Maximizing Potomac Inflow to the Chesapeake Bay During Drought and Examination of the Potential for Similar Enhancement in the Susquehanna River Basin

Prepared for the Maryland Department of Natural Resources
Water Resources Administration

by the

Interstate Commission on the Potomac River Basin

Maximizing Potomac Inflow to the Chesapeake Bay During Drought and an Examination of the Potential for Similar Enhancement in the Susquehanna River Basin

by

Stuart S. Schwartz and Kathleen Hogan

Interstate Commission on the Potomac River Basin

ACKNOWLEDGEMENTS:

Many individuals contributed both directly and indirectly to the completion of this work. Although each thoughtful discussion and useful insight cannot be fully referenced, some of the guidance and assistance offered to the authors is noted below.

Mr. Richard Olin of the Baltimore District, Army Corps of Engineers generously shared his expertise and understanding of flood control operation in many of the reservoirs considered in this report. Mr. Paul DeStefano of the Maryland Department of Health and Mental Hygiene provided salinity data for the Upper Chesapeake Bay. Mr. Marshal Goulding and Mr. Dick Jackson from the Susquehanna River Basin Commission provided useful comments and stimulating discussions which are gratefully acknowledged. Mr. Robert Miller, Dr. Nancy N. Ehrlich, and Mr. Bob Kort, from the Maryland Department of Natural Resources' Water Resources Administration all provided encouragement, support and thoughtful comments and discussion throughout the development of this work. Dr. James A. Smith of ICPRB freely contributed his insight and expertise in the development of the Markov precipitation model as well as the understanding of the rainfall runoff process. Dr. Roland Steiner of ICPRB offered useful insights into the composition of the flood hydrograph. Dr. Daniel P. Sheer, Director of Technical Services at ICPRB, offered animated enthusiasm for the initial work and his contribution to this report is acknowledged.

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 authors.

Maximizing Potomac Inflow to the Chesapeake Bay During Drought and Examination of the Potential for Similar Enhancement in the Susquehanna River Basin

Introduction

This report summarizes the Interstate Commission on the Potomac River Basin's study of the feasibility of maximizing Potomac inflow to the Chesapeake Bay during drought, and the potential for similar enhancement in the Susquehanna River Basin. The focus of this work is the enhancement of freshwater flow through the innovative operation of Bloomington reservoir, and the possibility of similar operation of reservoirs in the Susquehanna River Basin.

Overview of the Study

This study is organized in three main sections. First, Bloomington reservoir operating rules were examined to identify those which would allow some flood control storage to be utilized for freshwater flow enhancement without compromising the authorized project purposes. Models of the rainfall-runoff process on the North Branch of the Potomac River were developed and utilized to identify opportunities for innovative flood-control operation. Flood control operation was formulated as a multiple objective problem. Mathematical optimization was used to solve a simplified flood control problem, and a dynamic flood control operating procedure was demonstrated. Results suggest that operating changes could make significant volumes of storage available for enhanced freshwater inflow in existing facilities.

The second part of this study examined the impacts of a change in the allocation of flood-control storage in Bloomington reservoir, on the water quality goals of that multipurpose project. Any operating changes that would significantly change the level of the lake must also consider the impact on water quality, both within the lake, and in the river downstream. Bloomington reservoir was constructed with a multiple-level withdrawal system that control downstream water quality by selectively withdrawing waters of varying quality from the lake. In examining the potential for reallocating storage in Bloomington reservoir, the Army Corps of Engineers concluded that construction of additional withdrawal ports at a higher elevation would be required in order to meet the project's water quality functions. However, additional ports may not be necessary if operational decisions can incorporate the predictability of in-lake water quality. Joint optimization and simulation models were used to examine impacts of dynamic water quality operation with higher pool elevations. Results suggest that innovative operation of water quality storage can offset or improve water quality while obviating the need for structural modification of the withdrawal tower.

In the third part of this work, the potential benefits from dynamically allocating storage in the major reservoirs of the Susquehanna River Basin was examined. The upper bound on the volume of reservoir storage available through changes in operation was estimated based on two types of operating changes. In addition to dynamic use of flood control storage, altered timing of seasonal drawdown from recreational pools to flood control levels was considered, where possible. The relationship between the reliability of firm yield and available reservoir storage was developed for key streamflow gauges in the Susquehanna Basin. In this way, an upper bound was established for the potential modification of flow frequencies of the Susquehanna River through reservoir operation. A one-dimensional salinity model of the upper bay (where the influence of the Susquehanna is greatest) was used to relate potential changes in Susquehanna River flow to changes in Chesapeake Bay salinity. The modifications of salinity in the upper bay that could be realized are at best modest. However, using the storage potentially available, significant local improvements of instream habitat may be achievable.

Summary of Findings

1. Dynamic operation of Bloomington reservoir using some of the current flood control storage to enhance freshwater flow, can be achieved without significantly degrading downstream flood control benefits.

2. While the volume of storage available for enhanced freshwater flow must be balanced against the increased probability of flood damage, approximately 10000 acre feet of storage may be available for flow enhancement, with modest increases in the expected value of flood damages.

3. Major changes in the salinity of the Potomac Estuary are unlikely from the operation of 10000 acre feet of reservoir storage. However, this volume of storage could, for example, provide an additional 100 MGD of environmental flowby for 30 days (doubling the current flowby of 100 MGD); or, this storage could be operated to offset the impacts of a consumptive use of nearly 30 MGD, (roughly the equivalent of a major thermal electric power plant).

4. Downstream water quality goals can be satisfied with higher lake elevations, through dynamic operation of water

quality storage. Downstream acidity is uniformly improved with higher pool elevations. Downstream temperature is slightly degraded with higher pool elevations, but the maximum increase in temperature is less than 0.5 degrees C.

5. Using optimization and simulation modeling in water quality operation can obviate the need for structural modification of the withdrawal tower at Bloomington reservoir, with potential savings of $1,000,000.

6. Significant potential exists for modifying the operation of existing reservoirs in the Susquehanna River Basin.

7. Using optimistic, yet plausible assumptions, an upper bound of 100,000 acre feet of reservoir storage was identified that could be used to enhance freshwater flows to the Chesapeake Bay.

8. Changes in flow frequency from operating 100,000 acre feet would be significant, though not dramatic. For example, this volume of storage could reduce the recurrence interval of flows under 5000 cfs at Marietta, Pa. from one year in two to one year in four.

9. The 100,000 acre feet of potentially available storage is insufficient to have a significant impact on salinity levels in the upper bay.

10. Instream habitat benefits could be substantial if operations could be coordinated with the four major hydroelectric dams on the lower Susquehanna. Although these benefits may be technically feasible, such operation would also have to overcome substantial institutional constraints.

11. Overall, potential exists for significant environmental improvement through the dynamic operation of existing reservoirs. The size of the bay compared with the volume of existing reservoir storage makes major changes in Chesapeake Bay hydrology unlikely. Innovative operation of existing reservoirs could be used to support additional growth in the region by offsetting the impacts of projected consumptive withdrawals.

1. Flood Control Operation of Bloomington Reservoir

Bloomington Reservoir, located on the North Branch of the Potomac River, is the largest impoundment in the Potomac River Basin. Bloomington is a multipurpose project, operated to serve water supply, water quality, recreational, and flood control functions. This section examines flood control operation of Bloomington Reservoir, and develops a prototype flood control operating procedure that can use forecast information routinely produced by the National Weather Service.

Historical high flow events at the United States Geological Survey (USGS) gauge at Kitzmiller, Md. are first reviewed to characterize the hydrology at Bloomington. Using the Sacramento Soil Moisture Model, a conceptual hydrologic model that is one component of the National Weather Service River Forecast System, antecedent conditions contributing to high runoff events are examined. Using historical mean areal precipitation from 1949 through 1968, large precipitation events from the historical record on the North Branch are routed through the Sacramento model. Streamflows are produced to determine the utility of using soil moisture storages in assessing probable flood risk. A first order Markov model of mean areal precipitation is calibrated for the North Branch, and used to evaluate the relative influence of persistence in precipitation and soil moisture conditions in determining the structure of flood flows on the North Branch. Finally, a prototypic flood control operating model is formulated, and optimal operating solutions are derived. The tradeoff between short term flood damage, and the risk from uncertain forecasts is quantified, producing a family of efficient operating decisions.

1.1.1 Flow at Kitzmiller

The period of record for the USGS streamflow gauge at Kitzmiller was reviewed and all daily average flows greater than 5000 cfs were identified. The frequency distribution of these flows indicates the majority of historical high flows are under 6000 cfs.

Kitzmiller Flow (cfs)	NUMBER OF OBSERVATIONS	
4000	18	******************
5000	24	************************
6000	3	***
7000	2	**
8000	3	***
9000	1	*
10000	0	
11000	0	
12000	0	
13000	1	*

Caution must be exercised in weighing historical flows too heavily in assessing risk of rare events. Additionally, these daily average flows mask the instantaneous peaks attained during these high flow conditions. Nevertheless, they do suggest that critical flood control releases on the North Branch are relatively rare events. Dynamic operation of Bloomington's flood control storage would retain spring flood waters for release in summer or early fall. The ability to recognize periods of low runoff potential, when water could be stored in the flood control pool without significantly increasing the downstream risk of flood damages, would be a valuable aid in dynamic flood control operation. The rainfall-runoff relationship for high flows and historical precipitation data has been analyzed to identify soil moisture conditions in the Spring, for which the flood risk is low.

A Markov model of precipitation has been calibrated and used to derive statistically representative mean areal precipitation for the North Branch. Used in conjunction with the Sacramento Soil Moisture Accounting Model, this representation of precipitation provides insight into the relative importance of persistence in precipitation and soil moisture conditions in determining the structure of flood flows in the North Branch.

1.1.2 Markov Precipitation Model

Incorporating our understanding of the persistence of hydrologic time-series into reservoir operations offers a non-structural means to expand the range of achievable benefits. Using conceptual soil moisture storages, the value and feasibility of extended water quality operations may be anticipated in advance of critical low flow conditions. Decomposition of high flow events into the separable components of soil moisture and precipitation enhances the identification of flood risks.

As a first step toward incorporating basin wide hydrologic conditions in flood control operation, this study uses a conceptual soil moisture model to examine the interaction between precipitation and soil moisture in producing streamflow. Historical mean areal precipitation (MAP) at 6 hour intervals for the month of March was routed through the Sacramento Soil Moisture Accounting Model to produce historically derived runoff depths over the entire North Branch Basin. For comparison, synthetic precipitation was simulated using a first-order Markov chain and used to produce simulated runoff using identical initial soil moisture conditions. To evaluate the relative importance of persistence in precipitation, a second model of MAP was developed. This second model reproduced precipitation depths in the same frequency as the historical data in a completely random order. Each simulated MAP sequence from this model could be viewed as a random sample taken from the multinomial distribution in which the probabilities of success corresponded to the observed frequency of occurrence of MAP in each depth class. This model is referred to herein as the multinomial precipitation generator. Imbedded in these streamflows are errors in estimation of MAP, as well as the calibration and model errors of the Sacramento model. Though present, these errors are not significant for the purposes of the present study.

1.1.3 Description of Precipitation

Mean areal precipitation at 6-hour intervals for the month of March is used as input to the Sacramento model and this is the meteorological variable for which statistical models are developed. Summary statistics for historical MAP show a seasonal pattern of storm occurrence and storm depths. As indicated in Figure 1a, the occurrence of 6-hour periods with non-zero MAP is highest in the winter and early spring, and lowest in August and September. In contrast to the frequency of wet events, the average depth per wet event (Figure 1c) is highest in the summer and early fall and lowest in winter, reflecting the seasonal change in storm patterns. Total precipitation depth in any month is clearly the product of the number of events and the depth per event. The seasonal decrease in frequency of events, with a parallel increase in mean depths, results in monthly precipitation totals achieving their maximum value in the spring (Figure 1b).

1.1.4 Markov Model of MAP

Since Gabriel and Neumann (1) demonstrated the fit of a Markov chain to daily rainfall occurrence, a number of workers have explored the first order Markov process as a model of persistent precipitation sequences with considerable, though not unequivocal, success. Treating wet and dry periods as distinct states, 20 years of MAP were used to estimate monthly transition probabilities for a first-order Markov chain. The sequences of wet and dry runs were tabulated, and tested against the geometric distribution parameterized with the estimated transition probabilities. Despite the visible scatter indicated in Figures 2a and 2b, the null hypothesis of a geometric distribution of run lengths could not be rejected at the 0.005 percent significance level using the chi-square statistic.

The monthly transition probabilities also provided additional insight into the seasonal characteristics of precipitation on the North Branch. The "wet-wet" transition probability (Figure 2a) is highest in winter and early spring, declining steadily to a seasonal minimum in mid summer. The probability of a "dry-wet" transition (the initiation of a storm event) is highest in early fall, and lowest in March (Figure 2b). Combining this description of precipitation occurrence with mean monthly depths per event gives a more complete picture of the seasonal change in precipitation patterns. Spring precipitation tends to occur as extended sequences of moderate depth events. The presence of frozen ground and snowmelt in the North Branch, with relatively longlasting precipitation events, is typically the cause of spring floods on the North Branch.

In summer and late fall, the probability of initiation of a storm event is highest. The relatively low number of events during this time of the year indicates that precipitation in late summer and fall tends to be sporadic, consisting of relatively large magnitude, isolated events. Fall precipitation commonly results from airmass thunderstorms, with intense, localized cells of storm activity. The largest events in the historical record occurring in the fall result from the passage of tropical cyclones over the basin.

A first order Markov chain was adopted as a simple model of March precipitation for the North Branch. Based on the historical distribution of MAP depths, 45 depth intervals were identified, and transition probabilities for a 45 state Markov chain were estimated. Using a pseudo-random number generator, the 45-state transition matrix was used to generate Markov sequences of synthetic March MAP. The historical frequencies of March MAP depths were similarly used to generate multinomial MAP. Cumulative density functions for the resulting sequences of synthetic MAP presented in Figure 4 show good agreement with the historical density of precipitation depths. Both sequences of synthetic precipitation were applied to the Sacremento Model to generate synthetic streamflow. These were compared to streamflow using historical MAP and identical initial soil moisture conditions. Comparing the Markov chain model to the multinomial derived streamflows also provided a way to gauge the importance of persistence in precipitation, on streamflow.

1.1.5 The Sacramento Soil Moisture Accounting Model

The Sacramento Model provides a conceptual accounting of the precipitation input to a drainage basin. The model represents the storage and movement of water beneath the surface, the transmission of groundwater to stream channels, and the evaporation and transpiration of water from the soil and stream channel. Soil moisture is represented in the model by several storage zones. Outflow components from the various conceptual soil moisture storage zones can be interpreted as baseflow, interflow, and overland flow.

The Sacramento Model, used in conjunction with the Extended Streamflow Prediction procedure of the National Weather Service River Forecast System, has been shown to be particularly well suited for representing streamflow characteristics in the Potomac River Basin (Smith et al. (1982)). The formulation of the model does introduce error into the derived streamflow sequences. Whereas comparison of streamflows produced with alternate representations of MAP is internally consistent, comparisons to actual streamflows must be made with caution. For this reason, the scope of this analysis is restricted to streamflows derived using the Sacremento Model.

1.1.6 Comparison of Derived Streamflows

Comparing streamflows derived from historical, Markov, and multinomial sequences of MAP indicates persistent temporal characteristics of precipitation in streamflow. The cumulative density function in figure 5 shows the close similarity between the distribution of streamflow depth generated from historical MAP and the Markov model. Whereas the agreement of flow frequencies was good, the Markov derived streamflow tended to under-represent intermediate flows in the 5-10 mm. range (Figure 6). In the Markov MAPs, precipitation occurrences greater than 10 mm. tended to occur in clusters. In the estimated transition probability matrix, several of the states corresponding to depths over 10 mm. only had non-zero transition probabilities to other intense rainfall states. This is attributable to the small number of large precipitation events in the historical record for March. Nonetheless, this suggests that the meteorological conditions producing infrequent intense storm events in March need to be modeled as a separate, distinct process. The multinomial precipitation sequences produced streamflows in which low flow events (1-3 mm.) were under-represented. This can be attributed to the low frequency of extended dry periods in the random precipitation sequences. Similarly, intermediate depth events (5-10 mm.) were over-represented (Figure 6). In the multinomial precipitation sequences, long runs of successive wet periods are uncommon, as are higher flow depths. The lack of persistence in the multinomial precipitation is clearly reflected in the frequency distribution of derived streamflow.

To explore the temporal structure of derived streamflow, autocorrelation functions and partial autocorrelation functions for the three classes of derived streamflow were examined. The autocorrelation and partial autocorrelation functions for streamflow show a striking similarity, despite the significant differences built into the precipitation models. The value of the lag 1 autocorrelation coefficient is approximately the same for all three of the derived streamflow sequences. Since the multinomial precipitation is uncorrelated, the high value of the lag one autocorrelation coefficient suggests the dominant role of temporal structure of the Sacremento Model.

For a pure autoregressive process, an exponential decay of the autocorrelation function would be expected. Autocorrelations decrease uniformly with lag for historically derived streamflow, but remain significantly different from zero beyond lag 10. One explanation for this is the routing component of the Sacramento Model. The timing of instantaneous runoff in the Sacramento Model is modified with a unit hydrograph to account for the temporal lag in runoff contribution from subareas in the basin. For the North Branch, the unit hydrograph distributes the runoff from a single period over ten consecutive periods. The presence of significant autocorrelation beyond lag 10 strongly suggests model imposed structure. This inference is again reinforced by the persistence of significant autocorrelations in streamflow derived from multinomial precipitation.

1.1.7 Discussion

The relative roles of precipitation and soil moisture in determining streamflow characteristics can be identified. The consequences of persistence in precipitation appear to be more prominent in determining overall runoff volumes, and longer term flow frequency. Without extended wet and dry periods, the natural variation in streamflow is reduced, irrespective of soil moisture conditions.

The temporal relationship of successive streamflow values appears to be significantly affected by the storage and movement of groundwater, as represented by the Sacramento Model. Soil moisture storage appears to play a more significant role in the "memory" of March streamflow, whereas persistence in precipitation seems to have a more direct bearing on the magnitude and frequency of extreme events. This can be contrasted with summer and fall streamflow. During low flow periods, soil moisture storage largely determines the characteristics of extreme events by controlling baseflow.

1.1.8 Summary

Antecedent soil moisture conditions exert a profound influence on the memory, or persistence of streamflow in the North Branch. This is clear from the autocorrelation function of streamflow produced using the multinomial precipitation model. Since this precipitation is uncorrelated by construction, all of the autocorrelation in the multinomial derived streamflow must come from the soil moisture conditions. Soil moisture also exerts dominant control over low flows, which consist largely of baseflow. In spite of the influence of soil moisture conditions generally, the magnitude of flood events is largely determined by persistence in precipitation. To examine this more closely, several large precipitation events from the historical record are applied to the full range of historically observed soil moisture conditions. In this way the variation in spring flood flows attributable to soil moisture (and our ability to use soil moisture to recognize low flood risk potential) can be better identified.

1.2 Evaluation of Flood Risk

Mean areal precipitation data for the period 1 January 1949 through 31 December 1968 at six hour intervals was used to estimate the range in variation of runoff, based on soil moisture conditions. The record was simulated, and soil moisture conditions for every day in March for the period 1949-1968 were generated and stored. These soil moisture storages were successively used as initial conditions to rout the 5 largest March storms from rainfall to runoff.

The unanticipated result was that for all initial March soil moisture conditions considered (20 years of 31 daily values), the change in runoff was insignificant. Both upper and lower zone tension water stay virtually full through March, and don't begin to drain until evapotranspiration is significantly higher (at least 1 mm per day).

This observation, though obvious in retrospect, lead to a subtle change in the analysis. Instead of identifying safe conditions to store water when flood risks are low, dynamic operation depends on recognizing the conditions when water must be released, and allowing flood control storage to partially fill at other times in the spring.

1.2.1 Flood Control Operation

In this section, a real-time procedure to operate Bloomington reservoir in order to attenuate downstream flood damage is developed. Flood control operation reduces the peak of the outflow hydrograph, as well as delaying the time to peak discharge. Reducing the peak discharge reduces maximum flood stages and resulting damages in the reaches immediately downstream from Bloomington. The operating rule developed in this section concentrates on flood peak reduction to balance short-term flood damage and intermediate-term flood risk. At damage centers further downstream, the peak flood stage is largely determined by runoff from the uncontrolled intervening drainage area. If the peak discharge from Bloomington and the peak flow from the intervening drainage were to arrive at Cumberland simultaneously, flood damages would be substantially increased. Delaying the time of the peak discharge from Bloomington, provides flood control benefits at downstream damage centers. The optimal timing of the peak Bloomington discharge should be based on precipitation and runoff from downstream subbasins. Such a coordinated operating procedure, though beyond the scope of the present work, is feasible; operational requirements for such a system are outlined at the end of this section.

Two consequences of flood control operation are considered in this analysis. The goal of flood control operation is to reduce downstream damages by reducing peak floodflows. Peak discharge is the central measure of flood control operating effectiveness. The instantaneous volume of flood control storage available -freeboard- is reduced when flood waters are stored to attenuate the flood peak. This increases the vulnerability of the system to a second, unanticipated flood wave, such as that caused by a flash storm in an already saturated basin. The immediate reduction in flood damages associated with routing a particular storm, (which is known with relative certainty), must be balanced against the risk of being caught with too little freeboard to attenuate a second, unanticipated storm, resulting in even greater damage downstream.

The peak discharge is used as a performance measure for the effectiveness of flood control operation. The discharge rate can be related to a flood stage and, thereby, flood damages using stage-discharge and stage-damage tables, which have been provided by the U.S. Geologic Survey and the U.S. Army Corps of Engineers, respectively. This assumes that flood damage is a function of stage alone, ignoring the duration of flood stages. While extended periods at high stages can, for example, lead to added structural damages, by far the greatest proportion of damage is caused by the initial inundation. For this reason peak discharge is an acceptable and easily quantifiable measure of flood damage.

Quantifying the risk from an additional storm and the resulting damage downstream is much more difficult. Assessing this risk requires the joint analysis of the conditional probability of runoff producing precipitation, the temporal availability of freeboard as flood flows enter the reservoir - determined by the operating rule used to route the initial flood wave- and the peak flood control release resulting from the operating rule used to route the second flood wave.

The appropriate time scale for flood control routing is on the order of hours. Significant changes in freeboard can be expected to occur over this time scale. For this reason, assessing the joint probability of freeboard and flood flow to the reservoir would require an assessment of the hourly probability of precipitation over the basin. Such resolution is beyond present capability. Any probabilistic assessment of precipitation -and thereby runoff potential- can reasonably be used as though peak precipitation and flows are equally likely in any flood routing period. The worst case would occur if the peak inflow occurred just as the maximum volume was in flood control storage -minimum freeboard. Therefore, the risk of added flood damage from a sudden storm, can be represented by the maximum storage volume retained during the routing of a flood wave.

The choices in making flood control releases for a given or anticipated flood wave can be represented as a trade-off between minimizing the maximum flood control release, and minimizing the maximum volume held in storage -minimum freeboard. The maximum flood control release determines downstream flood damages, and the reasons for reducing this discharge as much as possible are obvious. Minimizing the maximum volume in storage, is a way to retain as much capability as possible for handling worsening flood conditions while attenuating a flood wave.

1.2.2 Evaluating Flood Control Operation

Beard (1964) provides a clear and comprehensive description of the tradeoffs and difficulties involved in flood control operation. This treatment particularly addresses flood control in multiple purpose projects and offers considerable insight for the present work. The adequacy of flood control storage volumes, is most often based on design hydrologic events such as the standard project flood (SPF), or the maximum probable flood (MPF). For a given downstream flood stage, representing a level of downstream flood protection, the SPF can be back-routed through the reservoir to derive the time trace of storage and releases.

Operating decisions implicit in this routing are based on perfect knowledge of the inflow hydrograph. True flood control operation will be based on predicted hydrographs. Adequate gauging can substantially reduce hydrologic uncertainty. Nevertheless, flood control effectiveness based on deterministic routing, must be viewed as an upper bound, to be approached through good operating practice. The greater this upper bound, the greater the margin of safety, to allow for uncertainty of inflow.

For comparative purposes, routing of the Standard Project Flood (SPF) for Bloomington Reservoir performed by the U.S. Army Corps of Engineers is described. An optimizing flood control procedure is then developed which is capable of trading off peak release and peak storage. Performance of the optimizing release rule using the SPF hydrology is compared to the Corps' operation. A procedure to account for uncertainty in the inflow hydrograph is described. Finally, available forecasting tools for flood operation are reviewed, and directions for further work are outlined.

1.2.3 Bloomington Standard Project Flood

The SPF for Bloomington Reservoir derived by the U.S. Army Corps of Engineers is presented in Figure 7. The peak instantaneous flow is roughly 59000 MGD. The Corps' design operating rule will reduce this peak by roughly 28% for a flood control pool at elevation 1466 feet msl. The peak instantaneous flow is reduced to roughly 42480 MGD and the time to peak is delayed approximately 4 hours, utilizing approximately 12 billion gallons of flood control storage.

The outflow hydrograph is reduced for all flows which were originally above 42480 MGD. Flows on the falling limb of the inflow hydrograph, which were originally below 42480 MGD increase to this maximum flow rate, in order to drawdown the flood control storage in a timely manner. Additional constraints such as maximum changes in release rates also modify the outflow hydrograph. The overall effect of flood control operation is to flatten or clip the peak flows, producing a flattened outflow hydrograph, with a period of constant releases. The duration of high releases is increased, while the peak discharge is reduced. In return for the attenuation and translation of the flood peak, the lower peak flow of 42480 MGD is sustained for an additional 11 hours compared to the inflow hydrograph of the SPF.

1.2.4 An Optimizing Flood Operating Rule

Deterministic routing of a single flood peak through a single reservoir is formulated as a linear program. The objective of this optimization problem is to minimize the maximum release which must be made in order to pass the SPF through Bloomington Reservoir. The solution must satisfy constraints which :

1. impose continuity of inflow, outflow and storage
2. bound the volume which can be stored in any time period
3. require flood control storage to be emptied at the end of the routing period.
4. define the maximum release, and ensure that the release in any period is less than this quantity.

This single objective problem was solved deterministically for the SPF hydrograph of Figure 7. The resulting peak discharge of approximately 42360 MGD represents a reduction of roughly 28%, comparable to the reduction reported earlier. The releases scheduled with this algorithm use a maximum of approximately 4.6 billion gallons of flood control storage. The additional 7.4 billion gallons required by the Corps' design operating rule are mainly used to delay the peak discharge 4 hours. In the operating rule developed in this section, a delay of the flood peak is not considered and the absolute volume of flood control storage required is consequently reduced.

The storage required for even a modest translation of the flood peak can be much greater than that required for peak attenuation. The value of a 4 hour delay of the flood peak must be assessed with respect to the flood hydrographs at downstream damage centers. The most significant opportunities to utilize flood control storage in a dynamic fashion may come from recognizing conditions when the value of peak attenuation far exceeds the downstream benefits from delaying the time to peak. Detailed analysis of this problem is beyond the scope of the current study. The extension of the methodology developed in this section, to address upstream-downstream trade-offs in flood damages and the resulting storage requirements, is outlined in the final section on future work.

The single objective linear program produces an optimal set of releases to minimize the maximum discharge required to pass the SPF hydrograph, subject to the constraints described above. If a higher maximum discharge could be tolerated, a smaller volume of flood control storage would be required. In the extreme case, releases would equal inflow, reproducing the SPF hydrograph with no peak attenuation, without utilizing any flood control storage. Treating peak storage as a surrogate for intermediate-term flood risk, a multiple objective optimization problem is formulated, in which peak discharge is traded against peak storage. Efficient combinations of storage and discharge are represented with a trade-off curve, presented in Figure 8. The trade-off curve indicates the increasing rate at which flood control storage is used, as the peak discharge is incrementally reduced.

As part of the U.S Army Corps of Engineers' Reformulation Study for Bloomington Reservoir, a number of reallocations of flood control storage were considered. A rise in the lake elevation from 1466 to 1475, reducing the flood control pool by approximately 3 billion gallons produced only modest increases in flood damages, which would be realized infrequently. The trade-off curve indicates that the 9 billion gallons of storage remaining after such a reallocation, could be operated in such a way as to leave the peak discharge unchanged, while still having 4.4 billion gallons available to delay the time to flood peak.

Potential increases in downstream damages could result from a loss of flood peak translation. These events would, however, only occur under conditions when the routed Bloomington peak, and the peaks from downstream subbasins arrived simultaneously. The joint probability of such flood flows would be extremely low; the resulting value of **expected** flood damages would therefore be insignificant compared to the incremental damages immediately downstream from Bloomington.

1.2.5 Predicting Flood Hydrographs

The operating rule developed in the previous section assumed the inflow hydrograph was known in advance. An operational procedure which could be used to derive an approximate inflow hydrograph is outlined in this section. Using unit hydrographs, precipitation over the North Branch of the Potomac River can be converted to runoff. The U.S. Army Corps of Engineers has developed a representation of the North Branch using unit hydrographs on 3 sub-basins to route excess precipitation to runoff, and Muskingum routing to deliver channel flow to Bloomington Lake.

Two inputs are required to use this routing model of the North Branch: 1) precipitation estimates over the basin, and 2) an evaluation of infiltration, in order to convert precipitation depth to runoff depth. Precipitation estimates could come from the National Weather Service rain gauges at Mt. Storm and Bayard. Additional gauges could be located in the basin to support flood control operation. Thoughtful placement of added gauges could significantly reduce the uncertainty in the estimates of precipitation, and the resulting flood hydrograph.

For estimated precipitation in the basin, infiltration must be accounted for in order to produce an effective runoff volume to apply to unit hydrographs. An operational assessment of runoff potential is provided twice each week by the National Weather Service in the "Potomac Headwaters Report". For example the NWS's Final Index (FI) is a dimensionless number, resulting from the use of an antecedent precipitation index (API) for the region. The current API value is modified by seasonal, and storm duration factors to produce the FI. Given the current FI value, the relationship between storm depth and storm runoff can be read from regionally calibrated charts such as that shown in Figure 9. Used in conjunction with a unit hydrograph for the basin, this provides an operational tool for developing an inflow hydrograph to Bloomington Reservoir. The National Weather Service prepares current FI values as part of their River Forecast activity, and reporting of the representative FI value for the region including the North Branch has been requested from NWS.

The simple procedure described above, though not the most sophisticated, is dependable, reproducible, and more important, implementable. At the current time this system could be made operational with minimal effort. Modest upgrading of the gauging network on the North Branch could provide accurate real-time data for dynamic flood control operation.

1.2.6 Operating Under Uncertainty: Open Loop Feedback Control

In real-time operation, the forecast procedure outlined in the previous section could be used to derive inflow hydrographs for the flood control operating model described earlier.

Uncertainty in the inflow forecast could be significantly reduced through improved data collection. Nevertheless, any operating procedure must account for the uncertainty inherent in any estimate of the inflow hydrograph, as well as the continually changing nature of hydrometeorologic conditions. As flood operations progress, inflows will deviate from the anticipated hydrograph and operating decisions must be modified accordingly. Real-time monitoring of precipitation will permit updating of the estimated inflow hydrograph. To use this updated information in real-time flood control operation, a procedure called "open-loop feedback control" is proposed.

In open-loop feedback control, the current best estimate of the inflow hydrograph is used as a deterministic input. The optimal releases under this assumed inflow trace are derived, and the release prescribed for the first period is implemented. After observing the actual inflow to the reservoir and updated precipitation measurements, the estimate of the inflow hydrograph is updated, and the optimal releases are recalculated using the current value of initial storage. In this way the anticipated release and storage trajectories are regularly updated as more current information becomes available.

This kind of operation is called "open-loop" because the release decisions are derived by assuming they will not be changed. The feedback, and response to changing conditions is introduced by recalculating the optimal releases at each time step, using the most current conditions, particularly the current storage in the reservoir.

1.2.7 Future Work

The potential for innovative flood control operation has been outlined above. Implementing the operational model would require detailed analysis and validation, which is beyond the scope of this report. This section suggests useful areas for future investigation to support the operating system that has been presented.

1. The operating model for flood control operation could readily be extended to consider flood damages at key damage centers downstream. This would quantify the value of flood peak translation in reducing downstream flood damages. Substantial volumes of storage are required for relatively modest translation of Bloomington's flood peak. Quantifying the trade-off of storage volume and peak translation will greatly clarify the consequences of flood pool reallocation.

2. The downstream damage reduction from flood peak translation is critically linked to the timing of flow events on all of the subbasins of the North Branch. When the probability of critical flow events for which peak translation provides substantial damage reduction, the large volume of storage required for peak translation may not be needed. Using a point process model of precipitation for the North Branch developed by Smith and Karr (1985), the probability associated with such jointly occurring events can be evaluated, quantifying the expected value of the change in damages resulting from dynamic flood control operation.

3. Reducing hydrologic uncertainty can greatly increase the realizable benefits from real-time operation. Optimal location of additional streamflow and precipitation gauges on the North Branch offers a cost effective means to significantly improve operating efficiency. Future work would profitably be directed towards the design of a sampling network for spatial precipitation estimation on the North Branch, both upstream and downstream of Bloomington.

1.2.8 Summary

An optimal procedure is developed to operate flood control storage in Bloomington reservoir, to balance local flood damages and intermediate-term flood risks. The procedure depends upon the timely availability of flood hydrograph forecasts. Currently available operational procedures to provide these forecasts are described, and directions for their improvement are suggested. A simple operating procedure that dynamically responds to uncertainty and changing conditions is outlined and can be made operational with existing information.

The interaction of the flood control pool with the water quality pool and, to a lesser extent, the water supply pool, is a major concern. Throughout this discussion, the flood control pool at Bloomington has been treated as though it were a separate, independent reservoir. In fact, pool elevations during the spring-summer transition are largely controlled by water quality releases. A significant increase in pool elevation could raise the level of higher quality water above the elevation of selective withdrawal ports, defeating the water quality function for which one-third of Bloomington storage has been authorized.

A significant permanent increase in pool elevation could require the construction of additional withdrawal ports in the control tower, at a cost of several million dollars. The next section establishes the link between water quality operations and higher pool elevations, and evaluates an operational alternative to the construction of additional withdrawal ports in the control tower.

2.0 Water Quality Impacts of Higher Pool Elevations

Recognizing the potential for using flood control storage for freshwater flow enhancement, the incremental effect of a higher reservoir pool on the project's ability to meet downstream water quality targets must be assessed. The effect of the higher pool on the water quality operations of the reservoir is unclear. Bloomington Reservoir was constructed with a selective withdrawal system, allowing the release of water from six different depths. Selective withdrawals mix lake waters of varying quality to produce a blend that meets downstream targets. In examining potential reallocations of storage within Bloomington reservoir, the Corps of Engineers concluded that construction of additional withdrawal ports would be necessary if pool elevations were raised. This would allow access to the higher quality water near the surface. However, these ports may not be necessary if operating decisions can incorporate the predictability of lake water quality. Access to the entire range of extant water quality values does not necessarily improve the attainment of downstream water quality targets.

The water quality impacts of reallocating a portion of flood control storage have been examined through the use of a series of simulation/optimization models. These models have been run with various sets of input data representing the climatological and hydrologic conditions most likely to promote lake conditions that would, in turn, adversely affect downstream water quality. A brief description of the models used in this analysis and how these models correspond to measured phenomena within the lake is provided in Section II. The selection of data and operational alternatives are discussed in Section III. The results of the simulations are tabulated and discussed in Section IV, followed by directions for further analysis in Section V.

2.1 Methodology and Applicability to Bloomington Reservoir

The methodology employed in this analysis consists of the joint operation of simulation and optimization models. These models describe the physical processes of a reservoir system and provide water quality information required for the daily operational decisions made at Bloomington. The physical processes of interest are those that influence the temperature structure of the lake. In the late spring and summer, the dominant heat sources are heat exchange at the air-water interface, solar heating, and the advective inflow of heat. These sources heat the upper regions of the lake, the epilimnion, which then becomes lighter in weight, resulting in a density or thermal gradient. The gradient becomes more pronounced with the progression of the warm months. Thermal profiles constructed from Bloomington Lake data collected by the COE are shown in Figure 2.1. Two curves are provided that describe temperature changes with depth in the reservoir for the summer and winter seasons. The summer profile is representative of the degree of stratification that develops by late summer. The winter profile shows that a reverse stratification can occur with deep reservoirs in cold regions. The invariable lower temperatures are characteristic of deep reservoirs. From an operational standpoint, it is important to notice that the warm season profile is monotonically increasing with elevation above sea level. Thermal instabilities that may result from the inflow or release of water are resolved through density driven mixing. Therefore, a wide range of temperatures exists in the lake by late summer, and the range develops in a systematic fashion responding to natural phenomena.

A confounding feature of water quality operations at Bloomington Reservoir results from the occurrence of highly acidic inflows to the lake during late summer months. Both the acidity and the temperature of the releases from Bloomington are controlled through the operation of the selective withdrawal ports. In effect, the reservoir is being used to attenuate the effects of acid mine drainage from abandoned upstream coal mines.

The distribution of acid within the lake is governed by the density gradient that exists when the acidic waters enter the lake. That is, the inflow enters the water column of the lake at a neutrally buoyant elevation, as determined by comparative densities, and the acidity of that elevation is determined by the acidity of the inflow modified slightly by mixing with adjacent waters. Both the temperature and the acidity values within the lake are predicted by the simulation model, WESTEX, a thermal stratification model developed by COE at the Waterway Experimental Station in Vicksburg.

WESTEX is a one-dimensional finite-difference model. One-dimensionality implies that the vertical variations in water quality dominate the horizontal variations. This is a reasonable assumption in deep reservoirs. Figures 2.2 and 2.3 display data from Bloomington Lake that are consistent with this assumption. Figure 2.2 exhibits thermal profiles in Bloomington for the monitoring stations located along the axis of the lake. Station 9 is at the headwaters and station 2 is near the withdrawal tower, five miles down the lake. A marked degree of horizontal homogeneity is present. Figure 2.3 is the analogous picture for pH values in the lake which may be used to reflect concentrations of acid.

Release decisions are made to meet downstream targets. However, it is also important to realize that the release of 'good' quality water depletes the reservoir of 'good' quality water;

i.e., the release decisions affect the water quality of the lake as well as the river. The operating model derives releases that minimize deviations from desirable water quality ranges, while releasing prescribed volumes of water. The model also seeks to maximize the release of undesirable water in an effort to maintain the lake's capacity to dilute future inflows of acidic water.

2.2 Outline of Scenarios

The simulation/optimization models were run for twelve sets of input data for each maximum pool level, for a total of 24 runs. The input data is representative of the range of conditions expected on the North Branch of the Potomac River. Three characteristics of the reservoir system were varied to produce the twelve scenarios. These are discussed below:

1. Hydrologic Input -- Two historical water years were selected, one typical of an average rainfall year, 1962, and one typical of an above average rainfall year, 1973. A dry year was not chosen because the reservoir level would fall below the elevation of the top port early in the summer, and a minimal effect on downstream water quality would be observed. The data was obtained from the USGS water data publications for Kitzmiller, (Tables 2.2,2.3).

2. Water Quality of Inflow -- Two sets of acidity values were associated with each hydrologic sequence. One set was obtained by constructing sequences that maintain the inverse relationship between acidity and magnitude of flow observed in the monthly acidity data collected by COE. These sequences are representative of post-1980 acid conditions. A second set of sequences represents 10% more severe acid conditions for the months August, September, and October. Temperature of the inflow was not varied. Temperature values were taken from USGS water quality publications for Kitzmiller, . See Tables 2.4-2.7 for acid and temperature data.

3. Magnitude of Release -- A constant daily release was made over the time horizon. The magnitude of the release assumed the values of 100 cfs, 200 cfs, and 300 cfs. The volume of water released under these settings brackets the volume released under current practices.

The time horizon for each run was May 1 until October 31. This horizon encompasses the critical water quality period of August, September, and October and allows the water quality profiles to develop in response to the climatological inputs earlier in the year. Each simulation began from identical water quality profiles for May 1 (Table 2.8).

Downstream water quality targets were specified with an emphasis on the ability of the downstream area to support fish life. That is, the port decisions are made on a daily basis to minimize the deviations from downstream targets which coincide with the requirements for a cold-water fishery. The temperature and acidity targets used in this study are stated below:

Release temperature between 15 and 18 degrees C

Release acidity less than 8 mg/l CaCO.

2.3 Summary of water Quality Operation Simulations

Two basic statistics were compiled for each of the twenty-four simulations. These were the maximum deviation from the water quality target observed over the study period and the sum of deviations observed over the study period. Each statistic represents violations in one direction only. That is, releasing water with an acidity concentration less than 8 mg/l is desirable; only values above 8 mg/l were counted as violations. The statistics are presented in Tables 2.9 and 2.10 with the values in the second table corresponding to the set of runs with more severe acidic inflows.

Focusing on the first of the two tables, comparison of the maximum acidity target deviations observed for the pool level of 1475 ft. shows a relatively constant improvement over the maximum deviations observed for the runs corresponding to a 1466 ft. pool. For the upper temperatures target, the higher pool causes larger violations and the additional violations appear to increase with the magnitude of the release. Examining the statistics for the lower temperature target, the differences in the maximum deviations are favorable for releases of 100 cfs and 200 cfs. That is, the largest violation corresponding to the 1475 ft. pool is smaller than the largest violation corresponding to the 1466 ft. pool. However, the statistics are not favorable for a release of 300 cfs. Considering the sum of the deviations in each instance leads to the same set of conclusions, while providing information regarding the size of daily violations on average. Similar patterns are exhibited in Table 2.10 with larger values appearing in the acid categories reflecting the greater acid concentrations of the inflows.

Examination of these results shows that it is not possible to categorically state that a higher reservoir pool does not adversely affect the attainment of downstream water quality targets. However, the results also indicate that there are potential benefits to be realized in lower overall acidity values in return for small additional violations of the temperature targets. That is, maintaining the three water quality targets may be conflicting goals, and depending on the ultimate effects of acidity and temperature variations on fishlife, a higher initial pool may contribute to better overall water quality as measured by acidity and temperature indices.

2.4 Summary

For Bloomington reservoir, maintaining project goals with the reallocation of nine feet of flood control storage seems technically feasible. Dynamic water quality operation may obviate the need for construction of additional withdrawal ports. Water quality could well be maintained, while realizing a cost savings. Significant potential exists for the creation of reservoir storage for the enhancement of freshwater inflows through the dynamic operation of Bloomington.

The next section describes the potential for similar gains in the existing reservoirs of the Susquehanna River Basin.

3. Susquehanna River Basin Enhancement Potential

Identification of potential for operating modifications of reservoirs of the Susquehanna River basin was conducted on a preliminary screening level. Optimistic yet plausible assumptions were used in considering possible operational changes, in order to rule out obviously infeasible alternatives. The approach has been to try to answer three types of questions, and the accompanying material is grouped accordingly:

1. Is there potential for useful reregulation or operation modifications of existing Susquehanna reservoirs?

2. How might flow patterns be changed by modifying operations?

3. How do flow modifications on the Susquehanna affect Chesapeake Bay?

The two operating changes considered were partial enchroachment on the flood control pool, and altering the timing of the fall drawdown from recreation pool to flood pool elevation. This excluded reservoirs with heavy recreation development, as well as flood control reservoirs on flashy catchments where flood risks are particularly high. This is admittedly a very rough cut and is intended to get a crude upper bound on the volume that may be available for reallocation. There does seem to be potential for using some of the existing storage for flow modification. This screening indicates no more than 100,000 acre feet could be made available for augmentation. This volume is a rough upper bound on the potential storage available.

To bound the potential for low flow augmentation using this storage, yield-reliability plots for each of the major subbasins, and for the Susquehanna at Marietta were prepared. Each curve represents a particular firm yield. The curves of each plot relate the reliability with which a given minimum flow can be provided (on an annual basis), to storage. For example, to provide a firm yield of 5000 cfs at Marietta with a reliability of at least 90% would require about 300,000 acre feet of storage.

The 100,000 acre-foot upper bound, if operated perfectly at Marietta, (again, an optimistic upper bounding assumption) would provide a yield of 5000 cfs with reliability no greater than 75%. (The 5000 cfs flow has been discussed in connection with salinity control at Havre de Grace, Md.) The yield reliability curves indicate that even with the 100,000 acre-foot upper bound of potential storage, the Susquehanna flow could be expected to fall below 5000 cfs one year in four. In contrast the low-flow duration curve for the Marietta gauge indicates that natural Susquehanna flow at Marietta could be expected to fall below 5000 cfs approximately 50% of the time or one year in two. At this optimistic screening level, there may be an opportunity for modest modification of discharge frequencies of the Susquehanna. The significance of any such change for Chesapeake Bay is the third area of inquiry.

To bound the impact of Susquehanna River flow on Chesapeake Bay a one-dimensional salinity model of the upper bay was employed. This model, developed by Boicourt (1969), is a weekly averaged, vertically averaged, laterally averaged representation of the first 75 km of Chesapeake Bay from Havre de Grace to the Bay Bridge (Rt. 50). Weekly average salinity profiles are produced based on Susquehanna streamflow. This provides a tool to evaluate the effects of modified Susquehanna flows on Chesapeake Bay.

3.1 Description of Salinity Model

Substantial effort has been directed to modeling transport in estuarine systems, particularly Chesapeake Bay and its tributary estuaries. Three layer tidal flow, augmented by substantial and varying tributary inflow, as well as wind driven flow in shallows, produces extremely complex mixing and transport patterns in Chesapeake Bay. The conservative nature of salinity somewhat simplifies the modeling process. Nevertheless, an accurate model of salinity with intra-tidal temporal resolution would require a three dimensional model, accounting for hourly changes in tidal levels and tributary flows, as well as wind direction and velocity. While such modeling efforts are under way, it is not at all clear that sufficient data exist to calibrate, much less drive such a detailed representation of flow.

While a detailed three dimensional representation of flow, capable of describing the changes in salinity within each tidal cycle would be of obvious value in the present investigation, it is felt that a simpler representation of upper Bay salinity can adequately resolve salinity changes due to Susquehanna River inflow. Estuarine fauna respond to the twice daily changes of flow and salinity caused by the tidal cycle, as well as lower frequency lunar and seasonal changes. Despite the continuous and frequent changes in physical and chemical environments, habitat preferences of seasonal and annual durations have clearly emerged for fauna and flora of the Chesapeake Bay . Sessile fauna, while sensitive to extremes of salinity, temperature, depth, and other physical parameters, are surprisingly tolerant of short term variations in their physical habitat. The densest populations of these organisms are found in areas in which the conditions, averaged over the year, are optimal. The ability of sessile fauna to integrate and respond to average conditions argues for a representation of salinity that emphasizes longer term variation at the expense of resolution within each tidal cycle. Such a model would be predominantly driven by the Susquehanna River, deemphasizing the effect of tidal, wind, and gravity circulation in the upper bay.

A temporally averaged model would require substantially less data to calibrate and run. Solution of a two or three dimensional model would still be a formidable task. In some situations lateral and vertical gradients are small compared with longitudinal gradients. The tendency for water bodies to stratify vertically depends on the relative balance between water through-flow, or discharge, and the gravitational forces due to water bouyancy. This balance is roughly expressed in the **densiometric Froude number.** For the upper bay, this number suggests weak stratification is present, with more completely mixed conditions prevailing compared to the lower bay. Mixing in the Bay is a three-layer phenomenon, with an oscillating salt wedge separated from freshwater surface flow by a turbid, brackish, mixing layer. In the upper bay, the characteristics of three-layer flow have been minimized as the mixing layer grows upstream. A one-dimensional model treating only the longitudinal salinity gradient, while not an accurate representation of the detailed mixing processes of the upper bay, is judged sufficiently detailed for the present investigation.

The model chosen was developed by Boicourt(1969) after Pritchard's (1968) model of the Delaware estuary. The model solves the advection-effective diffusion equation for the uppermost 75 km of Chesapeake Bay using finite difference approximations for successive 1-km segments. The solution gives a vertically and laterally averaged value for each of the 1-km thick slices at weekly intervals. Salinity changes are driven by freshwater inflow, salinity values at the previous time step, and two boundary conditions. At the upstream boundary, the flow is assumed fresh, and assigned an arbitrary salinity of 0.001 ppm. The downstream salinity (roughly at the Bay Bridge) is calculated at each time interval, based on the rate of change of cumulative freshwater inflow at the upstream boundary. The regression relationships for this calculation, as well as the conceptual and computational description of this model, is found in Boicourt(1969).

3.2 Historical Summer Salinity Patterns

3.2.1 Freshwater Inflow Record

The first stage of this investigation set out to describe, with respect to longitudinal salinity gradients, the historical patterns of flow that could drive summer salinities to values as low as 3 ppm below the mouth of the Chester River. Flows at the USGS gauge at Marietta were taken to represent freshwater inflows to the upper Bay. This might tend to underestimate freshwater inflow, since there are nearly 3000 square miles of intervening drainage between Marietta and the mouth of the Susquehanna at Havre de Grace. This also ignores the effect of the four major impoundments of the lower Susquehanna: York Haven, Safe Harbor, Holtwood, and Conowingo dams. While these are considered run-of-river hydropower reservoirs, in the past Conewingo had been occasionally operated so as to completely restrict flows into the bay on weekends. While the current, interim Federal Energy Regulatory Commission permit has a low-flow standard of the minimum of 5000 cfs or the daily average flow, it is clear that, at least during low-flow periods, Conowingo has not always been a run-of-river reservoir. Furthermore, in obtaining Conowingo releases from 1961-1962 for model calibration, Boicourt found that despite the contribution from the 3000 square miles of Susquehanna Basin drainage, the releases from Conowingo were, on the average, 250 cfs **LESS** than the gauge records at Marietta. Whether this discrepancy represents leakage or excessive evaporation or both is unclear; until a better verified record of flow into the Bay can be assembled, the uncorrected gauge records from Marietta are used as freshwater input to the model.

3.2.2 Salinity impact from flow modification

The salinity model reinforced the judgment that modified operation in the Susquehanna basin would have no effect on long-term salinities in the upper bay. Following the approach of the

Corps' low freshwater inflow study, the salinity impacts of projected consumptive losses were evaluated. These losses ranged between 1000 and 1300 cfs, depending on the month of year. Using the predicted incremental losses, historical streamflow records from 1960 through 1975 were adjusted and rerun through the salinity model. Resulting salinities were compared to those generated using the unadjusted historical hydrology. Differences in any week, at any location greater than 1 ppt were noted and all such changes were recorded in Table 3.1. In some years, the greatest increase in salinity occurred in the first 10 to 20 km, whereas in other years, the greatest changes were produced closer to the Bay Bridge (e.g. week 7 of 1968). Using changes greater than 1 ppt as an arbitrarily chosen measure of impact, the effect of 2020 projected consumptive uses is felt in a maximum of 10 weeks in 1964. If the consumptive impact in only these critical weeks were to be offset, a volume of roughly 12000 cfs-weeks would be required, or 168000 acre-feet. The required make up flow would presumably be needed for a longer antecedent period, necessitating an even larger, unattainable volume of storage.

While reregulation of existing storage cannot reasonably be expected to offset all consumptive losses all the time, it may be possible to mitigate losses in some years using existing storage. For example, in 1967 only two weeks have an increase in salinity of more than 1 ppt due to consumptive withdrawals, and 28000 acre-feet of storage could more than offset consumptive losses during this period. Recognizing the need for augmentation preceding these critical weeks raises the required storage considerably. However, the required volume is still within the 100,000 acre-foot upper bound which may be attainable from existing projects. In short, while severe impacts of low Susquehanna flows could only be offset with infeasibly large storage volumes, it may be possible to mitigate low flows of shorter return periods.

3.2.3 Local impacts of flow regulation

Even with the optimistic volume of 100,000 acre-feet of storage available, the few weeks of yield augmentation that could be provided to the Bay would have a marginal impact on salinity. Since 100,000 acre-feet is roughly equivalent to 50000 cfs-days, the focus of investigation shifted to the identification of beneficial uses of (e.g.) 2000 cfs for 25 days. Flow of this magnitude would represent an order of magnitude increase of the fall weekend shutdowns of Conowingo Reservoir. Providing 100,000 ac.-ft. could augment flows 2000 cfs for up to twelve weekends. If the equivalent volume could be reliably delivered to Conowingo by the start of their Monday operating cycle, the utility might be willing to make weekend releases. In order to deliver this water to Conowingo by Monday, operation would have to be coordinated with the other hydroelectric reservoirs as well as the headwater reservoirs. If Holtwood, Safe Harbor and York Haven are not spilling during the week, upstream releases could be scheduled during the week and collected in these reservoirs, to be rereleased to Conowingo by Monday morning.

3.2.5 Summary

This is a coarse overview of the Susquehanna system. Nevertheless it suggests that some potential exists for garnering additional benefits from the existing system. The possibility for affecting fall weekend releases at Conowingo may offer interim habitat improvements, until pending litigation is resolved.

To summarize, this effort can best be characterized as a screening of operating changes, eliminating clearly infeasible plans. Long term changes in Chesapeake Bay salinity are impractical with the volume of storage that might realistically be available. Some of the plans considered are not obviously infeasible and a more detailed examination appears worthwhile.

4. Future work

First, whereas this study shows the reallocation to be feasible, further investigation into the operational assumptions incorporated in this study could reveal that actual system performance is better than these results indicate; this study employed a conservative approach. Operational parameters warranting further investigation include the magnitude of the daily release and the specification of downstream standards. This study used a constant daily release which, while accurately capturing the volume of water released over the course of the season, ignores a degree of operational flexibility. Similarly, the downstream targets employed in this study had a rigid structure. Linking the targets to seasonal temperatures may provide additional flexibility while maintaining the stated objectives.

Another direction for further research involves determining alternative operating rules for the reservoir that respond to a quantification of flood risk, varying with estimates of expected precipitation or existing soil moisture conditions. With additional flexibility in water quality operations and estimates of flood risks, it would be possible to investigate the effects of raising the reservoir pool above the 1475 ft. level.

Appendix-References

1. Gabriel, K.R., and Neumann,J., "A Markov chain model for daily rainfall occurrence at Tel Aviv," Journal of Royal Meteorological Society of London, Vol. 88, pp. 90-95

2. Smith,J.A., Sheer,D.P. and Schaake,J.C., "The use of hydrometeorological data in drought management: Potomac River Basin case study", International Symposioum on Hydrometeorology, American Water Resources Association, June, 1982, pp.347-354