Priority Based Reservoir Optimization using Linear Programming: Application to Flood Operation of the Iowa/Des Moines River System

By

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ABSTRACT

A general method is presented for determining unit penalty values that reflect operating priorities and economic flow damage functions for linear programming (LP) optimization models of river reservoir systems. The method applies "priority preserving" penalty theory, previously developed for a monthly water supply optimization network flow programming (NFP) model, along with supplemental logic reflecting flow related economic damage functions and reservoir "equal-storage" functions, to a daily flood control optimization LP model. The approach formulates these mathematical relationships into a linear program that can be used as a preprocessor to the LP model. The method provides consideration for both storage and flow related penalties over relatively short-term historical flood events and is applied to multiple subsystems of the Iowa/Des Moines River Reservoir System. Results are investigated for preservation of selected operating priorities and the effect that operating constraints have on system penalties and operating conditions. Conclusions discuss feasibility of the theory and method to provide reasonable estimates for storage and flow penalties used in LP optimization applications based on given flow related economic damage functions and specified operating priorities.

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CHAPTER 1: INTRODUCTION

Reservoir operators consider many factors simultaneously when making water release decisions to accommodate competing objectives for water supply, flood control, power generation, navigation, recreation, and environmental requirements. Reservoir regulation manuals provide the operator with guidance or "rules" for release decisions that are often based on conditions of reservoir inflow, pool elevation, and downstream flow rates. Historically, these rules have been developed through trial-and-error model simulations of the river reservoir system where a set of proposed release rules are incrementally adjusted until desired results of release, storage, and flow conditions are observed (HEC 2000).

Optimization provides an efficient alternative of exploring reservoir releases based on minimization of total operational penalties associated with release, storage, and flow decisions that diverge from desired conditions. Penalty functions are used in optimization to define the relative preferences (priorities) of incremental release, storage, and flow decisions with a corresponding quantitative penalty. The value of a penalty can be specified to define the priority of its corresponding decision (e.g., release, flow, and storage) within an operating policy structure. A systematic approach for determining penalty values is needed to ensure that water operations follow the order of priority of uses established for the system. For priority-based optimization based on generalized network flow programming (NFP), values of storage and flow penalties can be systematically determined to ensure proper allocation of operating objectives in order of specified priorities (Israel and Lund 1999).

When reservoirs are operated for flood control, primary operating decisions include the timing and amount of release based on pool elevation and downstream flow stages. Operators must therefore consider two primary hazards during a flood event: the chance of storage exceeding desired levels where dam overtopping is possible and downstream flow related damages. Both hazards can be represented with corresponding penalties, the values of which, should be systematically determined to ensure proper operation according to prioritized goals.

Needham, et al. (2000) present results of a reservoir optimization study of the Iowa/Des Moines system using a linear programming model where piecewise linear functions were used to represent penalties for release, storage, and flow parameters that diverge from desired conditions. The values of penalties were established through model calibration based on operations data from historical flood events, which included a fairly time-consuming procedure that incorporated subjective modeler interpretation to the optimization process. The primary author of that study recognized this limitation and provided several recommendations for future work including re-evaluation of penalty functions.

Purpose

The current study attempts to address the recommendations provided by Needham, et al. (2000) by presenting a process for deriving penalty functions for the same reservoir system based on prioritized operating policies combined with economic damage functions. The procedure presented in this study is provided to assist modelers that use linear programming optimization models to establish priority-based penalty values and to make related applications more practical in the professional community.

The study applies "priority preserving" penalty theory developed for a water supply simulation

NFP model using a monthly time step (Israel and Lund 1999) to a flood control optimization linear programming (LP) model using a daily time step and investigates the results for preservation of selected operating priorities. The established theory has been supplemented in this study with additional logic that maintains relative hierarchy of flow related economic damage functions for stream flow control points. Results of this analysis provide conclusions on the feasibility of the theory and method to provide reasonable estimates for storage and flow penalties used in LP optimization applications based on given flow related economic damage functions and specified operating priorities. Results also provide insight to the range of penalty values calculated by the method and the degree to which total system penalties are controlled by specified operating priorities or by system constraints (e.g., maximum allowable reservoir release capacity constraints) for the Iowa/Des Moines River Reservoir system.

Previous Research

Sigvaldason (1976) presents an early mathematical model of the Trent River system in Ontario, Canada for assessing alternative reservoir operating policies. The simulation model was developed with a nested optimization sub-model that uses storage and flow penalty coefficients to penalize divergence from desired conditions. Multiple storage and flow zones and values of corresponding penalty coefficients were established to represent the operator's "perception" of desired operations of the system, which include operating priorities for storage and flow objectives. An "equal function" relationship was established for inter-reservoir operating policies to ensure that the model attempts to maintain all reservoirs in the same zone to the extent possible. The study provides a good background on a systematic approach of representing multi-reservoir operating policy rules in an optimization model with penalty coefficients representing multi-zonal, varying-priority storage and flow operations. The current study supplements Sigvaldason's research with explicit formulation of penalty coefficients and additional consideration for varying-priority flow penalties that correspond to variable economic damage functions associated with flood events.

Yazicigil, et al. (1983) present a linear programming reservoir optimization model for the Green River Basin in Kentucky. The study provides a general description of a process for selecting penalty values for storage and flow objectives based on operating goal priorities and numeric conversions needed to relate storage and flow penalty values. Like Sigvaldason, the study also adopts an "equal function" policy for inter-reservoir operating priorities. The model, however, relies on user-supplied input from the reservoir operators to establish the values of penalty coefficients rather than providing specific criteria for their selection.

Can and Houck (1984) compare methods and results between the linear programming model used by Yazicigil (1983) and a preemptive goal programming model for optimization of the multi-purpose, multi-reservoir system of the Green River Basin. In preemptive goal programming, the user assigns operating goals and corresponding priorities for a variety of parameters related to physical operating phenomena. A "partitioning" algorithm is used in goal programming to ensure that the highest priority operations are secured before lower priority operations. The study illustrates that the primary advantage of goal programming is ease of implementation, where operators are not forced to assign numerical weights to "zonal" storage and flow penalty coefficients as is required for the linear programming approach. A comparison between the total system penalties for each method in the application indicates that the preemptive goal programming approach provides comparable results to the linear programming method.

Israel and Lund (1999) present a detailed algorithm for determining values for penalty coefficients that represent water use and storage priorities of the Truckee-Carson River Reservoir system. The priorities are set to reflect the hierarchy (senior and junior) water rights structure present in the basin with consideration for return flows. The algorithm is based on the principle that the value of a penalty that is used to represent divergence from a prescribed senior parameter must exceed the combined junior penalties associated with the system. The algorithm is presented as a linear program "pre-processor" to a network flow programming model and then "generalized based on a system connectivity matrix and vector of use priorities". HEC-PRM, a network flow optimization model developed by the U.S. Army Corps of Engineers Hydrologic Engineering Center (HEC 1994/1996), was used to test the algorithm for the Truckee-Carson system on a monthly time step. The current study uses a portion of the "priority preserving" penalty theory developed in the Israel-Lund study and applies it, with additional consideration for relative values of flow damage functions, to a flood control linear programming optimization model (HEC-ResFloodOpt) run on a daily time step.

Needham, et al. (2000) present results of a reservoir optimization study of the Iowa/Des Moines system using a linear programming model. The study investigates the potential flood control benefits of operating multiple reservoirs in combination versus individually. Piecewise linear functions were used in the study to represent penalties for release, storage, and flow parameters that diverge from desired conditions. The values of penalties were established through model calibration based on operations data from historical flood events. The study provided several recommendations for future work including re-evaluation of penalty functions and further sensitivity analysis of storage persuasion penalties. The current study attempts to address these recommendations by deriving penalty functions for the same reservoir system based on prioritized operating policies combined with economic damage functions.

Labadie (2004) presents a review of methods used for optimization of multireservoir operations and provides discussion on future directions for related research and application. The study references a host of papers covering a multitude of programming and optimization models and related theory and applications. Several of the models reviewed: MODSIM (Labadie, et al. 2000), CALSIM (Munevar and Chung 1999), and OASIS (Hydrologics, Inc.) use priority-driven simulation routines with optimization engines (Lund 2005) including network flow optimization, mixed integer linear programming, and linear programming, respectively. Labadie (2004) describes the user-friendly interfaces and modeling languages that allow the user to specify system components, objectives, constraints, and operating priorities for each model.

Report Organization

Chapter 2 presents a summary of theory used for this study including principles that have been previously established for the referenced water supply NFP problem as well as logic that has been added for application to the flood control LP problem. Chapter 3 details the application of the theory to reservoir optimization for flood control on the Iowa/Des Moines River Reservoir System. Chapter 4 presents a summary of study results and implications on the feasibility of theory application. Chapter 5 presents the conclusions with suggestions for future work.

CHAPTER 2: THEORY

This chapter introduces the flood control LP model used in this study, discusses how penalties are used in the model, presents the theory of operating flood control reservoirs based on prioritized operating goals, and summarizes the theoretical basis and mathematical formulation of storage and flow penalties used for flood control LP optimization. The theory is based on principles established to relate storage and flow penalty values for monthly NFP optimization of water supply systems (Israel and Lund 1999), principles relating multiple storage penalties associated with equal inter-reservoir policies (Sigvaldason 1976, Yazicigil 1983), and principles for the current flood control LP problem to relate multiple flow penalties based on specified flow damage functions.

Linear Programming Model

HEC-ResFloodOpt (HEC 2000, Technical Reference Manual) is a reservoir optimization model for flood damage reduction studies. The model uses linear programming techniques to estimate ideal reservoir releases from multi-reservoir systems by minimizing total system penalty. Total system penalty is equated in the model as the sum of penalties associated with flood damages and deviations from prescribed reservoir storage levels and release rates and stream flows.

Unit penalties in the model represent the magnitude of penalty incurred when system operating parameters (storage, release, flow) diverge from desired conditions. Penalties are defined by multi-slope, piecewise linear functions relating the simulated system condition to a penalty value. Penalties are defined in the model for each reservoir and each control point and are applied in the optimization routine for every time step in the simulation.

Flood Control Operations

Flood control reservoirs can be operated according to prioritized goals representing tradeoffs among flow and storage objectives. For example, an operator may want to use storage in the normal flood control pool to minimize downstream small “low-damage” flows but release low-damage flows to minimize storage in the emergency flood control pool (reducing the likelihood of uncontrolled flood releases). Furthermore, the operator may want to use storage in the emergency flood control pool to minimize downstream “high-damage” flows but release high-damage flows to minimize storage in the surcharge pool (reducing the likelihood of dam failure). Such operating policies that alternate in priority between storage and flow objectives are based on information from reservoir regulation manuals (HEC 1999), which constitute basis for determining storage and flow penalties. In this study, storage and stream flow operations are assigned either a senior (higher) or junior (lower) priority. This study tests the theory that such priority-based operations can be optimized in the LP model while ensuring proper allocation of the priorities by setting flow and storage unit penalties at specific values. The formulation of storage and flow penalty values is described in the following sections partially with theory that has been developed in previous studies using various optimization techniques and partially with additional logic that accounts for damage functions associated with flood events.

Storage Penalties

This section presents the mathematical formulation of storage penalties, which consider two primary relationships: 1) Relationships between senior storage penalties associated with a specified reservoir and junior flow penalties associated with stream flow control points located downstream of the reservoir and 2) Relationships between storage penalties associated with comparable storage zones in multiple reservoirs for the specified system.

1. Senior Storage – Junior Flow Penalty Relationship

When senior priority is given to maintaining a specific range of storage levels (i.e., within a specific storage zone) in a reservoir and junior priority is given to maintaining a specific range of flow levels (i.e., within a specific flow zone) at stream points located downstream of the reservoir, the senior storage penalty value must exceed the combined junior flow penalties as shown below (Israel and Lund 1999).

$$P_S > \sum P_F \text{ , where}$$

- P_S is the unit penalty incurred when storage level for the reservoir is within a specified zone.
- $\sum P_F$ is the sum of unit penalties for all stream points located downstream of the reservoir incurred when flow level for each point is within a specified zone.

2. Storage-Storage Penalty Relationship

A storage penalty for a specific reservoir storage zone will have a value that is the same magnitude as the penalty associated with a comparable operating storage zone for any other reservoir in the system, when it is desired to ensure that all reservoirs in the system are operated in the same storage zone to the extent possible (Sigvaldason 1976, Yazicigil 1983).

$$P_S = P_{Si} \text{, where}$$

- P_S is the unit penalty incurred when storage level for the reservoir is within a specified zone.
- P_{Si} is the unit penalty incurred when storage level for any other reservoir in the system is within a comparable operating zone.

Flow Penalties

The mathematical formulation of flow penalties here considers two primary relationships: 1) Relationships between senior flow penalties associated with stream flow control points downstream of a specified reservoir and junior storage penalties associated with the specified reservoir and 2) Relationships between flow penalties associated with multiple stream flow control points in the given system based on assumed economic flow damage functions.

1. Senior Flow – Junior Storage Penalty Relationship

When senior priority is given to maintaining a specific range of flow levels (i.e., within a specific flow zone) at a stream point and junior priority is given to maintaining a specific range of storage levels (i.e., within a specific storage zone) in a reservoir upstream from the control point, the value of the senior flow penalty must exceed the junior storage penalty as shown below (Israel and Lund 1999).

$$P_F > 2 \cdot T \cdot P_S \text{, where}$$

- P_F is the unit penalty incurred when the flow level for the stream point is within a specified zone.
- P_S is the unit penalty incurred when the storage level for the reservoir located upstream from

the stream point is within a specified zone.

- The “2” multiplier accounts for a conversion between flow penalty units (penalty per cfs-day/day) and storage penalty units (penalty per AF/day), 1 cfs-day = 1.98 AF.
- The “T” multiplier accounts for the number of time-steps in the model. A unit of water held in storage may incur a penalty in each time step of the analysis, whereas the same unit of water may incur a flow penalty only once when it is released. For this reason, the “T” multiplier is set to the number of time periods in the analysis to ensure that the value of the flow penalty is large enough to account for the conservative estimate where storage levels are in the specified zone for the duration of the storm event.

2. <u>Flow-Flow Penalty Relationship</u>

Flow unit penalties are set at values that maintain the relative priority of economic damage for comparable flow zones (i.e., low or high damage zones) in all stream flow control points in the system.

$$P_{Fi} > \frac{P_{Ei}}{Min(P_E)}, \text{ where}$$

- P_{Fi} is the unit penalty incurred when the flow level for a specified stream point is within a specified flow zone.
- P_{Ei} is the estimated unit economic damage incurred when the flow level for the stream point specified above is within the flow zone specified above. This number is based on multi-slope, piecewise linear functions provided by others (HEC 1999) as estimates of flow-damage relationships.
- $Min(P_E)$ is the minimum value of unit economic damage incurred for all comparable flow zones (i.e., low or high damage zone) of all stream points in the system. The minimum economic damage has been chosen as the denominator to scale all unit flow penalties from a common reference point.

These sets of inequalities and equations provide the theoretical basis for establishing values of storage and flow penalties to be used in the flood control LP optimization model. This theoretical basis includes the four listed mathematical relationships based on the following three specific, priority-based operating policies:

1. A specified ranking of operating priorities that determines the hierarchy relationship between senior and junior storage and flow penalties.
2. A specified “equal storage function” policy that determines the relationship between storage penalties for comparable storage zones in multiple system reservoirs.
3. A series of specified flow damage functions that determine the relationship between flow penalties for comparable flow zones of multiple system flow control points.

The flood control formulation presented above does not include consideration for return flow penalties as provided for water supply formulations (Israel and Lund 1999). In this study, return flows are regarded as generally insignificant for flood events as the majority of flows are assumed to be in-stream.

CHAPTER 3: APPLICATION

The formulation of storage and flow penalty values involves mathematical relationships based on specific, priority-based operating policies. This chapter applies this formulation to derive priority-based storage and flow penalties for flood control optimization of the Iowa/Des Moines River Reservoir system. The following sections provide a brief description of the Iowa/Des Moines system and an overview of the steps used to calculate storage and flow penalty values for the Iowa-Des Moines system.

Iowa/Des Moines River Reservoir System

The Iowa-Des Moines River Reservoir system consists of three major reservoirs on two major tributaries of the Mississippi River: Coralville Reservoir, on the main stem of the Iowa River just upstream of Iowa City, and Saylorville Reservoir and Lake Red Rock, located in series on the main stem of the Des Moines River just upstream and downstream, respectively, of Des Moines. The main stems of both rivers extend generally parallel to one another from north central Iowa at their sources to the southeastern portion of the state where they connect to the Mississippi River at confluence points approximately 70 miles apart. Each reservoir in this system is operated for flood control, low-flow augmentation, fish and wildlife, water supply, and recreation (HEC 1999). The reservoirs provide flood control benefits to several towns and cities situated along both of the rivers downstream of the reservoirs as well as to several populated centers along the Mississippi River downstream of the Iowa and Des Moines River confluences.

Calculation of Priority-Based Penalty Values

This section summarizes the steps used to calculate storage and flow penalty values for priority-based flood control optimization of the Iowa/Des Moines system, including:

1. Identification of system components (i.e., which reservoirs and flow control points).

2. Specification of multiple storage penalty zones for each reservoir and multiple flow penalty zones for each stream flow control point.

3. Prioritization of operating policies (i.e., ranking of operating priority between the multiple storage and penalty zones and locations specified in the previous step).

4. Selection of historical flood events to be analyzed.

5. Estimation of storage and flow penalty values based on the above specifications and priorities and the theory presented in the previous chapter.

1. <u>Identify System Components</u>

The first step in application of the proposed theory is identification of system components (i.e., reservoirs and flow control points) in the Iowa/Des Moines system. To test the theory presented in the previous chapter, multiple geographical subsystems of the Iowa/Des Moines river reservoir system have been chosen to be used in the current analysis. The choice of system components is based on subsystem delineations of the Iowa/Des Moines system used by Needham, et al. (2000), where several subsystems were used to investigate potential benefits of operating the Iowa/Des Moines reservoirs individually and in tandem for flood control at multiple downstream towns. Figure 3-1 provides a schematic of the Iowa/Des Moines system partitioned into subsystems A through G as used in the Needham 2000 study. Optimization of these subsystems provides insight into operations of single and multiple reservoir systems that is not readily apparent by analyzing the entire system by itself. The current study derives priority-based storage and flow penalties for the reservoirs and stream flow control points shown in Figure 3-1 as subsystems C, F, E, and A. These subsystems were chosen for this study to provide a variety of storage and flow point system layouts including simple single-reservoir systems on both the Iowa and Des Moines Rivers (Subsystems C and F, respectively), a system with multiple reservoirs in series (Subsystem E), and a system with multiple reservoirs in series and parallel (Subsystem A).

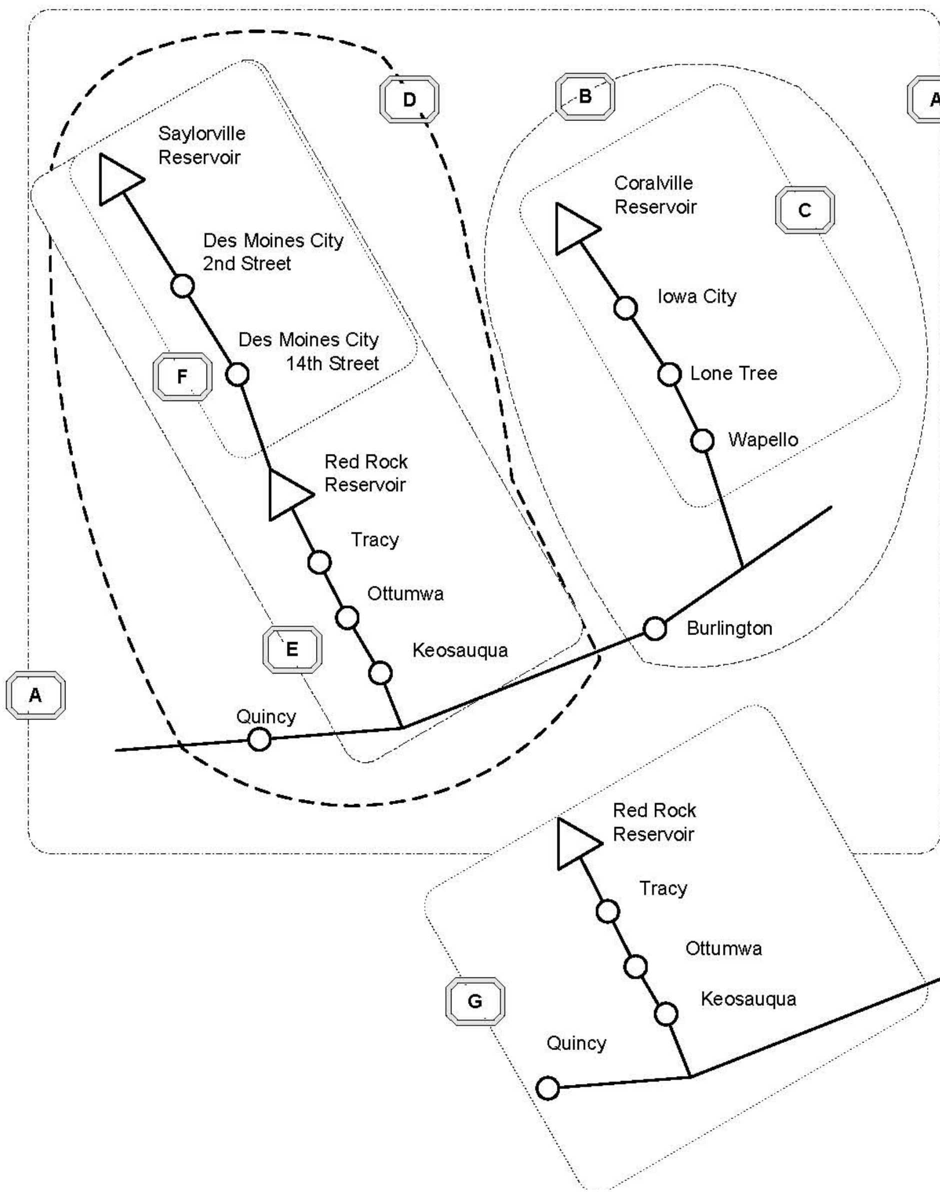

Figure 3-1. Iowa / Des Moines System Decomposition (Needham 2000)
(Reservoirs and stream flow stations represented by triangles and circles, respectively)

2. <u>Specify Storage and Flow Penalty Zones</u>
Penalty functions are used in reservoir optimization to define the relationship between the value of incremental storage and flow decisions and the value of corresponding penalty incurred when operating decisions (storage and flow) diverge from desired conditions. Penalty functions are defined by multi-slope, piecewise linear functions relating the simulated system decision to a penalty value for each reservoir and each control point in the system. Each linear segment of a penalty function represents a different storage or flow "zone" and its corresponding penalty value, which defines the priority level of ensuring that system operations remain outside of that particular zone.

Two levels of penalty (low damage and high damage) are used in the current study to define the general flow penalty function for each stream control point as shown in Figure 3-2. Since the focus of the analysis is on flood control operations, no penalty is applied for violating minimum flows.

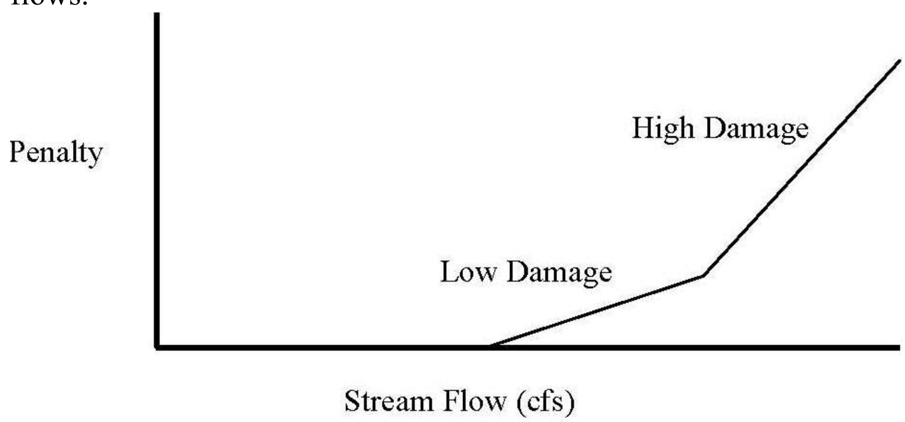

Figure 3-2. General Flow Penalty Function

Three levels of penalty (normal flood control pool, emergency flood control pool, and surcharge pool) are used to define the general storage penalty function for each reservoir as shown Figure 3-3. Since the focus of the analysis is on flood control operations, the model is constrained to not allow storage to fall below the normal flood control pool.

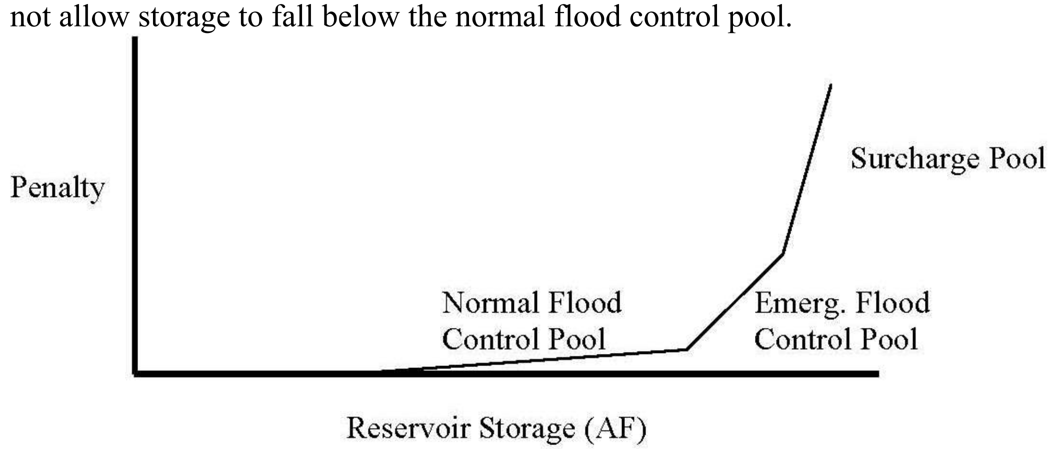

Figure 3-3. General Storage Penalty Function

3. <u>Prioritize Operating Policies</u>

The two flow zones and three storage zones of operation presented above were ranked according to operating priority and are listed below from highest to lowest priority. The hierarchy of operating priorities among storage and flow considerations loosely represents operating policies denoted in regulation schedules written for the three reservoirs in the Iowa/Des Moines system (USACE 1983, 1988, 1990):

a. Keep reservoir storage below the surcharge pool; i.e., minimize the number of storage volume-days within the surcharge pool.
b. Keep stream flow below the high damage zone; i.e., minimize the number of flow-days (cfs-days) within the high damage zone.
c. Keep reservoir storage below the emergency flood control pool; i.e., minimize the number of storage volume-days within the emergency flood control pool.
d. Keep stream flow below low damage zone; i.e., minimize the number of flow-days (cfs-days) within the low damage zone.
e. Keep reservoir storage at the bottom of normal flood control pool; i.e., minimize the number of storage volume-days within the normal flood control pool.

4. <u>Select Historical Flood Events</u>

To test the proposed theory over a range of hydrologic events, several historical flood events in the Iowa, Des Moines, and Mississippi Rivers were chosen for the current analysis. The historical flood events for this study are based on hydrologic data used by Needham, et al. (2000) representing the ten largest historical flood events recorded for the Iowa/Des Moines system. Of those ten events, historical hydrologic flow records and corresponding data associated with three of the historical flood events (occurring in 1990, 1991, and 1993) were chosen for this study (Table 3-1).

Table 3-1. Flood Event Dates

Year	Starting Date	Ending Date	Daily Time Steps
1993	February 21	October 18	240
1991	February 20	August 12	175
1990	April 22	October 1	163

Analysis of the Iowa/Des Moines system over these three historic hydrologic periods provides insight to operations of the reservoir system that may not be apparent from analyzing a single flood event.

5. <u>Estimate Unit Penalties</u>

Quantitative flow and storage unit penalties are presented below as a linear program (Israel and Lund 1999) based on the theory presented in the previous chapter and the application to the Iowa/Des Moines system presented above. The objective function of the linear program is to minimize the range of unit penalties. The method presented below was used as the basis to calculate storage penalty values for each "zone" of each reservoir and flow penalty values for each "zone" of each flow control point for each of the subsystems (C, F, E, and A) of the Iowa/Des Moines system and each of the historical flood events (1990, 1991, and 1993) chosen for the current analysis.

Minimize:

$Z = P_N - P_n$ where P_N = largest penalty and P_n = smallest penalty (used to minimize the range of unit penalties)

Subject to:

$P_S \geq \sum P_F + \varepsilon$	for all senior storage and junior flow priorities
$P_F \geq 2 \cdot T \cdot P_S + \varepsilon$	for all senior flow and junior storage priorities
$P_S = P_{Si}$	for all comparable storage zones for all reservoirs
$P_{Fi} \geq \dfrac{P_{Ei}}{Min(P_E)} + \varepsilon$	for all comparable flow damage zones for all control points

Where:

- P_S is the unit penalty incurred when storage level for the reservoir located upstream of specified flow control point(s) is within a specified zone.
- $\sum P_F$ is the sum of unit penalties for all stream points located downstream of the reservoir specified above incurred when flow level for each point is within a specified zone.
- P_F is the unit penalty incurred when the flow level for a stream point is within the specified zone.
- P_{Si} is the unit penalty incurred when storage level for any other reservoir in the system is within a comparable operating zone.
- The "2" multiplier accounts for a conversion between flow penalty units (penalty per cfs-day/day) and storage penalty units (penalty per AF/day), 1 cfs-day = 1.98 AF.
- The "T" multiplier accounts for the number of time-steps in the model. A unit of water held in storage may incur a penalty in each time step of the analysis, whereas the same unit of water may incur a flow penalty only once when it is released. For this reason, the "T" multiplier is set to the number of time periods in the analysis to ensure that the value of the flow penalty is large enough to account for the conservative estimate where storage levels are in the specified zone for the duration of the storm event.
- P_{Fi} is the unit penalty incurred when the flow level for a specified stream point is within a specified flow zone.
- P_{Ei} is the estimated unit economic damage incurred when the flow level for the stream point specified above is within the flow zone specified above. This number is based on multi-slope, piecewise linear functions provided by others (HEC 1999) as estimates of flow-damage relationships.
- $Min(P_E)$ is the minimum value of unit economic damage incurred for all comparable flow zones (i.e., low or high damage zone) of all stream points in the system. The minimum economic damage has been chosen as the denominator to scale all unit flow penalties from a common reference point.
- ε is an arbitrarily small positive number greater than 0 (used to ensure that variables on the left side of the inequalities are slightly larger than values on the right side).

CHAPTER 4: RESULTS

Results of the application are provided below as two primary categories:

1. Results of the method that calculates storage and flow penalty values for the specified systems and flood events.
2. Results of the HEC-ResFloodOpt model that utilizes the calculated penalty values for priority based optimization of the specified systems and flood events.

Unit Penalty Results

Unit penalty values were calculated for each storage zone of each reservoir and for each flow zone of each stream flow control point for each of the subsystems (C, F, E, and A) of the Iowa/Des Moines system and each of the historical flood events (1990, 1991, and 1993) chosen for the current analysis. A spreadsheet linear program solver was used for the calculations. Appendix A provides a detailed summary of calculated unit penalty values for each subsystem/flood event combination. Table 4-1 provides a summary of the unit penalty values calculated for the entire Iowa/Des Moines system (System A) for the three specified flood events.

Table 4-1. Calculated Unit Penalty Values (System A)

RESERVOIRS									
Storage Zone	Normal Flood			Emergency Flood			Surcharge		
Flood Year	1990	1991	1993	1990	1991	1993	1990	1991	1993
All Reservoirs	0.001	0.001	0.001	238	242	264	3,978,870	4,312,613	6,457,381

FLOW CONTROL POINTS						
Flow Zone	Low Damage			High Damage		
Flood Year	1990	1991	1993	1990	1991	1993
2nd Ave	91.0	92.5	101.4	1,956,984	2,121,175	3,176,332
14th St	6.0	6.1	6.7	NPA	NPA	NPA
Tracy	21.2	21.6	23.7	NPA	NPA	NPA
Ottumwa	48.3	49.1	53.8	900,431	975,977	1,461,466
Keosauqua	7.0	7.1	7.8	87,138	94,449	141,432
Iowa City	10.9	11.0	12.1	214,215	232,188	347,688
Lone Tree	5.8	5.9	6.5	NPA	NPA	NPA
Wapello	4.3	4.4	4.8	132,886	144,035	215,684
Burlington	1.3	1.4	1.5	78,134	84,690	126,818
Quincy	32.0	32.5	35.6	608,081	659,099	986,961

NPA = No Penalty Assigned
Number of daily time steps for 1990, 1991, and 1993 flood events = 163, 175, and 240, respectively.

HEC-ResFloodOpt Results

Flow and storage penalties calculated for each combination of the four subsystems and three historical flood events (i.e., 12 total combinations) were entered into the HEC-ResFloodOpt optimization program and run independently to optimize reservoir releases according to the chosen hierarchy of operating priorities. Other parameters used in the HEC-ResFloodOpt model for the current study (e.g., hydrology, reservoir storage zones, reservoir release rate capacities, system routing parameters, stream flow capacities, and stream flow economic damage functions) have been taken from datasets provided by the U.S. Army Corps of Engineers Hydrologic Engineering Center (HEC 1999).

Appendix B provides a detailed summary (by subsystem and storm event) of the number of time periods (days) when specific storage and flow operating conditions occur. The results in Appendix B differentiate between times when operating conditions are caused by reservoir release constraints (Columns A and B), by tributary inflow conditions (Column C), or by operating priorities (Columns D, E, and F). The discussion below summarizes Appendix B details related to the control of system penalties and operating conditions by reservoir release constraints, tributary inflow conditions, and operating priorities.

Reservoir Release Constraints

System penalties and operating conditions are occasionally controlled by reservoir release constraints, which supersede allocation of operating priorities for several days in the analysis period. The constraints include maximum allowable release capacity and maximum allowable change in rate of release. The following reservoir release constraints control system penalties and operating conditions, indicating which reservoirs' release constraints impede flood control operations. Table 4-2 summarizes the number of days in each storm event where these constraints bind operations (results shown for analysis of the entire Iowa/Des Moines system, System A).

1. **Maximum allowable release capacity forces Coralville and Saylorville operations within the surcharge pool and emergency flood control pool.**
2. **Maximum allowable change in rate of release forces Coralville and Red Rock operations within the emergency flood control pool.**
3. **Coralville's maximum allowable change in rate of release forces high damage flows at Iowa City and low damage flows at Iowa City, Lone Tree, Wapello, and Burlington.**
4. **Red Rock's maximum allowable change in rate of release forces low damage flows at Tracy, Ottumwa, and Keosauqua.**

Table 4-2. Operations Bound by Reservoir Release Constraints (System A)

Bound Operation	Number Days Specified Release Constraint Binds Operations					
	Max Allowable Release Capacity			Max Allowable Δ Release Rate		
	1990	1991	1993	1990	1991	1993
Storage						
Coralville	-	-	4	-	-	7
Saylorville	-	13	58	-	-	-
Red Rock	-	-	-	-	-	7
Flow						
Iowa City	-	-	-	-	-	8
Lone Tree	-	-	-	-	-	3
Wapello	-	-	-	-	-	9
Burlington	-	-	-	-	-	1
Tracy	-	-	-	-	-	11
Ottumwa	-	-	-	-	-	1
Keosauqua	-	-	-	-	-	9

Examining the shadow values on these constraints would determine which operating priorities are affected by the constraints. Thus, one could systematically change the level of constraint and note corresponding changes in the objective function of the linear program model. This exercise is left for future study.

Tributary Inflow Conditions

System penalties and operating conditions are occasionally controlled by tributary inflow conditions (i.e., non-reservoir-release-related flows) at various flow control points. Following is a summary of tributary inflow conditions that control flow damages, indicating which flow control points experience damages regardless of upstream reservoir operations. Table 4-3 summarizes the number of days in each storm event where tributary inflows control flow damages (results shown for analysis of the entire Iowa/Des Moines system, System A).

1. **Tributary inflows force high damage flows at Wapello, Burlington, and Quincy.**
2. **Tributary inflows force low damage flows at Lone Tree, Wapello, Burlington, Ottumwa, and Keosauqua.**

Table 4-3. Flow Damages Controlled by Tributary Inflows (System A)

Flow Control Point	Number Days Tributary Inflows Control Damages at Specified Flow Control Points		
	1990	1991	1993
Lone Tree	3	-	10
Wapello	13	11	81
Burlington	11	15	122
Ottumwa	-	-	2
Keosauqua	1	-	1
Quincy	-	-	11

Operating Priorities

System penalties and operating conditions are controlled by operating priorities during days when reservoir release constraints or tributary inflow conditions are not binding operations. Following is a summary of how simulated operating conditions correlate to the chosen operating priorities:

1. **Results of the analysis indicate proper allocation of operating priorities from the perspective of the entire analysis period.**
   When reservoir release constraints or tributary inflow conditions do not control system penalties, storage or flow in a specific priority "zone" occurs only if the next lower priority storage or flow "zone" has been reached at some point in the analysis period. This observation holds true for all 12 storm/subsystem combinations analyzed from the perspective of the entire analysis period. Exceptions occur periodically on a daily basis as described below.

2. **Proper allocation of operating priorities from the perspective of the entire analysis**

period can include occasional daily operations that oppose priority order. Storage and flow penalties are minimized in the chosen order (i.e., higher priority before lower priority) with respect to the entire period of analysis, with occasional daily operations that run counter to priority rank. Thus, a higher priority condition can occur on an individual day when the next lower priority condition is not present to minimize the occurrence of an even higher priority condition in the analysis period. For example, to minimize the total number of days that storage is within the surcharge pool (priority #1) of any system reservoir, high damage flows (priority #2) are periodically allowed to occur during days when storage in an upstream reservoir is below emergency flood control pool (priority #3). However, the lower priority condition (priority #3) will have occurred at some point in the analysis period prior to a higher priority condition occurring.

This condition was evident during several days in the analysis period for the System A, 1993 storm model run. On August 14, 16, and 17, 1993, simulated flow rates downstream of Coralville Reservoir at Wapello exceeded high damage flow rates (priority #2) and the water storage level in Coralville was below the emergency flood control pool (priority #3) for those three days. The optimization model permits this condition to occur to eliminate subsequent operation of Coralville within the surcharge pool (priority #1). That is, Coralville storage exactly reached, without exceeding, the top of the flood control pool from August 31 through September 3, 1993. However, Coralville operated periodically within the emergency flood control pool (priority #3) a total of 24 days prior to the three high damage flow-days (priority #2) at Wapello.

3. **Undesirable operating conditions with senior priority are minimized at the expense of undesirable operating conditions with junior priority.**
   The number of days in an analysis period with senior penalties is less than or equal to the combined number of days in the analysis period with junior penalties of the next lower priority (excluding days when reservoir release constraints or tributary inflow conditions control system penalties). For example, results of analysis for the 1993 storm event for the entire Iowa/Des Moines system (System A) indicate that when reservoir release constraints and tributary inflow conditions do not control system penalties:

   a. The number of surcharge pool storage-days (priority #1) for each reservoir is less than or equal to the combined number of high damage flow-days (priority #2) for all stream flow control points downstream of the reservoir.
   b. The number of high damage flow-days (priority #2) for each stream flow control point is less than or equal to the combined number of emergency flood control pool storage-days (priority #3) for upstream reservoirs.
   c. The number of emergency flood control pool storage-days (priority #3) for each reservoir is less than or equal to the combined number of low damage flow-days (priority #4) for all stream flow control points downstream of the reservoir.

CHAPTER 5: CONCLUSIONS

Several conclusions can be made about priority-based reservoir optimization using linear programming techniques for flood control operations on the Iowa/Des Moines system, including conclusions about priority based reservoir optimization, operating constraints, and calculated penalty values for the Iowa/Des Moines system.

Priority-Based Reservoir Optimization

The primary purpose of this study was to apply "priority preserving" penalty theory developed for a water supply simulation NFP model using a monthly time step to a flood control optimization linear programming (LP) model using a daily time step and investigate the results for preservation of selected operating priorities. The established theory has been supplemented in this study with additional considerations for maintaining relative hierarchy of flow related economic damage functions for stream flow control points and "equal storage function" concepts for system reservoirs. The theoretical basis includes several mathematical relationships based on three priority-based operating policies:

1. A specified ranking of operating priorities that determines the hierarchy relationship between senior and junior storage and flow penalties.
2. An "equal storage function" policy determines the relationship between storage penalties for comparable storage zones in multiple system reservoirs.
3. A series of economic flow damage functions determine the relationship between flow penalties for comparable flow zones for multiple system flow control points.

Results of this analysis support conclusions on the feasibility of the theory and method to provide reasonable estimates for storage and flow penalties used in LP optimization applications based on given flow related economic damage functions and specified operating priorities. The theory described here can be applied with success as described below to preserve operating priorities for a flood control optimization linear programming model (HEC-ResFloodOpt):

1. Results of the analysis indicate proper allocation of operating priorities from the perspective of the entire analysis period.
2. Proper allocation of operating priorities from the perspective of the entire analysis period can include occasional daily operations that oppose priority order.
3. Undesirable operating conditions with senior priority are minimized at the expense of less undesirable operating conditions with junior priority.

These conclusions are based on application of the theory to multiple subsystems and historical flood events associated with the Iowa/Des Moines system.

Iowa/Des Moines Operating Constraints and Hydrology Conditions

This study also provides insight to how total system penalties and operating conditions are controlled by operating constraints and hydrology conditions for the Iowa/Des Moines River Reservoir system. Reservoir release constraints of the Iowa-Des Moines system lead to several system penalties and undesirable operations. Maximum allowable release capacity forces Coralville and Saylorville to occasionally operate within the surcharge and emergency flood control pools. Maximum allowable change in rate of release forces Coralville and Red Rock to occasionally operate within the emergency flood control pool and contributes to flow damages downstream of the two reservoirs. Tributary inflow conditions force flow-related damages at Lone Tree, Wapello, Burlington, Ottumwa, Keosauqua, and Quincy regardless of upstream reservoir operations.

Penalty Values

The theory presented for this study was applied to the Iowa/Des Moines system based on a linear programming method to calculate penalty values representing divergence from desired storage and flow zones and a ranking of assumed operating priorities. Application of this theory to the Iowa/Des Moines system resulted in a wide range of storage and flow penalty values used to optimize the system (e.g., from 0.001 to over 6 million for the “System A, 1993 Storm” model run). The optimization program used in this study was able to operate with this wide range of penalty values. Addition of penalty zones, reservoirs, or flow control points could increase the range of penalty values and exceed the model’s numerical limitations.

Limitations

The theory used for this study was developed for a network flow simulation model using a monthly time step that did not require consideration for time lags associated with flow routing. The current study uses a linear programming model with a daily time step requiring consideration for time lags between select flow control points (Muskingum routing method). Observation of study results, however, indicates that the routing method used in the current study does not adversely affect priority-based optimization results.

Five operating priorities were considered for this study that alternated between three storage penalty zones and two flow penalty zones for up to three reservoirs and ten flow control points. This resulted in penalty values ranging in magnitude from 0.001 to over 6 million, which were able to be handled by the linear programming optimization model. Addition of penalty zones, reservoirs, or flow control points could increase the range of penalty values and exceed the model’s numerical limitations.

Storage and flow operating priorities and reservoir release constraints are assumed in the current study to not change with time over the study period.

Future Work

It is recommended that the theory and method be further tested on additional reservoir systems with multiple variations of reservoir storage priorities, storage and flow zones, and operating priorities. The method could be further developed to include peak flow penalty values used in HEC-ResFloodOpt. The study could also be extended by examining shadow values on release constraints to determine which operating priorities are affected by the constraints.

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