even superior flood control operation. This dynamic allocation will also provide additional water supply storage in extreme years. Compared to a fixed allocation of storage, the expected value criterion indicates the randomized reallocation can be a superior use of existing storage. The cost of this reallocation is the increase in damages, with lowered probability, resulting from the largest flood events.

## 1.3 Operating consequences

In spite of the favorable expected value of damages resulting from the randomized reallocation, reservoir operators are unlikely to accept a (rare) increase in damages that may otherwise be preventable. For the randomized reallocation to be implementable (or any other reallocation for that matter) operation with the proposed flood pool must result in an acceptable distribution of flood damages (as well as expected value). This requires modifying not only the allocation of storage, but also the relevant operating rules used for the new allocation.

Non-structural tools to better utilize existing project storage will combine dynamic allocation of storage throughout the year with improved operating rules using expanded hydrometeorologic data collection and forecasting. Traditional operation of multipurpose impoundments allocates fixed volumes of storage to each authorized project purpose. Hedging against hydrologic uncertainty is managed by increasing the allocation for each purpose, providing an incremental volume of storage which will rarely be operated. Annual reallocation of storage with a randomized reallocation rule, as well as dynamic allocation of storage using probabilistic seasonal runoff forecasts are two ways in which the utilization of existing storage can be improved. The combination of improved operating rules and dynamic allocation offers a non-structural framework for realizing increased benefits from multipurpose reservoirs. Strategic allocation of reservoir storage in response to seasonally changing risks can make additional storage available for critical operating periods. Tactical operation with strategic storage allocation offers the non-structural means to significantly increase the range of attainable benefits in multipurpose reservoirs, while explicitly managing system risks. The remainder of this report describes the tactical problem of efficiently operating the available volume of flood control storage.

## 2. Overview of Flood Control Operation

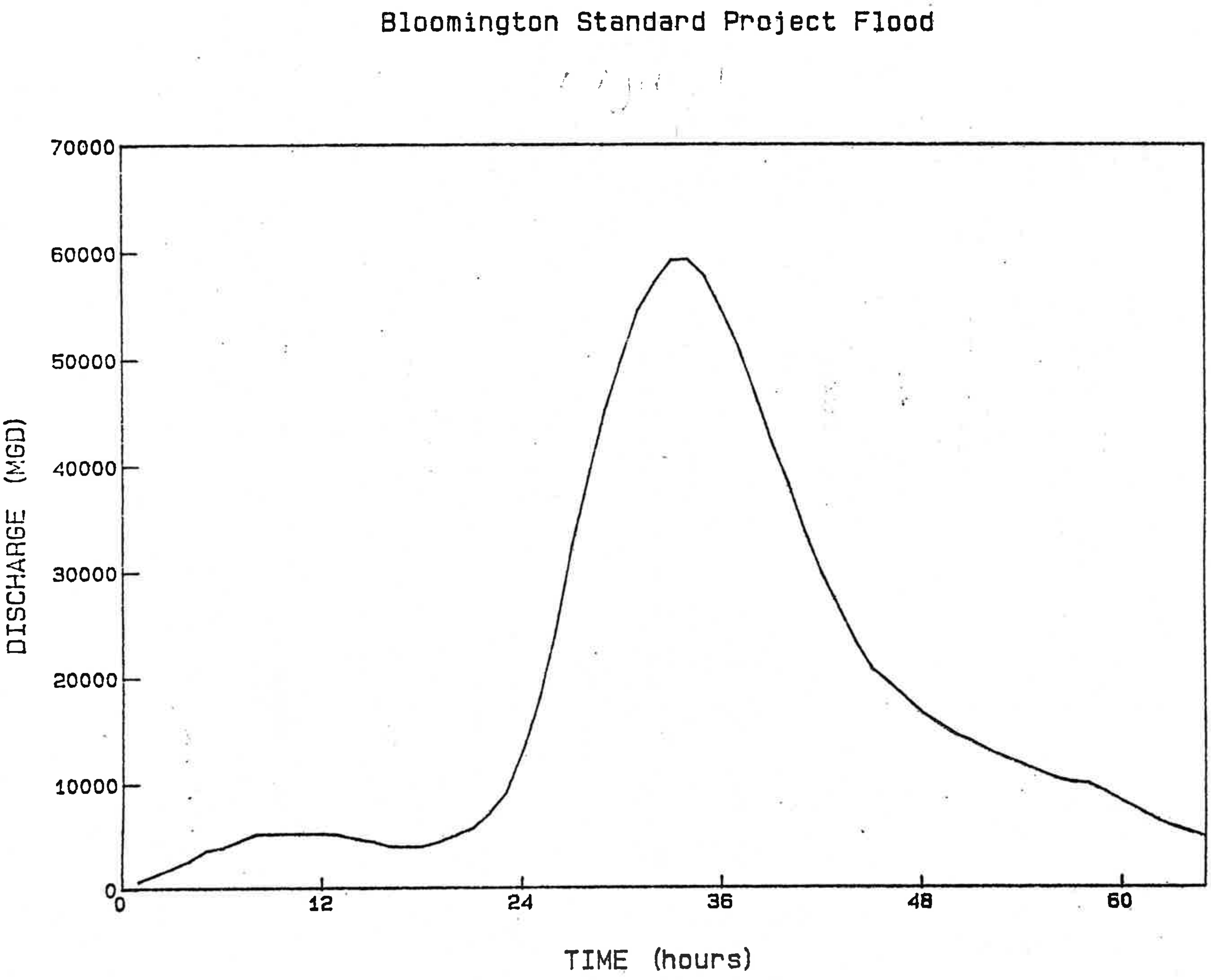
In order to mitigate damages from flooding, reservoirs must store streamflow that cannot be released without causing damage downstream. Beard (1963) describes good flood control practice as "releasing water whenever necessary at the highest practical rates, so that minimum space need be reserved for flood control." Increasing the non-damaging discharge (using levees and channel improvements for example) can reduce the required volume of flood control storage. Non-structural methods of flood control protection such as land rights acquisition, floodproofing, and flood forecasting and warning systems, have become increasingly prominent parts of integrated floodplain management plans. The present work focuses only on structural means of hydrologic modification of floods through reservoir operation.

The available storage in a flood control reservoir is operated to retain damaging inflows for subsequent release at rates below the threshold of damage. With adequate flood control storage (often expressed as freeboard) the runoff from a storm can be completely stored, and later released at much lower rates. When insufficient storage is available to store all storm runoff, the most effective use of storage is to attenuate the peak flows. Emphasis on peak flows reflects the common practice of relating flood damages to maximum water surface elevation (stage).

### 2.1 Optimal flood routing

Considering only the peak discharge as an operating criterion, an optimal utilization of flood control storage can be identified to minimize the maximum discharge. As an example, Schwartz and Hogan (1985) used the Standard Project Flood (SPF) for Bloomington Reservoir (Figure 2.1) as the deterministic input to a flood control reservoir. The operating problem was to identify a release pattern which would provide the greatest reduction in the peak discharge. To make the problem more realistic (and comparable to previous work on the Bloomington SPF) a requirement was added that the flood control reservoir must be evacuated by hour 60. The shorter this drawdown period, the larger the peak release. The drawdown target was chosen to be comparable to the COE's SPF routing (USACOE 1983).

The release trajectory that minimized peak discharge required only 4 billion gallons of storage, compared to the nearly 12 billion gallons available in Bloomington. Part of the reason for this lies in the deterministic way in which the SPF hydrology was used. By assuming future inflow is known without error before it is observed, storage can be operated in a more efficient manner than would be possible during an actual event. The use of reservoir storage to hedge against uncertainty is not accounted for in this optimal release schedule.



Bloomington Standard Project Flood

Figure 2.1

In comparing the utilization of flood control storage in the COE's routing of the Bloomington SPF, to the deterministic operating policy, it is clear that most of the remaining 8 billion gallons of storage is used to delay the flood wave. The delay in discharges compared to inflow is about 4 hours. This delay effectively provides some hedging against inflow uncertainty, but mainly provides damage reduction downstream.

Downstream damages can be reduced through delay of the flood wave by removing the runoff contribution of the controlled drainage from damaging flows at critical downstream locations. When travel times and concentration times are short, a delay of 4 hours could provide a significant reduction in downstream damages. The relative volume of storage required for a 4 hour delay of the SPF compared to an attenuation of the SPF peak from 60000 mgd to 40000 mgd suggests a high marginal cost (in terms of storage) for delay compared to attenuation.

## 2.2 Attenuation and Delay

Attenuation of the flood hydrograph (Figure 2.2) produces discharges which are identical to the inflow hydrograph until a discharge target is exceeded. Above the discharge target, excess flow is stored, producing a clipped or flattened outflow hydrograph. This causes flood control storage to rise until the inflow falls below the critical discharge on the falling limb of the flood hydrograph. When inflow has fallen, the discharge target is maintained in order to evacuate the flood control pool as rapidly as possible, without exceeding the maximum flow. The operating rule for attenuation can be described as:

$$R(t) = \min \{ I(t)+S(t) \ , R^* \} \qquad (2.2.1)$$

where:

$R(t)$ is the release in time period t,
$I(t)$ is the inflow in time period t, and
$S(t)$ is the volume of water in storage during time period t
$R^*$ is the discharge target

The continuity equation relates the inflow, and release to current reservoir storage:

$$S(t) = S(t-1) + I(t) - R(t) \ . \qquad (2.2.2)$$

Delay of the flood wave (Figure 2.3) is simply a shift of the inflow hydrograph in time. On the rising limb of the flood hydrograph, current release rates will be less then current

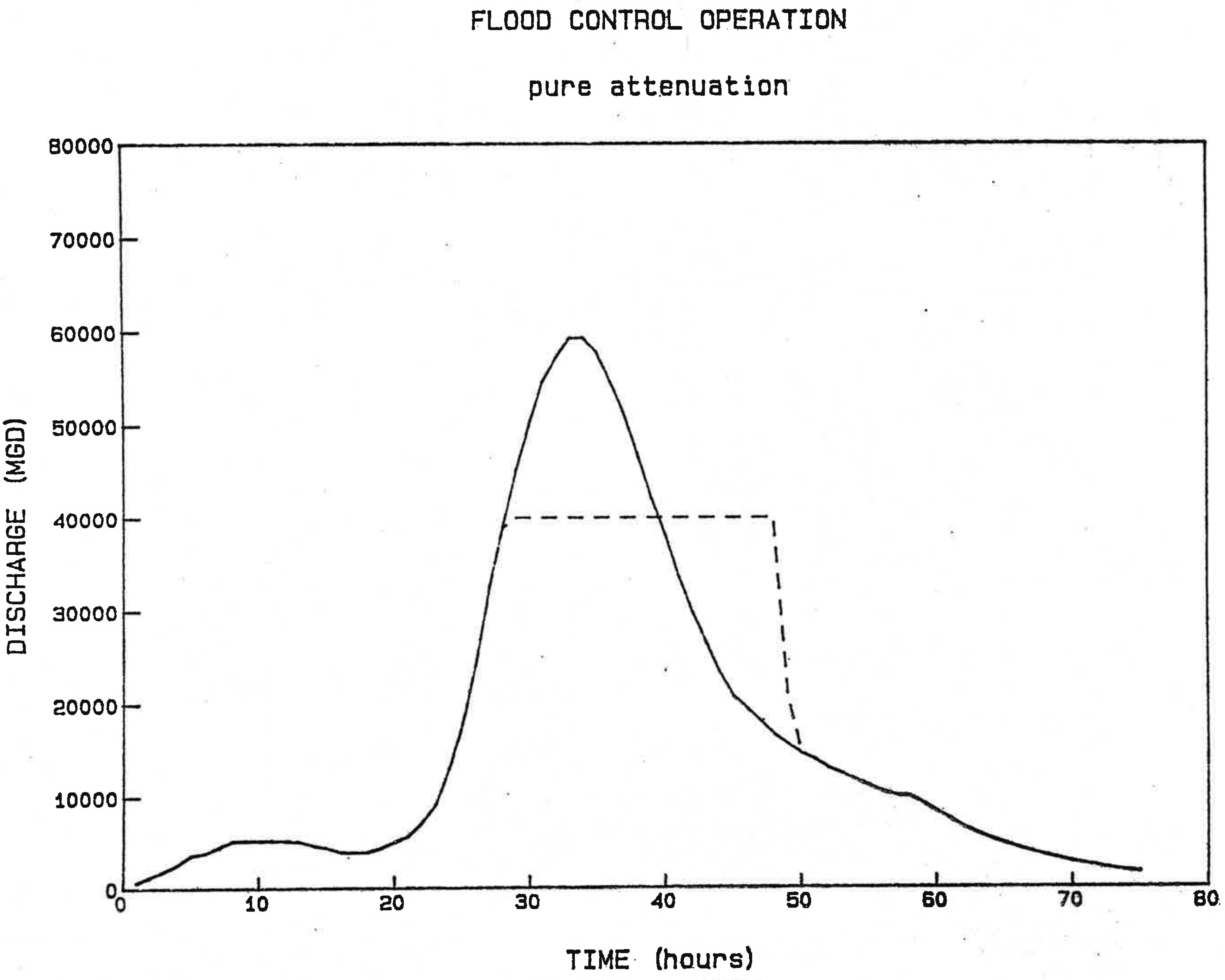

FLOOD CONTROL OPERATION
pure attenuation
DISCHARGE (MGD)
80000
70000
60000
50000
40000
30000
20000
10000
0
0
10
20
30
40
50
60
70
80
TIME (hours)

Figure 2.2

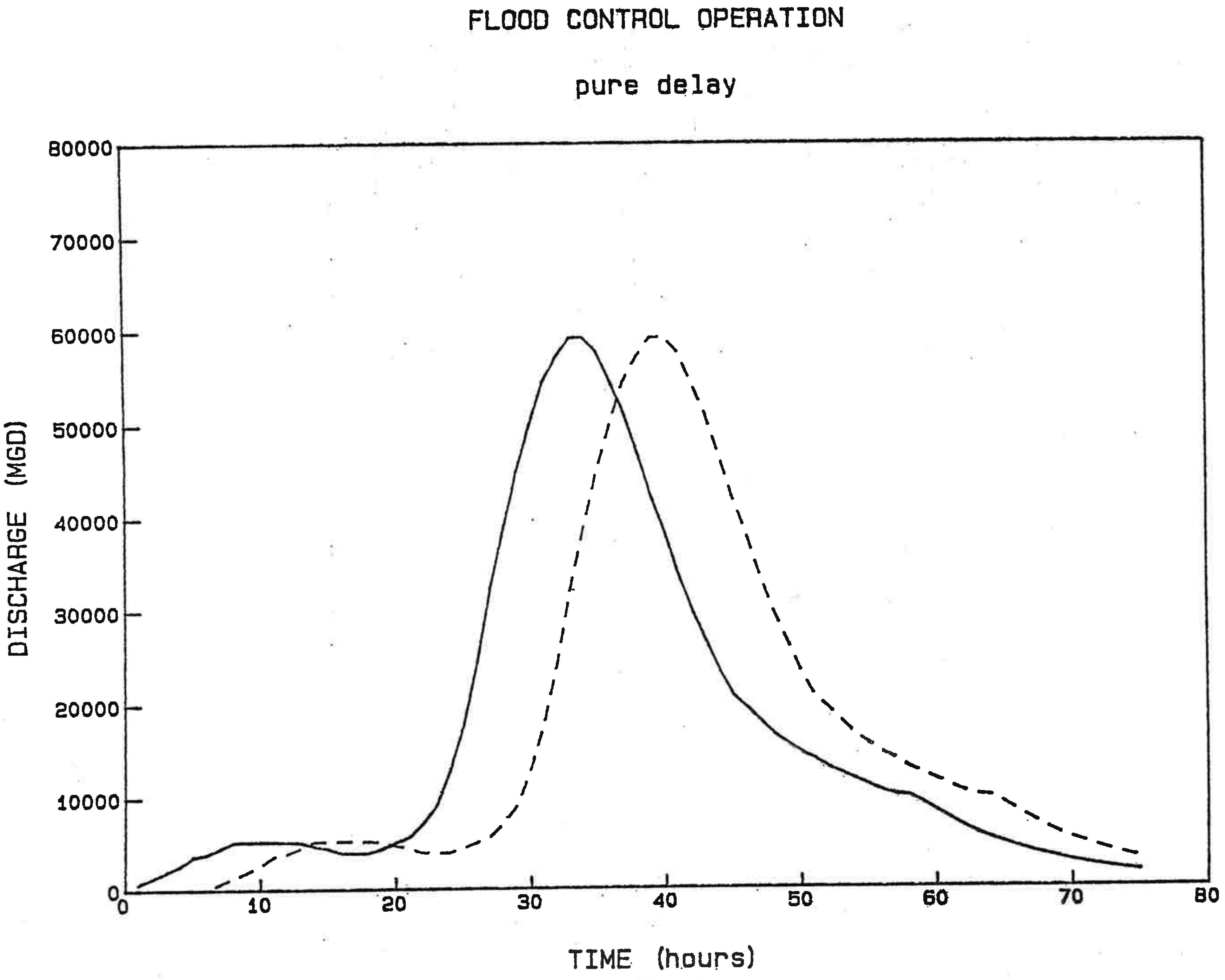

FLOOD CONTROL OPERATION
pure delay
DISCHARGE (MGD)
80000
70000
60000
50000
40000
30000
20000
10000
0
0
10
20
30
40
50
60
70
80
TIME (hours)

Figure 2.3

inflow. The difference will be held in storage, and the flood control pool will rise. The release rule for a delay of n time periods is simply:

$$R(t) = I(t-n) \ . \qquad (2.2.3)$$

The continuity equation again relates the reservoir contents to the release rule.

An attenuating operating rule will reduce the peak discharge, thereby lowering maximum flood stages and reducing the area and severity of inundation downstream. In contrast a delaying operating rule changes only the timing of discharge not its magnitude. This delay may have value in providing added time for warning and evacuation at downstream damage areas. Delaying the flood wave may also lower peak stages downstream, depending on the timing of runoff from intervening watersheds downstream from the dam.

In practice, reservoirs are operated to both delay and attenuate the flood hydrograph. Both delay and attenuation of the flood wave require reservoir storage. The necessary volume will depend upon the flood hydrograph, the lag (in the case of a delaying rule) or the maximum release (in the case of attenuation). Characterization of release rules as having components of both delay and attenuation (Figure 2.4) provides a useful way to examine the flood control storage required for alternate operating rules.

## 2.3 Storage,Delay,Peak Discharge

The interaction of delay and attenuation in flood control operation can be made more concrete by simulating alternate operating rules on the same flood hydrograph. For this purpose a simple hybrid operating rule was developed incorporating both attenuation and delay. The rule has two parameters: the maximum release, $R^*$, and the lag or delay, n. The release on the rising limb of the flood hydrograph is defined by:

$$R(t) = \min\{ I(t-n), R^* \} \qquad (2.3.1)$$

Specifying values for the parameters $R^*$ and n, defines a particular rule from the family of parametric operating rules in (2.3.1). Applying this rule to a flood hydrograph, a set of parameters is mapped to a maximum storage volume through the continuity equation.

The SPF for Bloomington Reservoir on the North Branch of the Potomac River (Figure 2.1) was routed through a hypothetical flood control reservoir using the hybrid parametric operating rule. Repeated simulation over a range of parameter values was used to develop the tradeoff between attenuation, delay, and required storage in Figure 2.5. Each curve of Figure 2.5

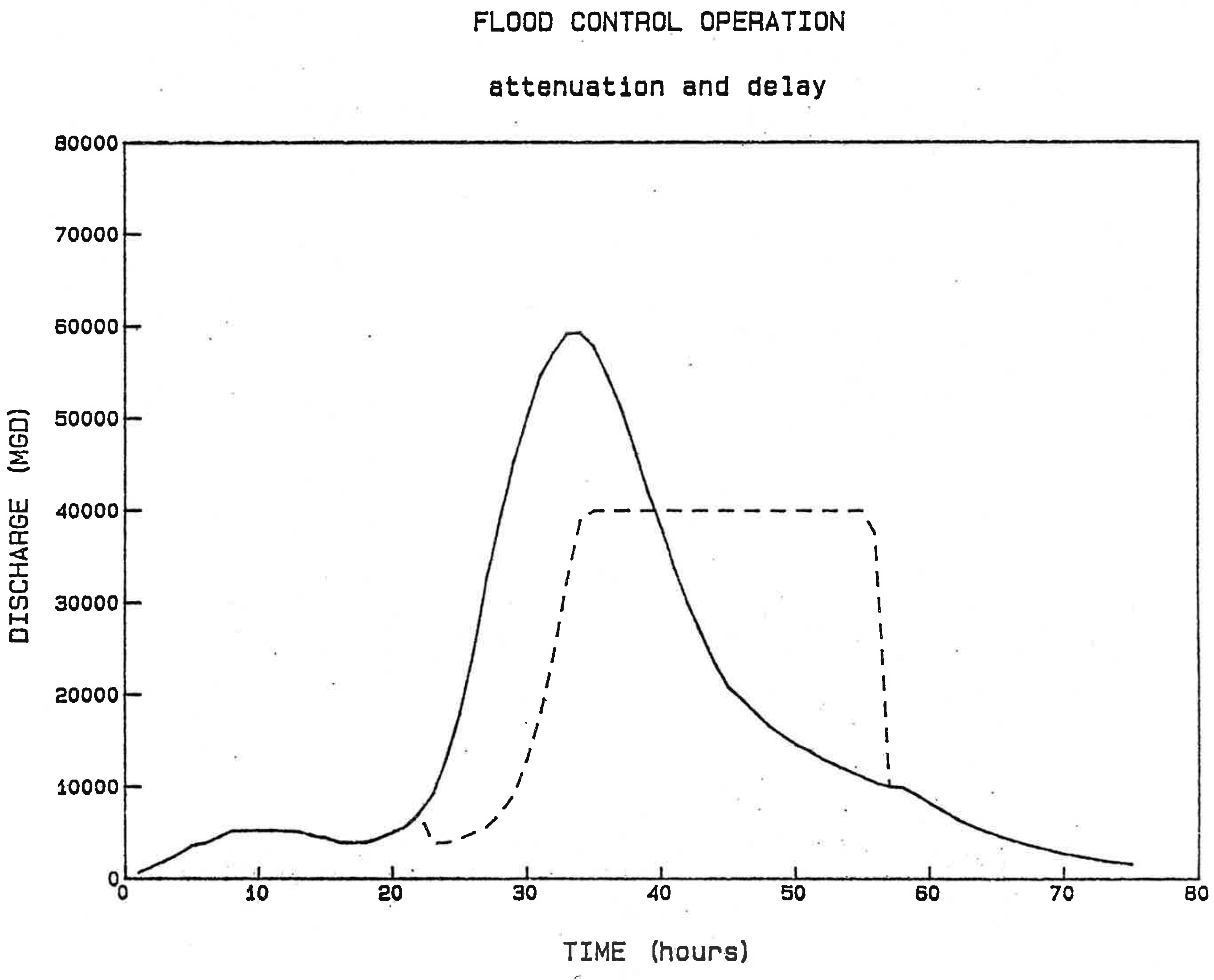

FLOOD CONTROL OPERATION
attenuation and delay
DISCHARGE (MGD)
80000
70000
60000
50000
40000
30000
20000
10000
0
0
10
20
30
40
50
60
70
80
TIME (hours)

Figure 2.4

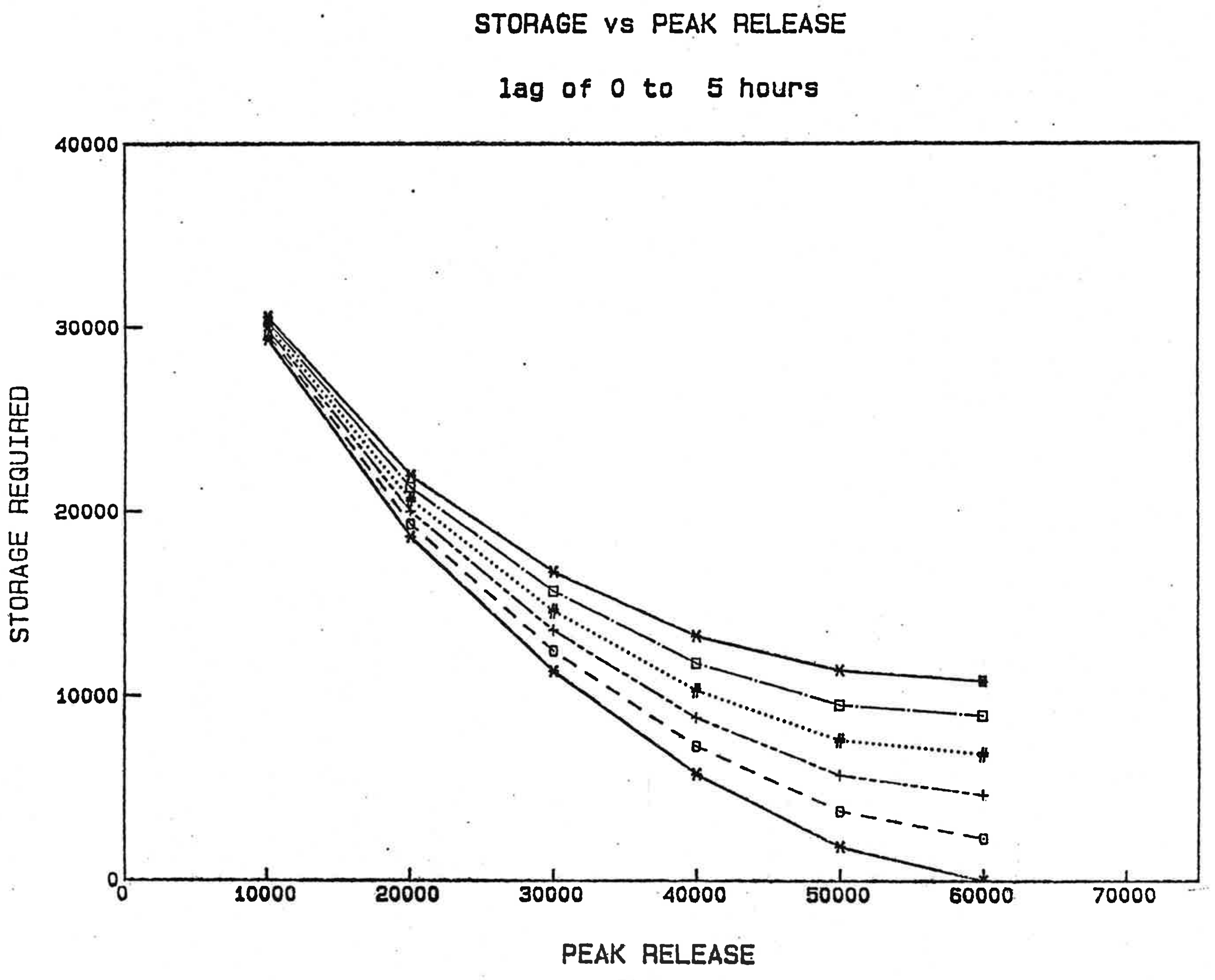

STORAGE vs PEAK RELEASE
lag of 0 to 5 hours
STORAGE REQUIRED
40000
30000
20000
10000
0
0
10000
20000
30000
40000
50000
60000
70000
PEAK RELEASE

Figure 2.5

corresponds to a particular value of n, the delay in hours. Delays of 0 to 5 hours were simulated. Maximum discharges considered ranged from 10,000 mgd to 60,000 mgd.

Although the relationship between storage, delay, and maximum release in Figure 2.5 is specific to the SPF, general features of the operational tradeoffs become clear. The increased need for storage with an increase in delay or decrease in peak release is expected. The convergence to about 30,000 mg of storage for extremes in delay or peak release reflects the equivalence of total delay and total attenuation. In either case the required storage volume is equal to the total runoff volume; the entire storm is stored.

Beyond these general features of the storage-delay-peak release tradeoff, the tradeoffs associated with the Bloomington SPF are particularly interesting. Comparing incremental changes in delay and discharge, it appears that reducing the delay by only a few hours, can support a significant reduction in the magnitude of the peak release for a wide range of storage. For example, with 10 billion gallons of storage available, delaying the flood wave five hours leaves only enough storage to reduce the peak release to about 50,000 mgd; if the delay of the flood wave is reduced to only one hour, the maximum release can be reduced to about 35,000 mgd. The value of an extra delay of 4 hours (in a storm lasting over 60 hours) must be weighed against a flood peak reduction of nearly 40 percent.

This simplified simulation of the SPF suggests that the cost of even a few hours delay is high in terms of the storage it requires. The storage required for actual operation would be higher than that indicated in Figure 2.5. General operating procedures impose constraints on the maximum rate of increase in discharge. The uncertainty in discharge from uncontrolled basins downstream is managed by restricting releases before downstream flows reach flood stage. Nevertheless, the incremental volume required for these purposes is small compared to that required to store the SPF. The tradeoffs depicted in Figure 2.5 capture the qualitative alternatives for flood control operation. The relationship between storage volume required to delay rather than attenuate a flood wave will vary between storms. While tactical decisions for managing a particular flood will be specific to that flood, the strategic operating decisions aimed at damage minimization will be more closely related to overall basin hydrology, subbasin concentration times and travel times between critical locations in the drainage-channel network.

## 2.4 Flood Control Operation: Minimizing the Flood Peak

In analyzing the modification of the flood hydrograph through reservoir operation, the reduction of the peak discharge provides a useful measure of damage reduction. For damage sites immediately downstream from a flood control reservoir, minimizing the largest release is equivalent to minimizing the largest damaging stage. As damage locations further downstream are considered, the contribution to the flood peak from uncontrolled drainage areas will increase. This section considers short term flood operation for a damage site just below the reservoir.

The tradeoffs in Figure 2.5 were developed in a design context, identifying the minimum required volume of reservoir storage for a design flood. Once a volume is chosen, operating rules must prescribe hourly releases accounting for the limited storage that is available. Normal flood control operation seeks to minimize the peak discharge of the flood hydrograph. In addition to damage reduction below the reservoir, operation must also prevent overtopping of the dam which could result in a catastrophic structural failure. As flood control storage continues to rise, releases will be made to control the risk of overtopping. While releases are significantly less than inflow on the rising limb of the flood hydrograph, the fraction of inflow released will increase as the flood pool rises. When no flood storage is available, releases are set equal to inflow and the flood hydrograph is no longer modified

### 2.4.1 Rising Limb vs. Falling Limb

Release decisions will differ on the rising and falling limb of the flood hydrograph. On the rising limb, operating decisions seek to reduce damages, and prevent overtopping as flood storage fills. On the falling limb releases are chosen to evacuate the flood pool as rapidly as possible without causing damage downstream. Prompt drawdown of the flood pool minimizes the risk of having insufficient storage available during a subsequent flood rise. While releases on the rising limb emphasize damage reduction, releases on the falling limb reflect the need to hedge against hydrologic uncertainty.

### 2.4.2 Flood Operations With Capacity Constraints

A parametric operating rule has been developed which incorporates delay, attenuation, and drawdown, with cautious releases to prevent overtopping. The peak discharge and the delay of the flood wave (in hours) are specified as parameters, representing operating targets. The rule is designed to be used in real-time using only information available to the reservoir operator. No runoff forecasts or precipitation estimates are utilized. A simple criterion is used to increase releases as flood control storage is filled, in order to reduce the risk of overtopping. In addition, a target drawdown release may be specified for the falling limb of the hydrograph, in order to accelerate storage drawdown after the flood peak has passed.

The parametric rule divides operating decisions into three distinct phases based on the state of the watershed-reservoir system. When streamflow is rising, conservative releases are made to delay and attenuate the flood wave, storing inflow. When conditions over the basin are clearly falling and the flood hazard has passed, the stored flood waters are discharged in order to empty the flood control pool without causing downstream damages. In the event that high flows persist as flood control storage is filled, a third phase of operation begins. When flood storage is nearly full, reservoir releases pass the flood wave without attenuation or delay. These releases are made to prevent overtopping of the dam which could lead to structural failure. When flood control storage is full and conditions are rising, flood control goals must be abandoned in order to save the dam.

The different classes of operation can be characterized by the difference between observed inflow and releases. When conditions are rising discharge will be less than inflow and flood waters will be stored. Falling conditions allow flood storage to be safely drained, and releases will exceed inflow. When flood control storage is full, rising flows are passed by setting reservoir releases equal to the observed inflow, maintaining a constant pool elevation.

The qualitative difference in the releases made on the rising and falling limbs of the flood hydrograph are operational tools to account for hydrologic uncertainty. Uncertainty about the inflow hydrograph can cause two types of operating errors. If flood control storage is committed too soon in the storm event, storage may be unavailable during the true flood peak. This would necessitate damaging releases which could have been prevented. If flood control storage is committed too late in the storm, damaging flows may be passed unnecessarily, again causing flood damage that could have been prevented.

At each time step the state of the basin is checked in three ways. For a target delay of 'n' hours the inflow to the reservoir at time t-n is compared to the inflow at time t-n-1 and categorized as rising or falling. Similarly the current reservoir inflow is compared to the inflow in the previous time period. Finally the current reservoir storage is compared to the storage in the previous time period. If any of these quantities are increasing in time, the state of the system is considered to be rising. In this way releases are based on the damage reducing parameters of delay and attenuation until there is no doubt that streamflows are falling steadily. When flows are clearly falling, the release at time t is equal to the inflow at time t-n unless this value exceeds the maximum release target. The maximum release target will only be exceeded when the fraction of flood storage that is full is greater than the fraction of the current period's inflow that would otherwise be released. For example, if flood storage is 90% full, the parametric rule would release at least 90% of the current inflow.

Using the parametric operating rule the effect of a finite volume of flood storage on release targets for large events can be evaluated within the framework of a tradeoff between delay and attenuation of the flood wave. To illustrate the effect of capacity constraints, the parametric operating rule is applied to the Bloomington SPF. The main effect of the constraint on reservoir contents is seen when parameter values are inappropriate for the particular hydrograph. Figure 2.6 shows the release pattern resulting from routing the SPF hydrograph through Bloomington reservoir with a peak release target of 40,000 mgd and a delay target of 5 hours (comparable to the effective operating rules employed in Bloomington). To reduce flood damages further, the SPF hydrograph was again routed with a five hour delay, and a maximum release target of 35,000 mgd. As Figure 2.7 shows, the peak release resulting from this parameterization exceeds the 35,000 mgd target (indeed it exceeds 40,000 mgd). As greater attenuation is attempted, flood storage fills too quickly to attenuate the peak. In order to control the risk of overtopping, releases are increased resulting in an overall reduction in flood protection.

Figure 2.8 shows two SPF routings with parameterized targets of 5 hours and 40,000 mgd, and 10 hours and 20,000 mgd. Although the latter targets, if achieved, would produce significant reductions in flood damages, the parameters are inappropriate for this flood hydrograph. Excessive storage is committed too early in the storm, significantly reducing protection at the flood peak. The actual peak discharge exceeds 46,000 mgd - more than 26,000 mgd above the release target.

Finally two achievable operating rules are compared in Figure 2.9. The 5 hour, 40,000 mgd rule is compared to an operating rule with parametric targets of 0 hours and 35,000 mgd. Here the tradeoff between attenuation and delay is clear. To reduce the peak discharge 5000 mgd the volume of storage used to delay the flood wave must be totally utilized for attenuation.

While these examples were again specific to the Bloomington SPF hydrograph, they illustrate the general features of flood control operation in a finite reservoir. The consequences of poor choices of operating parameters are more severe when storage is limited. Bad operating rules will waste storage resulting in increased flood damages. The sensitivity of the peak release to delay is again evident, with modest delays of only a few hours consuming large volumes of reservoir storage before the flood peak arrives. The relative value of

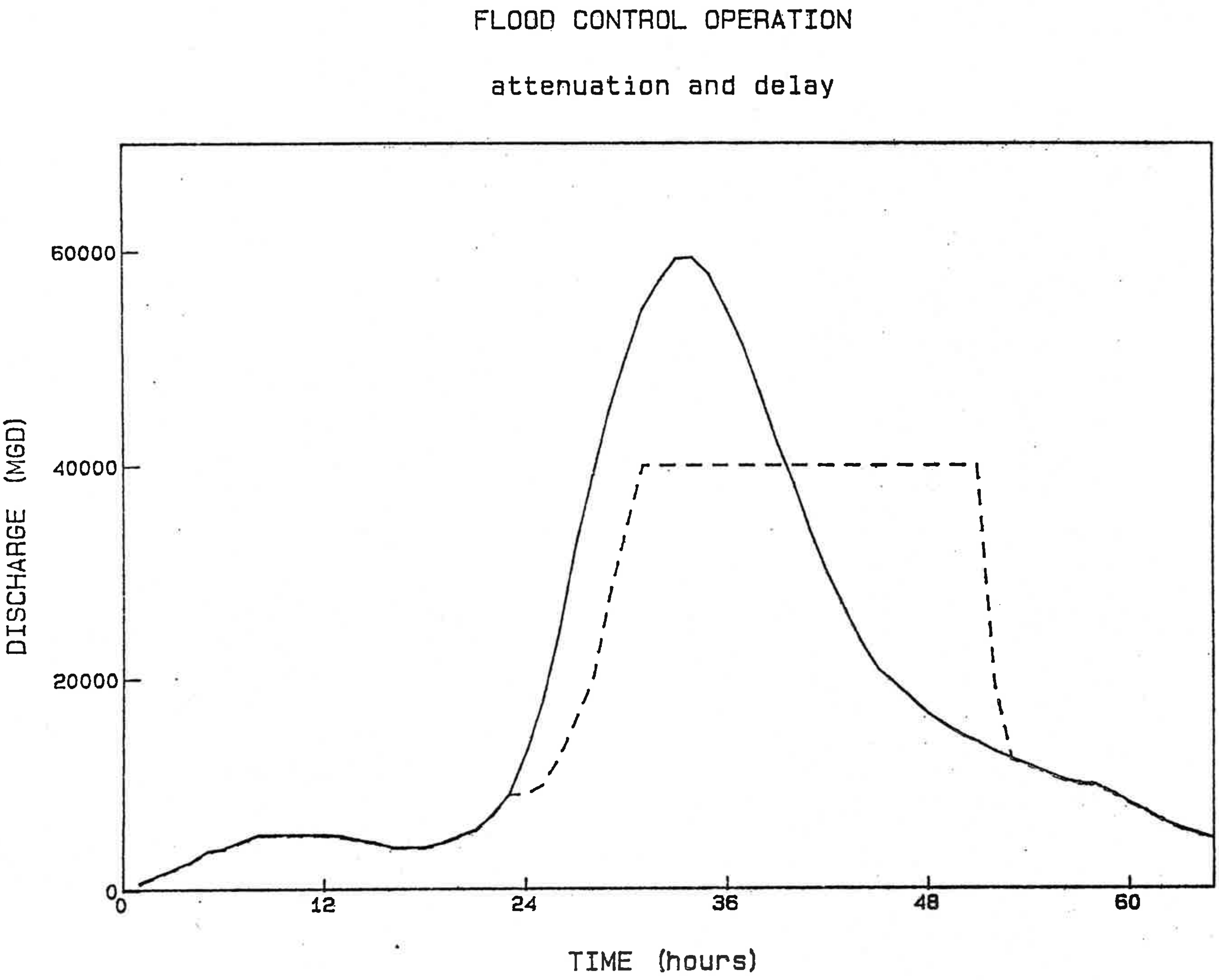

FLOOD CONTROL OPERATION
attenuation and delay
DISCHARGE (MGD)
60000
40000
20000
0
0
12
24
36
48
60
TIME (hours)

Figure 2.6

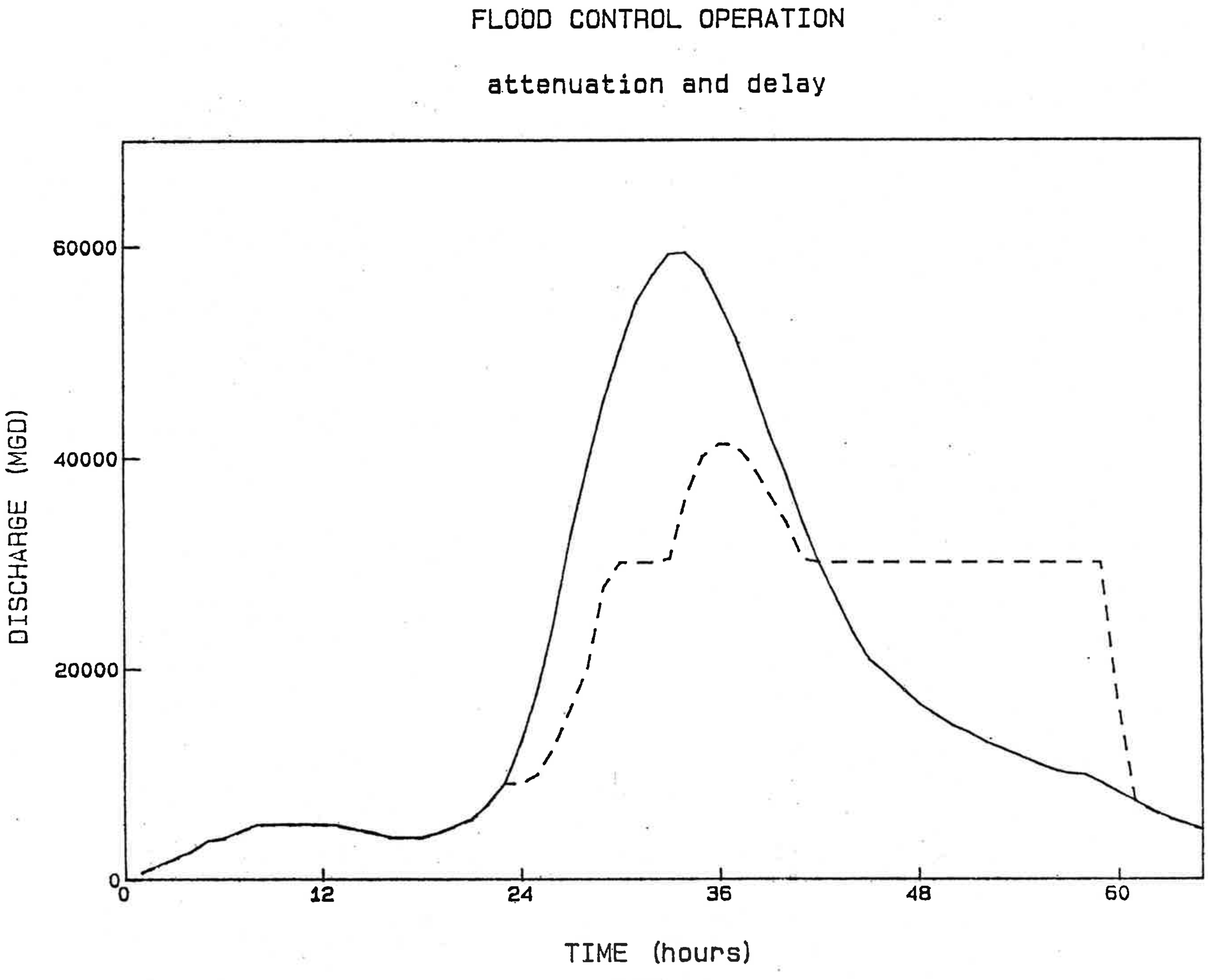

FLOOD CONTROL OPERATION
attenuation and delay
DISCHARGE (MGD)
60000
40000
20000
0
0
12
24
36
48
60
TIME (hours)

Figure 2.7

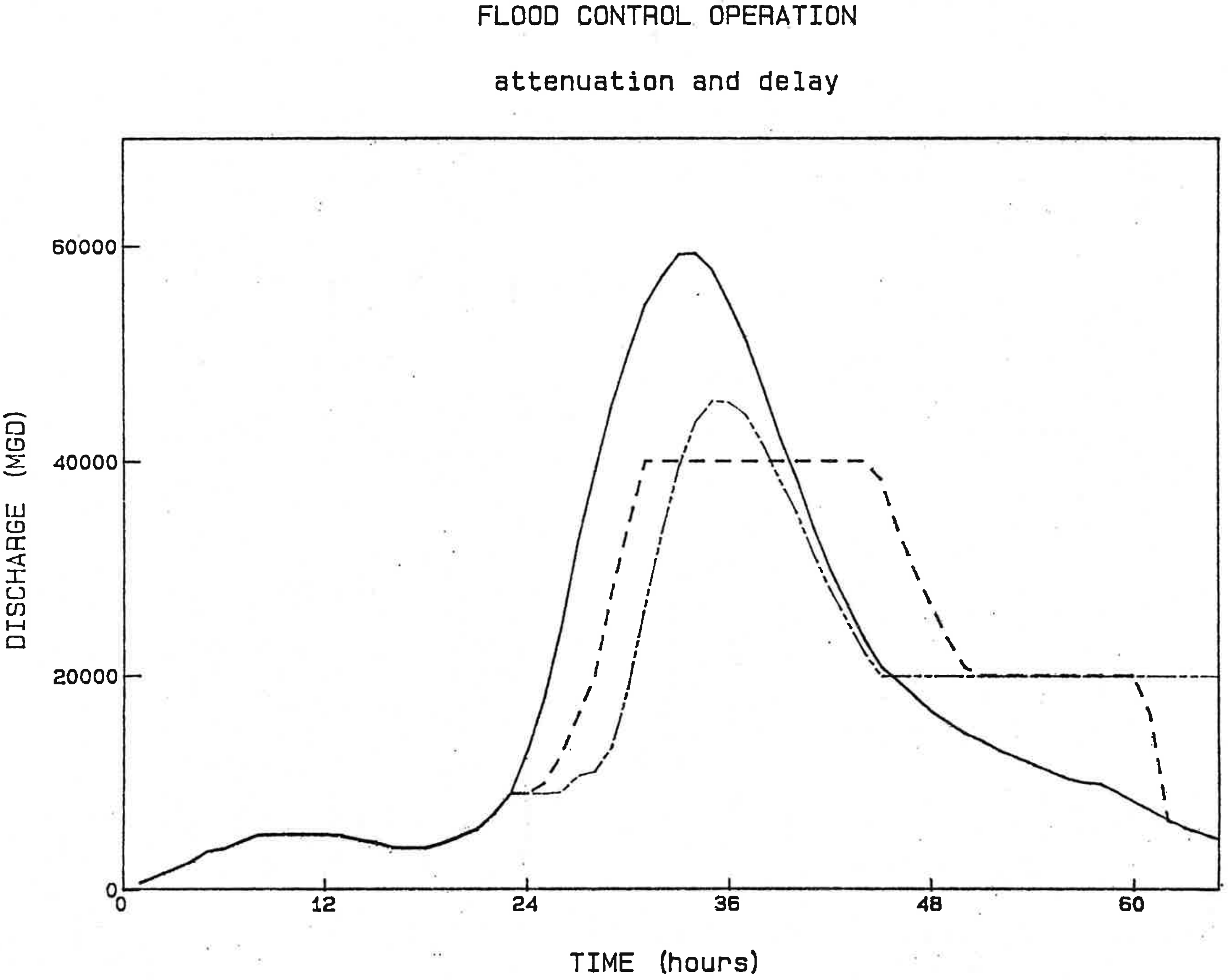
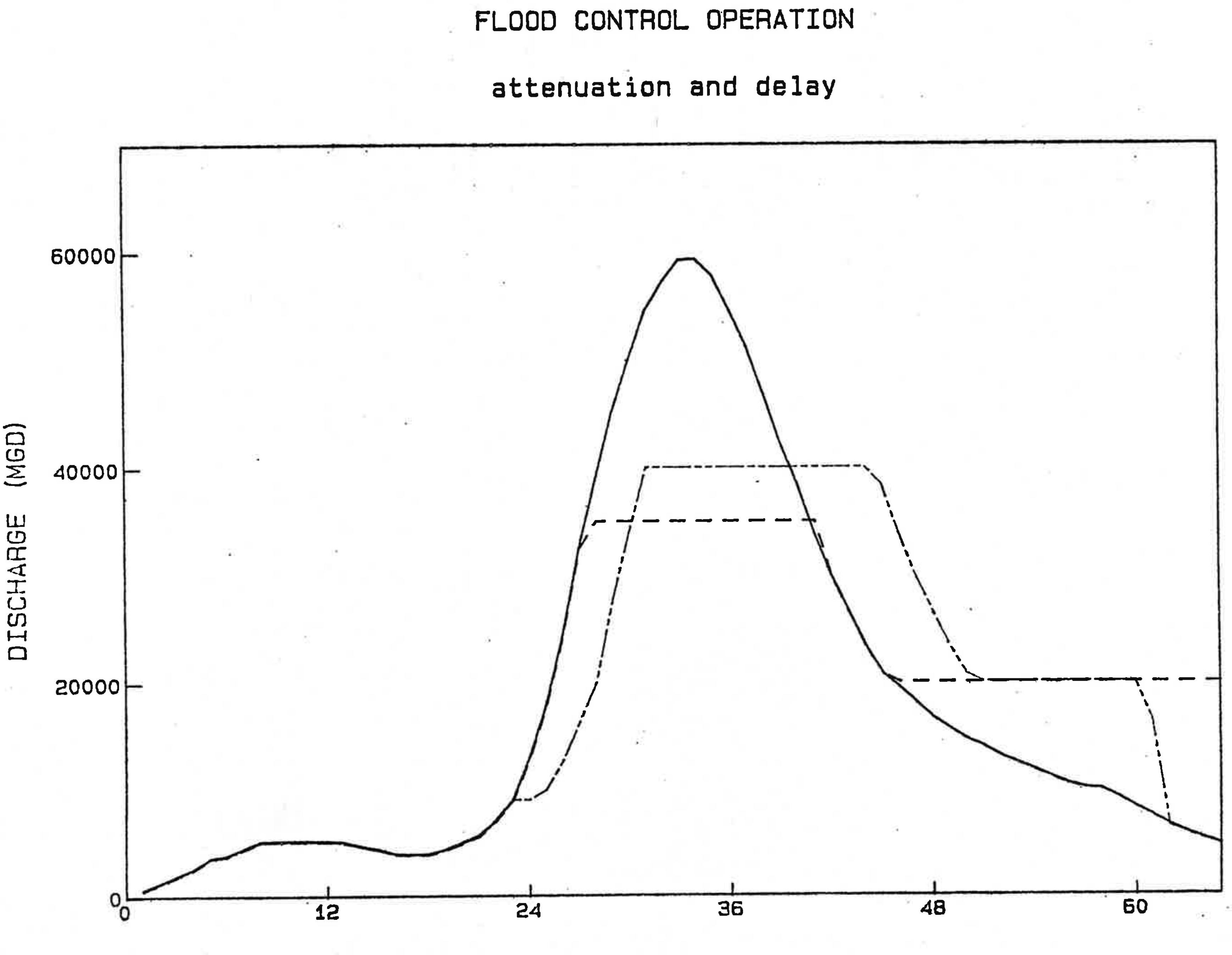

FLOOD CONTROL OPERATION
attenuation and delay
DISCHARGE (MGD)
60000
40000
20000
0
0
12
24
36
48
60
TIME (hours)

Figure 2.8


FLOOD CONTROL OPERATION

attenuation and delay

Figure 2.9

attenuation compared to delay is even greater for flood routings that are affected by reservoir capacity. Operating rules emphasizing attenuation in favor of delay commit the finite storage available later in the event. This retains more flexibility to respond to unexpected conditions, and uses less storage overall. This implementable hourly operating rule, suggests operating changes may allow more efficient utilization of flood control storage.

## 3.0 Downstream Damage Locations

While delaying the flood wave has no beneficial effect on damaging flood stages immediately below the reservoir, damage sites affected by significant uncontrolled drainage can experience damage reduction through an operating rule which delays the floodwave with no attenuation. The flood hydrograph at downstream locations is composed of routed runoff hydrographs from several drainage basins. Based on both storm and runoff timing, the peak discharge could be greatly exaggerated if the peak runoff from several contributing basins arrived at a damage site simultaneously. For such runoff patterns, delaying the runoff from an upstream basin even a few hours, can significantly reduce the maximum stage at a downstream damage site.

### 3.1 Simulating the value of delay

In order to quantify the relative value of using flood control storage to delay the flood hydrograph, a hydrologic simulation model was linked with a space-time model of thunderstorm rainfall for the North Branch, to simulate a delaying reservoir operating rule at Bloomington Reservoir. The hydrologic model was reproduced from the representation of the North Branch used in the Bloomington Lake reformulation Study prepared by the Baltimore District of the U.S. Army Corps of Engineers (USACOE 1983). The hydrologic model of the North Branch uses unit hydrographs to transform effective precipitation into runoff and Muskingum channels to route runoff to key damage sites. Effective precipitation was generated using a space-time model of thunderstorm precipitation developed by Smith and Karr (1985) using rain gage data from the North Branch, Potomac River. Using the thunderstorm model, hourly precipitation was generated over the North Branch and routed with the hydrologic model to produce hourly streamflow. At the modeled site representing Bloomington reservoir, the inflow hydrograph was alternately passed without modification, and routed with a delay of 1 to 5 hours. In this way the effect of a pure delay on downstream damage sites could be evaluated.

## 3.2 Hydrologic Model of the North Branch Potomac River

The hydrologic model of the North Branch was derived from the representation of the North Branch above Cumberland, Md. developed by the Corps of Engineers for the Bloomington Reservoir Reformulation Study (USACOE 1983). The model was used in the HEC-5 system for flood control simulation. North Branch flood control operation in the present work was performed with the same hydrologic model so results could be compared. The hydrologic model is depicted in Figure 3.1. Runoff producing areas transform effective precipitation to runoff using unit hydrographs. Flood peaks are routed to critical discharge points corresponding to Bloomington reservoir and the five USGS streamflow gages identified in Table 2. A total of 21 Muskingum channel segments link the thirteen runoff producing areas identified in Table 3 to the six critical discharge points.

### 3.2.1 Precipitation Model of the North Branch

The precipitation model used to produce effective runoff generates convective thunderstorm cells over each of the subbasins represented in Figure 3.1. Precipitation is modeled as the combination of three stochastic processes. The occurrence of precipitation is modeled over a sequence of wet and dry days. On wet days a random number of convective cells are generated and distributed over the basin. The intensity of precipitation within each cell is modeled as an exponential distribution based on a stochastic intensity for the storm system.

Daily transitions between wet days and dry days are treated as a first order markov chain with fixed transition probabilities. Wet days are days on which precipitation is possible. On wet days a random number of cells are generated based on the mean spatial intensity over the basin. There is a non-zero probability that no cells will be generated on a wet day, corresponding to conditions of high precipitation potential without measurable rainfall. This counter-intuitive feature of the model is crucial for parameter estimation. Unlike other models of convective precipitation, the parameters of this space-time model can be estimated directly from standard precipitation records at National Weather Service precipitation gages. One feature of the precipitation gage network is that not all precipitation cells are recorded by the available gages. The occurrence of unrecorded rain cannot be distinguished from a day without precipitation. Parameter estimation techniques developed for this model allow realistic parameters to be estimated from gage records despite this ambiguity. Smith and Karr (1985) describe parameter estimation techniques for calibration of this model using data available from rain gages in the North Branch Potomac Basin.

## Table 2

### North Branch Potomac River
### Hydrologic Model

| Critical Damage Point | USGS Streamgage | Drainage Area |
|---|---|---|
| Kitzmiller Md. | 1595500 | 225 |
| Bloomington Lake | none | |
| Savage Dam | 1597500 | 115 |
| Luke | 1598500 | 404 |
| Pinto | 1600000 | 596 |
| Cumberland | 1603000 | 875 |

Table 3

## North Branch Potomac River
## Hydrologic Model

| Runoff Producing Area | Location | Drainage Are (square miles) |
|---|---|---|
| 1. | North Branch Potomac at Steyer, Md. | 73 |
| 2. | Stony River, Md. near Mt. Storm | 48.8 |
| 3. | Local Area above Kitzmiller, Md. | 103 |
| 4. | Local Area above Bloomington Lake | 38 |
| 5. | Savage River at Barton, Md. | 49.1 |
| 6. | Local Area above Savage Dam | 56 |
| 7. | Local Area above Luke, Md. | 36 |
| 8. | Georges Creek at Franklin, Md. | 72.4 |
| 9. | New Creek near Keyser, Md. | 45.7 |
| 10. | Local Area above Pinto, Md. | 73.9 |
| 11. | Wills Creek at Cumberland, Md. | 146 |
| 12. | Local Area above Wills Creek | 101 |
| 13. | Local Area above North Branch Potomac at Cumberland, Md. | 32 |

# North Branch Potomac River
# Hydrologic model schematic

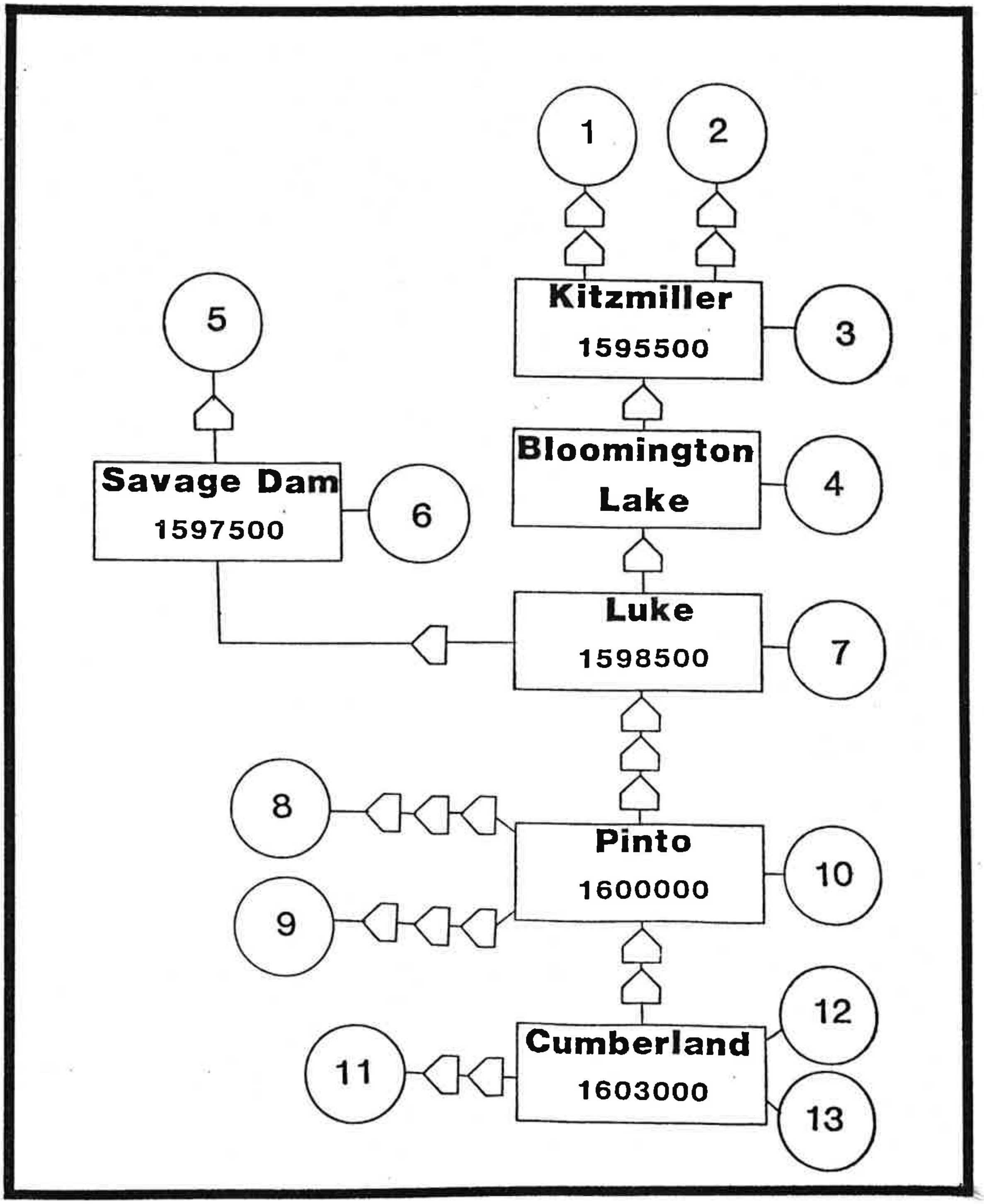
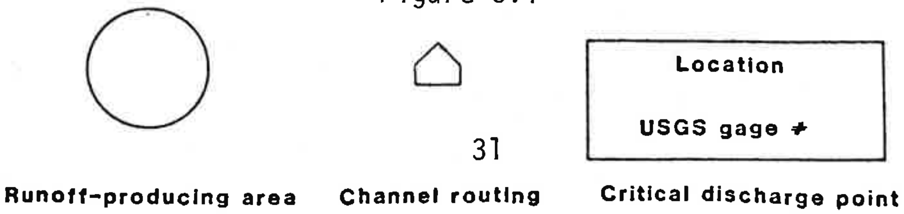


Figure 3.1



### 3.2.2 Flood Control Simulation on the North Branch

The space-time model of precipitation was calibrated on the North Branch of the Potomac and provided a valuable tool for generating runoff producing storms as input to the hydrologic model. The mean spatial rate of occurrence and the mean intensity for a cell were chosen to produce a range of flood flows over the North Branch. For each runoff producing area, the effective precipitation was routed through the hydrologic model and the hourly flows were simulated at the critical damage points in Figure 3.1 for the entire period of simulation.

To provide a basis for comparison, simulated flows into Bloomington Lake were routed without modification. Flood peaks at each critical discharge point were recorded for all simulated storm events. To identify the value of a pure delay of the inflow hydrograph, the simulated precipitation was again routed through the hydrologic model of the North Branch, with a simple operating rule applied at Bloomington Lake. Five operating simulations were performed corresponding to delaying the inflow to Bloomington Lake one to five hours with no attenuation. In this way the value of delaying the flood wave could be judged by comparing the stages at each of the critical discharge points below Bloomington Lake.

The results of this simulation are represented in Figures 3.2 and 3.3. For the critical discharge point corresponding to the USGS gage at Luke, the simulated flood peaks are plotted against their exceedance probability for the simulation. The unmodified flood peaks are plotted along with the peaks resulting from a 5 hour delay. At the Luke gage, a pure delay of 5 hours produces peak flows less than or equal to the unmodified peaks at all discharges. The proximity of Luke and Bloomington will tend to produce precipitation and hence runoff that is temporally correlated. The runoff peaks from each drainage area could be expected to occur within a few hours of each other. Under these circumstances a delay of only a few hours could prevent the peak runoff from the large area controlled by Bloomington from contributing to the peak at Luke. In contrast, the critical discharge point at Cumberland captures a drainage of nearly 900 square miles. The structure of precipitation on this scale would have considerably more spatial variability. The 12 hour travel time from Bloomington to Cumberland, combined with the variability of runoff from the intervening watersheds makes the coincidence of the timing of runoff peaks much less likely at Cumberland. As Figure 3.3 shows, when the Bloomington inflow is delayed 5 hours, some of the flood peaks at Cumberland are reduced, while others are increased.

The value of delaying a flood hydrograph must be judged using the best estimates of precipitation and runoff over the entire drainage basin. A relatively modest delay of 5 hours can require a large volume of storage. Considering the potential increase in downstream damages such a delay could produce

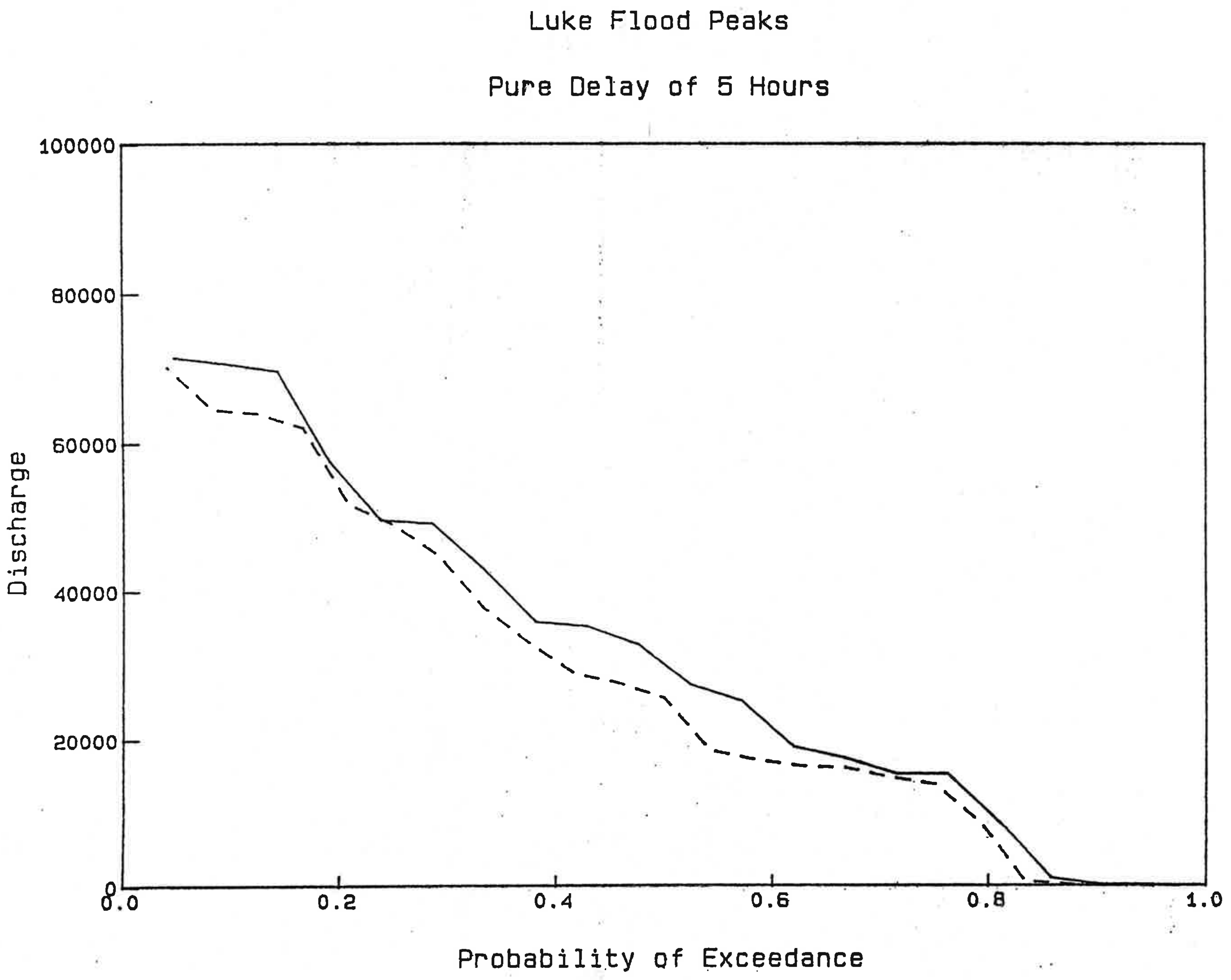

Luke Flood Peaks
Pure Delay of 5 Hours
100000
80000
60000
40000
20000
0
Discharge
0.0
0.2
0.4
0.6
0.8
1.0
Probability of Exceedance

Figure 3.2

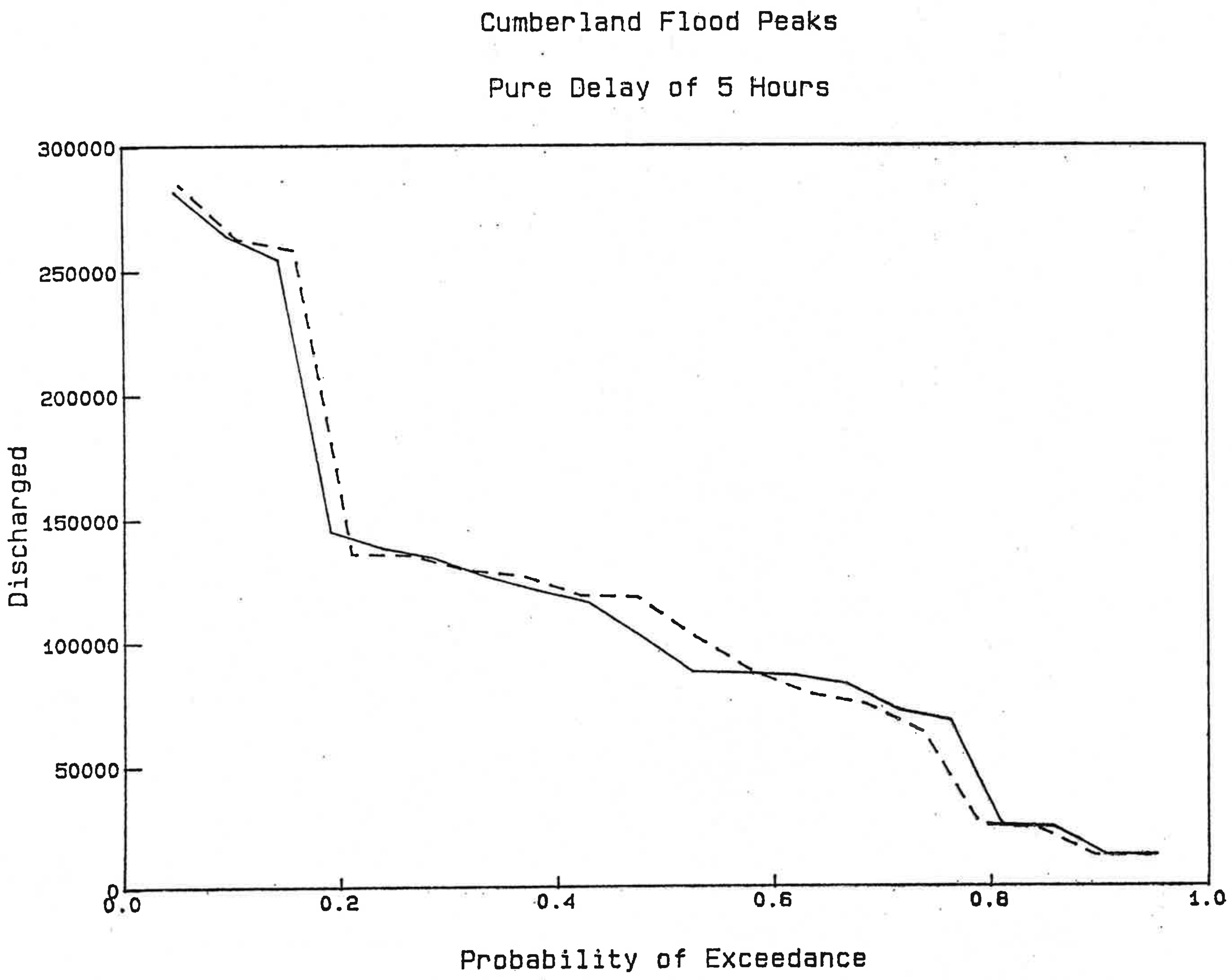

Cumberland Flood Peaks
Pure Delay of 5 Hours
Discharged
300000
250000
200000
150000
100000
50000
0
0.0
0.2
0.4
0.6
0.8
1.0
Probability of Exceedance

Figure 3.3

(Figure 3.3), operating strategies committing significant volumes of storage to delay rather then attenuation must be viewed with great caution. This example indicates the need to incorporate observations and forecasts of both precipitation and streamflow in flood operations. The next section describes an operating rule that uses current hydrologic forecasts in real-time to choose optimal hourly flood control releases.

## 4.0 Optimal Releases with Streamflow Forecasts: An Integrated Operating Rule

The operational choice between an emphasis on delay versus attenuation must be made based on the best available forecasts of runoff from both controlled and uncontrolled watersheds. With current forecasts the operating problem is to identify a release trajectory that uses available storage most effectively. Short term (event based) flood control operation may be described as balancing the risks of flooding below the dam against the risk of overtopping and structural failure. Considering a possible release trajectory, these risks can be represented by the peak discharge and the maximum reservoir contents realized through the storm.

Considering the tradeoff of maximum discharge versus maximum storage for the routing of a predicted flood hydrograph, provides a useful way to summarize the operating alternatives presented by the current hydrologic forecast. Each tradeoff represents a release trajectory which will pass the predicted flood wave without overtopping the dam. Balancing these risks is equivalent to choosing operational targets for maximum storage and maximum discharge. As the utilization of available storage increases, hedging against uncertainty shifts the operating choice to release schedules which allow higher discharges. This serves to retain a margin of safety in the form of available reservoir storage.

### 4.1 Optimizing releases

A simple mathematical optimization model is presented which prescribes optimal releases for a specified flood hydrograph. The model seeks to minimize both the peak discharge and the maximum volume of water in flood control storage. These goals conflict since achieving a lower peak discharge requires increased use of flood control storage. The tradeoff of peak release and peak storage can be developed by solving a multiple objective linear optimization problem. The problem can be stated as:

$$\text{Minimize } (Q(\max),\ S(\max))$$

s.t.

$$S(t) - S(t-1) + R(t) = I(t) \tag{4.01}$$

$$Q(t) - K(0)R(t) - K(1)R(t-1) - K(2)R(t-2) = U(t) \tag{4.02}$$

$$Q(t) - Q(\max) <= 0 \tag{4.03}$$

$$S(t) - S(\max) <= 0 \tag{4.04}$$

where :

$S(t)$ is the reservoir storage volume in time period t

$R(t)$ is the reservoir release made in time period t

$I(t)$ is the inflow to the reservoir during time period t

$Q(t)$ is the discharge at a downstream damage site during time period t

$U(t)$ is the runoff from uncontrolled watersheds downstream from the reservoir, arriving at the downstream damage site in time period t

$S(\max)$ is the maximum volume of water in flood storage

$Q(\max)$ is the maximum discharge at a downstream damage site

$K(0), K(1), K(2)$ are the linear routing coefficients to transform upstream releases to discharge at a damage site

Equations 4.01 through 4.04 hold for each time period $t=1,2,\ldots T$, where T is the duration of the flooding runoff. The continuity equation in constraint 4.01 maintains mass balance over the optimization horizon. Constraint 4.02 incorporates linear channel routing of reservoir releases to a downstream damage site. The $K(i)$ coefficients can be derived directly from the calibrated Muskingum channels. In this way damage at sites below the reservoir, influenced by multiple uncontrolled watersheds, can be considered explicitly in choosing a strategy to pass the forecasted flood. Constraints 4.03 and 4.04 define the maximum discharge and maximum reservoir storage during the flood routing.

Treating the forecasted hydrographs {I(t)} and {U(t)} as deterministic flows, the optimization problem 4.01-4.04 is easily solved using the technique of linear programming. For the current forecasts, the strategic decision focuses on the choice between operational targets for storage and discharge. This strategic decision leads directly to the tactical choice of hourly releases to route the flood hydrograph. The operating model is implemented by solving the optimization problem described by 4.01-4.04 and choosing one of the efficient tradeoffs which balance flood risks. Once a particular balance of risks is chosen, the releases associated with that alternative are implemented.

As long as hydrograph forecasts are available for every runoff producing area, the problem is well specified and can be solved. The complex network representation of the North Branch shown in Figure 3.1 can be readily incorporated within the framework of the basic formulation.

In choosing a strategic operating position, three qualitatively different classes of flood events can be identified. Floods which pose no significant probability of overtopping the dam can be managed to minimize damaging stages using as much flood control storage as necessary. For such events there is no need to hedge against hydrologic uncertainty; the strategic choice is unambiguous. For extreme events in which runoff significantly exceeds the volume of flood control storage, strategic alternatives are limited. Operations will have to shift to passing the flood wave to protect the dam. This consideration will dominate strategies for incremental damage reduction. For floods which are large enough to create a significant risk of overtopping, but small enough to offer significant damage reduction benefits, the strategic choice of operating goals must reflect the operator's judgement and attitude toward risk.

## 4.2 Strategic Switching

An integrated operating rule must be able to operate in both damage dominated and reservoir dominated modes. Damage dominated operations choose releases to minimize damaging flows downstream. Reservoir dominated operations make release decisions that ensure the dam will not be breached. The integrated operating rule links both operating modes with a rule for switching between the two types of operations based on changing hydrologic conditions. The operator's choice of a non-inferior strategic target is one mechanism for making this transition.

The operating rule described in section 2 offers an additional switching mechanism. The fractional availability of flood control storage provides an indicator of the risk of overtopping. The switching criteria of the parametric operating rule can be added to the basic optimizing release model of 4.01 - 4.04 relating the hourly release to the current storage volume. At each time period the prescribed release is compared to the current reservoir contents and inflow. If the fraction of the inflow prescribed to be released is less then the fraction of the total flood control pool that is full, operations switch from damage dominated to reservoir dominated. In each time period the release is set as :

$$R(t) = \max\{R(opt,t) \ , \ \frac{S(t)}{CAP} * I(t) \} \qquad (4.2.1)$$

where:

R(t),S(t),I(t) are as in 4.01-4.04

R(opt,t) is the release prescribed by the optimization problem for time t

CAP is the total reservoir volume designated for flood control storage.

In this way releases are increased as storage is filled, releasing 100% of the inflow when the reservoir is full. As the flood wave passes and the hydrograph falls the releases prescribed in (4.2.1) will also fall. Switching back to the optimal releases returns to normal operation on the falling limb of the flood hydrograph. In this "falling" state the releases are returning the flood pool to its normal elevation.

An additional benefit of this integrated operating rule is the identification of operating targets for the parametric rule. While the optimal release rule is superior to the parametric rule, the need for complete hydrologic forecasts for the basin makes this rule vulnerable to the failure of telemetry equipment. During severe floods it is not uncommon for such equipment to be disabled. Loss of this information puts the reservoir operator in the position of making hourly release decisions when the only dependable information he has is the reservoir elevation and the current inflow to the reservoir. The parametric rule described in section 2 was developed to prescribe hourly releases using just this information. Once delay and attenuation targets have been set, the parametric rule provides a backup operating rule in the event of a failure in the data collection network.

By examining the prescribed releases from the optimal rule at each time step, operating targets for the parametric rule (delay and max release) can be identified . In the event of equipment failure the operator would use the last set of parameters derived from the optimal release rule to continue operation until the equipment was repaired or until the flood waters had clearly receded. The integrated operating rule merges the parametric rule from section 2 with the optimal rule of section 4 to manage flood damage, risk of overtopping, and the transition between these two modes of operation.

The dynamic implementation of this operating model is driven by forecasts of flow at all of the runoff producing areas in the basin. In practice the tradeoffs and release decisions derived from the model of section 4 will be updated each time the streamflow forecasts change. The strategic choice of operating goals based on the relative risk of damage versus overtopping will be continually reassessed as the storm progresses based on precipitation and streamflow observations. This procedure has been implemented on a minicomputer and the strategic as well as the tactical operating alternatives can be updated in less than ten minutes, making hourly updates operationally feasible once a new hydrologic forecast is produced.

In the North Branch a relatively dense network of telemetered streamflow and precipitation data is available to guide hourly operating decisions. Nevertheless considerable uncertainty surrounds short-term flood predictions due to the difficulty in both measuring precipitation that has already fallen, as well as forecasting the volume and temporal distribution of precipitation in the near future. Hedging against this uncertainty takes the form of additional flood control storage.

By providing a safety margin in the form of storage volume that will rarely be needed, operating decisions become less sensitive to the uncertainty in short-term flood forecasts. If the uncertainty in short-term forecasts could be reduced the size of this safety margin could be reduced without significantly increasing flood risk. The flood forecasting procedure described in the next section is one tool for improving short-term flow predictions. The procedure can be implemented using the existing streamflow gages on the North Branch. Short-term forecasts are produced as updated runoff hydrographs which can be used directly in the integrated operating rule described above.

## 5.0 Operational Flood Forecasting

Improved flood forecasting has been recognized as a valuable means for improving flood control operations. Beard (1963) indicated that delaying operating decision by 12 hours could be "disasterous" for the Central Valley Project. Schwartz and Hogan (1985) showed that a delay of as little as 4 hours in routing the SPF through Bloomington could translate into the commitment of nearly 8 billion gallons of flood control storage. Efficient operation of flood control storage will depend on the availability of accurate, current hydrologic forecasts. Current observations of streamflow and precipitation over the basin allow the timely commitment of flood control storage within a storm event. The loss of telemetered observations during a storm would require a more cautious use of reservoir storage, to hedge against hydrologic uncertainty. Telemetered hydrometeorological data and accurate forecasts of flood flows are an essential part of efforts to improve reservoir operation.

### 5.1 Telemetered Hydrologic Data

The North Branch of the Potomac River Basin has a fairly dense network of telemetered precipitation and streamflow gages used to support the operation of Bloomington Reservoir. Data Collection Platforms (DCP's) installed at the gages transmit hourly observations to a Geostationary Operational Environmental Satellite (GOES) relay providing relevant data in near real time. Streamflow, precipitation, and pool elevations in reservoirs are available through the GOES relay from the stations indicated in Tables 4 - 6. Most of the gages and DCP's are operated by the Baltimore District of the Corps of Engineers. Two nearby precipitation gages useful for North Branch operations are maintained by the Pittsburgh District of the Corps of Engineers.

Although the network on the North Branch is unusually dense compared to the national network of rain gages, accurate short-term estimation of mean areal precipitation from rainfall gages requires intensive monitoring. Osborn et al. (1972) conclude that for drainage basins larger than ten square miles, a network of gages with mean spacing of 1.5 miles is necessary to adequately correlate thunderstorm rainfall with observed runoff. Precipitation gages provide useful data on storm timing and intensity at a site. When supplemented with radar observations, significant improvements in precipitation estimation can be realized. For hourly operation using the integrated release rule described above, reducing forecast uncertainty will allow the available storage to be used more fully while controlling flood risk.

Table 4

# TELEMETERED PRECIPITATION GAGES
# ON THE
# NORTH BRANCH POTOMAC RIVER

| GOES PLATFORM ADDRESS | GAGE |
|---|---|
| CE698E7A | OAKLAND |
| CE7B7246 | MT. STORM |
| CE593556 | KITZMILLER |
| CE7B6FE2 | BAYARD |
| CE718D42 | PINTO |
| CE71B6A | SPRINGFIELD* |
| CE4363E6 | SAVAGE DAM |

---

* The data collection platform at Springfield is programmed to report cumulative precipitation. The precipitation channel was not operational at the time of this writing.

Table 5

## TELEMETERED STREAMFLOW GAGES
## ON THE
## NORTH BRANCH POTOMAC RIVER

| GOES PLATFORM ADDRESS | LOCATION |
|---|---|
| CE59262 | LUKE |
| CE5928F2 | BARNUM |
| CE593556 | KITZMILLER |
| CE6C4CA4 | BARTON |
| CE718D42 | PINTO |
| CE719E6 | CUMBERLAND |
| CE719E34 | WILLS CREEK |
| CE71A57C | PAW PAW |
| CE71ABAE | HANCOCK |
| CE71B6A | SPRINGFIELD |
| CE717DC6 | BELOW SAVAGE DAM |
| CE59262 | LUKE |

Table 6

## TELEMETERED POOL ELEVATIONS* FOR RESERVOIRS ON THE NORTH BRANCH POTOMAC RIVER

| GOES PLATFORM ADDRESS | LOCATION |
|---|---|
| CE4363E6 | SAVAGE LAKE |
| CE436D34 | BLOOMINGTON LAKE |

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* Elevations are reported as height above elevation 1400 msl. For example a conservation pool elevation of 1465 msl is reported as 65.0

## 5.2 Flood Forecasting by Deconvolution

An accurate short term flood forecasting model is developed using only observed streamflow and the existing rainfall-runoff model for the North Branch. Rainfall runoff models are commonly used in conjunction with precipitation observations to produce short-term runoff forecasts. The error in transforming point estimates of precipitation to effective rainfall over a basin results in considerable uncertainty surrounding the derived streamflow forecasts (Troutman 1983). Pegram (1982) has developed an alternate approach based on the deconvolution of the output from a calibrated rainfall runoff model with a Kalman filter. The basic approach is to rely on the rainfall runoff model to provide an accurate description of the way in which precipitation is transformed to runoff. Filtering the observed streamflows through the calibrated rainfall runoff model provides a conditional estimate of the input: effective precipitation. Using this estimate of precipitation, a forecast of short-term streamflow is then produced. The procedure is repeated iteratively at each time step. A filtering step provides the current best estimate of precipitation; using this estimate a prediction step provides short-term forecasts. The observed errors in the short-term prediction are used as feedback in the next estimation step to update precipitation.

Pegram's methodology operates reasonably well, using a conceptual hydrologic model for prediction and a Kalman filter for estimation. The main problem with this procedure is the unconstrained nature of the precipitation estimation. The maximum likelihood estimator for precipitation is derived so as to minimize the sum of the squared deviations between observed and predicted streamflow. The minimization is unconstrained, and negative values for precipitation are sometimes produced. While these negative values are optimal in the least squares sense, they are unacceptable estimates for physical inputs. After deriving the maximum likelihood estimators and their accompanying confidence limits, Pegram is forced to resort to an ad hoc procedure to redistribute hourly precipitation depths in a plausible manner.

The short term flood forecasting procedure developed here is simpler than that of Pegram and does not produce negative estimates of precipitation. The method is conceptually similar to Pegram's in that effective precipitation is inferred from streamflow using a calibrated rainfall runoff model. Constrained optimization is used to impose non-negativity on estimates of precipitation totals. The estimation procedure uses all recent observations of streamflow as input and produces the best estimates of the hourly effective precipitation totals which could have produced the observed flows.

The transformation of precipitation to runoff is assumed to be accurately represented by the unit hydrograph. Use of the unit hydrograph has several advantages compared to the conceptual hydrologic model employed by Pegram. The linearity of the unit hydrograph simplifies estimation procedures. The linear ordinates of the hydrograph allow hourly observations of streamflow to be defined as a linear combination of effective precipitation. At each time step, the current estimate of precipitation can be produced by solving a simple linear program. Each hour, as another streamflow observation becomes available a larger linear program is solved. Each new observation of streamflow provides both an updated estimate of precipitation that has already fallen, as well as an initial estimate of the additional precipitation that has fallen in the last hour.

The principal value of the estimation technique using unit hydrographs is the forecast lead time. The subbasins of the North Branch above Cumberland have average times of concentration of about six hours. This means that the precipitation we estimate for the current hour will not make its maximum contribution to runoff for another five hours. By accepting the runoff pattern of the unit hydrograph, short-term (five hour lead time) forecasts of runoff can be produced without trying to estimate future precipitation. While these forecasts will generally be lower bounds on runoff, one strength of this technique is the 5-6 hour lead time it provides in identifying the flood peak.

### 5.3 Forecasting multiple event runoff hydrograhs

To demonstrate the procedure, the forecasting model was applied to a multi-event runoff hydrograph (Table 7) first presented in Linsley et al (1975). The results are summarized in Table 8. The actual effective precipitation and runoff are shown at the bottom of the table. The consecutive estimates of precipitation and runoff made at each time step are shown for comparison. The largest error in estimating precipitation is only 0.015 inches occurring for the first estimate of precipitation at 1400 hours. This error is largely attributable to rounding error in the ordinates of the unit hydrograph. The largest error in streamflow estimation is significantly larger. This is to be expected since the procedure is only forecasting streamflow based on precipitation that has already fallen. The time of concentration of the basin in this example is only two hours. Predictions more than one hour into the future must be viewed as lower bounds on runoff and will be subject to considerable error if precipitation persists. For the North Branch, with significantly longer times of concentration, forecast lead times would increase.

## Table 7

## Runoff Hydrograph after Linsley Kohler & Paulus (1975)

| Hour | runoff inches | baseflow cfs | total flow cfs |
|---|---|---|---|
| 0500 |  | 300 | 300 |
| 0800 | 0.4 | 300 | 1150 |
| 1100 | 0.9 | 290 | 3530 |
| 1400 |  | 290 | 4290 |
| 1700 |  | 280 | 3330 |
| 2000 | 1.2 | 280 | 5130 |
| 2300 |  | 290 | 5970 |
| 0200 |  | 300 | 4510 |
| 0500 |  | 310 | 3340 |
| 0800 |  | 320 | 2390 |
| 1100 |  | 320 | 1660 |
| 1400 |  | 330 | 1110 |
| 1700 |  | 340 | 760 |
| 2000 |  | 350 | 500 |
| 2300 |  | 360 | 360 |

# Table 8

## Real-Time Estimation of Effective Precipitation

## After Linsley, Kohler & Paulus (1975)

| Estimate | Hour<br>0500 | 0800 | 1100 | 1400 | 1700 | 2000 | 2300 | 0200 | 0500 | 0800 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.0 | | | | | | | | | |
| 2 | 0.0 | 0.4 | | | | | | | | |
| 3 | 0.0 | 0.4 | 0.889 | | | | | | | |
| 4 | 0.0 | 0.4 | 0.889 | 0.015 | | | | | | |
| 5 | 0.0 | 0.4 | 0.889 | 0.01 | 0.0 | | | | | |
| 6 | 0.0 | 0.4 | 0.889 | 0.01 | 0.0 | 1.196 | | | | |
| 7 | 0.0 | 0.4 | 0.889 | 0.01 | 0.0 | 1.196 | 0.003 | | | |
| 8 | 0.0 | 0.4 | 0.889 | 0.01 | 0.0 | 1.196 | 0.001 | 0.0 | | |
| 9 | 0.0 | 0.4 | 0.889 | 0.01 | 0.0 | 1.196 | 0.001 | 0.0 | 0.0 | |
| 10 | 0.0 | 0.4 | 0.889 | 0.01 | 0.0 | 1.196 | 0.001 | 0.0 | 0.0 | 0.0 |
| Actual Precipitation: | 0.0 | 0.4 | 0.9 | 0.0 | 0.0 | 1.2 | | | | |

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## Runoff Forecast Using Precipitation Estimate

| Estimate | 0500 | 0800 | 1100 | 1400 | 1700 | 2000 | 2300 | 0200 | 0500 | 0800 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | | 850 | 1330 | 1010 | 770 | 570 | 410 | 260 | 140 | 50 |
| 3 | | | 3219 | 3966 | 3015 | 2281 | 1677 | 1171 | 718 | 361 |
| 4 | | | | 3998 | 3065 | 2319 | 1706 | 1193 | 733 | 371 |
| 5 | | | | | 3048 | 2307 | 1696 | 1185 | 728 | 368 |
| 6 | | | | | | 4848 | 5673 | 4205 | 3030 | 2072 |
| 7 | | | | | | | 5679 | 4215 | 3038 | 2078 |
| 8 | | | | | | | | 4209 | 3033 | 2074 |
| 9 | | | | | | | | | 3033 | 2074 |
| Actual runoff: | 0 | 850 | 3220 | 4000 | 3050 | 4850 | 5680 | 4210 | 3030 | 2070 |

The estimation procedure is a promising source of short term flood forecasts. The uncertainty in extrapolating point measurements of precipitation as well as predicting precipitation in the near term is avoided. Constrained optimization gives very good estimates of effective precipitation while avoiding physically unrealistic solutions. The procedure is readily implemented with the existing gage network. The predicted hydrographs that are produced are well suited for the integrated operating model described in section 4. For most of the subbasins in the North Branch the forecast lead time will be about five hours, significantly improving our present short term forecasting capability on the North Branch.

# CONCLUSION

During low flow periods in the summer and early fall, freshwater inflow to the Chesapeake Bay and its tributaries may be enhanced through non-structural means by modifying current operating procedures for multiple purpose reservoirs. Low flow enhancement through reservoir operation could provide incremental improvements to water quality and aquatic habitat as well as enhancing recreational opportunities and water supply reliability. This study examined techniques for allocating and operating shared reservoir storage. The emphasis of this report was operating procedures which would allow all authorized project purposes to be satisfied, while providing additional reservoir storage for use during the low flow period.

Two techniques for dynamically allocating storage are described. A randomized allocation rule is described in which the allocation of flood control and conservation storage varies from year to year. A randomized storage allocation can reduce the expected monetary value of flood damages and provide additional conservation storage in years with below average streamflow. A risk based allocation rule is proposed in which monthly storage targets are explicitly linked to the changing probability of refill during the year. Risk based allocation can provide additional water quality releases in late fall as well as additional flood control storage for parts of the fall-winter refill period. A risk based storage allocation can reliably refill shared conservation storage.

Two tools for flood control operation are developed which will allow flood control storage to be used more effectively. A multiple-objective operating rule is described that identifies hourly releases which will balance the risks of flood control operation during a high flow event. Current hydrologic forecasts are used to continually update and describe the feasible operating choices available to the reservoir operator.

An optimal estimation procedure is developed for short-term operational flood forecasting. The procedure filters streamflow through a calibrated watershed model to estimate the effective precipitation contributing to runoff. The peak runoff can be anticipated with a lead time comparable to the time of concentration of the watershed. In addition to providing peak flow estimates, this estimation procedure is insensitive to errors in both the extrapolation of point measurements of rainfall to mean areal precipitation, as well as the estimation of infiltration.

The feasibility of enhancing freshwater inflow to the Chesapeake Bay requires that modified operating procedures preserve, if not enhance, the achievable benefits of each authorized project purpose in a multiple purpose reservoir. Strategic allocation of storage can increase the volumes available for both flood control and enhanced freshwater inflow. Tactical operation of flood control storage ensures that flood protection will not be compromised by sharing reservoir storage. The combination of strategic storage allocation and tactical reservoir operation offers the non-structural tools to realize enhanced benefits for all authorized project purposes in multiple purpose reservoirs.

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