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Analysis of Flood Control Operation of the Iowa/Des Moines River Reservoir System Using Linear Programming Techniques

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Preface

This report presents the results of a flood control system optimization study of the Iowa and Des Moines Rivers performed by the Hydrologic Engineering Center (HEC) for the U.S. Army Corps of Engineers Rock Island District (CEMVR). Flood Control Linear Program Software (FCLP), originally developed by David Ford Consultants, was used for the analysis. Michael Tarpey of CEMVR directed data collection and assisted in establishing the parameters for the model. Theresa Carpenter and Shirley Johnson of CEMVR reviewed the report and provided extensive comments and suggestions. S.K. Nanda, Chief, Hydraulics and Hydrology Branch, CEMVR, provided general study oversight and review.

Jason Needham, HEC Intern, Planning Analysis Division, prepared the data for model execution, performed the model runs, analyzed the results, and authored the first draft of this report. David Watkins, Planning Analysis Division, assisted in model execution and analysis and completed final revisions to the report. Dustin Jones, HEC Intern, Planning Analysis Division, assisted in final phases of the analysis. Jay R. Lund, Professor of Civil and Environmental Engineering at the University of California at Davis, provided direction and substantial technical assistance. Mike Burnham, Chief, Planning Analysis Division, provided overall study direction and management. David Ford and Michael Lindquist, Engineering Consultants, provided technical assistance and support for the FCLP model along with ideas for the study. Kenneth W. Kirby provided post-processing advice and support for the Visual HEC-DSS program. Judy Cheng helped with word processing for the final report. Darryl Davis was Director of HEC during the study.

Summary

This report presents the methods, results, and conclusions from the reservoir system analysis of three U.S. Army Corps of Engineers (USACE) projects on the Iowa and Des Moines River system. A flood control linear programming model was developed and applied to perform the analysis. The objective of this study is to address questions related to flood control operating policies followed by the USACE Rock Island District. Another goal of this study is to assess the strengths and weaknesses of the linear programming model for this type of study.

FCLP is a deterministic optimization model designed to minimize flood control penalties throughout a river-reservoir system. Given time series of reservoir inflows and tributary flows downstream of the reservoirs, linear programming techniques are used to determine time series of reservoir releases that minimize system-wide penalties over an entire flood event. These penalties are based on the following: (1) flow-damage relationships at a number of control points throughout the system; (2) storage-penalty functions for each reservoir, representing operators' preferences for maintaining storage levels in particular reservoir zones; and (3) change-in-release penalties, intended to prevent reservoir releases from increasing or decreasing too rapidly. The flow-damage relationships used herein do not necessarily represent current economic damages for the reaches of this study. The relationships were developed during flood damage reduction studies in past decades and updated to current price levels. Changes in flood characteristics and damage potential were not re-surveyed as a part of this study.

Using the flow-damage and storage-penalty relationships, observed operation for the ten largest flood events on record is compared with the "optimal" historical operation determined by the model to identify possible shortcomings in the current operating procedures. Results of this study indicate that operating Coralville Reservoir, on the Iowa River, for flood control on the Mississippi River does not provide appreciable benefits. Therefore, an operation plan coordinating releases from Coralville Reservoir with the two reservoirs on the Des Moines River appears unnecessary. In fact, the optimal result for most of the floods was obtained by operating each reservoir independently. A review of the operating procedures for the Flood of 1993 also indicates that the damage could not have been significantly reduced unless inflows were accurately predicted 2-3 months in advance, which is not possible with current forecasting technology.

This study illustrates that FCLP is effective for addressing questions regarding strategies for operating a system of reservoirs. Suggestions for future work on the Iowa/Des Moines System include a re-evaluation of storage- and flow-penalty functions; a sensitivity analysis on storage persuasion penalties; and a statistical analysis of flood events and risk. Model improvements are recommended which will increase the effectiveness of this tool on this and more complex studies.

Chapter 1

INTRODUCTION

1.1 Purpose

This report describes the application of deterministic optimization to assess flood control operations for the Iowa/Des Moines River Reservoir System and provides insights for possible modifications to the current operating plan. This report also describes a general strategy for performing this type of analysis and interpreting the results.

1.2 Description of Iowa/Des Moines River Reservoir System

The Iowa/Des Moines River Reservoir System consists of three major reservoirs, one on the Iowa River main stem and two on the Des Moines River main stem. The locations of these reservoirs and the major streams in the system appear in Figure 1-1. Authorized purposes for these reservoirs include flood control, low-flow augmentation, fish/wildlife, water supply, and recreation. In each case, access and facilities are provided for recreation but water is not controlled for that purpose (USACE 1992). Total capacities and average inflows are shown in Table 1-1.

Table 1-1 Capacities of and Average Inflows to the Three Reservoirs

Reservoir	Inflows acre-ft/yr.	Capacity (acre-ft) Conservation	Flood Control	Total	%[a]
Coralville (Iowa River)	1,271,800	25,900*	435,300	461,200	18
Saylorville (D.M. River)	1,540,600	90,000	586,000	676,000	20
Red Rock (D.M. River)	3,568,000	265,500*	1,494,900	1,760,400	62

* Varies seasonally, value is minimum which corresponds to maximum flood storage

a Percent of total federal project flood storage in Des Moines/ Iowa system

Due to the relatively short distance between the confluence of the Iowa River with the Mississippi and that of the Des Moines River with the Mississippi, operation of the two systems as one larger system could, in theory, provide greater benefits than operating them independently. However, coordinated operation may also require more complex operating procedures, leading to greater uncertainty in the benefits realized.

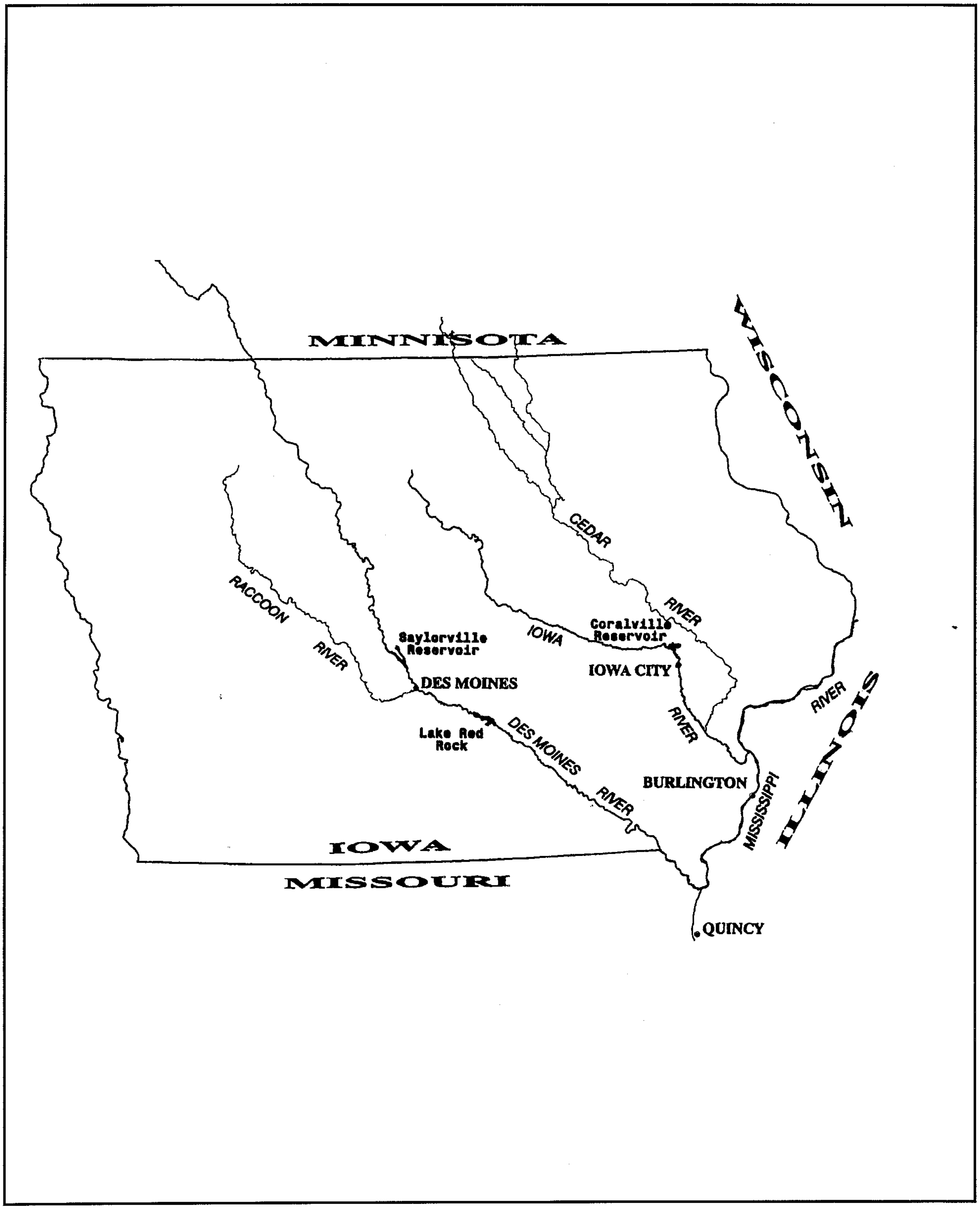

FIGURE 1-1 Map Showing Location of Iowa/Des Moines River Reservoir System

1.2.1 Iowa River System. A detailed map of the Iowa River main stem and major tributaries is provided in Figure 1-2. Pertinent characteristics of the Iowa River system are shown in Table 1-2.

TABLE 1-2 Iowa River Characteristics

Location	Drainage Area (sq. mi.)	Mean Annual Inflow (cfs)
Coralville Reservoir	3,115	1,760
Iowa River (Confluence w/Cedar R.)	4,770	2,360
Cedar River (Confluence w/Iowa R.)	7,870	4,230
Iowa River (Confluence w/Mississippi R.)	12,980	7,120
Mississippi River (Confluence w/Iowa R.)	89,000	49,000

As shown here, Coralville Reservoir can regulate no more than 25% of the total average annual flow entering the Mississippi from the Iowa River because the Cedar River has a larger drainage area than the Upper Iowa River. This limits the effectiveness of the flood control operation of the reservoir below the confluence of Cedar River and on the Mississippi River especially downstream of the Des Moines River. Modeling efforts by the Rock Island District have shown the effect of Coralville Reservoir on the Iowa River downstream of the Cedar River confluence reduced the stage a maximum of 2.5 feet for events before 1990 (USACE 1990). Under current operations, benefits are appreciable for the entire Iowa River, even though the reservoir regulates a relatively small portion of the total flow on the reaches farthest downstream.

1.2.2 Des Moines River System. The Des Moines River main stem, reservoirs, and major tributaries are displayed on the map in Figure 1-2. Pertinent characteristics of the Des Moines River system are shown in Table 1-3.

TABLE 1-3 Des Moines River Characteristics

Location	Drainage Area (sq. mi.)	Mean Inflow (cfs)
Saylorville Reservoir	5,823	2,200
Lake Red Rock	12,323	4,928
Des Moines (Confluence w/Mississippi R.)	14,540	8,210
Mississippi (Confluence w/Des Moines R.)	119,000	64,520

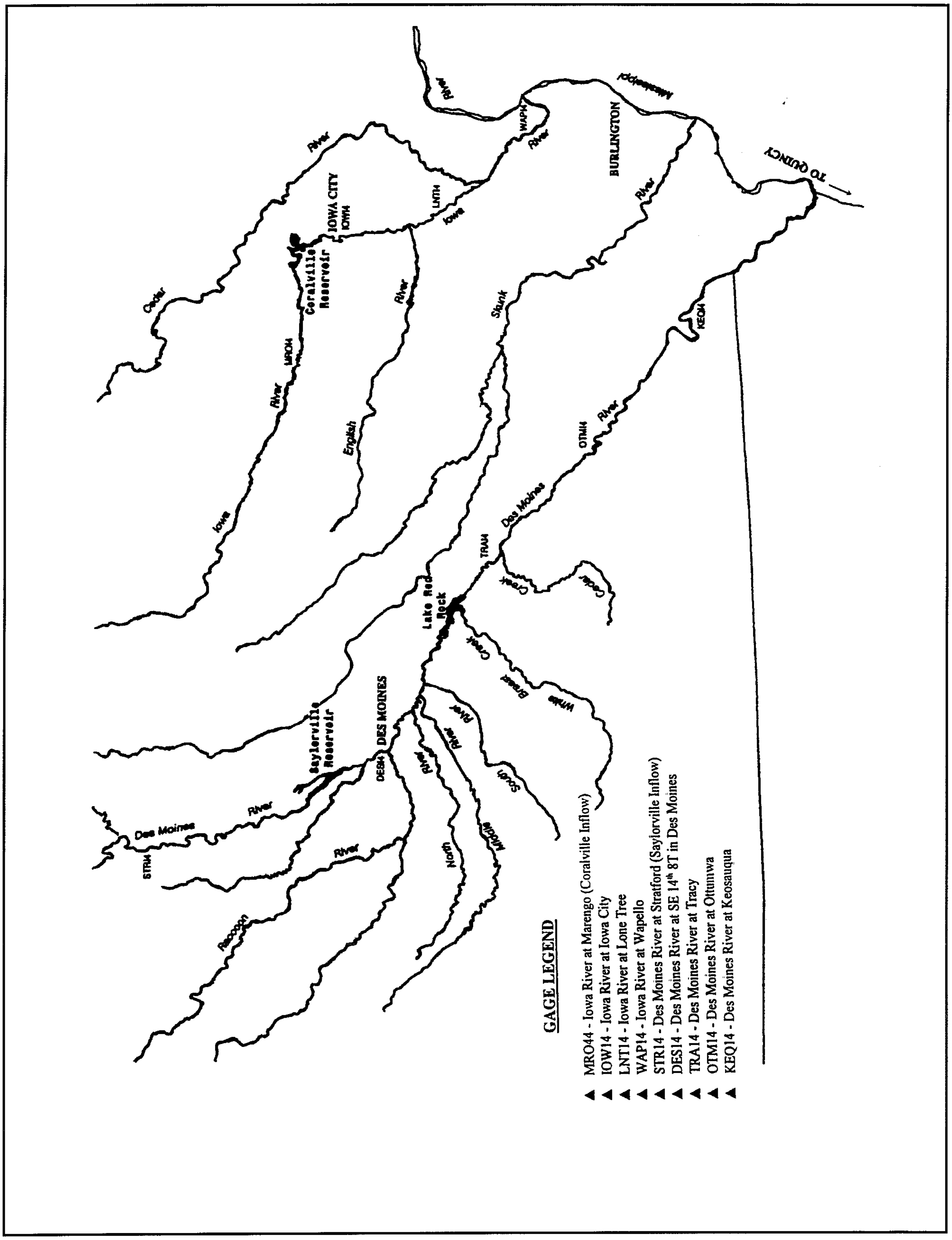

FIGURE 1-2 Detailed Iowa/Des Moines River Reservoir System Layout

Table 1-3 illustrates that Saylorville and Red Rock regulate over half of the average flow entering the Mississippi River from the Des Moines River. The main tributaries of the Des Moines River join the main stem upstream of or at Lake Red Rock. An important tributary is the Raccoon River which converges in the southern part of the City of Des Moines and has a large effect on the stage there. The hydrographs of Ottumwa and Keosauqua are similar because no major tributaries join the Des Moines River downstream of Ottumwa.

1.3 Problem Statement

The Great Flood of 1993 was devastating to the Midwest and led to questions regarding operation of the facilities located on tributaries to the Mississippi River. The Iowa and Des Moines Rivers are two major tributaries on the upper Mississippi River and had some of the largest increases in runoff for the 1993 water year when compared to the mean annual runoff (Scientific Assessment and Strategy Team 1994). Due to the enormous damage and the high media visibility in this area, the flooding of the City of Des Moines and Iowa City along with reaches on the Mississippi River has been carefully reviewed. As a result of this scrutiny, critics have questioned whether the U.S. Army Corps of Engineers (USACE) operated the main reservoirs on these rivers in a manner that would best limit the flood damage.

This study will help assess the performance of the USACE Rock Island District operation policies for the three reservoirs. Two main questions will be addressed.

1. Should the three reservoirs, one on the Iowa River and two on the Des Moines River, be operated independently or as a coordinated system? More specifically, should releases from Coralville Reservoir be based on stages on the Mississippi River? Also, should the two reservoirs on the Des Moines River be operated in tandem?

2. How well did the system operate in 1993?

Other objectives of this study are to evaluate the performance of this type of optimization tool for flood control and demonstrate how to use the results.

1.4 Report Organization

Chapter 2 presents background material related to the existing operations of the Iowa/Des Moines River Reservoir System. It also provides a description of the regional hydrology, as well as information on the flood of 1993 and its impacts. Chapter 3 provides a general overview of optimization analysis procedure, along with a more detailed description of the Flood Control Linear Program (FCLP) model used in this study. Chapter 4 presents the model calibration, providing a comparison of the USGS observed data with the results from FCLP and describing the shortcomings of the model. Chapter 5 details the application of the model for the 1993 flood event and provides a summary of the results from the nine other flood events that were studied. Chapter 6 presents an interpretation of the results followed by the implication of this study on reservoir operations. Finally, Chapter 7 presents the conclusions of this study along with some suggestions for future work.

A number of appendices provide supplemental information pertaining to current operating procedures, the FCLP model, and study data and results. Appendix A contains the current operating rules for the three reservoirs on the Iowa and Des Moines Rivers. Appendix B is the technical report and user's manual for FCLP, the optimization model used in this analysis. Appendix C contains charts illustrating time series of incremental inflows at each location for the ten flood events studied. Appendix D contains a series of charts illustrating the difference between model results and observed data for the ten flood events studied. Appendix E contains a series of charts illustrating the results obtained by dividing the Iowa/Des Moines River system into various combinations of sub-systems.

Chapter 2

BACKGROUND

2.1 Existing Operations

Coralville Reservoir was completed and placed in operation during September of 1958 as a unit in the general comprehensive plan for flood control in the Upper Mississippi River Basin. The reservoir was designed to store 492,000 ac-ft of water of which variable amounts, based on season, were set aside for conservation and low flow augmentation. Since 1958, several modifications have been made to the reservoir operation plan due to sediment accumulation, adverse environmental effects, and agricultural demands. In 1990, the Rock Island District prepared the "Draft Water Control Plan" which stipulates the current operation policy. The current release schedule is provided in Appendix A (USACE 1990).

According to the Reservoir Regulation Manual, Coralville Reservoir is to be operated for flood control at Lone Tree and Wapello on the Iowa River and Burlington, Iowa, on the Mississippi River. When operated in conjunction with the reservoirs on the Des Moines River, the flood peaks can be offset enough to cause a significant difference in the water levels on the Mississippi River during flooding. This is illustrated in Table 2-1, which shows the stage and average daily flows at Quincy, Illinois, downstream of the Des Moines River during past major flood events.

TABLE 2-1 Estimated Reservoir Operation Effect at Quincy, Illinois

	Natural		Modified [a]		Modified [b]	
Year	Stage	Discharge	Stage	Discharge	Stage	Discharge
1944	22.9	308,200	21.5	275,000	18.5	229,500
1947	23.8	324,400	23.0	302,800	21.4	281,200
1965	25.0	347,000	24.6	339,300	24.3	333,700

[a] Coralville Reservoir Operation only
[b] Coralville Reservoir Operation when combined with Red Rock - Saylorville Operation

(USACE 1990)

Saylorville Reservoir and Lake Red Rock projects also are associated with the comprehensive plan for flood control in the Upper Mississippi River Basin. Lake Red Rock was completed in May 1969, while Saylorville Dam did not go into operation until July of 1975. Red Rock Dam and Saylorville Dam are currently operated as a system for flood protection on the Des Moines and Mississippi Rivers. The conservation pool for Lake Red Rock was initially set at 725 ft elevation which corresponded to a storage of 90,000 ac-ft. It has been raised over the years to account for lost storage due to sedimentation and an increased need for low flow augmentation. Conservation storage is now 265,000 ac-ft at a level of 742 ft. Refer to Table 1-1 for a complete listing of current reservoir capacities.

The Des Moines River reservoirs are required to meet certain low flow and water quality constraints. A minimum release of 200 cfs is required from Saylorville Reservoir to meet these constraints. Since this study focuses on large flood events, the constraints on minimum releases should not be important. Currently, the Rock Island District uses a simulation model for the Des Moines River which assures these requirements are met.

The flood control effect of these reservoirs is appreciable, as shown in Table 2-2, with respect to stage on the Des Moines River both above and below Red Rock. According to the Reservoir Regulation Manuals, Saylorville Reservoir is operated not only to reduce flood damage in the City of Des Moines, but also in tandem with Lake Red Rock to reduce flood damage at Ottumwa and Keosauqua on the Des Moines River and Quincy, Illinois, on the Mississippi River. Refer to Table 2-1 for effects of the reservoirs on Mississippi River stage below the confluence of the Des Moines River.

TABLE 2-2 Estimated Reservoir Operation Effect at Des Moines and Keosauqua

	Des Moines (Flood Stage = 23 ft)				Keosauqua (Flood Stage = 25 ft)			
	Natural		Modified		Natural		Modified	
Year	Stage	Discharge	Stage	Discharge	Stage	Discharge	Stage	Discharge
1944	27.6	51,500	23.3	36,600	18.0	70,900	10.4	33,200
1947	31.0	74,000	28.0	60,700	25.1	115,800	13.6	51,100
1965	29.6	65,000	25.2	31,600	19.3	79,200	10.4	34,500

(USACE 1983)

Current operating rules for the Saylorville Reservoir and the Lake Red Rock can be found in Appendix A (USACE 1983; USACE 1988).

2.2 Regional Hydrology

The most common floods in the Upper Mississippi River Basin result from rainfall and, to a lesser degree, snowmelt in the spring of each year. The average annual precipitation over the Iowa River Basin above Coralville Dam and the Des Moines Basin above Lake Red Rock is 35 and 29 inches, respectively. Approximately 70% of the precipitation occurs during the six-month period from April through September. These are not sudden floods, but rather a gradual and steady rise in water level. Occasional floods caused by thaws or ice-jam release occur in winter and thunderstorms in spring. These are generally local in nature and easily curtailed by the reservoirs. Average flows for the Iowa and Des Moines Rivers for the period of 1917 - 1993 are illustrated in Figures 2-1 and 2-2.

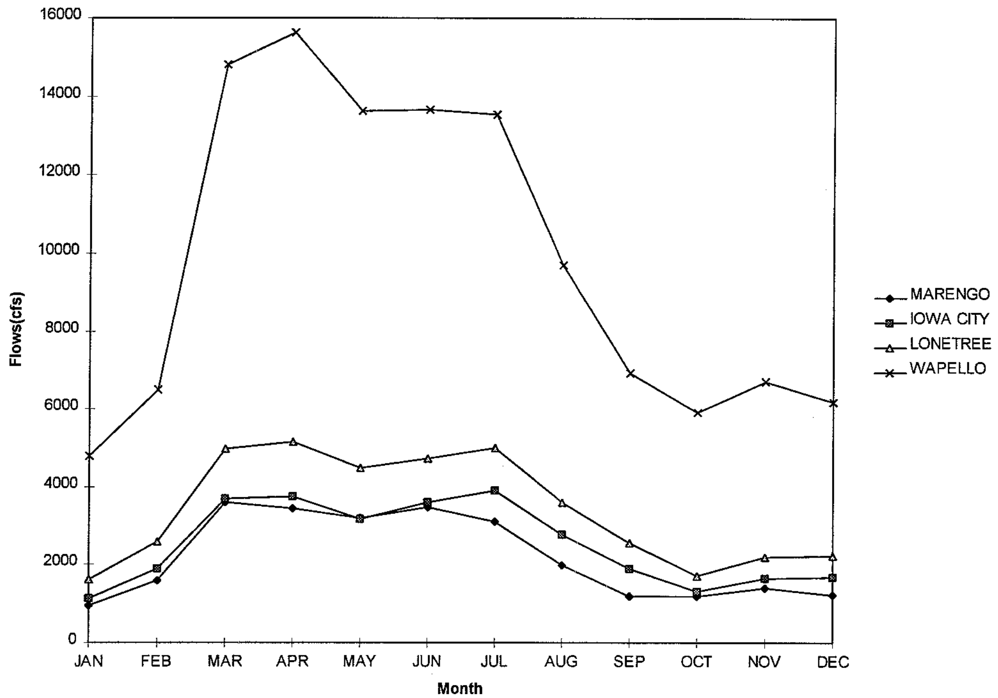

FIGURE 2-1 Mean Monthly Flows on the Iowa River

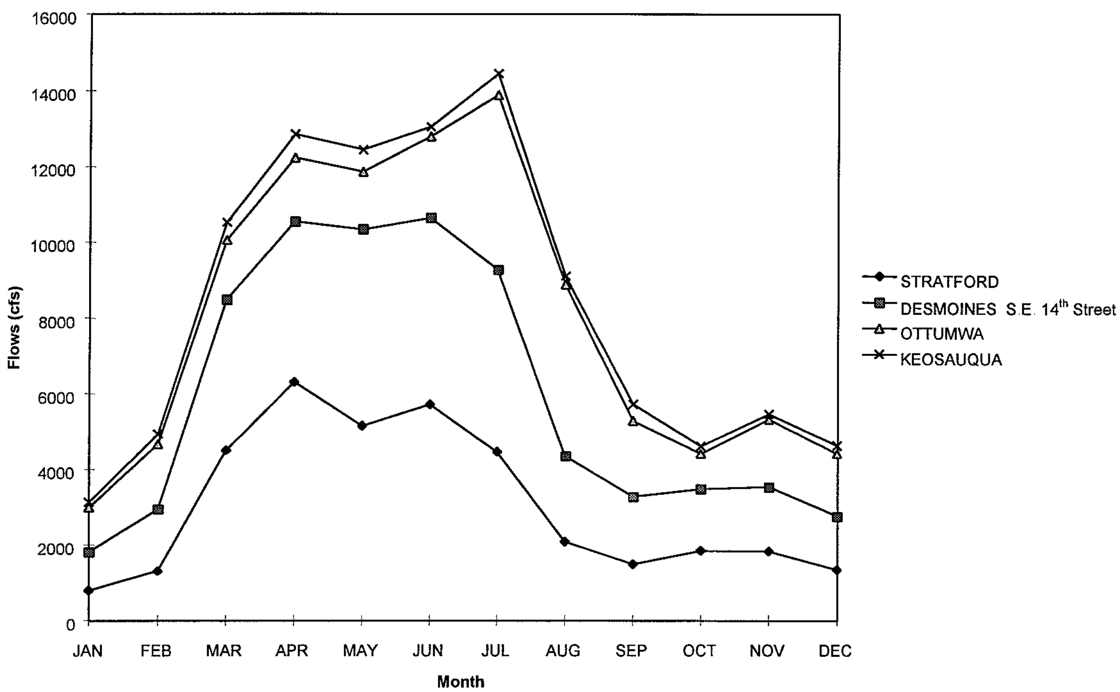

FIGURE 2-2 Mean Monthly Flows on the Des Moines River

Snowmelt is a large contributor to the more common floods in the region. One of the larger floods on record resulted from snowmelt alone. January of 1962 was recorded as a cold and dry month with 2-5 inches of snow throughout the Iowa basin. Record snowfall occurred during the month of February, followed by above average snowfall in March. At the end of March, an increase in temperature from a daily high of 35 degrees on the 20th to 75 degrees on the 28th caused rapid snowmelt. The majority of snow accumulation, 44 inches at Iowa City and 53 inches at Marshalltown, melted during that week. The flow in the Iowa River at Lone Tree on the 21st of March was 26,000 cfs. On the 25th of March, a crest of 15,000 cfs was recorded at Marengo. At Wapello, on the 6th of April, a flow of 53,700 cfs was recorded. No major flooding occurred on the Des Moines River.

Snowmelt augmented by rainfall produced widespread flooding on both the Iowa and Des Moines Rivers in 1965. During the winter, then the coldest in 30 years, heavy accumulations of snow developed over the central and upper Des Moines basin. The water content of the snow cover above the City of Des Moines averaged 2 to 4 inches at the end of March. With the beginning of April came higher temperatures and rain. At the same time, snowfall over the Iowa River Basin had increased the snow depth to 12 inches in some places. During the last week of March, a warming trend accompanied by rain melted all snow in the Iowa River Basin. Rain continued through the first week in April. The combination of rainfall and snowmelt produced flows of 19,800 cfs at Marengo and 70,800 cfs at Wapello along the Iowa River, as well as peak flows of 78,200 cfs at Ottumwa and 79,600 cfs at Keosauqua on the Des Moines River. Flooding on the Mississippi was the greatest on record as snowmelt and rainfall runoff from the Upper Mississippi River Basin tributaries combined to produce record stages from St. Paul, Minnesota, to Hannibal, Missouri (USACE 1990). Table 2-3 illustrates the peak daily flows throughout the study area for the flood of 1965 along with the some of the other major floods on record.

TABLE 2-3 Maximum Daily Average Flows for Selected Years

Location	Maximum Daily Average (cfs)							
	1993	1991	1990	1979	1974	1973	1965	1960
Stratford	41,400	33,400	18,100	29,300	13,600	20,100	47,100	27,900
Des Moines	113,000	44,600	44,100	34,800	44,800	43,000	65,000	65,600
Tracy	107,000	35,200	23,100	27,800	19,600	28,700	76,300	73,200
Ottumwa	110,000	35,700	28,300	33,000	26,600	32,000	77,600	70,500
Keosauqua	108,000	41,900	44,300	34,800	34,600	57,100	79,200	73,200
Marengo	35,600	15,300	17,100	20,700	19,000	15,900	19,300	29,000
Iowa City	26,200	13,000	10,500	10,200	11,200	10,800	9,900	9,820
Lone Tree	55,100	15,300	25,600	21,300	30,600	19,300	29,200	27,300
Wapello	106,000	49,100	76,100	62,400	78,900	84,200	70,300	66,900

2.3 Flood of 1993

The size and impact of The Great Flood of 1993 was unprecedented. Record river stages, areal extent of flooding, persons displaced, crop and property damage, and flood duration surpassed all floods in the United States in modern times (National Disaster Survey Report 1994).

2.3.1 Explanation of Magnitude. The enormous magnitude of the 1993 flood can be attributed to many factors. The most important of these are the record precipitation and storm timing.

The extent and duration of the flooding in the Upper Mississippi River Basin was due mostly to excessive precipitation in the region from January through August 1993 and an unusually wet period from the previous summer and fall. By the end of May, 1993, soil moisture throughout most of the region was excessive, river stages were above normal, and reservoirs were reaching capacity. In many locations, precipitation amounts for July and August were greater than twice the normal amounts. By the end of June, most soils throughout the region were saturated, and the rainfall that occurred in July produced excessive runoff and severe flooding throughout the region (SAST 1994).

Flooding on the main stems of the Mississippi and Missouri Rivers was compounded by the timing of several rainstorms in late June through July. Record flooding on the Minnesota and Mississippi Rivers in Minnesota produced flood crests that reached Clinton, Iowa, on July 5, 1993. Rainstorms in early July caused record peaks on the Iowa, Skunk, and Des Moines Rivers and major flooding throughout these areas. The flood crests from these rivers entered the Mississippi River at about the same time that the flood peak from Minnesota reached the Mississippi River at Keokuk (just below the Des Moines confluence). The discharge from these combined floodwaters reached St. Louis, Missouri, on July 20, 1993 (SAST 1994). Because of the timing of these events, the mainstem flows tended to be more extreme than the individual tributary floods.

These factors combined to create record flooding throughout the Midwest. This can be illustrated by comparing the stage of an average year and that of 1993 at Quincy, Illinois (Figure 2-3).

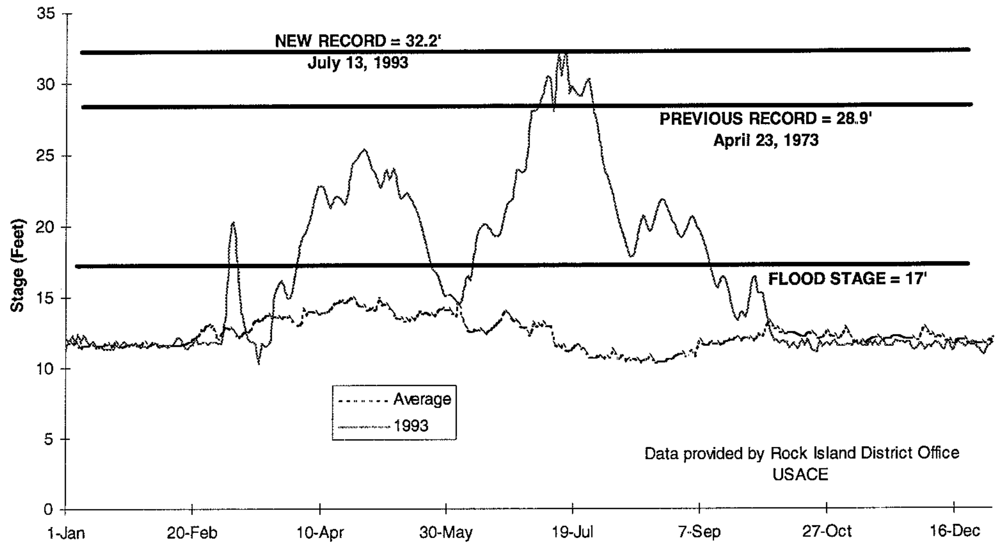

FIGURE 2-3 1993 Hydrograph for Mississippi River at Quincy, Illinois

2.3.2 Impact of Flooding. The Flood of 1993 caused significant economic damage and human suffering. At least 75 towns and 20 million acres of land in nine states were flooded. The number of human fatalities caused by the flood is estimated to be 48, while the economic losses are estimated at $15-20 billion (NDSR 1994). Agriculture was greatly affected by the erosion of more than 600 billion tons of topsoil. In areas inundated by the flood, the harvest of 1993 was a total loss (USDA SCS 1994). Due to the amount of topsoil erosion, the impact on farm productivity is long-term. The environment had additional stress placed on it from pollutants and raw sewage released by the flood.

Iowa was the state hardest hit by the floods of 1993. As reported earlier, runoff from the Iowa and Des Moines River basins increased more than any other place in the Upper Mississippi River basin. Table 2-4 illustrates the enormous increase in flow during 1993 at these two locations.

TABLE 2-4 Comparison of Mean Flows and Record Stage with 1993 Water Year

Location	Through Water Year 1992			Water Year 1993		
	Mean Flow (cfs)	Runoff Depth (in)	Record Stage (ft)	Mean Flow (cfs)	Runoff Depth (in)	Stage (ft)
Iowa River confluence with Mississippi	7,120	7.74	28.9	30,550	33.2	29.5
Des Moines River confluence with Mississippi	12,323	7.65	29.4	26,920	26.05	32.7

2.3.3 Effects of Reservoirs. Flow volumes on the Mississippi River tributaries, from the Iowa and Des Moines River basins, were as much as ten times greater than the reservoir storage volumes. Nonetheless, flood damage was reduced through the operation of these reservoirs. In July, maximum daily outflow was reduced by an estimated 20 percent upstream of the City of Des Moines by storage operations at Saylorville Reservoir. This resulted in a reduction in stage of about 2 feet in the City of Des Moines. Although the flood peaks on these tributaries were reduced, the overall effect on the main stem of the Mississippi River was minimal. In contrast, the larger reservoirs on the Missouri River had a much greater effect (SAST 1994).

Chapter 3

ANALYSIS APPROACH

3.1 Optimization

Two categories of models are generally used when modeling river reservoir systems: descriptive and prescriptive. Descriptive models simulate operation with a user specified operation policy. This type of analysis usually involves an iterative process in which small changes are made to the operation policy every time the model is run until desired results are obtained. An optimal result for flood control would be the one that minimizes damage throughout the represented system. A prescriptive tool, on the other hand, systematically generates the optimal operations using an embedded simulation model to estimate the system's response. The tool suggests the optimal operations by evaluating the results of the simulations based on defined objectives, goals, and constraints for the system. In this case, the operations are comprised of reservoir release decisions, and the objective is to minimize total flood damage.

In the past, the Hydrologic Engineering Center (HEC) has used both approaches to finding desirable release schedules for reservoir systems. Most recently, the HEC Prescriptive Reservoir Model (HEC-PRM) was used for the Missouri and Columbia River Systems (USACE 1994; USACE 1996). This is an efficient tool for developing operational rules on a seasonal basis for conservation purposes. However, HEC-PRM has some critical limitations which restrict its effectiveness for flood control optimization.

One of the most important limitations of HEC-PRM for this type of analysis is the time step required. HEC-PRM was designed to analyze monthly operation, so all flow released from a reservoir during a month reaches downstream control points during the same month. Flood operations require that decisions be made much more frequently than HEC-PRM can accommodate. While using monthly time steps, attenuation and translation of flows do not significantly affect the results, but during flood events these must be accounted for. Also, the rate of change of release from reservoirs must be regulated to ensure reasonable, safe operation of the system. The rates that flood gates can be raised or lowered, as well as the effect of changing flow rates on bank stability, need to be taken into account.

It is important to note the benefits of using models such as HEC-PRM. The operation problem is addressed systematically - the system is represented by a mathematical program with flow, release, and storage as decision variables. In most cases, the understanding of the system gained by organizing and setting up the mathematical program is a significant contribution to solving the problem. Developing the optimization model requires rationalization of inflows, quantification of operating objectives, and reasonable representation of the system and its operational limitations.

This type of model represents the goals of operation with penalty functions which allow the program to minimize cost throughout the system instead of operating based on specific control points. The cost-based penalty functions represent the economic loss as flow, storage, and release deviate from a desired range of values.

3.2 Linear Programming Model (FCLP)

To accommodate the flood control modeling needs not met by HEC-PRM, a linear programming (LP) model termed FCLP (Flood Control Linear Program) was developed by David Ford Consulting Engineers. The model treats the flood-operation problem as one of finding a system-wide set of releases that minimize total system penalty for too much or too little release, storage, and flow. A simulation model embedded in the LP model uses given releases to compute storage and downstream flows, accommodates reservoir continuity and linear channel routing, and accounts for hydraulic limitations.

FCLP reads a description of the flood control system from an input file similar to a HEC-5 input file. It then generates a set of linear equations that constitute the LP. Using either XMP (Marsten, 1987) or IBM/OSL (IBM, 1995), both general-purpose, large-scale LP solvers, it calculates the optimal values of decision variables and then translates the LP results into terms familiar to hydrologic engineers (release, flows, storage values). FCLP is linked to the HEC Data Storage System, HEC-DSS, from which it reads the historical incremental flows and writes the results. The Technical Report and User's Manual for FCLP is attached in Appendix B.

Currently, FCLP calculates the daily system-wide damage and sums them over the entire flood event to calculate the total penalty; this is termed the *model-computed penalty* for the remainder of this report. This method of flood penalty calculation is not an accurate depiction of the actual damage, which for urban areas is dependent almost entirely on the peak flow of the flood. Also, reservoir operators can often take advantage of the fact that an area has already been flooded by releasing flows that would normally flood that area in order to lower storage levels; there may be no reason to reduce flows immediately after an area has been flooded since the damage has already occurred. This allows faster emptying of flood control space in a reservoir to prepare for possible future floods. On the other hand, agricultural damage is affected by the duration of flooding. A more desirable, though more complex, flood optimization model would account for these different types of damages.

Another shortcoming of FCLP is its inability to deal with seasonally varying stage (flow)-damage relationships. There are some cases in this study in which the flood event lasts into the planting season. Current operating procedures address this problem by reducing the maximum flow at agricultural locations. These limitations cause results that are, in a few cases, not representative of the optimal operation of the reservoir system.

Finally, the FCLP model is deterministic and therefore makes release decisions for all periods simultaneously, with perfect foresight of future inflows. The model would have to be modified for use in real-time operations with forecasts of inflows. Nonetheless, current results are useful for determining general operational policies. By comparing the observed historical operation with the "optimal" historical operation, it may be possible to determine shortcomings in the current operating procedures. Furthermore, questions regarding revised operating strategies following changes in physical aspects of the system can be addressed quickly by the model.

3.3 Strategy

An important part of any optimization study is calibrating the model so that it reasonably represents the goals and constraints of the system under consideration. A more detailed explanation of the calibration process is presented in Chapter 4. Once the model is shown capable of producing results similar to the observed data, it is assumed to be calibrated and the analysis begins.

The first step was selecting from the 70-year record which flood events to use in the study. The ten largest flood events were determined based on a combination of peak flow and total volume at each gage. For each of the selected events, beginning and ending dates where estimated visually from the hydrographs. These hydrographs are included as Appendix C. Dates of the flood events used in this study are shown in Table 3-1.

TABLE 3-1 Flood Event Dates

Year	Starting Date	Ending Date
1993	February 20	November 25
1991	February 20	August 18
1990	April 22	October 1
1979	February 20	July 3
1974	April 1	August 10
1973	February 20	August 5
1965	February 21	July 25
1960	March 20	July 25
1947	May 25	September 10
1944	February 1	September 12

To estimate the benefits from operating the reservoirs as a coordinated system, the larger Iowa/Des Moines/Mississippi River System was divided into various sub-systems as illustrated in Figure 3-1. By optimizing the operations of each sub-system independently, and comparing the results to those obtained from optimizing the operations of the entire system, the benefits of coordinating reservoir operations can be quantified. Since the optimization model is deterministic, this analysis actually provides an upper bound on the benefits of reservoir operations. Determining to what extent these potential benefits are obtainable in practice would require more detailed simulation analysis.

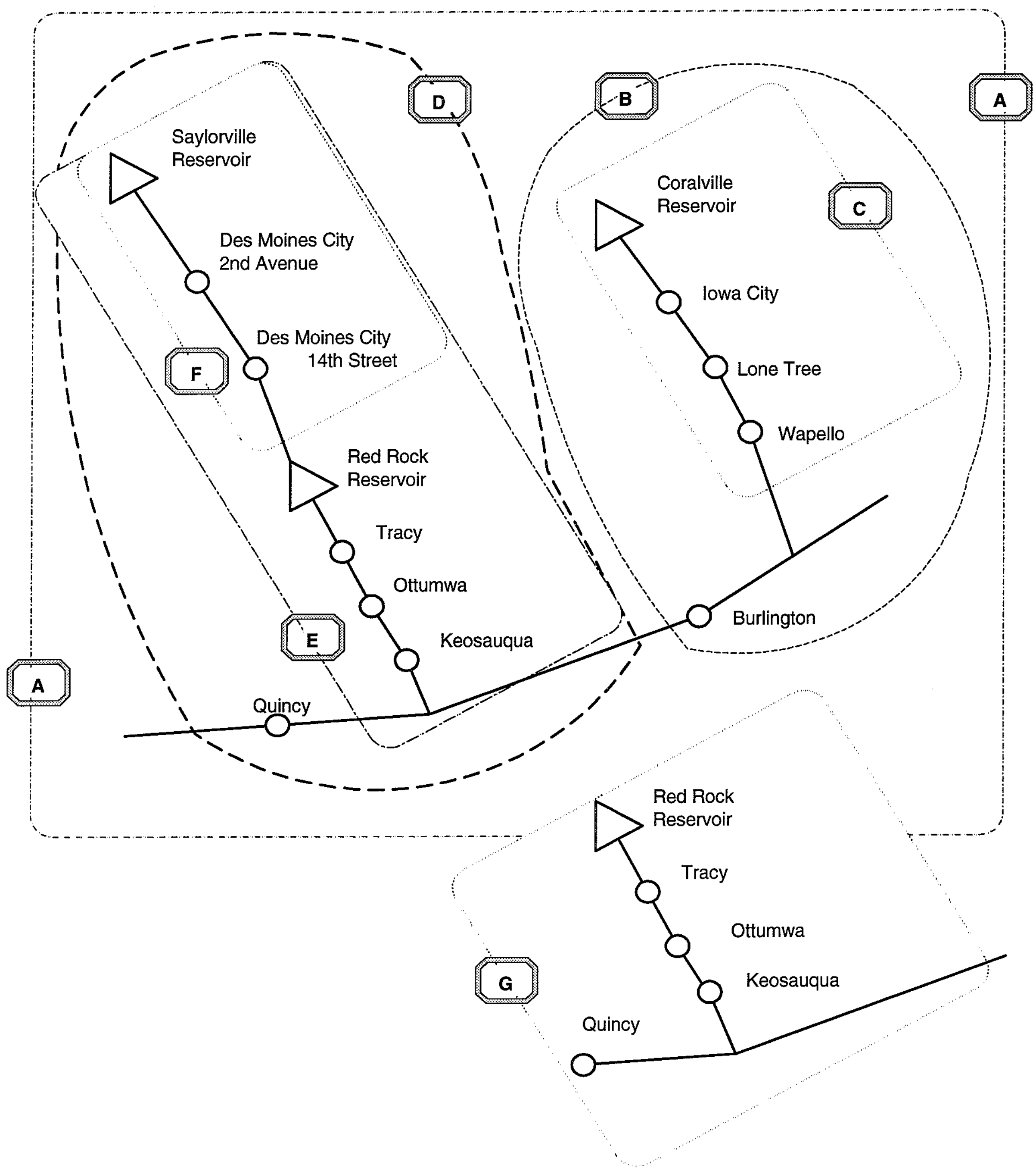

FIGURE 3-1 System Decomposition

System A, the most complex, consists of the three reservoirs located on the Iowa and Des Moines Rivers and all ten control points, of which two are on the Mississippi River. System B isolates the Iowa River, causing Coralville Reservoir to operate only for damage locations on the Iowa River plus Burlington on the Mississippi River. System C is similar to System B, but Burlington is removed from consideration. This illustrates the effect of Burlington on the operation of Coralville Reservoir. System D represents the two reservoirs on the Des Moines River operating in tandem for control at all damage locations on the Des Moines River plus Quincy on the Mississippi River. System E is identical to System D except that the damage location at Quincy removed. Dividing System D just upstream of Lake Red Rock to form systems F and G helps illustrate the effect of operating Saylorville Reservoir and Lake Red Rock independently. The seven possible combinations of these systems are A, BD, CD, BE, CE, BFG, and CFG.

Chapter 4

MODEL CALIBRATION

4.1 Origin and Discussion of Parameters

The parameters used in the model are listed below, followed by an explanation of their origin.

4.1.1 Reservoir Levels and Releases. The initial storage level in each reservoir was assumed to be the top of the conservation pool. Presumably, this would be the highest storage level obtainable following the low-flow season. In the model, reservoir storage is divided into five levels: Dead Pool, Top of Drought, Top of Conservation, Top of Flood, Top of Dam. These are quantified in Figures 4-1 through 4-3 for each of the three reservoirs. Values for the relationship between storage level and maximum possible outflow are based on outlet and spillway rating curves. All values came from the Master Reservoir Regulation Manuals of the three reservoirs.

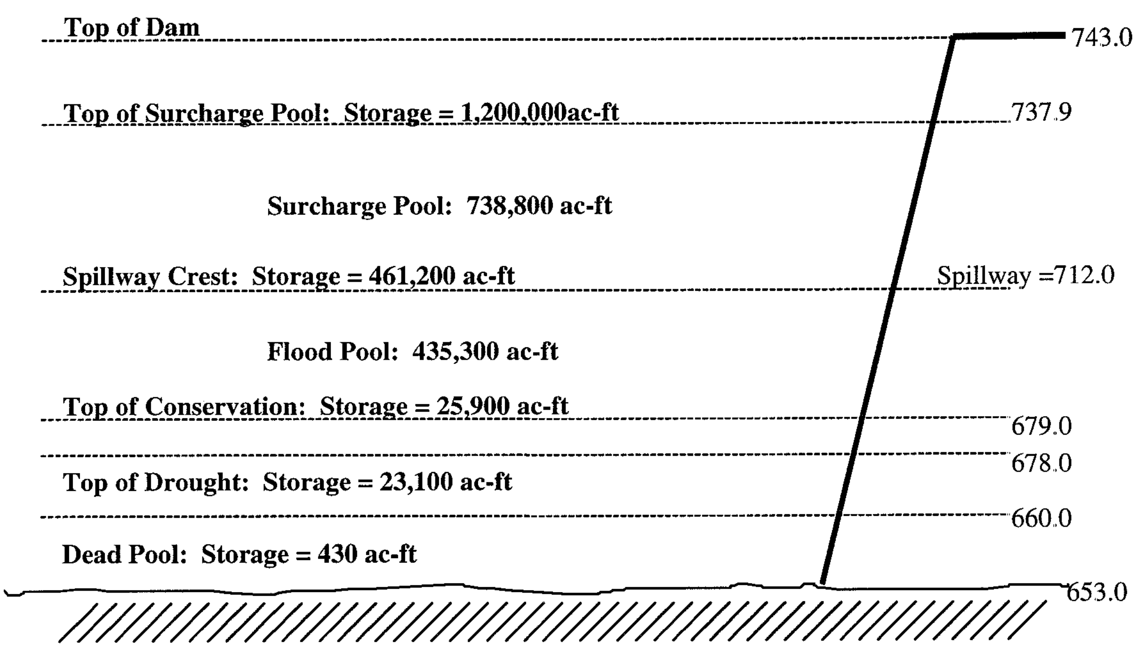

FIGURE 4-1 Coralville Reservoir Storage Levels.
Values from 1990 Regulation Manual (1983 Survey)

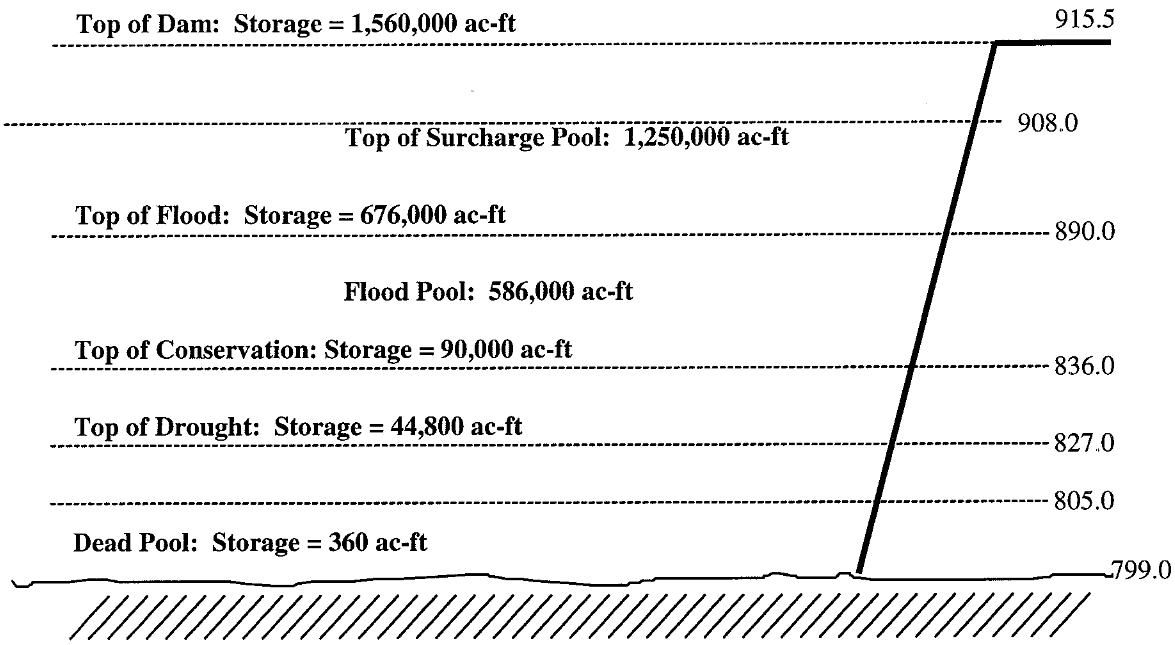

FIGURE 4-2 Saylorville Reservoir Storage Levels.
Values from 1983 Regulation Manual (1977 Survey)

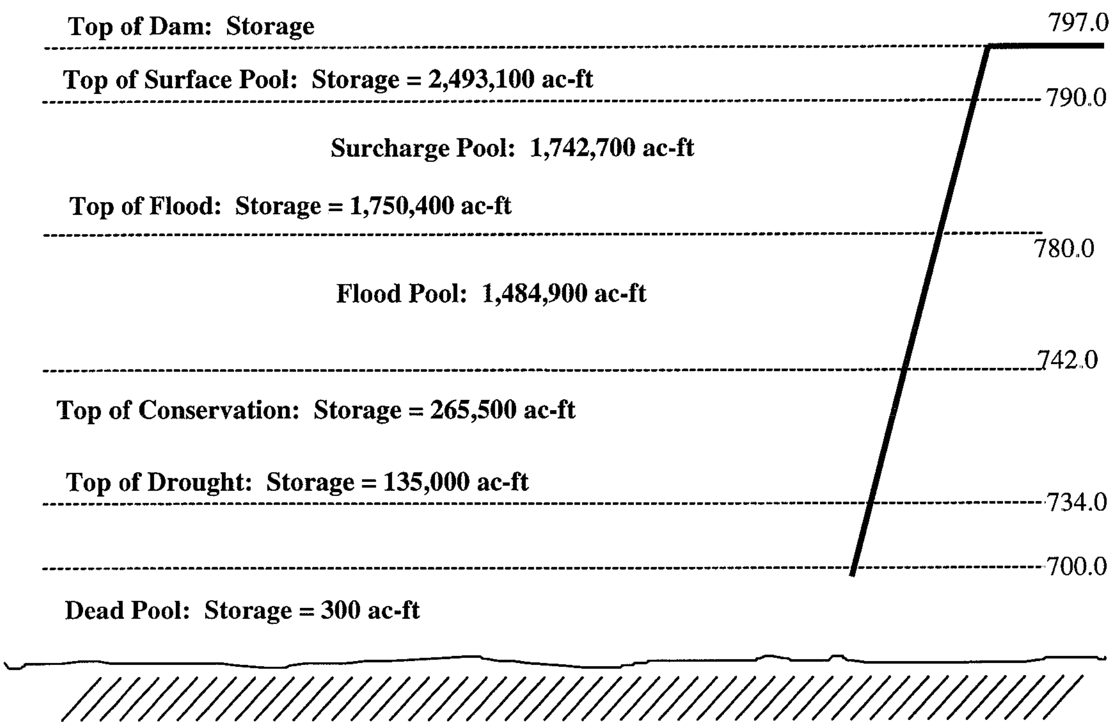

FIGURE 4-3 Lake Red Rock Storage Levels.
Values from 1988 Regulation Manual (1988 Survey)

4.1.2 Flow Values. Historical average daily incremental flow data were used as input into the model. Natural flow data (without regulation) were obtained from the Rock Island District Office for each of the U.S.G.S gages in the system. Natural flow data were then converted into incremental flows for each reach using linear routing methods (see below). Mississippi flow data were developed in a different manner due to the lack of U.S.G.S gages in the reach of interest. Flow data were obtained from the U.S.G.S gage at Clinton, Iowa, and routed downstream to the confluence with the Iowa River. The combined flows were then routed downstream, added to the flow from the unregulated Skunk River, and routed to the Des Moines Confluence. Flows were combined to give a total flow at Quincy. Plots of incremental flows for the ten flood events used in this study are included as Appendix C.

In some cases, the computed incremental flow for a given reach was negative. This could be caused by a number of circumstances including levee breaks, malfunctioning or frozen gauges, and routing discrepancies between high and low flow periods. Since FCLP is unable to use negative flow values, they were set to zero. This increased the total volume of flow for a given flood event by 2-6%.

4.1.3 Routing Parameters. The Muskingum routing method (Ponce, 1989) is used in this analysis. Attenuation and lag parameters were found by a trial and error process in which the parameters were modified until upstream routed flows closely resembled observed downstream flows. Some locations do not have routing because the lag was too short for the acceptable range of routing parameters when using a daily time-step. Reaches with routing are listed in Table 4-1.

TABLE 4-1 Routing Parameters

River	Upstream End	Downstream End	Attenuation (X)	Lag (K)
Iowa	Lone Tree	Wapello	0.3	24 hr.
Des Moines	Tracy	Ottumwa	0.3	20 hr.
Des Moines	Ottumwa	Keosauqua	0.3	24 hr.
Mississippi	Iowa River Conf.	Skunk River Conf.	0.3	18 hr.
Mississippi	Skunk River Conf.	Des Moines R. Conf.	0.3	18 hr.

4.1.4 Penalty Functions. Storage penalties were set to force the model to operate within the flood pool when feasible. This was accomplished by placing relatively large penalties on storage that did not fall in the Flood Pool. A small "persuasion" penalty was placed on storage within the flood pool so that the reservoir would drain to Top of Conservation when it would not incur economic flooding penalties. Because of the manner in which FCLP calculates total penalty, the model is sensitive to these persuasion penalties. During calibration, these persuasion penalties were modified until the model results were similar to the observed data. This resulted in minor differences in persuasion penalties for some events. An example storage penalty function is illustrated in Figure 4-4.

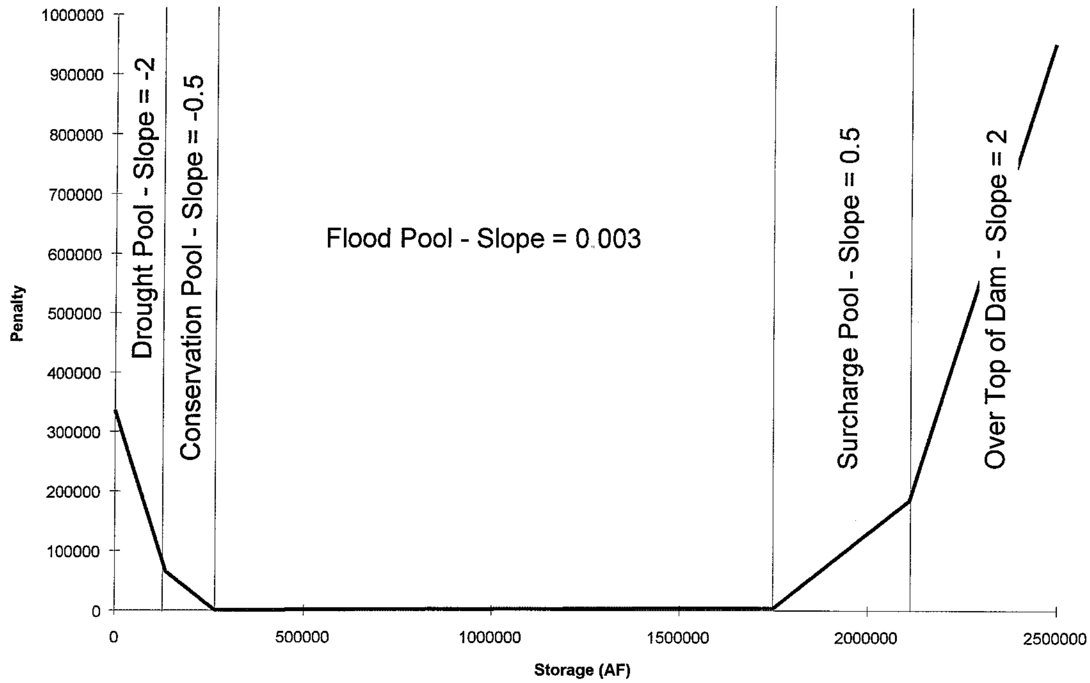

FIGURE 4-4 Storage Penalty Function for Lake Red Rock

Penalties for high flow are based on economic data found in the reservoir regulation manuals and data provided by the Rock Island District. The penalty functions used in this study represent the total damage along each reach, which is a combination of urban, rural, and agricultural damage. The damage reaches considered in the analysis are shown in Figure 4.5.

The flow-damage relationship used for each reach is intended for model-testing purposes only. These damage relationships are *not* to be construed as current or accurate. The relationships were originally developed during flood damage reduction studies, completed during past decades (1950s and 1960s in some cases). Generalized price-level indices were used to update damages to current price levels. However, changes in the characteristics of floodplain inventories (such as number, type, and value of structures) are not known.

Piecewise linear penalty functions were developed by approximating the nonlinear flow-damage relationships with straight line segments. Flow was divided into zones based on vertices of the penalty functions. For each flow zone, a unit penalty (per cfs) is assessed according to the slope of the penalty function in that zone. All penalty functions must be convex (i.e., the slope of each line segment must be greater than the preceding one) so that lower flow zones are filled before flow is added to a higher flow zone. Without this requirement, the model could add flow to an upper flow zone before a lower zone is filled, which would constitute an unrealistic and physically impossible solution. Flow penalty functions used in this study appear in Figures 4-6 through 4-9. The same penalties were used for all flood events studied

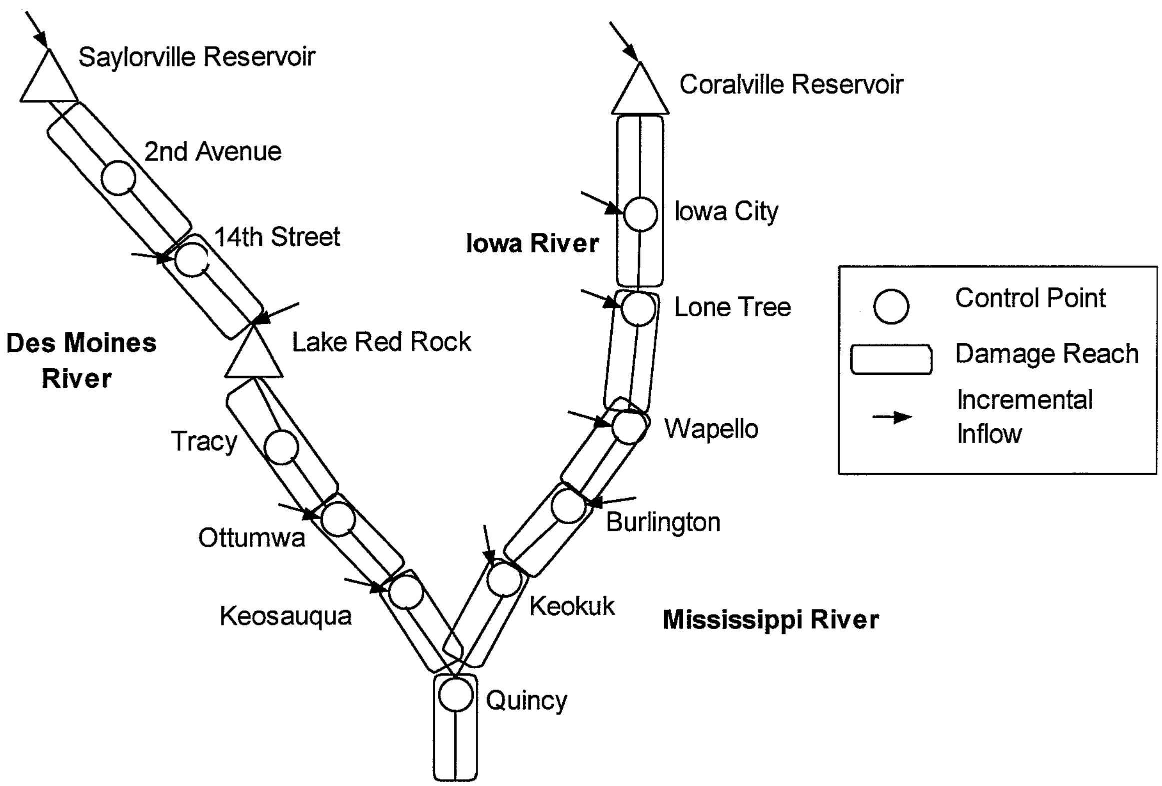

FIGURE 4-5 Damage Reaches for Flow-Damage Functions

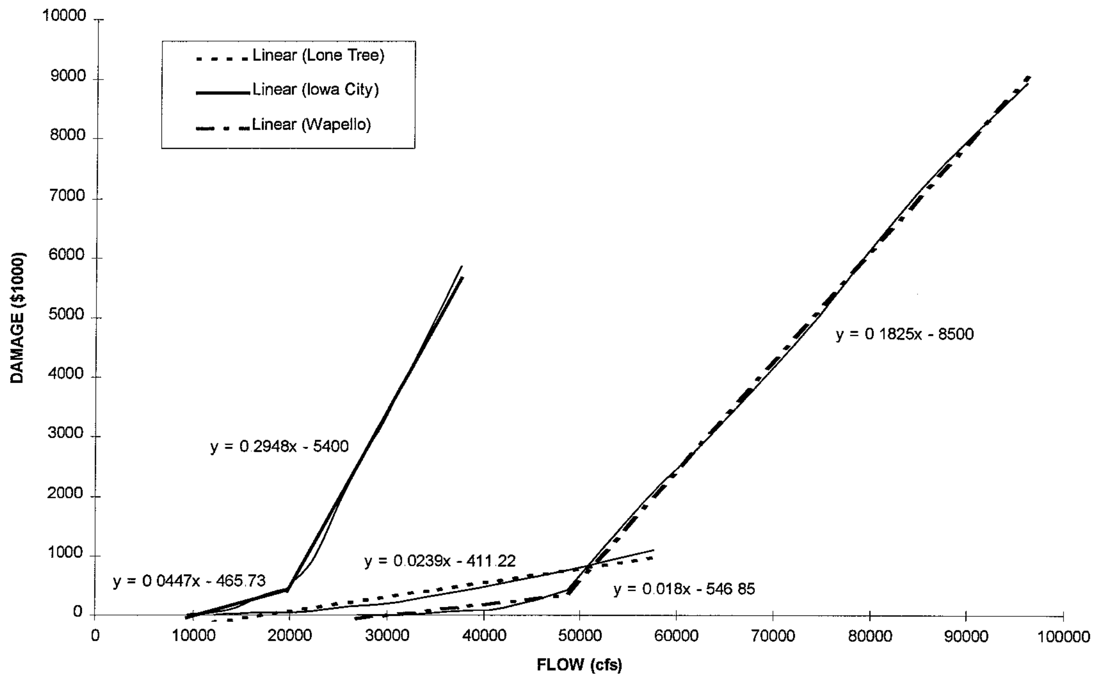

FIGURE 4-6 Iowa River Penalty Functions

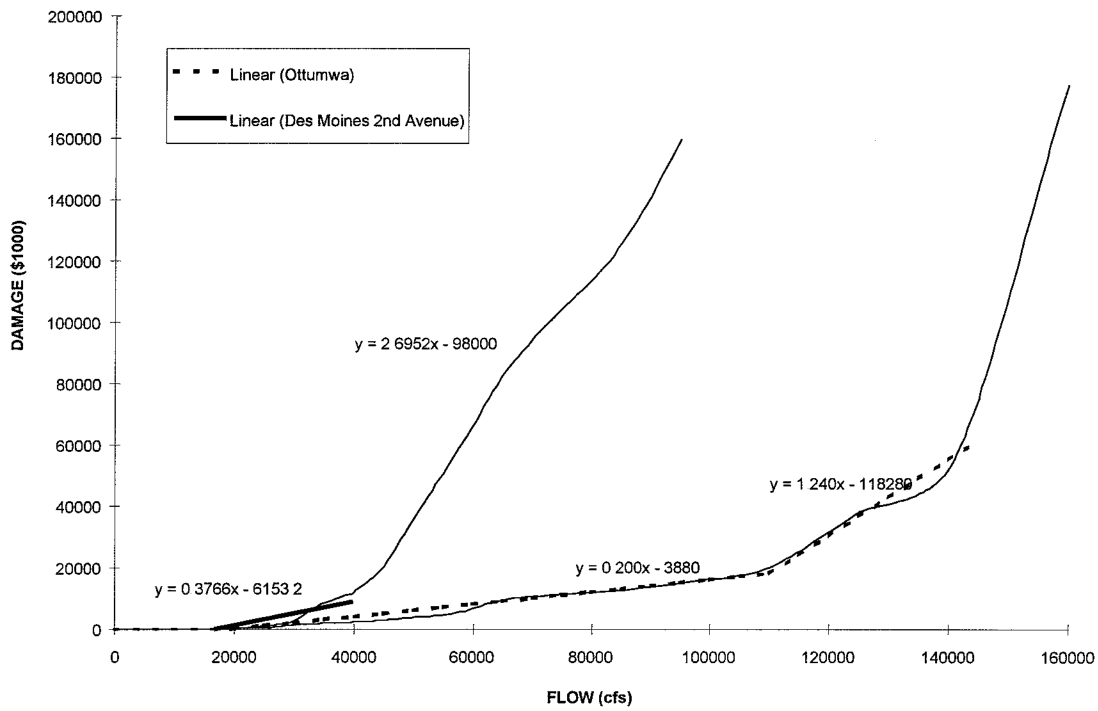

FIGURE 4-7 Des Moines River Penalty Functions

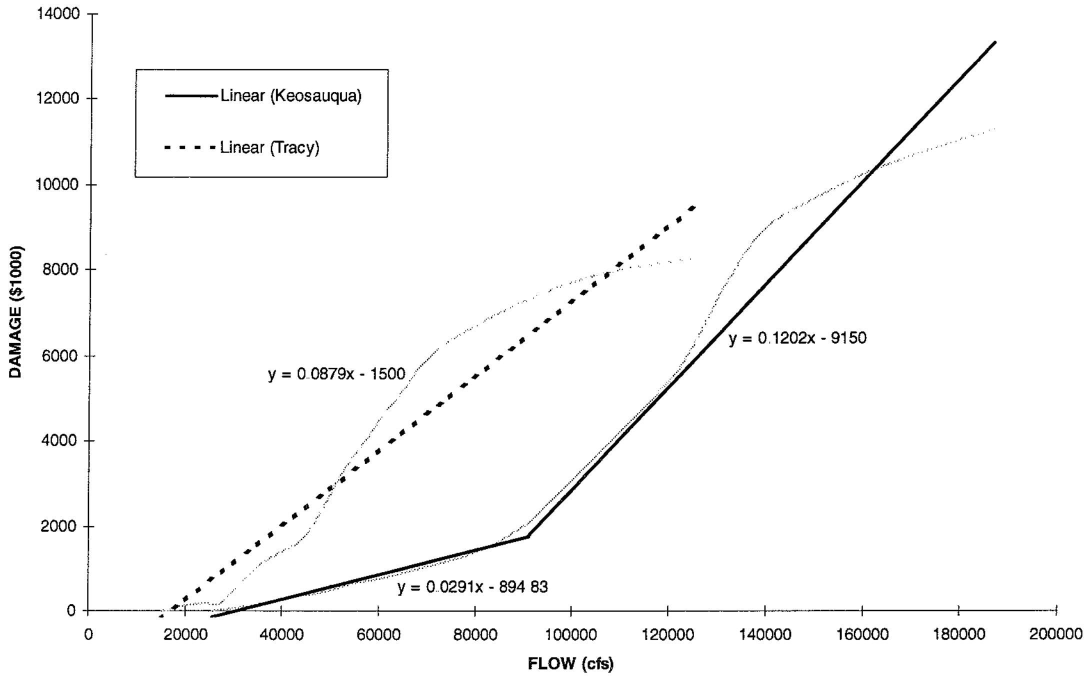

FIGURE 4-8 Des Moines River Penalty Functions

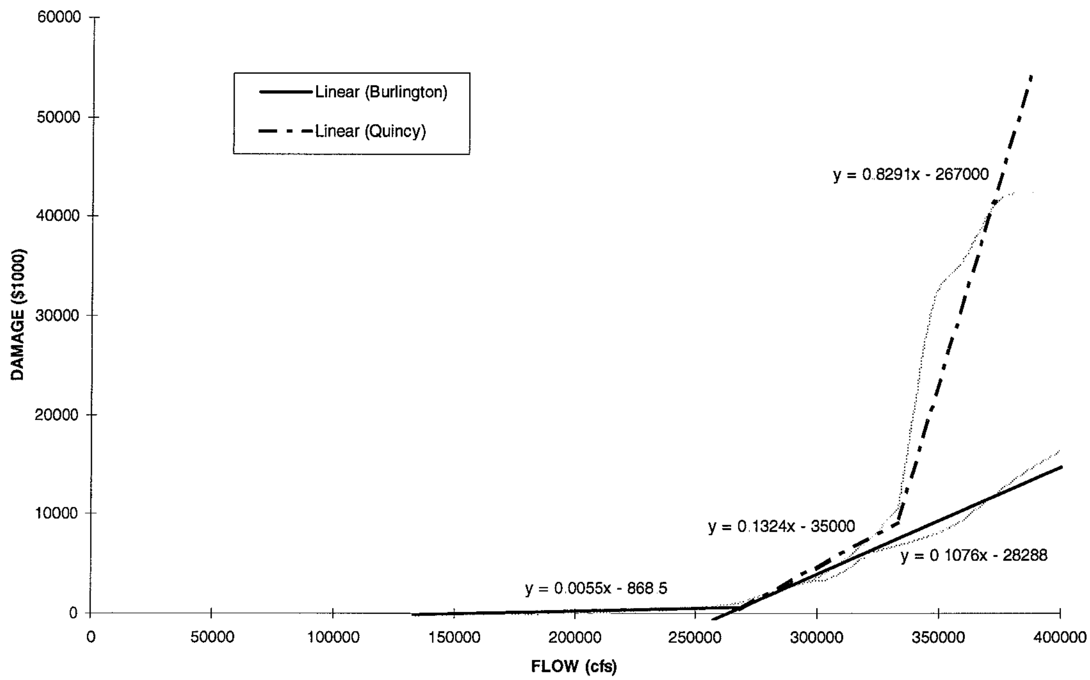

FIGURE 4-9 Mississippi River Penalty Functions

Unit penalties for excessive rates of change in release are difficult to determine. The Reservoir Regulation Manual for Saylorville states that a maximum change of 3000 cfs/day is allowable during normal flood operations. This limits bank sloughing in the reservoir and along the downstream channel. A relatively large penalty of 0.1 $/cfs for rates of change greater than 3000 cfs/day or 125 cfs/hr was set to discourage larger rates of change but still allow them when necessary. Coralville Reservoir and Lake Red Rock did not have specific values for maximum rates of change of releases in the operation manuals. Values of 125 cfs/hr for Coralville and 250 cfs/hr for Lake Red Rock were determined through discussions with the Rock Island District and comparisons with historical reservoir storage data.

4.2 Comparison of FCLP Results and Observed Data

The results from the optimization model are not identical to the observed data for many reasons. Most importantly, historical operation is never truly optimal for the objective function used in this model which, in turn, does not quantify exactly all goals of the system. It is important, however, to analyze the differences to illustrate the limitations of the model and put model results into perspective. It is also important to gain insights to improved operating policies. Plots of observed data versus model results for each event are found in Appendix D. These plots represent results from the system model with all three reservoirs included (model A). Pre-1975 results differ from observed data since Saylorville Reservoir did not go into operation until 1975. Also, there were no reservoirs on line in this system during the 1944 and 1947 flood events, so the plots for these years only illustrate the benefits that these reservoirs would have provided.

In some cases, the results of the model were practically identical to historical observed data (See Appendix D - 1990 results). Others did not match as well, but the differences can be explained. Consider the 1991 flood event, for example, which had the largest discrepancy between observed data and model results. Figures 4-10 through 4-12 show selected hydrographs for the flood event.

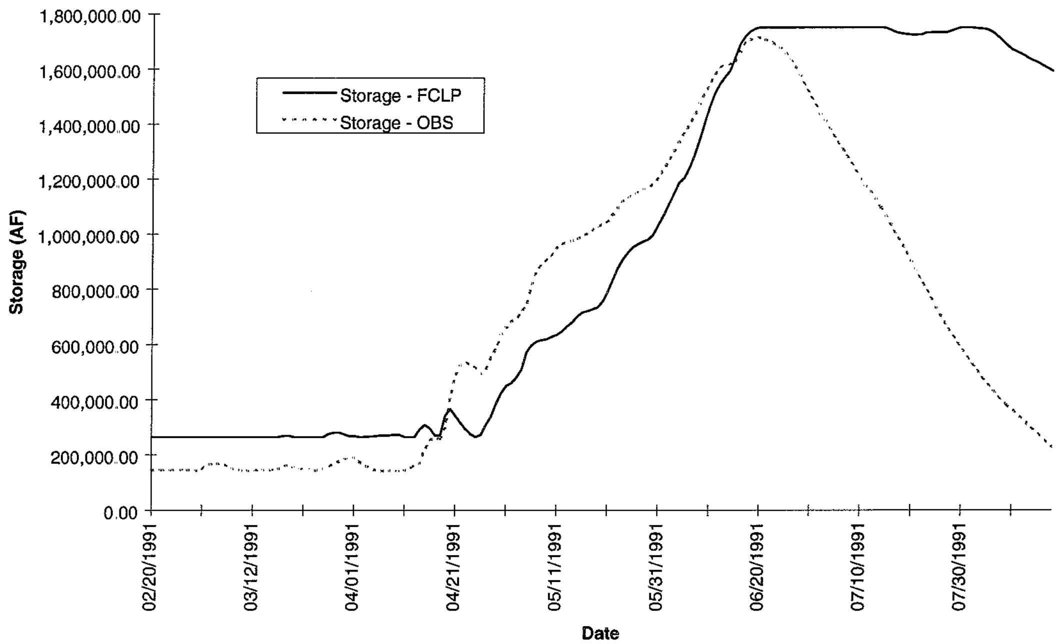

FIGURE 4-10 Lake Red Rock Storage - Flood of 1991

As seen in Figure 4-10, the model results (FCLP) closely resemble historical storage data (OBS) on the rising side of the storage curve, except for the initial storage. (All model runs used the current "top of conservation" level specified by the Reservoir Regulation Manuals for initial storage and zero-value of storage penalty function, even though the actual level has changed over the years). A more important discrepancy on the rising side of the storage plot is the offset of approximately 10 days, the result of FCLP making higher releases in anticipation of higher inflows. This causes a significant difference directly downstream of Lake Red Rock at Tracy (Figure 4-11), which resonates throughout the downstream reaches of the Des Moines River to Quincy on the Mississippi River, as seen in Figure 4-12. The observed storage at Lake Red Rock falls sooner because the operators, knowing the area had already flooded, continued making high releases. FCLP, however, continues to minimize flow-based penalties.

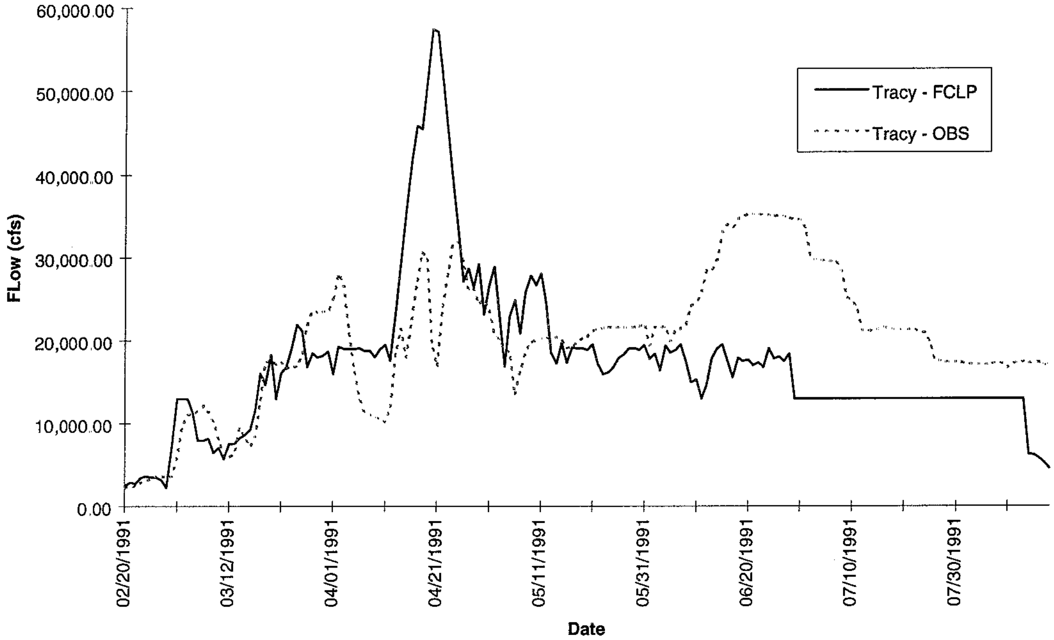

FIGURE 4-11 Hydrograph at Tracy - Flood of 1991

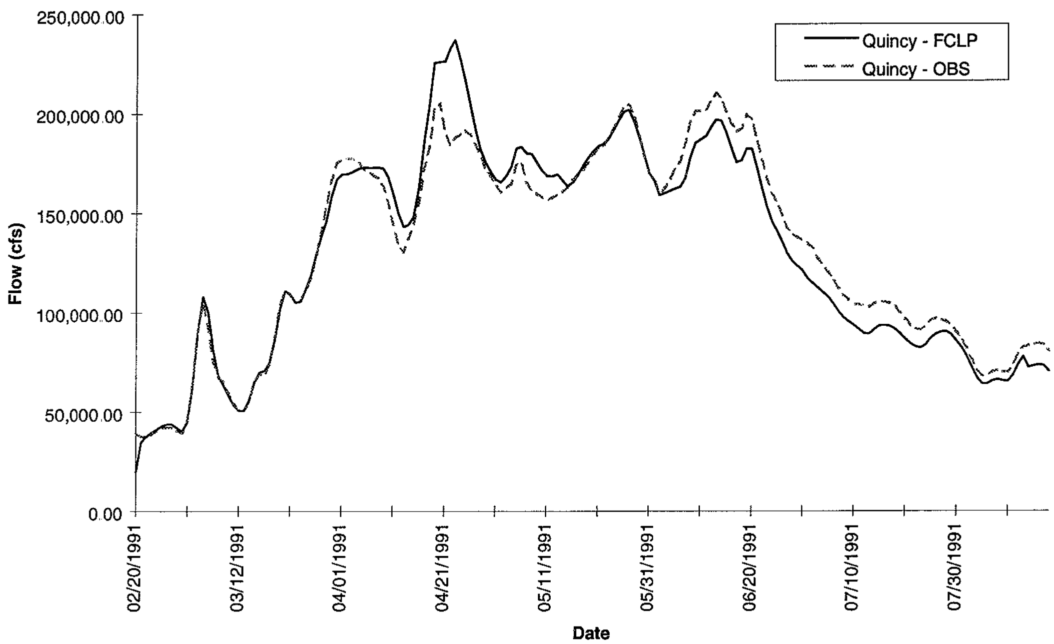

FIGURE 4-12 Hydrograph at Quincy - Flood of 1991

It should also be noted that the historical operation (OBS) of this system appears to be better than the model results (FCLP), since the observed peak flow at Quincy is almost 25,000 cfs lower than the model-computed peak flow. In this case, the model allows the high-flow, short-duration peak in late April in order to dampen the long-duration yet lower flow peak that begins in the middle of June. This behavior is an artifact of using duration-based penalty functions instead of computing penalties based on peak flows. Comparisons show that, despite the significantly larger peak flow, the system penalty computed by the model is lower than that resulting from the observed data (see results in Chapter 5 for each event). For this reason, inferences and conclusions drawn in this report will be based on the model-computed penalties. Better representation of flood damages through consideration of peak flows is recommended for future work.

Chapter 5

MODEL APPLICATION AND RESULTS FOR MAJOR FLOOD EVENTS

Tables 5-1 through 5-10 display the peak flow damages and the model-computed flow penalties for each of the seven different (sub)systems and each of the ten flood events used in this analysis. In post-optimization analysis peak flow damage was calculated by finding the maximum flow at each location for the entire event and reporting the corresponding damage from the penalty functions shown in Chapter 4. As discussed in Chapter 3, the model-computed penalty is the value of the FCLP objective function, and can be calculated by determining the damage for each day and then summing up these damages over the entire flood event. The total penalty with storage includes the summation of daily storage penalties and rate-of-change-in-release penalties. Observed damage and penalty values are computed in a similar manner. Hydrographs illustrating the results for different combinations of sub-systems appear in Appendix E.

5.1 Pre-1993 Flood Events

Results are displayed in order of magnitude, based on peak flow damage, beginning with the least severe. Refer to Figure 3-1 on page 18 for sub-system description.

Tables 5-1 and 5-2 illustrate the results from the 1944 and 1974 floods, the least severe of the ten floods studied. For both events, regulated flows on the Mississippi River at Quincy, Ill., are well below flood stage. In 1944, observed flows at Quincy were above flood stage, because the reservoirs had not yet been constructed. This is the primary reason for the large reduction in peak flow damage and model-computed penalties over the observed values in 1944. In 1974, the model determines regulated flows which lead to more modest, but still significant, reductions in damage (8.4% reduction in peak flow damage and 16.7% reduction in model-computed penalty).

Considering the different combinations of sub-systems for the 1944 and 1974 flood events, the damages incurred under each operating scheme are practically identical. Since the differences between the results with sub-system B and the results with sub-system C are negligible, there is practically no benefit from operating Coralville Reservoir for flood control on the Mississippi River for these floods. Saylorville Reservoir releases need only to control flow at the City of Des Moines, while releases from Lake Red Rock need only to control flows on the lower Des Moines River. The fact that damage results for runs with sub-systems D and G are equal to results for runs with sub-system E suggests that operation of Lake Red Rock for flood control at Quincy is unnecessary. For these smaller, more localized flood events, in which flows on the Mississippi river are well below damage levels at Quincy, a basic operating policy in which each reservoir operates only for control directly downstream appears to be the most practical.

TABLE 5-1 Flood of 1944 Calculated Penalties

Site	Peak Flow Damage ($1000)							
	Observed	***A***	***BD***	***CD***	***BE***	***CE***	***BFG***	***CFG***
Iowa City	3,430	1	1	1	1	1	1	1
Lone Tree	-	-	-	-	-	-	-	-
Wapello	1,230	182	182	182	182	182	182	182
2nd Ave.	5,165	-	-	-	-	-	-	-
14th St.	-	-	-	-	-	-	-	-
Tracy	5,051	1,179	1,179	1,179	1,179	1,179	1,179	1,179
Ottumwa	10,000	2,194	2,194	2,194	2,194	2,194	2,194	2,194
Keosauqua	1,244	561	561	561	561	561	561	561
Burlington	413	395	395	395	395	395	395	395
Quincy	5,117	-	-	-	-	-	-	-
Total	31,650	4,511	4,511	4,511	4,511	4,511	4,511	4,511

Site	Model-Computed Penalty ($1000)							
	Observed	***A***	***BD***	***CD***	***BE***	***CE***	***BFG***	***CFG***
Iowa City	13,084	1	1	1	1	1	1	1
Lone Tree	-	-	-	-	-	-	-	-
Wapello	6,848	1,374	1,374	1,511	1,374	1,511	1,374	1,511
2nd Ave.	33,591	-	-	-	-	-	-	-
14th St.	-	-	-	-	-	-	-	-
Tracy	85,360	47,097	47,097	47,097	47,097	47,097	47,097	47,097
Ottumwa	148,020	14,626	14,626	14,626	14,626	14,626	14,626	14,626
Keosauqua	15,614	1,355	1,355	1,355	1,355	1,355	1,355	1,355
Burlington	5,126	4,257	4,257	4,321	4,257	4,321	4,257	4,321
Quincy	16,446	-	-	-	-	-	-	-
Coralville		2,555	2,555	2,385	2,555	2,385	2,555	2,385
Saylorville		33,056	38,944	38,944	40,226	40,226	6,267	6,267
Red Rock		74,572	68,683	68,683	67,401	67,401	101,360	101,360
Total w/o Stor.	324,089	68,709	68,709	68,911	68,709	68,911	68,709	68,911
Total w/ Stor.		178,891	178,891	178,923	178,891	178,923	178,891	178,923

TABLE 5-2 Flood of 1974 Calculated Penalties

Site	Peak Flow Damage ($1000)							
	Observed	*A*	*BD*	*CD*	*BE*	*CE*	*BFG*	*CFG*
Iowa City	54	-	-	-	-	-	-	-
Lone Tree	314	203	203	203	203	203	203	203
Wapello	5,896	5,486	5,486	5,486	5,486	5,486	5,486	5,486
2nd Ave.	-	-	-	-	-	-	-	-
14th St.	-	-	-	-	-	-	-	-
Tracy	581	658	658	658	658	658	658	658
Ottumwa	1,440	1,368	1,368	1,368	1,368	1,368	1,368	1,368
Keosauqua	191	61	61	61	61	61	61	61
Burlington	308	272	272	277	272	277	272	277
Quincy	-	-	-	-	-	-	-	-
Total	8,784	8,048	8,048	8,052	8,048	8,052	8,048	8,052

Site	Model-Computed Penalty ($1000)							
	Observed	*A*	*BD*	*CD*	*BE*	*CE*	*BFG*	*CFG*
Iowa City	293	-	-	-	-	-	-	-
Lone Tree	694	524	524	524	524	524	524	524
Wapello	14,594	13,139	13,139	13,216	13,139	13,216	13,139	13,216
2nd Ave.	-	-	-	-	-	-	-	-
14th St.	-	-	-	-	-	-	-	-
Tracy	27,887	25,203	25,203	25,203	25,203	25,203	25,203	25,203
Ottumwa	5,600	2,039	2,039	2,039	2,039	2,039	2,039	2,039
Keosauqua	386	140	140	140	140	140	140	140
Burlington	2,236	2,023	2,023	2,048	2,023	2,048	2,023	2,048
Quincy	-	-	-	-	-	-	-	-
Coralville		4,495	4,495	4,402	4,495	4,402	4,495	4,402
Saylorville		28,224	9,114	9,114	16,608	16,608	19	19
Red Rock		38,287	57,396	57,396	49,903	49,903	66,491	66,491
Total w/o Stor.	51,690	43,067	43,067	43,169	43,067	43,169	43,067	43,169
Total w/ Stor.		114,073	114,073	114,082	114,073	114,082	114,073	114,082

Results from the next group of floods, which were slightly larger events, are illustrated in Tables 5-3 through 5-5. For these floods, 0.2–10% reductions in total model-computed penalty and 0.5-2% reductions in peak damage ($50,000 - $200,000) are obtained by operating the reservoirs on the Des Moines River in tandem as opposed to separately (e.g., compare BE and CE results with BFG and CFG results). Although a small benefit is obtained theoretically, it may be impractical for real-time operations to capture this difference. Once again, negligible differences between damage results from runs including sub-system B and sub-system C suggest that operation of Coralville Reservoir for flood control at Burlington or Quincy is unnecessary.

One important observation from Table 5-3 is that the observed peak flow damage is actually lower than the damage caused by operations from FCLP, even though the model-computed penalty is larger for the observed data. In this case, the model prefers a short-duration, higher peak flow over the long-duration, lower peak flow that was observed.

TABLE 5-3 Flood of 1979 Calculated Penalties

Site	Peak Flow Damage ($1000)							
	Observed	***A***	***BD***	***CD***	***BE***	***CE***	***BFG***	***CFG***
Iowa City	9	-	-	-	-	-	-	-
Lone Tree	91	-	-	-	-	-	-	-
Wapello	2,877	2,533	2,533	2,533	2,533	2,533	2,533	2,533
2nd Ave.	-	-	-	-	-	-	-	-
14th St.	-	-	-	-	-	-	-	-
Tracy	1,302	1,440	1,440	1,440	1,440	1,440	1,462	1,462
Ottumwa	2,720	3,979	3,979	3,979	3,979	3,979	3,979	3,979
Keosauqua	197	378	378	378	378	378	411	411
Burlington	290	275	275	275	275	275	275	275
Quincy	-	-	-	-	-	-	-	-
Total	7,486	8,606	8,606	8,606	8,606	8,606	8,660	8,660

Site	Model-Computed Penalty ($1000)							
	Observed	***A***	***BD***	***CD***	***BE***	***CE***	***BFG***	***CFG***
Iowa City	36	-	-	-	-	-	-	-
Lone Tree	91	-	-	-	-	-	-	-
Wapello	14,622	11,227	11,227	11,425	11,227	11,425	11,227	11,425
2nd Ave.	-	-	-	-	-	-	-	-
14th St.	-	-	-	-	-	-	-	-
Tracy	57,772	43,034	43,034	43,034	43,034	43,034	45,050	45,050
Ottumwa	34,080	32,938	32,938	32,938	32,938	32,938	40,674	40,674
Keosauqua	377	1,106	1,106	1,106	1,106	1,106	1,518	1,518
Burlington	7,436	7,552	7,552	7,606	7,552	7,606	7,552	7,606
Quincy	-	-	-	-	-	-	-	-
Coralville		4,680	4,680	4,440	4,680	4,440	4,680	4,440
Saylorville		42,559	45,241	60,445	45,821	45,821	8,905	8,905
Red Rock		103,560	100,878	85,674	100,299	100,299	141,591	141,591
Total w/o Stor.	114,414	95,856	95,856	96,108	95,856	96,108	106,021	106,273
Total w/ Stor.		246,656	246,656	246,668	246,656	246,668	261,197	261,209

TABLE 5-4 Flood of 1990 Calculated Penalties

Site	Peak Flow Damage ($1000)							
	Observed	*A*	*BD*	*CD*	*BE*	*CE*	*BFG*	*CFG*
Iowa City	23	-	-	-	-	-	-	-
Lone Tree	194	237	237	237	237	237	237	237
Wapello	5,366	5,532	5,532	5,522	5,532	5,522	5,532	5,522
2nd Ave.	-	-	-	-	-	-	-	-
14th St.	-	-	-	-	-	-	-	-
Tracy	889	680	680	680	680	680	693	693
Ottumwa	1,780	2,009	2,009	2,009	2,009	2,009	2,009	2,009
Keosauqua	473	482	482	482	482	482	547	547
Burlington	175	164	164	164	164	164	164	164
Quincy	-	-	-	-	-	-	-	-
Total	8,900	9,104	9,104	9,093	9,104	9,093	9,181	9,171

Site	Model-Computed Penalty ($1000)							
	Observed	*A*	*BD*	*CD*	*BE*	*CE*	*BFG*	*CFG*
Iowa City	23	-	-	-	-	-	-	-
Lone Tree	490	459	459	459	459	459	459	459
Wapello	21,561	19,225	19,225	19,209	19,225	19,209	19,225	19,209
2nd Ave.	-	-	-	-	-	-	-	-
14th St.	-	-	-	-	-	-	-	-
Tracy	42,082	27,102	27,102	27,102	27,102	27,102	27,295	27,295
Ottumwa	32,720	4,248	4,248	4,248	4,248	4,248	4,317	4,317
Keosauqua	1,902	1,079	1,079	1,079	1,079	1,079	1,162	1,162
Burlington	1,184	1,114	1,114	1,163	1,114	1,163	1,114	1,163
Quincy	-	-	-	-	-	-	-	-
Coralville		2,506	2,506	2,492	2,506	2,492	2,506	2,492
Saylorville		30,926	40,792	40,792	33,839	33,839	1,555	1,555
Red Rock		78,566	68,700	68,700	75,653	75,653	107,974	107,974
Total w/o Stor.	99,962	53,226	53,226	53,259	53,226	53,259	53,570	53,604
Total w/ Stor.		165,223	165,223	165,242	165,223	165,242	165,605	165,625

TABLE 5-5 Flood of 1960 Calculated Penalties

Site	Peak Flow Damage ($1000)							
	Observed	*A*	*BD*	*CD*	*BE*	*CE*	*BFG*	*CFG*
Iowa City	-	-	-	-	-	-	-	-
Lone Tree	235	30	30	30	30	30	30	30
Wapello	3,700	4,152	4,161	4,162	4,161	4,162	4,161	4,162
2nd Ave.	6,032	-	-	-	-	-	-	-
14th St.	-	-	-	-	-	-	-	-
Tracy	5,298	1,335	1,337	1,337	1,332	1,332	1,333	1,333
Ottumwa	10,220	3,406	3,168	3,168	3,047	3,047	3,364	3,364
Keosauqua	1,311	940	940	940	940	940	973	973
Burlington	319	302	303	304	303	304	303	304
Quincy	7,219	-	90	90	792	792	90	90
Total	34,334	10,164	10,028	10,030	10,604	10,606	10,254	10,256

Site	Model-Computed Penalty ($1000)							
	Observed	*A*	*BD*	*CD*	*BE*	*CE*	*BFG*	*CFG*
Iowa City	-	-	-	-	-	-	-	-
Lone Tree	434	53	53	53	53	53	53	53
Wapello	16,521	13,991	14,164	14,221	14,164	14,221	14,164	14,221
2nd Ave.	16,060	-	-	-	-	-	-	-
14th St.	-	-	-	-	-	-	-	-
Tracy	62,982	37,129	36,949	36,949	37,160	37,160	37,090	37,090
Ottumwa	124,860	27,158	26,119	26,119	27,234	27,234	26,679	26,679
Keosauqua	14,541	3,801	3,691	3,691	3,614	3,614	3,815	3,815
Burlington	3,003	3,050	3,074	3,095	3,074	3,095	3,074	3,095
Quincy	24,494	-	90	90	1,076	1,076	90	90
Coralville		4,192	3,956	3,887	3,956	3,887	3,956	3,887
Saylorville		37,603	36,902	36,902	44,032	44,032	2,344	2,344
Red Rock		37,258	39,327	39,327	30,769	30,769	73,918	73,918
Total w/o Stor.	262,895	85,183	84,141	84,218	86,375	86,453	84,965	85,042
Total w/ Stor.		164,236	164,325	164,333	165,132	165,140	165,183	165,191

As illustrated in Table 5-6, the flood of 1991 is another, more severe, case in which the FCLP model operations cause a larger peak flow damage than did actual operations. This occurs even though the model-computed penalty is significantly smaller (30.5%) for the model operations. As in the case of the 1973 flood, the model prefers a short-duration, high-flow peak to a long-duration, lower flow peak on the Des Moines River below Lake Red Rock. However, the model does prevent damage at the 2nd Avenue control point. On the Iowa River, the peak flow damages and the model-computed penalties are lower than the observed values at all control points.

Similar to the floods previously discussed, the total peak damages resulting from the different operating schemes for the flood of 1991 are within 2% of each other. However, the model-computed penalties for schemes BFG and CFG are 12.5% higher than the others, indicating that benefits could potentially be gained by operating Saylorville and Red Rock in a coordinated manner for flood control on the Des Moines River.

TABLE 5-6 Flood of 1991 Calculated Penalties

Site	Peak Flow Damage ($1000)							
	Observed	*A*	*BD*	*CD*	*BE*	*CE*	*BFG*	*CFG*
Iowa City	135	-	-	-	-	-	-	-
Lone Tree	-	-	-	-	-	-	-	-
Wapello	443	325	325	333	325	333	325	333
2nd Ave.	2,021	-	-	-	-	-	-	-
14th St.	-	-	-	-	-	-	-	-
Tracy	1,954	3,914	3,914	3,914	3,914	3,914	4,137	4,137
Ottumwa	3,260	9,996	9,996	9,996	9,996	9,996	9,500	9,500
Keosauqua	403	1,117	1,117	1,117	1,117	1,117	1,053	1,053
Burlington	131	137	137	137	137	137	137	137
Quincy	-	-	-	-	-	-	-	-
Total	8,347	15,489	15,489	15,496	15,489	15,496	15,153	15,160

Site	Model-Computed Penalty ($1000)							
	Observed	*A*	*BD*	*CD*	*BE*	*CE*	*BFG*	*CFG*
Iowa City	2,282	-	-	-	-	-	-	-
Lone Tree	-	-	-	-	-	-	-	-
Wapello	3,966	3,829	3,829	3,933	3,829	3,933	3,829	3,933
2nd Ave.	15,387	-	-	-	-	-	-	-
14th St.	-	-	-	-	-	-	-	-
Tracy	124,300	83,918	83,918	83,918	83,918	83,918	102,417	102,417
Ottumwa	135,960	102,492	102,492	102,492	102,492	102,492	135,726	135,726
Keosauqua	3,474	7,565	7,565	7,565	7,565	7,565	9,995	9,995
Burlington	1,767	1,717	1,717	1,866	1,717	1,866	1,717	1,866
Quincy	-	-	-	-	-	-	-	-
Coralville		2,350	2,350	2,169	2,350	2,169	2,350	2,169
Saylorville		16,421	16,391	16,391	15,751	15,751	10,484	10,484
Red Rock		50,921	50,951	50,951	51,591	51,591	40,946	40,946
Total w/o Stor.	287,136	199,520	199,520	199,774	199,520	199,774	253,684	253,938
Total w/ Stor.		269,212	269,212	269,285	269,212	269,285	307,463	307,537

For the next largest event, the flood of 1973, substantial benefits are obtained by operating the reservoirs on the Des Moines River in tandem. As shown in Table 5-7, there is more than a 20% reduction in peak flow damage and a 34% reduction in model-computed flow penalty. The fact that the total model-computed penalties (i.e., including the storage penalties) are nearly the same for all operational schemes results from the "myopic" operations of Saylorville Reservoir and Lake Red Rock under the BFG and CFG schemes. Since sub-system F does not consider flooding below Lake Red Rock, the model essentially passes inflows to Saylorville Reservoir in order to minimize its storage penalty. In turn, the model chooses to make larger, earlier releases from Lake Red Rock—resulting in higher flow penalties downstream—in order to keep its storage penalty low. Aside from the BFG and CFG schemes, the peak flow damages and model-computed penalties are all within 1% of each other. This indicates that, given the 1973 event, coordinated operations for flows on the Mississippi River are not necessary.

TABLE 5-7 Flood of 1973 Calculated Penalties

Site	Peak Flow Damage ($1000)							
	Observed	*A*	*BD*	*CD*	*BE*	*CE*	*BFG*	*CFG*
Iowa City	36	-	-	-	-	-	-	-
Lone Tree	43	34	34	34	34	34	34	34
Wapello	6,866	6,679	6,681	6,681	6,681	6,681	6,681	6,681
2^{nd} Ave.	15,851	-	-	-	-	-	-	-
14^{th} St.	-	-	-	-	-	-	-	-
Tracy	1,382	1,364	1,364	1,364	1,366	1,366	2,866	2,866
Ottumwa	2,520	2,103	2,103	2,103	2,040	2,040	5,545	5,545
Keosauqua	844	654	654	654	654	654	654	654
Burlington	601	596	596	596	596	596	596	596
Quincy	12,290	6,818	6,825	6,825	6,902	6,902	6,850	6,850
Total	40,433	18,249	18,257	18,257	18,274	18,274	23,226	23,226

Site	Model-Computed Penalty ($1000)							
	Observed	*A*	*BD*	*CD*	*BE*	*CE*	*BFG*	*CFG*
Iowa City	167	-	-	-	-	-	-	-
Lone Tree	79	34	34	34	34	34	34	34
Wapello	23,394	21,392	21,329	21,990	21,329	21,990	21,329	21,990
2^{nd} Ave.	40,017	-	-	-	-	-	-	-
14^{th} St.	-	-	-	-	-	-	-	-
Tracy	89,487	57,897	57,872	57,872	57,767	57,767	79,158	79,158
Ottumwa	80,720	26,579	26,579	26,579	26,335	26,335	76,168	76,168
Keosauqua	6,223	3,065	3,065	3,065	3,059	3,059	7,293	7,293
Burlington	13,929	14,057	14,125	14,376	14,125	14,376	14,125	14,376
Quincy	30,173	18,859	19,559	19,693	19,853	19,988	19,805	19,998
Coralville		4,321	4,149	3,332	4,149	3,332	4,149	3,332
Saylorville		52,032	54,300	62,109	53,096	53,096	2,515	2,515
Red Rock		192,294	190,009	182,200	191,467	191,467	167,791	167,805
Total w/o Stor.	284,189	141,884	142,563	143,610	142,504	143,550	217,913	219,018
Total w/ Stor.		390,530	391,021	391,250	291,216	291,445	392,368	392,670

Table 5-8 illustrates the results from the flood of 1947. Although this flood has the third largest observed peak flow damage, model results are similar to those for the smaller floods due to the relatively short duration of the event. Furthermore, the majority of damaging flows during the flood of 1947 occur downstream of Lake Red Rock, which limits the capability of the reservoirs to reduce flood damage. As a result, the operation scheme used does not significantly alter the results for this type event.

As with the 1944 event, the fact that none of the reservoirs were in operation during the 1947 flood event explains why the observed peak flow damages and model-computed penalties are more than twice the values from the model results. These results are a good illustration of the impact the three reservoirs have on flood damage reduction.

TABLE 5-8 Flood of 1947 Calculated Penalties

Site	Peak Flow Damage ($1000)							
	Observed	***A***	***BD***	***CD***	***BE***	***CE***	***BFG***	***CFG***
Iowa City	4,167	324	324	324	324	324	324	324
Lone Tree	-	-	-	-	-	-	-	-
Wapello	8,367	3,549	3,549	3,549	3,549	3,549	3,549	3,549
2nd Ave.	7,465	-	-	-	-	-	-	-
14th St.	-	-	-	-	-	-	-	-
Tracy	10,824	4,121	4,121	4,121	4,121	4,121	4,028	4,028
Ottumwa	37,960	11,362	11,362	11,362	11,362	11,362	11,362	11,362
Keosauqua	4,798	1,231	1,231	1,231	1,231	1,231	1,243	1,243
Burlington	45	-	-	-	-	-	-	-
Quincy	-	-	-	-	-	-	-	-
Total	73,626	20,586	20,586	20,586	20,586	20,586	20,505	20,505

Site	Model-Computed Penalty ($1000)							
	Observed	***A***	***BD***	***CD***	***BE***	***CE***	***BFG***	***CFG***
Iowa City	21,225	2,572	2,572	2,572	2,572	2,572	2,572	2,572
Lone Tree	-	-	-	-	-	-	-	-
Wapello	41,543	11,812	11,812	11,812	11,812	11,812	11,812	11,812
2nd Ave.	24,957	-	-	-	-	-	-	-
14th St.	-	-	-	-	-	-	-	-
Tracy	120,833	75,563	75,563	75,563	75,563	75,563	77,022	77,022
Ottumwa	265,720	116,385	116,385	116,385	116,385	116,385	119,702	119,702
Keosauqua	34,094	14,275	14,275	14,275	14,275	14,275	14,730	14,730
Burlington	45	-	-	-	-	-	-	-
Quincy	-	-	-	-	-	-	-	-
Coralville		4,706	4,706	4,706	4,706	4,706	4,706	4,706
Saylorville		25,322	26,195	26,195	26,718	26,718	6,993	6,993
Red Rock		75,025	74,152	74,152	73,629	73,629	90,416	90,416
Total w/o Stor.	508,417	220,607	220,607	220,607	220,607	220,607	225,837	225,837
Total w/ Stor.		325,660	325,660	325,660	325,660	325,660	327,952	327,952

The second largest flood on record occurred in 1965. As illustrated in Table 5-9, operating Lake Red Rock for flood control at Quincy, Ill., reduces peak flow damage by nearly 33% and model-computed penalty by nearly 10%. In terms of peak flow damage, approximately $0.8 million is saved by operating the reservoirs on the Des Moines River in tandem, while operating Coralville Reservoir for flood control at Burlington reduces the damage by another $0.2 million. Even though the $1 million savings is only 3% of the total peak flow damage, this may still be considered an appreciable benefit. The large difference in model results and the observed damage and penalty values is due to the reservoirs on the Des Moines River not being in place in 1965.

At this point, a caveat is needed regarding the interpretation of model results. In several of the tables presented above (especially Tables 5-1 through 5-5), the sum of Saylorville and Red Rock storage penalties are essentially the same for the various operating schemes, even though the individual values may be quite different. For example, as shown in Table 5-3, Saylorville and Red Rock storage penalties for scheme A are 42,559 and 103,560, respectively, for a sum of 146,119. For scheme BD, the values are 45,241 and 100,878, while for scheme CD they are 60,445 and 85,674, both of which also sum to 146,119. This is an indication of the existence of multiple optimal solutions, arising from the fact that the same penalty coefficients were used for storage in the various zones of Saylorville Reservoir and Lake Red Rock (e.g., storage in the conservation zone of each reservoir was valued at \$0.12/ac-ft/day). The intent of using the same penalty coefficients for each reservoir was to promote balanced use of each for flood control, according to the reservoir regulation manuals. However, this leads to multiple optimal solutions whenever the model is indifferent between holding water in Saylorville and releasing it for storage in Red Rock. Such indifference occurs during any period in which the two reservoirs are operating in the same storage zone and increasing the release from Saylorville does not cause flooding at control points between the two reservoirs. If multiple optimal solutions are considered a problem, then a slight preference should be indicated for storage in one of the reservoirs.

TABLE 5-9 Flood of 1965 Calculated Penalties

	Peak Flow Damage (\$1000)							
Site	***Observed***	***A***	***BD***	***CD***	***BE***	***CE***	***BFG***	***CFG***
Iowa City	-	99	-	-	-	-	-	-
Lone Tree	74	-	-	60	-	60	-	60
Wapello	4,322	3,929	3,929	3,927	3,929	3,927	3,929	3,927
2nd Ave.	26,901	298	298	298	298	298	297	297
14th St.	-	-	-	-	-	-	-	-
Tracy	5,570	1,406	1,406	1,406	1,083	1,083	1,543	1,543
Ottumwa	11,640	1,961	1,961	1,961	1,521	1,521	2,635	2,635
Keosauqua	1,485	281	281	281	216	216	229	229
Burlington	8,415	8,316	8,316	8,509	8,316	8,509	8,316	8,509
Quincy	32,907	14,495	14,524	14,524	29,646	29,646	14,506	14,506
Total	91,324	30,786	30,714	30,965	45,009	45,259	31,455	31,706

	Model-Computed Penalty (\$1000)							
Site	***Observed***	***A***	***BD***	***CD***	***BE***	***CE***	***BFG***	***CFG***
Iowa City	-	320	-	-	-	-	-	-
Lone Tree	79	-	-	76	-	76	-	76
Wapello	23,601	18,900	18,699	18,219	18,699	18,219	18,699	18,219
2nd Ave.	142,433	611	611	611	611	611	601	601
14th St.	-	-	-	-	-	-	-	-
Tracy	81,567	47,227	47,227	47,227	46,252	46,252	48,357	48,357
Ottumwa	128,540	12,399	12,399	12,399	8,041	8,041	15,171	15,171
Keosauqua	14,428	626	626	626	476	476	749	749
Burlington	63,693	61,157	61,383	69,995	61,383	69,995	61,383	69,995
Quincy	180,020	90,411	93,733	93,733	149,324	149,324	93,360	93,360
Coralville		3,846	3,742	2,845	3,742	2,845	3,742	2,845
Saylorville		49,408	33,105	33,105	48,986	48,986	19,111	19,111
Red Rock		66,046	82,349	82,349	55,540	55,540	94,100	94,100
Total w/o Stor.	634,361	231,650	234,678	242,885	284,788	292,996	238,321	246,528
Total w/ Stor.		350,950	353,873	361,184	393,055	400,366	355,274	362,584

5.2 1993 Flood Event

The flood of 1993 is considered the most important event in this study because of its record peak flows and duration. Lasting from February to November—requiring 282 daily time steps in the optimization model—this event also provided the greatest test for the FCLP model. In fact, due to numerical instabilities in the matrix computations, the 1993 model could not be solved using the XMP solver. However, the model could be solved in a relatively short time using IBM/OSL (run times on a 200 Mhz Pentium PC ranged from 3 to 10 minutes, depending on the solver options selected).

Figures 5-1 through 5-10 illustrate the results from the FCLP model, compared with observed data during the flood of 1993. (Similar plots for the other nine events are included in Appendix D). The first notable difference is illustrated in Figure 5-1. In contrast to observed operations, which could not benefit from perfect foresight, FCLP operates Coralville Reservoir in order to prevent spills which lead to large storage and flow penalties. The model does this by making higher releases from mid-May to mid-June, in advance of extremely high inflows. As shown in Figure 5-2, this leads to higher flows at Iowa City from April through June, but lower flows during July and August. Figures 5-3 through 5-5 show that peak flows on the Iowa River downstream of Iowa City and at Burlington, IA, on the Mississippi River are not affected much by Coralville operations.

As shown in Figures 5-6 through 5-8, observed Saylorville storage levels and downstream flows are similar to those determined by FCLP. The second notable differences between observed and FCLP results is primarily related to Lake Red Rock operations for flood control at Quincy. As seen in Figure 5-9, Lake Red Rock maintains a low storage level until the beginning of July, at which time its releases are cut back (see Figures 5-10 and 5-11) and its flood control pool rapidly fills. As illustrated in Figures 5-10 through 5-12, this results in lower peak flows downstream on the Des Moines River and at Quincy on the Mississippi River. Considering the model-computed penalty, the greatest benefit is seen at Quincy, where high-penalty flows are reduced for a two-week period in July.

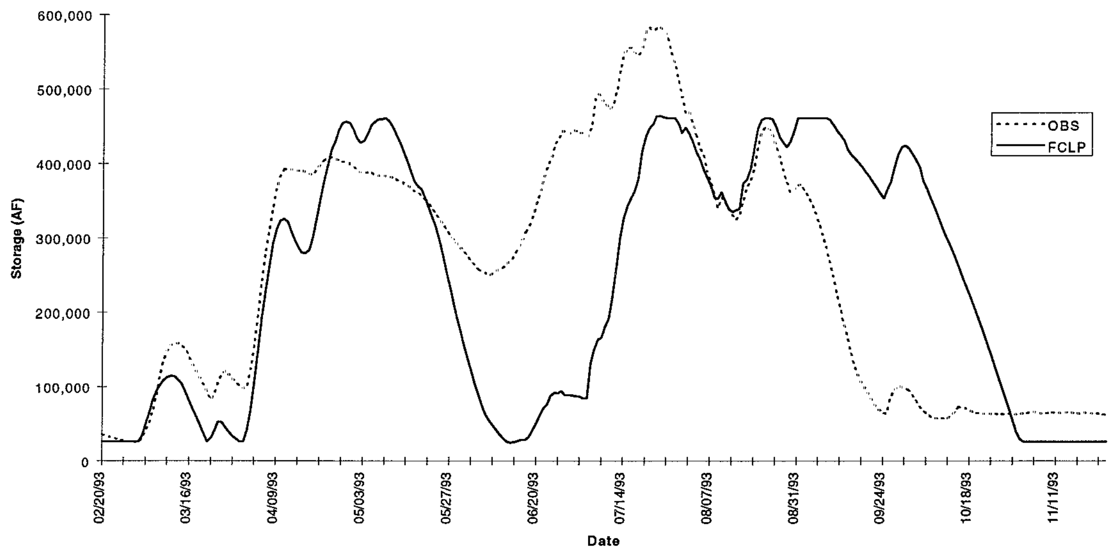

FIGURE 5-1 Coralville Reservoir Storage - Flood of 1993

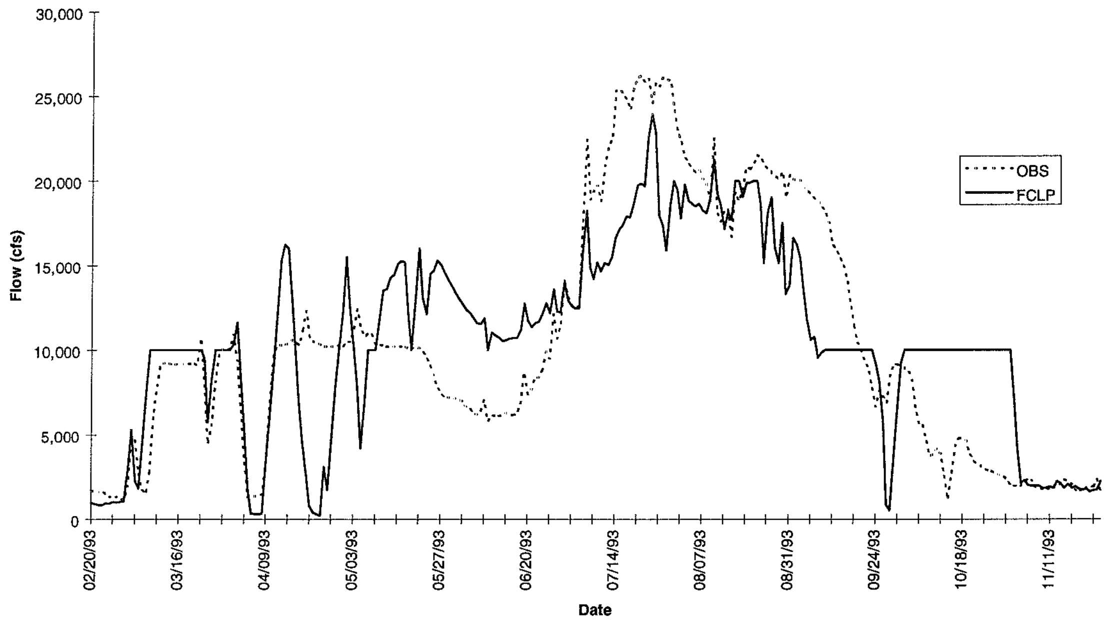

FIGURE 5-2 Iowa City Hydrograph - Flood of 1993

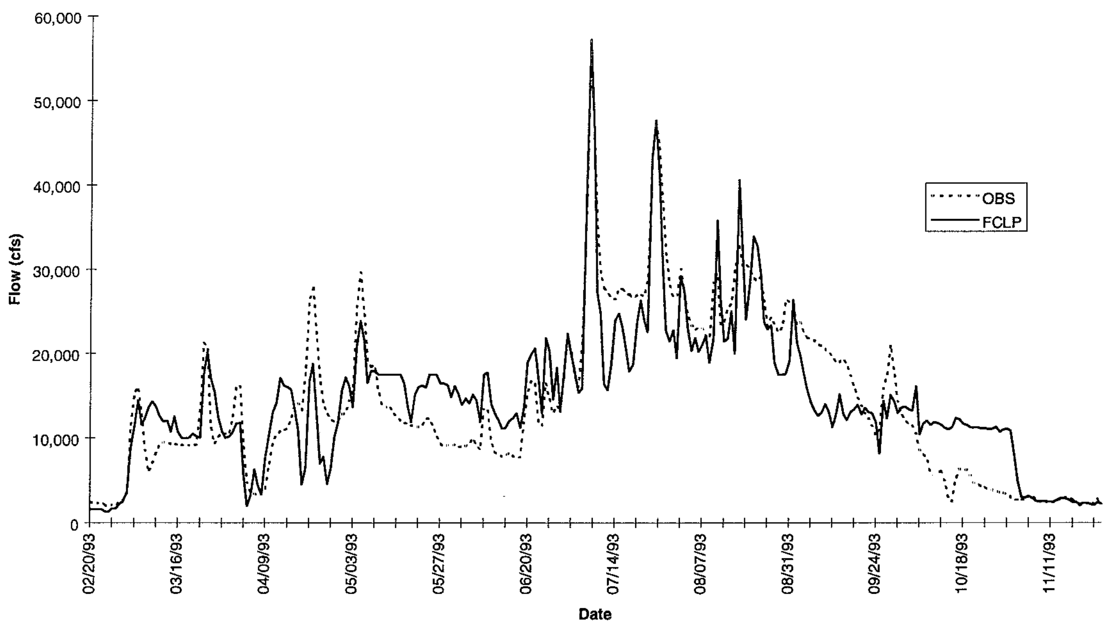

FIGURE 5-3 Lone Tree Hydrograph - Flood of 1993

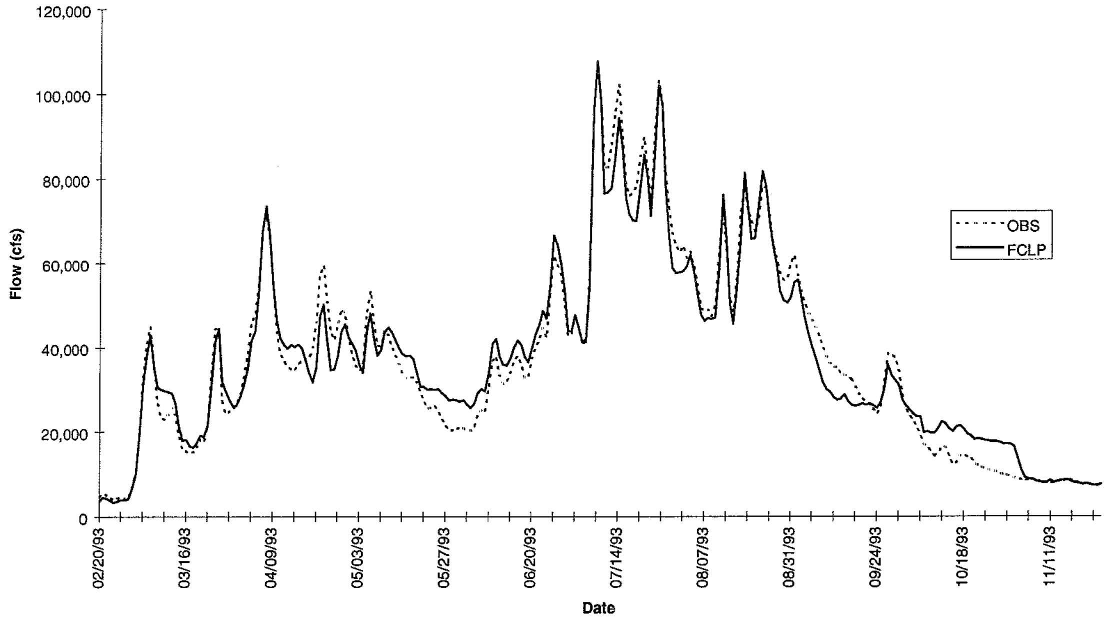

FIGURE 5-4 Wapello Hydrograph - Flood of 1993

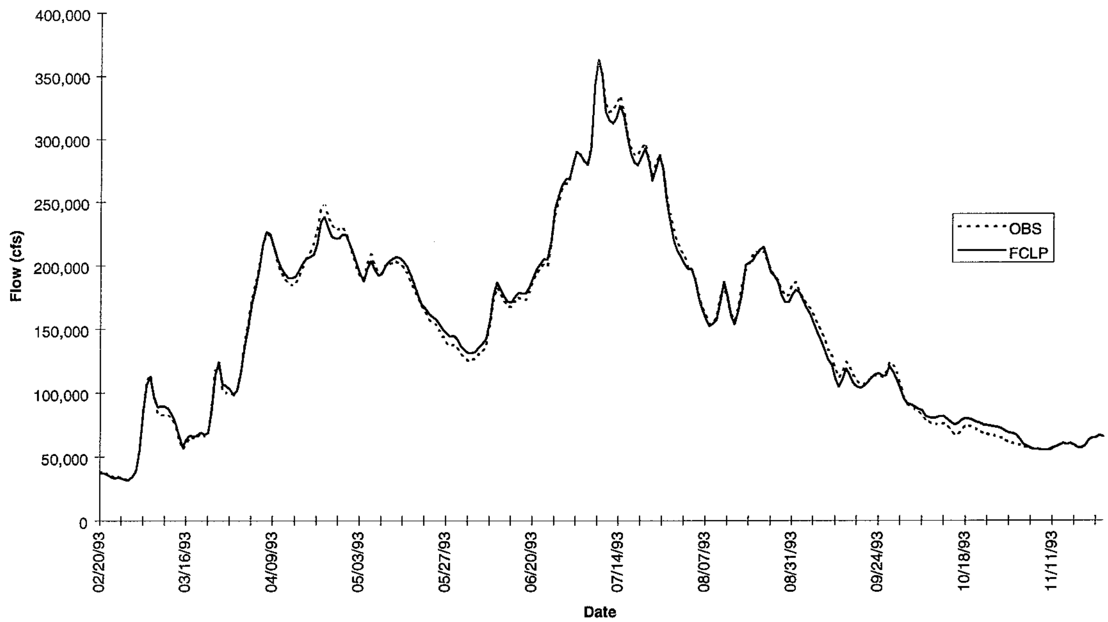

FIGURE 5-5 Burlington Hydrograph - Flood of 1993

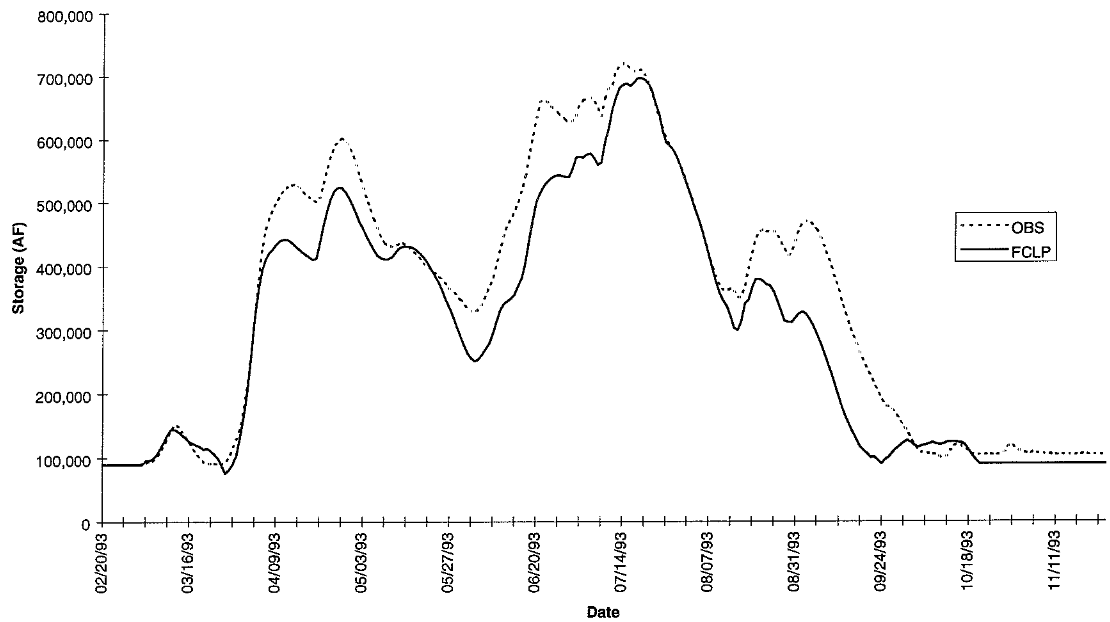

FIGURE 5-6 Saylorville Reservoir Storage - Flood of 1993

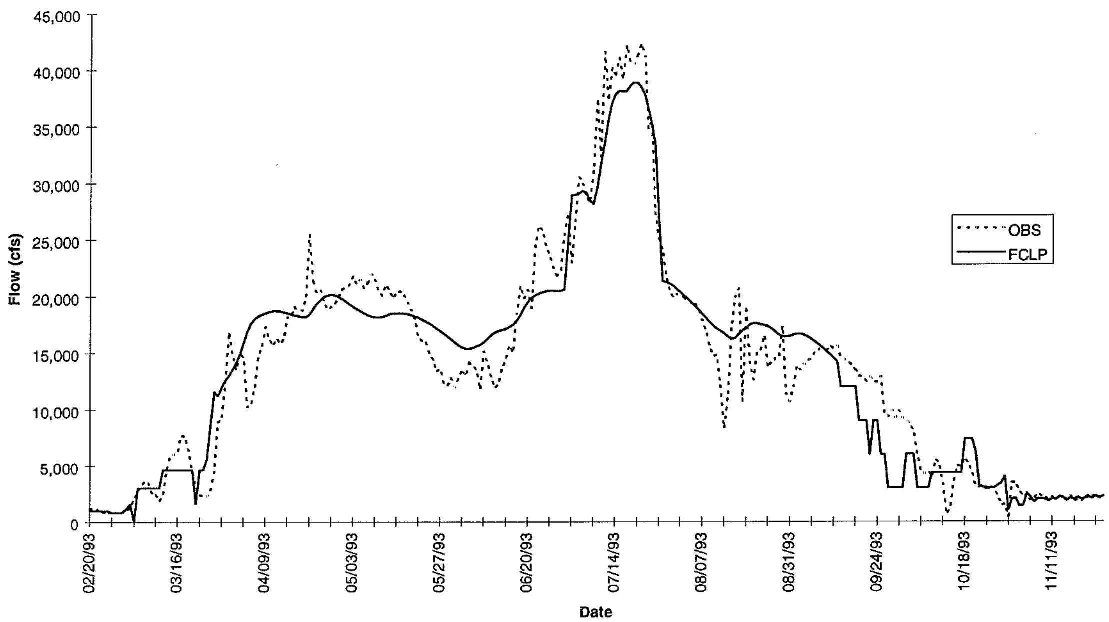

FIGURE 5-7 Des Moines 2nd Avenue Hydrograph - Flood of 1993

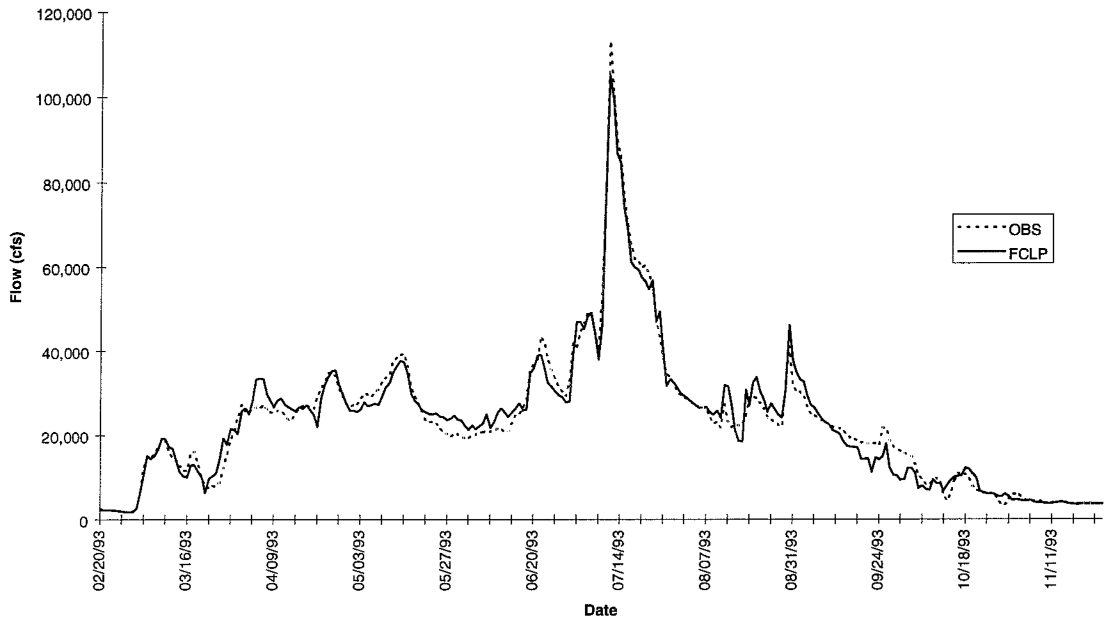

FIGURE 5-8 Des Moines 14th Street Hydrograph - Flood of 1993

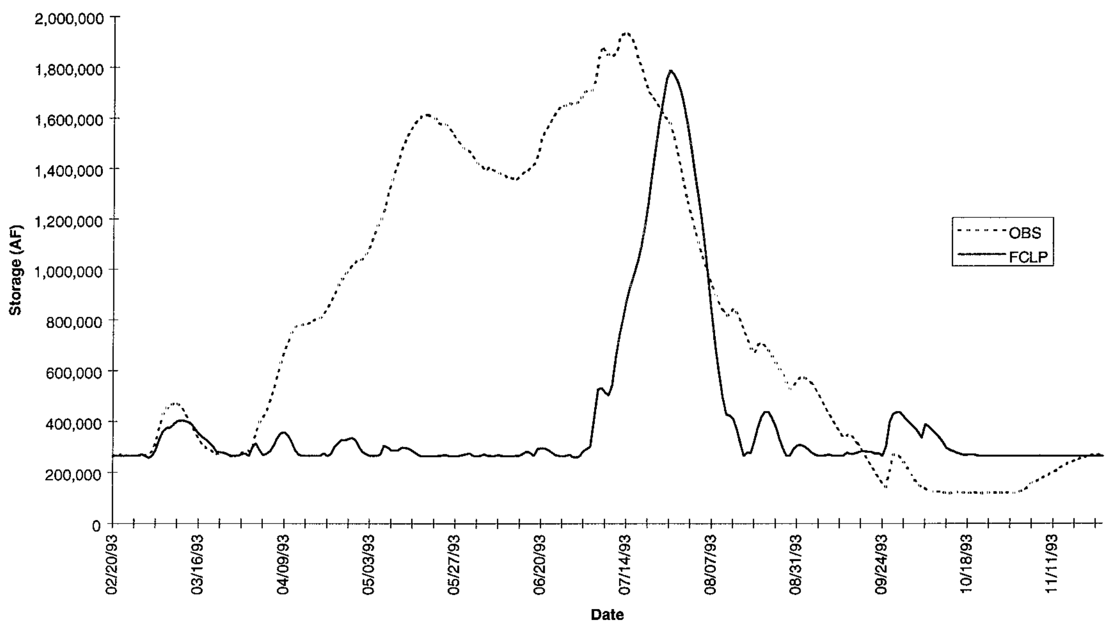

FIGURE 5-9 Lake Red Rock Storage - Flood of 1993

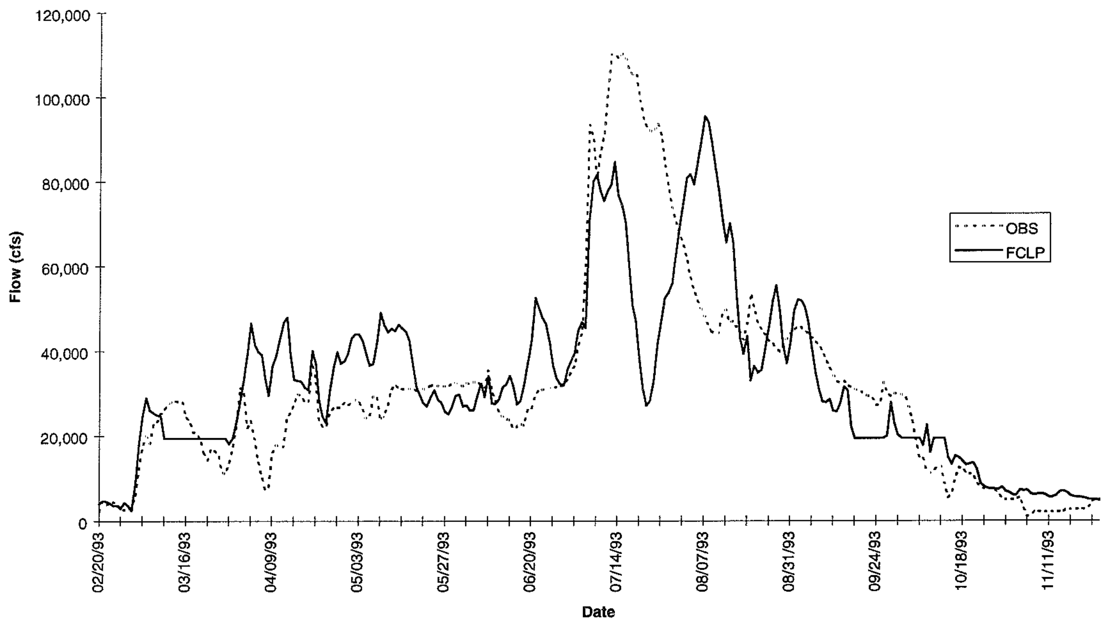

FIGURE 5-10 Ottumwa Hydrograph - Flood of 1993

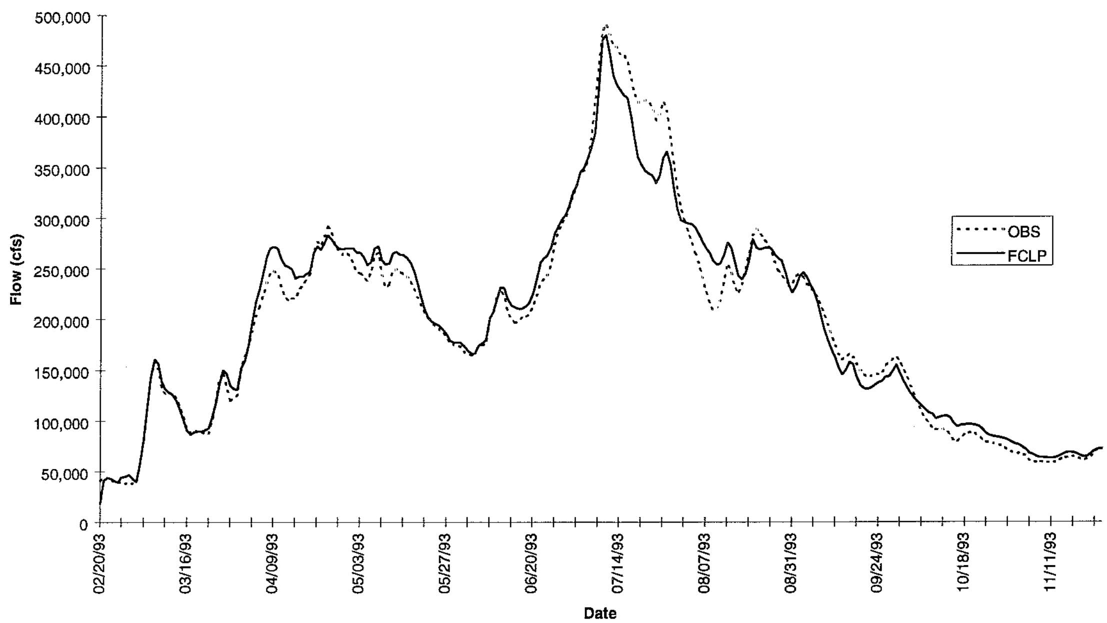

FIGURE 5-11 Quincy Hydrograph - Flood of 1993

Peak flow damages and model-computed penalties for 1993 are shown in Table 5-10. Based on these results, the conclusion from the flood of 1993 is similar that from the flood of 1965: as long as Lake Red Rock operates for flood control at Quincy, Ill., optimal operations of the various sub-systems produce basically identical results. In other words, there appears to be little benefit to be gained from coordinating the operation of the three reservoirs.

TABLE 5-10 Flood of 1993 Calculated Penalties

	Peak Flow Damage ($1000)							
Site	***Observed***	***A***	***BD***	***CD***	***BE***	***CE***	***BFG***	***CFG***
Iowa City	2,279	1,617	1,617	1,617	1,617	1,617	1,617	1,617
Lone Tree	902	953	953	953	953	953	953	953
Wapello	10,856	11,167	11,167	11,167	11,167	11,167	11,167	11,167
2nd Ave.	13,978	7,354	7,354	7,354	7,354	7,354	7,354	7,354
14th St.	-	-	-	-	-	-	-	-
Tracy	8,272	7,006	7,049	7,049	7,290	7,290	7,049	7,049
Ottumwa	18,120	15,190	15,242	15,244	18,120	18,120	15,242	15,244
Keosauqua	3,958	2,296	2,330	2,331	4,128	4,1281	2,330	2,331
Burlington	10,970	11,154	11,154	11,154	11,154	11,154	11,154	11,154
Quincy	138,979	129,982	129,983	129,983	129,998	129,998	129,983	129,983
Total	208,315	186,718	186,849	186,852	191,782	191,782	186,849	186,852

	Model-Computed Penalty ($1000)							
Site	***Observed***	***A***	***BD***	***CD***	***BE***	***CE***	***BFG***	***CFG***
Iowa City	68,717	33,010	30,858	30,858	30,858	30,858	30,858	30,858
Lone Tree	18,989	12,940	12,969	12,969	12,969	12,969	12,969	12,969
Wapello	312,580	277,966	278,308	278,336	278,308	278,336	278,308	278,336
2nd Ave.	211,887	147,491	147,491	147,491	147,491	147,491	147,491	147,491
14th St.	-	-	-	-	-	-	-	-
Tracy	449,979	421,968	421,968	421,968	421,968	421,968	421,968	421,968
Ottumwa	853,800	852,668	852,668	852,668	852,518	852,518	852,668	852,668
Keosauqua	102,365	89,237	89,174	89,175	96,610	96,610	89,174	89,175
Burlington	154,294	144,679	144,697	144,747	144,697	144,747	144,697	144,744
Quincy	2,207,830	1,426,780	1,429,771	1,430,582	2,005,800	2,007,361	1,429,771	1,430,582
Coralville		9,701	9,481	9,447	9,481	9,447	9,481	9,447
Saylorville		4,413,868	4,414,126	4,413,295	4,414,034	4,414,034	4,407,163	4,407,163
Red Rock		199,050	200,549	201,370	60,600	60,600	207,512	207,503
Total w/o Stor.	4,380,440	3,406,738	3,407,903	3,408,794	3,991,218	3,992,858	3,407,903	3,408,793
Total w/ Stor.		8,029,358	8,032,058	8,032,906	8,475,334	8,476,939	8,032,058	8,032,906

Chapter 6

INTERPRETATION OF RESULTS

6.1 Implication for Reservoir Operations

Theoretically, the greatest benefits can be gained from operating the reservoirs as one coordinated system. However, operating as a coordinated system also leads to the most complex operating procedures, as well as increased uncertainty in benefits obtained when reservoirs are operated for points far downstream. Therefore, upon comparing the model-computed penalties resulting from the different operating schemes, the simplest operating scheme which leads to penalty values within 2% of those from scheme A is considered "optimal." For example, if schemes BD and BFG lead to penalty values within 2% of scheme A, then BFG would be selected as the optimal system.

6.1.1 Should Reservoirs be Operated as a System? Table 6-1 summarizes the most optimal operating scheme (most basic set of sub-systems leading to optimal or near-optimal results) for each flood event, in order of decreasing severity. Refer to Figure 3-1 on page 18 for an illustration of the sub-systems.

TABLE 6-1 Optimal Combination of Sub-systems

Flood Year	Optimal System	Comments
1993	CFG	L. Red Rock operates for Quincy
1965	BFG	L. Red Rock operates for Quincy; Coralville for Burlington
1947	CFG	Major inflows occur below reservoirs
1973	CE/CFG	Possible benefit from tandem operation
1991	CE	14% benefit from tandem ops.; observed peak flows lower
1960	CFG	Negligible benefit from tandem operations (< 0.1%)
1990	CFG	Small benefit from tandem operations (< 0.5%)
1979	CE	Nearly 6% benefit from tandem operations
1974	CFG	Negligible differences among operating schemes
1944	CFG	Negligible differences among operating schemes

This table illustrates that for 6 of the 10 most severe flood events it is best to operate the reservoirs independently. That means Coralville Reservoir is operated only for flooding on the Iowa River, Saylorville Reservoir flood storage is used only for flood control in the City of Des Moines, and Lake Red Rock is operated to control flooding on the lower Des Moines River and at Quincy, Illinois. Model results indicate that this policy would be the easiest to implement while still providing optimal results. Surprisingly, results for the 1993 flood event also indicate that the reservoirs should be operated independently. In this case, the system was most likely overwhelmed, and the relatively small amount of flood storage provided by the three projects apparently could not be coordinated to make an appreciable difference.

For the floods of 1979 and 1991, significant benefits are obtained by operating Saylorville Reservoir and Lake Red Rock in tandem for flood control on the Des Moines River and at Quincy. Although operating Saylorville Reservoir for flood control downstream of Lake Red Rock would lead to a more complex operating procedure, the model indicates that substantial benefits could be realized. Results are inconclusive for the flood of 1973. Significant reductions in model-computed flow penalties are obtained through tandem operations; however, the total model-computed penalties (including storage penalties) are nearly the same for all operation schemes. This indicates that re-calibration of the model (i.e., adjustment of the storage penalties) for the BFG and CFG schemes could perhaps produce results similar to those from the BE and CE schemes. For all three of these events, however, it can be concluded that Coralville Reservoir should operate only for flood control on the Iowa River.

For the flood of 1965, benefits are gained by operating Coralville Reservoir for flood control at Burlington, Ia., and Lake Red Rock for flood control at Quincy, Ill. Tandem operations on the Des Moines River do not result in additional benefits.

6.1.2 Optimal Coralville Operations. The fact that, for several of the flood events studied, smaller peak damages corresponded to larger model-based penalties suggests that better results might be obtained with a model based on peak-flow damages. However, these results still provide some insight into whether Coralville Reservoir should be operated for flow regulation at Burlington on the Mississippi River. Model runs for the flood of 1965 are the only results in which an appreciable difference in peak-flow damage (0.8% or $250,000) and model-computed penalty (2.1%) was observed at Burlington with and without flood control from Coralville Reservoir. This is due to the large flows on the Mississippi during this event.

Table 6-2 shows the release priorities for Coralville Reservoir flood control operations based on the Iowa River and Burlington penalty functions. These were derived by comparing the penalty function slopes and arranging them in order starting with the steepest. Analysis of model results confirmed that FCLP determined releases according to these priorities.

TABLE 6-2 Coralville Release Priorities

Priority	Target Max. Flow (cfs)	at Location
1	20,000	Iowa City- Iowa River
2	48,500	Wapello - Iowa River
3	265,000	Burlington - Miss. River
4	10,000	Iowa City - Iowa River
5	17,500	Lone Tree - Iowa River
6	30,000	Wapello - Iowa River
7	150,000	Burlington - Miss. River

Hydrographs of 1965 model results show a release greater than 10,000 cfs from Coralville, which causes damage at Iowa City, in order to make space in the reservoir to dampen an upcoming peak at Burlington. This operation reduces the flow at Burlington approximately 2,000 cfs, which corresponds to an approximate savings of $250,000 in damage at Burlington based on peak flow. The 1993 flood event also recorded a peak flow above 265,000 cfs at Burlington; however, Coralville Reservoir's flood control resources were needed at the time to reduce the flow at Iowa City below 20,000 cfs. This analysis shows that operating Coralville Reservoir for flood control at Burlington is beneficial under special circumstances.

6.1.3 Optimal Des Moines River Operations. As illustrated in Table 6-3, results from the model indicate that modest benefits can be obtained from operating the two reservoirs on the Des Moines River in tandem. (All values in Table 6-3 are based on damages related to peak flow). During the majority of events, operating the reservoirs independently resulted in only a small portion of Saylorville Reservoir's flood storage capacity being utilized for flood control in the City of Des Moines, since inflows into the reservoir were rarely high enough and long enough to fill the flood control pool. Only for the 1965 and 1993 flood events did Saylorville Reservoir reach capacity when operated independently of Lake Red Rock. The flooding was so widespread for these events that Saylorville Reservoir's flood pool was used mainly for flood control in the City of Des Moines, regardless of whether or not it was operated in tandem with Lake Red Rock. When operated in tandem with Lake Red Rock, Saylorville Reservoir's flood control pool was filled during every event except for 1974. However, since reservoir operators do not have the perfect foresight of FCLP, it would seem imprudent to use the full capacity of Saylorville Reservoir's flood control space with the City of Des Moines directly downstream.

TABLE 6-3 Effects of Tandem Operation of Des Moines River Reservoirs

	Total Damage - Des Moines River and Quincy, Ill. ($1000)		
Year	**Independent**	**Tandem**	**% Savings**
1993	154,604	154,604	0
1991	14,691	15,027	-2.3
1990	3,248	3,171	2.4
1979	5,852	5,798	0.9
1974	2,087	2,087	0
1973	15,915	10,946	31.2
1965	19,210	18,469	3.9
1960	5,760	5,534	3.9
1947	16,633	16,714	-0.5
1944	3,933	3,933	0
Total	226,875	221,225	2.5

Thus, the question that needs to be addressed is whether or not the damage that could occur in the City of Des Moines is large enough to warrant keeping Saylorville Reservoir's flood pool empty during periods in which storage could be used for flood control downstream of Lake Red Rock. Table 6-4 provides some insight by illustrating flood reduction priorities based on the respective penalty functions. According to these priorities, Saylorville Reservoir's entire flood control pool should be used to insure that flow at 2nd Ave. in Des Moines is below 40,000 cfs. If this condition is met, then the combined pools of Saylorville and Lake Red Rock should be used to prevent flows from exceeding 110,000 cfs at Ottumwa. The remaining priorities are more complicated. For example, if the first two priorities are met, then both reservoirs should be used to keep the flow at Quincy less than 335,000 cfs. However, the question remains as to whether the burden should be placed evenly on the two reservoirs, or should Lake Red Rock control most of the flows and allow Saylorville Reservoir's flood storage to remain empty for protection of the City of Des Moines?

TABLE 6-4 Des Moines River Flood Control Priorities

Priority	Target Max. Flow (cfs)	at Location
1	40,000	2nd Ave. - Des Moines River
2	110,000	Ottumwa - Des Moines River
3	335,000	Quincy - Mississippi River
4	19,400	2nd Ave. - Des Moines River
5	19,400	Ottumwa - Iowa River
6	270,000	Quincy - Mississippi River
7	90,000	Keosauqua - Des Moines River
8	13,000	Tracy - Des Moines River
9	28,000	Keosauqua - Des Moines River

Referring back to Table 6-3, the only year a large benefit was obtained through tandem operation was 1973. During this event, large flows entered the Des Moines River system downstream of the City of Des Moines, while flows into Saylorville Reservoir were low. These hydrologic conditions allowed the model to use Saylorville Reservoir's flood pool to reduce damages downstream of Lake Red Rock. When modeled independently, Lake Red Rock did not have the flood control capacity needed to control this flood. During most of the other events studied, the flood pool of Lake Red Rock was large enough to control the flood peaks.

Since the risk assumed is large when filling Saylorville Reservoir's flood pool for control downstream of Lake Red Rock, and Lake Red Rock's flood storage is large enough to contain most floods, the majority of Saylorville Reservoir's flood pool should be reserved for flood control in the City of Des Moines. A possible solution would be to divide the flood pool into two variable pools--one for flood control downstream of Lake Red Rock and the other for flood control in the City of Des Moines.

In general, the results endorse operating the Des Moines reservoirs for flood control on the Mississippi River at Quincy, Ill. Benefits at Quincy are seen in all four of the years studied that had damaging flows on the Mississippi River. Table 6-5 illustrates the damage reduction when operating for flood control at Quincy.

TABLE 6-5 Effects of Operating Des Moines Reservoir for Flood Control at Quincy

	Total Damage - Des Moines River Tandem Operation ($1000)		
Year	**w/o Quincy**	**w/Quincy**	**% Savings**
1993	159,536	154,604	3.1
1991	15,027	15,027	0
1990	3,171	3,171	0
1979	5,798	5,798	0
1974	2,087	2,087	0
1973	10,963	10,946	0.2
1965	32,764	18,469	43.6
1960	6,110	5,534	9.4
1947	16,713	16,713	0
1944	3,933	3,933	0

6.2 Flood of 1993

FCLP model results and observed 1993 operations have many significant differences, and Table 5-10 shows the "optimal" peak-flow damage was $186.7 million, while the observed peak-flow damage was $208.3 million. However, it is unfair to conclude that current operating procedures are inadequate. The following paragraphs analyze the most significant differences between observed and model damages and explain why care must be taken in interpreting model results

The most notable difference for the 1993 flood is in the operation of Coralville Reservoir. FCLP drew down the reservoir much more in the first few weeks of June than was recorded. Historical data shows releases were cut back to prepare for the planting season even though the reservoir was relatively full. The additional FCLP drawdown allowed Coralville Reservoir to provide more protection from the large inflows that occurred in late July and August. Were this policy of rapidly drawing down Coralville Reservoir following a flood event adopted every year, it would likely result in greater agricultural losses. The procedures for drawdown of Coralville Reservoir should be reviewed with this trade-off in mind.

As mentioned before, deterministic models such as FCLP have perfect foresight. Current forecasting methods are unable to predict hydrologic conditions two to three months in the future with enough certainty to justify making damaging pre-releases. Furthermore, it would be difficult to convince the general public that they are being flooded today in order to reduce the overall damage months from now. This scenario occurred during the flood of 1993 at Lake Red Rock, when the model kept the flood control pool empty for three months in order to dampen the mid-July flood peak on the Mississippi River. The FCLP results are unrealistic in this regard and serve mainly to represent the lower bound of flood damage from a flood event.

Chapter 7

CONCLUSIONS

This chapter describes several conclusions not only for reservoir operations on the Iowa and Des Moines Rivers, but also for the use of linear programming models such as FCLP for flood control optimization.

7.1 Iowa/Des Moines River Reservoir Study

The main goal of this study was to determine whether operating Coralville Reservoir for control on the Mississippi River is beneficial. Results from the ten largest floods on record only show one occurrence where this is marginally true. During the flood of 1965, damage was reduced by approximately $250,000 out of an $8.3 million total at Burlington. Operating Coralville Reservoir for flood control on the Mississippi River is risky because flood control space is consumed that could prove more valuable for flood control at Iowa City. It is acceptable to operate Coralville Reservoir for flood control on the Mississippi River as long as current and forecasted flows on the Iowa River are low.

The method of dividing the system into various smaller systems produces results that quantify the benefits of making reservoir releases based on selected control points. By dividing the Des Moines River just upstream of Lake Red Rock, the effect of operating Lake Red Rock and Saylorville Reservoir in tandem was determined. The only time a large benefit appeared was for the flood of 1973. Minor benefits were obtained during other floods through tandem operation, but the model used most of Saylorville Reservoir's flood control capacity for protection downstream of Lake Red Rock. This procedure is not recommended. The majority of Saylorville Reservoir's flood storage should be saved for protection of the City of Des Moines, potentially the highest damage location on the river. A possible solution would be to divide the flood storage of Saylorville Reservoir into two flood pools - one set aside for flood control in the City of Des Moines and the other for flood control downstream of Lake Red Rock.

For the majority of flood events studied, the optimal policy would be to operate each reservoir independently. Coralville Reservoir should be operated for flood control on the Iowa River with secondary consideration of Burlington. Saylorville Reservoir's flood capacity should be used mainly for flood protection in the City of Des Monies. Lake Red Rock should be operated for flood control on the Lower Des Moines River and at Quincy, Ill.

Review of operations during the Great Flood of 1993 illustrate how much damage could have been reduced if inflows were known two to three months in advance. Obviously, this is not possible with current forecasting technology. However, the damage could also have been reduced during the 1993 flood if current reservoir operations were more averse to extreme events. Release decisions during the flood of 1993 were made based on knowledge of past events. With new data and a better idea of the runoff these drainage areas can produce, the release rules should be modified to account for the risk of events of this magnitude in the future.

One of the greatest benefits from this type of analysis is an increased understanding of the system. The flood control value of the reservoirs is put into perspective along with the magnitude of damage at various locations in the system. Uncertain data can be identified, and the value of additional studies to provide improved data can be estimated. In this study, the need for updated damage functions has been recognized, as well as the need for more statistical analysis of flows and forecasts in order to address questions related to operators' risk aversion.

Optimization models are only as good as their penalty functions and input data. Establishing accurate penalty functions and producing a "clean" set of historical inflows is an important, though a time consuming task. In addition to the model results, this study has produced a standardized set of flow data which will prove invaluable in future studies.

7.2 Future Work

Recommendations for future work on the Iowa/Des Moines River System include:

1. Re-evaluation of penalty functions.

2. Derivation of preliminary operating rules from the optimization results and testing/refinement with a detailed simulation model.

3. Sensitivity analysis of storage persuasion penalties.

4. Statistical analysis of flood events and forecasts to allow application of the model in a scenario-based manner (either in real-time or with simulated forecasts).

7.3 Linear Programming for Flood Control Optimization

Deterministic optimization models are useful for reviewing reservoir operating schemes. It is useful to know the potential of a reservoir system when analyzing operating procedures, but results from these models need to be kept in perspective. These omniscient optimization models should be accompanied by simulation models when developing operating rules for a reservoir or set of reservoirs, since simulation models give a more detailed and realistic estimate of the system performance given a set of operating policies.

FCLP currently optimizes system reservoir operations using a duration-based penalty. This study has shown that a tool which minimizes the damage associated with the peak flow might produce better results.

FCLP is currently being updated to accommodate the more sophisticated demands of this type of study. Areas of improvement will include:

1. Addition of peak-related penalties so that the user can decide to use the existing duration-based penalty structure, the peak-related penalties, or a combination of the two.

2. Incorporation of seasonally-varying penalties to account for agricultural damages related to planting, growing, and harvesting periods.

3. Limiting model foresight through the use of forecasted inflows and/or multiple inflow scenarios.

These improvements will allow a better representation of the system operation problem and increase the utility of the program.

Chapter 8

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Appendix A

CURRENT OPERATING RULES

List of Tables

TABLE A- 1

REGULATION SCHEDULE CORALVILLE LAKE

Regulation	Reservoir	Condition	Operation
A. Conservation Storage		I. Normal	Regulate pool level in accordance with Fig (c) of plate 2 as nearly as possible without adversely affecting downstream conditions as follows: Date / Operation 15 Feb-1 Mar — Lower from 683 to 679 01 Mar-15 Jun — Hold elev 679 15 Jun-15 Sep — Hold 683 15 Sep-15 Dec — Hold 686 15 Dec-15 Feb — Hold 683 Do not release less than a minimum outflow of 150 cfs, except as specified in Schedule D, nor exceed releases specified in Schedules B & C.
B. Flood Control		I. 15 December to 1 May	Maintain pool levels specified under schedule A as nearly as possible without exceeding release of 10,000 cfs except as limited by Conditions B.III, B.V, and Schedule C.
		II. 1 May to 15 December.	Maintain pool levels specified under Schedule A as nearly as possible without exceeding releases of 6000 cfs, except as Limited by Conditions B.IV, B.V, and Schedule C.
		III. 15 December through 1 May. Discharge at Lone Tree or Wapello are above, or forecast to exceed 15,000 cfs or 35,000, respectively.	Reduce release to not less than 1,000 cfs to control flow to those discharges at respective stations insofar as possible during 3 days of crest at respective station, except as limited by Schedule C.

Regulation	Reservoir	Condition	Operation
		IV. 1 May to 15 December discharge at Lone Tree or Wapello above or forecast to exceed 11,000 cfs or 32,000 cfs respectively.	Same as operation for Condition B.111.
		V. Any date, stage at, above or forecast to exceed 18.0 feet on Mississippi River gage at Burlington, Iowa.	Reduce release to 1,000 cfs during seven days corresponding to crest flow in the Mississippi River with due allowance for time of travel, except as Limited by Schedule C.
C. Major Flood Emergency		I. Any date reservoir elevation is rising and above or forecast to exceed elevation 707.0 feet.	When predictions indicate that anticipated runoff from a storm will appreciably exceed the storage capacity remaining in the reservoir when operated under Schedule B, increase in outflow rates will be made as necessary to prevent reservoir from exceeding elevation 712.0 on basis of those predictions. Release not more than the outflows shown in the following schedule:

Elev	Outflow	Elev	Outflow
707.0	7,000	711.3	14,000
708.0	8,000	711.4	15,000
709.0	9,000	711.5	16,000
710.0	10,000	711.6	17,000
711.0	11,000	711.7	18,000
711.1	12,000	711.8	19,000
711.2	13,000	711.9	20,000

Regulation	Reservoir	Condition	Operation
D. Drought Emergency		I. Any date the reservoir elevation is between 677.0 and 678.0.	Reduce Release to 100 cfs.
		II. Any date the reservoir elevation is below 677.0.	Reduce Release to 75 cfs.

TABLE A-2

SAYLORVILLE LAKE REGULATION SCHEDULE

Regulation	Reservoir	Condition	Operation
A. Normal flood control operation, pool elevation between 836-875 feet N.G.V.D. (Max daily change of outflow is 3,000 cfs)	Steady or rising or falling	I - 16 Dec through 20 Apr	Maintain permanent pool level 836 feet NGVD (except as described in para 7.03 of this regulation manual) by releasing inflow up to 16,000 cfs limited by the conduit capacity and balance the storage in accord with Lake Red Rock, releasing not less than 2000 cfs, except as limited by A-II
		II - 16 Dec through 20 Apr – discharge at SE 14th Street in Des Moines above or forecast to exceed 30,000 cfs (stage of 23 feet)	Release not less than 2000 cfs to control flow at SE 14th Street insofar as possible below 30,000 cfs and balance the storage in accord with Lake Red Rock, if Saylorville pool level is below 860.0 feet NGVD.
		III - 21 Apr through 15 Dec	Maintain permanent pool level 836 feet N.G.V.T). (except as described in para 7.03 of this regulation manual) by releasing inflow up to 12,000 c.f.s. and balance the storage in accord with Lake Red Rock, if pool level is below 860.0 feet N.G.V.D. releasing not less than 2,000 c.f.s., except as limited by A-IV.
		IV - 21 Apr through 15 Dec – discharge at SE 14th Street in Des Moines above or forecast to exceed 30,000 cfs (stage of 23 feet)	Release not less than 2,000 c.f.s. to control flow at SE 14th Street in Des Moines insofar as possible below 30,000 Above or forecast to cfs., and balance the storage in accord with Lake Red Rock, if Saylorville pool level is below 860.0 feet N.G.V.D.
		V - Any date, if Beaver Creek flow is above or forecast to exceed 10,000 cfs.	Release inflow up to a minimum of 2000 cfs.

<table>
<tr><th>Regulation</th><th>Reservoir</th><th>Condition</th><th>Operation</th></tr>
<tr><td>B. Intermediate Magnitude Flood Operation</td><td>Rising</td><td>I - Any date, reservoir is rising and forecast to exceed 875.</td><td>When predictions indicate that anticipated runoff will produce a peak reservoir elevation between 875 feet and 884 feet NGVD. If operated under Schedule A, the schedule listed below will be adapted with the purpose of minimizing releases.

<table>
<tr><th>Pool Elev</th><th>21 Apr - 15 Dec Outflow</th><th>16 Dec - 20 Apr Outflow</th></tr>
<tr><td>875</td><td>12,000</td><td></td></tr>
<tr><td>876</td><td>12 - 13,000</td><td>16,000</td></tr>
<tr><td>877</td><td>12 - 14,000</td><td>16,000</td></tr>
<tr><td>878</td><td>12 - 15,000</td><td>16,000</td></tr>
<tr><td>879</td><td>12 - 16,000</td><td>16,000</td></tr>
<tr><td>880</td><td>12 - 17,000</td><td>16 - 17,000</td></tr>
<tr><td>881</td><td>12 - 18,000</td><td>16 - 18,000</td></tr>
<tr><td>882</td><td>12 - 19,000</td><td>16 - 19,000</td></tr>
<tr><td>883</td><td>12 - 20,000</td><td>16 - 20,000</td></tr>
<tr><td>884</td><td>12 - 21,000</td><td>16 - 21,000</td></tr>
</table>

Schedule C will be adopted when predictions indicate runoff will cause pool elevation to exceed elevation 884 NGVD when operated under the above schedule.</td></tr>
<tr><td></td><td>Falling</td><td>II - Any date after reservoir elevation has peaked and pool elevation is between 884 and 875.</td><td>Hold outflow to the maximum rate reached in Schedule BI above until elevation 875 NGVD is reached; then follow Schedule A.</td></tr>
</table>

Regulation	Reservoir	Condition	Operation
C. Large Magnitude Flood Operation	Rising	I - Any date, reservoir elevation is rising and above or forecast to exceed elevation 875 feet msl.	When predictions indicate that anticipated runoff from a storm or snowmelt will appreciably exceed the storage capacity remaining in the reservoir when operated under Schedule A or Schedule B, release rates will be made in accordance with the following schedule:

Pool Elev	21 Apr - 15 Dec Outflow	16 Dec - 20 Apr Outflow
875	12,000	16,000
876	13,000	16,000
877	14,000	16,000
878	15,000	16,000
879	16,000	16,000
880	17,000	17,000
881	18,000	18,000
882	19,000	19,000
883	20,000	20,000
884	21,000	21,000

Above 884 feet msl, gradually close the conduit to release combined spillway and conduit flow of 21,000 cfs up to elevation 889 feet msl.

Above 889 feet msl, open the conduit gates gradually to achieve fully open condition at pool elevation of 890 feet msl., corresponding to a flow of 42,000 cfs.

Allow the pool to rise with uncontrolled spillway and conduit discharge above 890 feet msl.

Regulation	Reservoir	Condition	Operation
	Falling	II - Any date after reservoir elevation has crested and pool elevation	Maintain maximum conduit and spillway flow

Regulation	Reservoir	Condition	Operation
		III-Any date after reservoir elevation has crested and pool elevation is between 889 and 890.	Reduce combined spillway and conduit discharge from 42,000 cfs at elevation 890 feet NGVD to 21,000 cfs at elevation 889 feet NGVD, by operation of conduit gates, releasing not less than the estimated inflow to the reservoir.
	Steady, rising or falling	IV -Any date after reservoir elevation has crested and pool elevation is between 889 and 875.	Maintain a flow of 21,000 cfs until elevation 884 feet NGVD is reached, then maintain full conduit flow until elevation 875 feet NGVD is reached, then follow regulation Schedule A.
D. Drought Regulation for Water Supply and Water Quality	Any date reservoir elevation is below elevation 836.0 feet NGVD.	Pool above elevation 827	Release all water supply and water quality demands
		Pool is between elevation 827 and 826	Release 100 percent of water supply, maintain 175 cfs at dam, and 245 at SE 14th Street
		Pool is between elevation 826 and 825	Release 100 percent of water supply, maintain 150 cfs at dam, and 220 at SE 14th Street
		Pool is between elevation 825 and 824	Release 100 percent of water supply, maintain 125 cfs at dam, and 195 at SE 14th Street
		Pool is between elevation 824 and 823.5	Release 100 percent of water supply, maintain 100 cfs at dam, and 170 at SE 14th Street
		Pool is between elevation 823.5 and 819	Release 100 percent of water supply, no water quality releases made
		Pool is between elevation 819 and 816	Release 75 percent of water supply, no water quality releases made
		Pool is below elevation 816	Release 50 percent of water supply, no water quality releases made

TABLE A-3

LAKE RED ROCK REGULATION SCHEDULE

Regulation	Reservoir	Condition	Operation
A. Normal flood control operation	Rising	I - 16 Dec through 01 May	Maintain permanent pool level 742 by releasing inflow up to 22,000 cfs then, permit pool level to rise with uncontrolled outlet discharge until elevation 750 is reached then continue to release 30,000 cfs as pool continues to rise, except as limited by Conditions A-II, and Schedule B.
	Rising	II - 16 Dec through 01 May . Stage at Ottumwa or Keosauqua above or forecast to exceed 10.8 or 19.6 feet respectively	Release not less than 5000 cfs to control flow to those discharges at respective stations insofar as possible except as limited by Schedule B.
	Falling, steady or rising	III-01 May through 15 Dec. Reservoir at or above permanent pool elevation 742 but lower than elevation 775	Release 18,000 cfs until reservoir recedes to permanent pool level, after which it shall be held at that level insofar as possible without exceeding release of 18,000 cfs (22,000 cfs if pool above 750) except as limited by Conditions A-IV and Schedule B.
	Rising	IV -01 May through 15 Dec. Stage at Ottumwa or Keosauqua above or forecast to exceed 7.5 feet (8.7 feet if pool higher than 760) or 17.6 feet (18.4 feet if pool higher than 760) respectively including release in Condition A-III.	Release not less than 5,000 cfs to control flow to those discharges at respective stations insofar as possible except as limited by Schedule B.

Regulation	Reservoir	Condition	Operation
		V -Any date, stage at, above, or forecast to exceed 18.5 feet on Mississippi River gage at Burlington, Iowa, or 20.0 feet on Mississippi River gage at Quincy, Ill.	During period corresponding to time Mississippi River is above forecast stages provided reservoir inflow is greater than 5,000 cfs until reservoir elevation 757 is reached; then provided (a) reservoir inflow is greater than 15,000 cfs release not less than 15,000 cfs until reservoir elevation 765 is reached or (b) if reservoir inflow is between 5,000 cfs and 15,000 cfs release the inflow; then, if operation (a) was followed and at elevation 765, provided c) reservoir inflow is greater than 25,000 cfs until reservoir elevation 775 is reached, or (d) if reservoir inflow is between 15,000 cfs and 25,000 cfs release the inflow; then if operation c) was followed release not less than 30,000 cfs except as limited by Schedule B.
B. Large Magnitude flood operation.	Rising or Falling	I. - Any date, reservoir elevation is above or forecast to exceed elevation 775.	When predictions indicate that anticipated runoff from a storm will appreciably exceed the storage capacity remaining in the reservoir when operated under Schedule A, release rates will be made in accordance with the following schedule:

Pool Elev	Outflow (cfs)
775	30,000
776	35,000
777	40,000
778	45,000
779	50,000
780	60,000
780.5	80,000
	100,000
	115,000
	130,000
	130,000
	130,000
	130,000

Open spillway tainter gates as necessary to maintain reservoir elevation 785 until uncontrolled spillway and outlet conduit discharge prevails.

Regulation	Reservoir	Condition	Operation
C. Drought Regulation for Water Quality	Any date reservoir is below elevation 742 feet NGVD	Pool above elevation 727	Release 300 cfs.
		Pool is between elevation 726 and 727	Release 290 cfs.
		Pool is between elevation 725 and 726	Release 275 cfs.
		Pool is between elevation 724 and 725	Release 250 cfs.
		Pool is between elevation 723 and 724	Release 225 cfs.
		Pool is between elevation 722 and 723	Release 200 cfs.
		Pool is between elevation 718 and 722	Release 175 cfs.
		Pool is between elevation 713 and 718	Release 150 cfs.
D. Flash Flood Operation	Rising, Steady, or Falling	Pool is below elevation 716	Release 100 cfs.
		1 April through 30 Oct. Reservoir elevation at or below 757 and flows at Ottumwa at, above or forecast to exceed 30,000 cfs	Release no less than 500 cfs to control flows at Ottumwa insofar as possible for a maximum period of 48 hours.

Appendix B

Technical Report and User's Manual for Linear Programming Model of Flood Operation (Nov 97)

Table of Contents

Summary

This document describes a linear-programming (LP) model that addresses the problem of operating a reservoir system optimally for flood control. In the model, the operation problem is treated as a problem of finding system-wide reservoir releases that minimize a system penalty. The penalty is an index of the negative impact of too much or too little release, storage, and downstream flow. A simple simulation model is embedded in the LP model. That model computes storages and downstream flows, given releases, accounting for reservoir continuity, linear channel routing, and hydraulic limitations imposed by the reservoir outlets.

The LP model is implemented with a computer program that we designate FCLP. It:

- Reads a description of the flood-control system from an HEC-5-like input file;
- Generates the linear equations that constitute the LP;
- Uses XMP, a general-purpose, large-scale LP solver to find the optimal releases; and
- Translates the LP results into terms familiar to hydrologic engineers.

FCLP is linked to the HEC Data Storage System, HEC-DSS, thus providing a convenient mechanism for exchanging data with other hydrologic engineering programs, such as the HEC-1F runoff forecasting program, and with display and other data management programs.

Problem and solution

Overview

The problem that we address herein is the problem of operating a system with one or more flood-control reservoirs to reduce flood damage consistent with goals of and priorities for operation of the system. These priorities may include preferences regarding the order in which reservoirs are to fill, the method of filling the reservoirs, and the manner in which capacities are to be exceeded, if they must. To solve the operation problem, we reduce it to a mathematical problem of finding the optimal releases from system reservoirs, given initial conditions and boundary conditions and a mathematical representation of the goals and priorities.

Model formulation

The model that we have formulated to find optimal releases is a linear programming (LP) model. It includes:

1. An embedded simulation model. This model consists of a large set of simultaneous linear equations. (Any pertinent relationships that are nonlinear are approximated with linear functions.) The equations are written so that the right-hand side of each is known and the left-hand side includes variables that represent decisions that are to be made or the consequences of those decisions. The number of such *decision variables* exceeds the number of equations, so a large number of alternative solutions exist.
2. A single linear equation that defines the efficiency of each of the alternative solutions, based on the values of the decision variables. This equation is known as the *objective function*.

The best set of values for the decision variables is found via a trial-and-error solution technique. This technique, known as the *simplex* method, finds a solution to the set of simultaneous equations, evaluates the corresponding objective function, and repeats the process until the optimal set is found.

In formulating this solution to the operation problem, we draw a clear distinction between *inviolable constraints* of system operation and the *goals* of operation:

- Inviolable constraints are included in the simulation model and represent only the physical laws that must be satisfied. Any set of releases that satisfies these is classified as a *feasible* solution. If a feasible solution cannot be found, then no solution exists to the operation problem as formulated. In the model presented herein, the inviolable constraints include reservoir continuity, reservoir capacity, hydraulic outlet capacity, and information-point continuity.
- Goals of operation are included in the objective function and represent how we hope to operate the system: keeping downstream flows less than channel capacity, not storing

water in the flood-control pool, and so on. These goals are not inviolable. If a set of releases that meets the goals cannot be found, then we will operate the system nevertheless, using the best releases that we can find and wishing that we could do better.

Terminology

For purposes of modeling, we follow the HEC-5 example and identify all points at which water enters or leaves the system or at which we desire information about the flow as *control points*. The user defines the system by identifying these and by describing how they are linked by channels. We classify each system control point as either

- A *reservoir* if water may be stored; or
- An *information point*, otherwise.

Water may enter the system at any control point. For clarity, we refer to water entering the system at a reservoir as *inflow* and water entering at an information point as *local flow*. In either case, the flow is considered to be the runoff from the area upstream of the control point, but downstream of the immediately-upstream control point.

Boundary conditions

The LP model is a multi-period model. That is, on solution, it prescribes a set of releases for one or more time periods, based on the user's requirements. The model requires that the user specify boundary conditions in terms of system inflows and local flows for the entire period of analysis. These may be historical flows, design flows, or forecasted flows.

We consider only the case in which the boundary conditions are known with certainty (the deterministic case). Uncertainty regarding inflows might be addressed via implicit stochastic optimization with the model we present herein.

LP model

As noted, the LP model includes

- An embedded simulation model that includes reservoir continuity, reservoir capacity, hydraulic outlet capacity, and information-point continuity constraints; and
- An objective function that represents the goals and priorities of operation.

Reservoir continuity and capacity constraints

General form

These continuity constraints are equations that account for all volume in the system reservoirs. The LP model includes a continuity constraint for each reservoir for each time period. The general form of this constraint for reservoir j, time period i, is

$$\frac{1}{\Delta t}\left[S_{i,j} - S_{i-1,j}\right] + f_{i,j} - \sum_{k,k\in\Omega} \sum_{t=1}^{i} c_{t,k} f_{t,k} = I_{i,j}$$

in which $S_{i-1,j}$ and $S_{i,j}$= storage at the beginning and end of period i, respectively; $f_{i,j}$ = total release in period i; Ω= set of all control points upstream of j from which flow is routed to j; $f_{t,k}$= average flow at control point k in period t; $c_{t,k}$ = linear coefficient to route period t flow from control point k to control point j for period i; $I_{i,j}$= inflow to the reservoir. The routing coefficients are found directly from Muskingum model coefficients or are approximated from other routing models.

To insure that the LP model does not prescribe storages that cause the capacity of a reservoir to be exceeded, the following constraint is include for each reservoir j for each period i:

$$S_{i,j} \leq SMAX_j$$

in which $SMAX_j$ = the total capacity of the reservoir.

Storage zones

To model desired storage-balancing schemes amongst reservoirs, the total storage capacity of each reservoir in the system may be divided into storage zones. If it is, the total storage at any time i is the sum of storage in these zones:

$$S_{i,j} = \sum_{l=1}^{NLF} S_{i,j,l}$$

in which l = index of storage zone; and NLF = number of zones. Substituting this in the continuity equation yields

$$\frac{1}{\Delta t}\left[\sum_{l=1}^{NLF} S_{i,j,l} - \sum_{l=1}^{NLF} S_{i-1,j,l}\right] + f_{i,j} - \sum_{k,k\in\Omega} \sum_{t=1}^{i} c_{t,k} f_{t,k} = I_{i,j}$$

The storage in each zone l is constrained as

$$S_{i,j,l} \leq SMAX_{j,l}$$

Hydraulic capacity constraints

Overview

The maximum reservoir release physically possible may be limited as a consequence of the hydraulic properties of the reservoir outlet works,. This limitation commonly is expressed as a function of the storage in the reservoir. That is

$$f_{i,j} \leq \phi\left(\frac{1}{\Delta t}\sum_{l=1}^{NLF} S_{i-1,j,l} + \sum_{k,k\in\Omega}\sum_{t=1}^{i} c_{t,k} f_{t,k} + I_{i,j}\right)$$

in which $\phi(\bullet)$ = a functional relationship of maximum outflow to storage, and the term in parentheses represents the initial storage plus the total inflow during period i. The function typically is nonlinear, and in common application (for example, with program HEC-5) is presented in tabular form.

Implementation

For the LP model, the storage-maximum discharge function is linearly approximated. That is, the maximum release for period i is specified as a linear function of storage as

$$f_{i,j} \leq \beta_0 + \beta_1\left[\frac{1}{\Delta t}\sum_{l=1}^{NLF} S_{i-1,j,l} + \sum_{k,k\in\Omega}\sum_{t=1}^{i} c_{t,k} f_{t,k} + I_{i,j}\right]$$

in which β_0 and β_1 = coefficients of the linear approximation. These coefficients are determined at each stage of the decision-making process as follows:

1. $\left[\frac{1}{\Delta t}\sum_{l=1}^{NLF} S_{i-1,j,l} + \sum_{k,k\in\Omega}\sum_{t=1}^{i} c_{t,k} f_{t,k} + I_{i,j}\right]$ is computed, using the initial condition and forecasted inflow for the current stage;
2. An HEC-5-like user-provided storage-outflow relationship is searched to find the entry, ST_k that is just less than the volume computed in step 1. The corresponding maximum release associated with this volume QT_k, is found via table lookup.
3. The user-provided storage-outflow relationship is searched to find the entry, ST_{k+1} that is just greater than the volume computed in step 1. The corresponding maximum release associated with this volume QT_{k+1} , is found via table lookup.
4. The pair of points (ST_k, QT_k) and (ST_{k+1}, QT_{k+1}) are used to define β_0 and β_1. These values of β_0 and β_1 are used for decision making in the current stage.

The coefficients are re-estimated at each stage of the decision-making process, based on current values of $S_{i-1,j,l}$ and $I_{i,j}$.

Information-point continuity constraints

General form

A continuity constraint is included also for each information point for each time period. For each information point j for period i, this constraint takes the following general form

$$f_{i,j} - \sum_{k,k\in\Omega} \sum_{t=1}^{i} c_{t,k} f_{t,k} = I_{i,j}$$

in which $f_{i,j}$ = the average control-point flow during period j; $I_{i,j}$ = local inflow during period j; and all other terms are as defined before.

Discharge zones

To model system operating priorities, the discharge at each control point may be divided into discharge zones. In that case, the control-point continuity equation takes the form

$$\sum_{l=1}^{NF} f_{i,j,l} - \sum_{k,k\in\Omega} \sum_{t=1}^{i} c_{t,k} f_{t,k} = I_{i,j}$$

in which l = index of discharge zone; ;and NF = number of discharge zones.

Objective function

Any number of release schedules might satisfy all the constraints described. To find the *best* set, the efficiency of each must be quantified in terms of meeting the goals of operation. The LP objective function does this. It defines total penalty as a function of releases, storages, and flows throughout the system for the period of analysis: The release schedule that yields the minimum penalty is the optimal schedule.

The objective function includes penalty for too much or too little storage in each system reservoir; penalty for changing reservoir release too rapidly; and penalty for too much or too little flow at system information centers.

Penalty for too much or too little storage

Penalties in this category quantify the desire to avoid storage outside an acceptable range. The penalties are specified for each reservoir as a linear function of volume of water stored in the reservoir during the period. Like HEC-PRM, the LP formulation can accommodate nonlinear functions through piecewise linear approximations. For example, the nonlinear function shown with the dotted line in Figure 1 can be represented as shown with the solid line in that figure. If the independent variable in this illustration is reservoir storage, then each of the segments shown might correspond to a storage level, $S_{i,j,l}$, in the reservoir continuity equation.

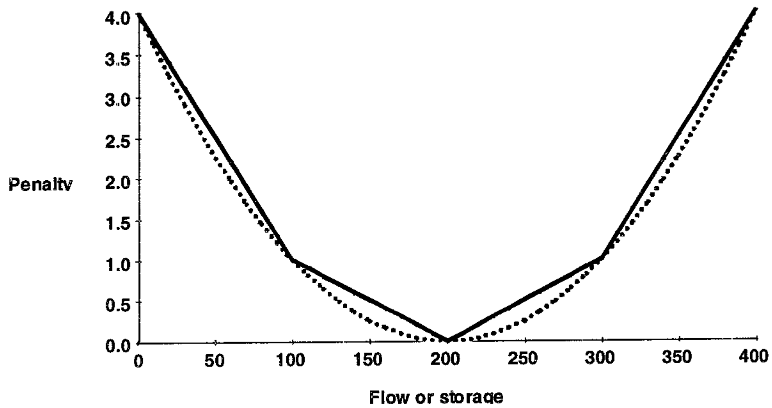

Figure 1. Linear approximation of nonlinear function

When used in combination with storage zones, these penalty functions can model inter-reservoir operating rules. For example, suppose that to the extent possible, the reservoirs shown in Figure 2 should be operated so that Reservoir B is at least 50% empty until and unless Reservoir A is full. To model this, the user could specify two storage zones for each reservoir. In Reservoir A, the first zone might be 99% of the total storage, and the second the remainder. A penalty of 10/unit of storage could be applied to the first zone, and 100/unit to the second. For Reservoir B, each zone could represent 50% of the total capacity. A penalty of 10/unit of storage could be defined for the first zone, and 100/unit to the second. The least-penalty operation then would be any that used all of the storage in zone 1 of both reservoirs before zone 2 is used. That is, all of Reservoir A and the lower 50% of Reservoir B will fill before the upper 50% of Reservoir B is used. Other storage allocations are feasible, but none would have less penalty.

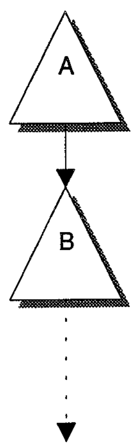

Figure 2. Example reservoir system

Penalty for changing release too rapidly

Penalties in this category quantify the negative impact of varying releases too quickly from one period to the next. Such rapid variations may be unacceptable if they would case bank sloughing downstream, or if they are impractical given the equipment available to change gate or outlet settings. To impose this penalty, the LP model, through a set of auxiliary constraints, segregates the release for each period into the previous period's release plus or minus a change in release. If the absolute value of this change in release exceeds a specified maximum, a penalty is imposed; otherwise, no penalty is imposed.

The auxiliary constraints relate the release for each period to release in the previous period by the equation

$$R_{i,j} = R_{i-1,j} + R^+_{i,j} - R^-_{i,j}$$

in which $R^+_{i,j}$ = the total increase in release from period *i*-1 to period *i*; and $R^-_{i,j}$ = the total decrease in release from period *i*-1 to period *i* . If $R_{i,j} \geq R_{i-1,j}$ then $R^+_{i,j}$ is positive and $R^-_{i,j}$ is zero. If $R_{i,j} \leq R_{i-1,j}$ then $R^-_{i,j}$ is positive and $R^+_{i,j}$ is zero. If $R_{i,j} = R_{i-1,j}$ then both $R^+_{i,j}$ and $R^-_{i,j}$ are zero.

To define allowable increase and decrease, $R^+_{i,j}$ and $R^-_{i,j}$ are partitioned into the portion that is acceptable plus the portion that is excessive, using the following relationships:

$$R^+_{i,j} = Ra^+_{i,j} + Re^+_{i,j}$$

$$R^-_{i,j} = Ra^-_{i,j} + Re^-_{i,j}$$

in which $Ra^+_{i,j}$, $Re^+_{i,j}$ = acceptable and excessive release increase, respectively; and $Ra^-_{i,j}$, $Re^-_{i,j}$ = acceptable and excessive release decrease, respectively. Thus the current release can be defined as

$$R_{i,j} = R_{i-1,j} + \left[Ra^+_{i,j} + Re^+_{i,j}\right] - \left[Ra^-_{i,j} + Re^-_{i,j}\right]$$

$Ra^+_{i,j}$ and $Ra^-_{i,j}$ are constrained not to exceeded the user-specified desirable limits, and a penalty is imposed on $Re^+_{i,j}$ and $Re^-_{i,j}$.

Penalty for too much or too little flow at information points

Penalties in this category quantify the desire to avoid downstream flows outside an acceptable range. The penalties are specified as a linear function of downstream flow, which is the sum of local runoff and routed reservoir releases. The LP formulation can accommodate nonlinear functions through piecewise linear approximations, such as illustrated by Figure 1.

If the user wishes to specify penalty for too much or too little release from a system reservoir, this can be accomplished by defining an artificial information point immediately downstream of the reservoir.

Computer program

Overview

The LP model described here is implemented with a computer program that we designated FCLP. The components of this program and the general flow of information within the program are illustrated in Figure 3.

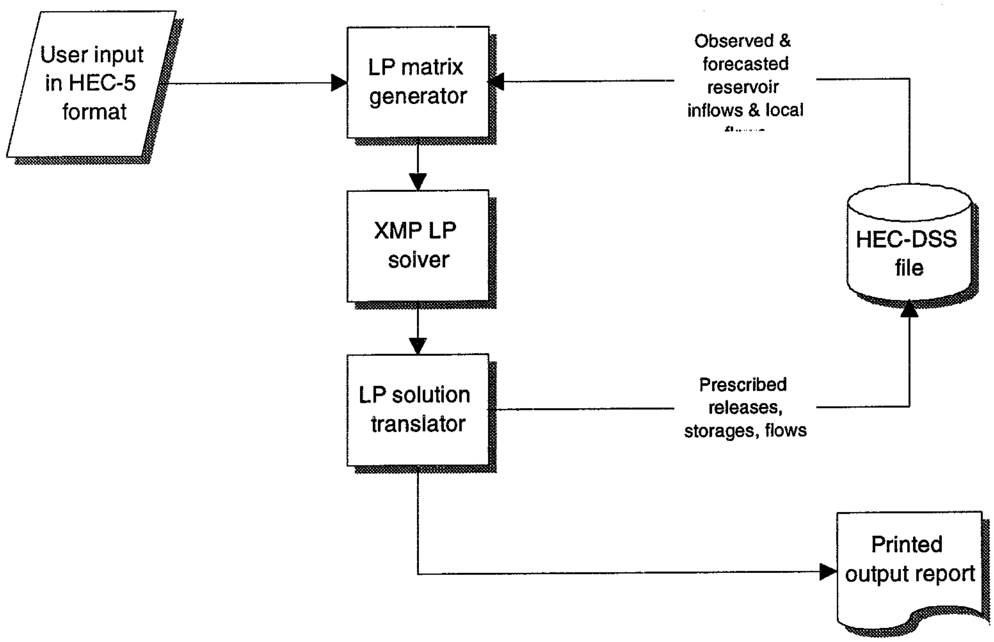

Figure 3. FCLP components

First, FCLP reads a description of the flood-control system from a user-prepared ASCII file. This file is identical, in most respects, to the ASCII input file that is read by computer program HEC-5. With the information from this file, FCLP generates the linear equations that constitute the inviolable constraints and the objective function of the LP. It then uses XMP, a general-purpose, large-scale LP solver, to find the optimal reservoir releases. The results are presented in a format similar to the output from HEC-5. In addition, releases, storages, and flows also are filed using HEC-DSS format.

User interface

We are fully aware of the popularity of graphical user interfaces. However, for the current version of FCLP we have limited the interface to one that is consistent with Corps's computer program HEC-5. Thus FCLP reads input from an ASCII text file (also known as a data file). That file is essentially identical in content and format to the file that a user would prepare for program HEC-5, as described in Exhibit 8 of the HEC-5 manual. We have, of necessity, added a few records to provide required information regarding the penalty functions. If the input file contains parameters or data required for HEC-5 but not pertinent to the LP formulation, we simply ignore them. The input is described in detail in Appendix A of this report.

In addition, we have linked FCLP with the HEC-DSS, thus permitting the user to read flow data directly from an HEC-DSS file and to write results to an HEC-DSS file. This simplifies interaction of FCLP with a runoff-forecasting model and eliminates the need for detailed post-processing and reporting.

LP solver

The LP model could be solved with any efficient LP solver. Currently FCLP uses the 1987 version of the XMP linear programming package. According to the XMP program user's manual:

> *The XMP library is an integrated collection of high-quality, portable, reliable, and widely used FORTRAN subroutines for optimization. Codes in the library can solve linear, linear mixed-integer, convex piecewise linear, and nonlinear programs. Large problems of all these types with thousands of rows and columns have been solved. All library routines utilize the XMP code for linear programming. In addition, the library contains a system for interactive LP solving and a simple modeling language.*
>
> *XMP solves large sparse linear programs with bounded variables using the primal or dual simplex method. There is a complete set of routines for sensitivity and parametric analyses.*

We elected to use XMP because it provides the following

1. *Subservience.* The library consists entirely of subroutines which may be called from user programs. All input of problem data and output of results may be handled by user routines.
2. *Portability.* XMP is written in a subset of ANSI standard FORTRAN-77, in such a way as to make it as portable as possible. According to the XMP user's manual, the mainframe version can be compiled with Microsoft or Lahey FORTRAN without any changes at all.
3. *Readability.* The XMP source code conforms to a very rigid outline and over half of the lines are comments.
4. *Modularity.* The library is hierarchically structured, and a user program may call a library routine from any level in the hierarchy. The average number of executable statements per routine is 90, while the maximum is 200.
5. *Hidden data structures.* The routines that implement the simplex method do not access the data structures directly. They interact with the data structures through special interface routines. This means that the standard data structure for the problem data (or

for the basis inverse representation) can be "unplugged" and a different one substituted.

6. *Ability to solve large problems.* XMP uses the LA05 routines, written by John K. Reid at Harwell, to manage an LU (lower triangular, upper triangular) factorization of the basis matrix. These are extremely effective on large, sparse problems. Multiple and partial pricing are both used. The XMP user's manual reports that problems with up to 25,000 constraints have been solved.
7. *Reliability.* XMP has been used since 1979 at over 200 different installations. It has been designed to stop immediately in the case of logical difficulties (i.e. inappropriate data values) or stop gracefully in the case of numerical difficulties.
8. *Extendibility.* The hierarchical, modular design and the strict coding conventions make it relatively easy to add new capabilities or substitute alternate versions of library routines.
9. *Precision.* We know from experience with HEC-PRM that precision is an issue when dealing with optimization of large systems. XMP is programmed to do most of the critical computations in double precision.

Programming details

FCLP originally was written in FORTRAN IV for a CDC 6600 computer. We ported it to the PC and recompiled it first with Microsoft FORTRAN and then with the new Lahey Fortran 90 32-bit compiler. Despite the extensive use of double precision arithmetic, we have discovered this new 32-bit compiled version is considerably faster than our older 16-bit version. Further, Lahey's modern compiler offers many advantages, including code optimization for Pentium processors and automatic checks for the Pentium flaw that could effect double-precision computations.

The current version of FCLP is an extended-DOS executable that will run in DOS or in the DOS windows of Windows 3.1x, Windows 95 or Windows NT.

Example application

System description

To illustrate application of FCLP, we include here input and output for a test problem. With minor modification, this is Test Problem 2 from Exhibit 6 of the HEC-5 user's manual. According to that manual, "This test problem illustrates the flood control operation of two parallel reservoirs being operated for a common downstream control point." The system is illustrated in Figure 4. Pertinent system characteristics are provided in the HEC-5 user's manual.

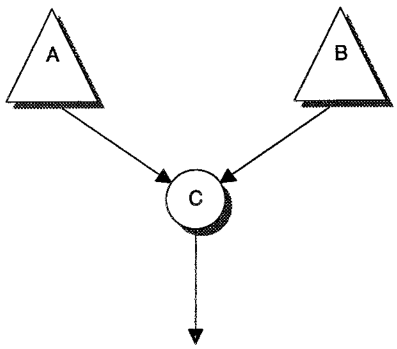

Figure 4 Reservoir system for test case

FCLP input

The input for program FCLP for the test case is included as Table 1. Only those lines that are shaded differ from the HEC-5 input for this same system. The additional input includes the following:

- Two additional information centers have been included in the FCLP input to permit specification of flow penalty functions for reservoir releases.
- RL and S$ records are included to specify the storage penalty functions for the reservoirs.
- LQ and L$ records are include to specify the flow penalty functions for the information centers.

Note that the ZR records are include to specify HEC-DSS pathnames for the observed and forecasted reservoir inflows and local flows.

Table 1. FCLP input for test case

```
T1 FCLP test problem 2 - 2 par. res. with 1 downstream c.p.
T2
T3 (same as ex. 2 of HEC-5 user's manual)
J1            2                          1
J3                                       1
C
RL   99    0    0 100000
S$              0   10
RO   1    1
RS   4    0  10000  50000  100000
RE   4    0    1    5    10
RQ   4  6000   6000   6000   6000
R2 6000   6000
P$  50   50
CP   99
ID RESERVOIR A
RT   99    89   1.9
CR   1    1
C
CP  89
ID DUMMY BELOW A
RT   89    70   1.9
CR   4    0  .333   .333   .334
LQ 6000
L$   0   1500
C
RL   98    0    0 250000
S$              0   10
RO   1    1
RS   2    0 250000
RE   2    0    10
RQ   2  12000  12000
R2 12000  12000
P$  50   50
CP   98
ID RESERVOIR B
RT   98    88   1.9
CR   1    1
C
CP  88
ID DUMMY BELOW B
RT   88    70   1.9
CR   3  .333   .333   .334
LQ 12000
L$   0   1500
C
CP   70
ID CP C
RT   70    0
LQ 25000
L$   0   1500
ED
BF   0   14        150100112       6          4
ZR=IN99  A=AAA B=99 C=FLOW E=6HOUR F=FORECAST
ZR=QA99  B=99 C=FLOW F=OBS-RELEASE
ZR=QA89  B=89 C=FLOW F=OBS-RELEASE
ZR=IN98  A=AAA B=98 C=FLOW E=6HOUR F=FORECAST
ZR=QA98  B=98 C=FLOW F=OBS-RELEASE
ZR=QA88  B=88 C=FLOW F=OBS-RELEASE
ZR=IN70  A=AAA B=70 C=FLOW E=6HOUR F=FORECAST
ZR=QA70  B=70 C=FLOW F=OBS-RELEASE
ZW A=FCLP F=TESTER
ER
```

Comparison with HEC-5 results

Penalty functions were selected for FCLP to achieve operation consistent with the rules followed by HEC-5, and FCLP was executed to find optimal releases for these functions. The results are summarized in Table 2. For comparison, this table shows also the releases and information-center flows found with HEC-5.

Table 2. Comparison of FCLP and HEC-5 results

Period	Reservoir A release		Reservoir B release		Information Center D flow	
	FCLP	HEC-5	FCLP	HEC-5	FCLP	HEC-5
1	0	0.00	0	0.00	0	0.00
2	0	0.00	0	0.00	5000	5000.00
3	0	0.00	0	0.00	15000	15000.00
4	6000	6000.00	0	0.00	25000	25000.00
5	6000	6000.00	12000	12000.00	20994	21000.00
6	6000	6000.00	12000	12000.00	13988	14000.00
7	0	0.00	8970	8999.40	21991	21999.80
8	0	0.00	0	0.00	20997	20999.80
9	0	0.00	0	0.00	25000	24999.80
10	6000	6000.00	0	0.00	30000	30000.00
11	6000	6000.00	9015	8999.40	25000	24999.80
12	6000	6000.00	12000	12000.00	20994	20999.80
13	6000	6000.00	12000	12000.00	18003	17999.80
14	6000	6000.00	12000	12000.00	18000	18000.00

Obviously, the flows prescribed by FCLP and those found with the rules embedded in HEC-5 are similar, just as one would hope. However, with FCLP, the user has much more flexibility in terms of specifying the priority of filling reservoirs, exceeding channel capacity, and so on. Often changes such as these can be accommodated with HEC-5 only by modifying code or by using clever work-arounds fashioned by experienced users.

Real-time application

The LP model described herein was designed so that it can be used as a tool for real-time operation decision making. In particular:

- It is oriented towards staged decision making. In real-time applications, decisions about reservoir releases are made at discrete points in time, in what operations researchers call *stages*. For example, suppose that at 9:00 AM we make a decision regarding releases and change reservoir gate settings accordingly. At 12:00 N, we make a new decision. These are two stages in the decision-making process. They occur at different times, they use different information, but they are interrelated. FCLP could be executed at each stage, with new information available at that stage.

- As is necessary for real-time decision making, the LP makes decisions at each stage based on the current *state* of the system. This specification of the state of the system includes a description of current storages, current flows, forecasted reservoir inflows, and forecasted local runoff downstream of the reservoirs. [Note that current flows may, in fact, be based on previous releases, so this historical information is also required.] Further, the computer program is linked with HEC-DSS, thus permitting access to updated forecasts computed with HEC-1F or a similar forecasting tool.

- It considers the future impact of current decisions. With the LP model, the decisions made at each stage for each reservoir include (1) the reservoir releases that should be made at that stage, and (2) releases that will be optimal for future stages if the optimal releases for the current stage are made and if the forecasted inflows are correct. This consideration of future stages is necessary to evaluate fully the impact of releases for the current stage, as those impacts may occur in future stages due to travel time in channels.

Appendix A: FCLP input description

This appendix describes the input required for program FCLP. As noted earlier, this input is in the form of an ASCII text file. That file follows the standard format established by the HEC for its computer programs:

- Each line in the file (record) consists of 80 characters and is divided into fields.
- Field 0 consists of the first two characters. These characters identify the type of information included on the record.
- Field 1 consists of characters 3-8. Fields 2-10 consist of 8 characters each.
- Number are right justified in each field.

Each input record required for FCLP is described briefly herein. Required records are indicated with double asterisks (**); optional records are indicated with a single asterisk (*).

To the extent possible, the FCLP input is based on input required for the Corps's program HEC-5. Exhibit 8 of the HEC-5 user's manual describes the HEC-5 input in detail. Here we have repeated parts of that description as appropriate, noting fields of the HEC-5 records that are not used by FCLP. Any HEC-5 records not described herein are not necessary for FCLP; if they are included in the input, they are ignored. In a few cases, additional records are required to provide information specific to FCLP. Those records are described in more detail here.

A.1 Documentation records

T1, T2, T3 records**

Three job title records are required. Both alphabetic and numeric information may be entered in columns 3-80 of these records. Information on these records is printed in the output for the user's reference.

C records*

These are optional comment records. They may be included anywhere within the input file to provide documentation of the input data. The record includes C in column 1, blank in column 2, and any alphabetic and numeric information in columns 3-80. The comment record is printed with the input listing at the beginning of the FCLP output.

A.2 Job records

J1 record**

Field	HEC-5 variable name	Value	Description
0		J1	Card identification.
1-2			Not used by FCLP.
3	NULEV	+	Number of index levels used in specifying storage penalty functions for project purposes and in apportioning reservoir releases amongst reservoirs.
4-9			Not used by FCLP.
10	NFL (new for FCLP)		Number of index levels used in specifying flow penalty functions for project purposes and in apportioning reservoir releases amongst reservoirs. Note that FCLP automatically adds one additional flow zone that represents all flow in excess of the final flow level.

J3 record**

All values in fields 1-9 of the J3 record are ignored by FCLP. Field 10 controls the printed output from FCLP. Three levels are available, each providing more output.

Field	HEC-5 variable name	Value	Description
0		J3	Card identification.
1-9			Not used by FCLP.
10	LPPRINT (new for FCLP)	1, 2, or 3	Output level. Level 1 is minimum output, 3 is maximum, and 2 is intermediate.

BF record**

Following the HEC-5 precedent, the BF record defines the time period for analysis.

Field	HEC-5 variable name	Value	Description
0		BF	Card identification.
1			Not used by FCLP.
2	NPER	+	Number of periods of flow data (forecast).
3			Not used by FCLP.
4	CNSTI	+	Factor which is multiplied times all inflows and local flows.
5	FLDAT	+	Date corresponding to the beginning of the time interval of the first flow. This date is specified as an 8-digit number: 2 digits for year, month, day, and hour, respectively. Thus 54120223 represents December 2, 1954, 11 PM.
6			Not used by FCLP.
7	IPER	+	Time interval, in hours, between data in all time series. Must be in whole hours, > 1.
8-9			Not used by FCLP.
10	NBAK (new for FCLP)	+	Number of time periods to look back to establish initial flow conditions throughout the system. FCLP reads control point flows for NBAK periods *prior* to the first period of the analysis and routes these flows to establish the initial conditions throughout the system.

A.3 Records for all reservoirs

RL record**

As with HEC-5, this record defines reservoir levels that define the manner in which system reservoirs are to be operated. FCLP input is limited to one RL record per reservoir.

Field	HEC-5 variable name	Value	Description
0		RL	Card identification.
1	MM	+	Control point identification number.
2	STOR1	+	Initial storage of reservoir MM in acre-feet.
3	STORL(1)	+	Cumulative reservoir capacity for level 1 for control point MM, in acre feet. This defines storage zone 1 as the storage between zero and STORL(1).
4	STORL(2)	+	Cumulative reservoir capacity for level 2 for control point MM, in acre-feet. This defines storage zone 2 as the storage between STORL(1) and STORL(2).
5-10 (as needed)	STORL(3) .... STORL(NULEV)	+	Cumulative reservoir capacity for each of NULEV levels (J1.3) for control point MM, in acre-feet. Each successive value defines a storage zone that is between that storage and the value in the previous field. Storage corresponding to level NULEV is assumed to be the reservoir capacity. FCLP will not prescribe an operation in which this value would be exceeded.

record (new for FCLP)**

This record defines the penalties for storage in zones that have been delineated by the reservoir levels specified on the RL record.

Field	HEC-5 variable name	Value	Description
0		S$	Card identification.
1-2			Not used by FCLP
3	PEN(1)	+	Penalty per ac ft of storage in zone delineated by STORL(1) in field 3 of RL record.
4	PEN(2)	+	Penalty per ac ft of storage in zone delineated by STORL(2) in field 4 of RL record.
5 - 10	PEN(3)..... PEN(NULEV)	+	Penalty per ac ft of storage in zones delineated by STORL values in corresponding fields of RL record.

The penalty for storing water in each reservoir is specified as a linear function of the volume stored in each zone of the reservoir during each period. Suppose, for example, that we wish to define only a single zone for Reservoir 99, which has capacity 100000 ac ft and an initial storage of 50 ac ft. We wish to define a penalty function for that reservoir that assigns 10 units per ac ft for storing water in that zone. In that case, specifying a single level of 100000 ac ft delineates one zone between zero and 100000 ac-ft. In that case, the RL and S$ records are as shown below:

```
Column          1         2
     123456789012345678901234
     RL    99      50  100000
     S$                 10
```

Note that the bottom of level one is assumed equal zero, so that value need not be specified on the RL record.

Suppose now that to model more complex goals for system operation, we want to operate Reservoir 99 so that we fill the upper storage only when downstream flow increases. In that case, we might subdivide the storage and define an increasing penalty function that assigns 0 units per ac ft for storing water in the lower 20000 ac ft, 5 units per ac ft between 20000 and 50000 ac ft, and 10 units per ac ft for the reminder of the reservoir. In that case, the RL and S$ records would be:

```
Column          1         2         3         4
     1234567890123456789012345678901234567890
     RL    99      50  20000   50000  100000
     S$                 0       5      10
```

RS record**

Values on RS and RQ records define the relationship of storage and maximum possible outflow.

Field	HEC-5 variable name	Value	Description
0		RS	Card identification.
1	NK	≥ 2	Number of values of that will be specified for the storage-outflow relationship for this reservoir.
2	STOR(1)	+	Reservoir capacity in acre-feet for first point on storage-outflow relationship for control point MM.
3-10 (as needed)	STOR(2) ... STOR(NK)	+	Reservoir capacity in acre-feet for remaining NK points on storage-outflow relationship for control point MM.

RQ record**

Field	HEC-5 variable name	Value	Description
0		RS	Card identification.
1	NK	≥ 2	Number of values of that will be specified for the storage-outflow relationship for this reservoir.
2	QCAP(1)	+	Total reservoir outlet capacity for control point MM in cfs, corresponding to storage in field 2 of RS record.
3-10 (as needed)	QCAP(2) ... QCAP(NK)	+	Total reservoir outlet capacity for control point MM in cfs, corresponding to storage in fields 3-10 of RS record.

R2 record**

This record defines the allowable rate of change for releases. Penalties for exceeding these rates are defined on the P$ record.

Field	HEC-5 variable name	Value	Description
0		R2	Card identification.
1	RTCHGR	+	Allowable rate of change of reservoir release, in cfs per hour, when the release from this reservoir increases from the previous period.
2	RTCHGF	+	Allowable rate of change of reservoir release, in cfs per hour, when the release from this reservoir decreases from the previous period.
3-10			Not used by FCLP.

record (new for FCLP)**

Values on this record define the penalty for exceeding allowable rates of release change that are shown on the R2 record.

Field	HEC-5 variable name	Value	Description
0		P$	Card identification.
1	PENRA (new for FCLP)	+	Penalty per cfs for exceeding RTCHGR (field 1 of the R2 record).
2	PENFA (new for FCLP)	+	Penalty per cfs for exceeding RTCHGF (field 2 of the R2 record).

R9 record (new for FCLP)**

Values on this record define the start and stop period to use an alternative storage and maximum possible outflow relationship. R9 record must be followed by RS and RQ records that define alternative relationship. RS and RQ records can contain only two entries.

Field	HEC-5 variable name	Value	Description
0		R9	Card identification.
1	START (new for FCLP)	+	Period when the alternative relationship starts.
2	STOP (new for FCLP)	+	Period when the alternative relationship stops.

A.4 Control point records for hydrologic data

CP, ID, and RT records are required for all control points, including reservoirs.

CP record**

Field	HEC-5 variable name	Value	Description
0		CP	Card identification.
1	MM	+	User integer identification number.
2-10			Not used by FCLP

ID record**

Field	HEC-5 variable name	Value	Description
0		ID	Card identification.
1-4	CPT	any	Title (alphanumeric) of control point in record columns 3-32. This will be printed in summary output.
5-10			Not used by FCLP

LQ record (new for FCLP) **

Values on the LQ and L$ record define the flow penalty function for an information center.

Field	HEC-5 variable name	Value	Description
0		LQ	Card identification.
1	Q(1)	+	Cumulative flow rate for flow level 1 for control point MM, in cfs. This defines flow zone 1 as the flow between flow = zero and flow = Q(1) cfs.
2	Q(2)	+	Cumulative flow rate for flow level 2 for control point MM, in cfs. This defines flow zone 2 as the flow between Q(1) and Q(2) cfs.
3-10 (as needed)	Q(3) ... Q(NLF)		Cumulative flow rate for flow levels 3, ... NFL (J1.10) for control point MM, in cfs. Each successive value defines a flow zone between that value and the flow in the previous field. Flow may exceed the value shown as level NLF.

record (new for FCLP)**

Field	HEC-5 variable name	Value	Description
0		L$	Card identification.
1	PEN(1)	+	Penalty per cfs for flow in first flow zone defined by values on LQ record.
2	PEN(2)	+	Penalty per cfs for flow in second flow zone defined by values on LQ record.
3-10	PEN(3)... PEN(NLF+1)		Penalty per cfs for flow in successive flow zones defined by values on LQ record + an additional penalty per cfs for flow that exceeds Q(NFL), the maximum flow level specified on the LQ record.

RT record**

Values on this record define parameters of the routing model for the reach downstream of control point MM. The routing of FCLP is restricted to either (1) user specified linear routing coefficients or (2) the Muskingum method. If the first option is selected, a CR record must be provided.

Field	HEC-5 variable name	Value	Description
0		RT	Card identification.
1	RTFR	+	Control point number of upstream end of routing reach. Equal to MM on the CP record.
2	RTTO	+	Control point number of downstream end of routing reach MM. Equal to MM of the CP record for the next downstream control point. May be left blank for the most downstream control point in the system.
3	RTMD	+X.Y	Number of sub-reaches (X) and code for method of routing (Y). For FCLP, X must equal 1, and Y is restricted to the following: Y = 2 for Muskingum routing Y = 9 for user-specified coefficients; in this case, the RT record must be followed by CR record.
4	X	$0 \leq X \leq 0.5$	Muskingum routing model parameter X. Must be specified if RT.3 = 1.2.
5	K	+	Muskingum routing model parameter K. Must be specified if RT.3 = 1.2.
6-10			Not used by FCLP

CR record*

Linear routing coefficients are specified on this record, if required. Note that (1) each coefficient must be between 0.0 and 1.0; (2) one to five coefficients can be specified; and (3) the sum of the coefficients must be 1.0 to maintain continuity in the routing.

Field	HEC-5 variable name	Value	Description
0		CR	Card identification.
1	NUMCOF	≤ 5	Number of routing coefficients specified on this record.
2-5	IRTCOF(1) ... IRTCOF(NUMCOF)	+	Routing coefficients (as coefficients of inflow).

A.5 Time series

ZR record**

Read time series data from HEC-DSS.

Record Columns	HEC-5 variable name	Value	Description
0	ID	ZR	Card identification.
3-5	Data type	Blank	
		Data Type	An equal sign and the time series record ID indicating what data type to read from DSS (i.e. =IN or =QA).
6-8	MM	+	Up to three digit CP number (left justified) as defined on CP record, causes data for only that location to be read from DSS.
10+	Pathname Parts		Free form identification of pathname parts. Each pathname part is separated by a comma or space. Unspecified pathname parts will assume values specified on previous ZR cards.

Examples:

```
ZR=IN1   A=IOWA B=IOWA CITY C=FLOW-INC F=COM
ZR=IN15  B=DES MOINES
ZR=IN20  B=OTTUMWA C=FLOW F=NATURAL
```

For each reservoir, ZR records specify the pathname for observed releases prior to the time and date of the start of the analysis (as specified on the BF record) and the pathname of forecasted inflows for the analysis. To differentiate what data are to be read from the HEC-DSS record with the given pathname, the ZR record must include either =QA to indicate that the pathname is for observed releases or =IN to indicate that the pathname is for forecasted inflows. If ZR records are not provided for the reservoir, if the record does not include either =QA or =IN, or if HEC-DSS records with the specified pathnames do not exist, FCLP assumes that the observed releases and/or forecasted inflows are zero.

Likewise, for each information center, ZR records specify the pathname for observed total flows prior to the time and date of the start of the analysis (as specified on the BF record) and the pathname of forecasted local flows for the analysis. To differentiate what data are to be read from the HEC-DSS record with the given pathname, the ZR record must include either =QA to indicate that the pathname is for observed flow or =IN to indicate that the pathname is for forecasted local flows. If ZR records are not provided for the information center, if the record does not include either =QA or =IN, or if HEC-DSS records with the specified pathnames do not exist, FCLP assumes that the observed flows and/or forecasted local flows are zero.

ZW record**

Write data to the HEC-DSS file. FCLP is designed to file all results in the HEC-DSS. FCLP will automatically assign the B, C, D, and E-part as appropriate. If the ZW record is included, FCLP will automatically file release, storage, and flows for reservoirs, and flows for information centers.

Record Columns	HEC-5 variable name	Value	Description
0	ID	ZW	Card identification.
3+	Pathname Parts		Free form identification of pathname parts. Each pathname part is separated by a comma or space. Only parts A and F can be specified. Other parts will be constructed using control point ID, type of data being written, and date specified on BF record.

Example: ZW A=FCX F=BASE RUN

Appendix C

INCREMENTAL INFLOWS

List of Figures

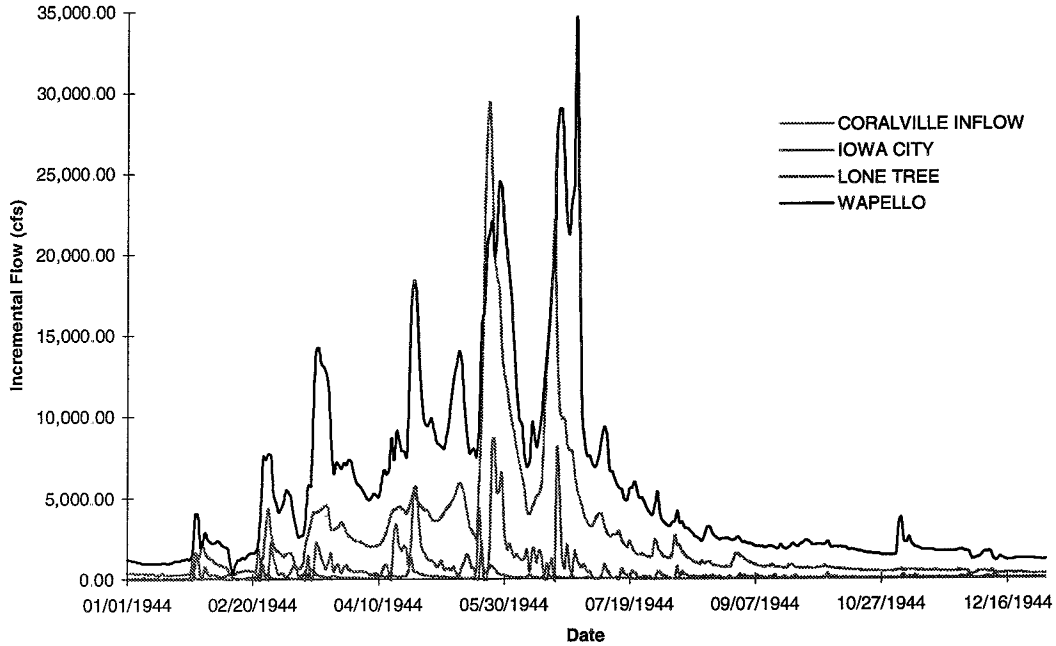

FIGURE C-1 Iowa River Incremental Inflows - Flood of 1944

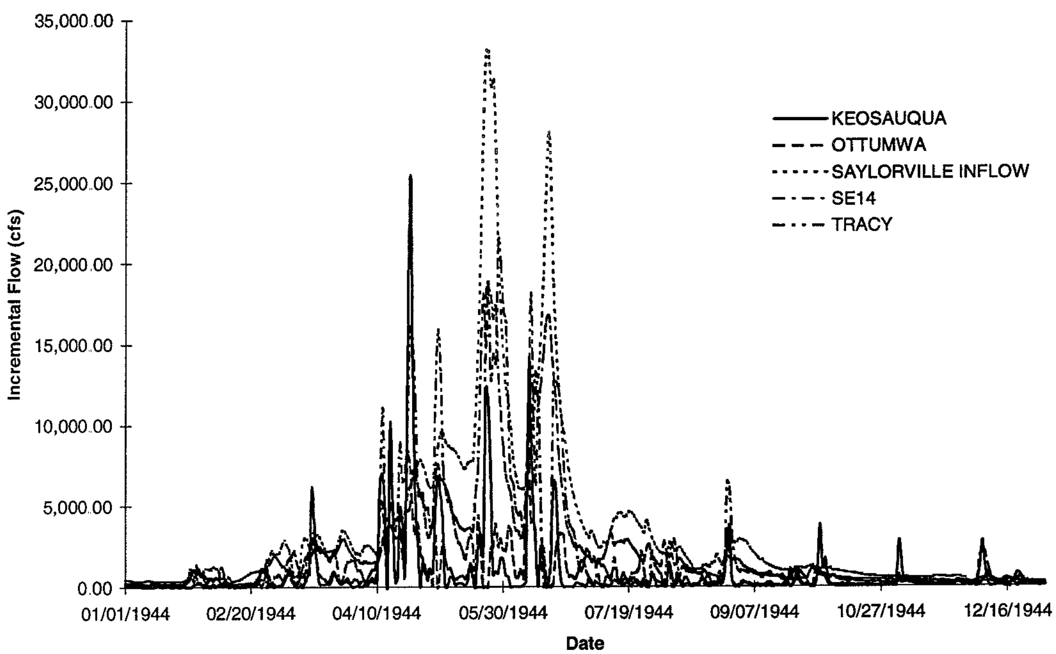

FIGURE C-2 Des Moines River Incremental Inflows - Flood of 1944

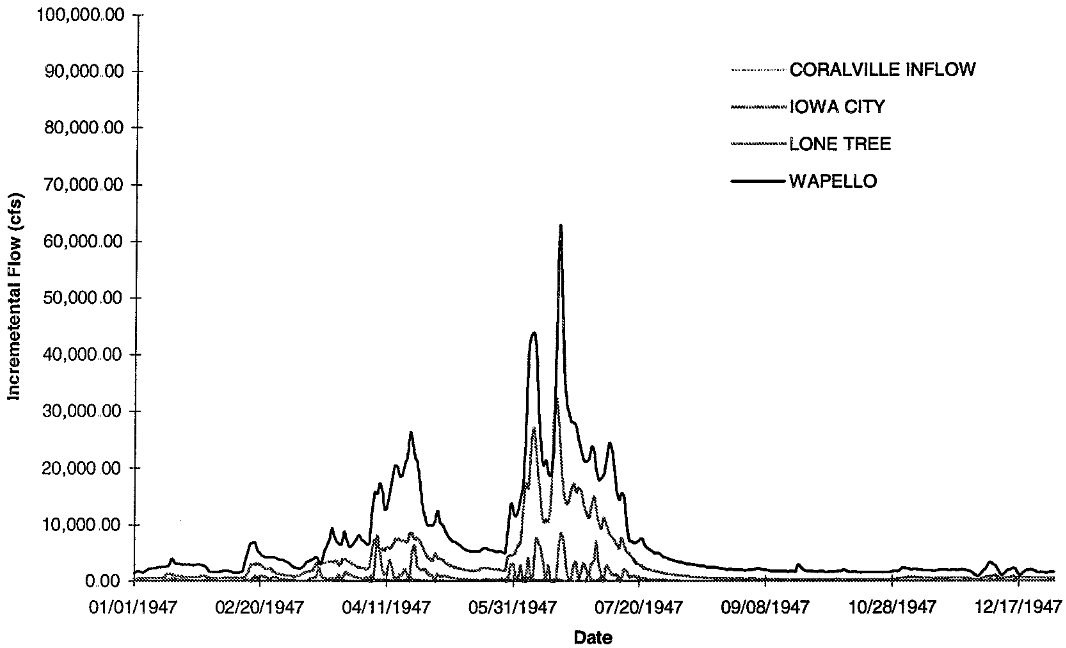

FIGURE C-3 Iowa River Incremental Inflows - Flood of 1947

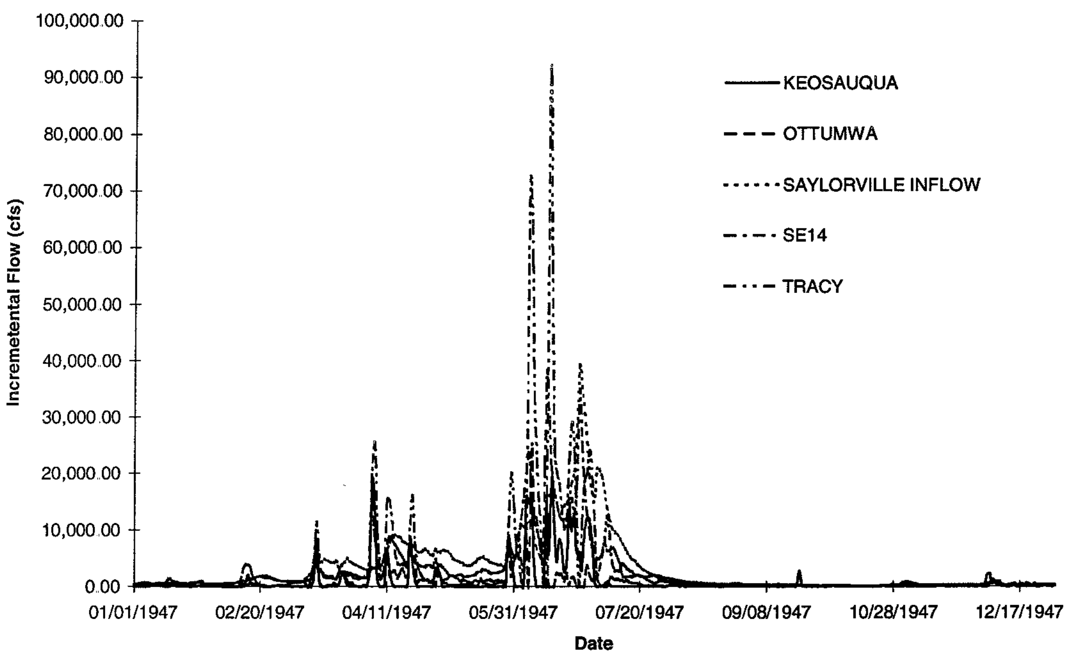

FIGURE C-4 Des Moines River Incremental Inflows - Flood of 1947

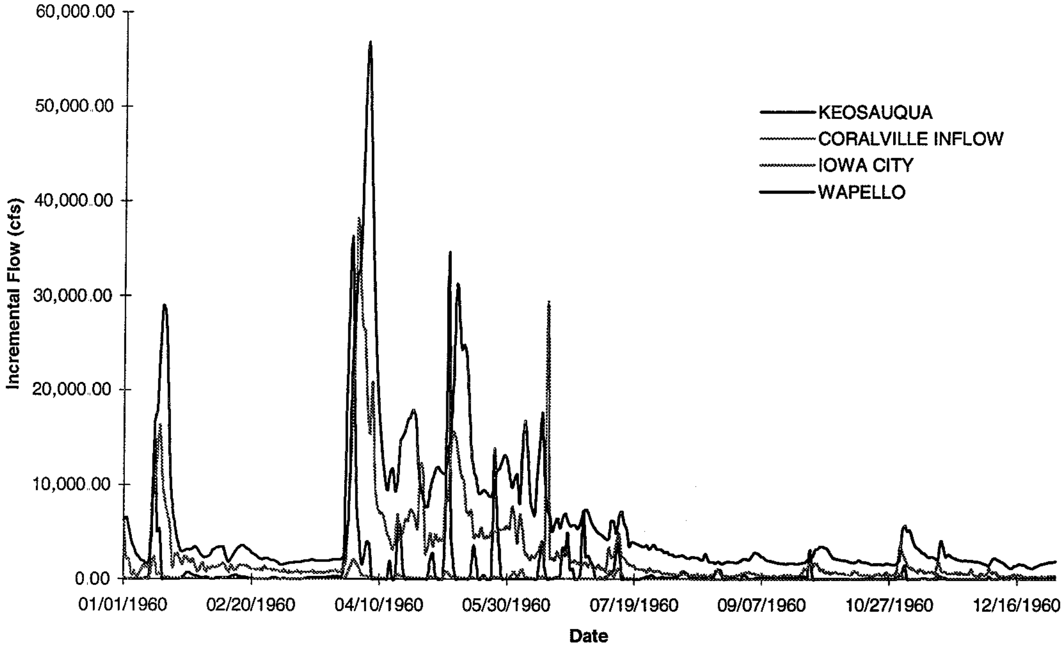

FIGURE C-5 Iowa River Incremental Inflows - Flood of 1960

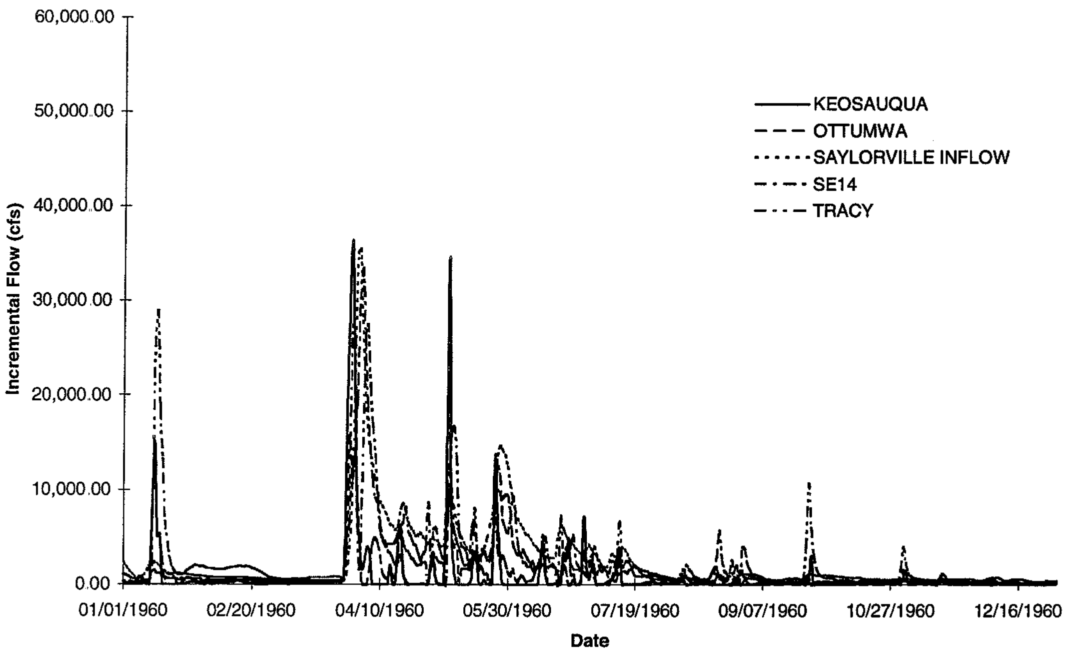

FIGURE C-6 Des Moines River Incremental Inflows - Flood of 1960

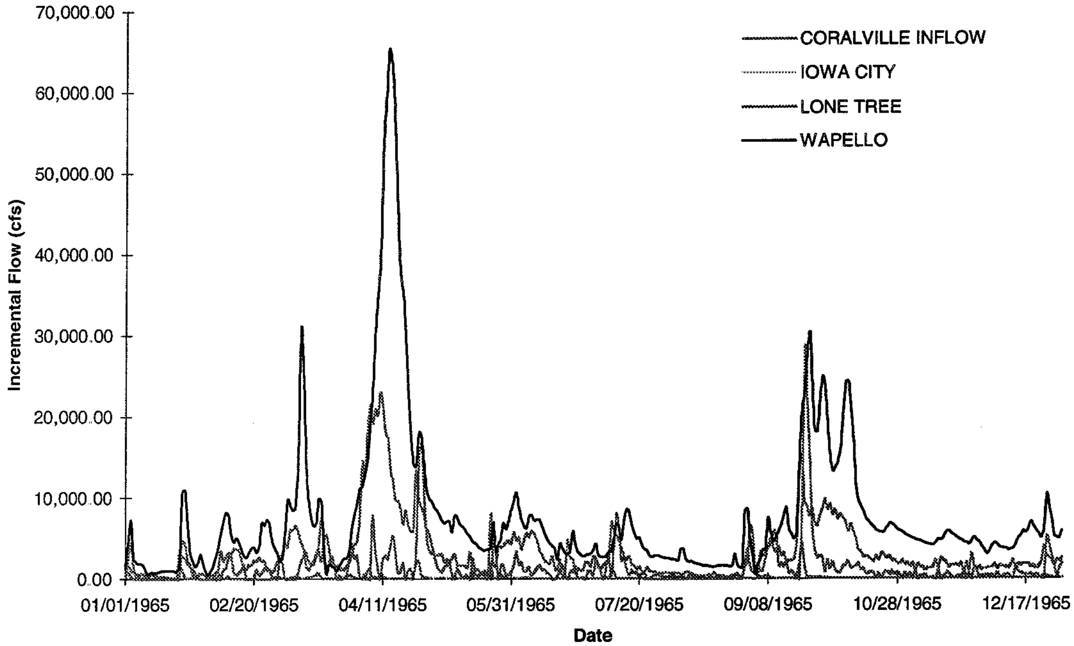

FIGURE C-7 Iowa River Incremental Inflows - Flood of 1965

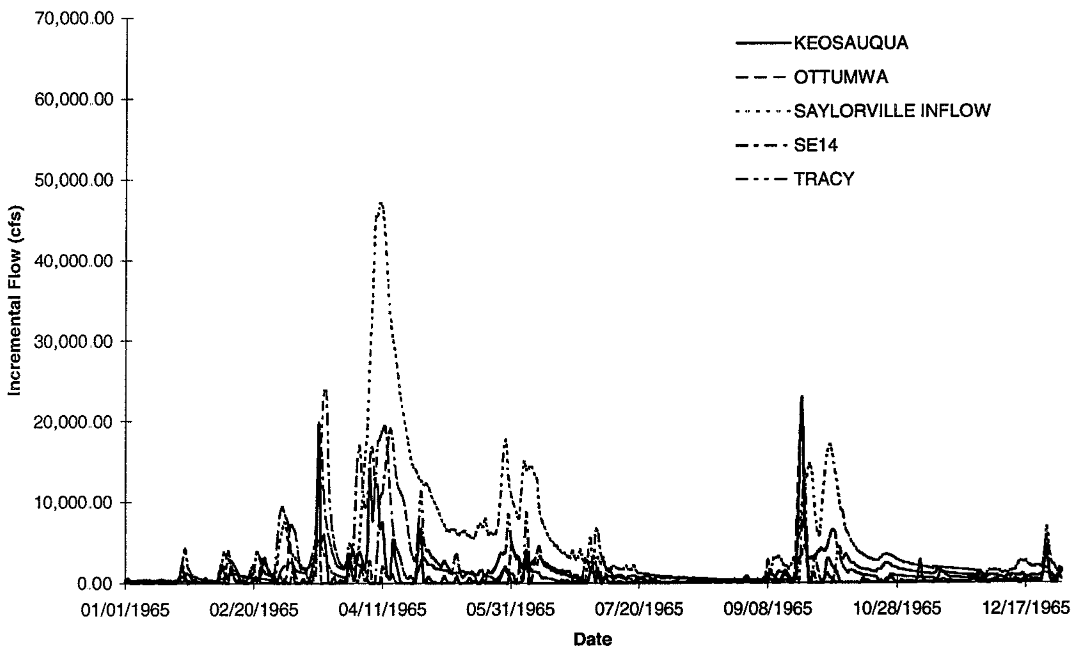

FIGURE C-8 Des Moines River Incremental Inflows - Flood of 1965

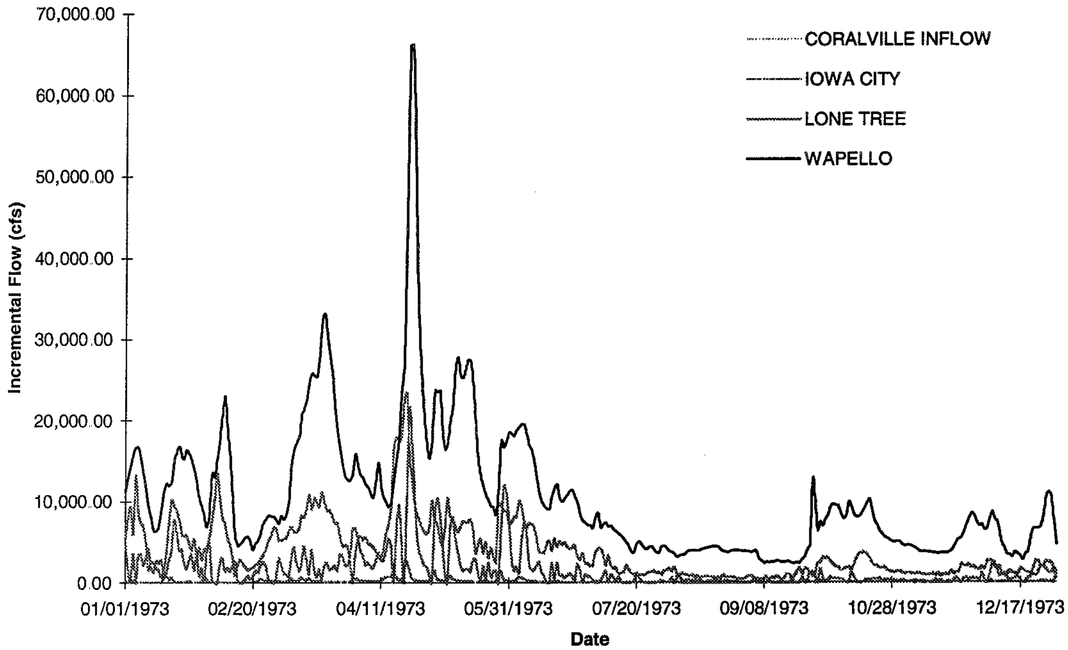

FIGURE C-9 Iowa River Incremental Inflows - Flood of 1973

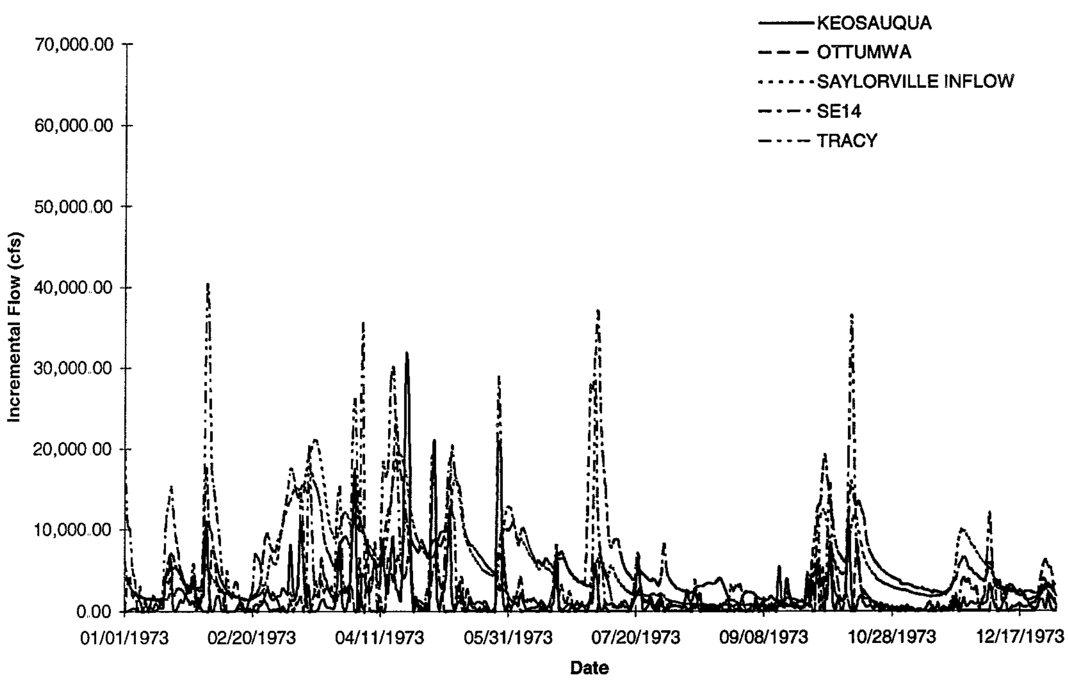

FIGURE C-10 Des Moines River Incremental Inflows - Flood of 1973

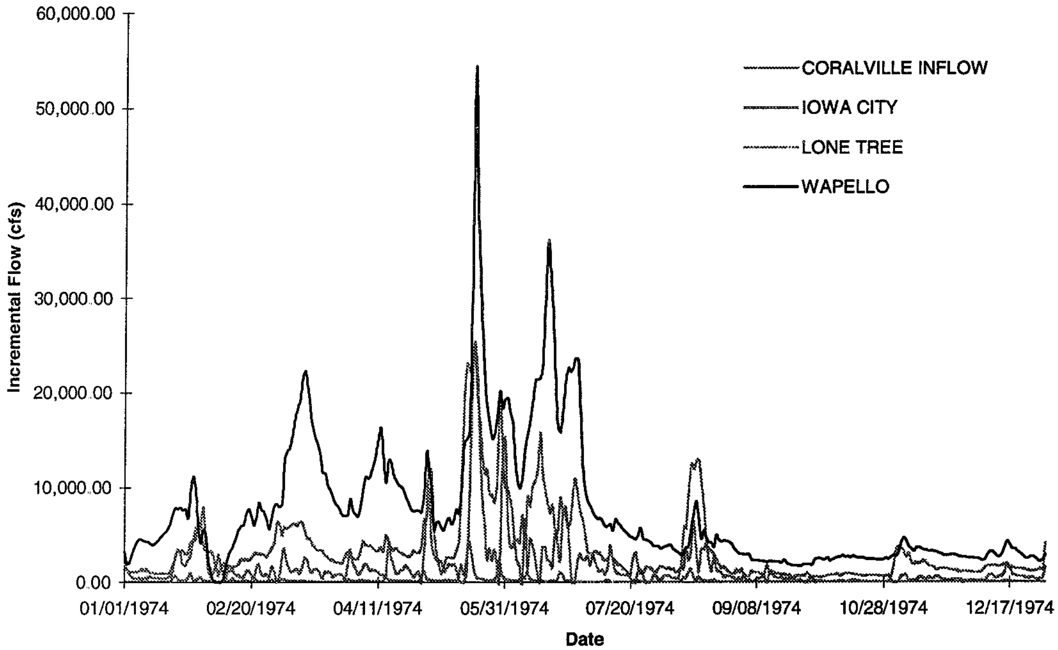

FIGURE C-11 Iowa River Incremental Inflows - Flood of 1974

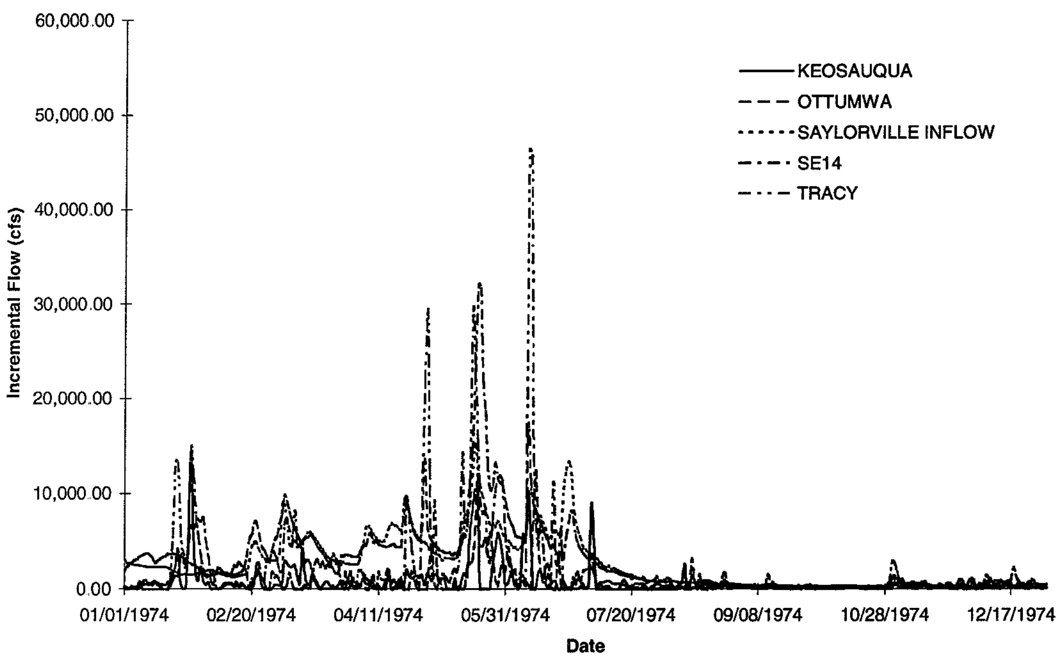

FIGURE C-12 Des Moines River Incremental Inflows - Flood of 1974

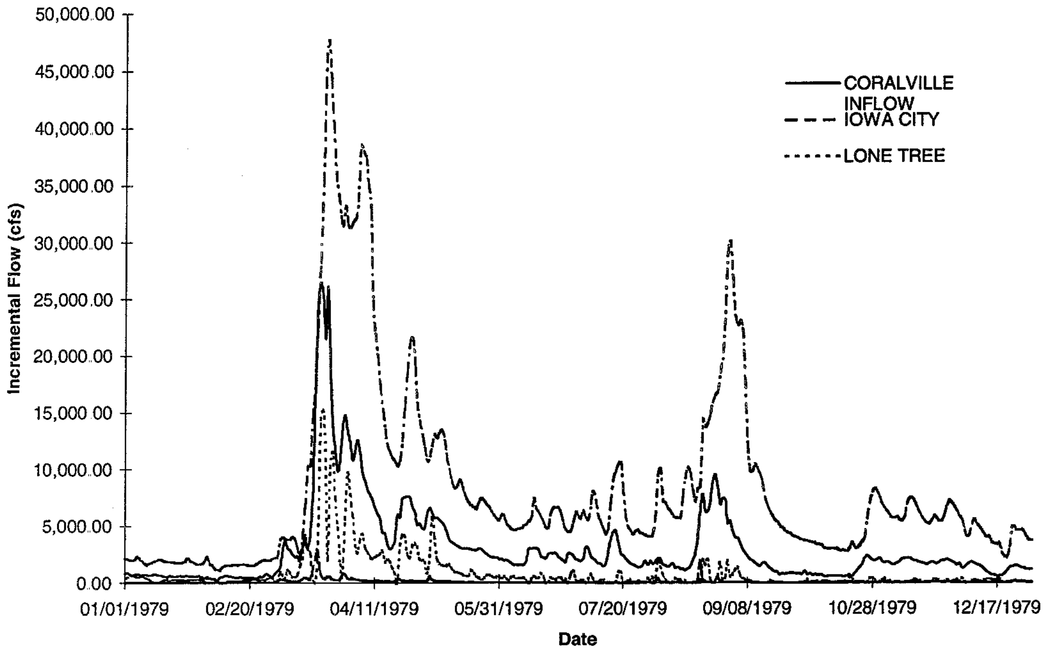

FIGURE C-13 Iowa River Incremental Inflows - Flood of 1979

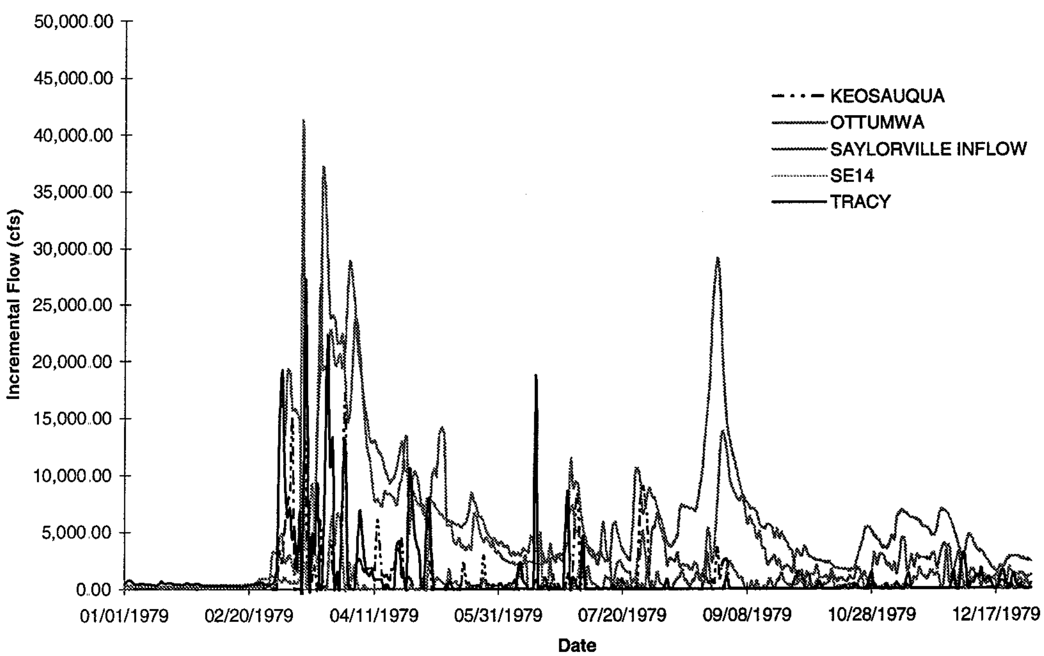

FIGURE C-14 Des Moines River Incremental Inflows - Flood of 1979

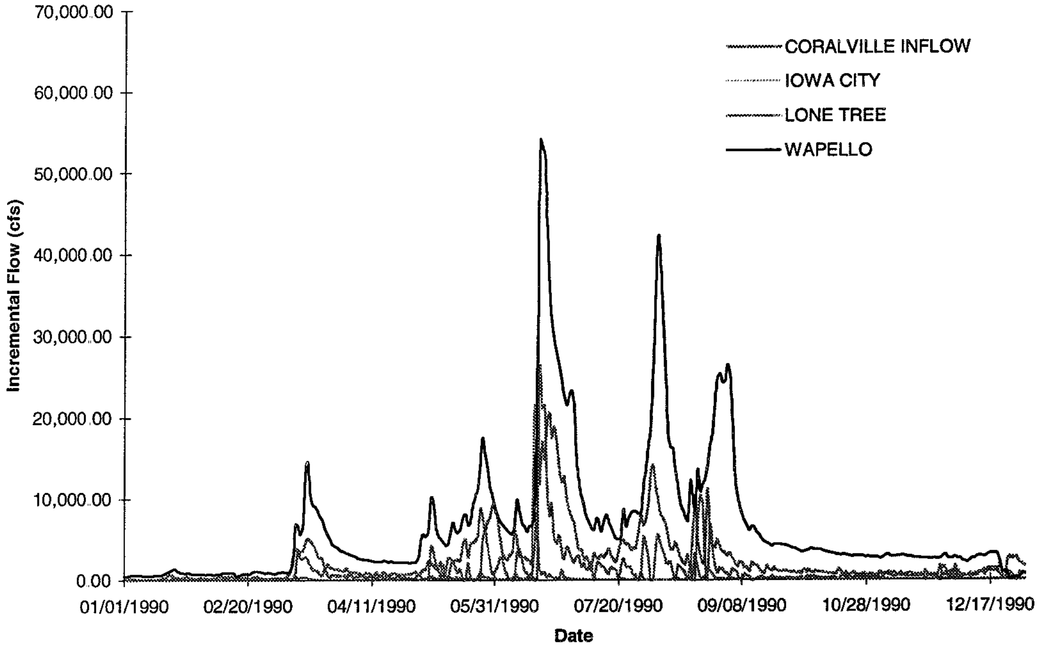

FIGURE C-15 Iowa River Incremental Inflows - Flood of 1990

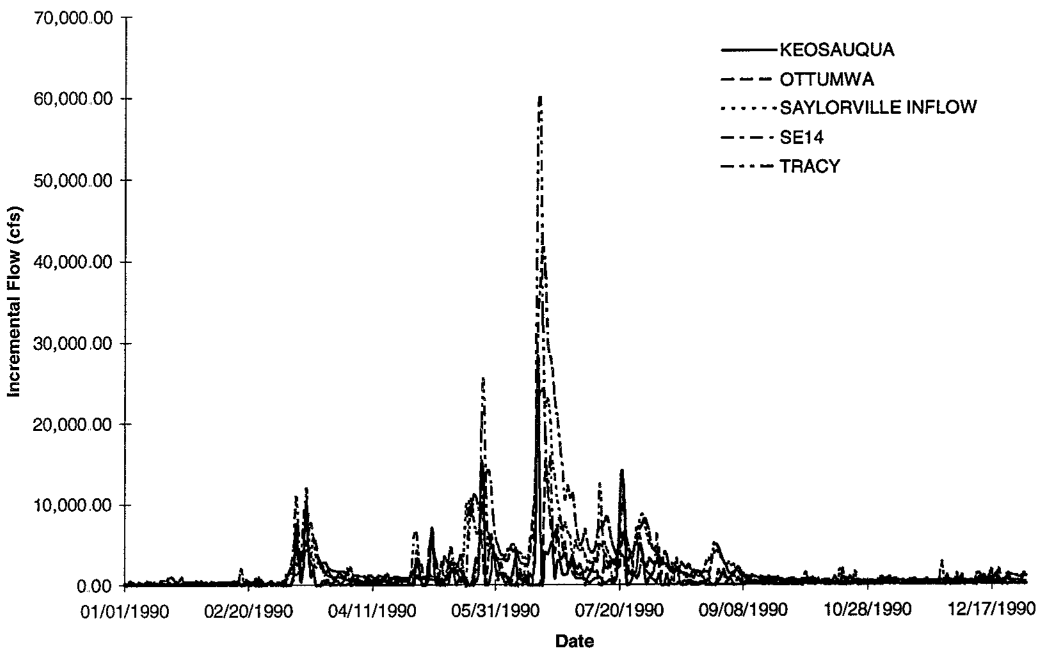

FIGURE C-16 Des Moines River Incremental Inflows - Flood of 1990

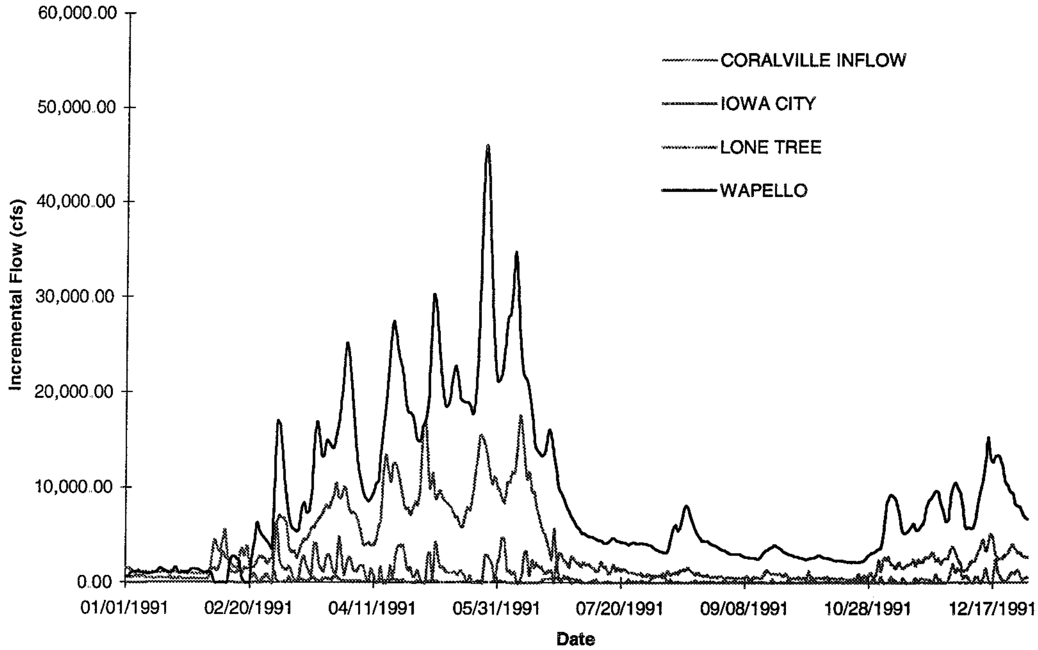

FIGURE C-17 Iowa River Incremental Inflows - Flood of 1991

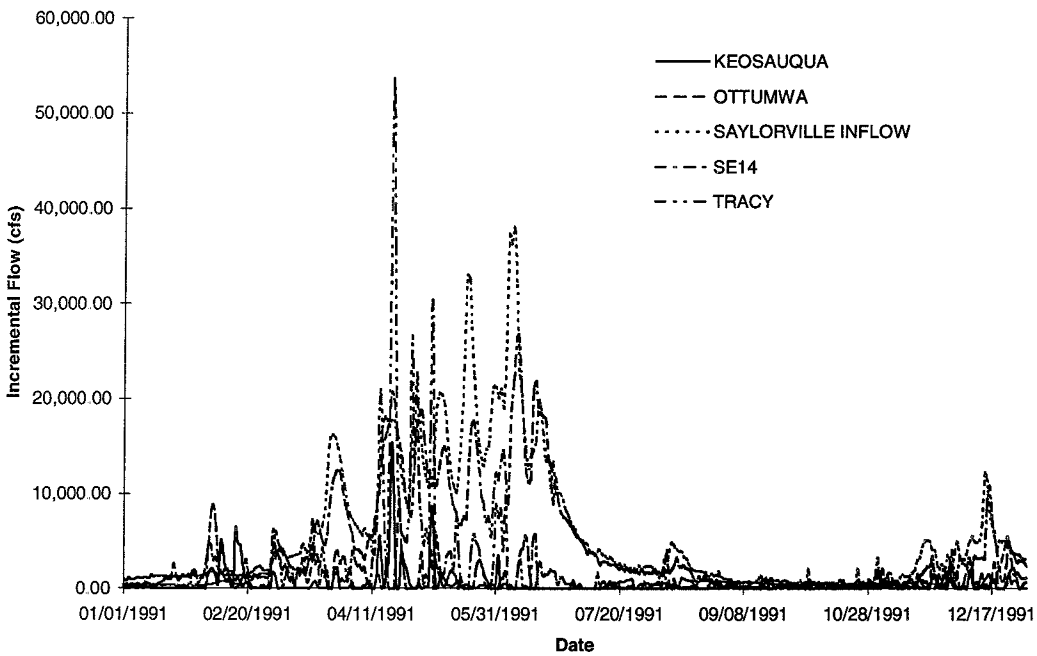

FIGURE C-18 Des Moines River Incremental Inflows - Flood of 1991

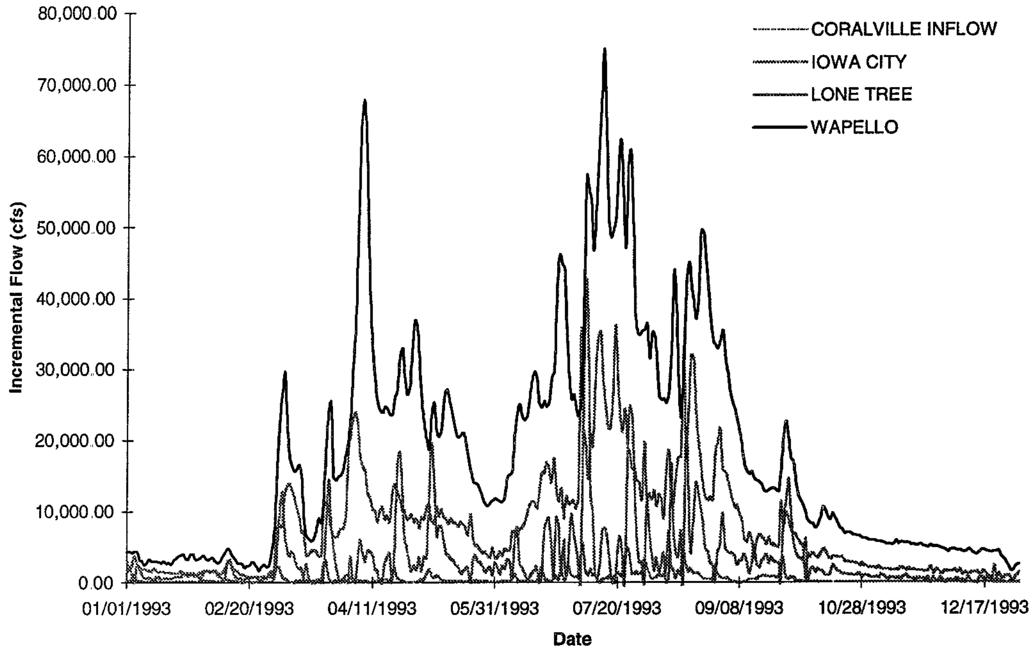

FIGURE C-19 Iowa River Incremental Inflows - Flood of 1993

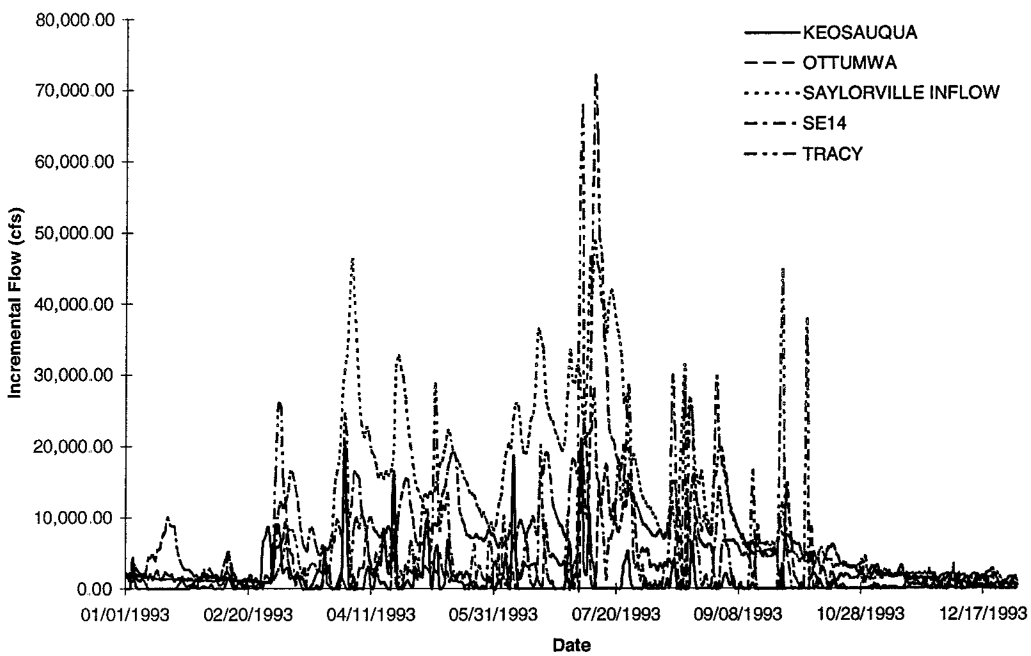

FIGURE C-20 Des Moines River Incremental Inflows - Flood of 1993

Appendix D

COMPARISON OF MODEL RESULTS AND OBSERVED DATA

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INTRODUCTION

The following charts illustrate natural flows, observed data, and model results at each of the control point on the Iowa, Des Moines and Mississippi River for the ten flood events studied. Natural flows are denoted by the abbreviation NAT, observed data is denoted by OBS, and model results for operating scheme A are denoted by FCX. (The acronyms FCX and FCLP are interchangeable).

Natural flow (NAT) is the flow that would occur at each location if there were no reservoirs in place. Incremental inflows used by the model were calculated from this data. Natural flow are plotted against observed and model results to illustrated the effect of the reservoirs. Values for natural flow were provided by the USACE Rock Island District.

Observed data (OBS, OBS_COM) is the actual data recorded by the USGS gages or values computed from upstream USGS gages if a gage did not exist in the required location. Observed data is equal to natural data on the Iowa River for the 1944 and 1947 flood events since Coralville Reservoir did not go into operation until 1958. On the Des Moines River, observed flows above Lake Red Rock are equal to natural flows for the 1944, 1947, 1960, 1965, 1973, and 1974 flood events since Saylorville Reservoir was not operational until 1975. Finally, Red Rock Reservoir did not go into operation until 1969 so observed flows below Red Rock are equal to natural flows for the flood of 1944, 1947, 1960, and 1965.

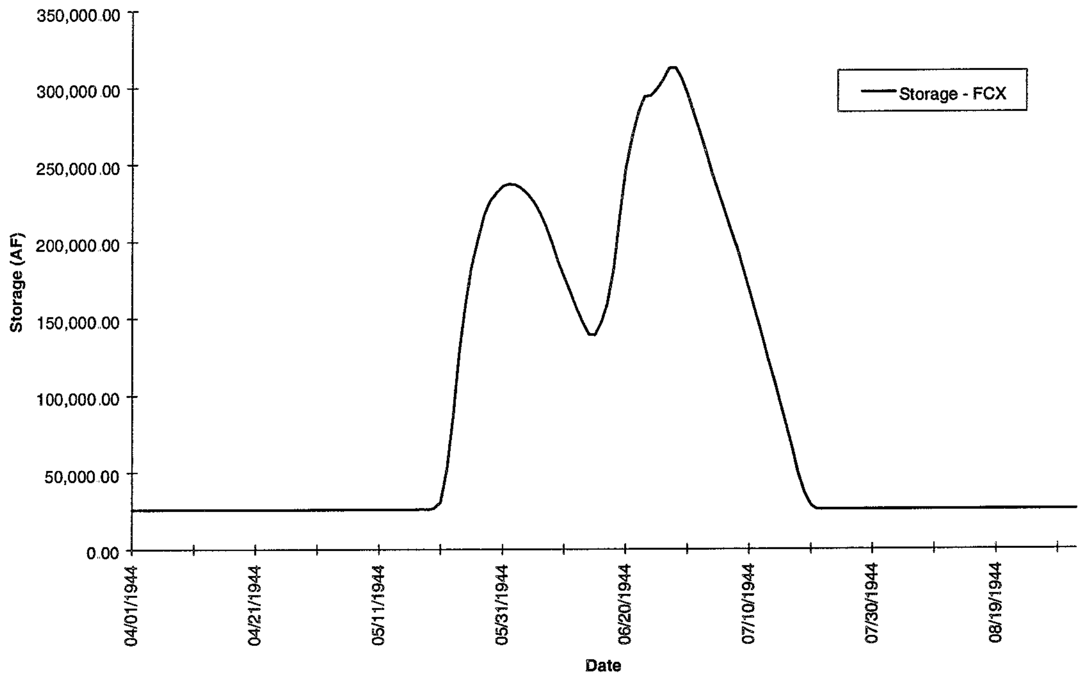

FIGURE D-1a. Coralville Reservoir Storage - Flood of 1944

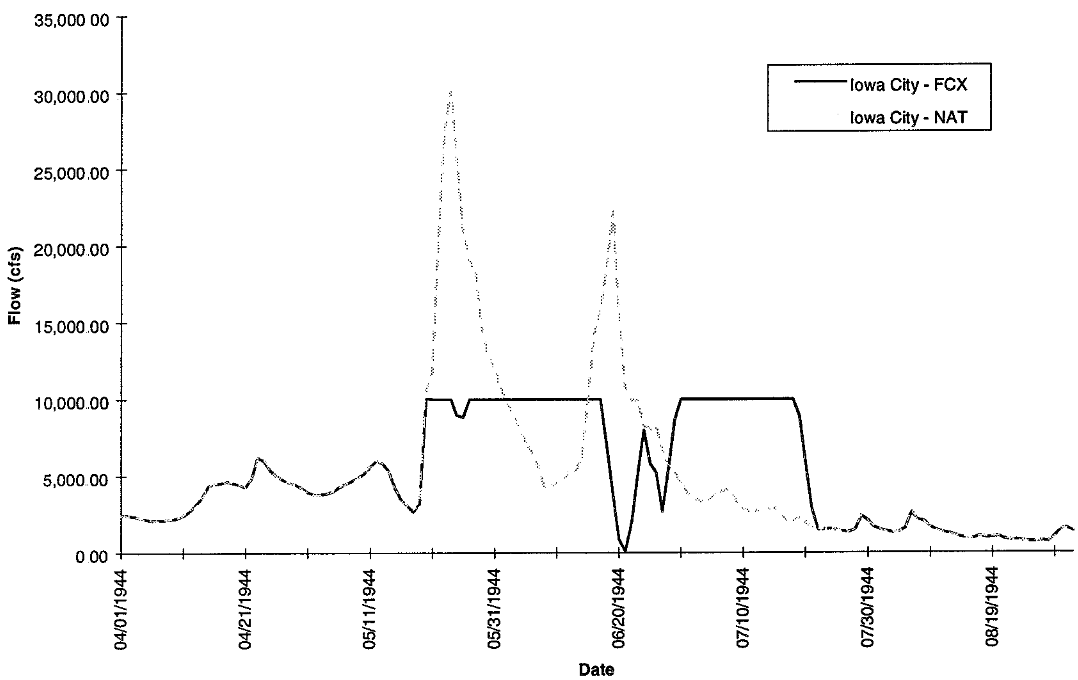

FIGURE D-1b. Iowa City Hydrograph - Flood of 1944

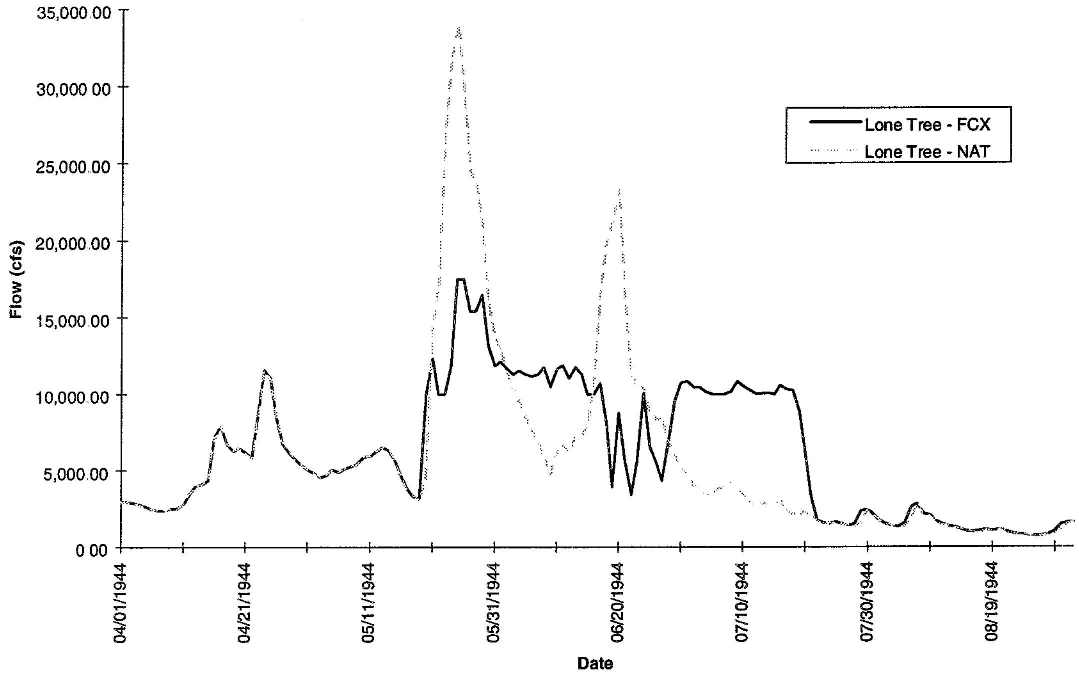

FIGURE D-1c. Lone Tree Hydrograph - Flood of 1944

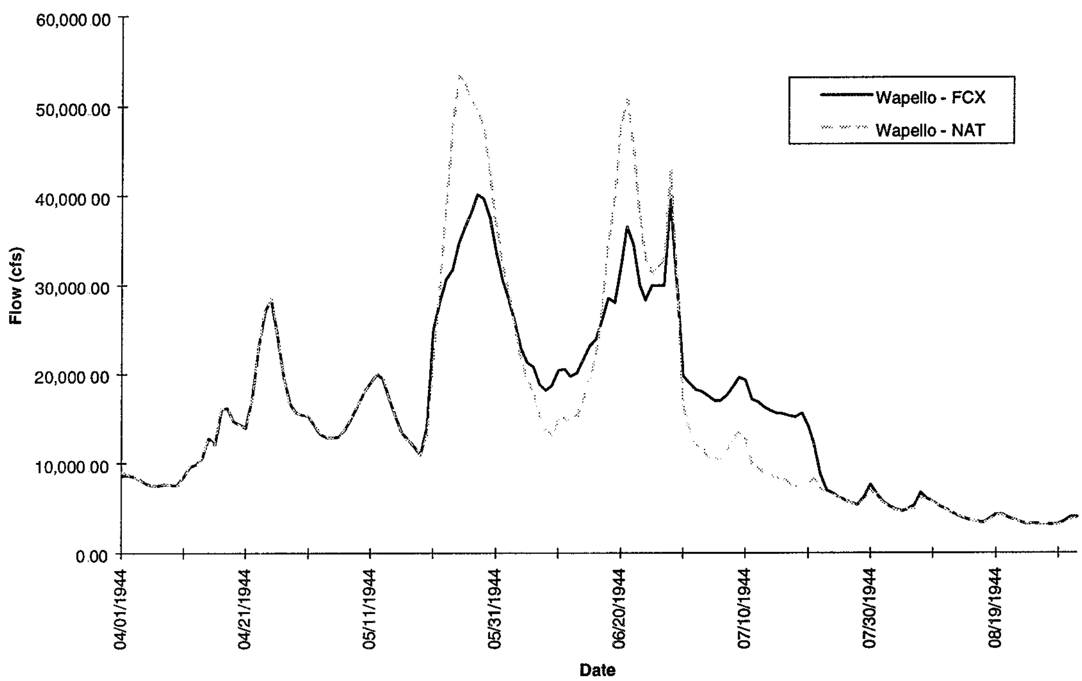

FIGURE D-1d. Wapello Hydrograph - Flood of 1944

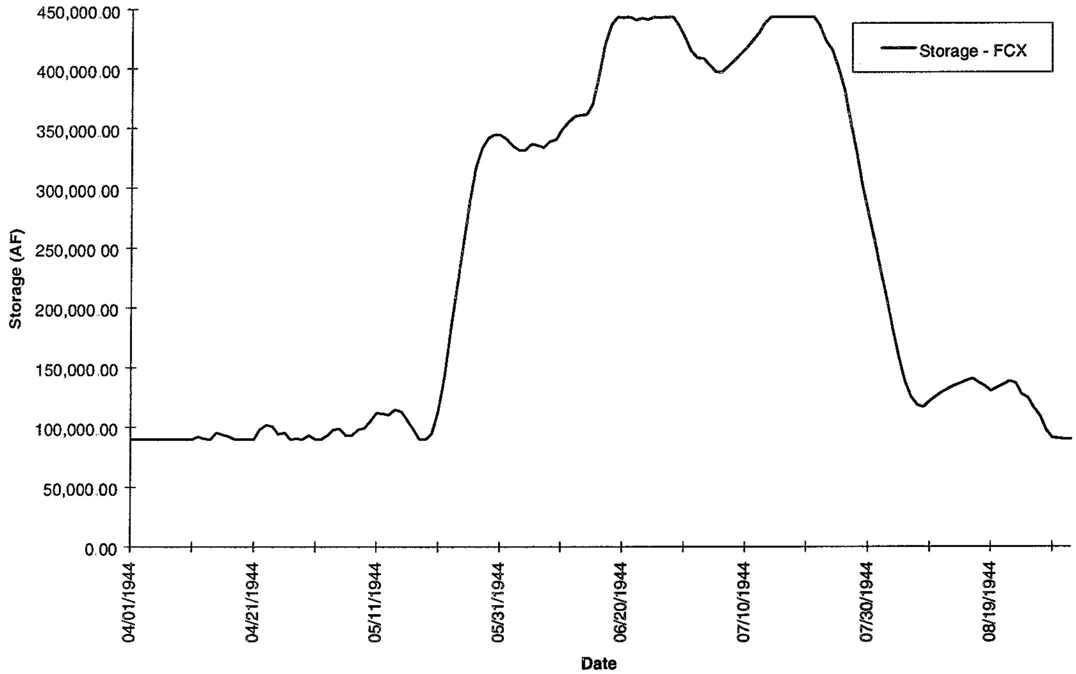

FIGURE D-1e. Saylorville Reservoir Storage - Flood of 1944

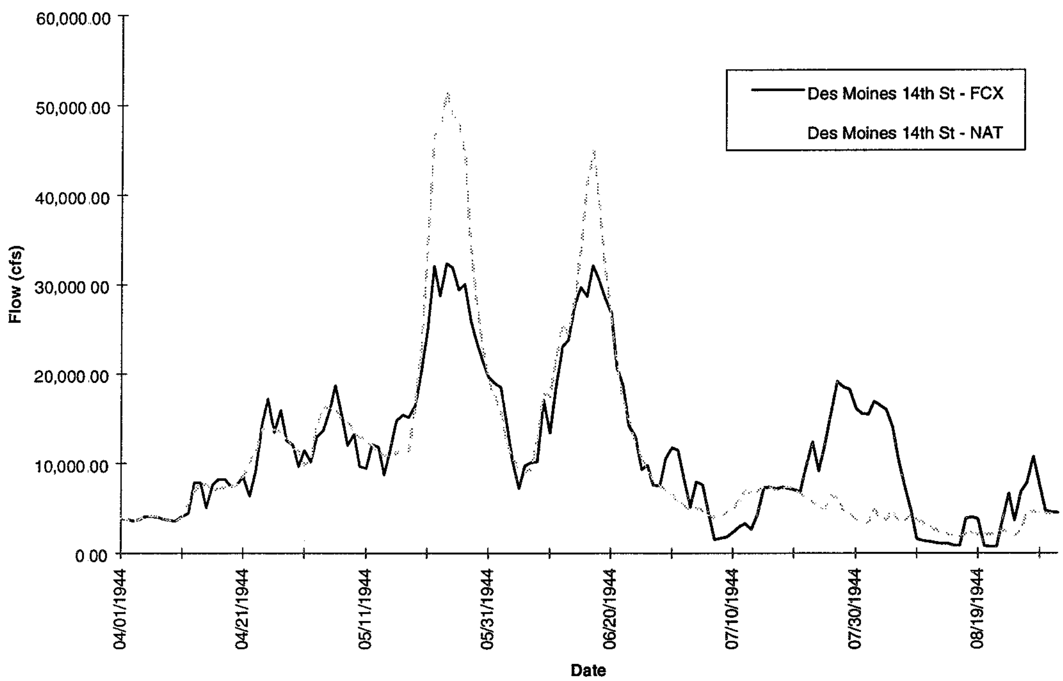

FIGURE D-1f. Des Moines 14th Street - Flood of 1944

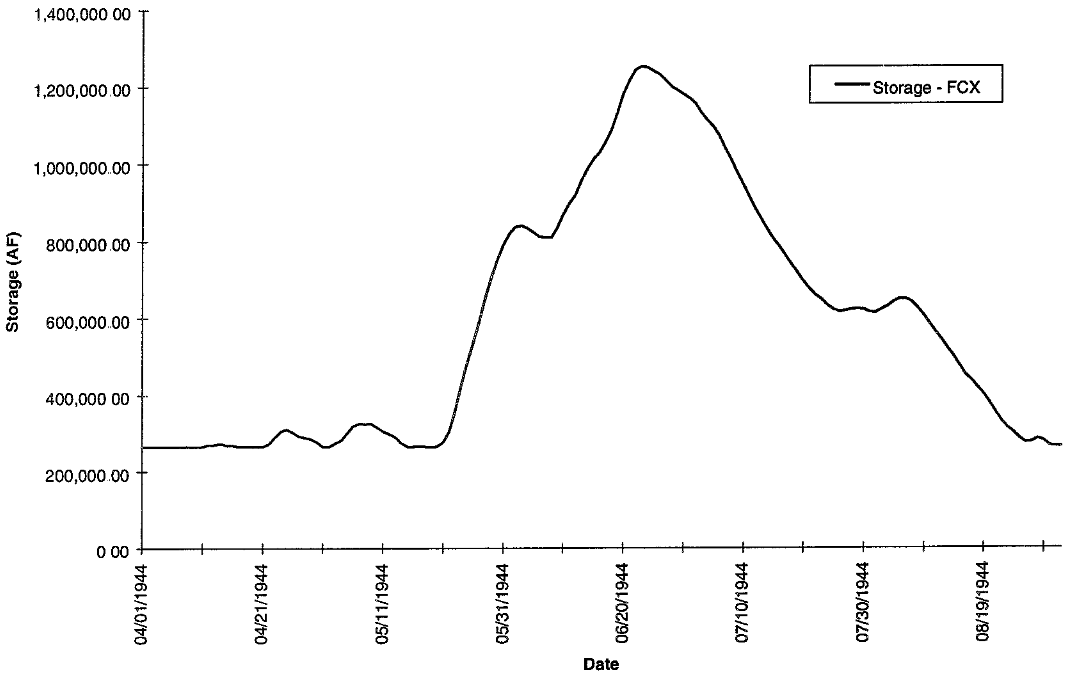

FIGURE D-1g. Lake Red Rock Storage - Flood of 1944

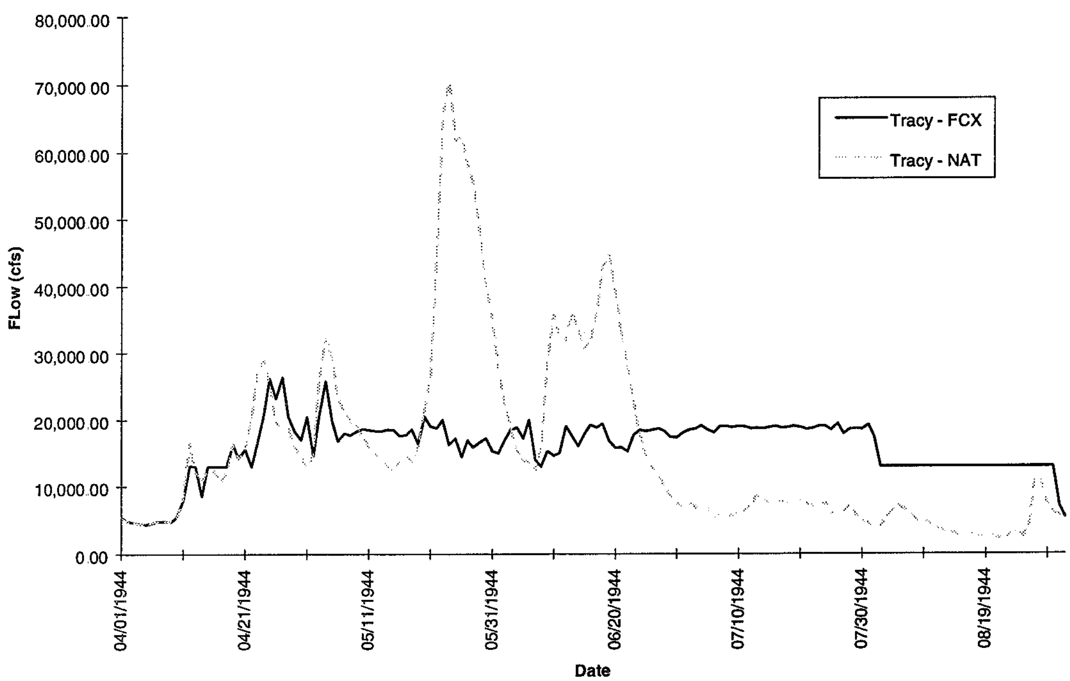

FIGURE D-1h. Tracy Hydrograph - Flood of 1944

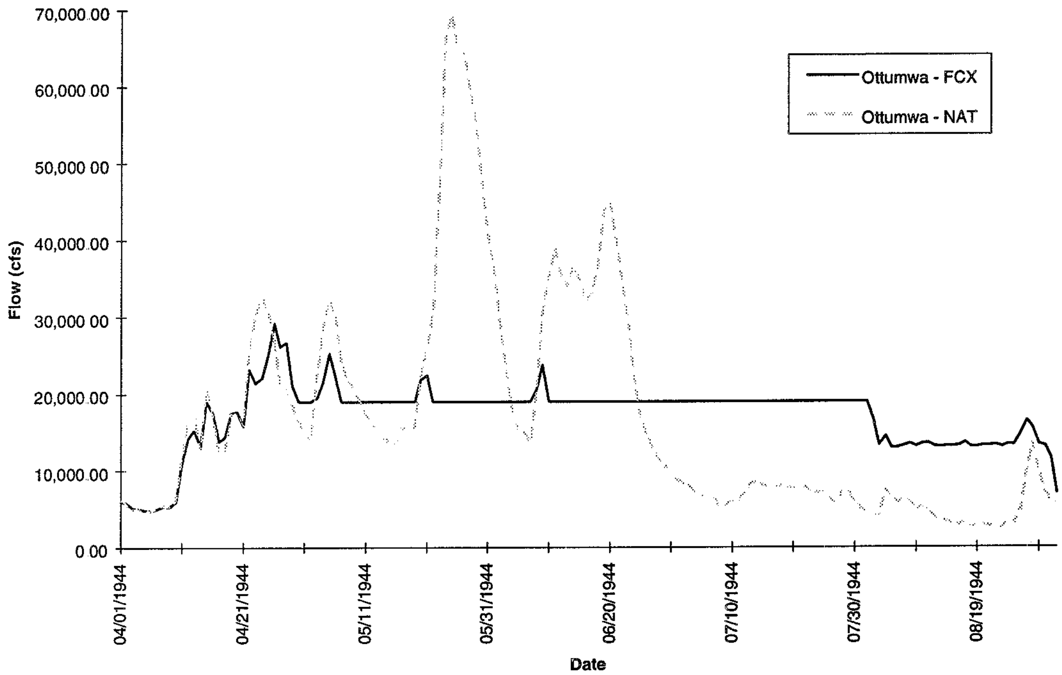

FIGURE D-1i. Ottumwa Hydrograph - Flood of 1944

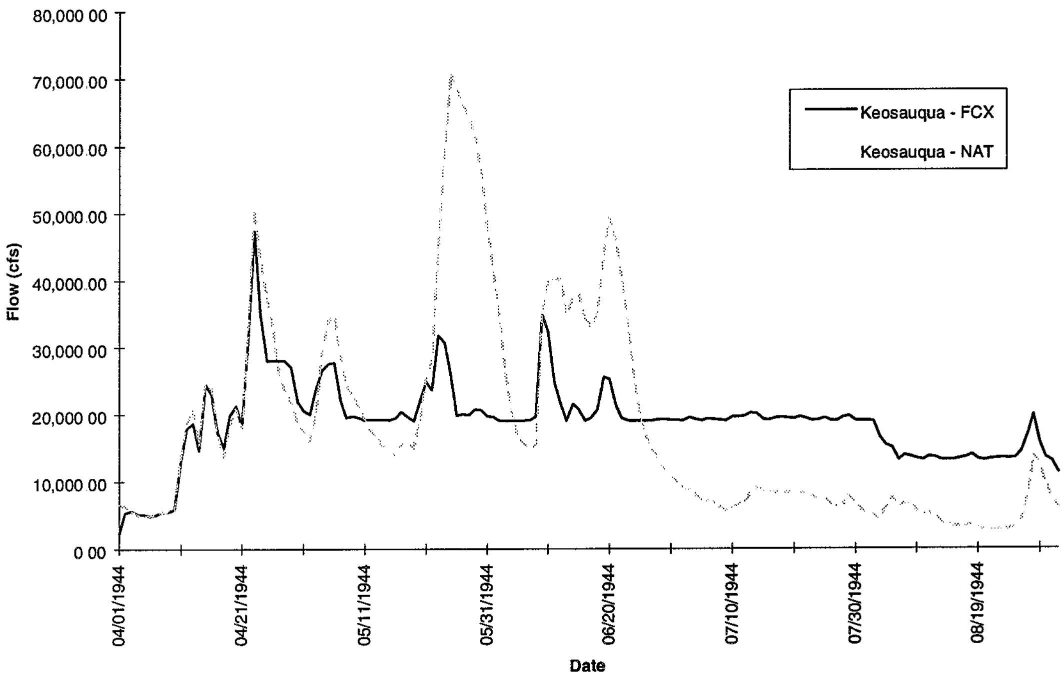

FIGURE D-1j. Keosauqua Hydrograph - Flood of 1944

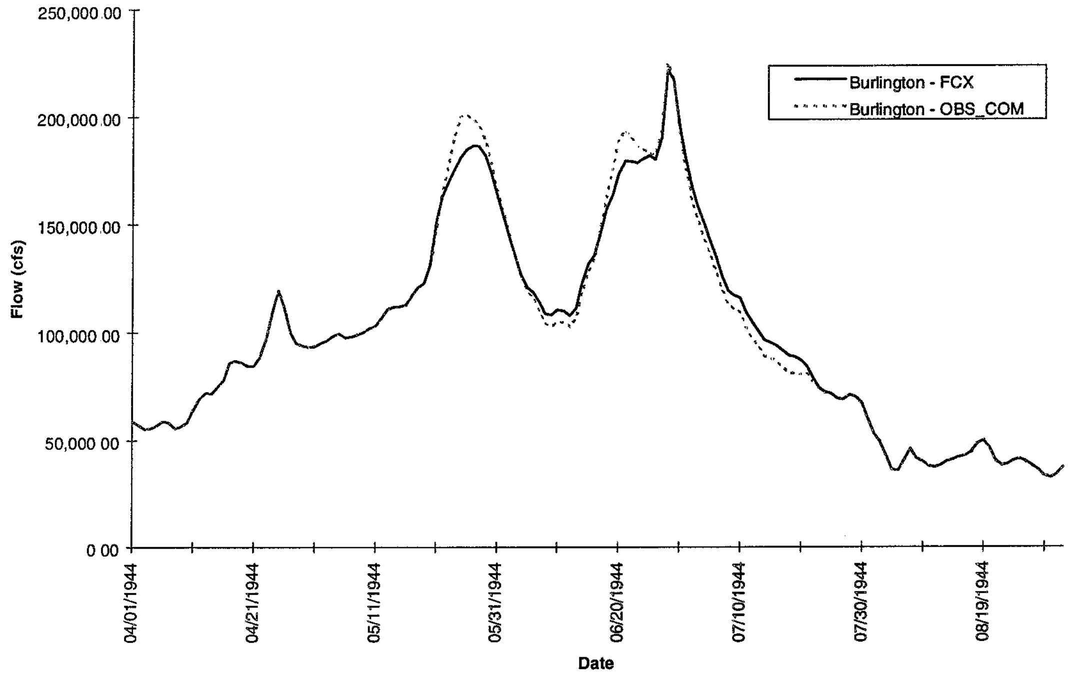

FIGURE D-1k. Burlington Hydrograph - Flood of 1944

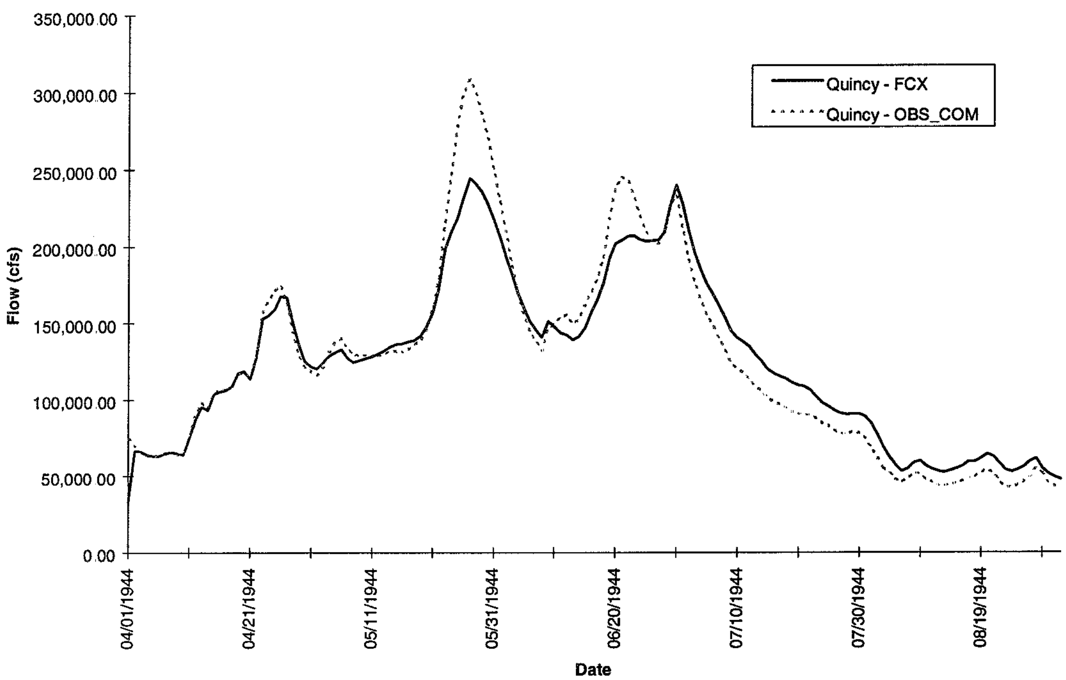

FIGURE D-1l. Quincy Hydrograph - Flood of 1944

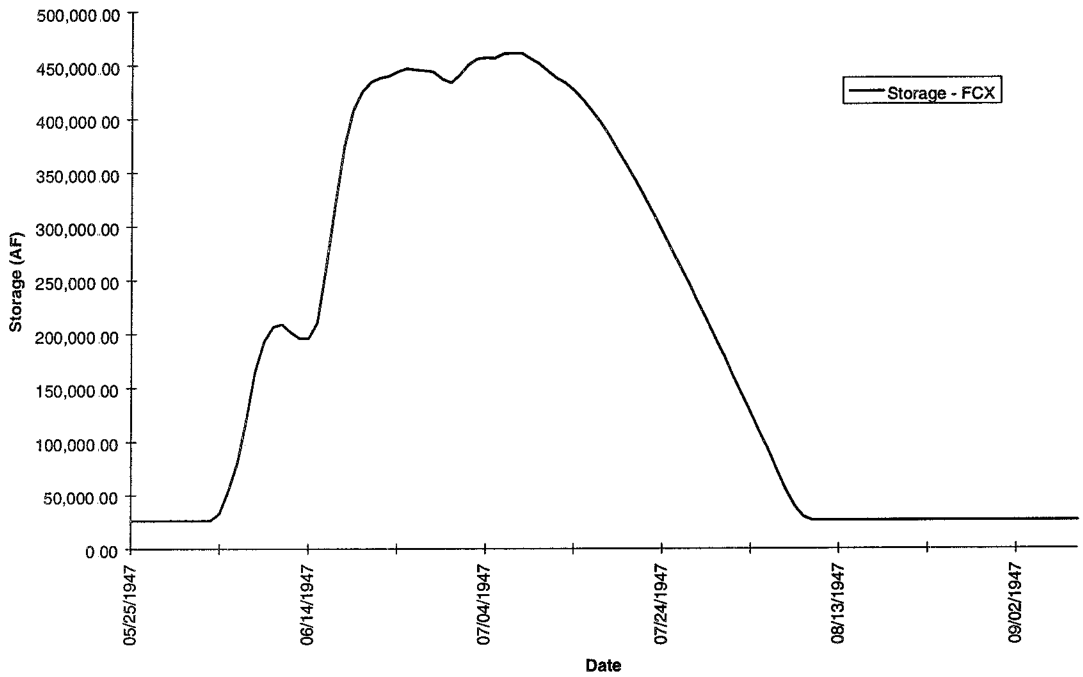

FIGURE D-2a. Coralville Reservoir Storage - Flood of 1947

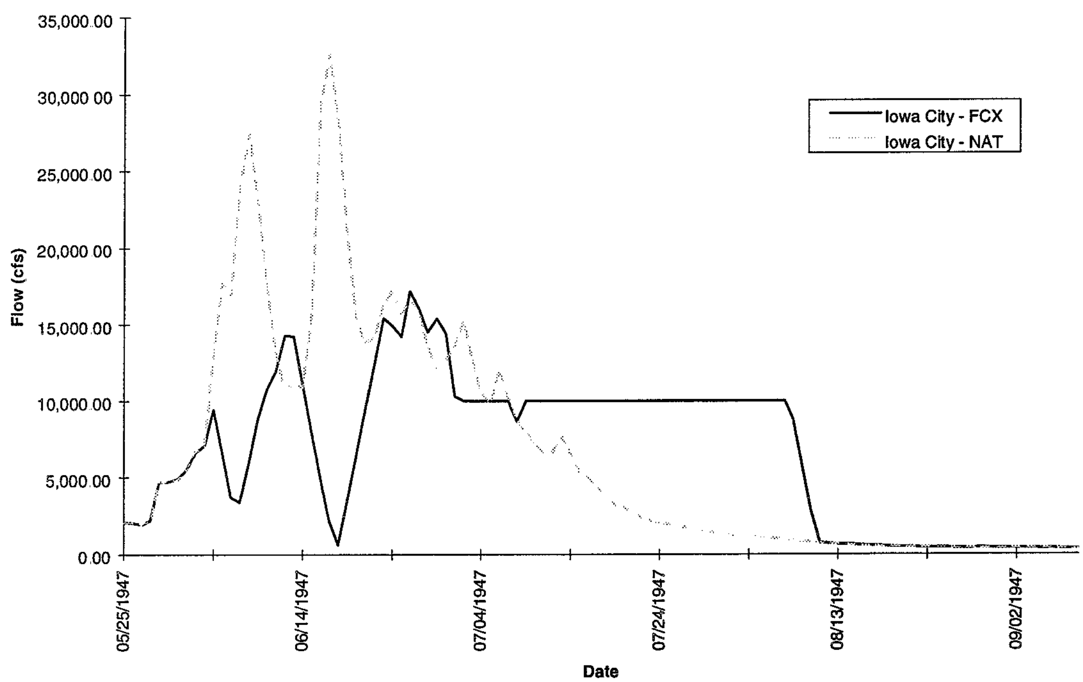

FIGURE D-2b. Iowa City Hydrograph - Flood of 1947

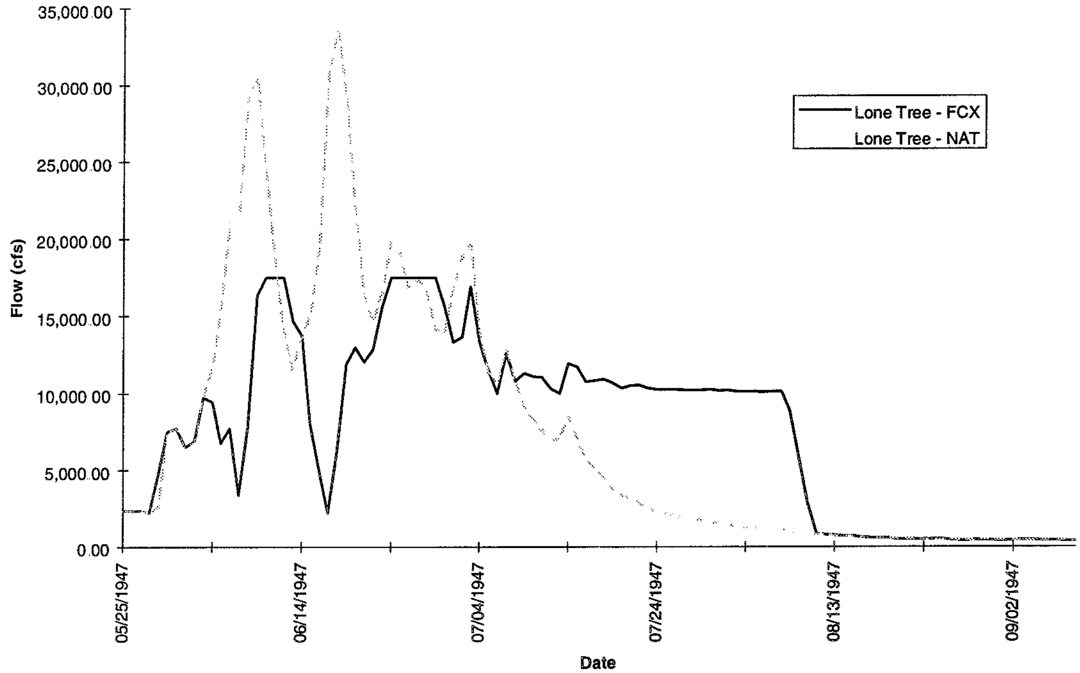

FIGURE D-2c. Lone Tree Hydrograph - Flood of 1947

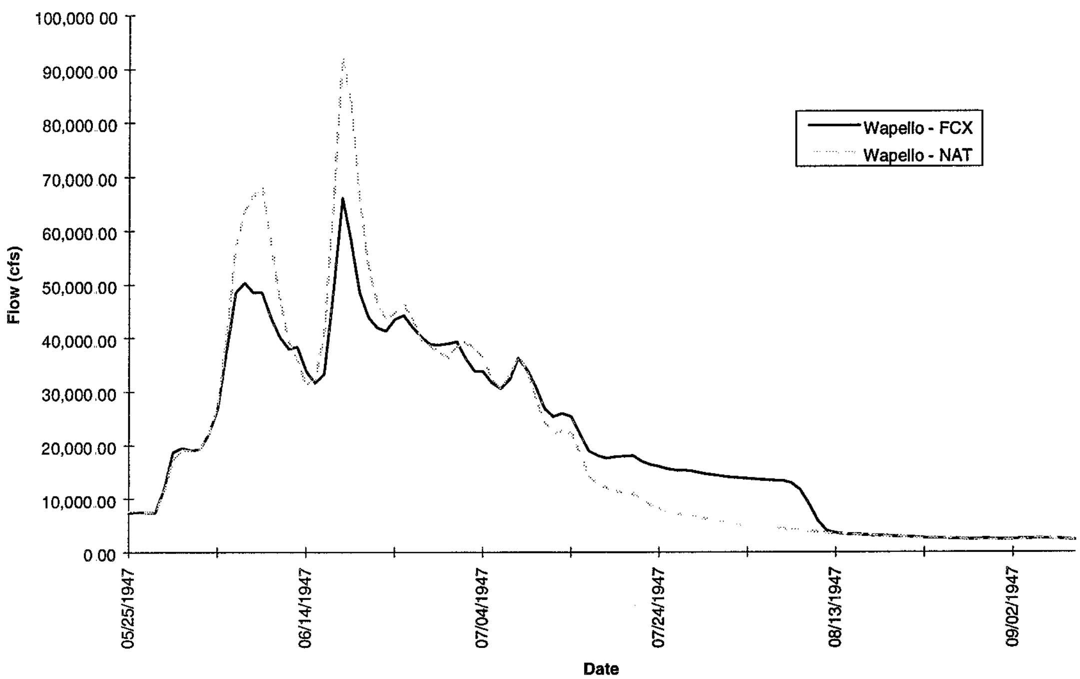

FIGURE D-2d. Wapello Hydrograph - Flood of 1947

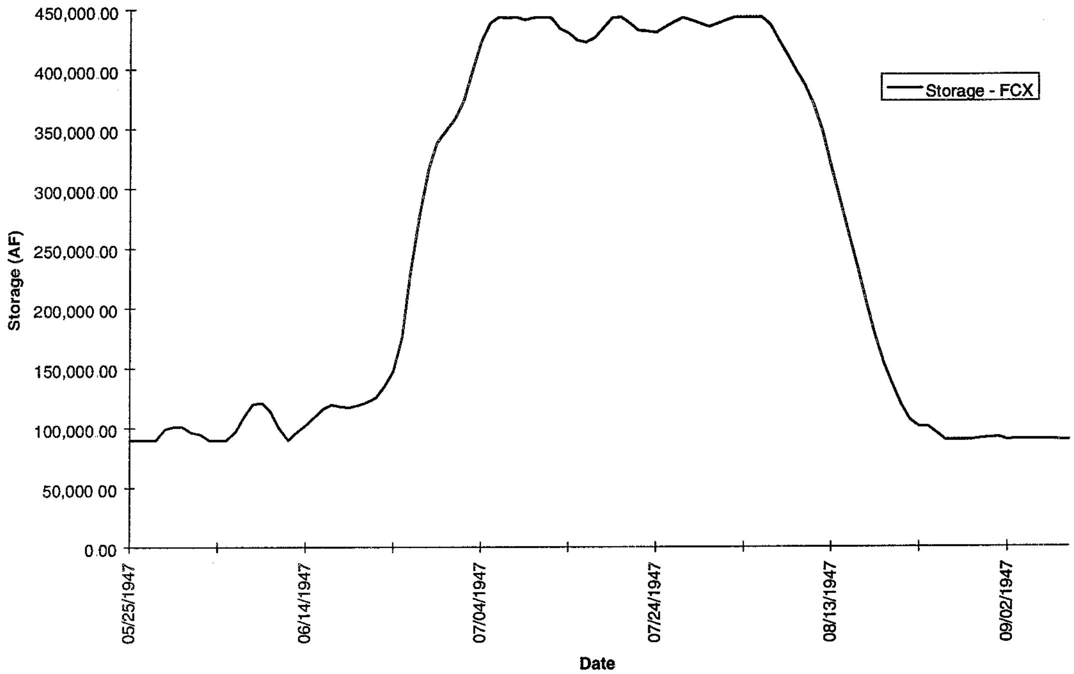

FIGURE D-2e. Saylorville Reservoir Storage - Flood of 1947

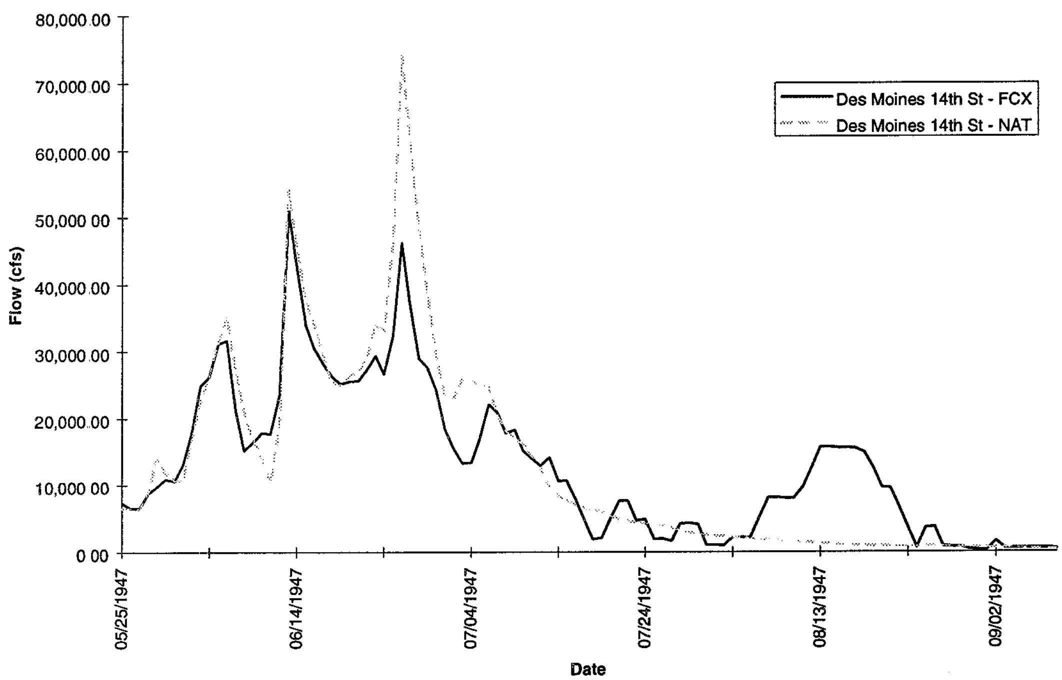

FIGURE D-2f. Des Moines 14th Street - Flood of 1947

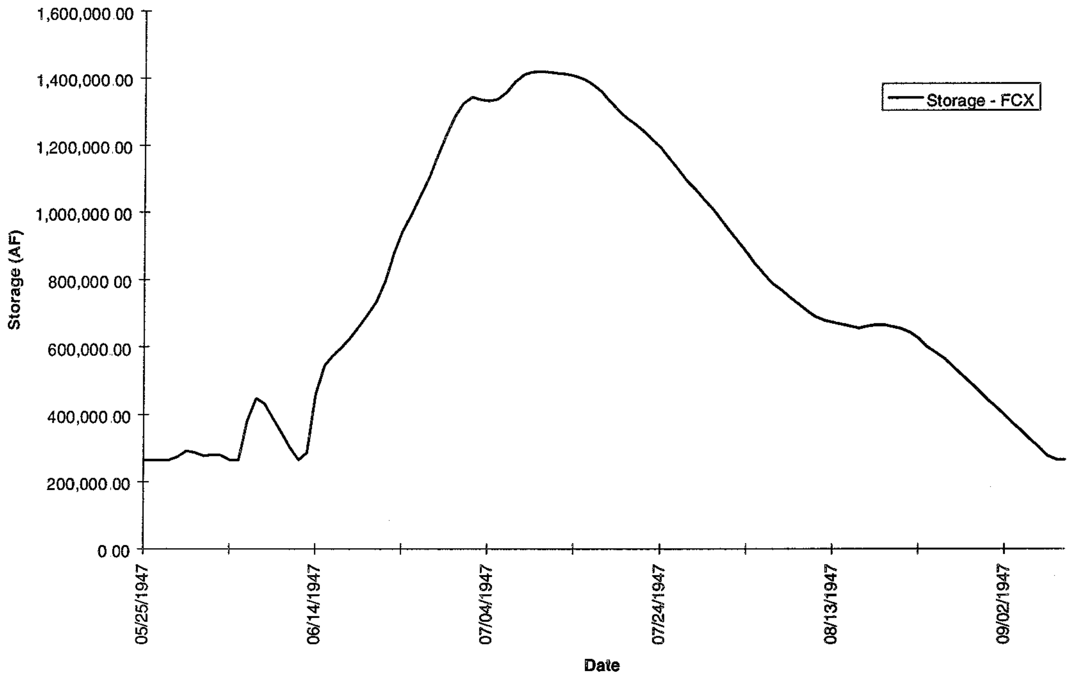

FIGURE D-2g. Lake Red Rock Storage - Flood of 1947

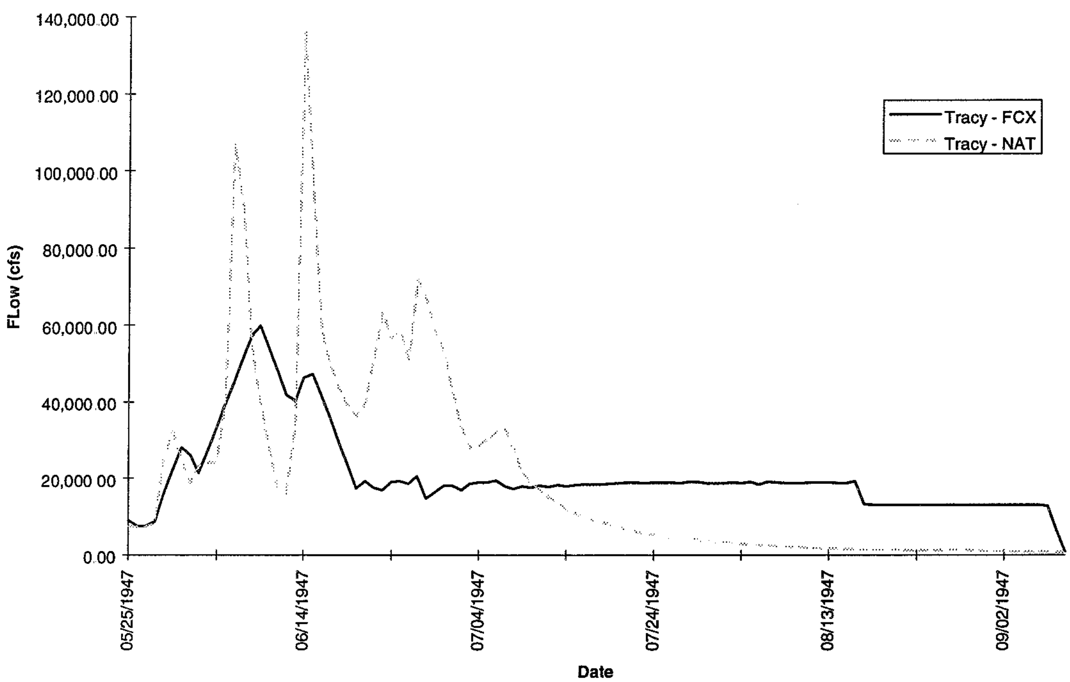

FIGURE D-2h. Tracy Hydrograph - Flood of 1947

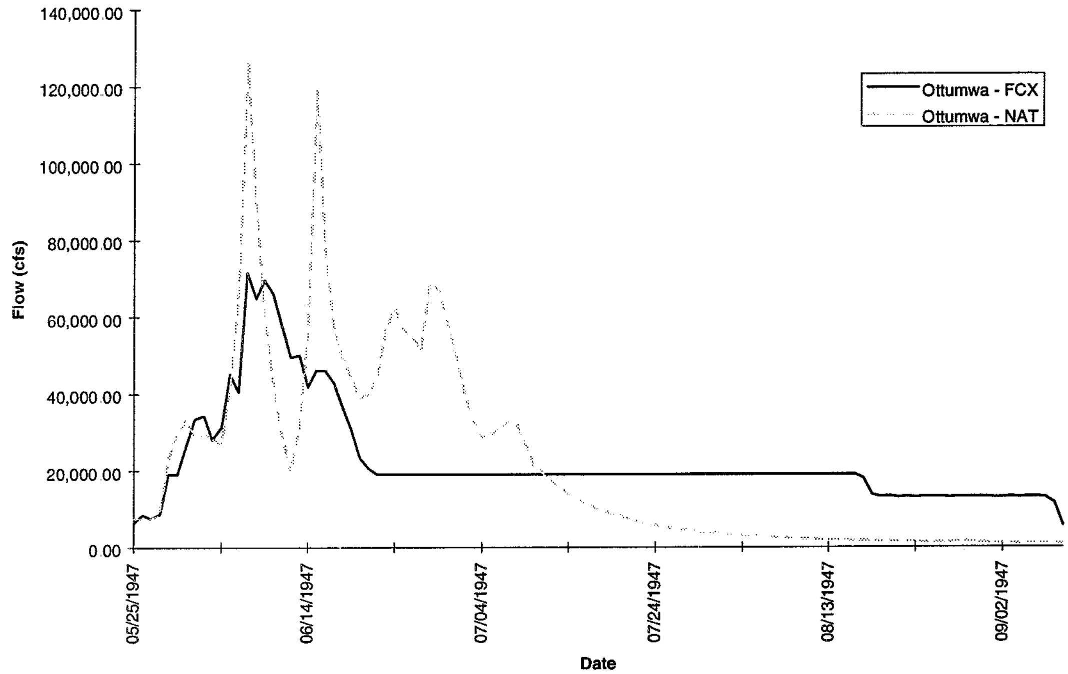

FIGURE D-2i. Ottumwa Hydrograph - Flood of 1947

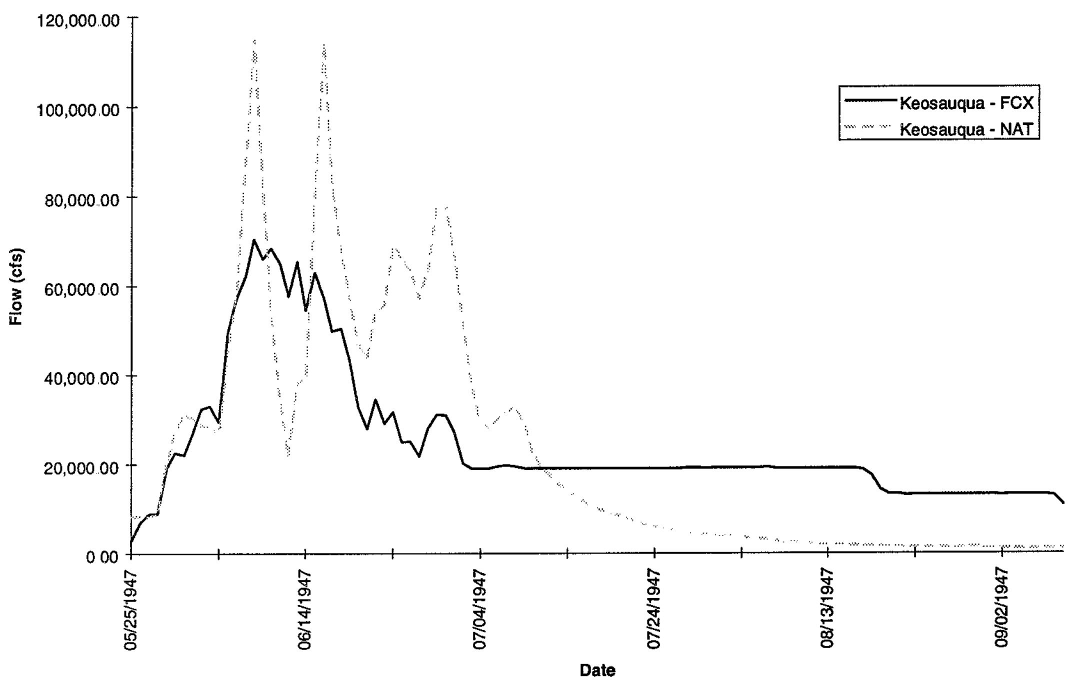

FIGURE D-2j. Keosauqua Hydrograph - Flood of 1947

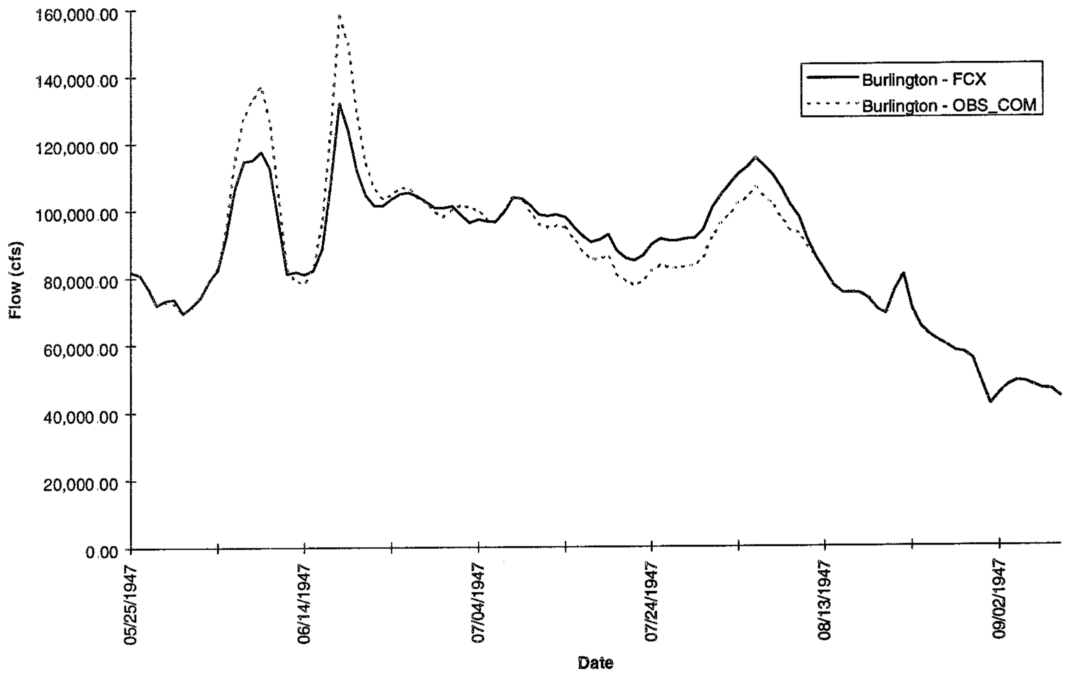

FIGURE D-2k. Burlington Hydrograph - Flood of 1947

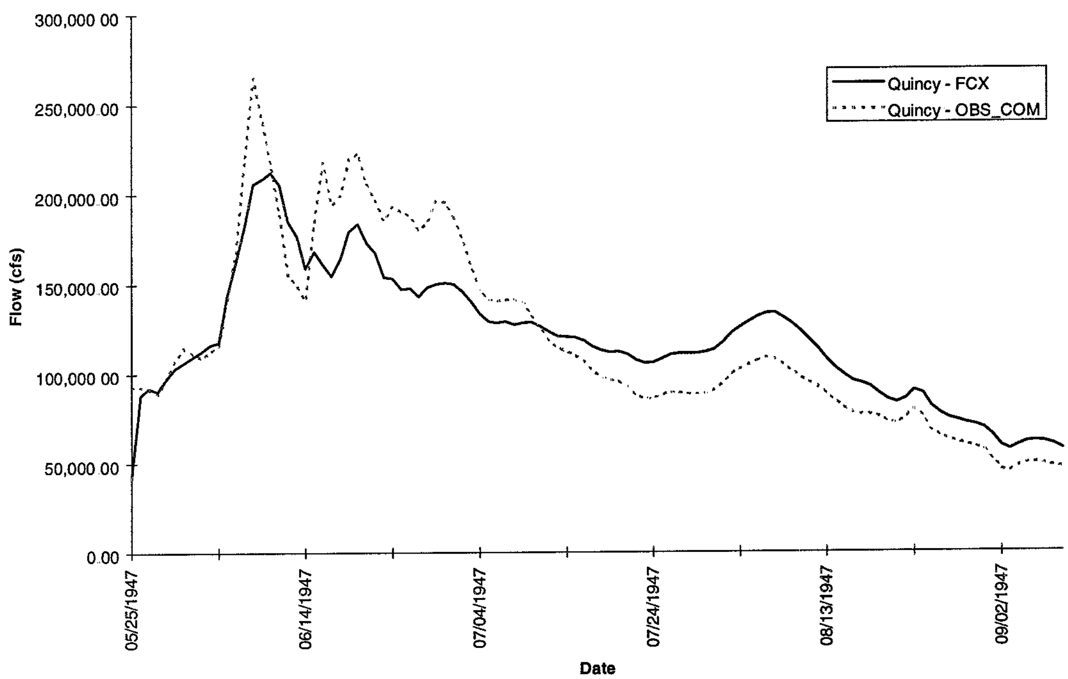

FIGURE D-2l. Quincy Hydrograph - Flood of 1947

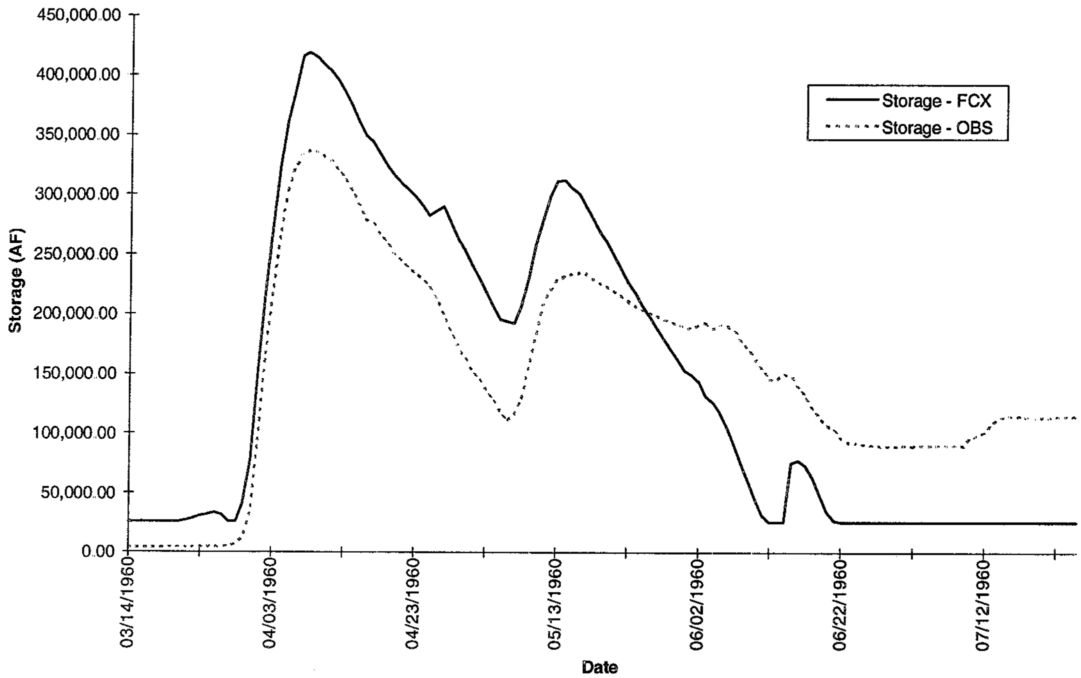

FIGURE D-3a. Coralville Reservoir Storage - Flood of 1960

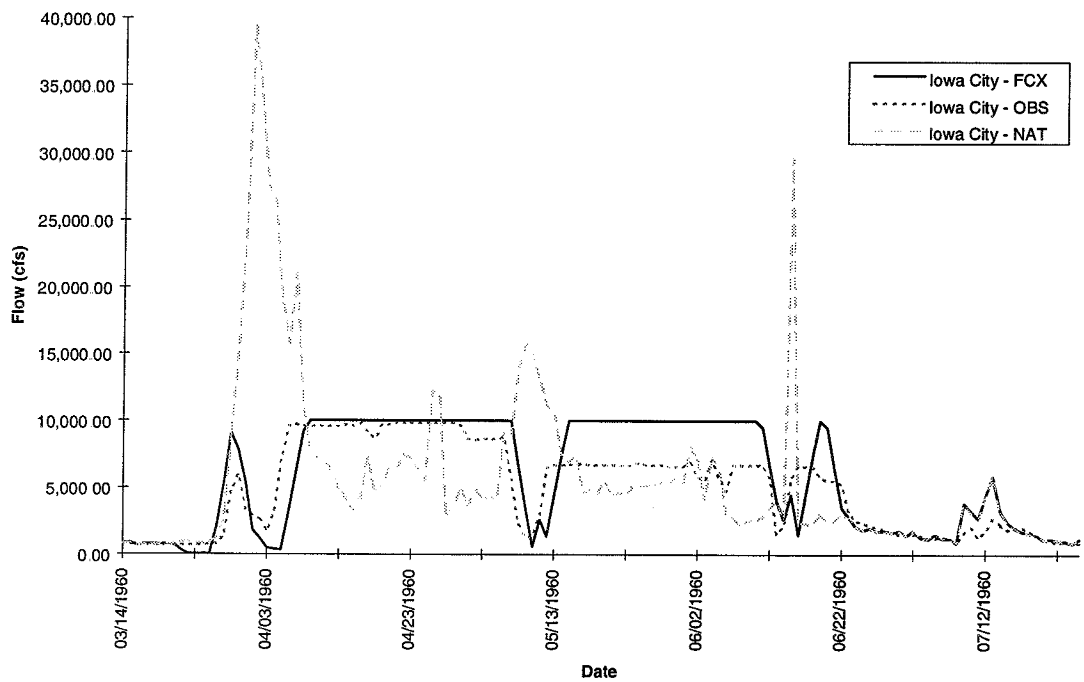

FIGURE D-3b. Iowa City Hydrograph - Flood of 1960

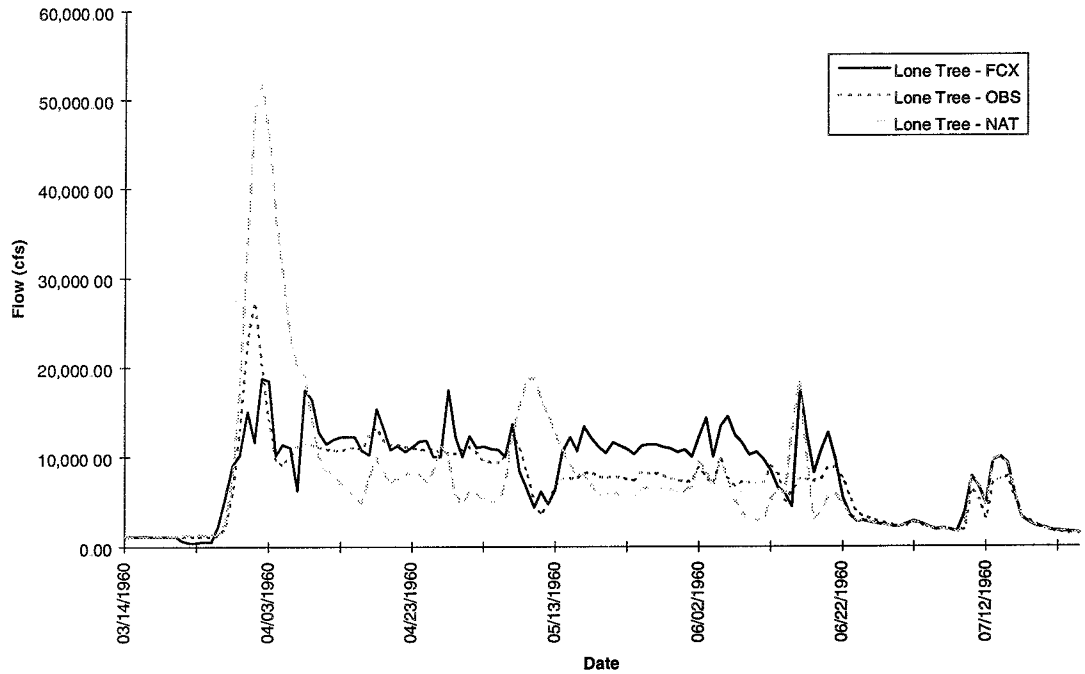

FIGURE D-3c. Lone Tree Hydrograph - Flood of 1960

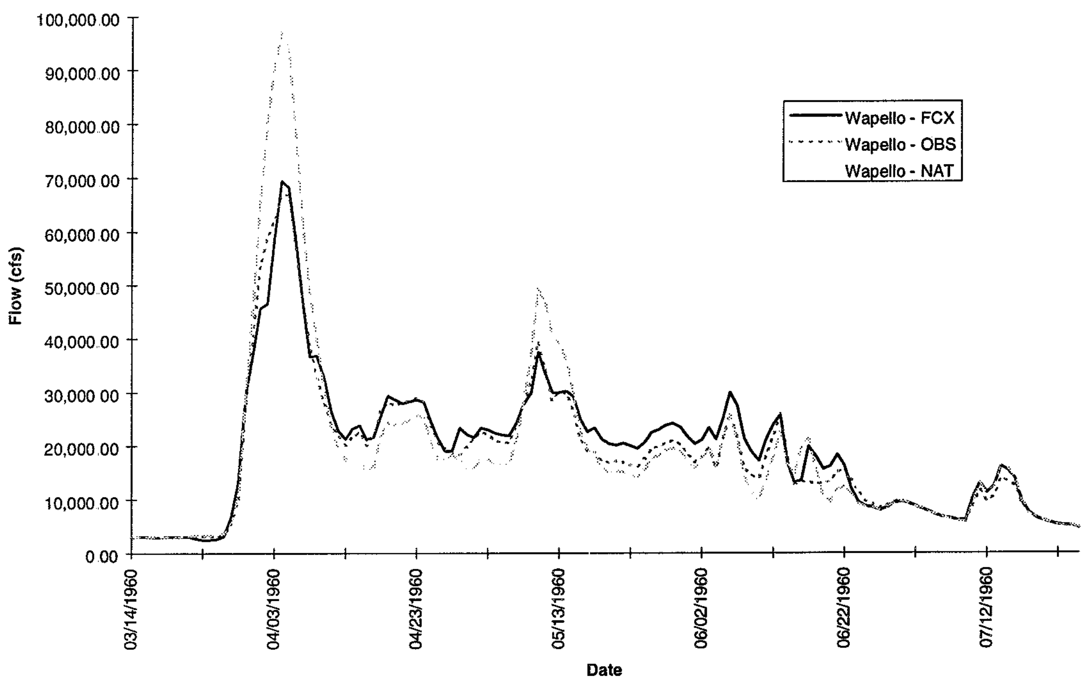

FIGURE D-3d. Wapello Hydrograph - Flood of 1960

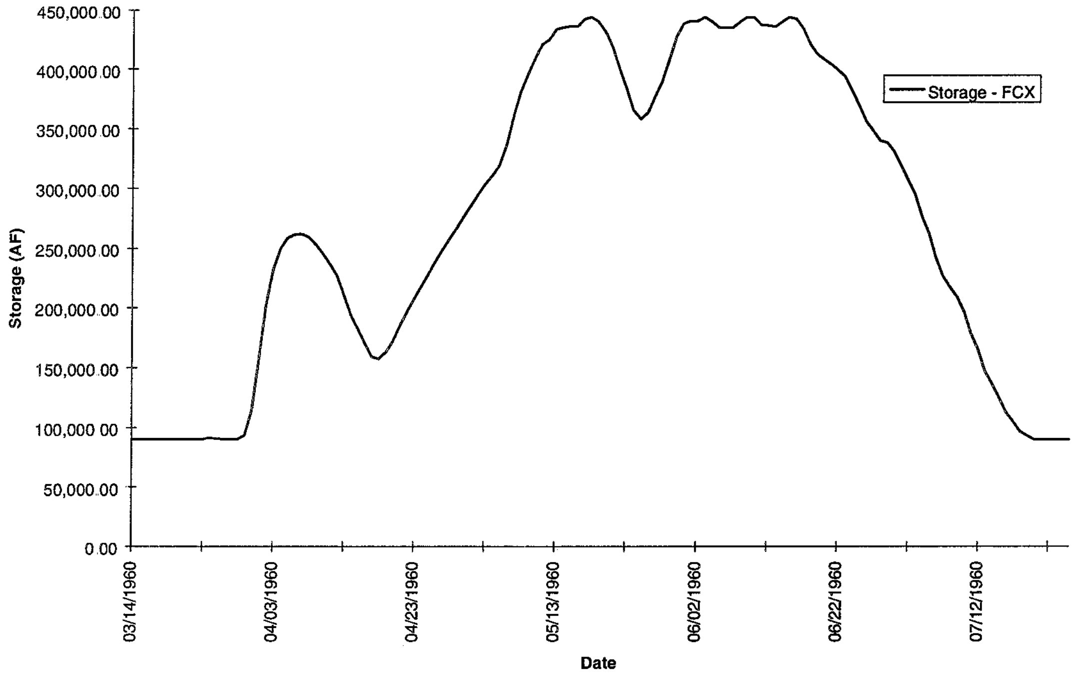

FIGURE D-3e. Saylorville Reservoir Storage - Flood of 1960

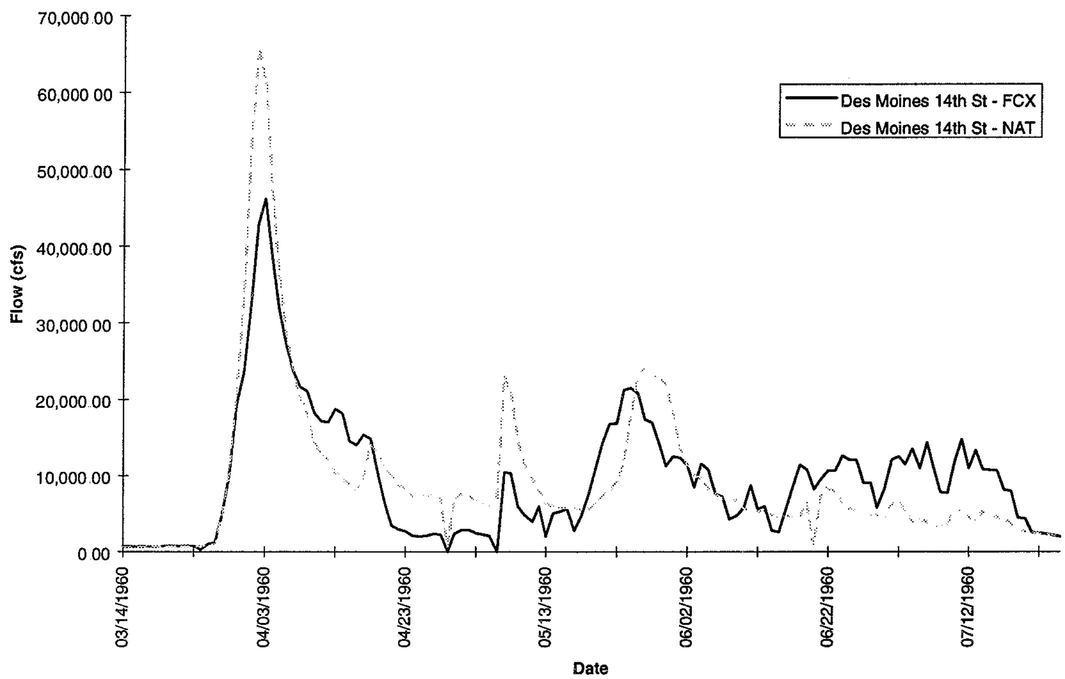

FIGURE D-3f. Des Moines 14th Street - Flood of 1960

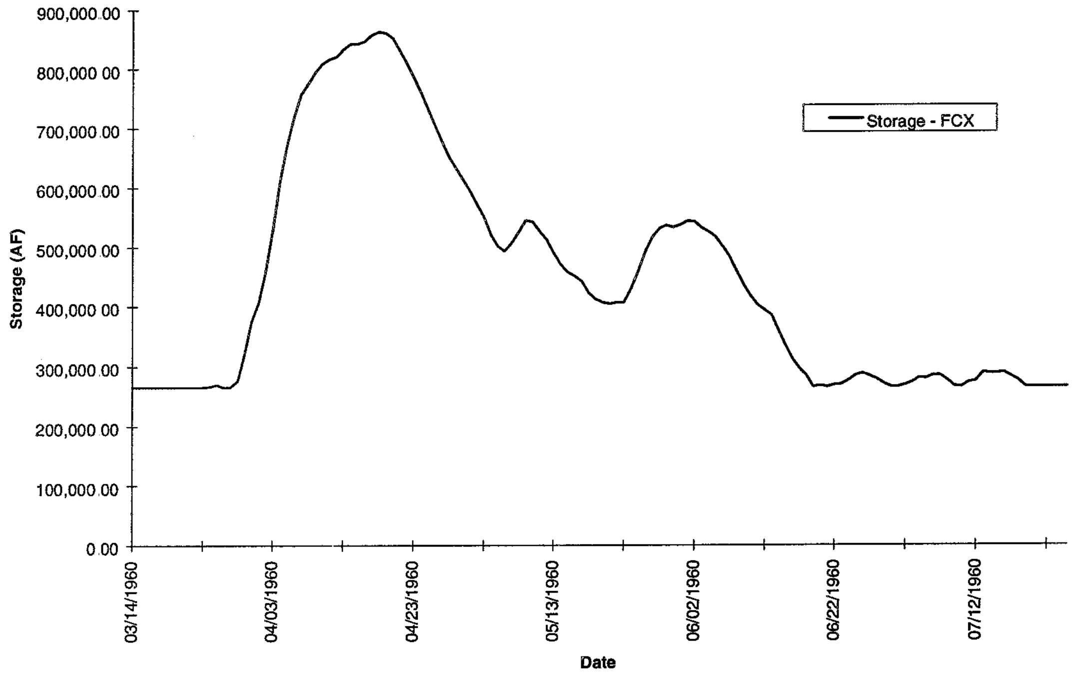

FIGURE D-3g. Lake Red Rock Storage - Flood of 1960

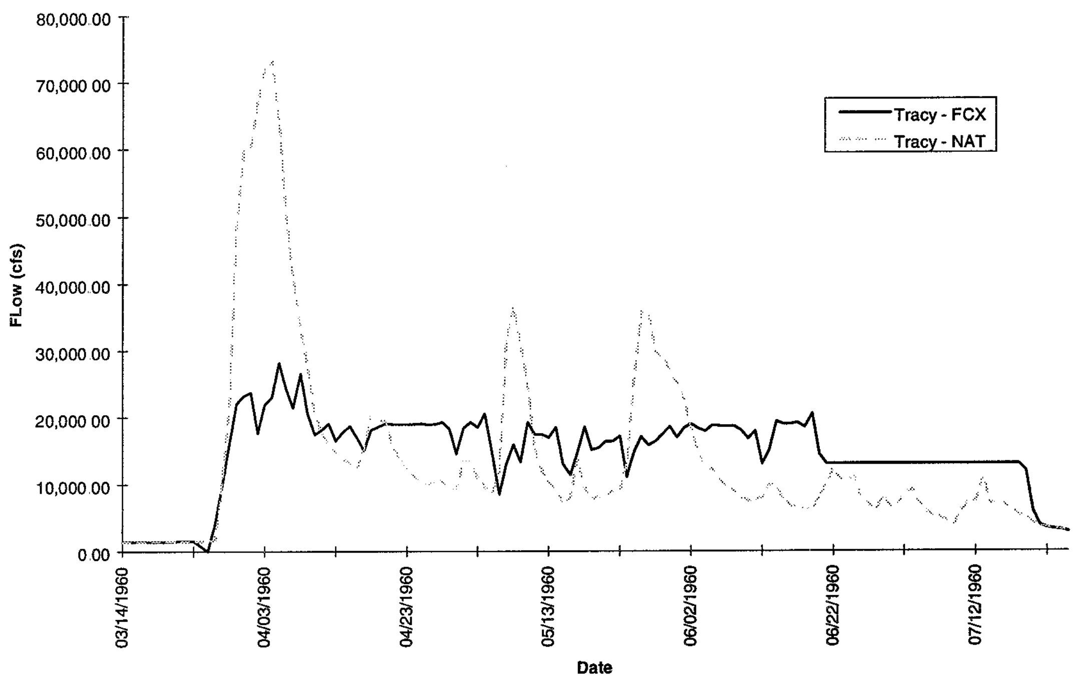

FIGURE D-3h. Tracy Hydrograph - Flood of 1960

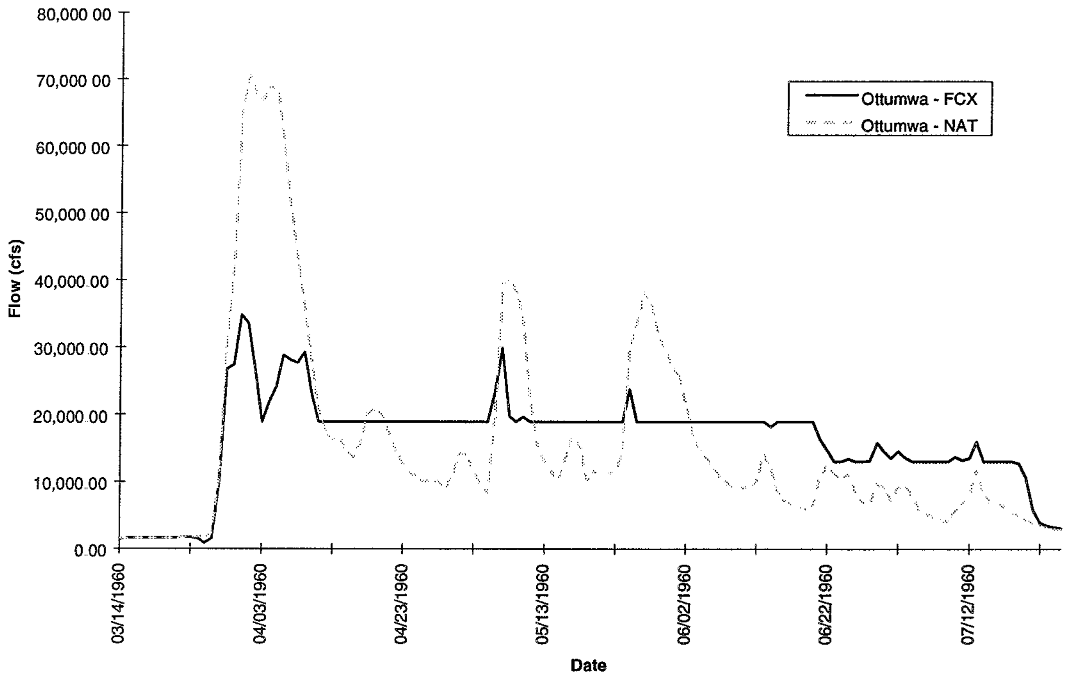

FIGURE D-3i. Ottumwa Hydrograph - Flood of 1960

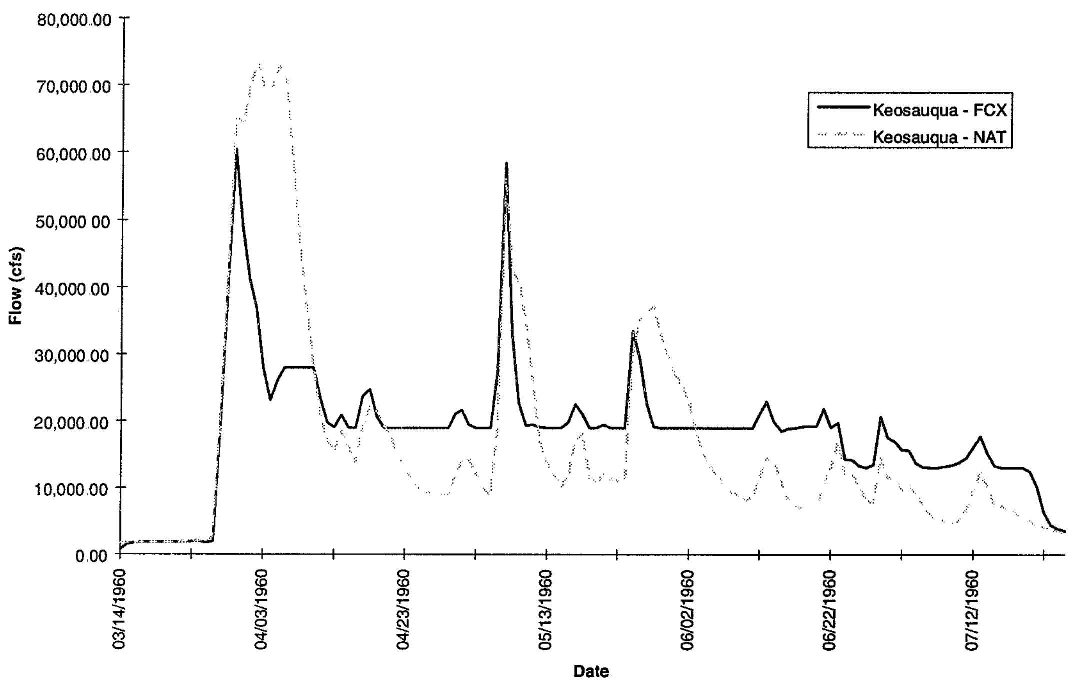

FIGURE D-3j. Keosauqua Hydrograph - Flood of 1960

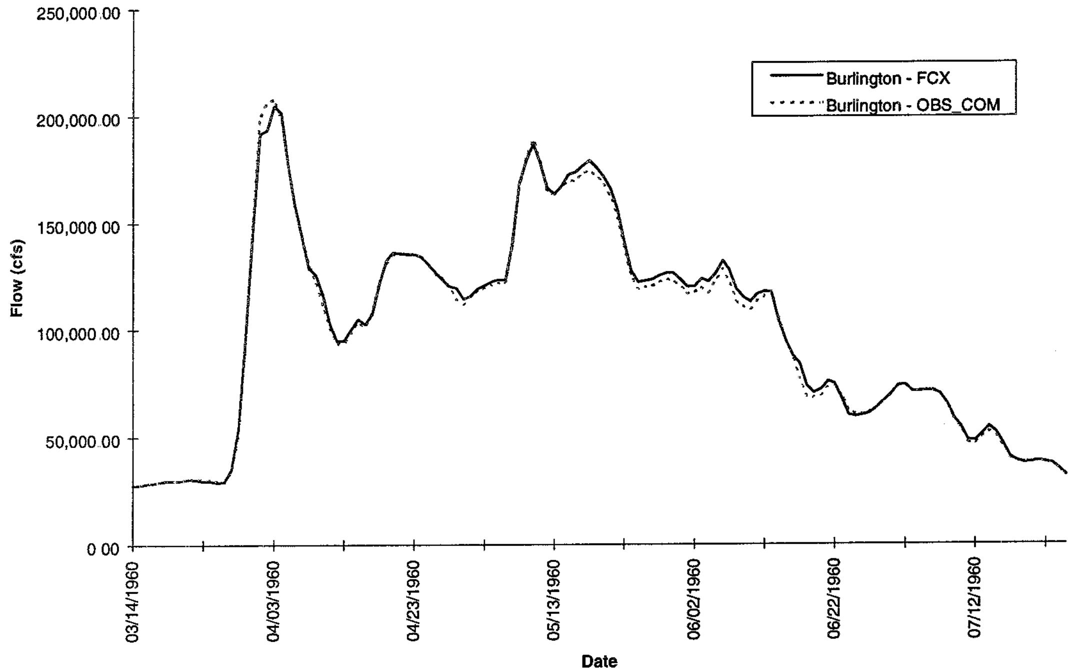

FIGURE D-3k. Burlington Hydrograph - Flood of 1960

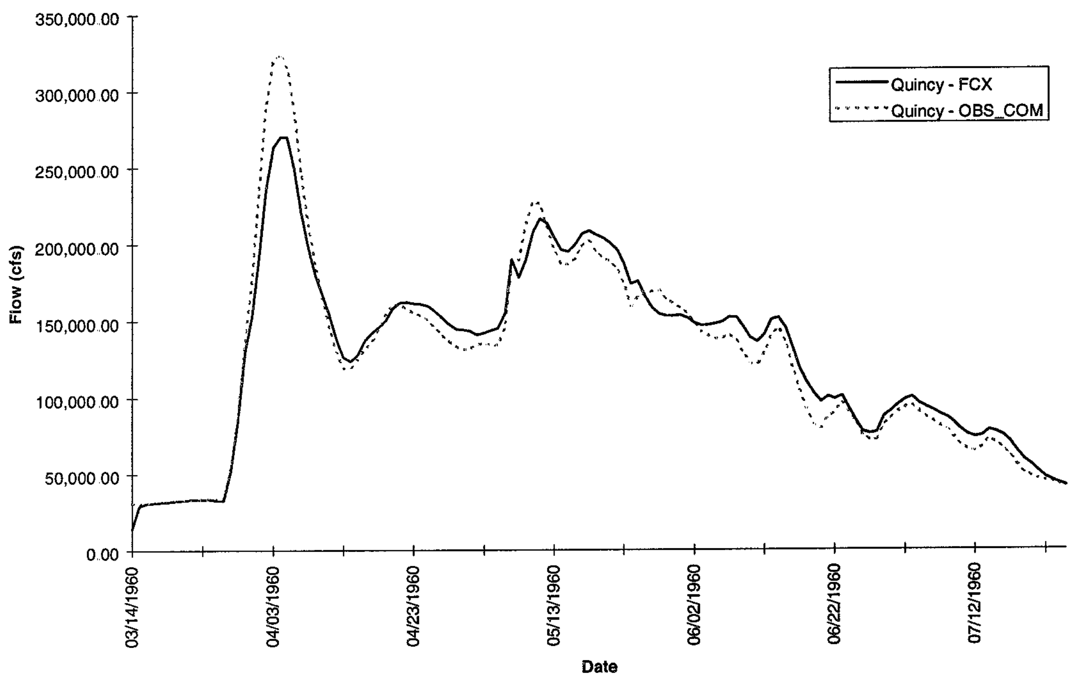

FIGURE D-3l. Quincy Hydrograph - Flood of 1960

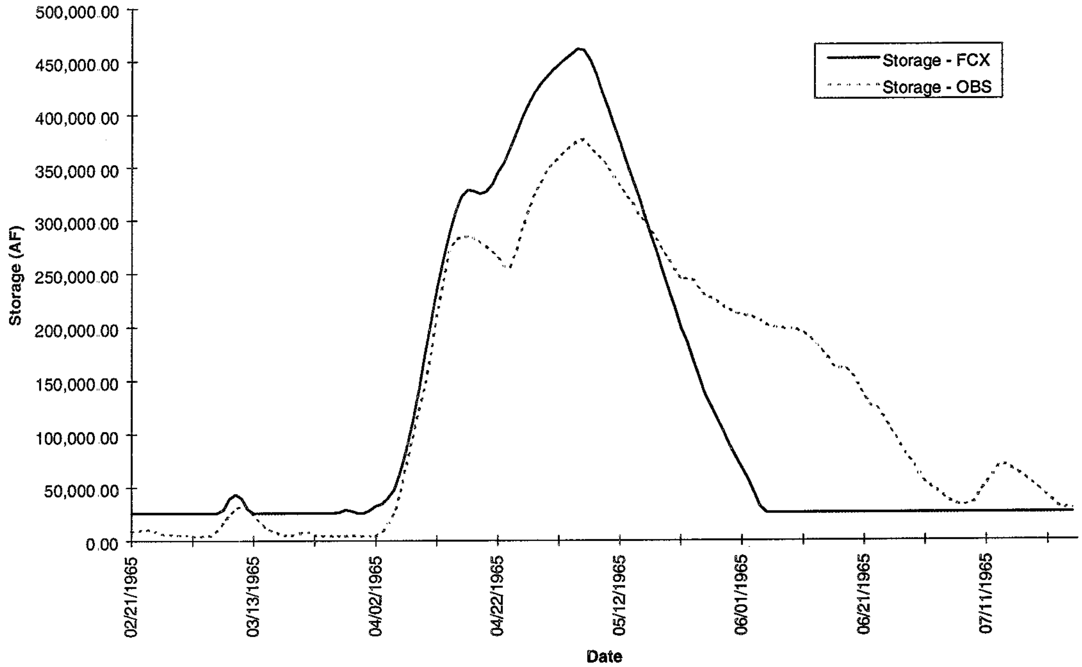

FIGURE D-4a. Coralville Reservoir Storage - Flood of 1965

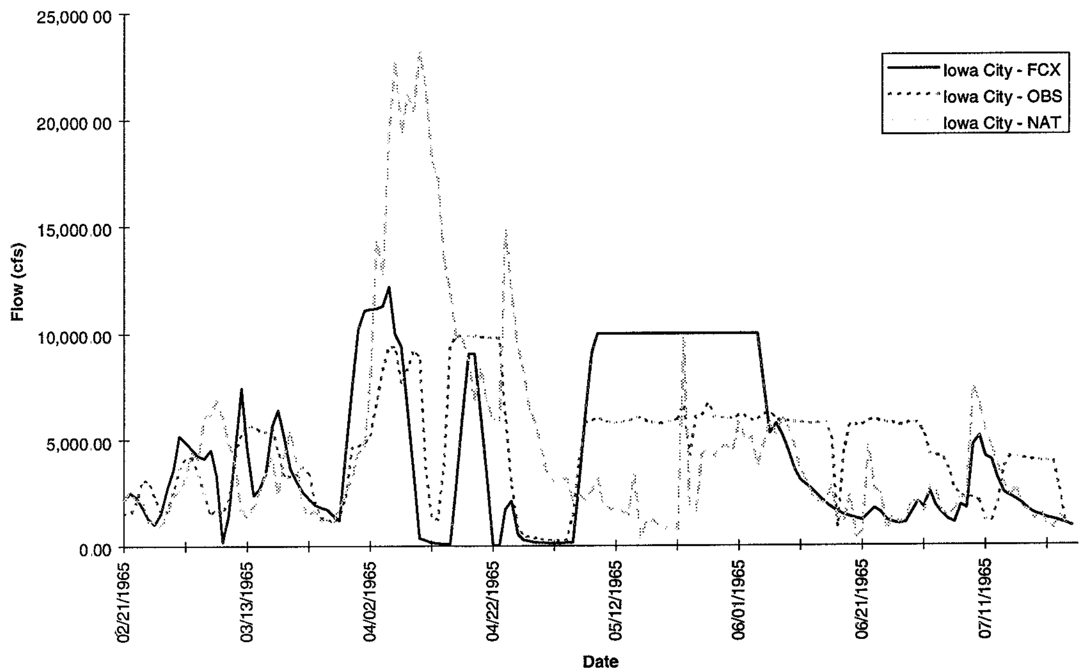

FIGURE D-4b. Iowa City Hydrograph - Flood of 1965

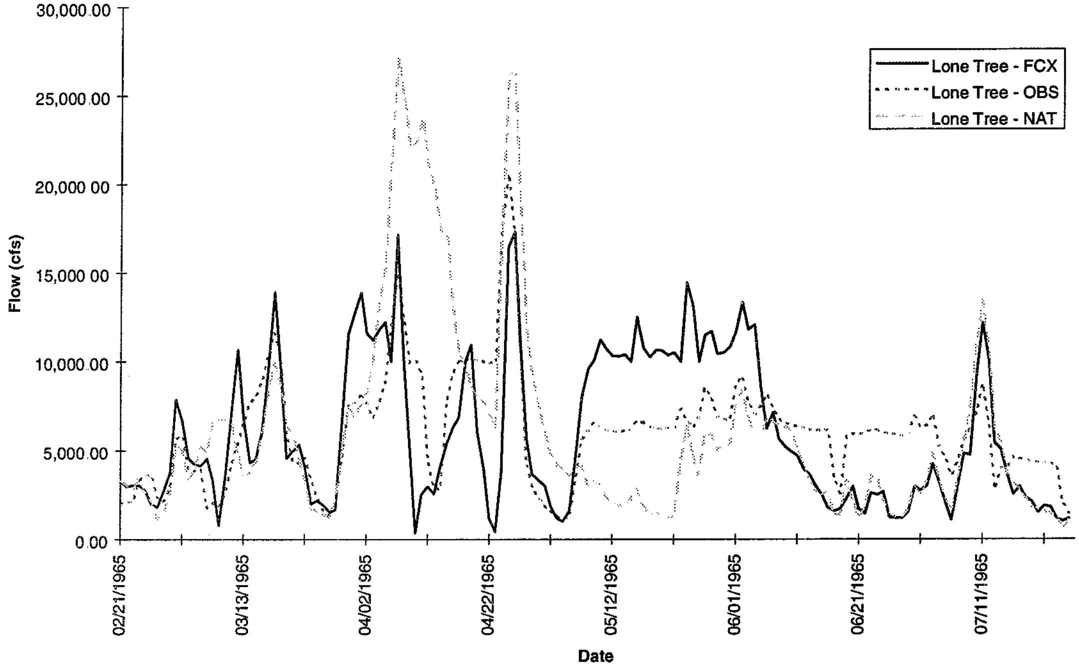

FIGURE D-4c. Lone Tree Hydrograph - Flood of 1965

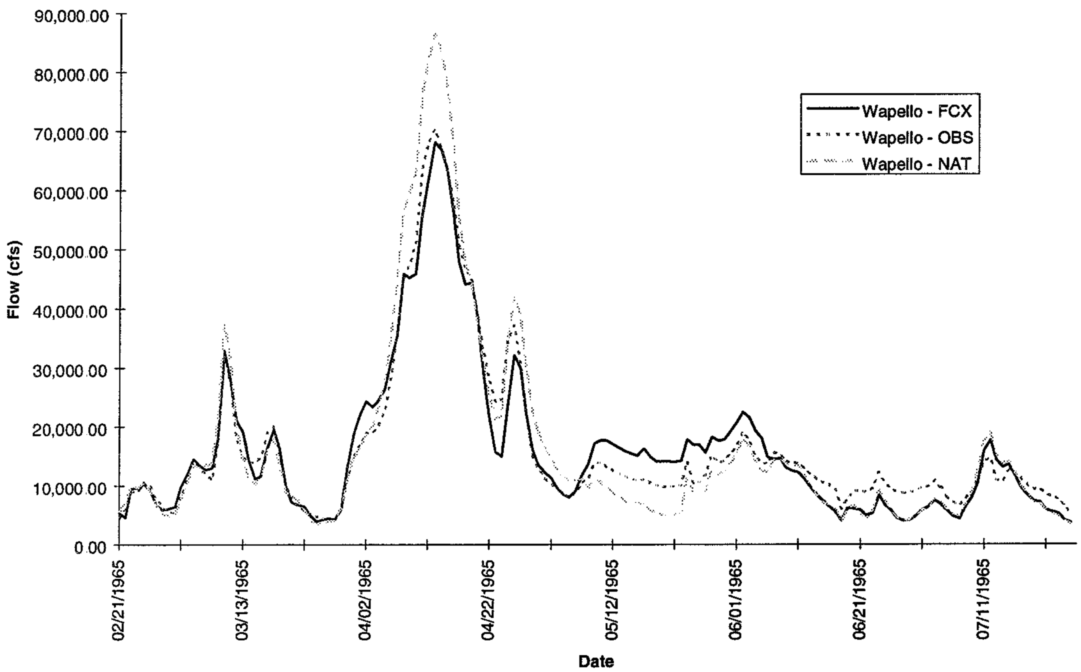

FIGURE D-4d. Wapello Hydrograph - Flood of 1965

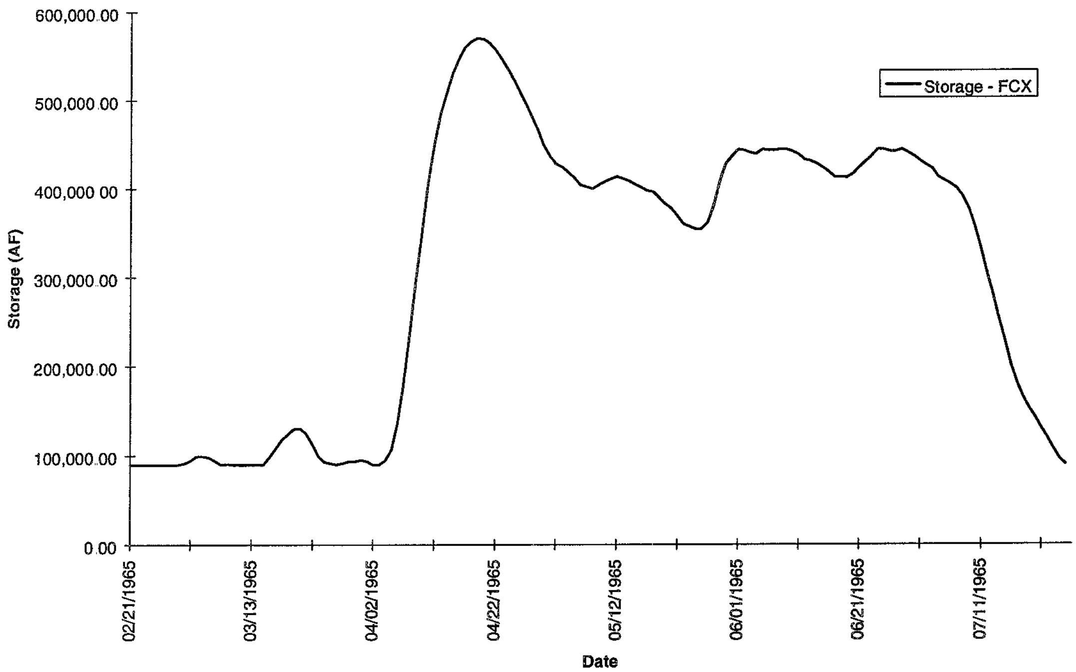

FIGURE D-4e. Saylorville Reservoir Storage - Flood of 1965

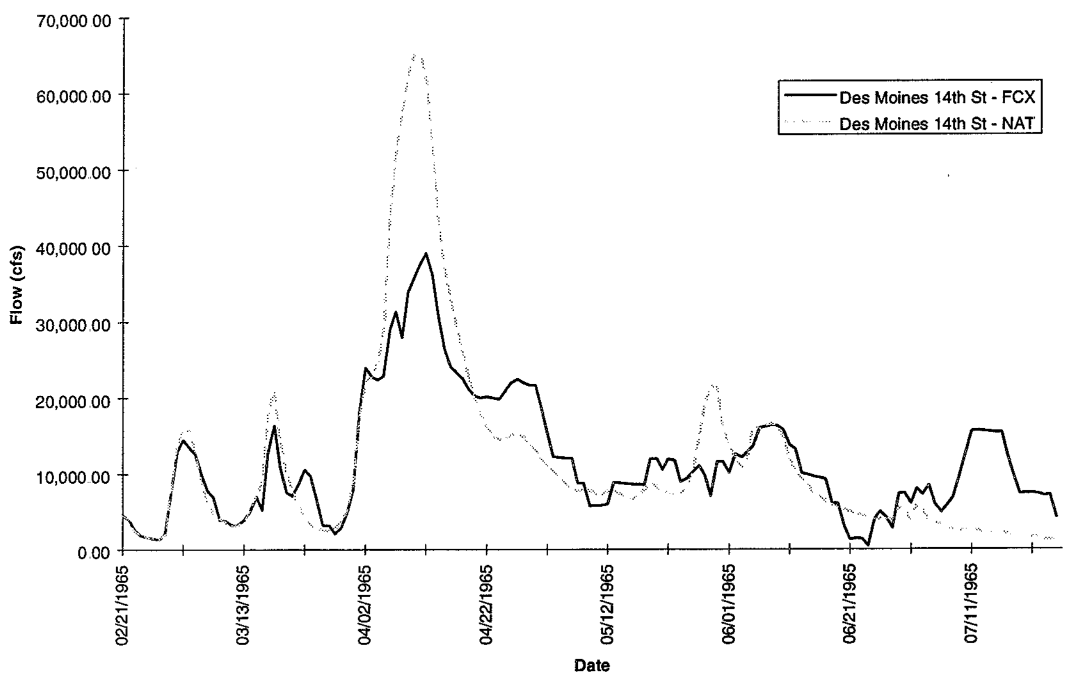

FIGURE D-4f. Des Moines 14th Street - Flood of 1965

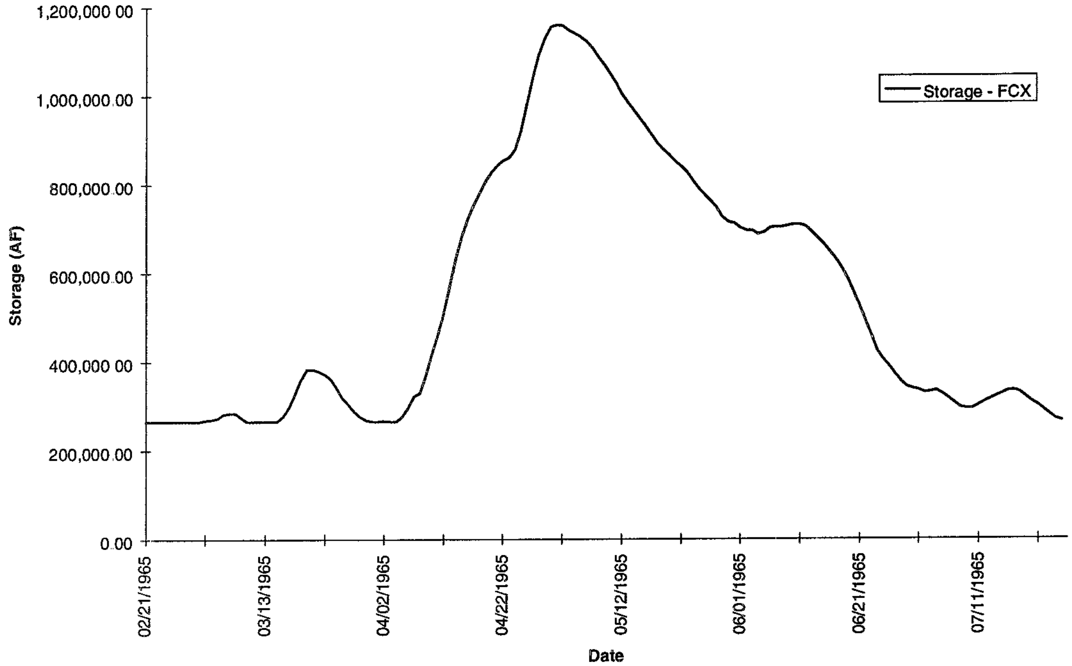

FIGURE D-4g. Lake Red Rock Storage - Flood of 1965

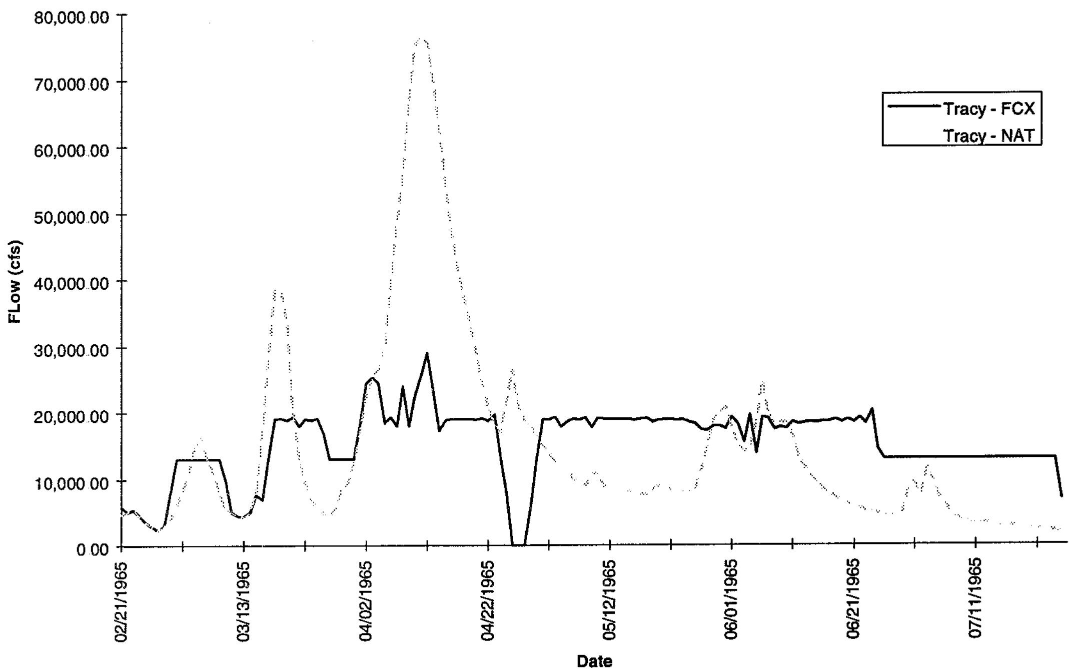

FIGURE D-4h. Tracy Hydrograph - Flood of 1965

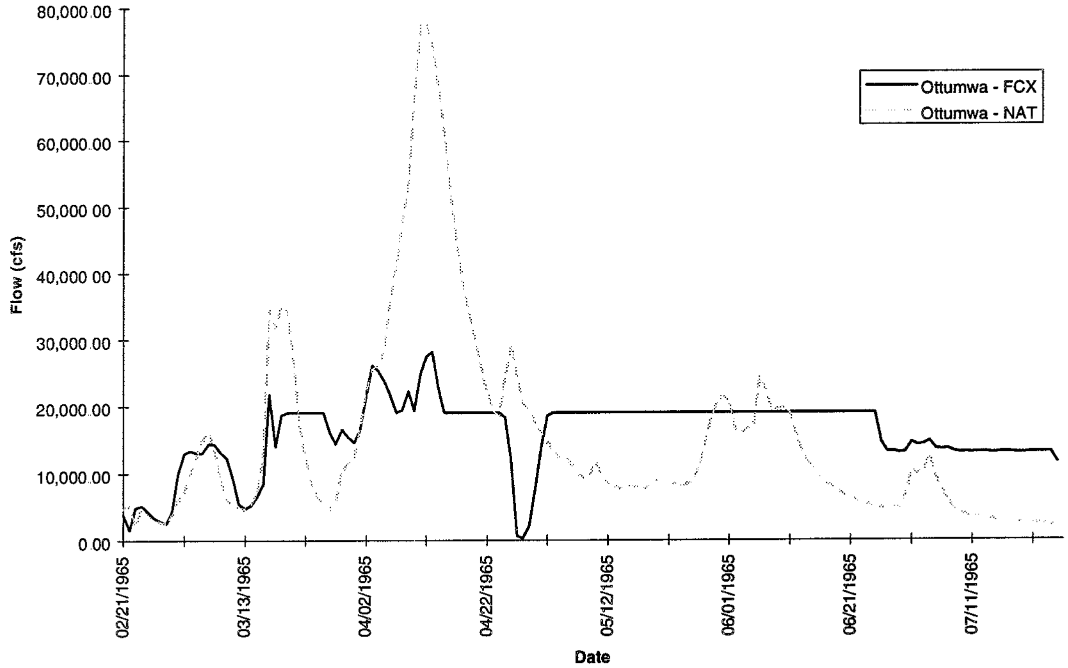

FIGURE D-4i. Ottumwa Hydrograph - Flood of 1965

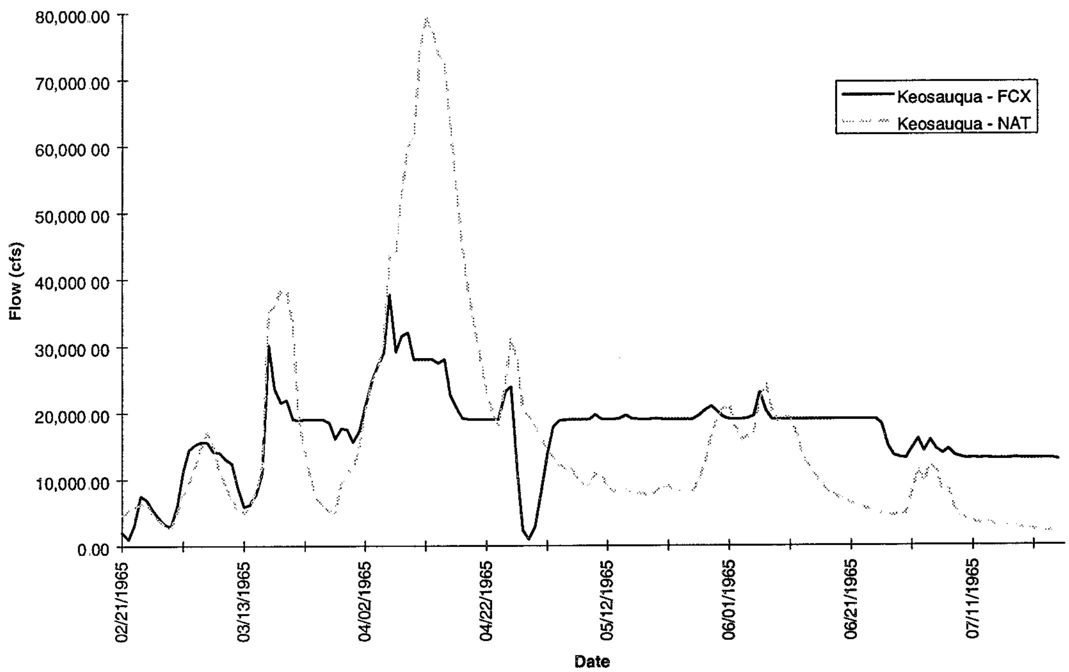

FIGURE D-4j. Keosauqua Hydrograph - Flood of 1965

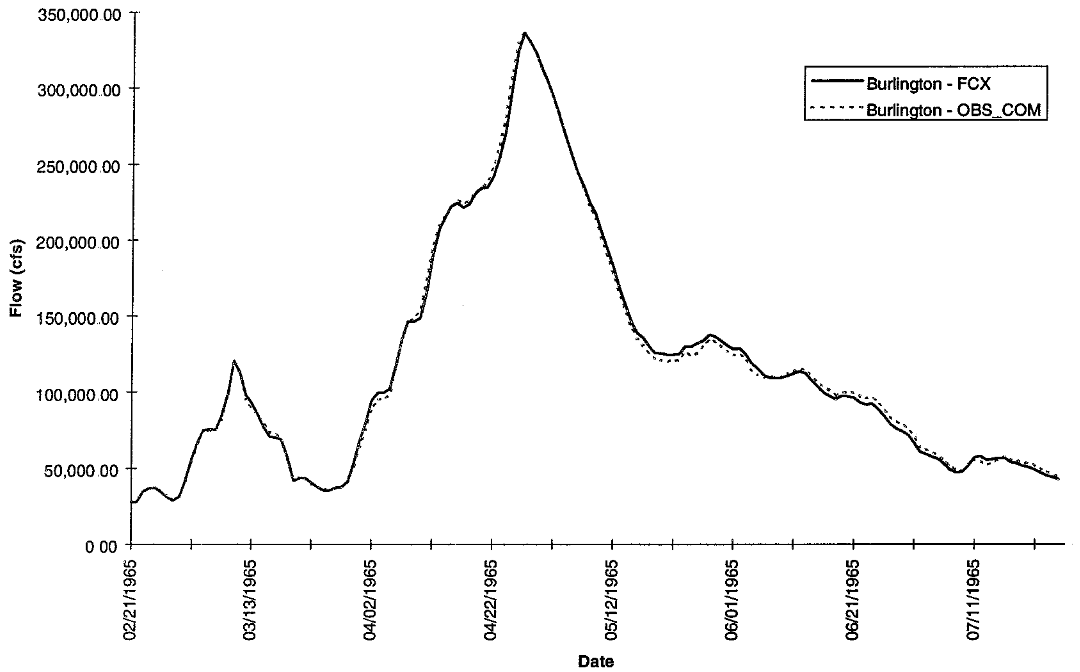

FIGURE D-4k. Burlington Hydrograph - Flood of 1965

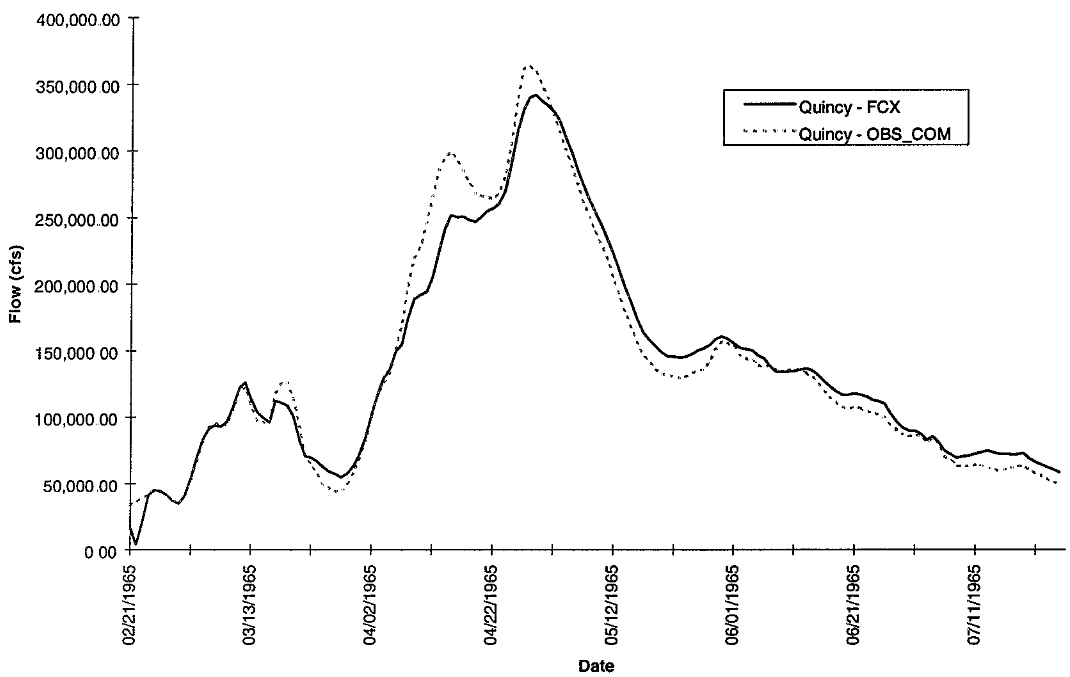

FIGURE D-4l. Quincy Hydrograph - Flood of 1965

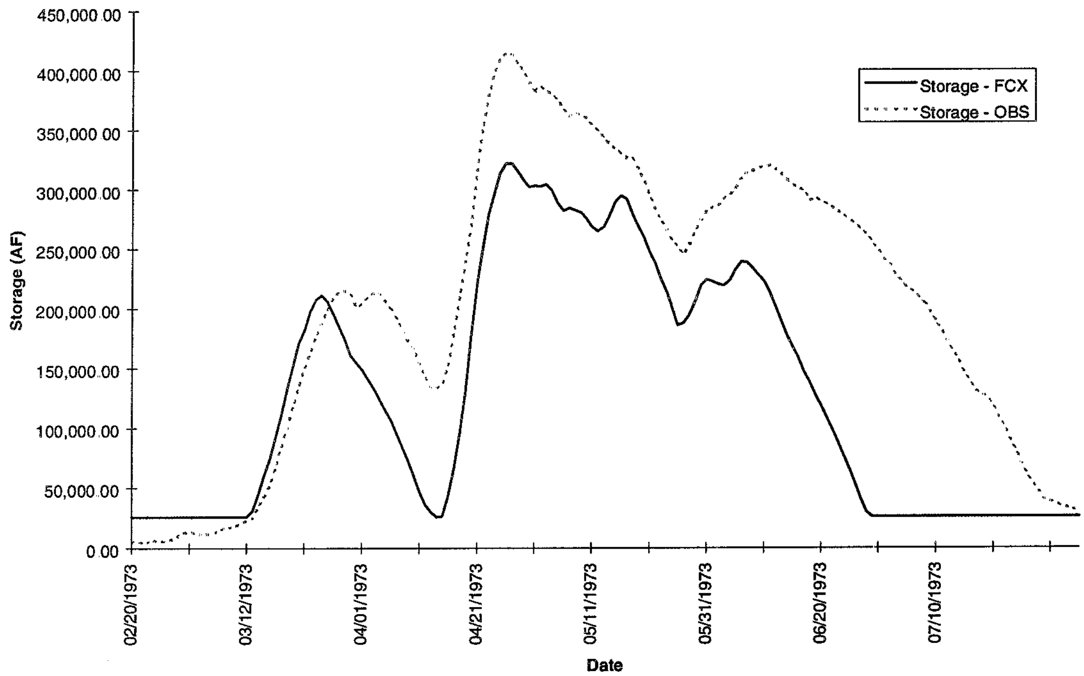

FIGURE D-5a. Coralville Reservoir Storage - Flood of 1973

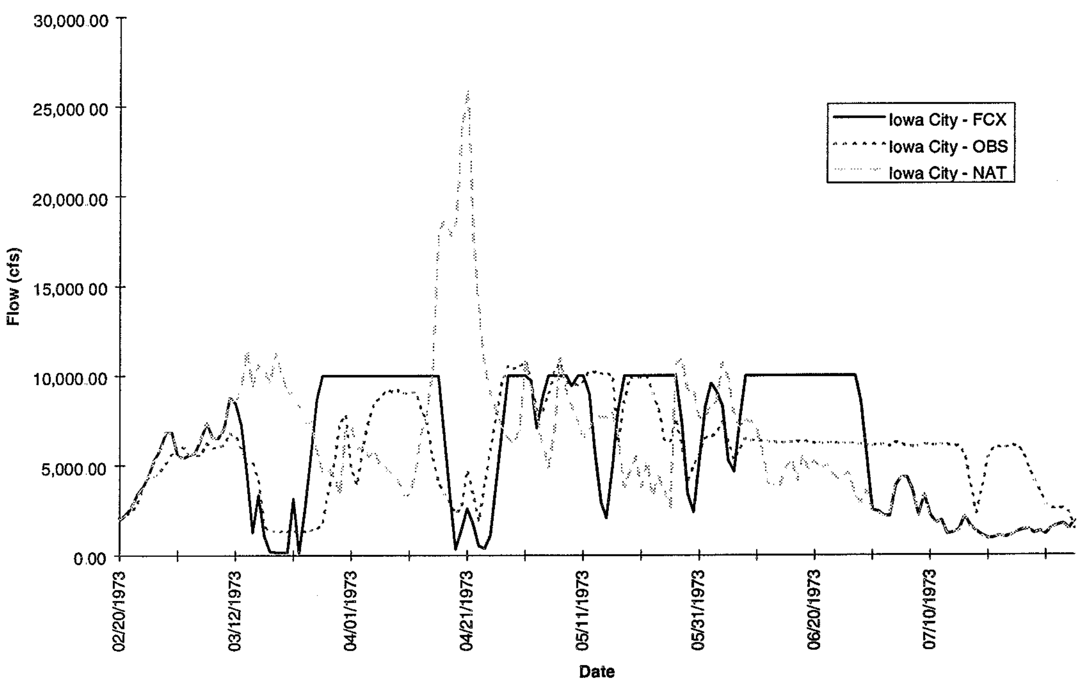

FIGURE D-5b. Iowa City Hydrograph - Flood of 1973

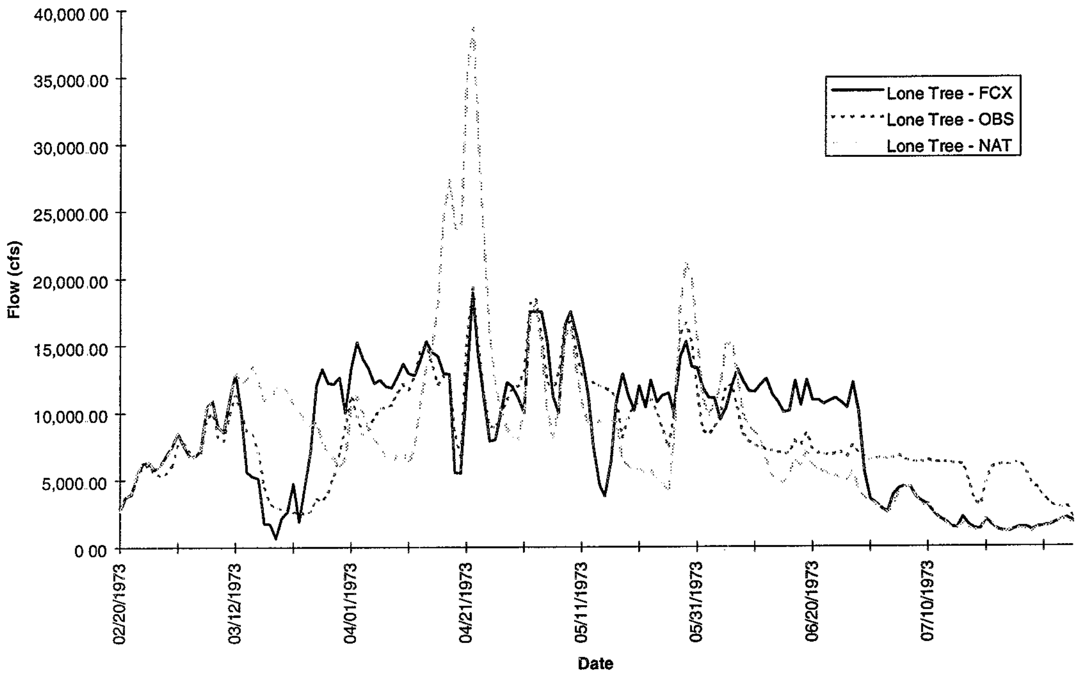

FIGURE D-5c. Lone Tree Hydrograph - Flood of 1973

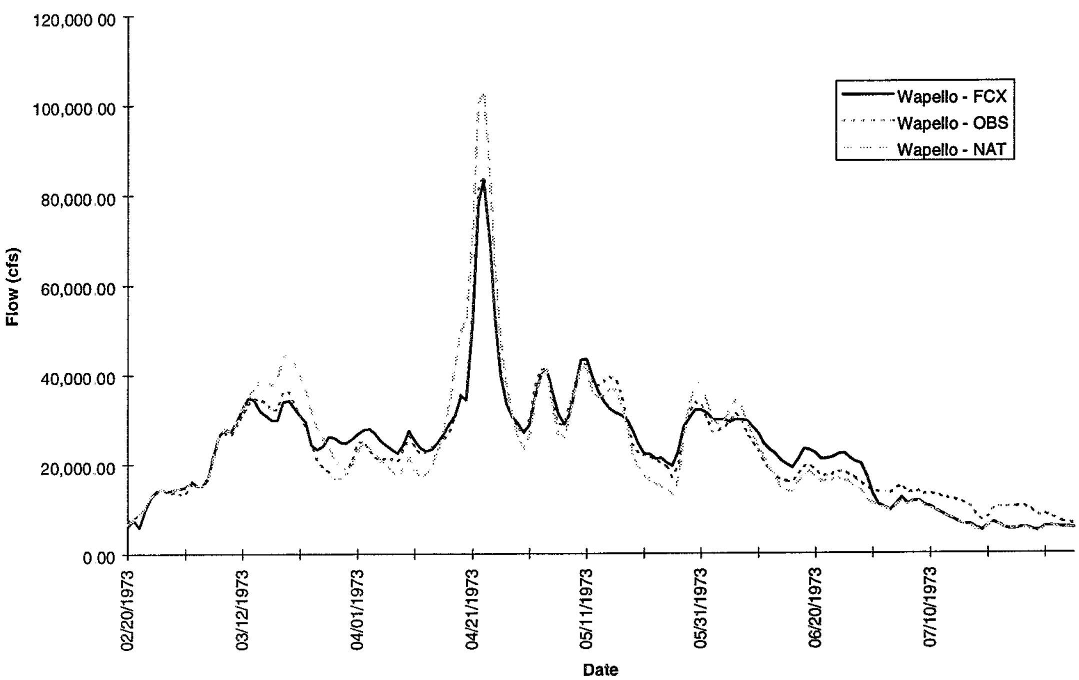

FIGURE D-5d. Wapello Hydrograph - Flood of 1973

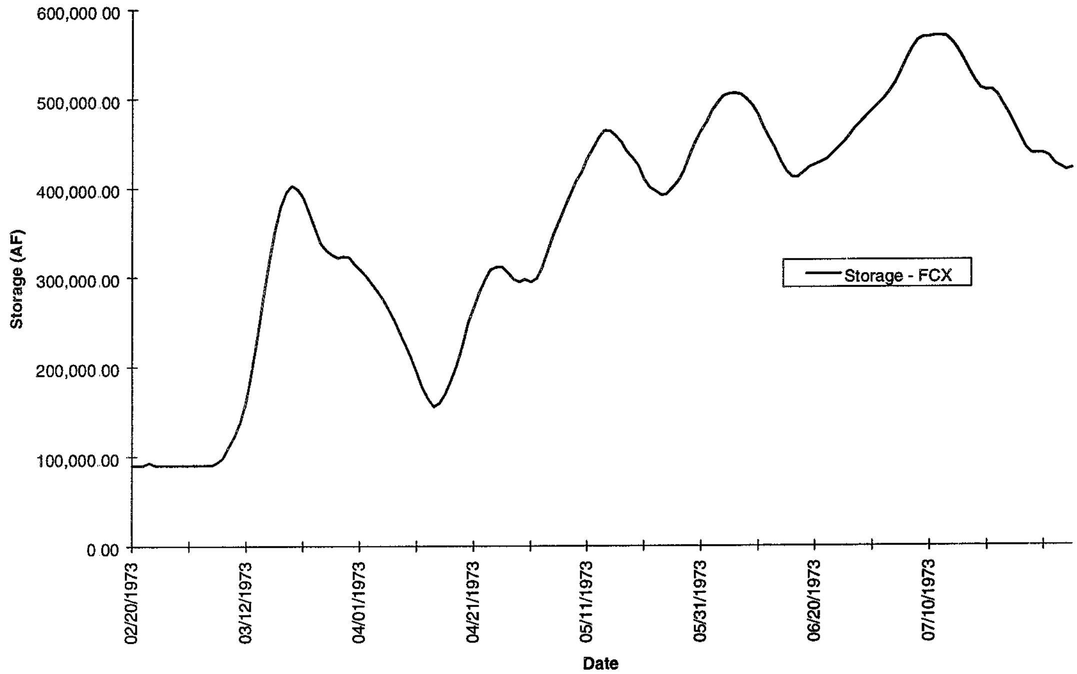

FIGURE D-5e. Saylorville Reservoir Storage - Flood of 1973

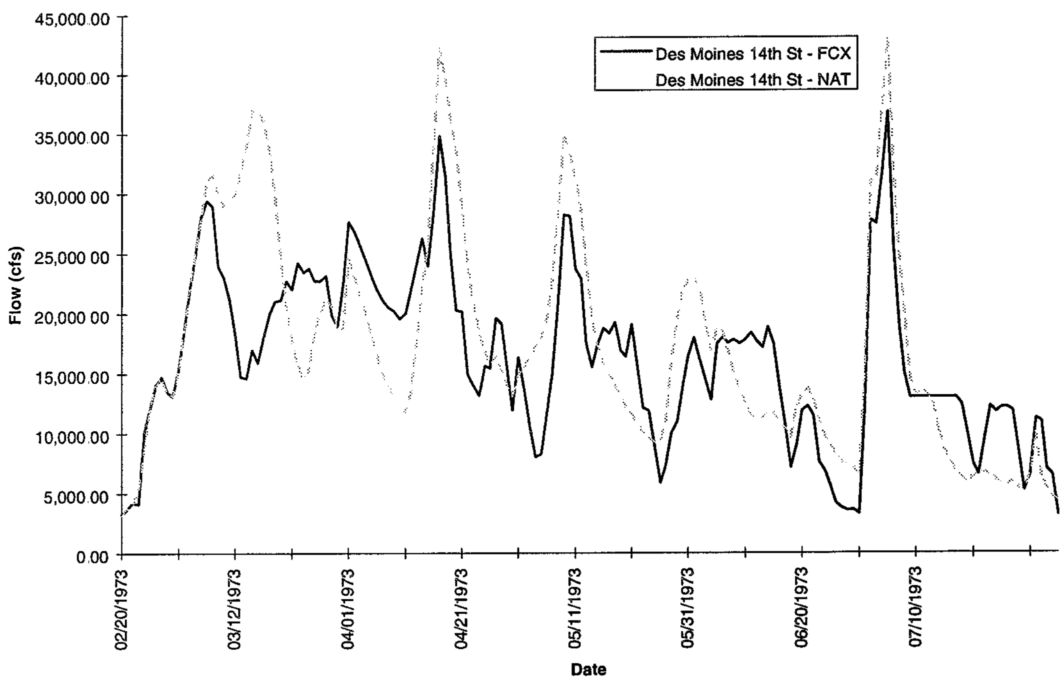

FIGURE D-5f. Des Moines 14th Street - Flood of 1973

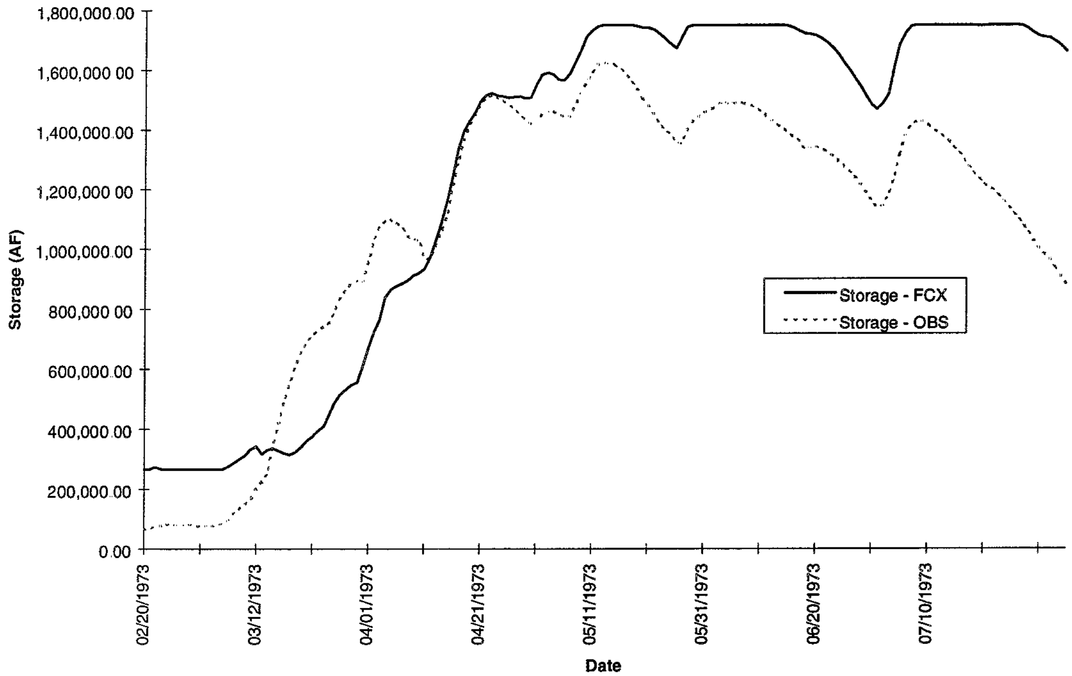

FIGURE D-5g. Lake Red Rock Storage - Flood of 1973

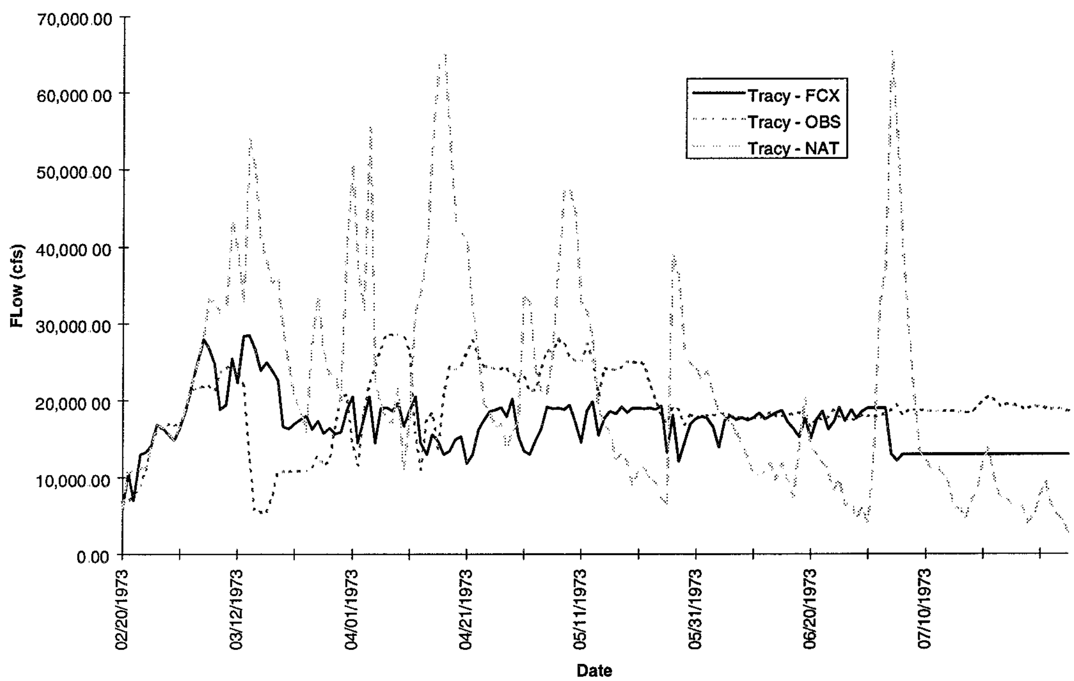

FIGURE D-5h. Tracy Hydrograph - Flood of 1973

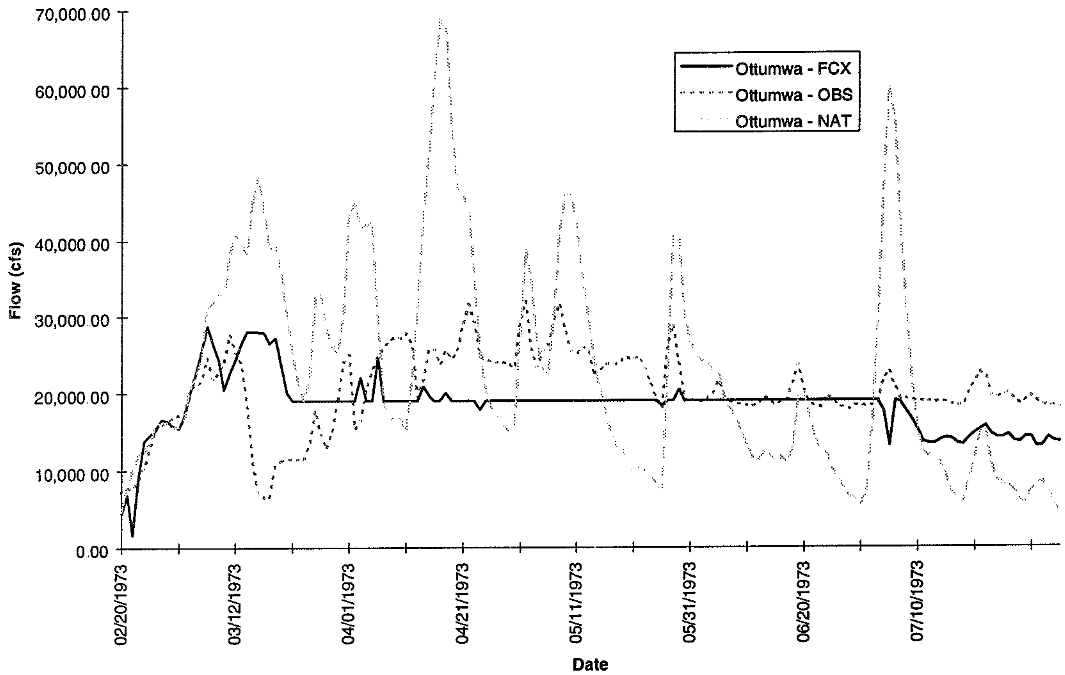

FIGURE D-5i. Ottumwa Hydrograph - Flood of 1973

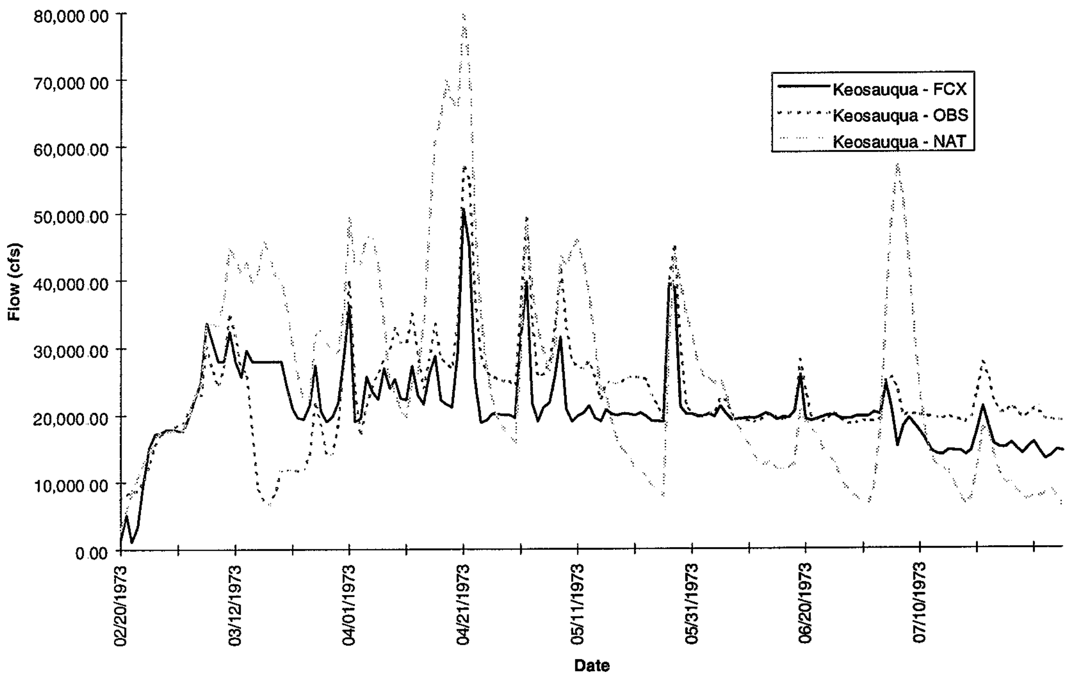

FIGURE D-5j. Keosauqua Hydrograph - Flood of 1973

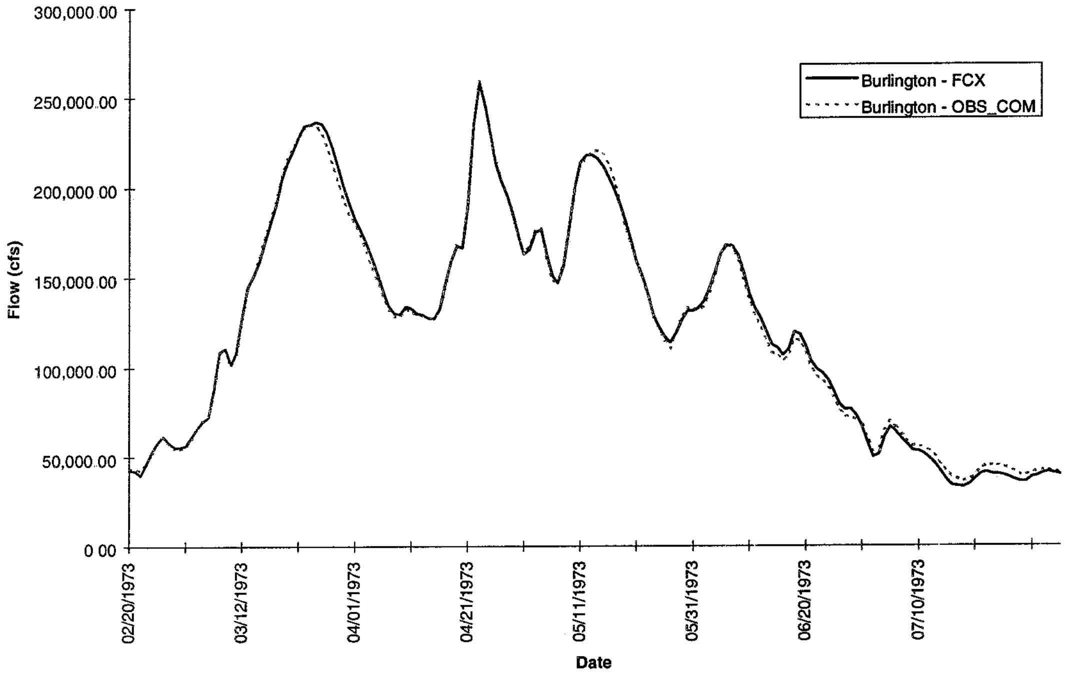

FIGURE D-5k. Burlington Hydrograph - Flood of 1973

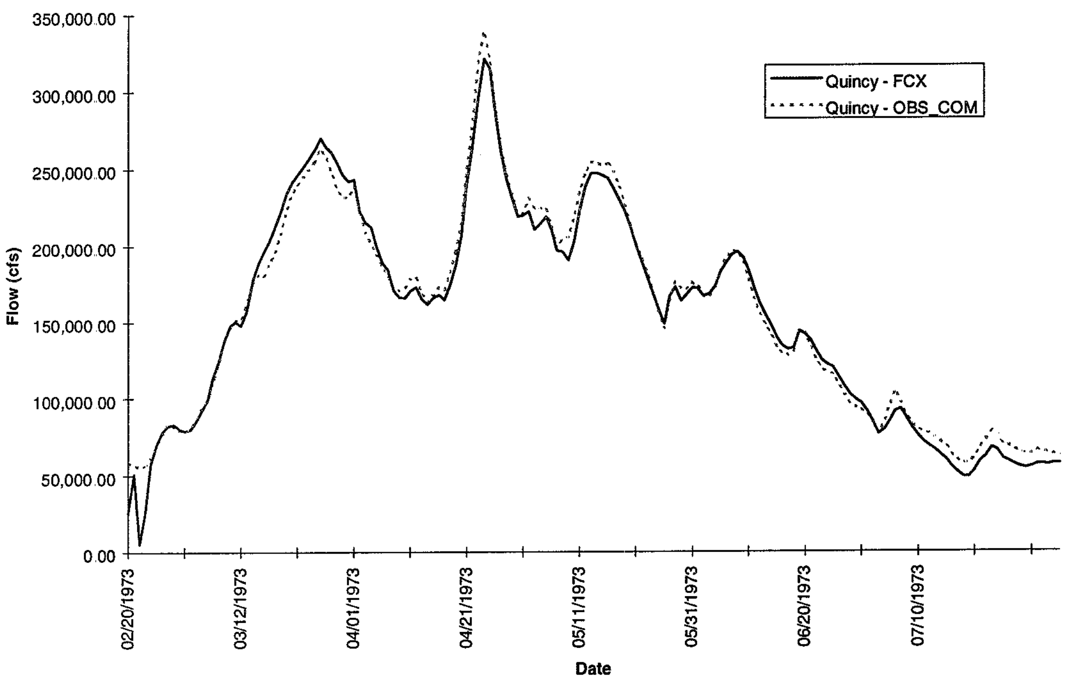

FIGURE D-5l. Quincy Hydrograph - Flood of 1973

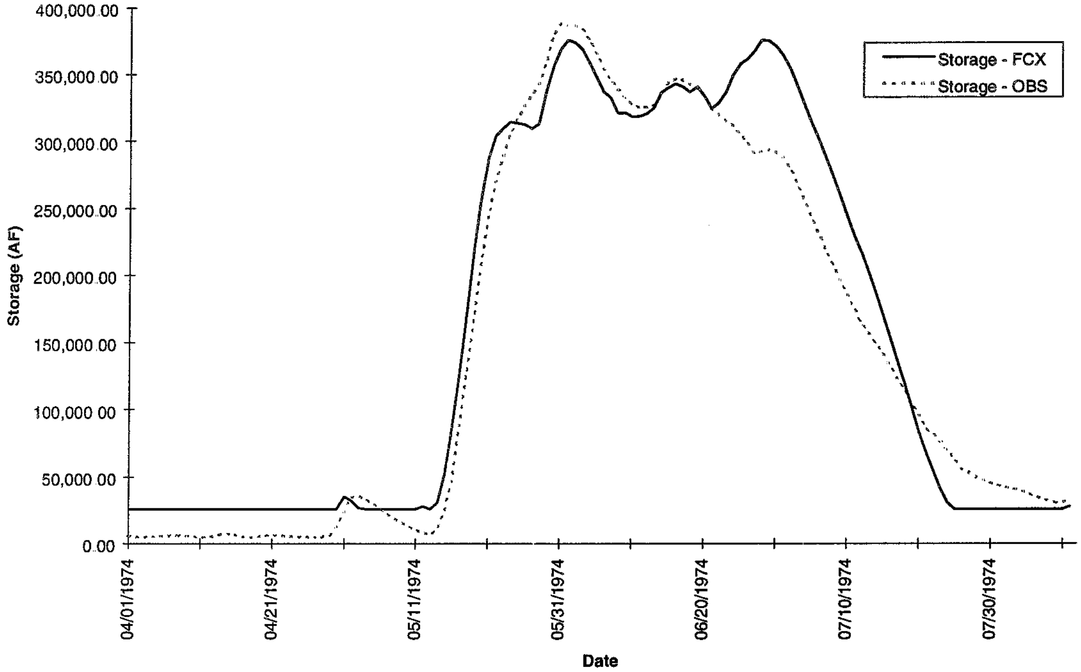

FIGURE D-6a. Coralville Reservoir Storage - Flood of 1974

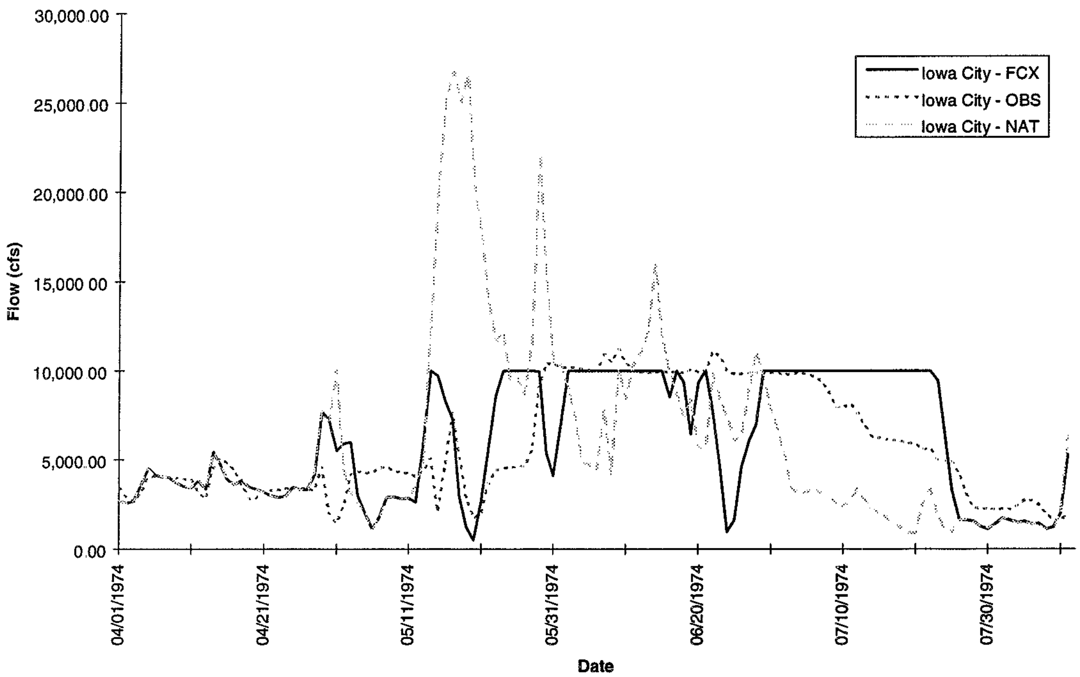

FIGURE D-6b. Iowa City Hydrograph - Flood of 1974

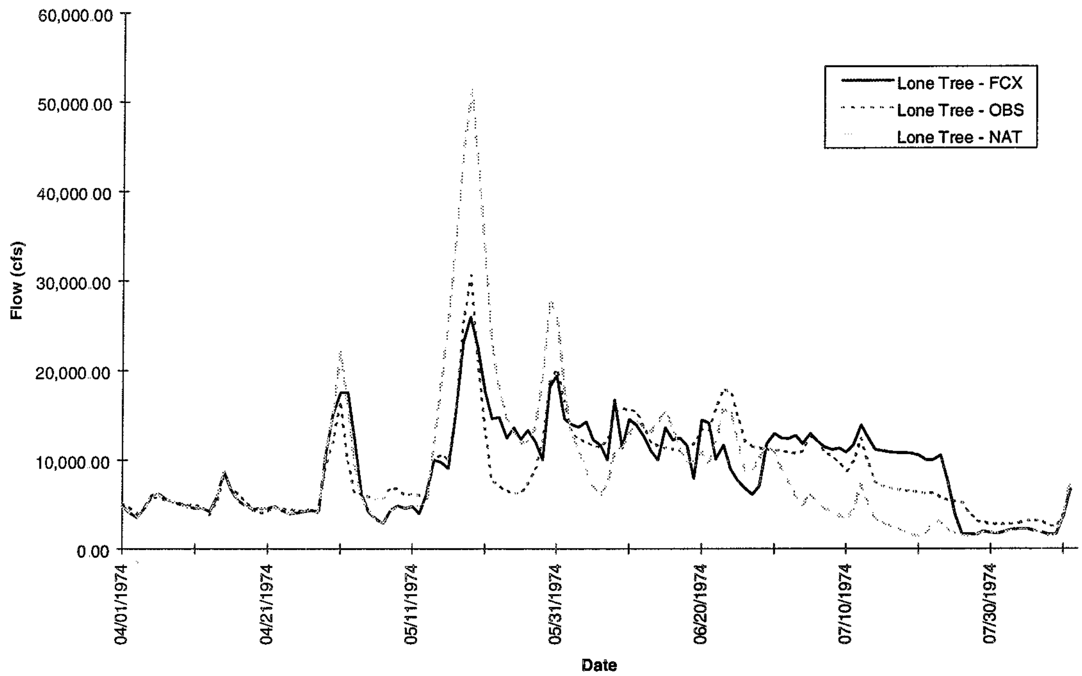

FIGURE D-6c. Lone Tree Hydrograph - Flood of 1974

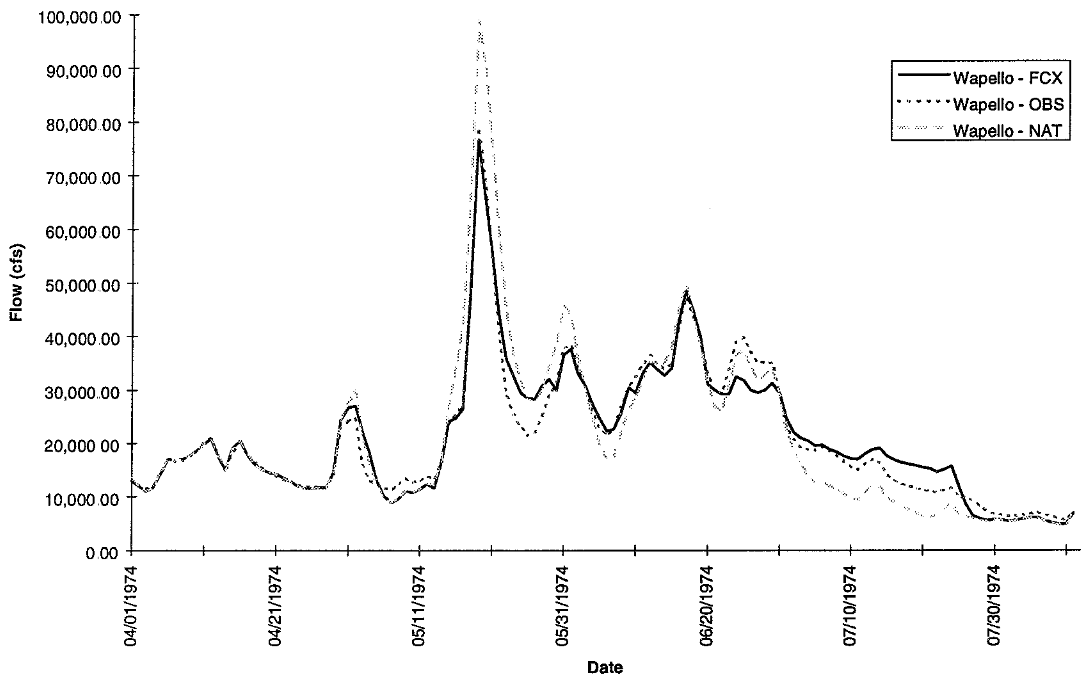

FIGURE D-6d. Wapello Hydrograph - Flood of 1974

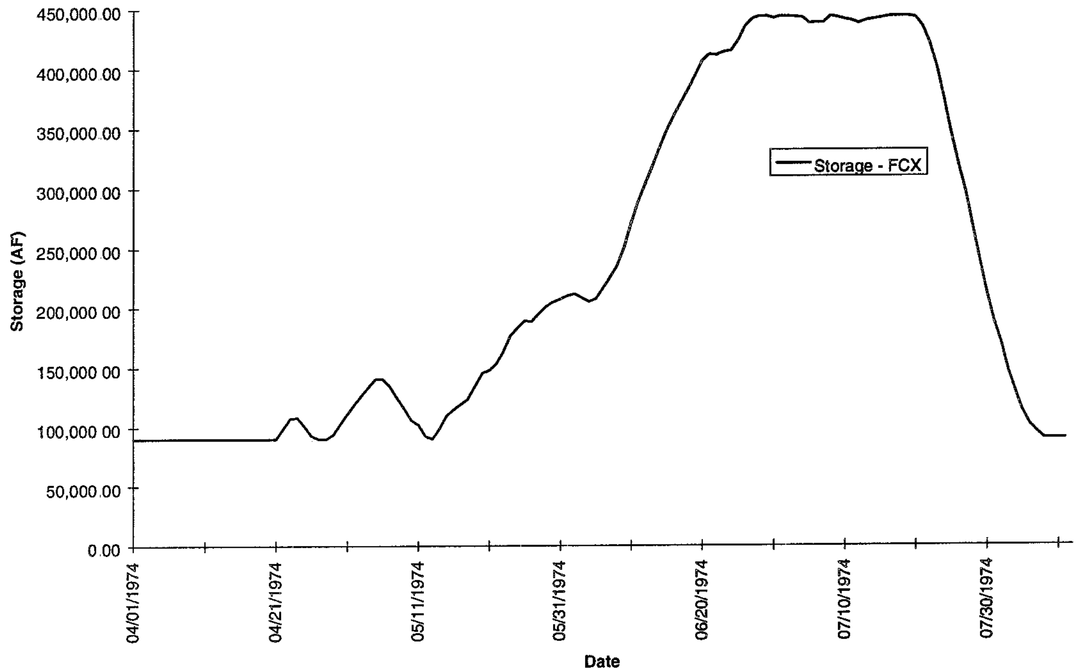

FIGURE D-6e. Saylorville Reservoir Storage - Flood of 1974

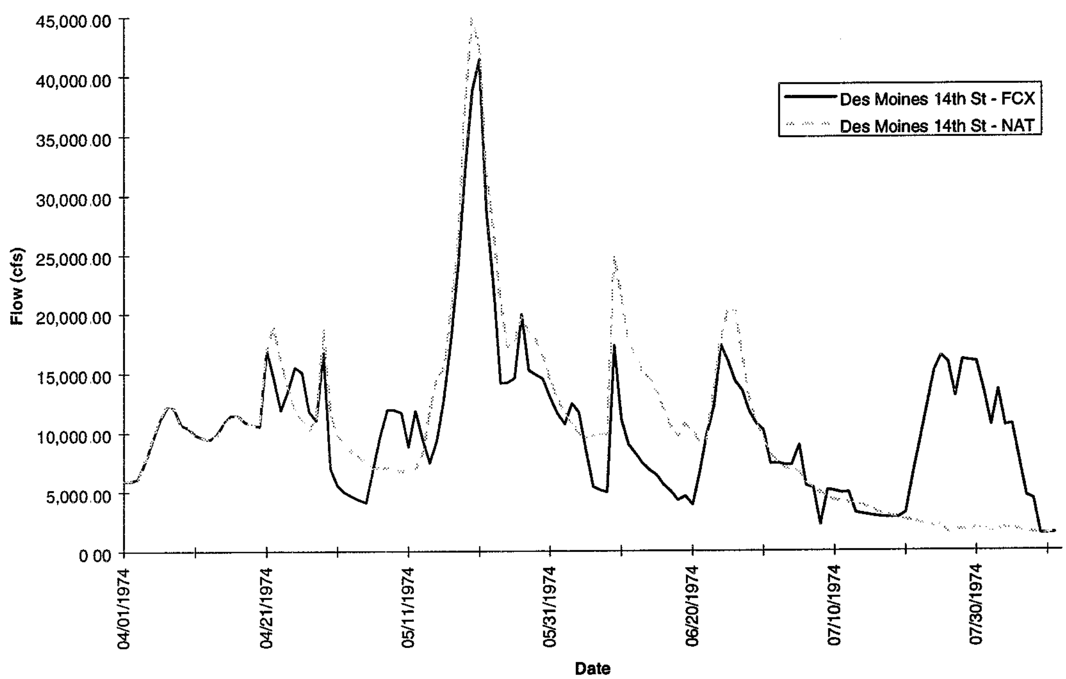

FIGURE D-6f. Des Moines 14th Street - Flood of 1974

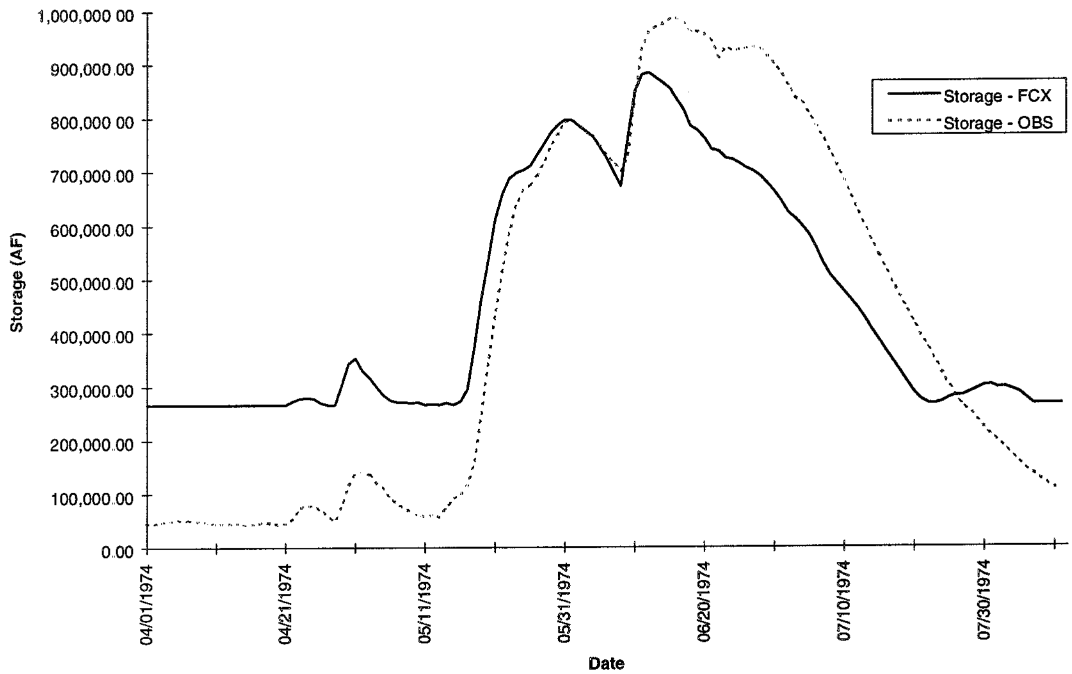

FIGURE D-6g. Lake Red Rock Storage - Flood of 1974

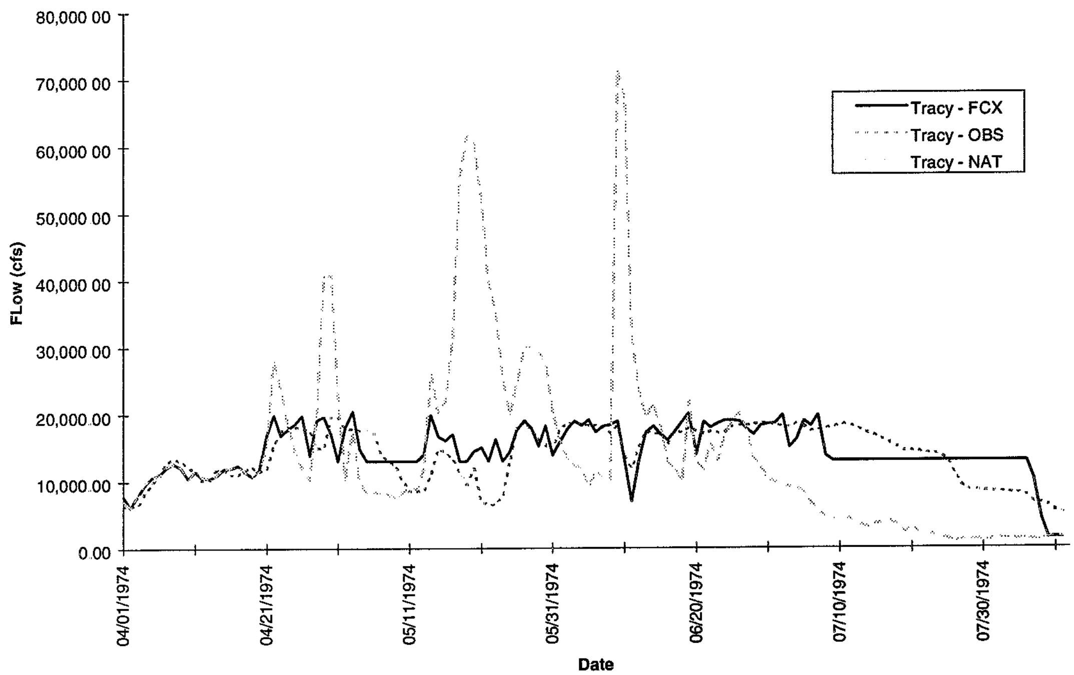

FIGURE D-6h. Tracy Hydrograph - Flood of 1974

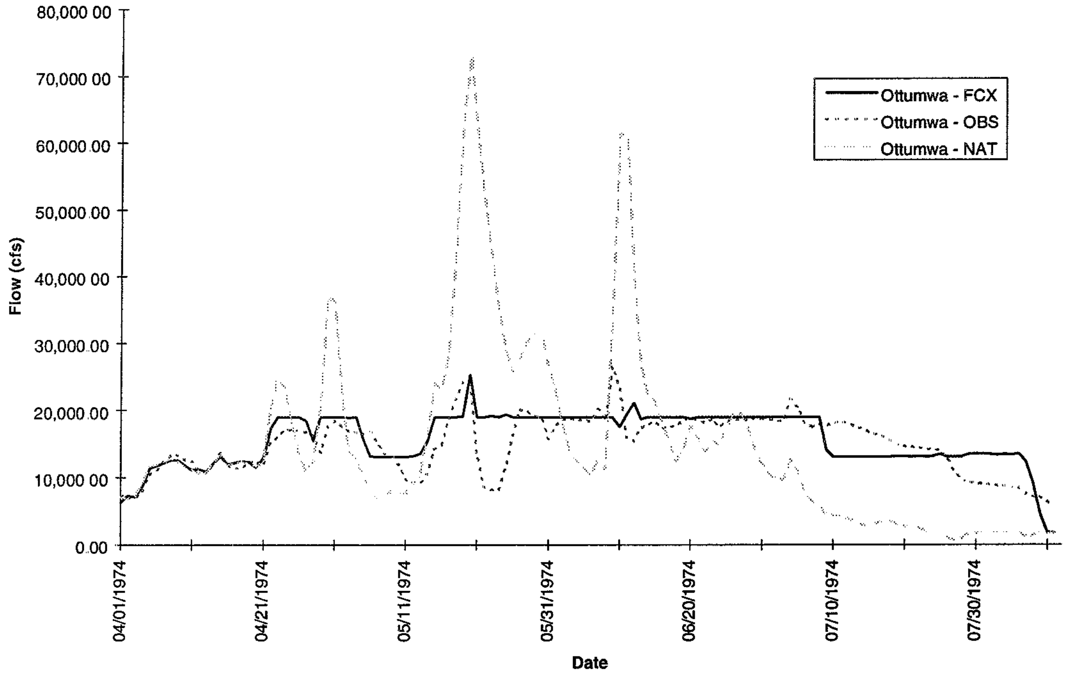

FIGURE D-6i. Ottumwa Hydrograph - Flood of 1974

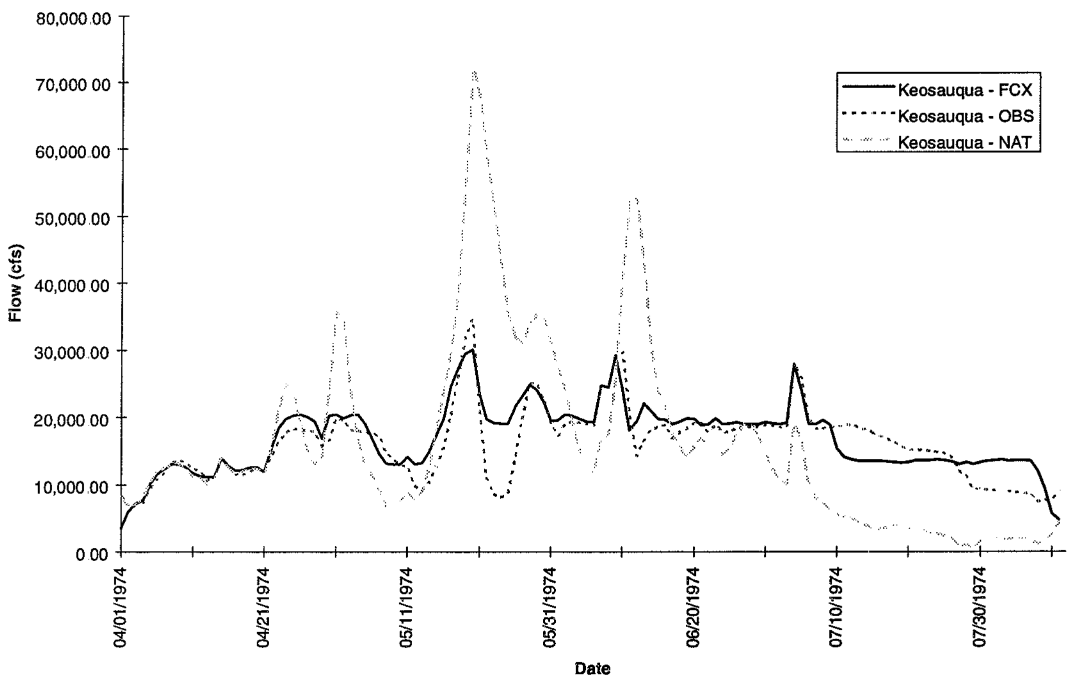

FIGURE D-6j. Keosauqua Hydrograph - Flood of 1974

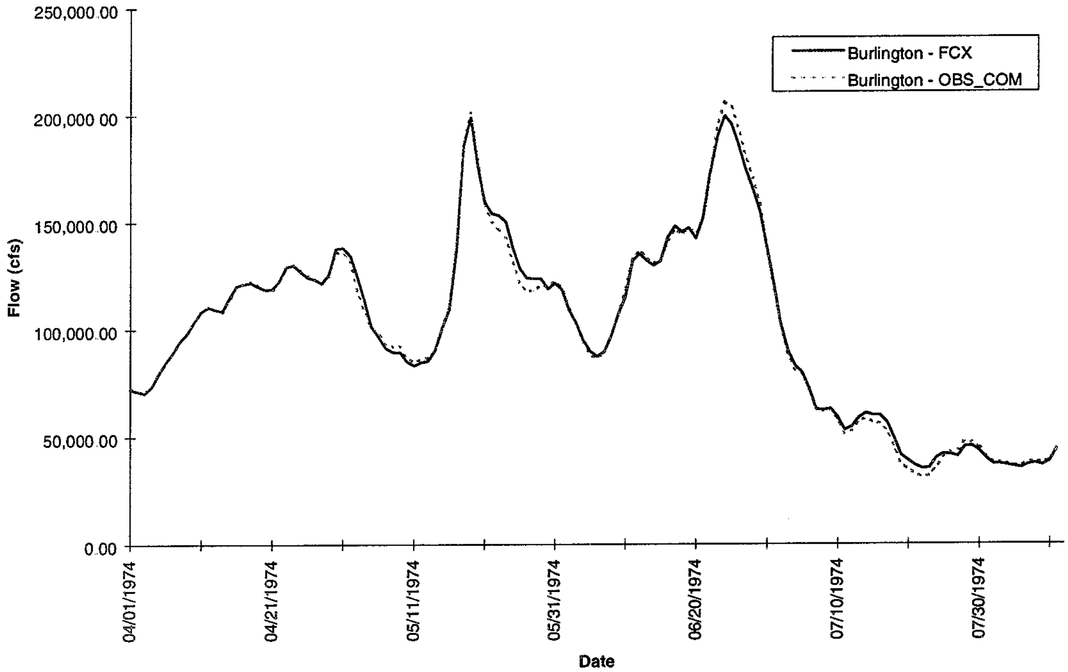

FIGURE D-6k. Burlington Hydrograph - Flood of 1974

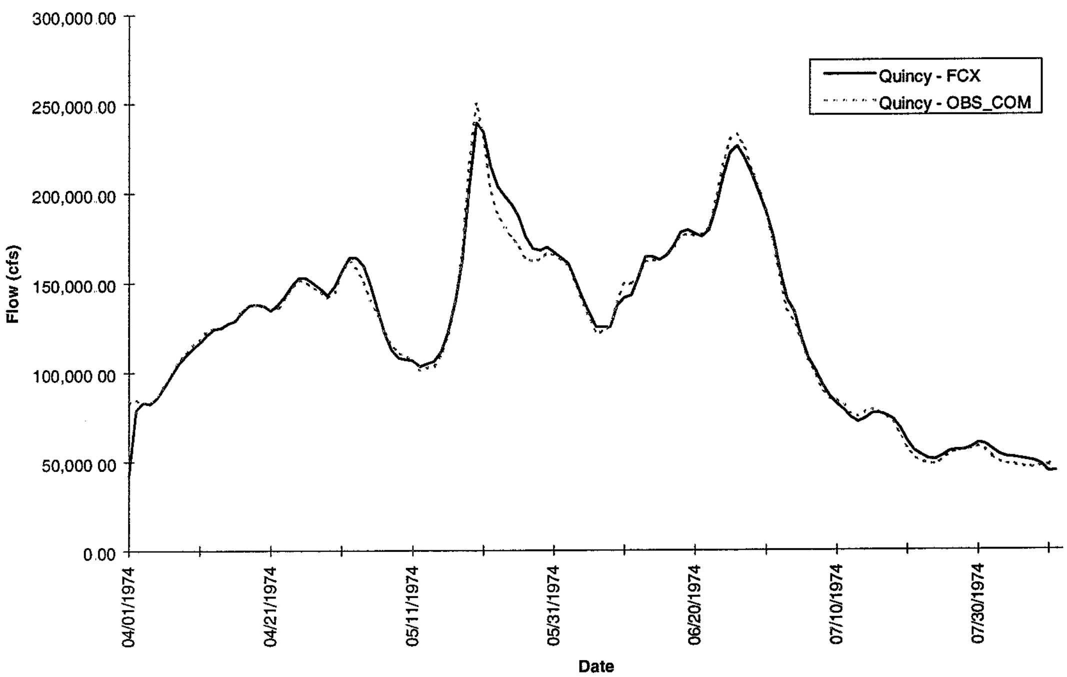

FIGURE D-6l. Quincy Hydrograph - Flood of 1974

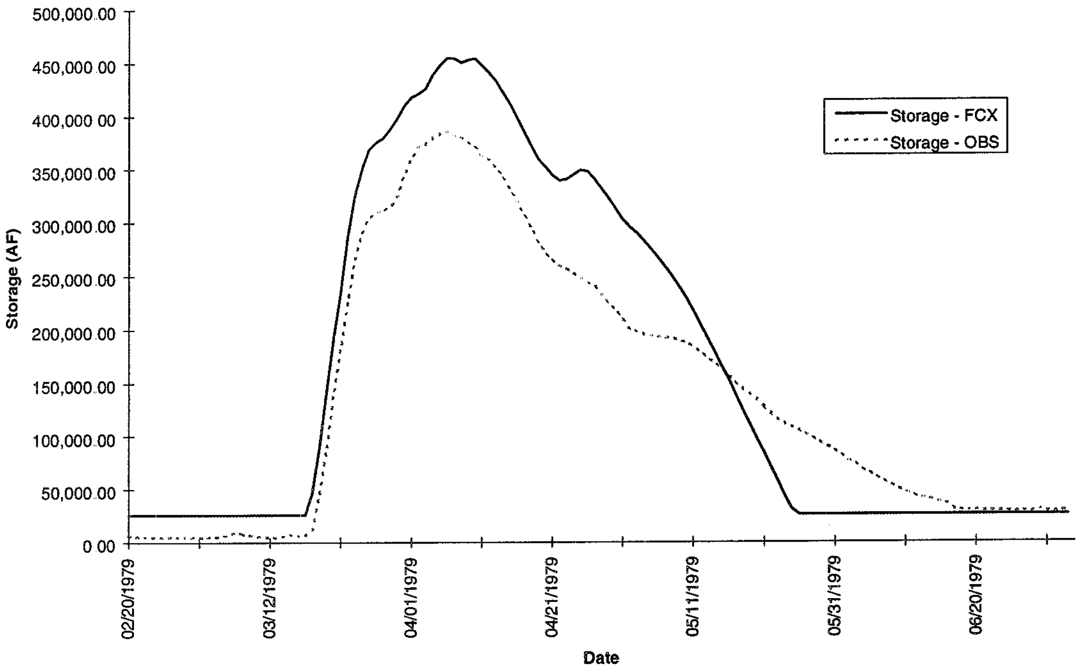

FIGURE D-7a. Coralville Reservoir Storage - Flood of 1979

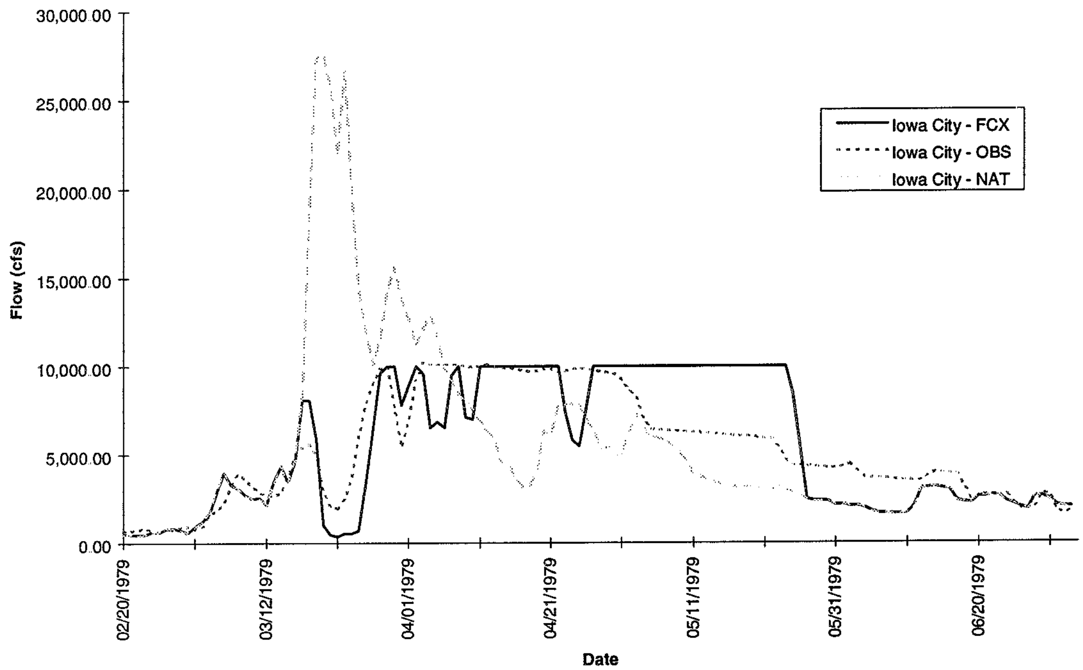

FIGURE D-7b. Iowa City Hydrograph - Flood of 1979

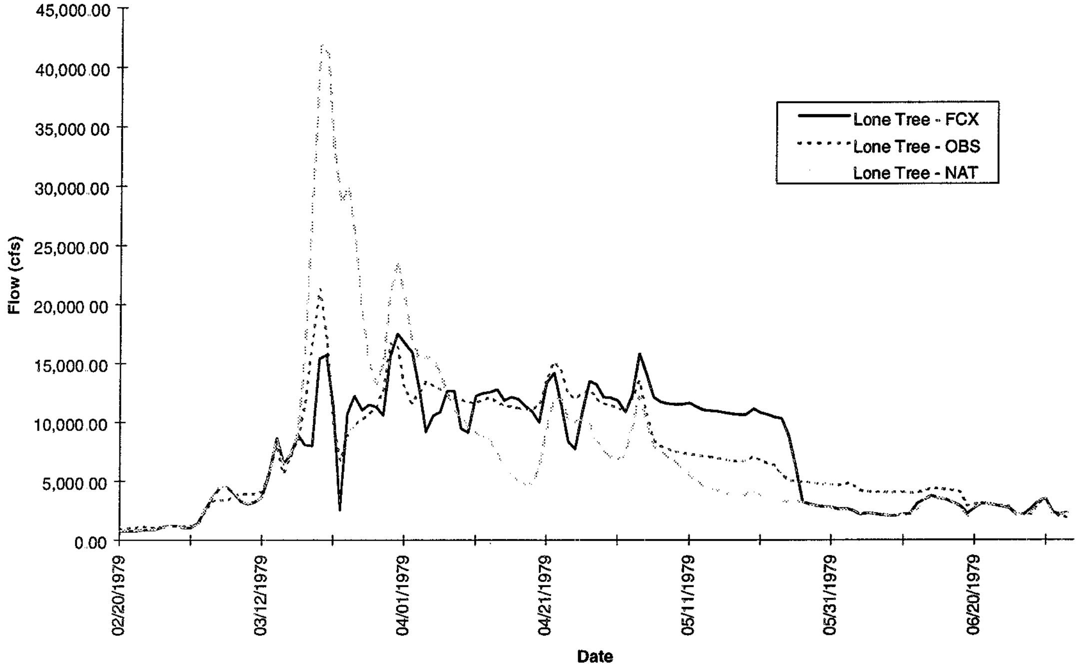

FIGURE D-7c. Lone Tree Hydrograph - Flood of 1979

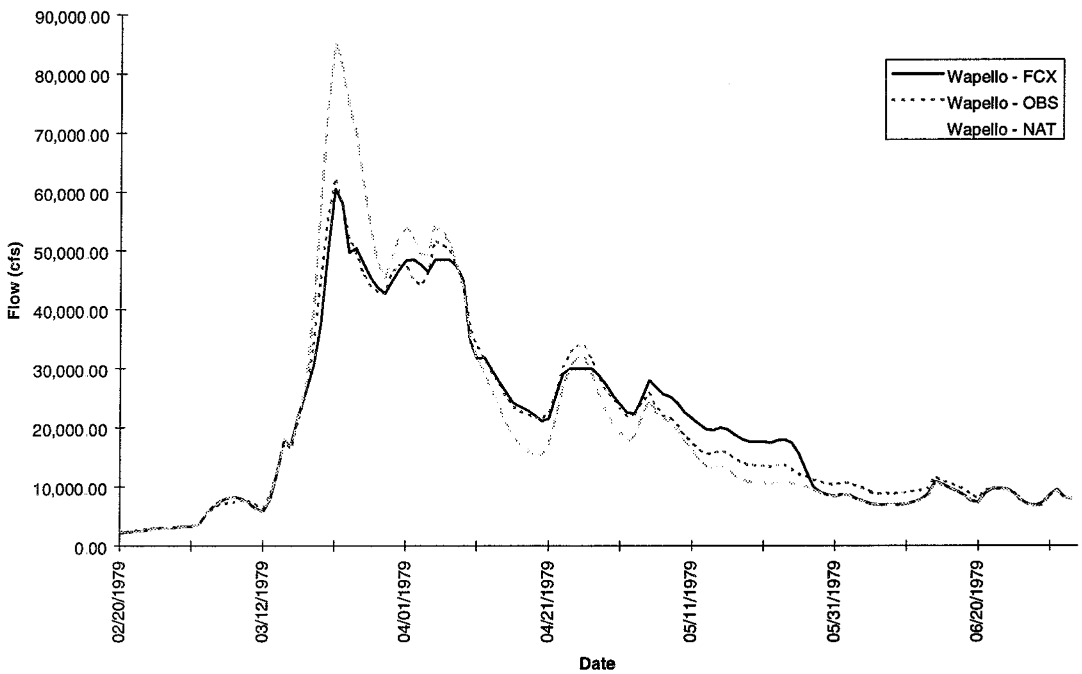

FIGURE D-7d. Wapello Hydrograph - Flood of 1979

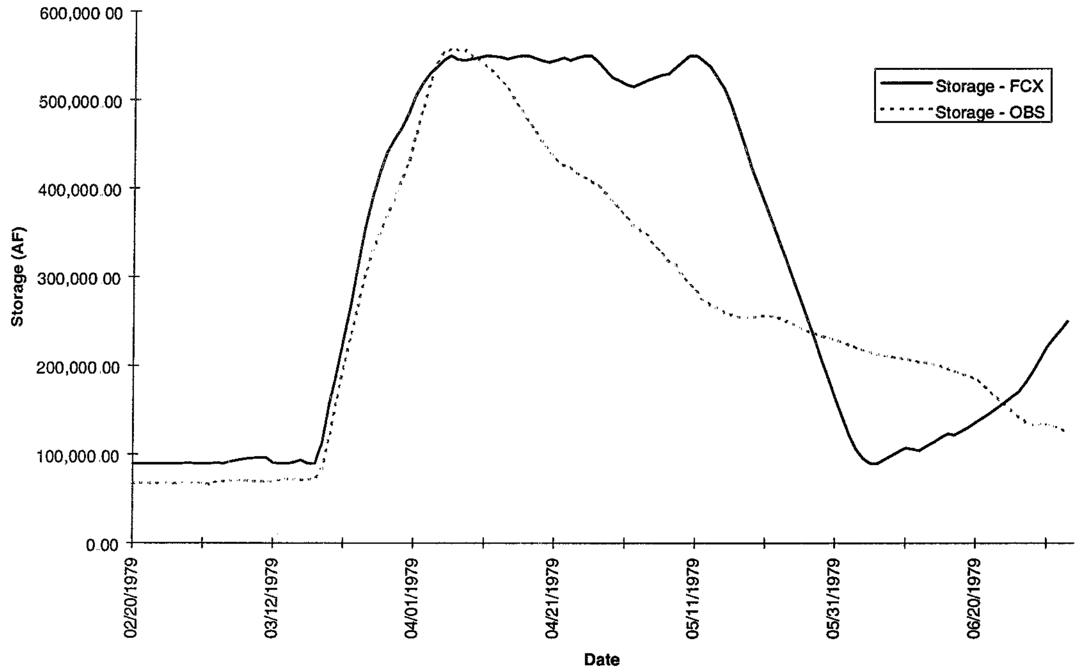

FIGURE D-7e. Saylorville Reservoir Storage - Flood of 1979

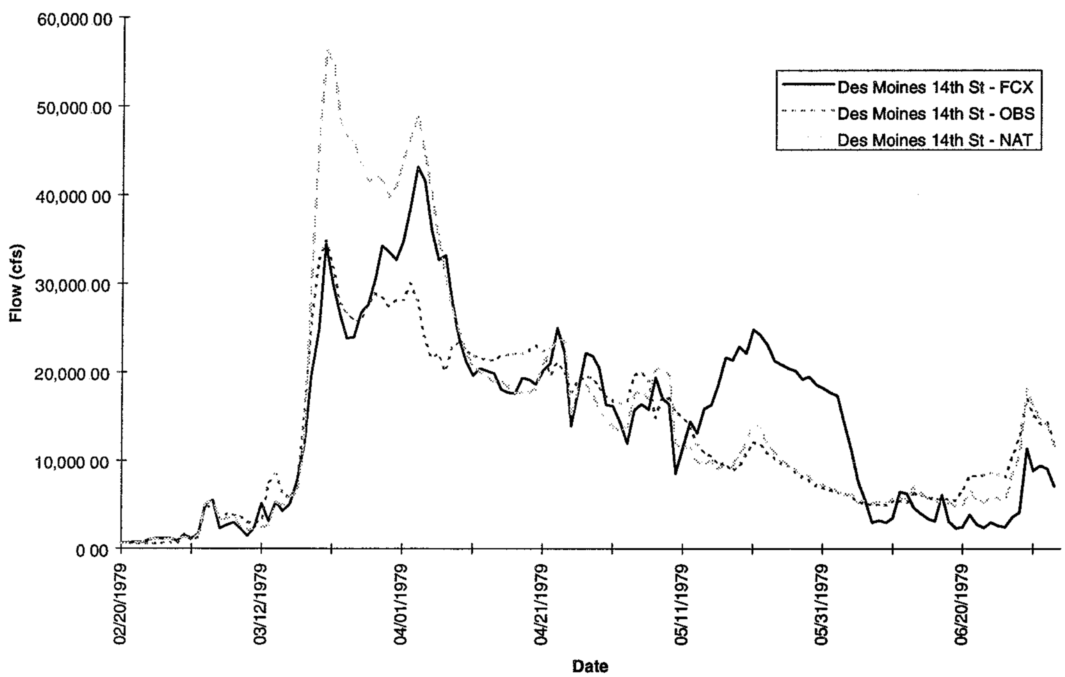

FIGURE D-7f. Des Moines 14th Street - Flood of 1979

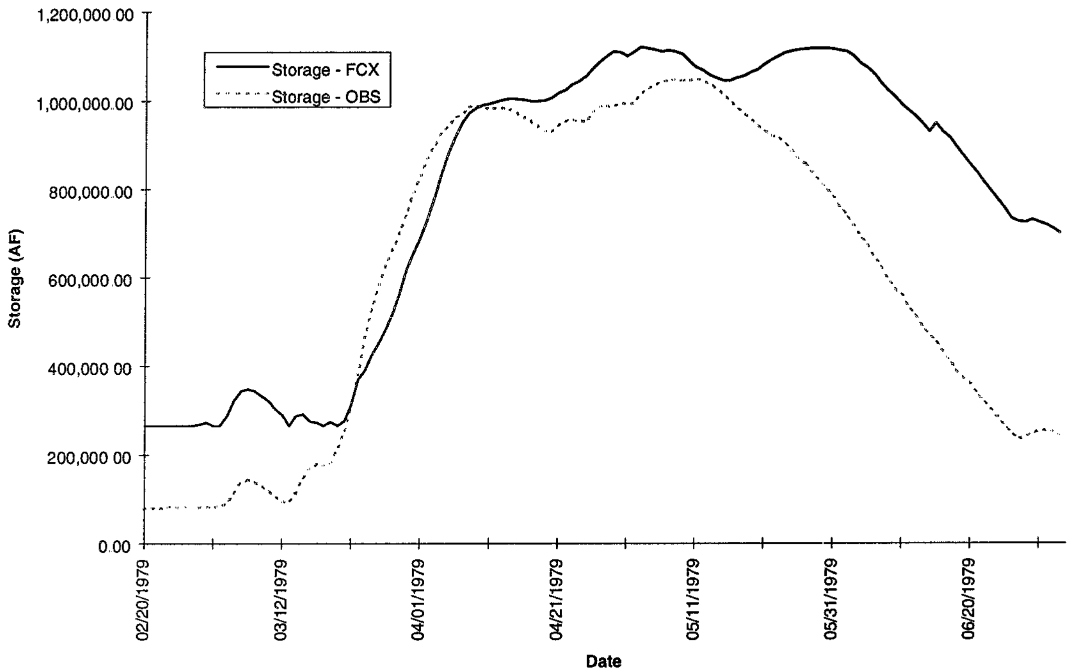

FIGURE D-7g. Lake Red Rock Storage - Flood of 1979

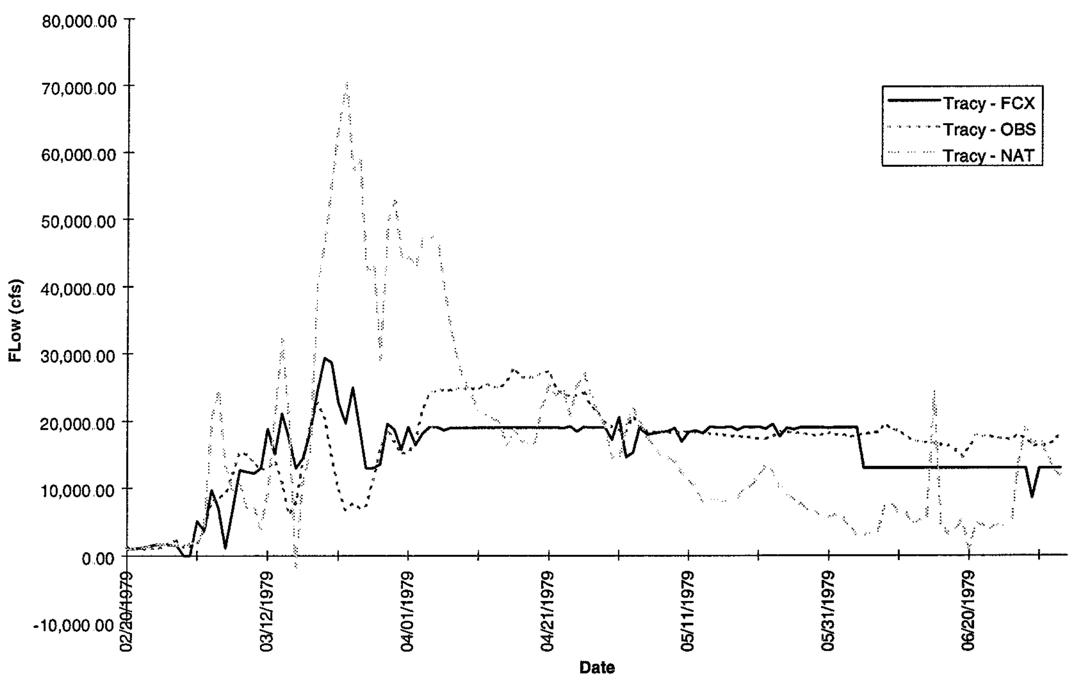

FIGURE D-7h. Tracy Hydrograph - Flood of 1979

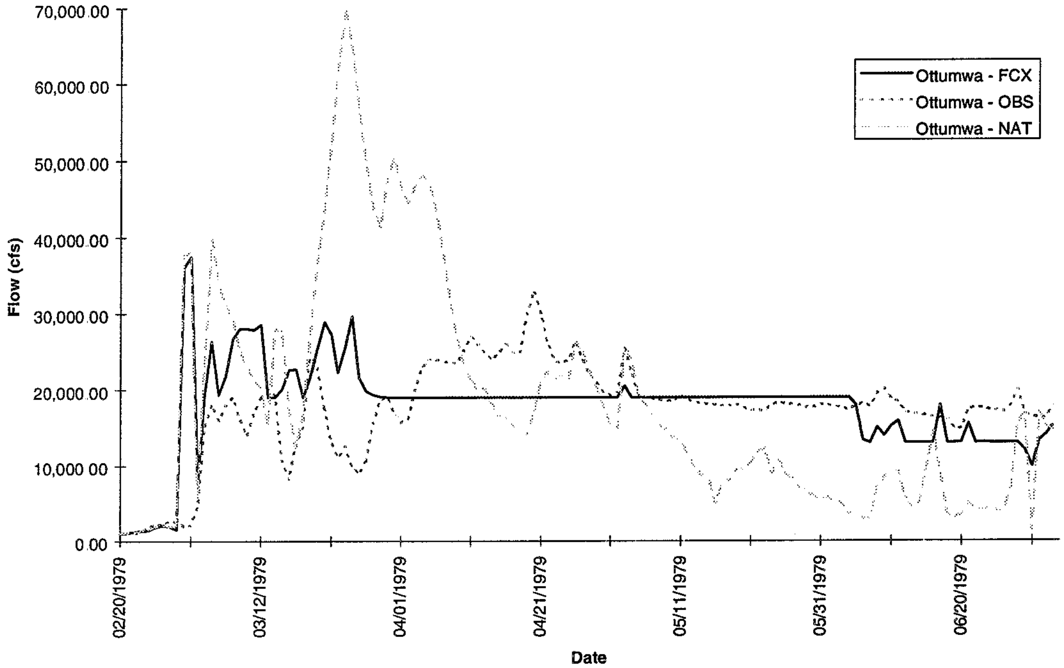

FIGURE D-7i. Ottumwa Hydrograph - Flood of 1979

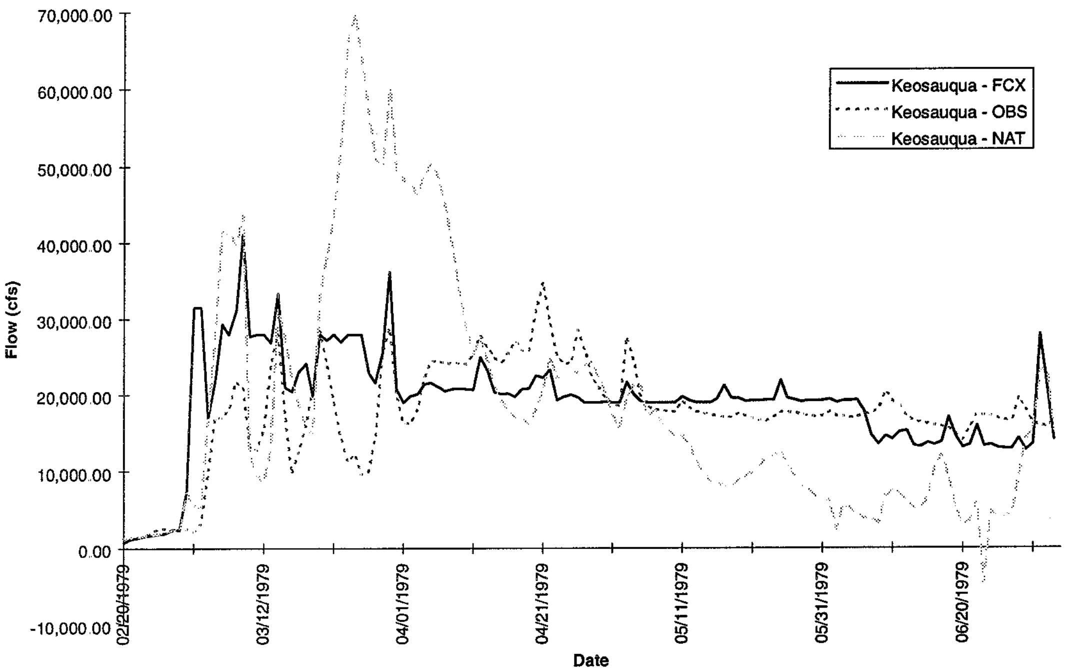

FIGURE D-7j. Keosauqua Hydrograph - Flood of 1979

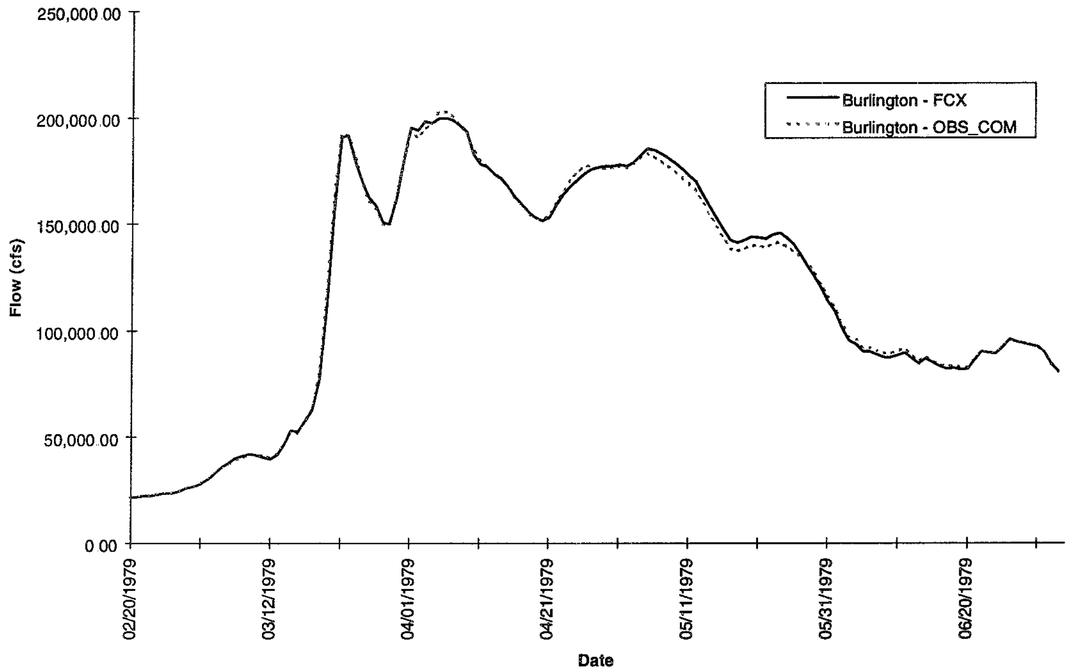

FIGURE D-7k. Burlington Hydrograph - Flood of 1979

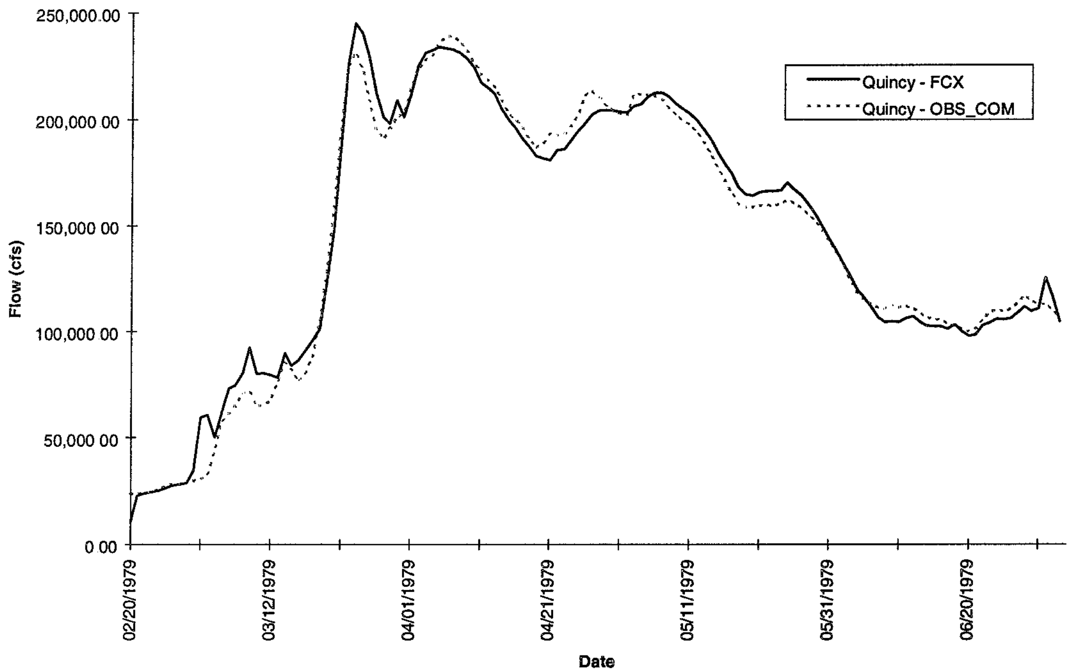

FIGURE D-7l. Quincy Hydrograph - Flood of 1979

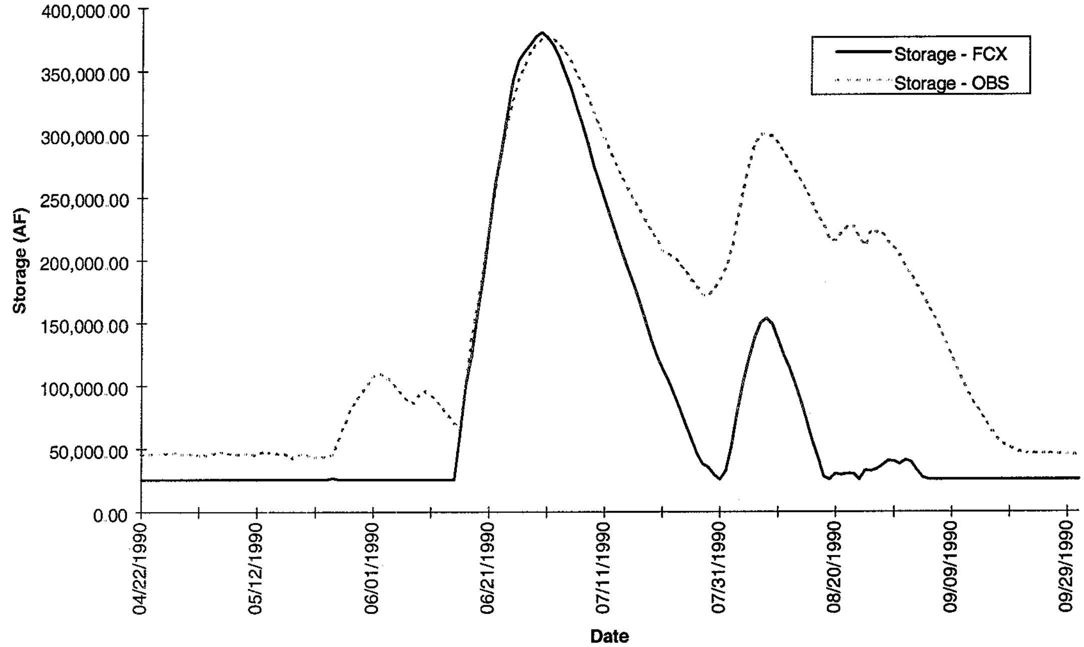

FIGURE D-8a. Coralville Reservoir Storage - Flood of 1990

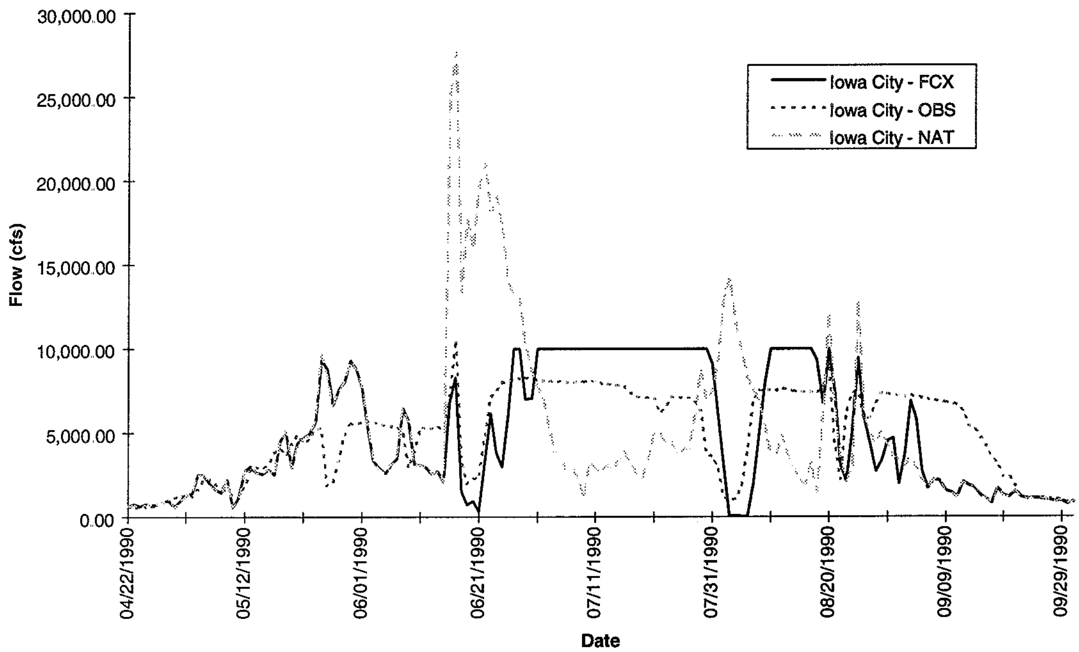

FIGURE D-8b. Iowa City Hydrograph - Flood of 1990

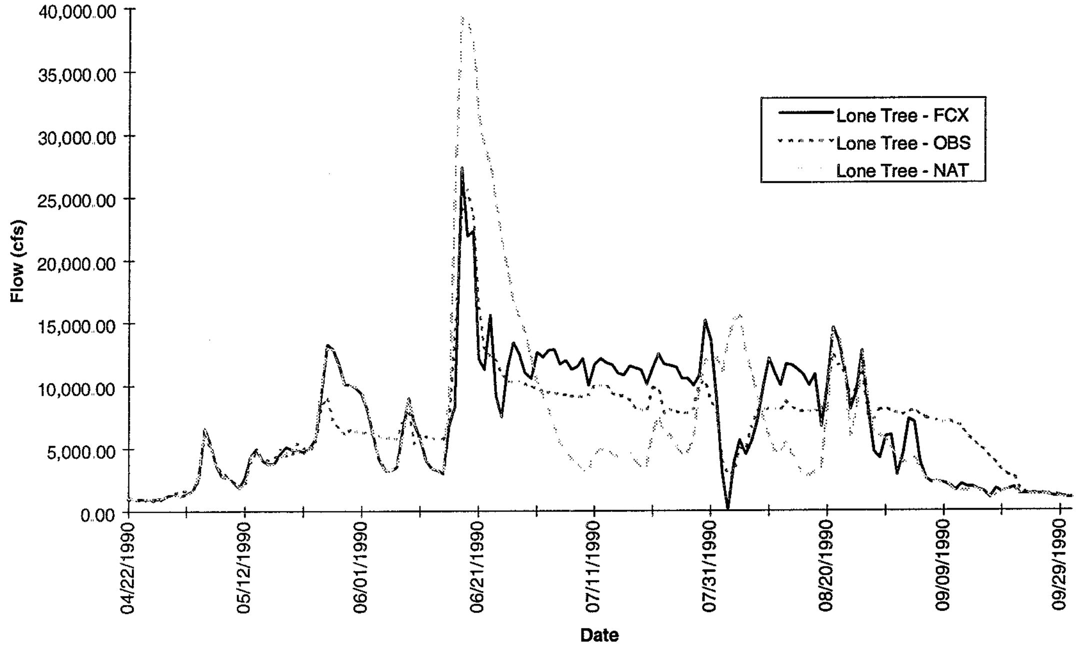

FIGURE D-8c. Lone Tree Hydrograph - Flood of 1990

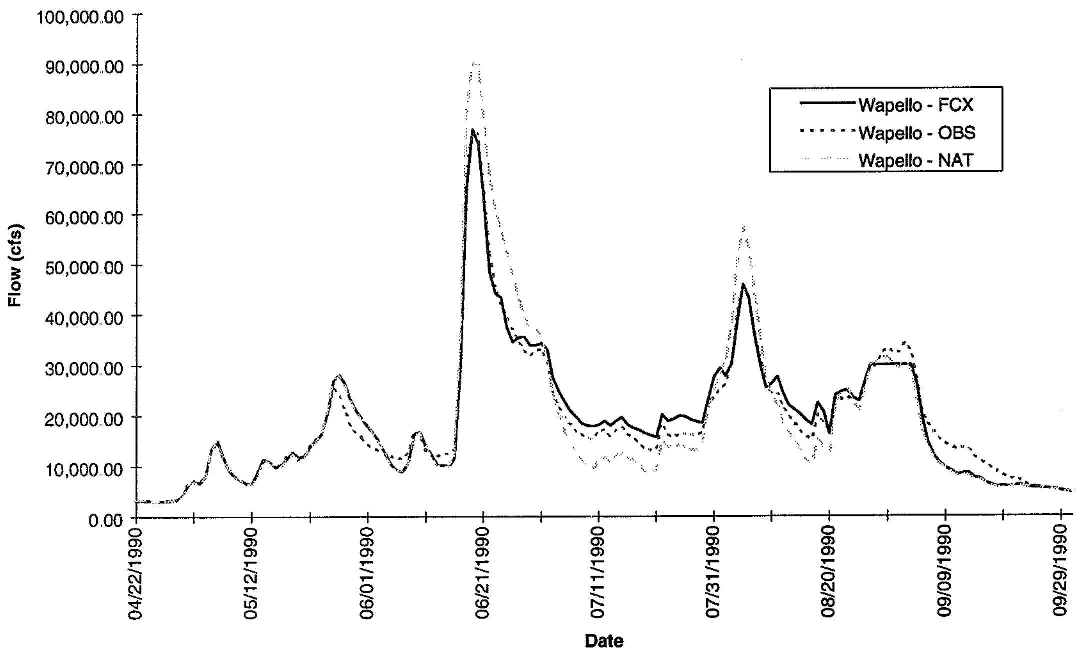

FIGURE D-8d. Wapello Hydrograph - Flood of 1990

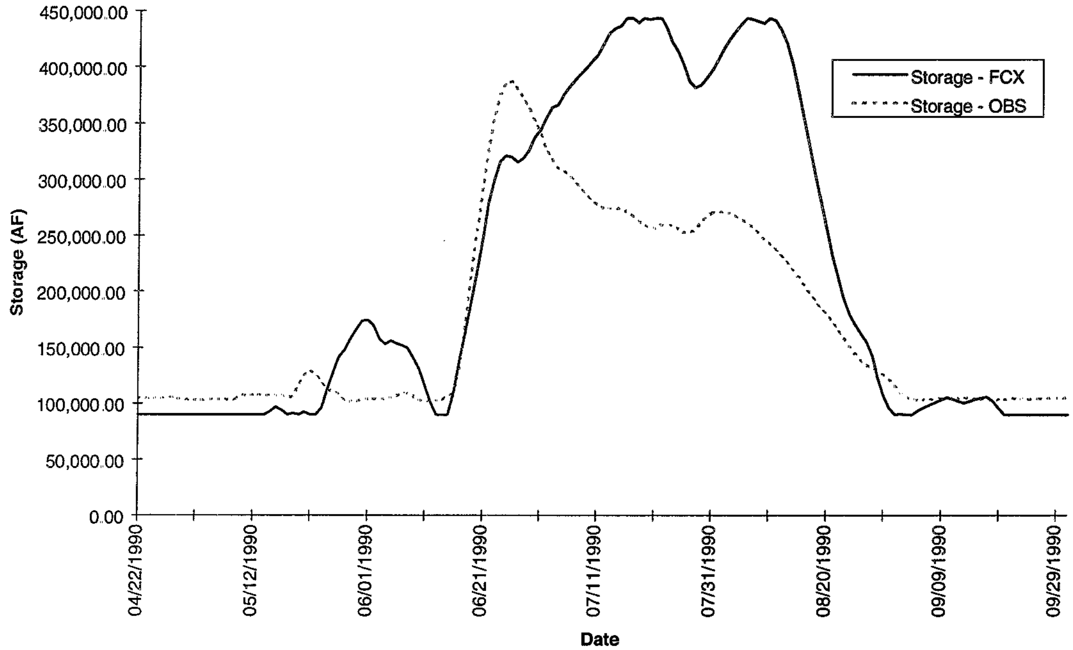

FIGURE D-8e. Saylorville Reservoir Storage - Flood of 1990

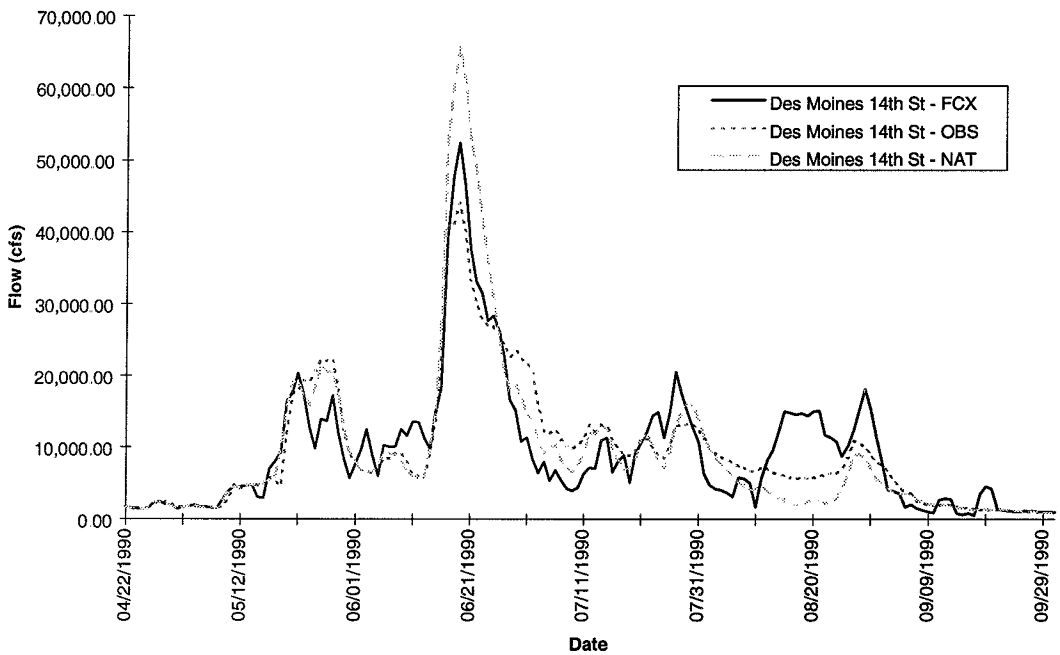

FIGURE D-8f. Des Moines 14th Street - Flood of 1990

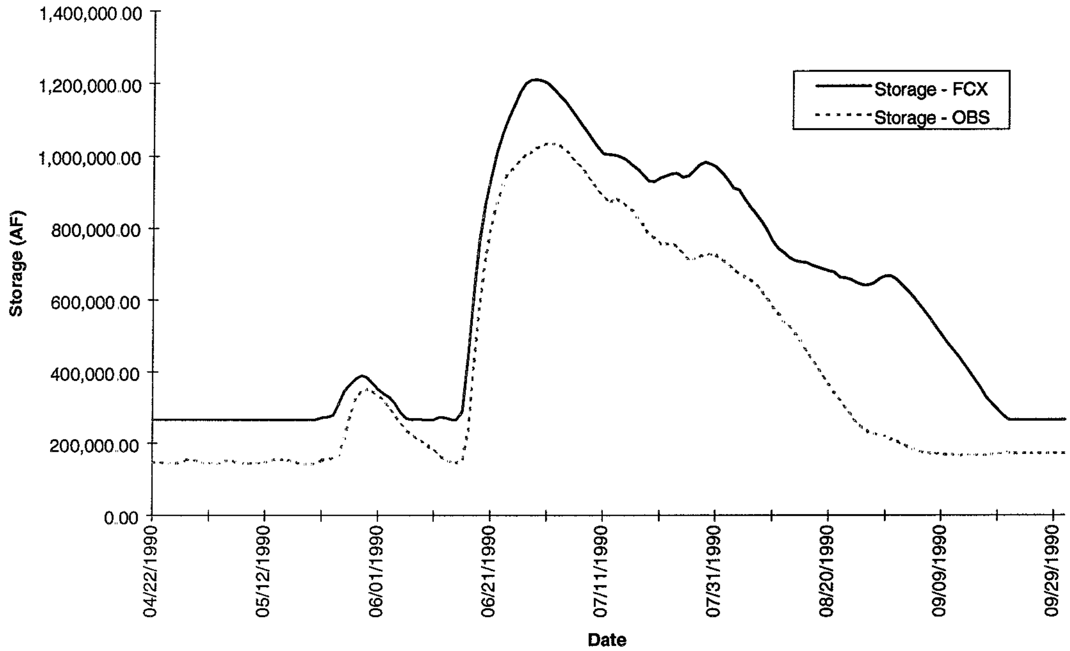

FIGURE D-8g. Lake Red Rock Storage - Flood of 1990

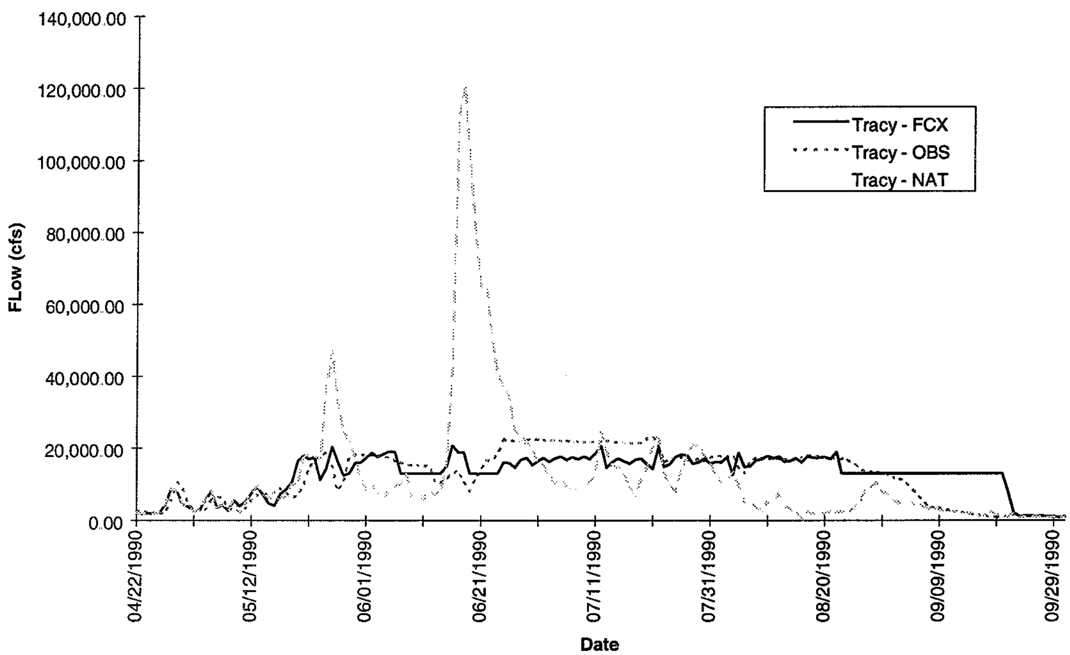

FIGURE D-8h. Tracy Hydrograph - Flood of 1990

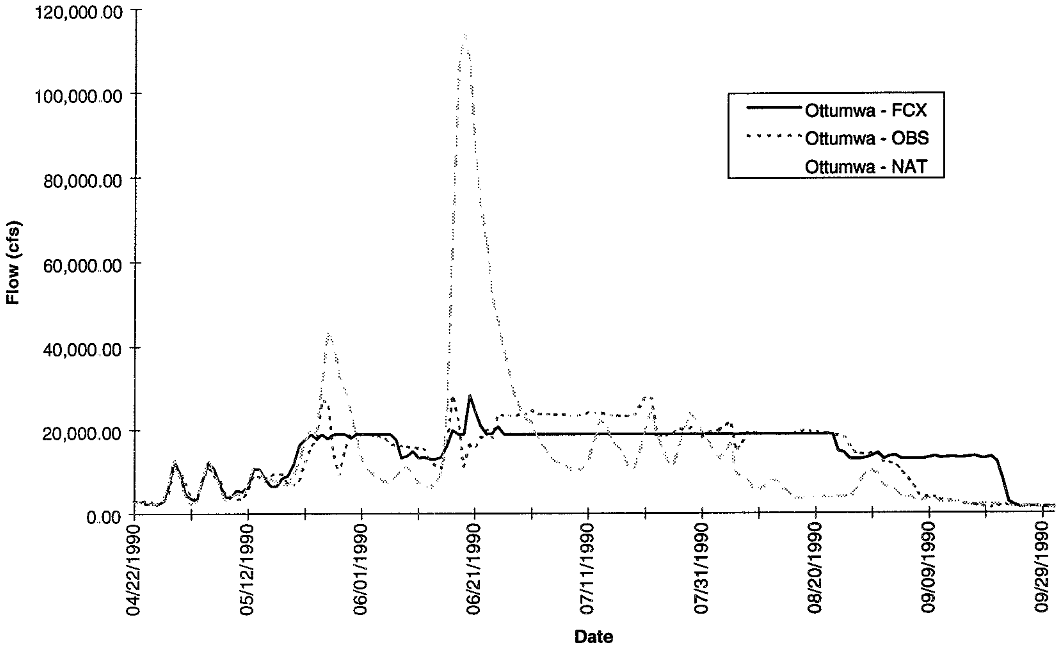

FIGURE D-8i. Ottumwa Hydrograph - Flood of 1990

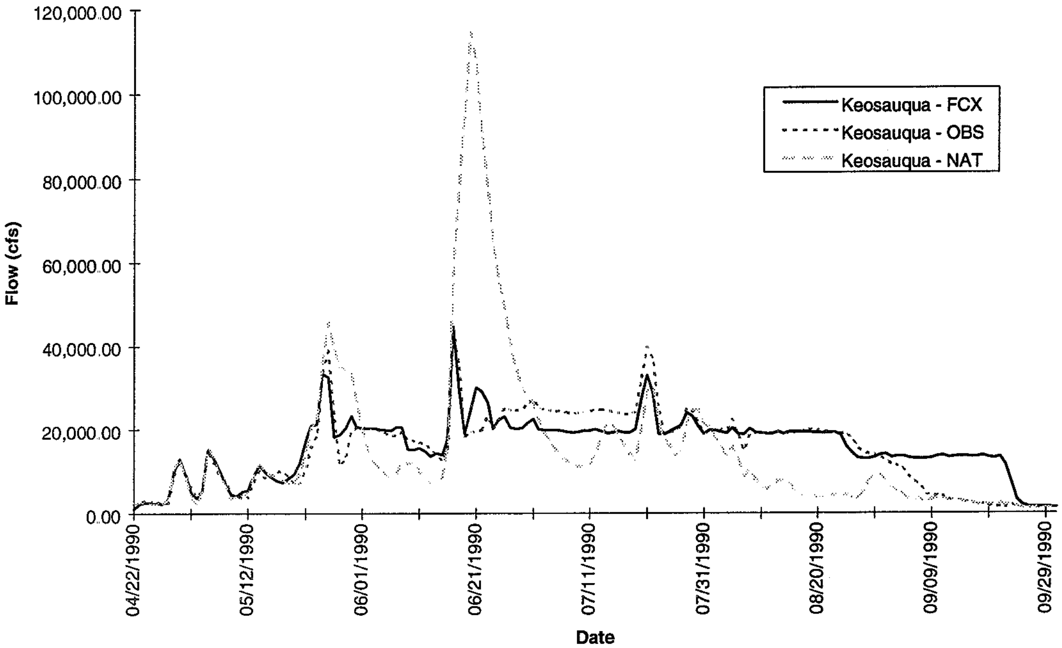

FIGURE D-8j. Keosauqua Hydrograph - Flood of 1990

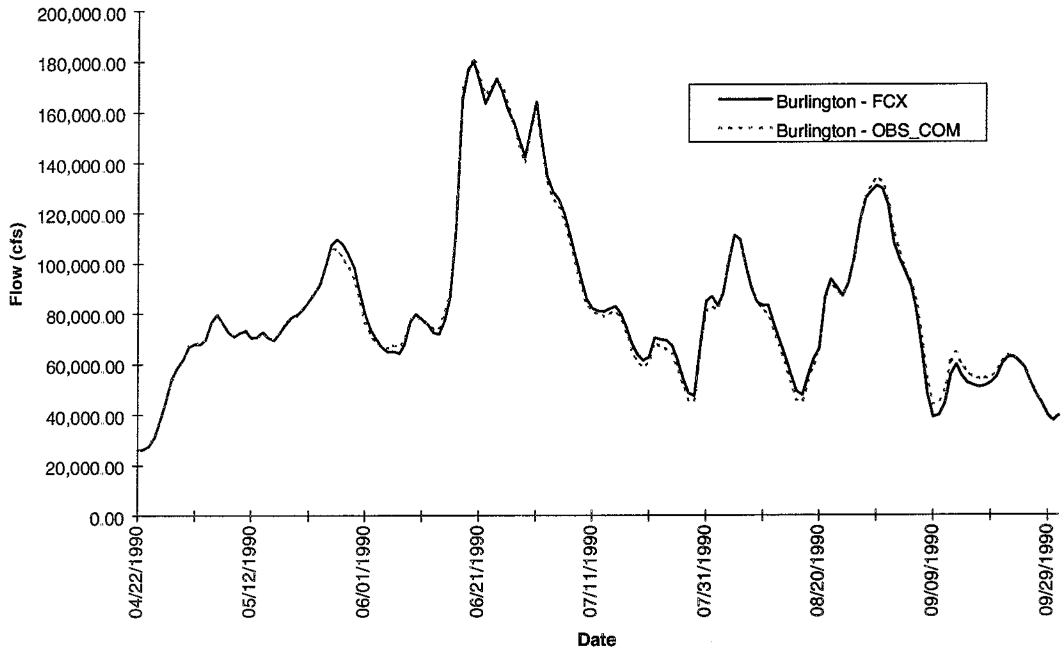

FIGURE D-8k. Burlington Hydrograph - Flood of 1990

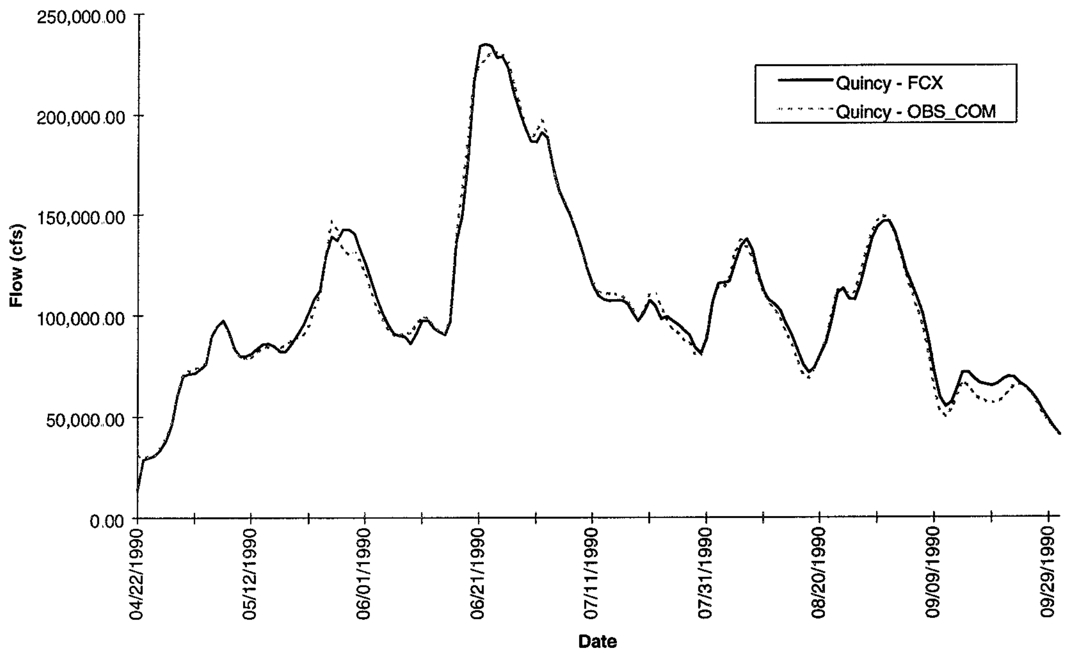

FIGURE D-8l. Quincy Hydrograph - Flood of 1990

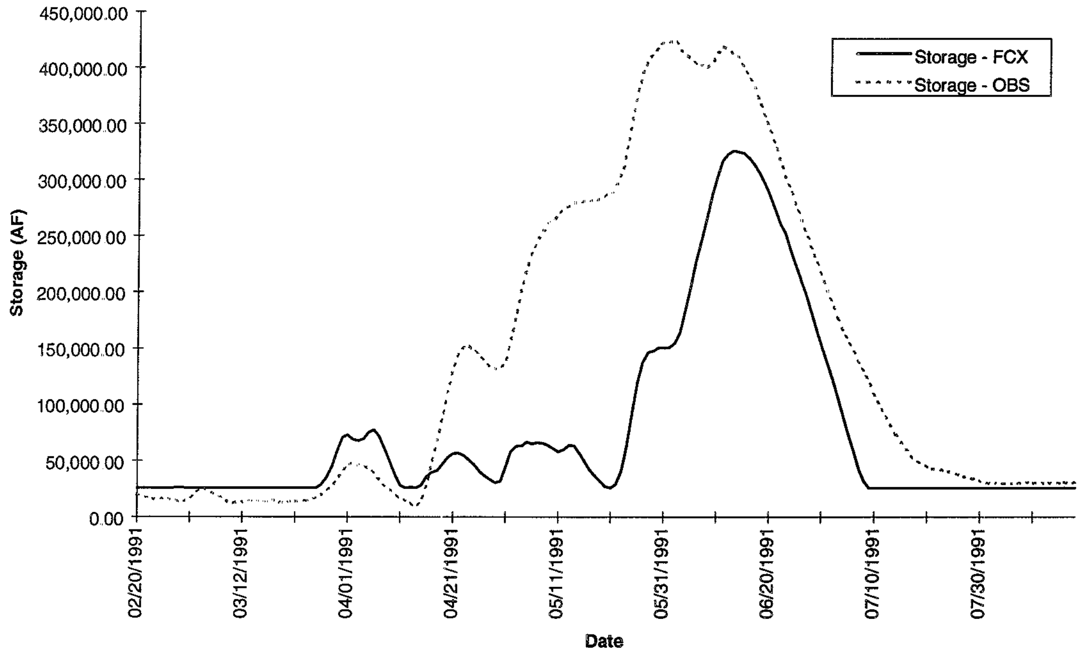

FIGURE D-9a. Coralville Reservoir Storage - Flood of 1991

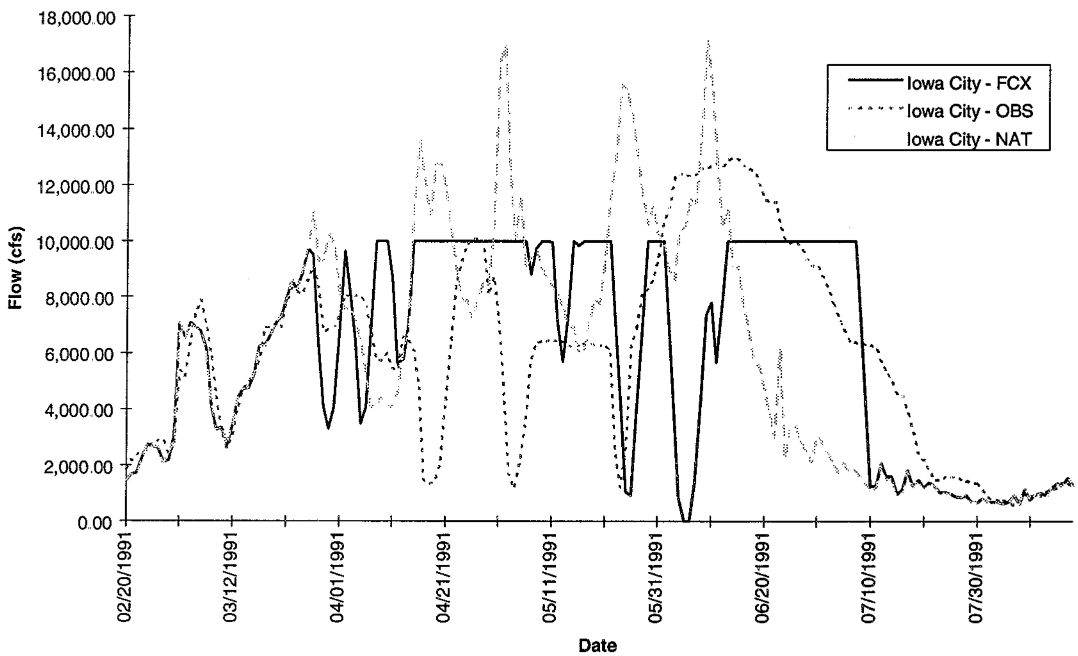

FIGURE D-9b. Iowa City Hydrograph - Flood of 1991

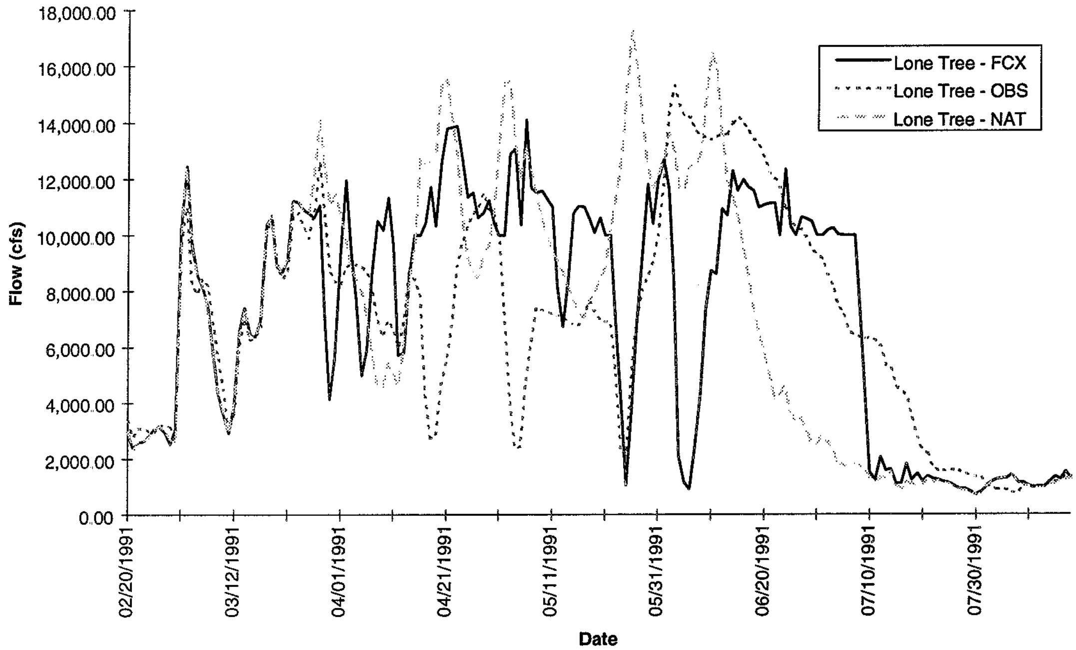

FIGURE D-9c. Lone Tree Hydrograph - Flood of 1991

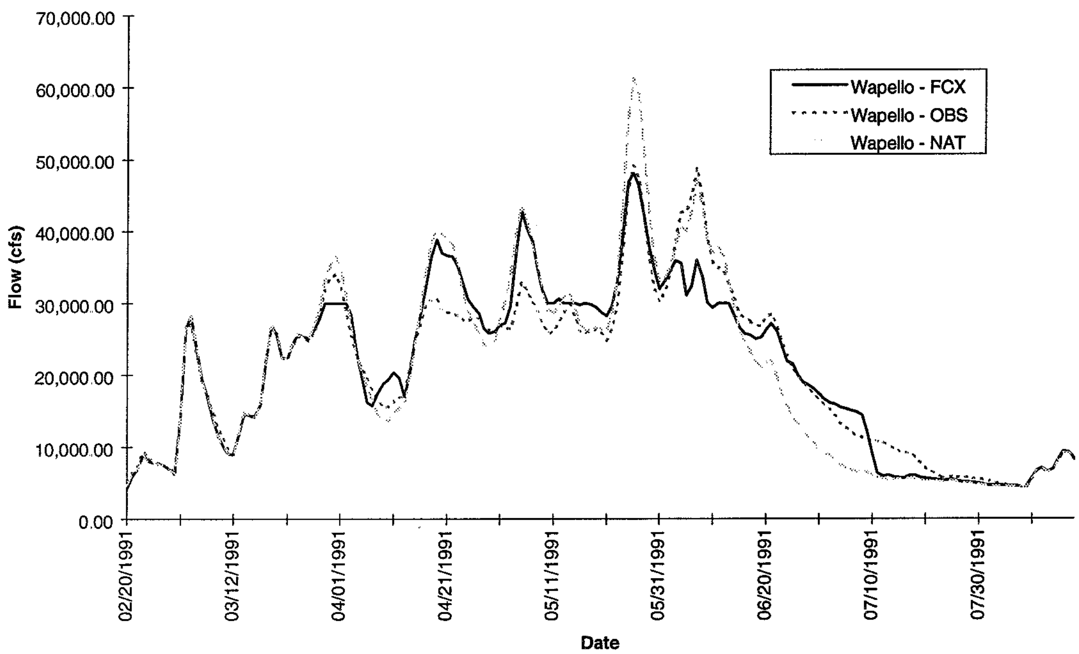

FIGURE D-9d. Wapello Hydrograph - Flood of 1991

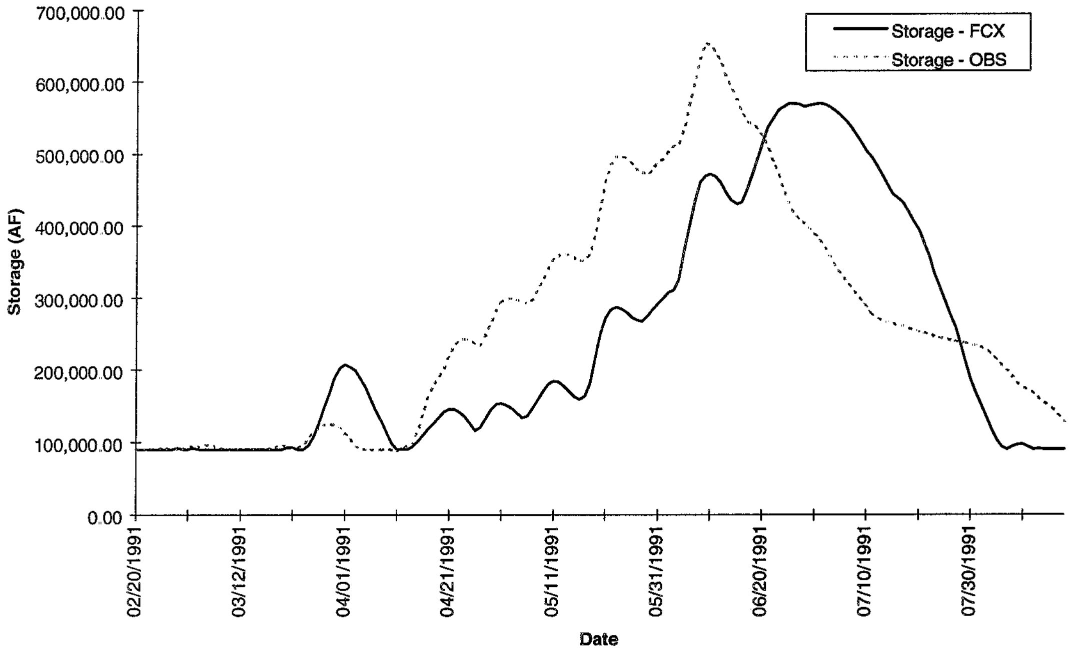

FIGURE D-9e. Saylorville Reservoir Storage - Flood of 1991

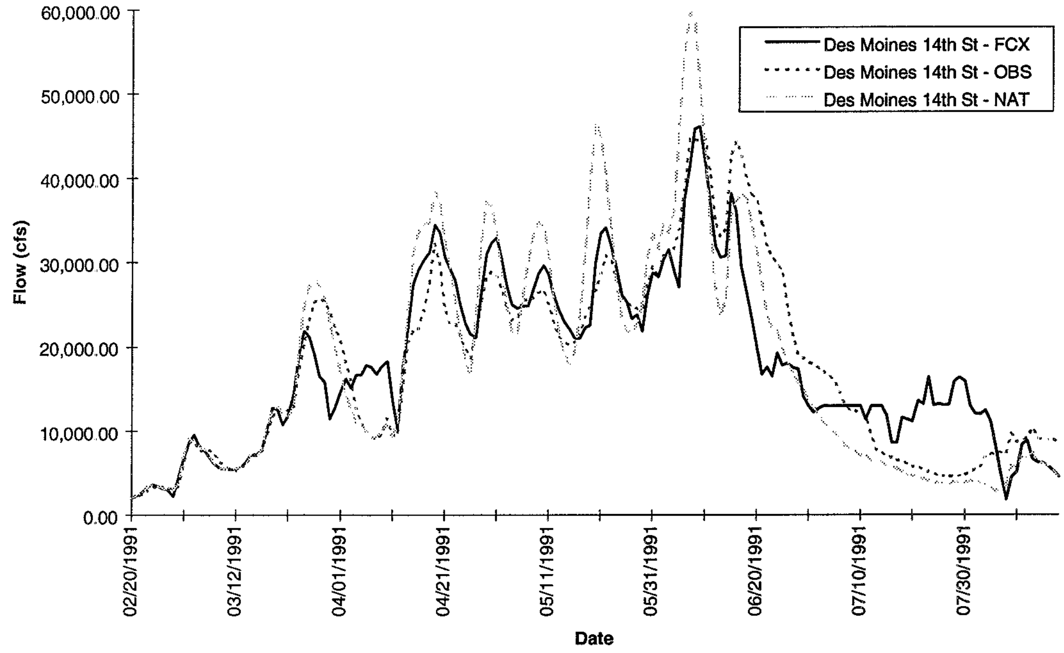

FIGURE D-9f. Des Moines 14th Street - Flood of 1991

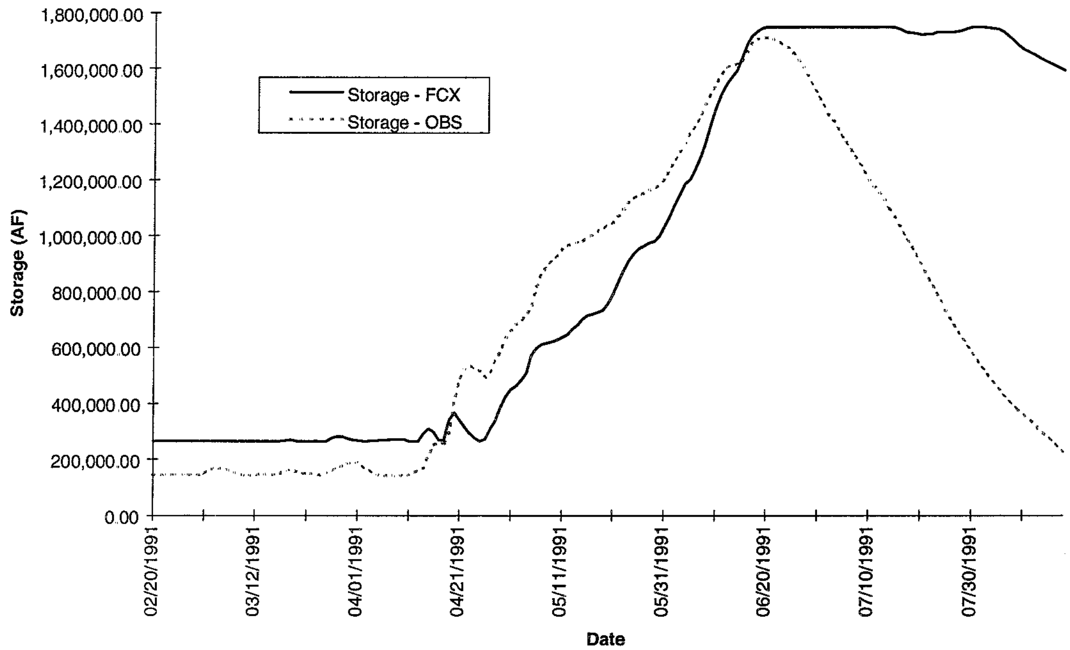

FIGURE D-9g. Lake Red Rock Storage - Flood of 1991

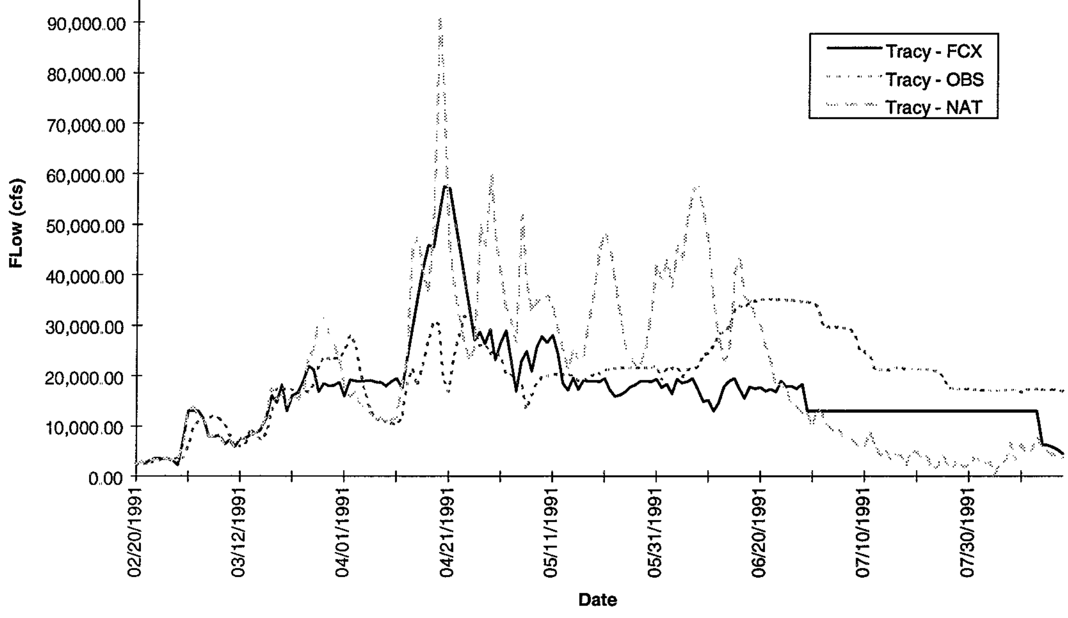

FIGURE D-9h. Tracy Hydrograph - Flood of 1991

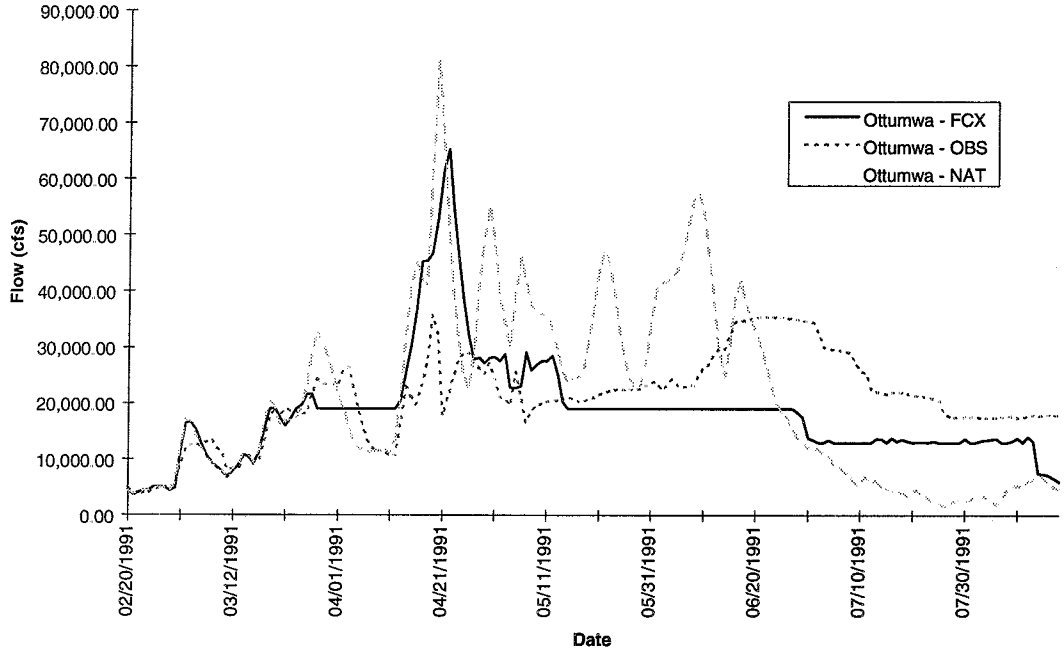

FIGURE D-9i. Ottumwa Hydrograph - Flood of 1991

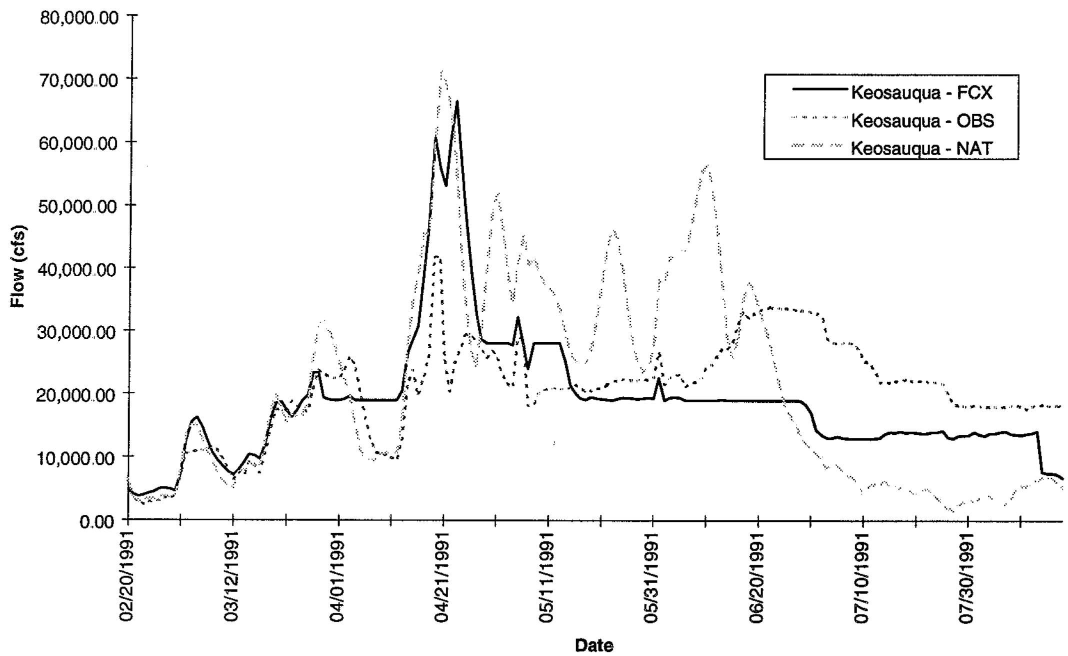

FIGURE D-9j. Keosauqua Hydrograph - Flood of 1991

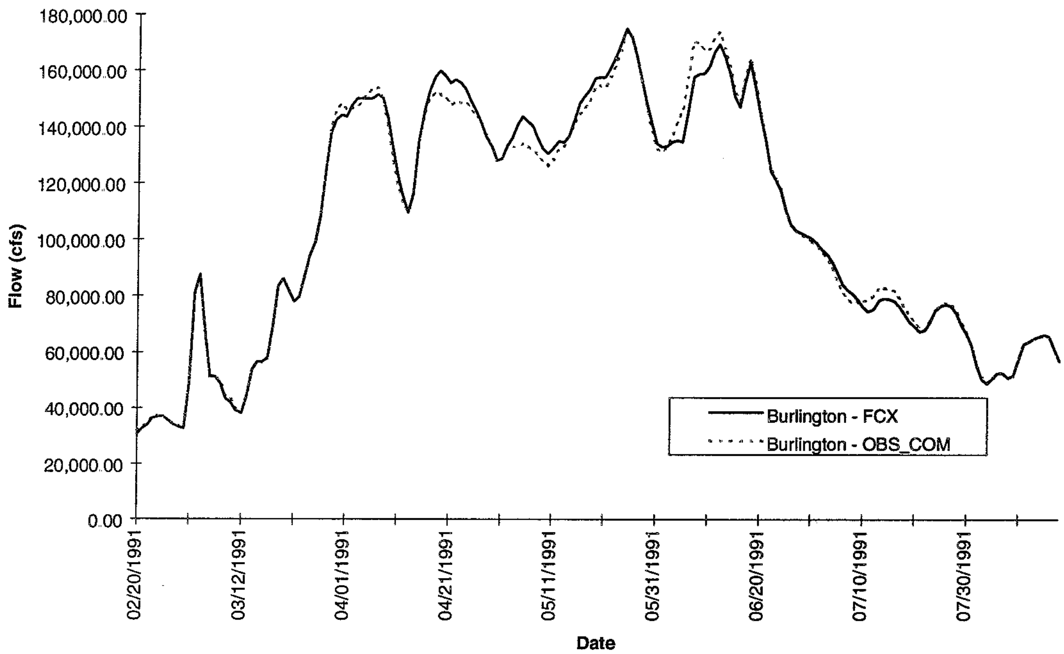

FIGURE D-9k. Burlington Hydrograph - Flood of 1991

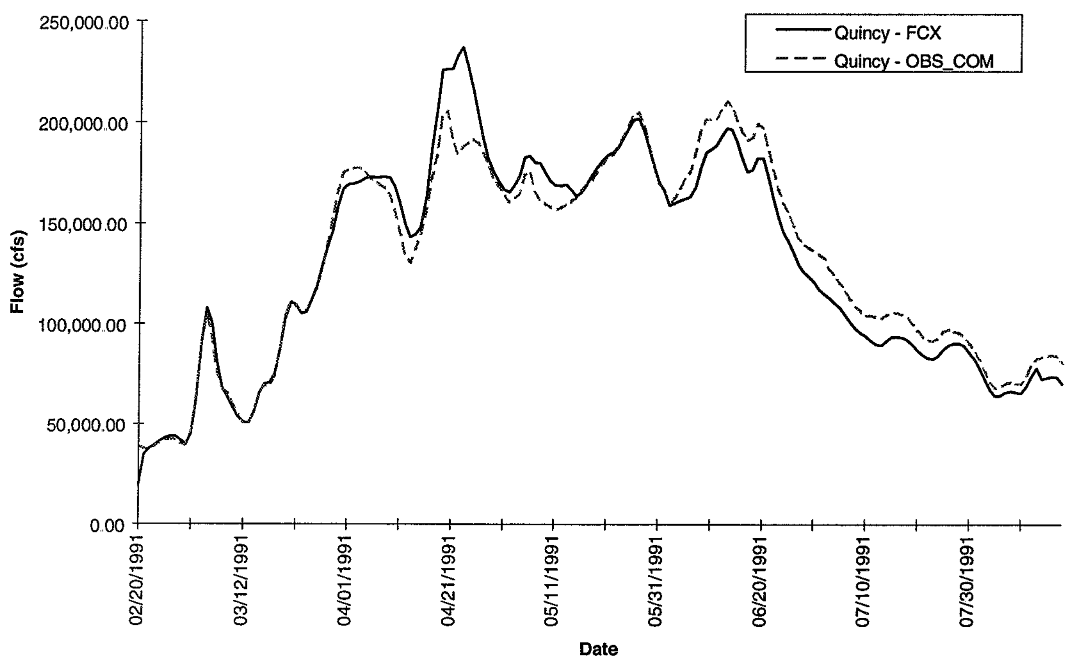

FIGURE D-9l. Quincy Hydrograph - Flood of 1991

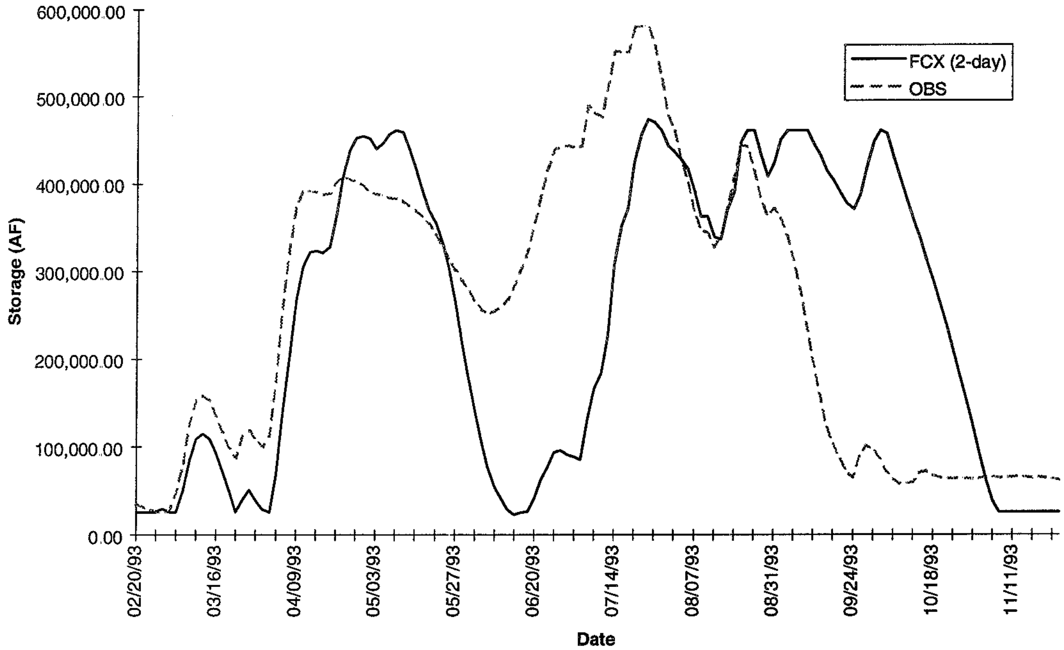

FIGURE D-10a. Coralville Reservoir Storage - Flood of 1993

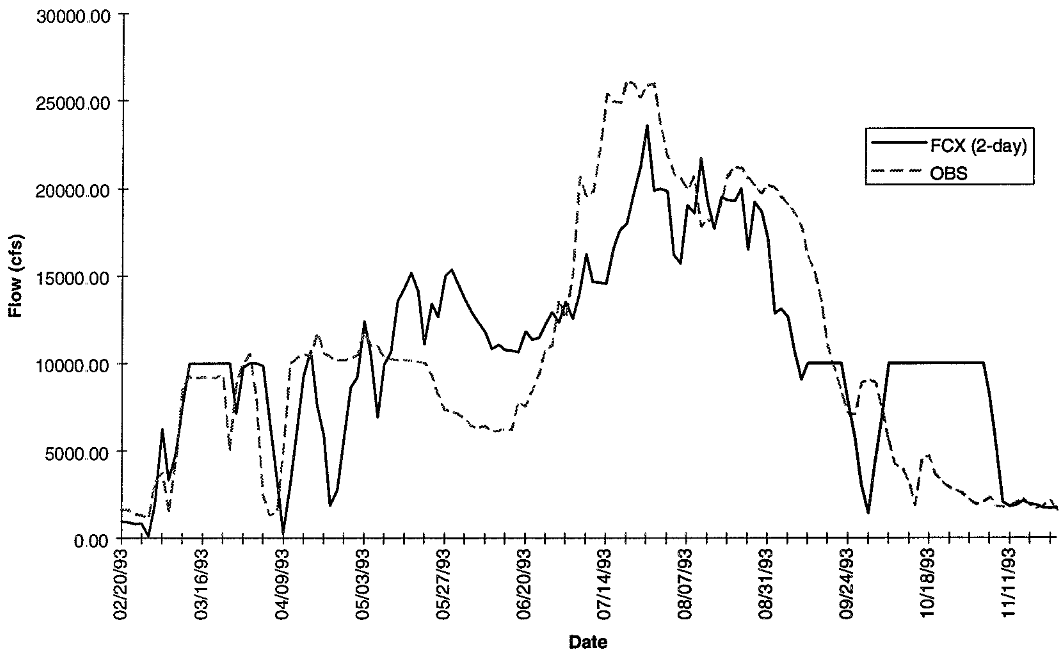

FIGURE D-10b. Iowa City Hydrograph - Flood of 1993

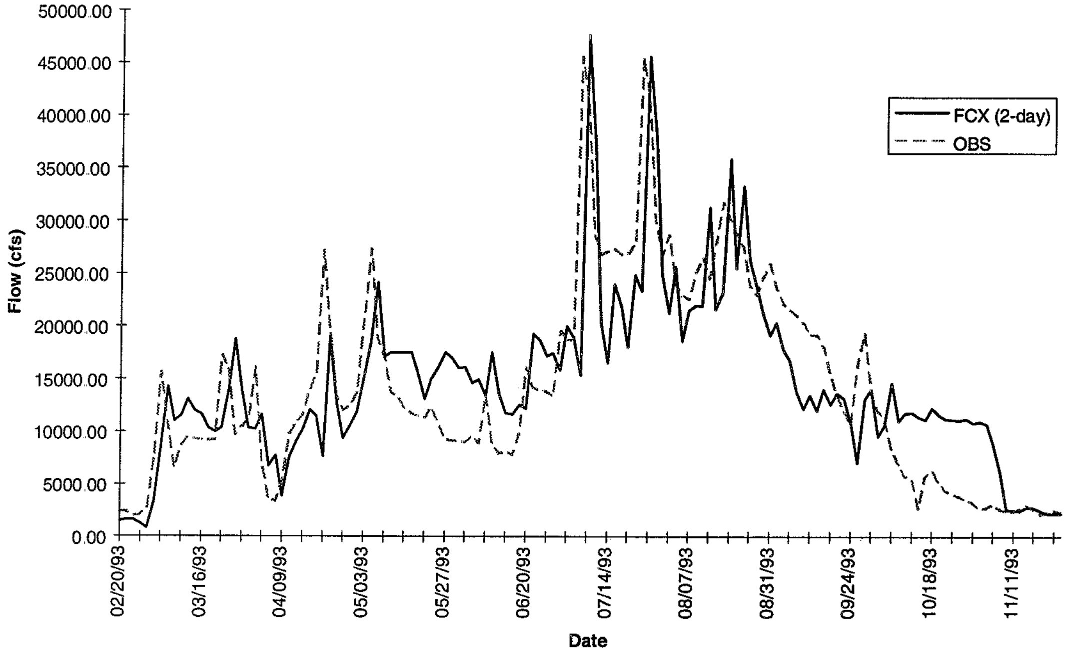

FIGURE D-10c. Lone Tree Hydrograph - Flood of 1993

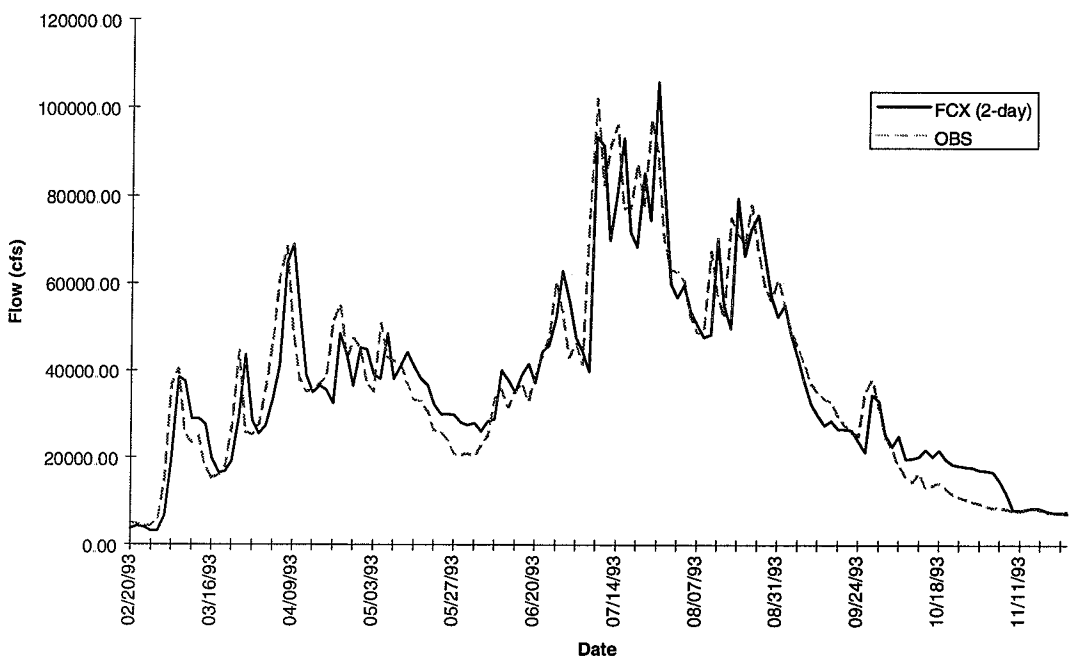

FIGURE D-10d. Wapello Hydrograph - Flood of 1993

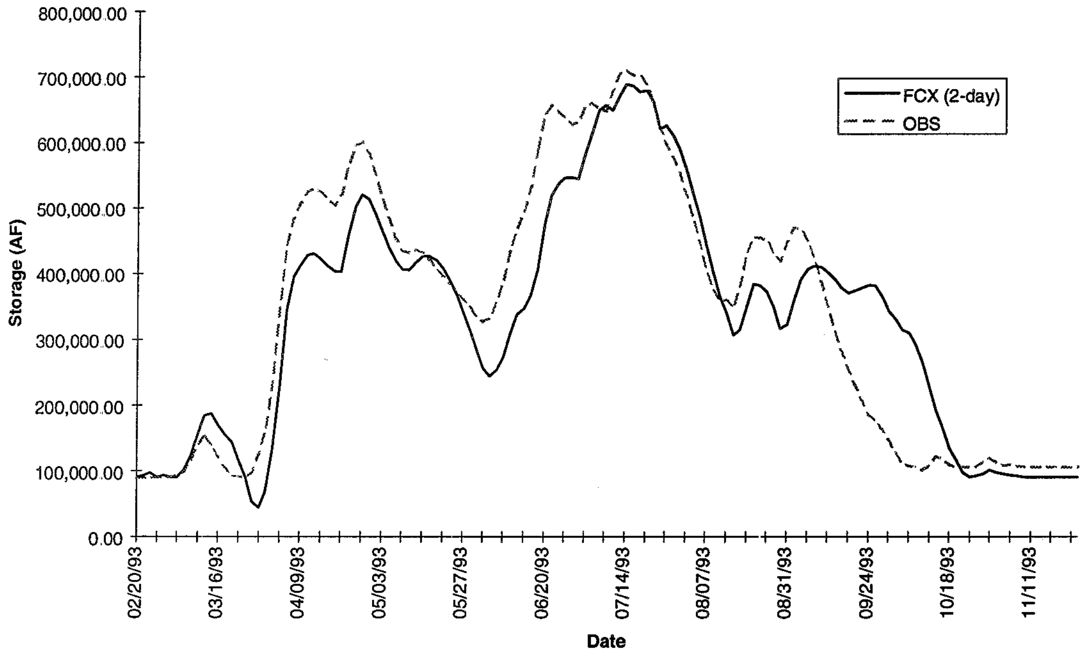

FIGURE D-10e. Saylorville Reservoir Storage - Flood of 1993

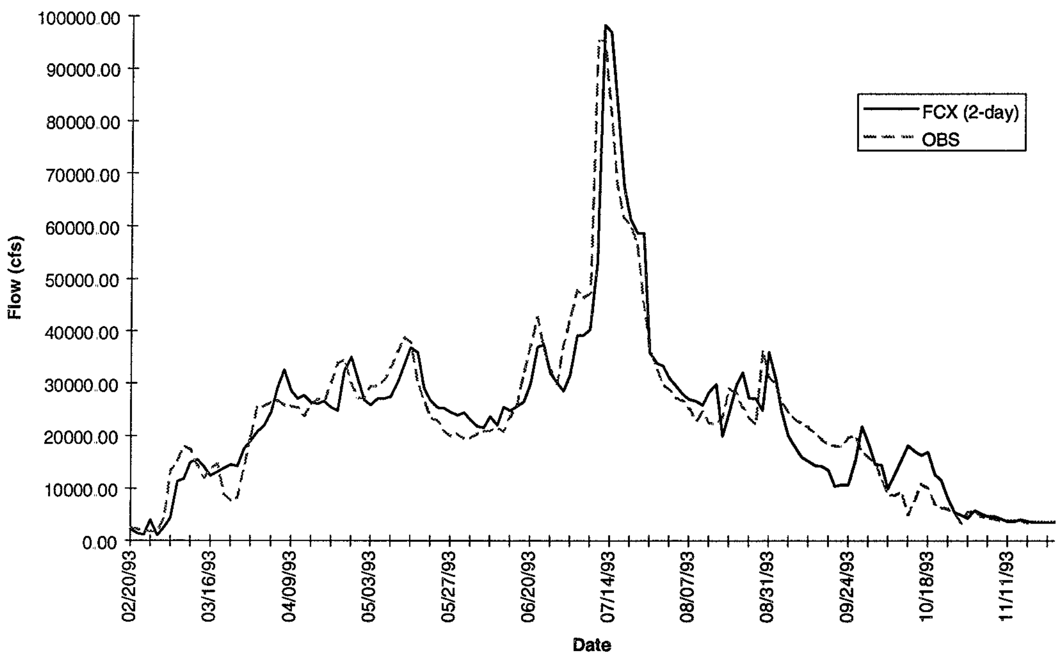

FIGURE D-10f. Des Moines 14th Street - Flood of 1993

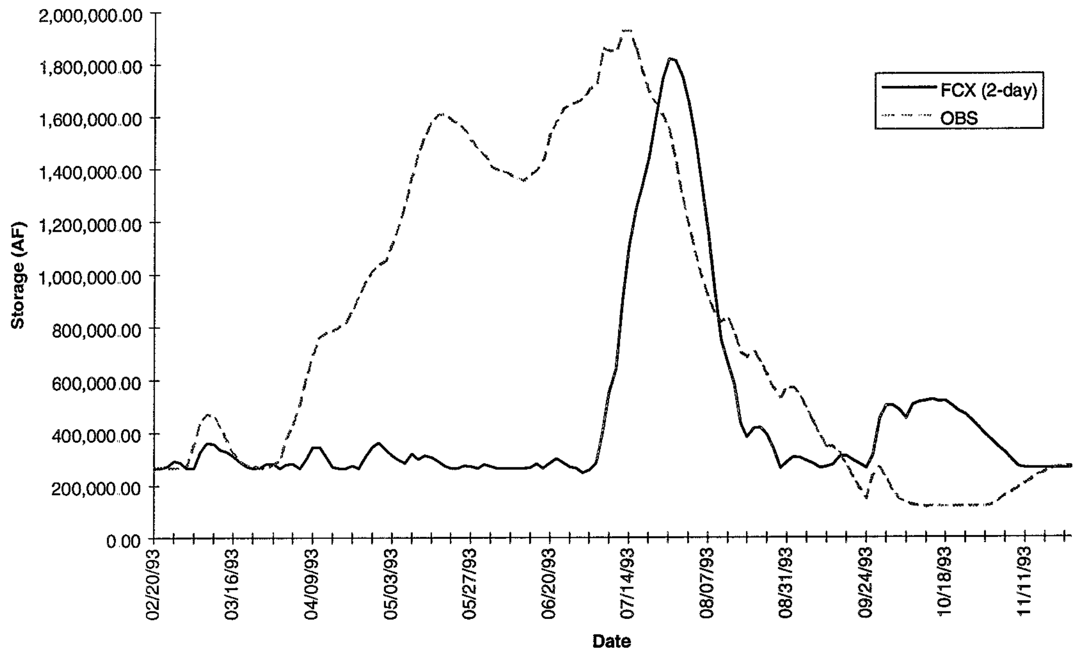

FIGURE D-10g. Lake Red Rock Storage - Flood of 1993

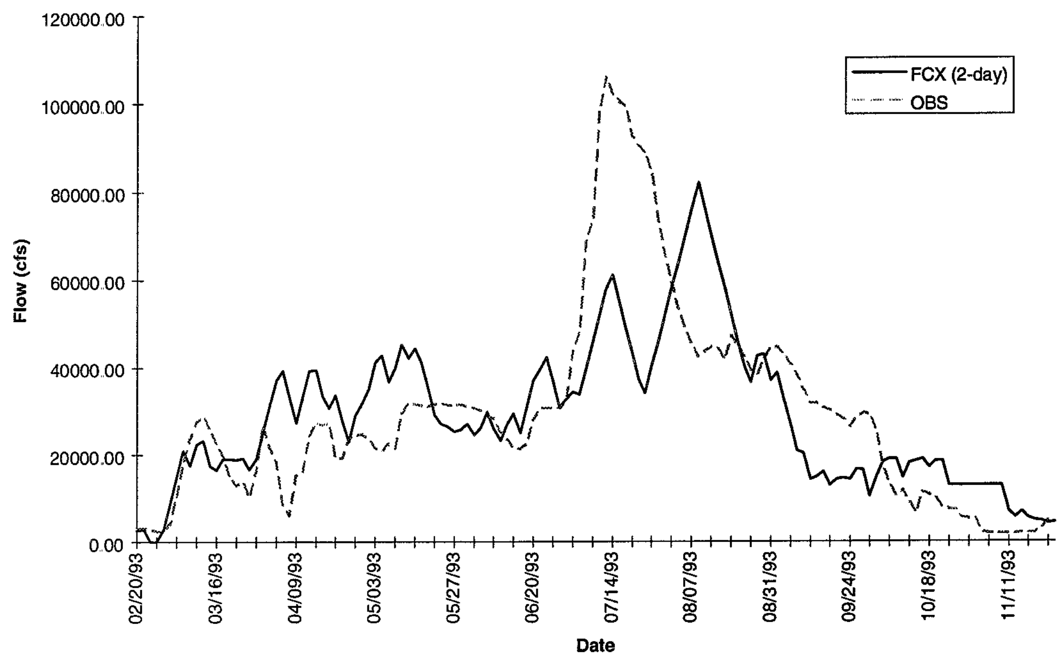

FIGURE D-10h. Tracy Hydrograph - Flood of 1993

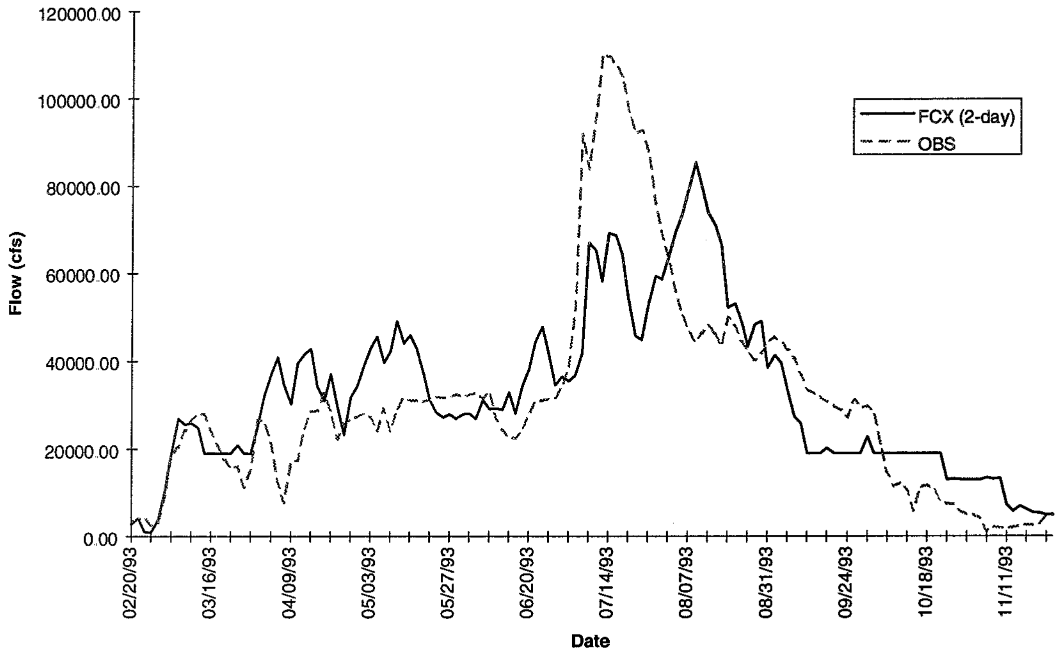

FIGURE D-10i. Ottumwa Hydrograph - Flood of 1993

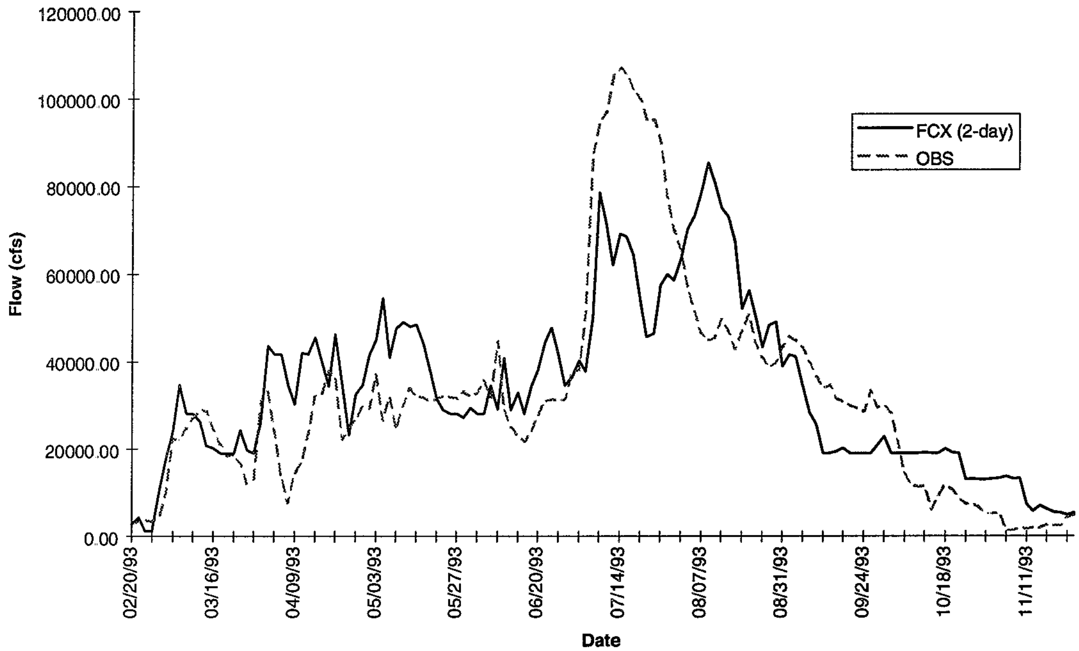

FIGURE D-10j. Keosauqua Hydrograph - Flood of 1993

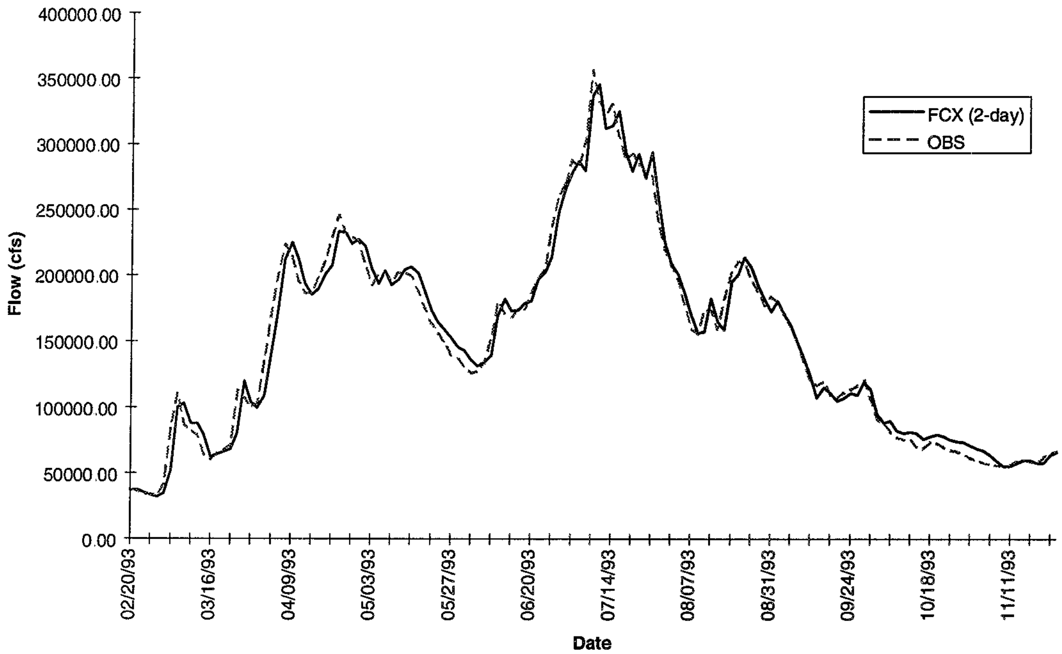

FIGURE D-10k. Burlington Hydrograph - Flood of 1993

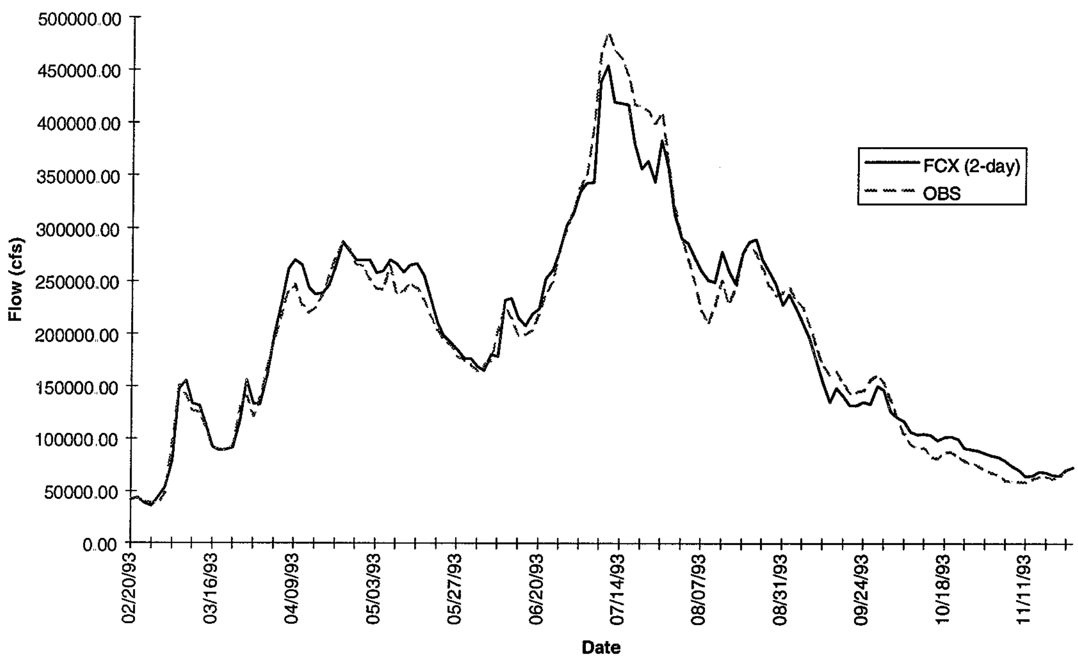

FIGURE D-10l. Quincy Hydrograph - Flood of 1993

Appendix E

HYDROGRAPHS FOR SUB-SYSTEM ANALYSIS

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INTRODUCTION

The following charts illustrate the difference between model operations for different combinations of sub-systems. The charts depict how the model would operate each reservoir for a each of the flood events given a specific set of downstream control points. Figure E illustrates the different ways the Iowa and Des Moines Rivers were divided for this study. A Table showing the cost of flooding and a brief commentary are included for each event.

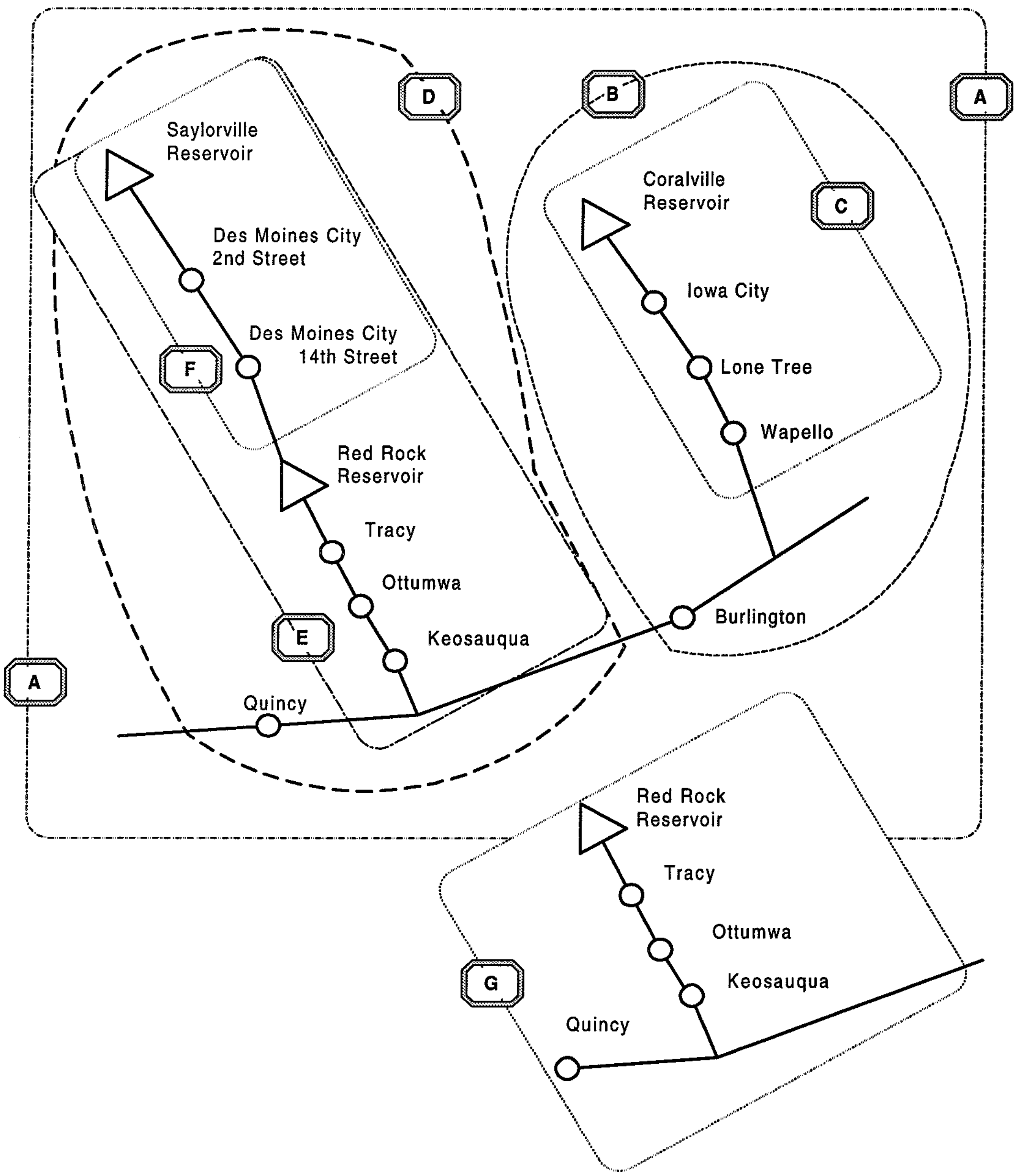

FIGURE E. System Decomposition

The following list relates the notation of Figure E to the legends of the charts:

System A = System

System B = Iowa W/Burlington

System C = Iowa Only

System D = Des Moines W/Quincy

System E = Des Moines Only

System F = Upper Des Moines

System G = Lower Des Moines

In the Tables following each event, peak-flow damage was calculated by finding the maximum flow at each location for the entire event and reporting the corresponding damage from the penalty functions shown in Chapter 4. The model-computed penalty is calculated by first calculating the damage for each day throughout the event based on the same penalty functions used for the peak-flow calculation and then summing up these damages. The total penalty with storage includes the summation of daily storage penalties. The reader is reminded that the model actually minimizes model-computed penalties, not peak-flow damage.

1944 Commentary

As illustrated in Table E-1, each of the different operating schemes produced the same amount of damage based on peak flow. However, looking at the storage and release from Saylorville Reservoir (Figures E-1f and E-1g), it seems that the model makes releases quite differently for each of the system configurations. The model has a large amount of leeway in how it operates since flows at the majority of locations are under flood stage. Therefore, the main difference in how the model makes releases from Saylorville Reservoir is attributed to balancing the storage penalty. When the Des Moines River is divided above Lake Red Rock, releases from Saylorville Reservoir are made first to keep the flow at 2nd Avenue below 19,400 cfs, and then to lower the storage in Saylorville Reservoir to the top of the conservation pool. That release schedule, as illustrated by "Upper Des Moines" on Figure E-1f, results in only a small portion of Saylorville Reservoir's flood storage being utilized. Consequently, as seen in Figure E-1i, much more of the flood storage in Lake Red Rock must be utilized in order for the penalties downstream of Lake Red Rock to be minimized. Each operating scheme results in identical flows downstream of Lake Red Rock.

Another slight difference in how the model operates can be seen on the Iowa River. Figure E-1a illustrates that when the model is operating to reduce penalties at Burlington on the Mississippi River, more of Coralville Reservoir's storage is used. This results in a small decrease in model-computed penalty at Burlington, but it does not effect the peak flow at Burlington. Thus, the peak-related penalty is the same.

TABLE E-1. Flood of 1944 Calculated Penalties

	Peak Flow Damage ($1000)							
Site	Observed	A	BD	CD	BE	CE	BFG	CFG
Iowa City	3,430	1	1	1	1	1	1	1
Lone Tree	-	-	-	-	-	-	-	-
Wapello	1,230	182	182	182	182	182	182	182
2nd Ave.	5,165	-	-	-	-	-	-	-
14th St.	-	-	-	-	-	-	-	-
Tracy	5,051	1,179	1,179	1,179	1,179	1,179	1,179	1,179
Ottumwa	10,886	2,194	2,194	2,194	2,194	2,194	2,194	2,194
Keosauqua	1,244	561	561	561	561	561	561	561
Burlington	413	395	395	395	395	395	395	395
Quincy	5,117	-	-	-	-	-	-	-
Total	32,535	4,511	4,511	4,511	4,511	4,511	4,511	4,511

	Model-Computed Flow Penalty ($1000)							
Site	Observed	A	BD	CD	BE	CE	BFG	CFG
Iowa City	13,084	1	1	1	1	1	1	1
Lone Tree	-	-	-	-	-	-	-	-
Wapello	6,848	1,374	1,374	1,511	1,374	1,511	1,374	1,511
2nd Ave.	33,591	-	-	-	-	-	-	-
14th St.	-	-	-	-	-	-	-	-
Tracy	85,360	47,097	47,097	47,097	47,097	47,097	47,097	47,097
Ottumwa	163,944	14,626	14,626	14,626	14,626	14,626	14,626	14,626
Keosauqua	15,614	1,355	1,355	1,355	1,355	1,355	1,355	1,355
Burlington	5,126	4,257	4,257	4,321	4,257	4,321	4,257	4,321
Quincy	16,446	-	-	-	-	-	-	-
Coralville		2,555	2,555	2,385	2,555	2,385	2,555	2,385
Saylorville		33,056	38,944	38,944	40,226	40,226	6,267	6,267
Red Rock		74,572	68,683	68,683	67,401	67,401	101,360	101,360
Total w/o stor.	340,012	68,709	68,709	68,911	68,709	68,911	68,709	68,911
Total w/ stor.		178,891	178,891	178,923	178,891	178,923	178,891	178,923

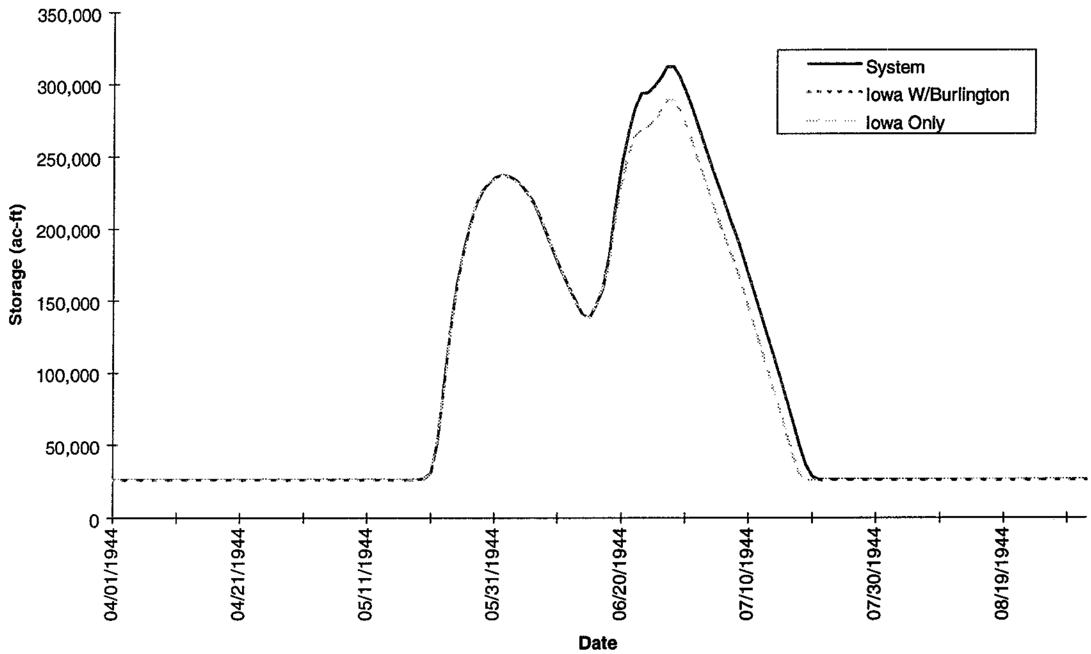

FIGURE E-1a. Model Results of Coralville Reservoir Storage - Flood of 1944

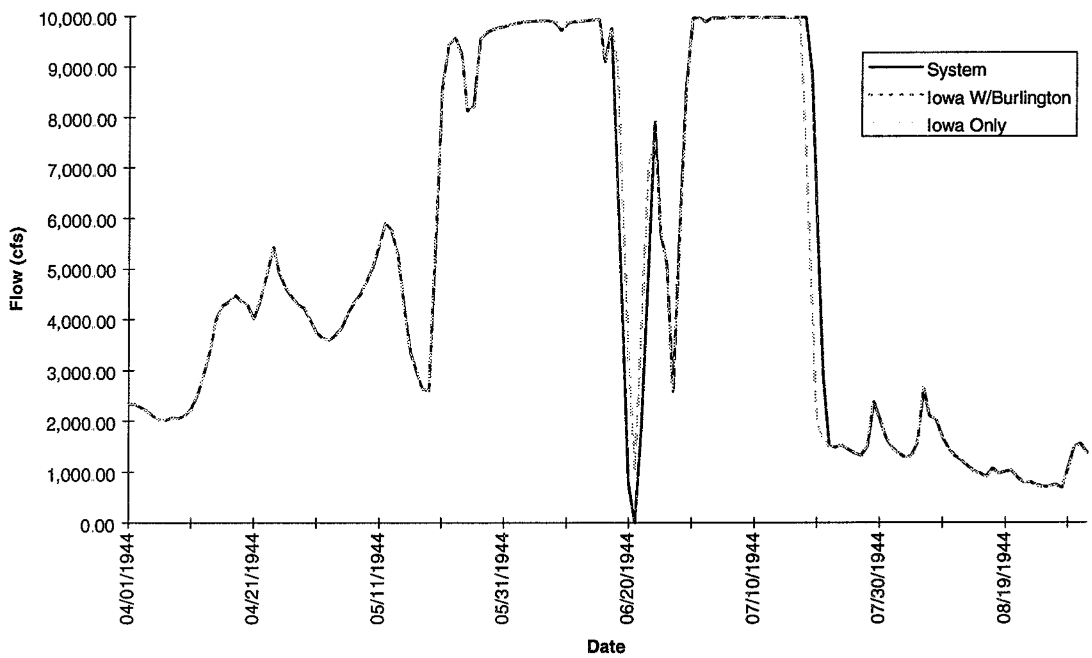

FIGURE E-1b. Model Results of Coralville Reservoir Release - Flood of 1944

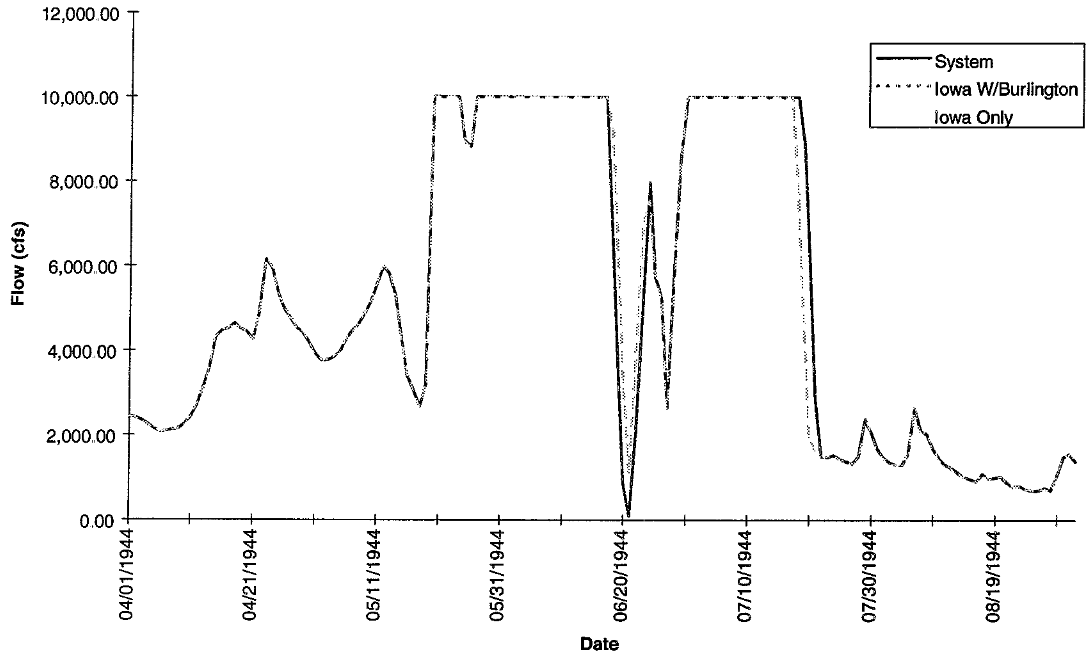

FIGURE E-1c. Hydrograph of Model Results at Iowa City - Flood of 1944

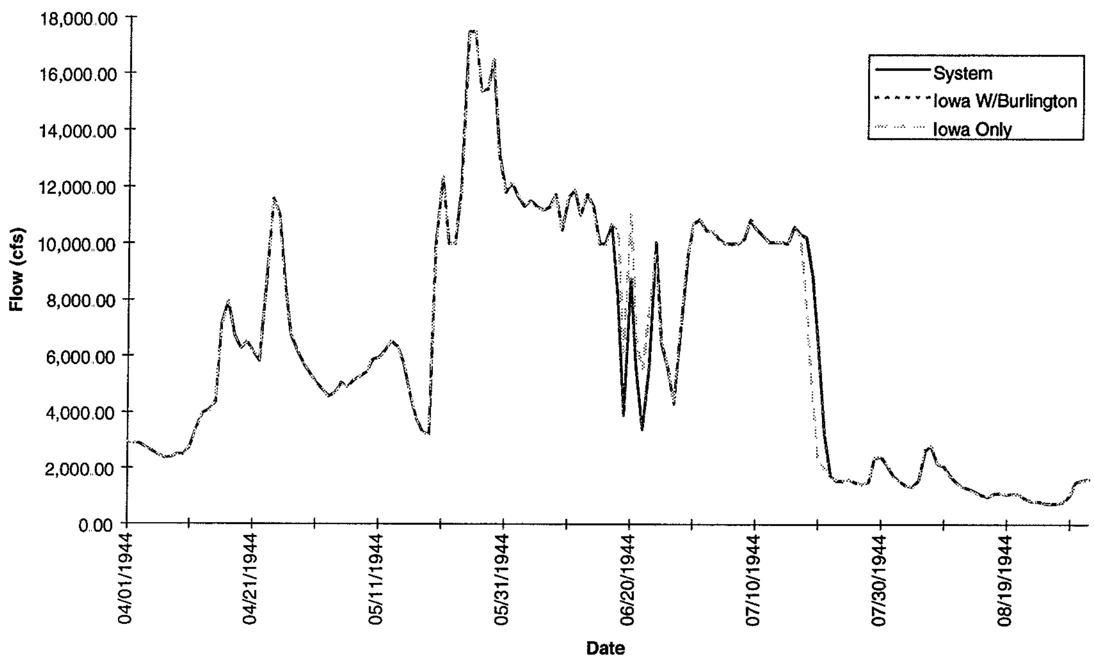

FIGURE E-1d. Hydrograph of Model Results at Lone Tree - Flood of 1944

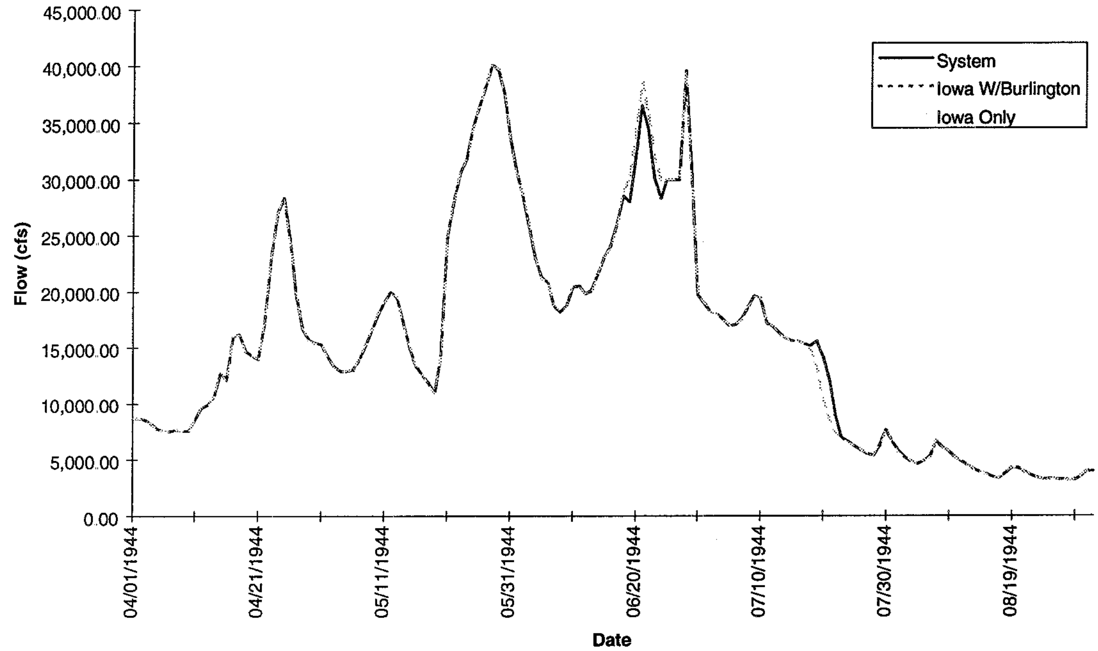

FIGURE E-1e. Hydrograph of Model Results at Wapello - Flood of 1944

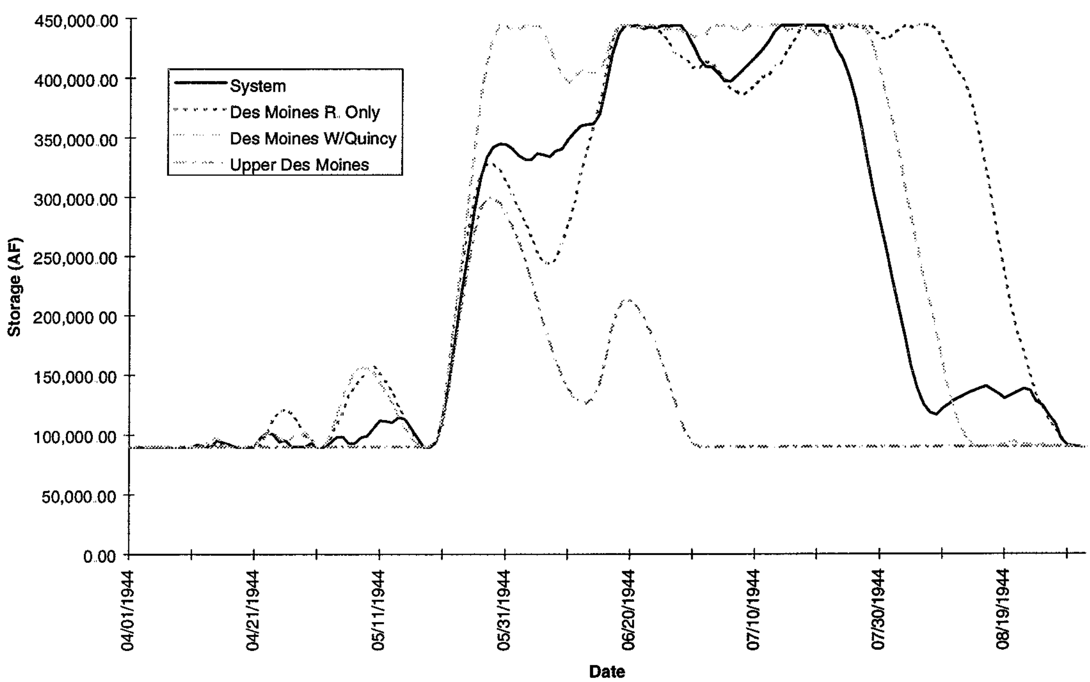

FIGURE E-1f. Model Results of Saylorville Reservoir Storage - Flood of 1944

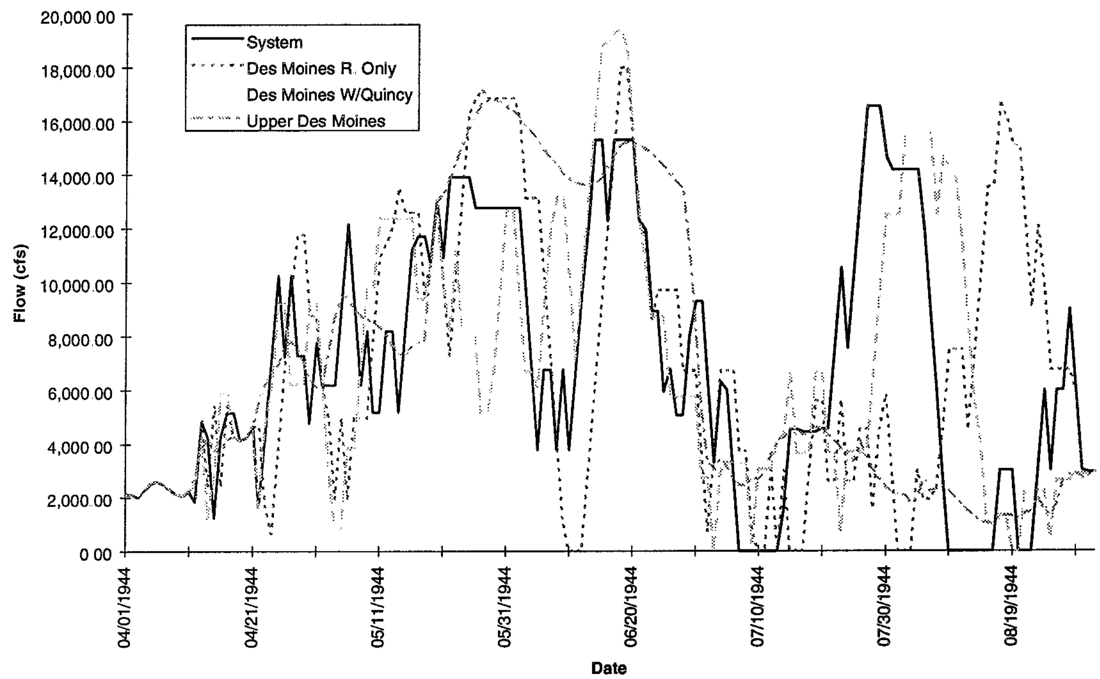

FIGURE E-1g. Model Results of Saylorville Reservoir Release - Flood of 1944

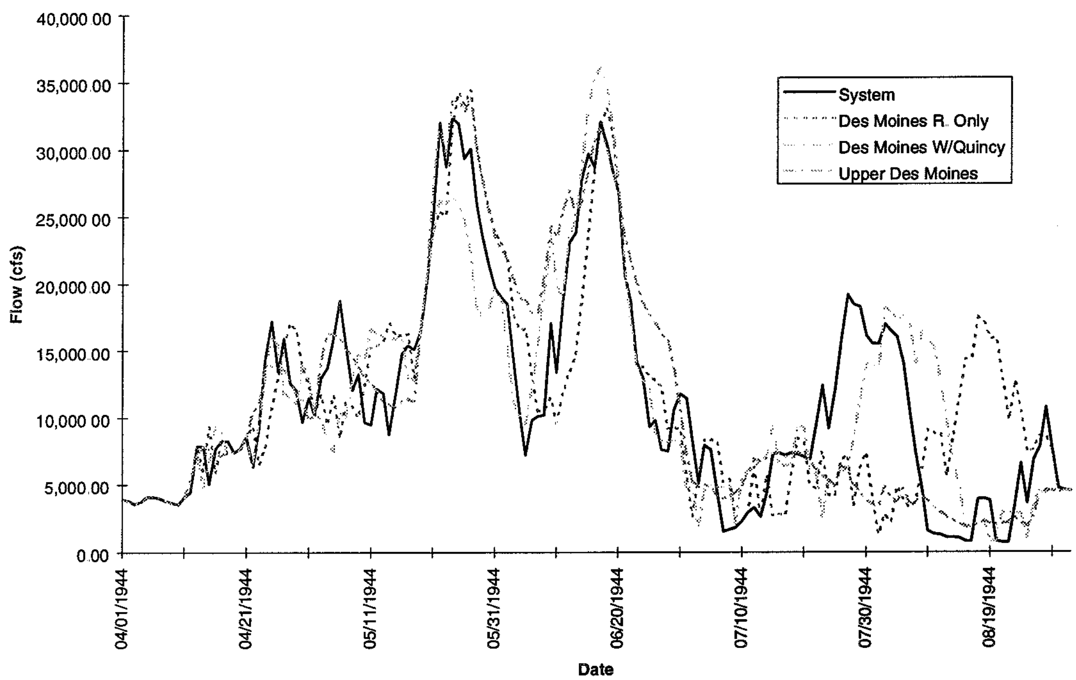

FIGURE E-1h. Hydrograph of Model Results at 14th Street - Flood of 1944

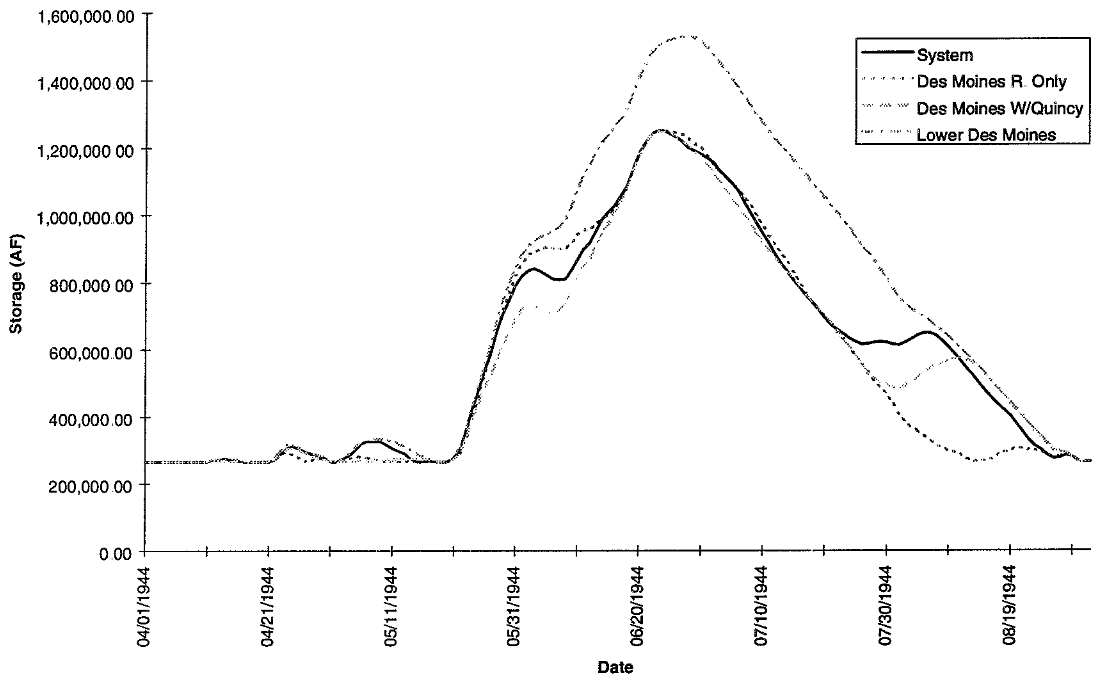

FIGURE E-1i. Model Results of Lake Red Rock Storage - Flood of 1944

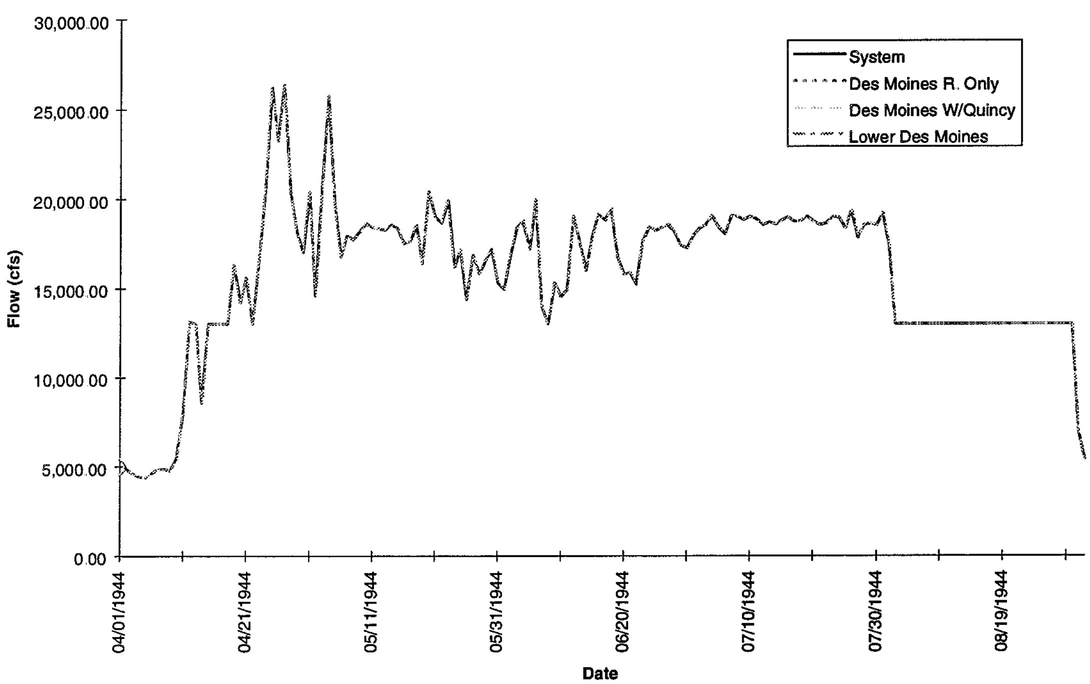

FIGURE E-1j. Model Results of Lake Red Rock Release - Flood of 1944

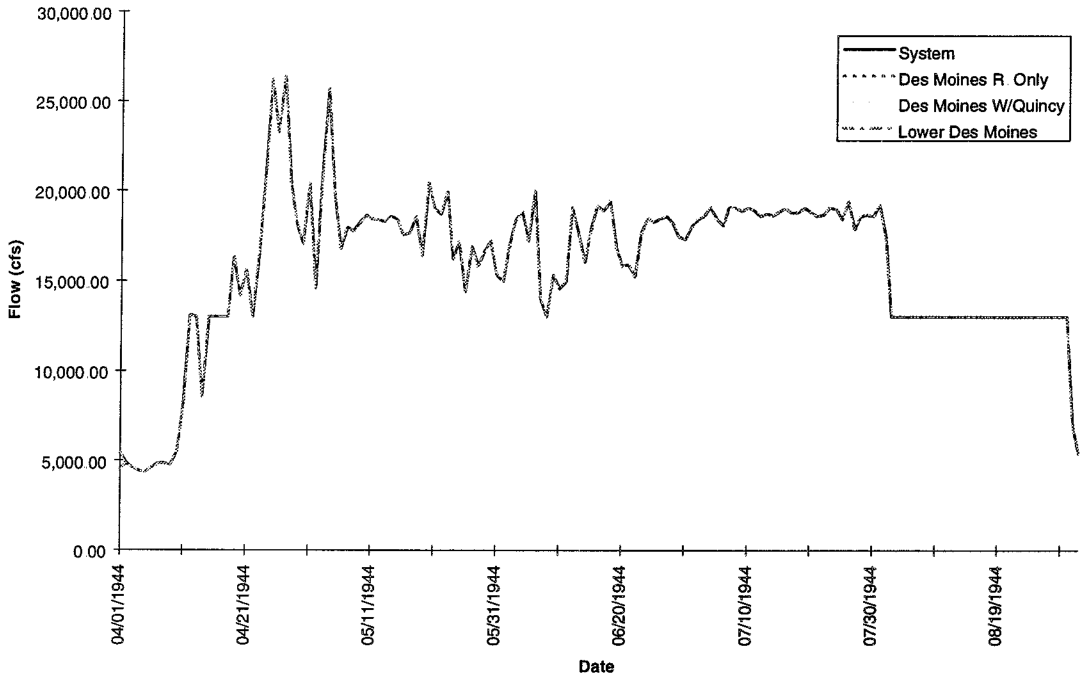

FIGURE E-1k. Hydrograph of Model Results at Tracy - Flood of 1944

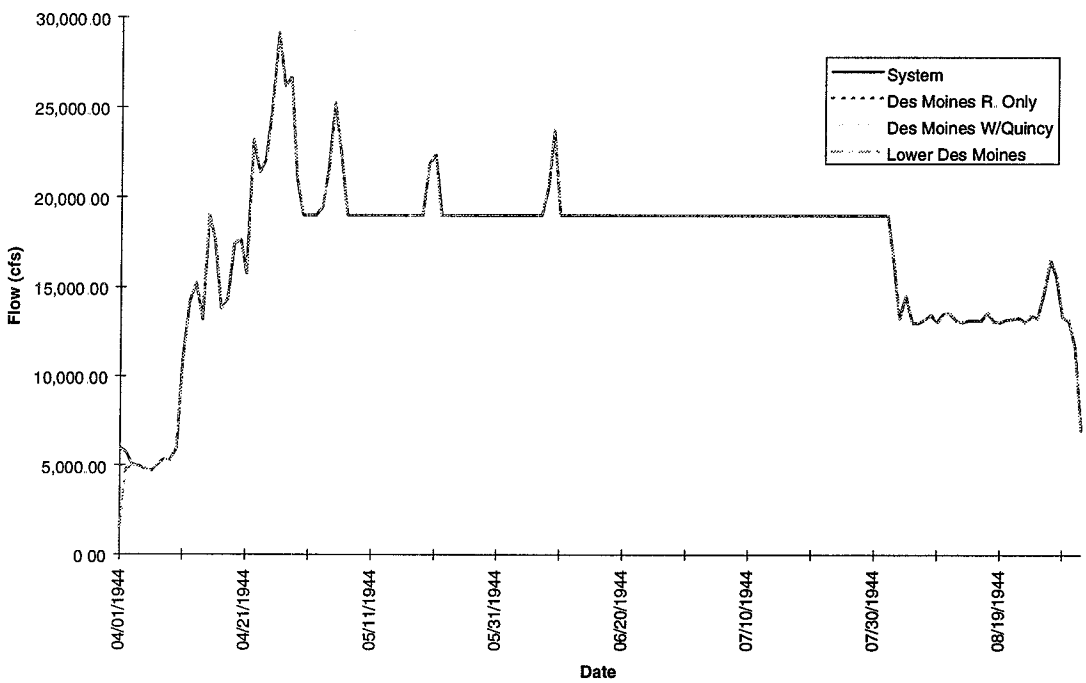

FIGURE E-1l. Hydrograph of Model Results at Ottumwa - Flood of 1944

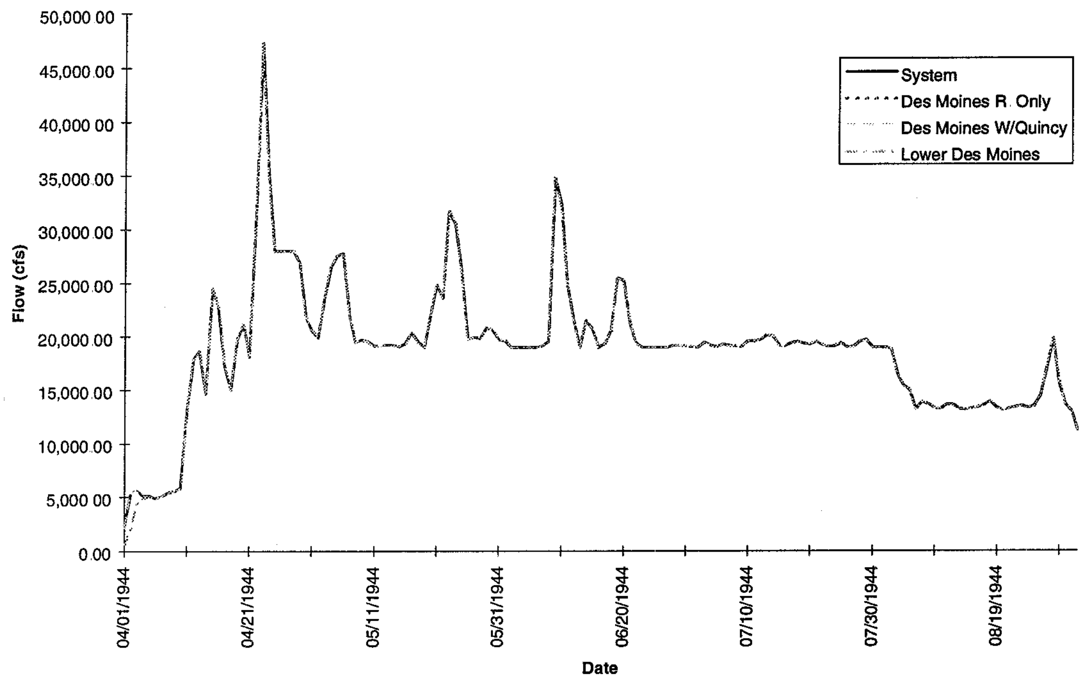

FIGURE E-1m. Hydrograph of Model Results at Keosauqua - Flood of 1944

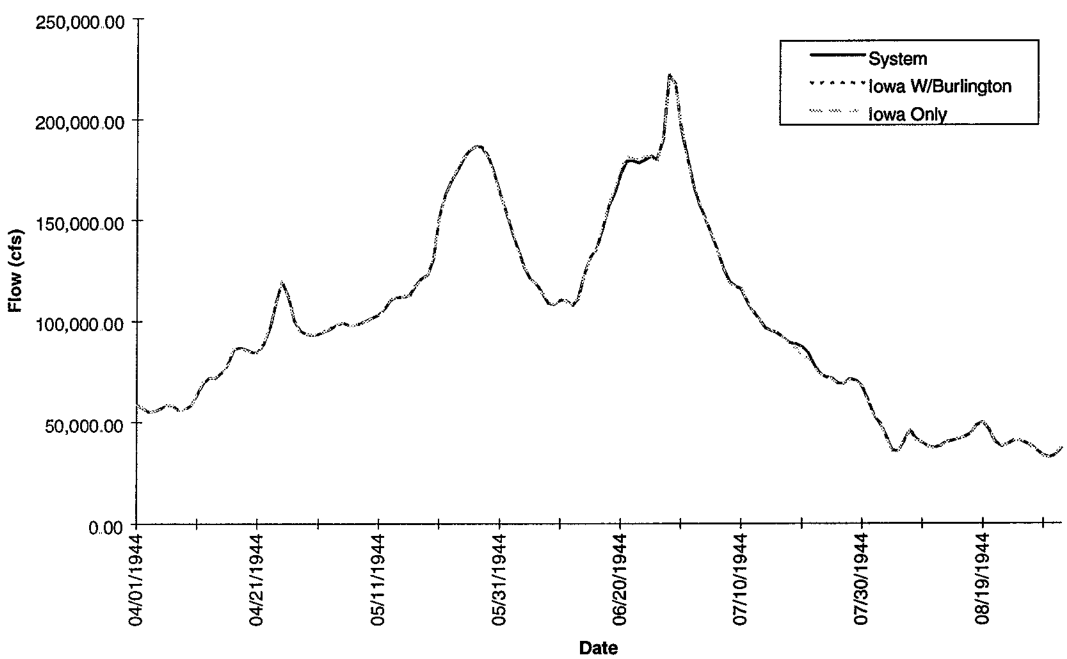

FIGURE E-1n. Hydrograph of Model Results at Burlington - Flood of 1944

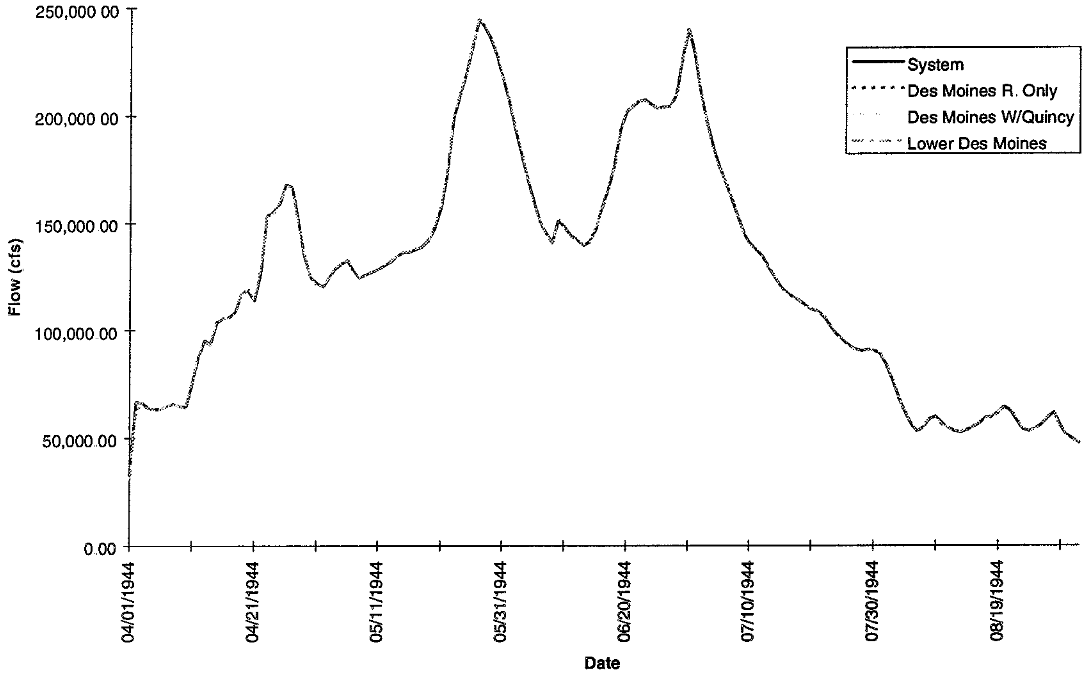

FIGURE E-1o. Hydrograph of Model Results at Quincy - Flood of 1944

1947 COMMENTARY

The flood of 1947 is similar to 1944 in that each of the different operating schemes results in basically the same amount of peak-related damage. The model is able to significantly reduce damage at Iowa City and prevent all damages at 2nd Avenue in Des Moines. The difference in how the model operates Saylorville Reservoir for different sub-systems, shown in Figures E-2f and E-2g, is related to balancing the storage penalties as in 1944, even though significantly larger penalties are incurred for the flood of 1947. The slightly larger model-computed penalty that occurs when the Des Moines River is divided above Lake Red Rock is seen because Lake Red Rock cannot regulate all the flows contained by Saylorville Reservoir under the other operating schemes. The longer duration, higher magnitude, release from Lake Red Rock at the beginning of the event actually results in a small reduction of the peak-related damage, as seen in Table E-2. Flows on the Iowa River are identical for each operating scheme.

TABLE E-2. Flood of 1947 Calculated Penalties

	Peak Flow Damage ($1000)							
Site	**Observed**	**A**	**BD**	**CD**	**BE**	**CE**	**BFG**	**CFG**
Iowa City	4,167	324	324	324	324	324	324	324
Lone Tree	-	-	-	-	-	-	-	-
Wapello	8,367	3,549	3,549	3,549	3,549	3,549	3,549	3,549
2nd Ave.	7,465	-	-	-	-	-	-	-
14th St.	-	-	-	-	-	-	-	-
Tracy	10,824	4,121	4,121	4,121	4,121	4,121	4,028	4,028
Ottumwa	296,432	11,362	11,362	11,362	11,362	11,362	11,362	11,362
Keosauqua	4,798	1,231	1,231	1,231	1,231	1,231	1,243	1,243
Burlington	45	-	-	-	-	-	-	-
Quincy	-	-	-	-	-	-	-	-
Total	332,097	20,586	20,586	20,586	20,586	20,586	20,505	20,505

	Model-Computed Flow Penalty ($1000)							
Site	**Observed**	**A**	**BD**	**CD**	**BE**	**CE**	**BFG**	**CFG**
Iowa City	21,225	2,572	2,572	2,572	2,572	2,572	2,572	2,572
Lone Tree	-	-	-	-	-	-	-	-
Wapello	41,543	11,812	11,812	11,812	11,812	11,812	11,812	11,812
2nd Ave.	24,957	-	-	-	-	-	-	-
14th St.	-	-	-	-	-	-	-	-
Tracy	120,833	75,563	75,563	75,563	75,563	75,563	77,022	77,022
Ottumwa	785,424	116,385	116,385	116,385	116,385	116,385	119,702	119,702
Keosauqua	34,094	14,275	14,275	14,275	14,275	14,275	14,730	14,730
Burlington	45	-	-	-	-	-	-	-
Quincy	-	-	-	-	-	-	-	-
Coralville		4,706	4,706	4,706	4,706	4,706	4,706	4,706
Saylorville		25,322	26,195	26,195	26,718	26,718	6,993	6,993
Red Rock		75,025	74,152	74,152	73,629	73,629	90,416	90,416
Total w/o stor.	1,028,121	220,607	220,607	220,607	220,607	220,607	225,837	225,837
Total w/ stor.		325,660	325,660	325,660	325,660	325,660	327,952	327,952

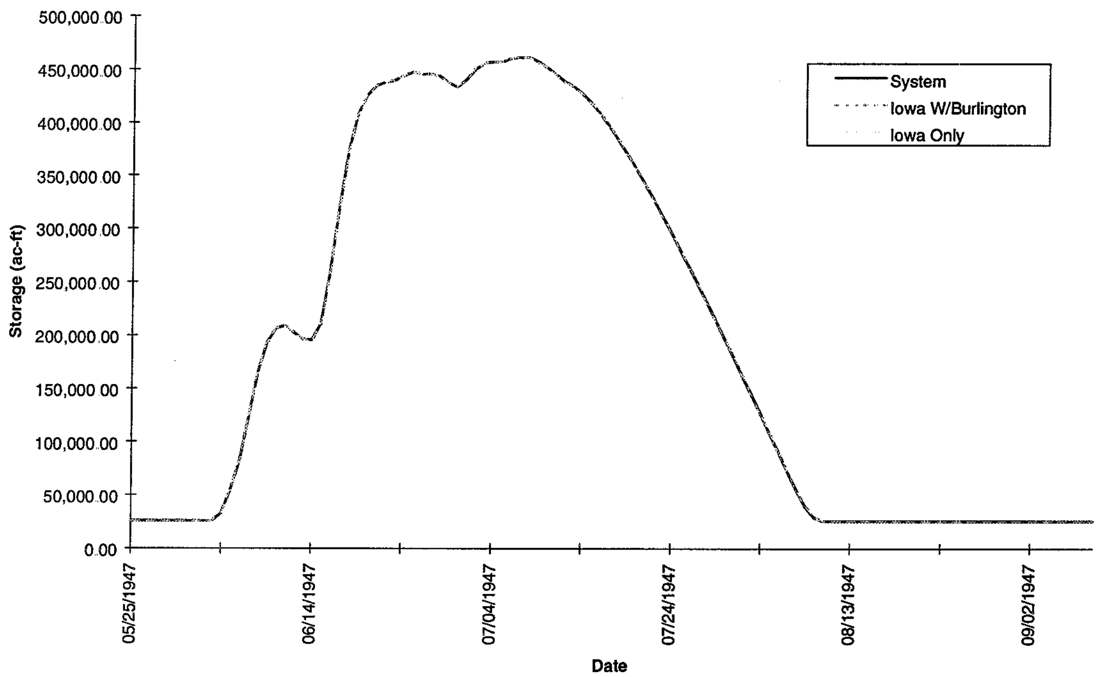

FIGURE E-2a. Model Results of Coralville Reservoir Storage - Flood of 1947

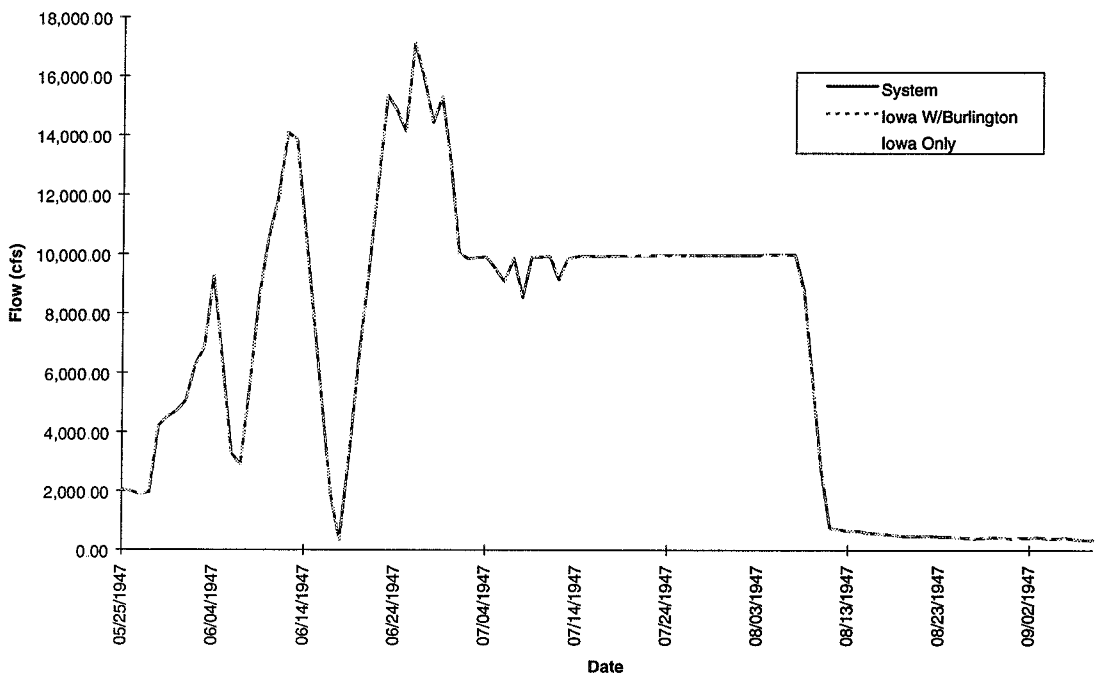

FIGURE E-2b. Model Results of Coralville Reservoir Release - Flood of 1947

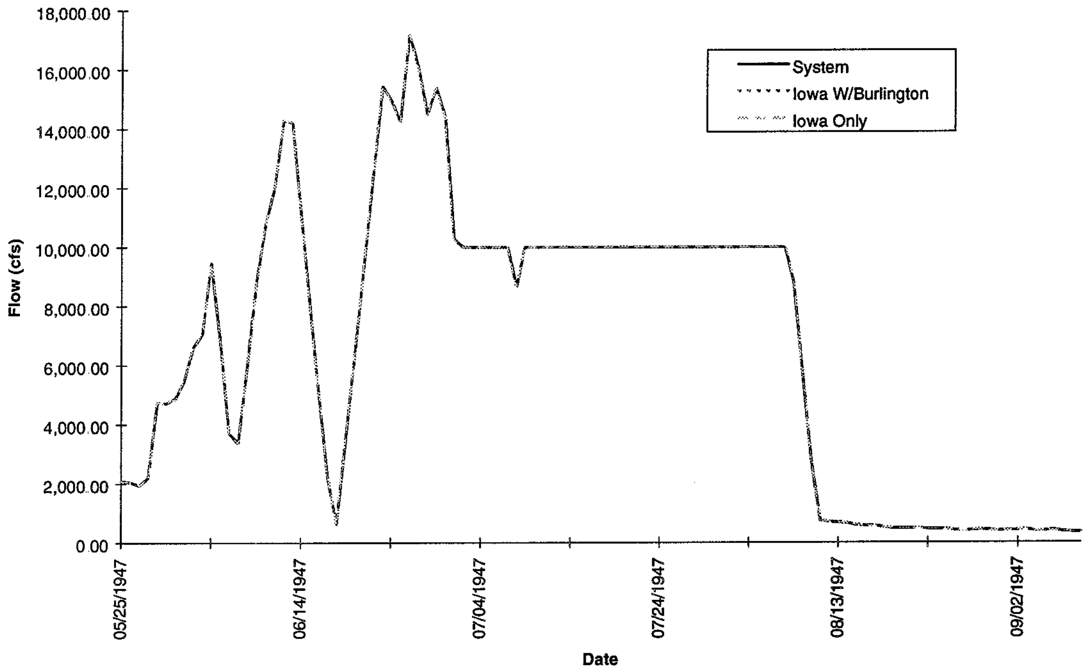

FIGURE E-2c. Hydrograph of Model Results at Iowa City - Flood of 1947

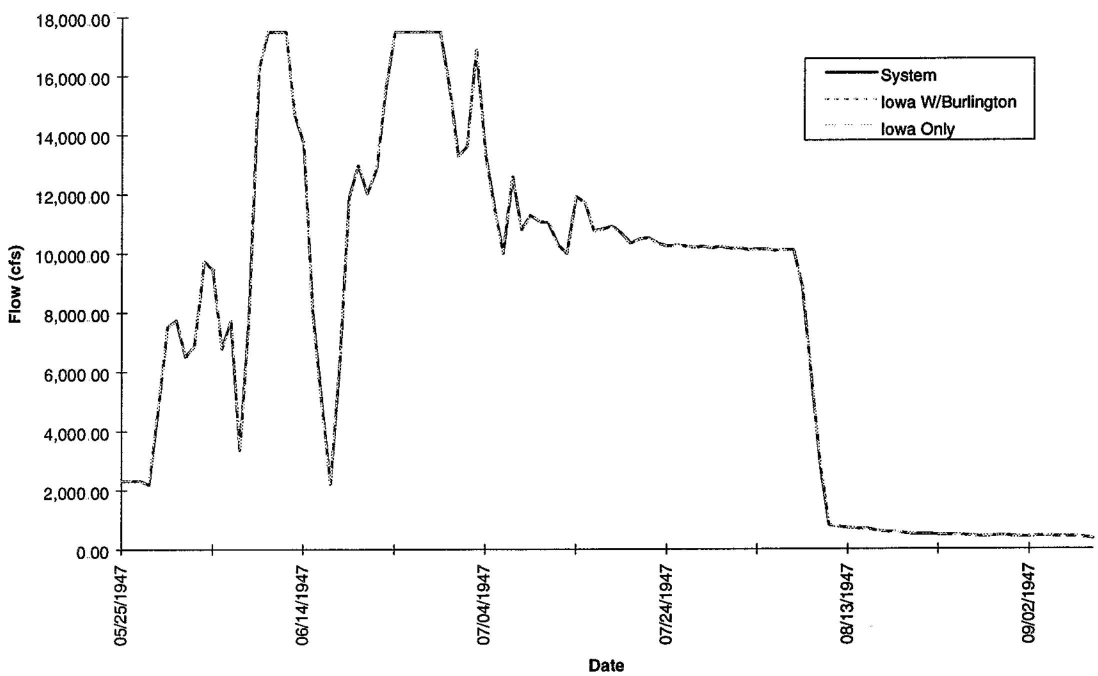

FIGURE E-2d. Hydrograph of Model Results at Lone Tree - Flood of 1947

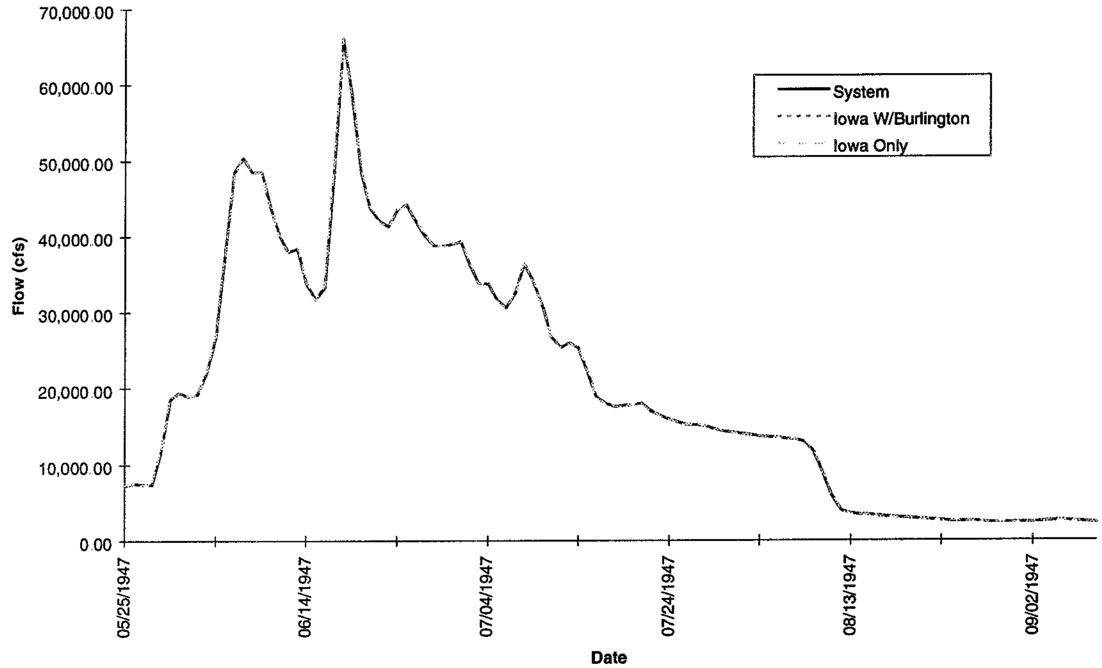

FIGURE E-2e. Hydrograph of Model Results at Wapello - Flood of 1947

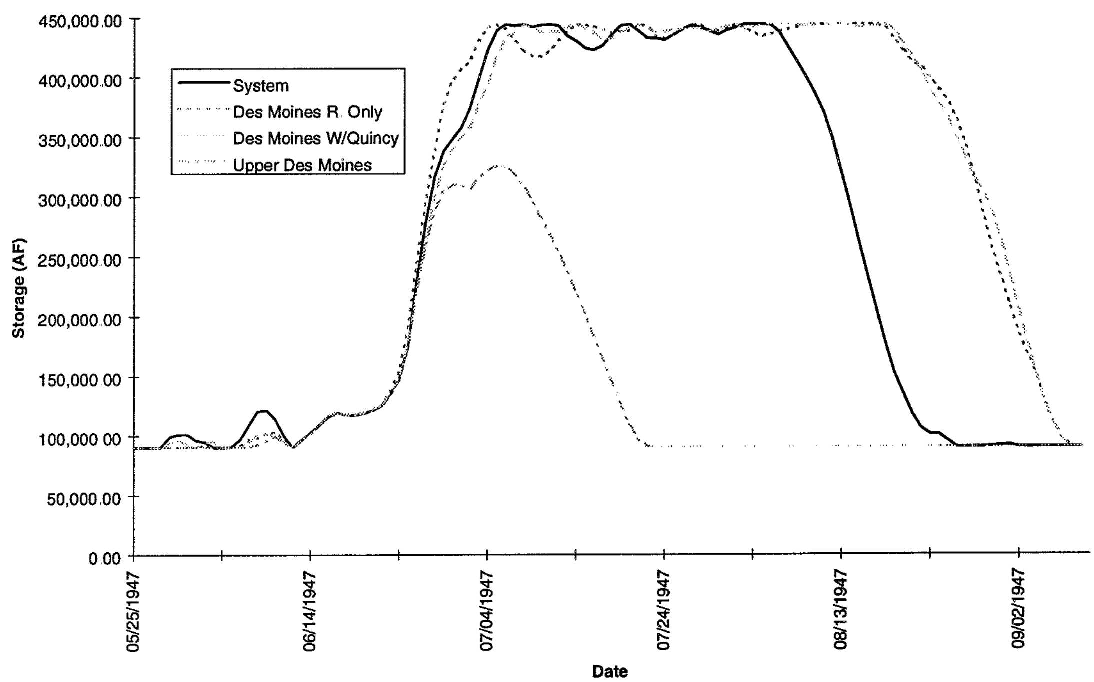

FIGURE E-2f. Model Results of Saylorville Reservoir Storage - Flood of 1947

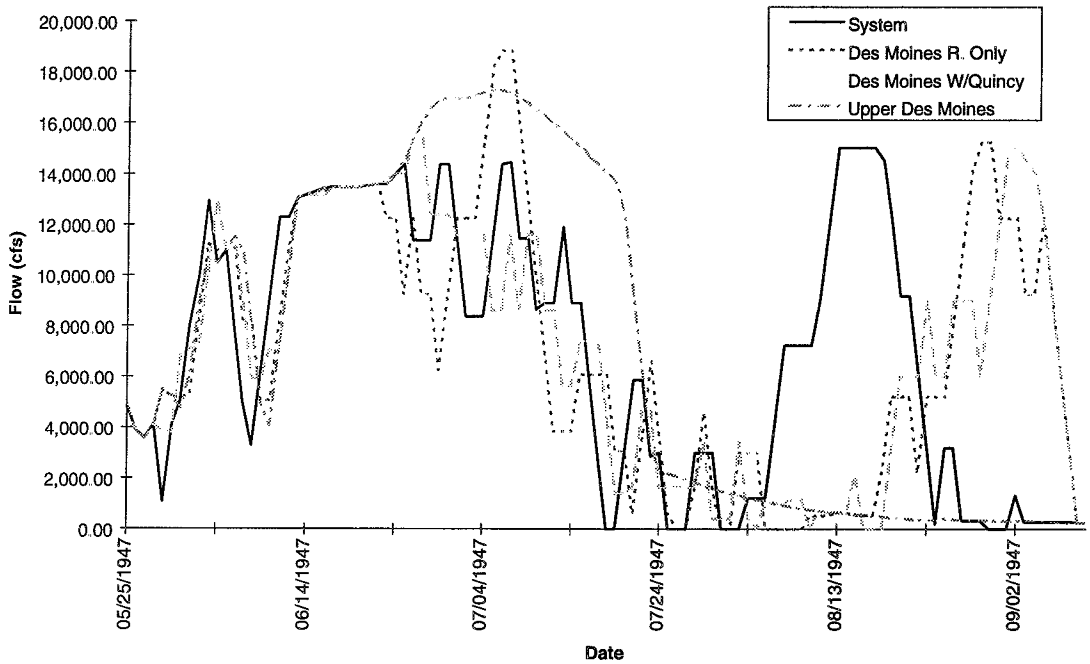

FIGURE E-2g. Model Results of Saylorville Reservoir Release - Flood of 1947

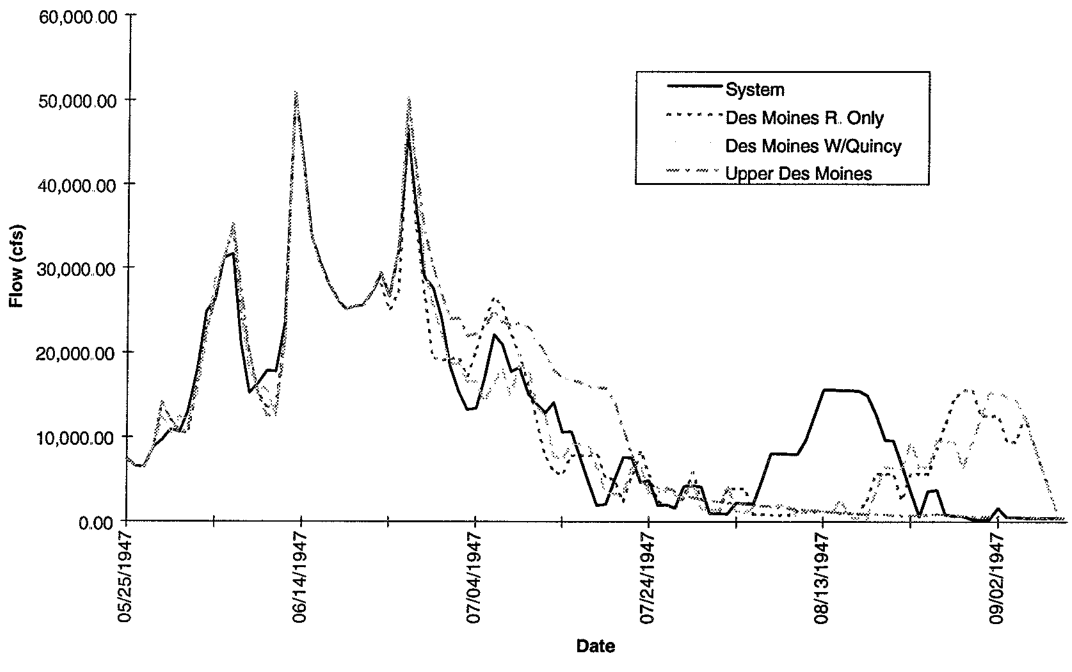

FIGURE E-2h. Hydrograph of Model Results at 14th Street - Flood of 1947

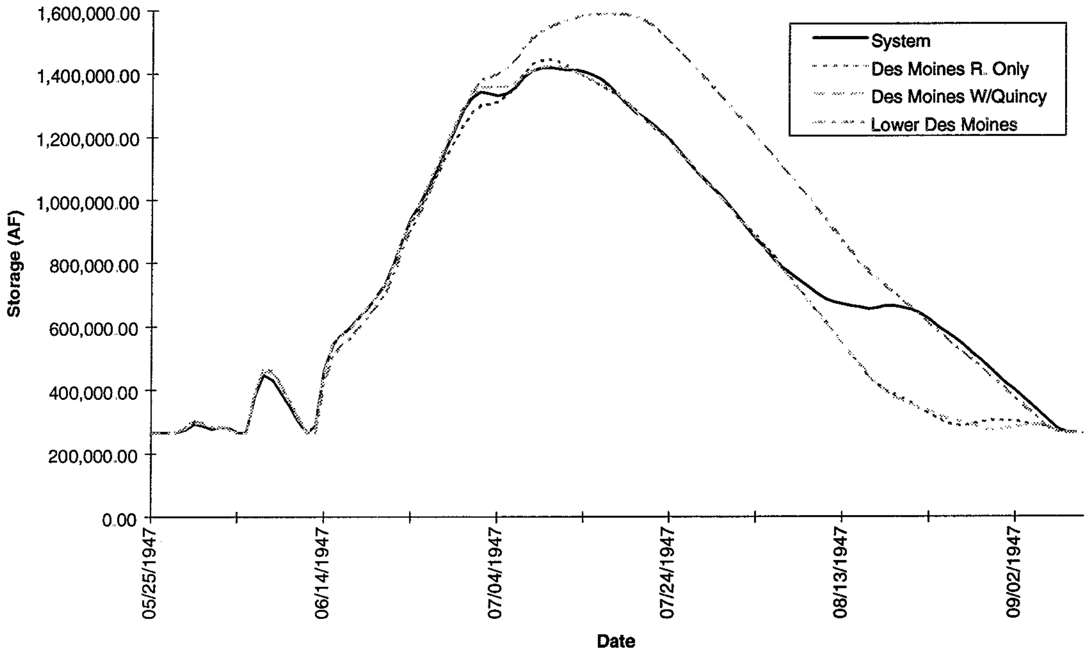

FIGURE E-2i. Model Results of Lake Red Rock Storage - Flood of 1947

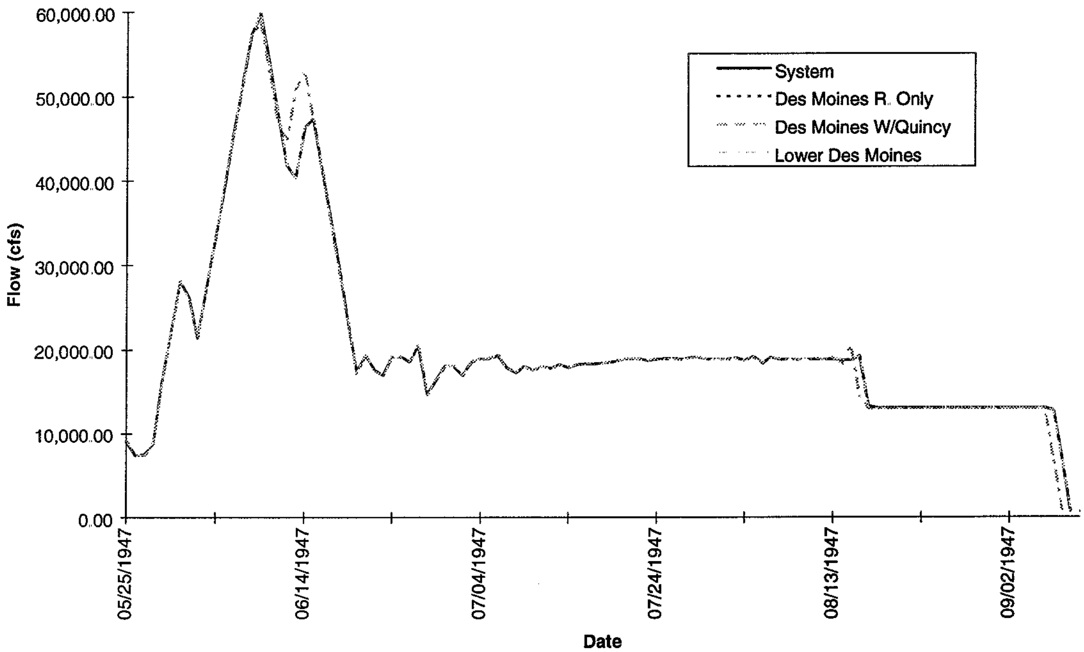

FIGURE E-2j. Model Results of Lake Red Rock Release - Flood of 1947

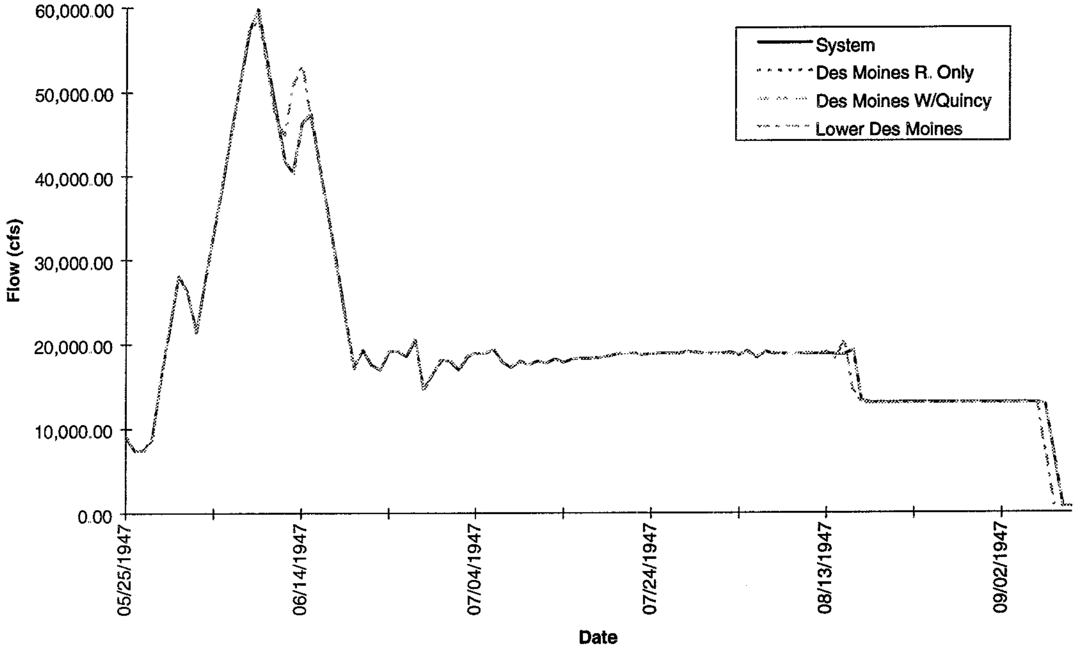

FIGURE E-2k. Hydrograph of Model Results at Tracy - Flood of 1947

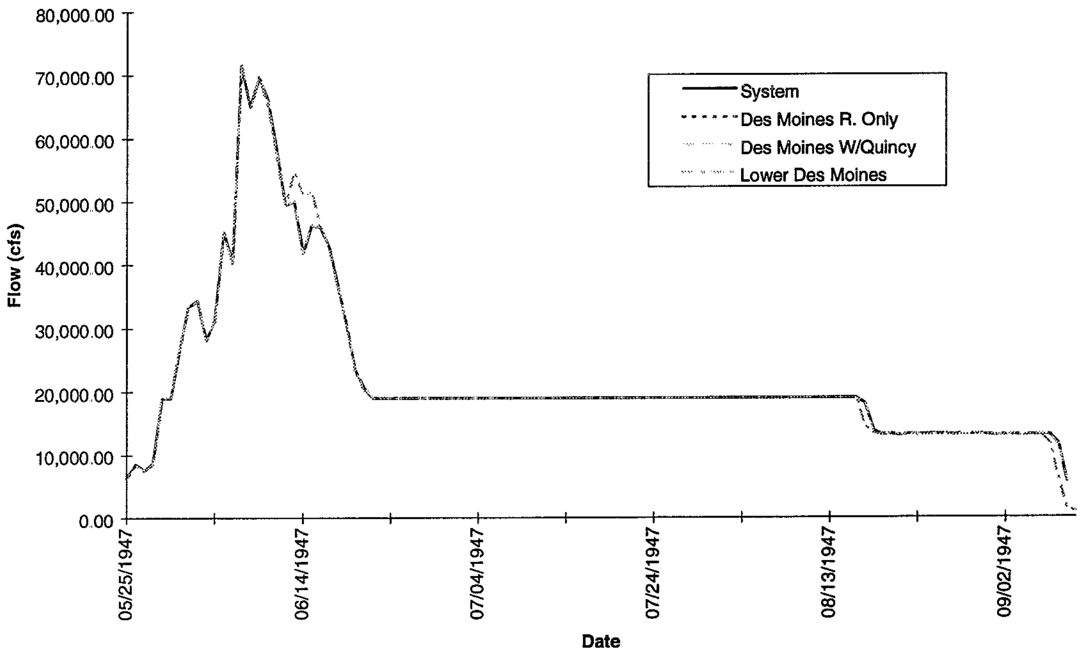

FIGURE E-2l. Hydrograph of Model Results at Ottumwa - Flood of 1947

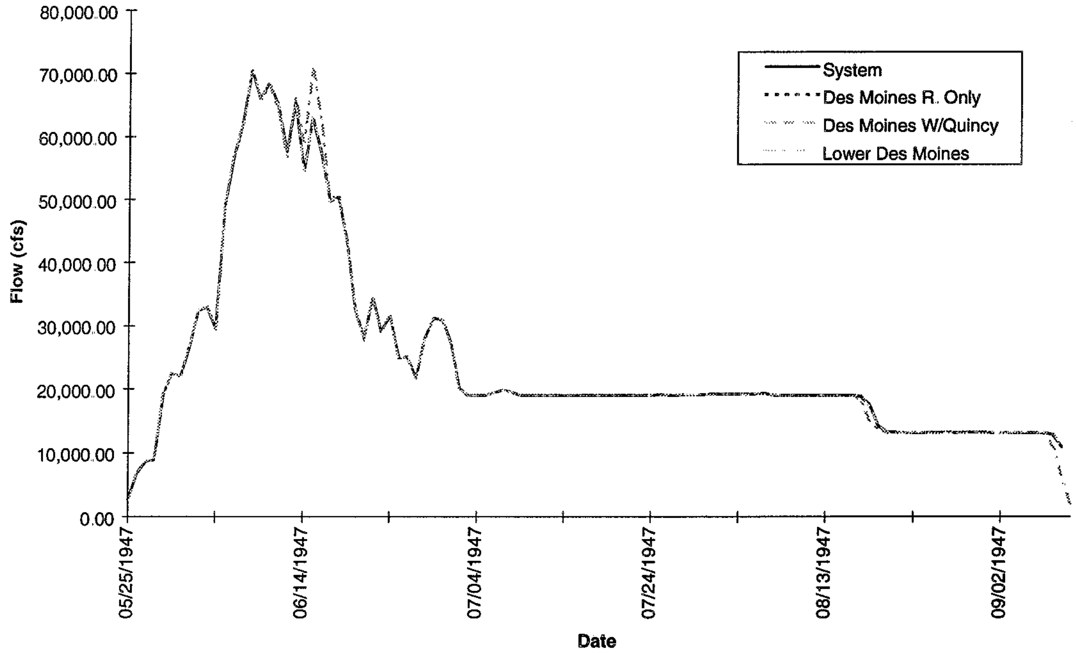

FIGURE E-2m. Hydrograph of Model Results at Keosauqua - Flood of 1947

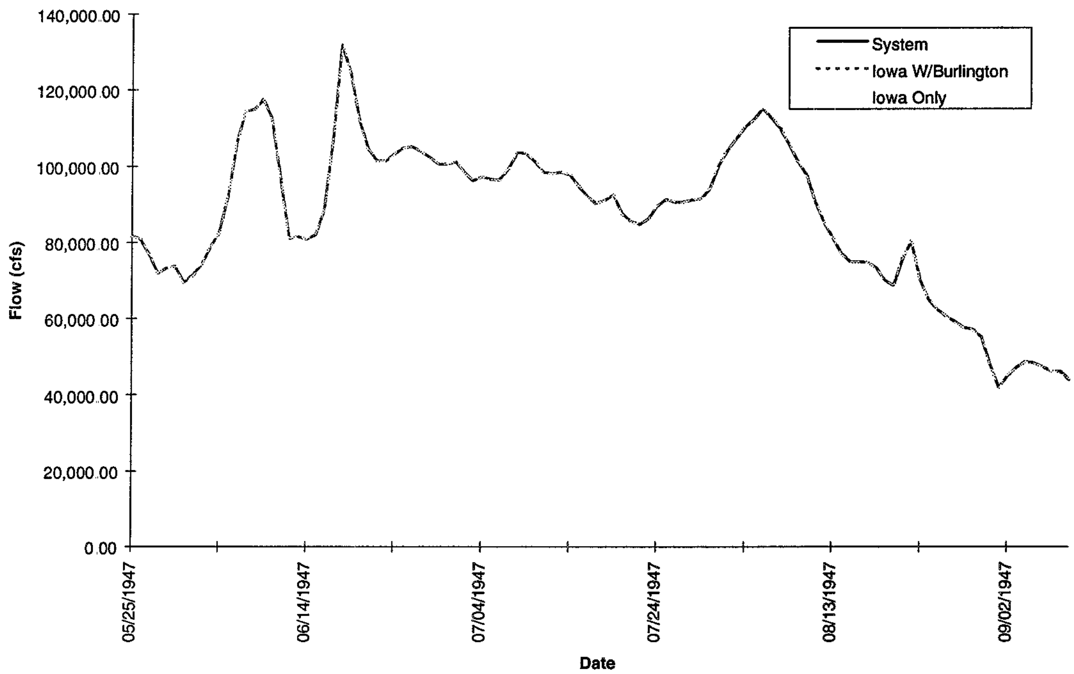

FIGURE E-2n. Hydrograph of Model Results at Burlington - Flood of 1947

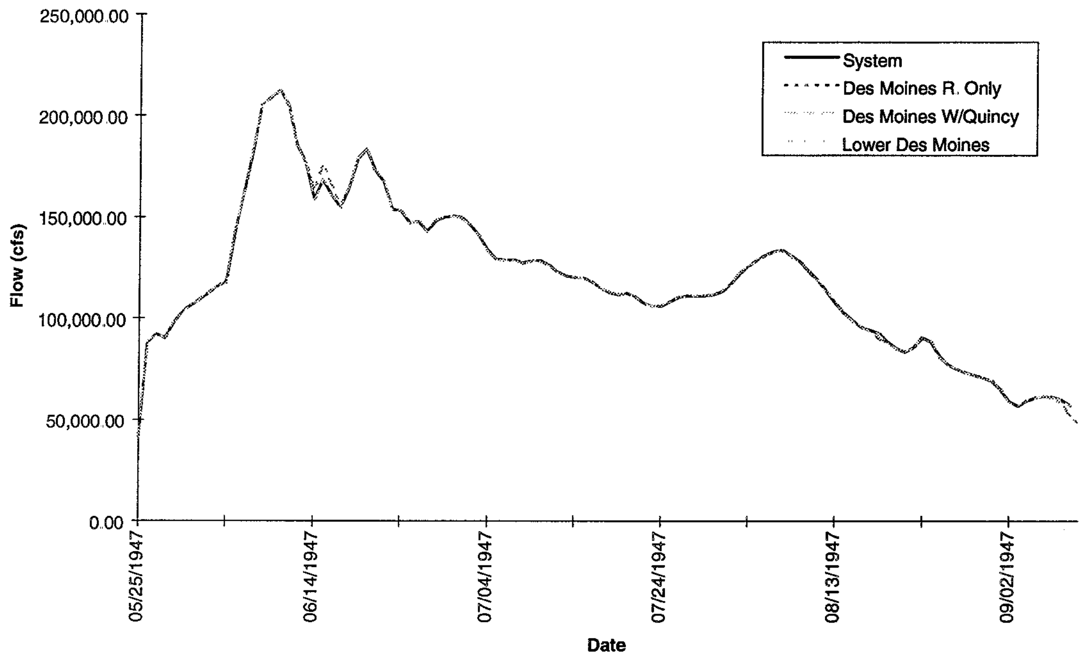

FIGURE E-2o. Hydrograph of Model Results at Quincy - Flood of 1947

1960 COMMENTARY

All model runs prevent damage at Iowa City and the City of Des Moines, and they also significantly reduce damage at Quincy, Ill., on the Mississippi River. The main reason the model's operations vary with different system configurations for the flood of 1960 is due to flooding at Quincy, Ill. As illustrated in Figures E-3i and E-3j, when not making releases for flood control at Quincy ("Des Moines R. Only"), the model makes larger releases from Lake Red Rock early in the event in order to avoid the persuasion penalty associated with storage. This operation causes a slightly larger flow at Ottumwa (Figure E-3o), which results in a peak-related damage of approximately $600,000 more than when the model operates for flood control at Quincy.

Damage caused by peak flow along the Iowa River and at Burlington is almost identical for the different operating schemes. The storage penalty in Coralville Reservoir under system configuration A ("System") is slightly larger because the model is reducing the damage at Quincy on the Mississippi River.

TABLE E-3. Flood of 1960 Calculated Penalties

	Peak Flow Damage ($1000)							
Site	**Observed**	**A**	**BD**	**CD**	**BE**	**CE**	**BFG**	**CFG**
Iowa City	-	-	-	-	-	-	-	-
Lone Tree	235	30	30	30	30	30	30	30
Wapello	3,700	4,152	4,161	4,162	4,161	4,162	4,161	4,162
2nd Ave.	6,032	-	-	-	-	-	-	-
14th St.	-	-	-	-	-	-	-	-
Tracy	5,298	1,335	1,337	1,337	1,332	1,332	1,333	1,333
Ottumwa	11,124	3,406	3,168	3,168	3,047	3,047	3,364	3,364
Keosauqua	1,311	940	940	940	940	940	973	973
Burlington	319	302	303	304	303	304	303	304
Quincy	7,219	-	90	90	792	792	90	90
Total	35,238	10,164	10,028	10,030	10,604	10,606	10,254	10,256

	Model-Computed Flow Penalty ($1000)							
Site	**Observed**	**A**	**BD**	**CD**	**BE**	**CE**	**BFG**	**CFG**
Iowa City	-	-	-	-	-	-	-	-
Lone Tree	434	53	53	53	53	53	53	53
Wapello	16,521	13,991	14,164	14,221	14,164	14,221	14,164	14,221
2nd Ave.	16,060	-	-	-	-	-	-	-
14th St.	-	-	-	-	-	-	-	-
Tracy	62,982	37,129	36,949	36,949	37,160	37,160	37,090	37,090
Ottumwa	137,614	27,158	26,119	26,119	27,234	27,234	26,679	26,679
Keosauqua	14,541	3,801	3,691	3,691	3,614	3,614	3,815	3,815
Burlington	3,003	3,050	3,074	3,095	3,074	3,095	3,074	3,095
Quincy	24,494	-	90	90	1,076	1,076	90	90
Coralville		4,192	3,956	3,887	3,956	3,887	3,956	3,887
Saylorville		37,603	36,902	36,902	44,032	44,032	2,344	2,344
Red Rock		37,258	39,327	39,327	30,769	30,769	73,918	73,918
Total w/o stor.	275,649	85,183	84,141	84,218	86,375	86,453	84,965	85,042
Total w/ stor.		164,236	164,325	164,333	165,132	165,140	165,183	165,191

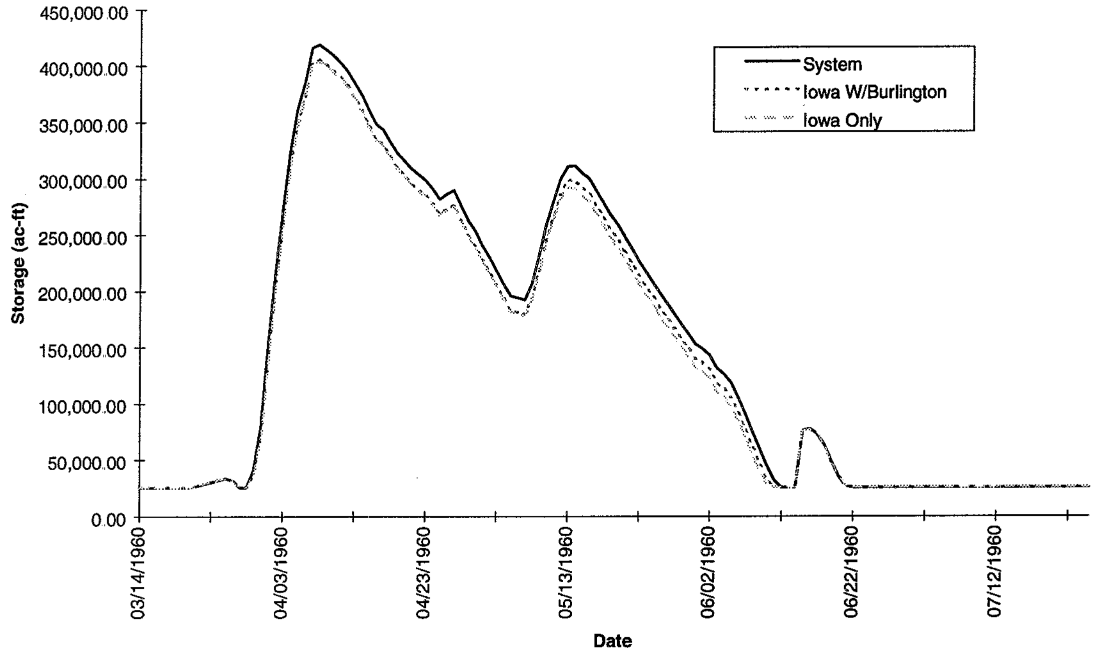

FIGURE E-3a. Model Results of Coralville Reservoir Storage - Flood of 1960

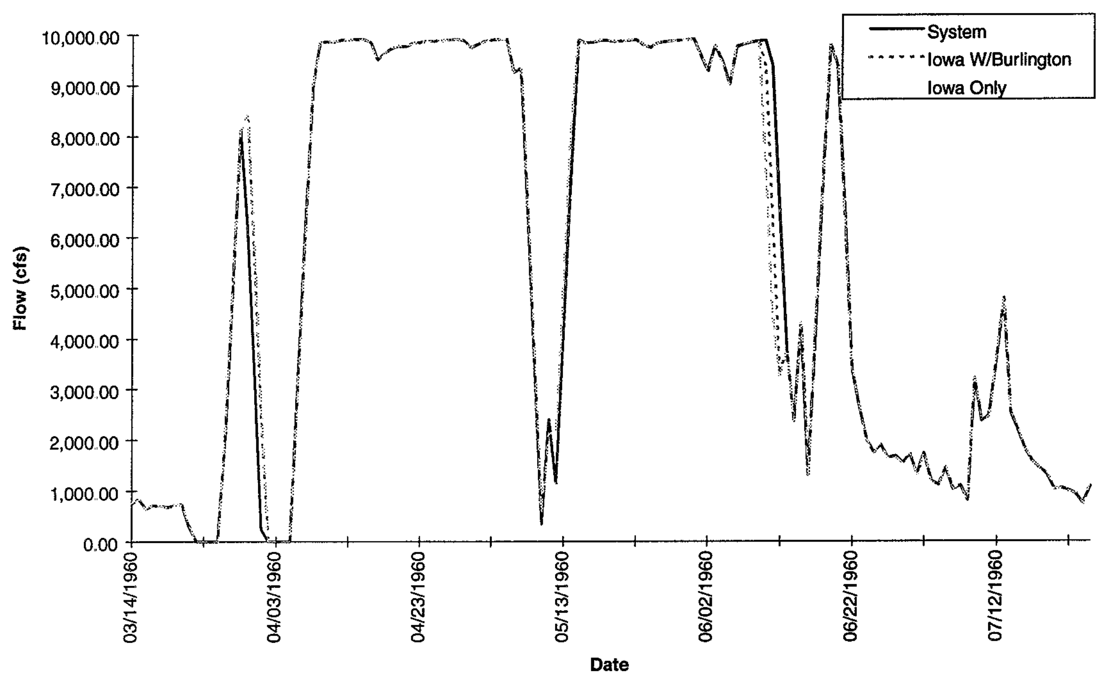

FIGURE E-3b. Model Results of Coralville Reservoir Release - Flood of 1960

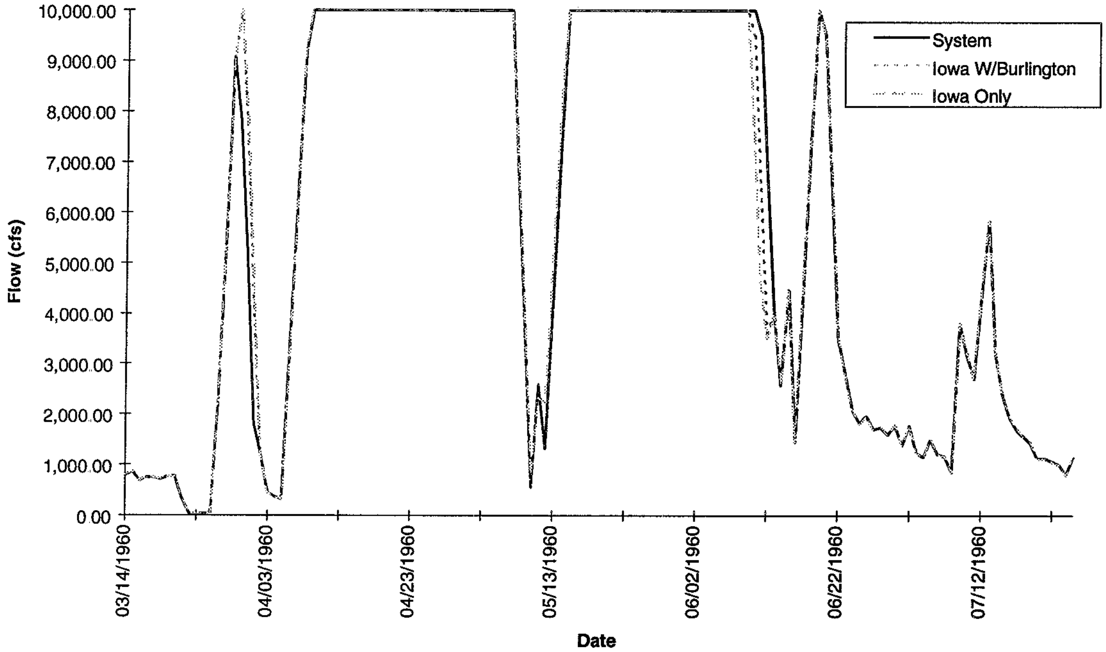

FIGURE E-3c. Hydrograph of Model Results at Iowa City - Flood of 1960

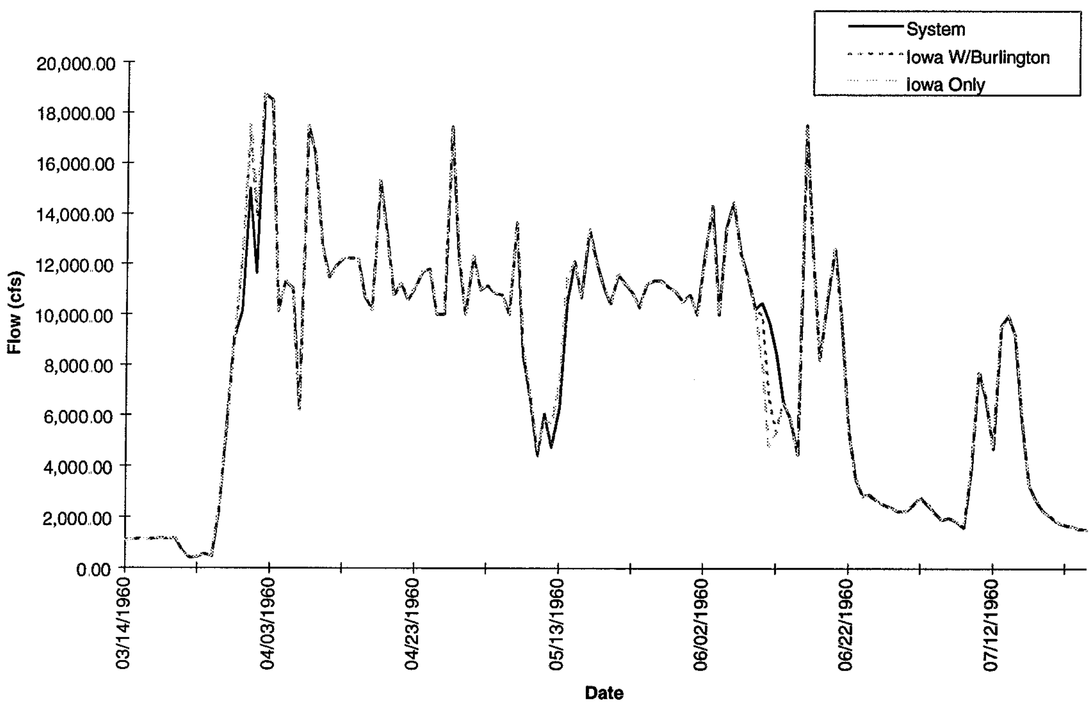

FIGURE E-3d. Hydrograph of Model Results at Lone Tree - Flood of 1960

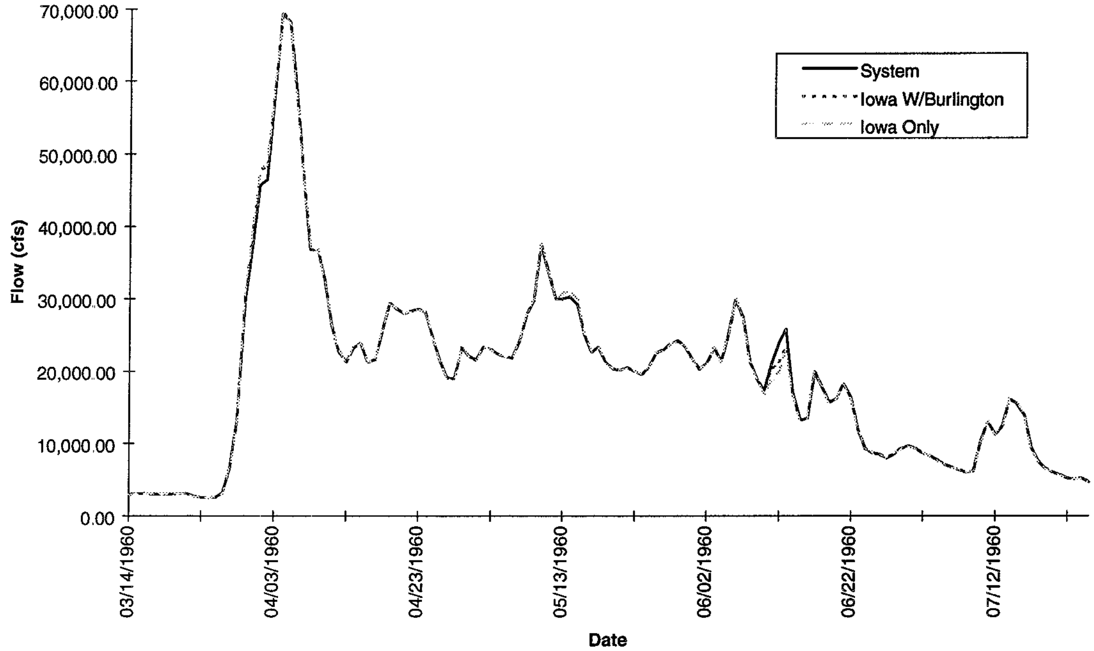

FIGURE E-3e. Hydrograph of Model Results at Wapello - Flood of 1960

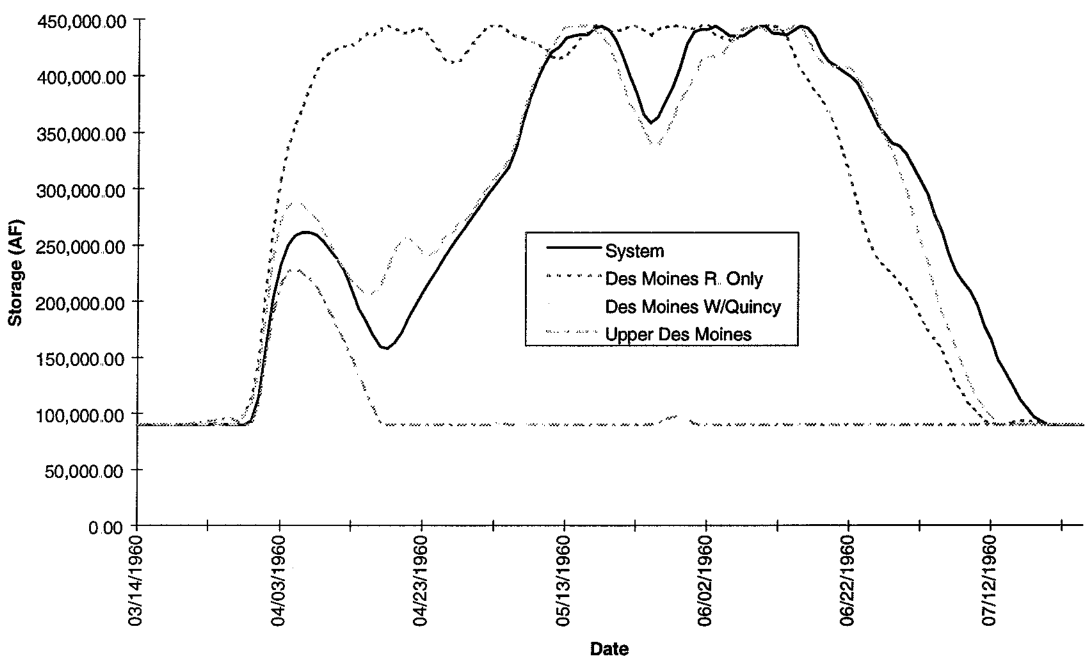

FIGURE E-3f. Model Results of Saylorville Reservoir Storage - Flood of 1960

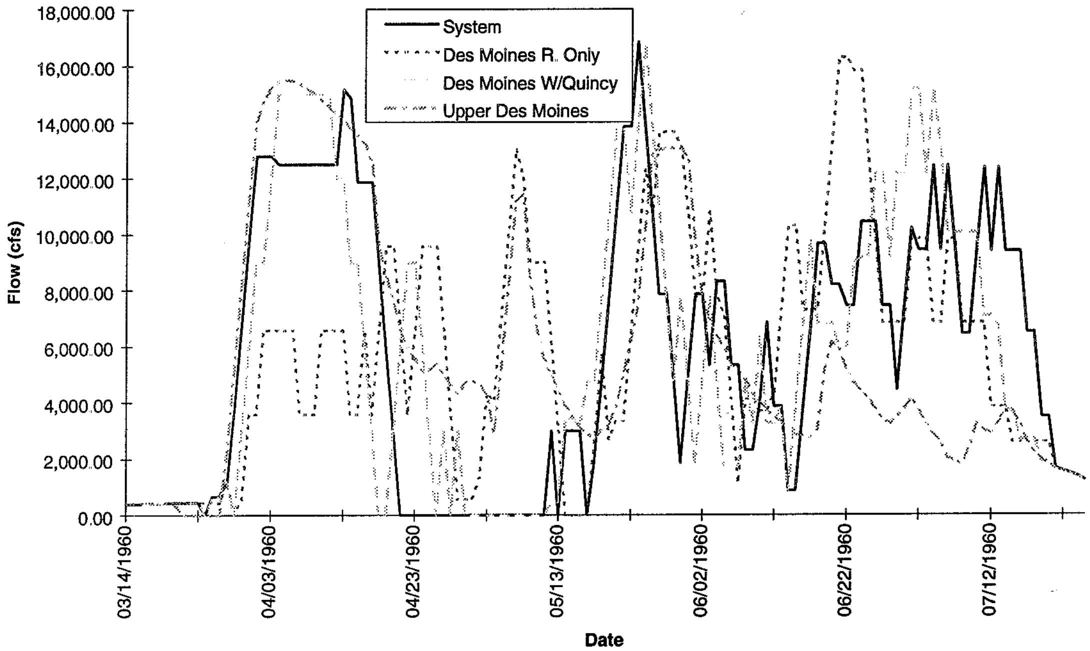

FIGURE E-3g. Model Results of Saylorville Reservoir Release - Flood of 1960

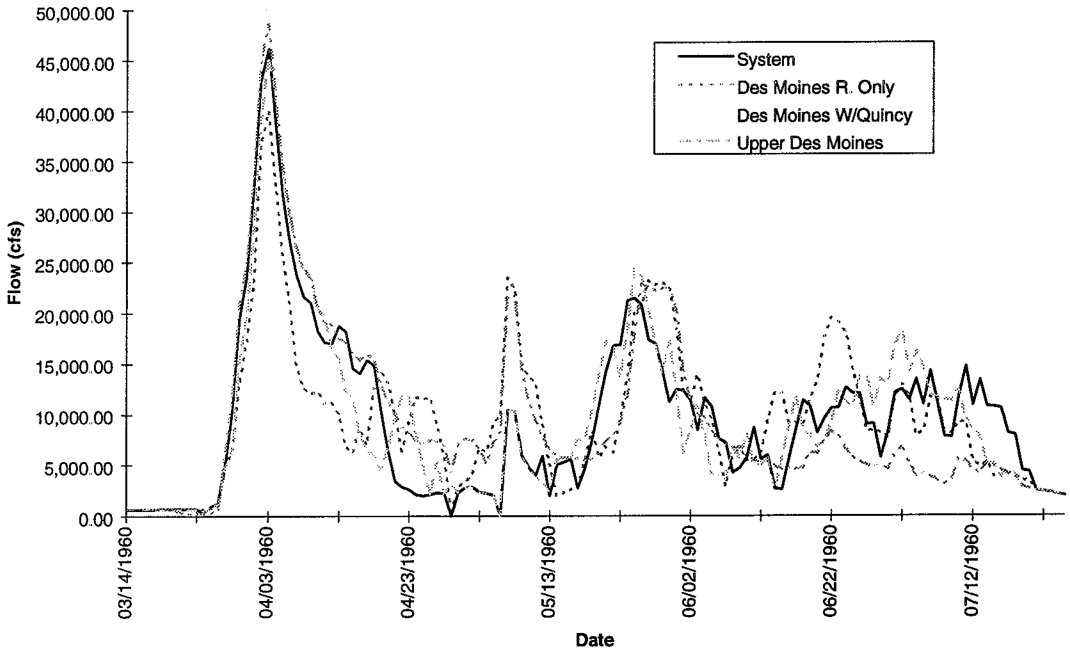

FIGURE E-3h. Hydrograph of Model Results at 14th Street - Flood of 1960

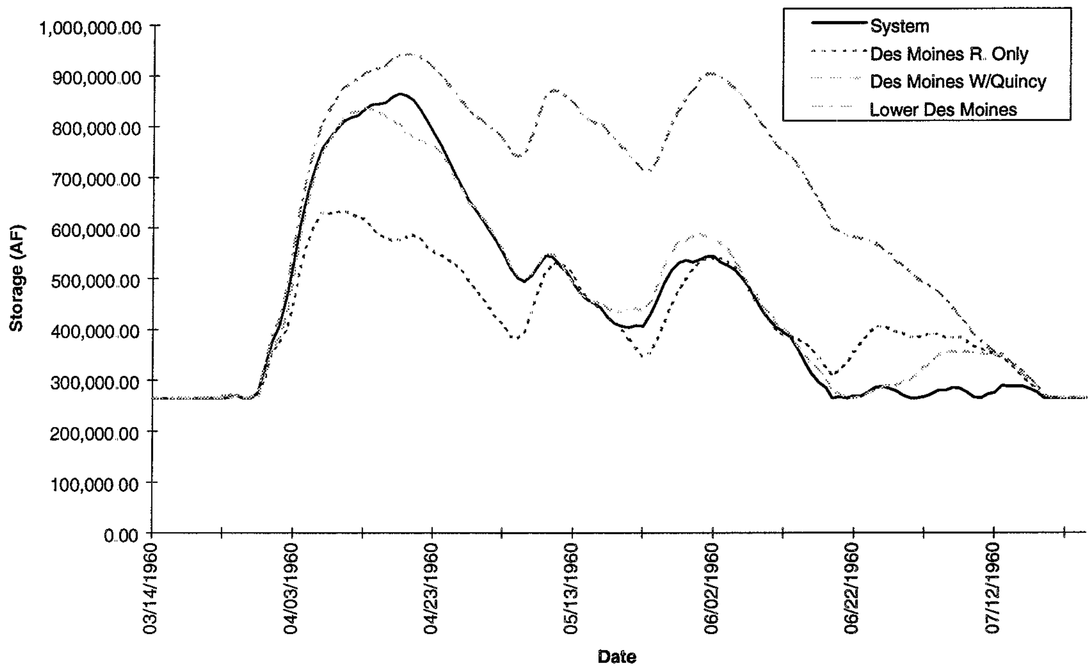

FIGURE E-3i. Model Results of Lake Red Rock Storage - Flood of 1960

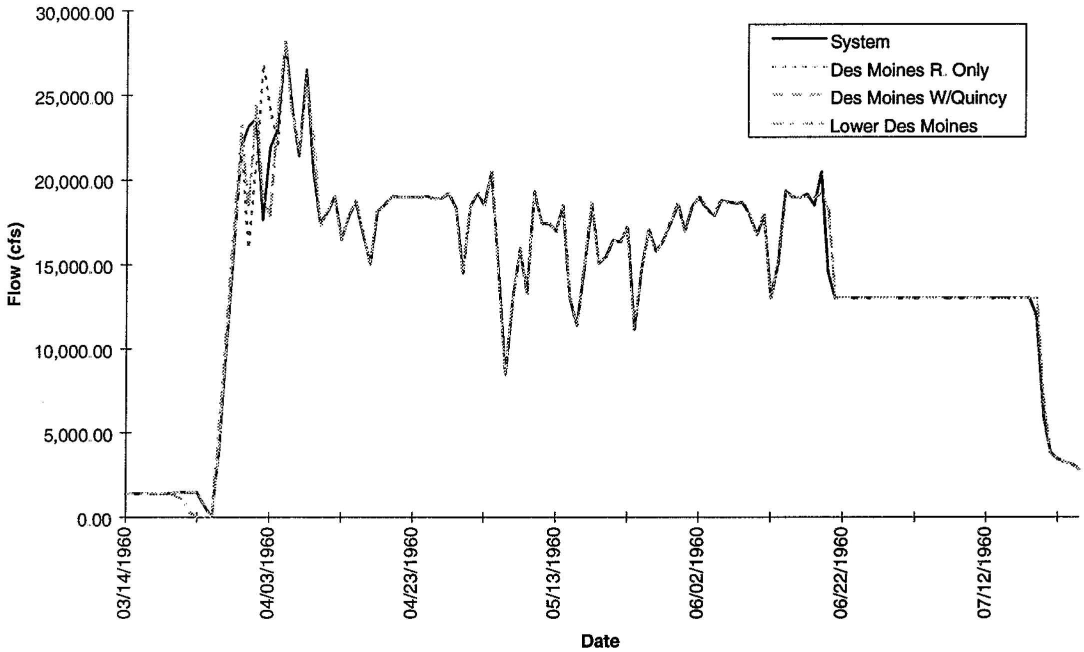

FIGURE E-3j. Model Results of Lake Red Rock Release - Flood of 1960

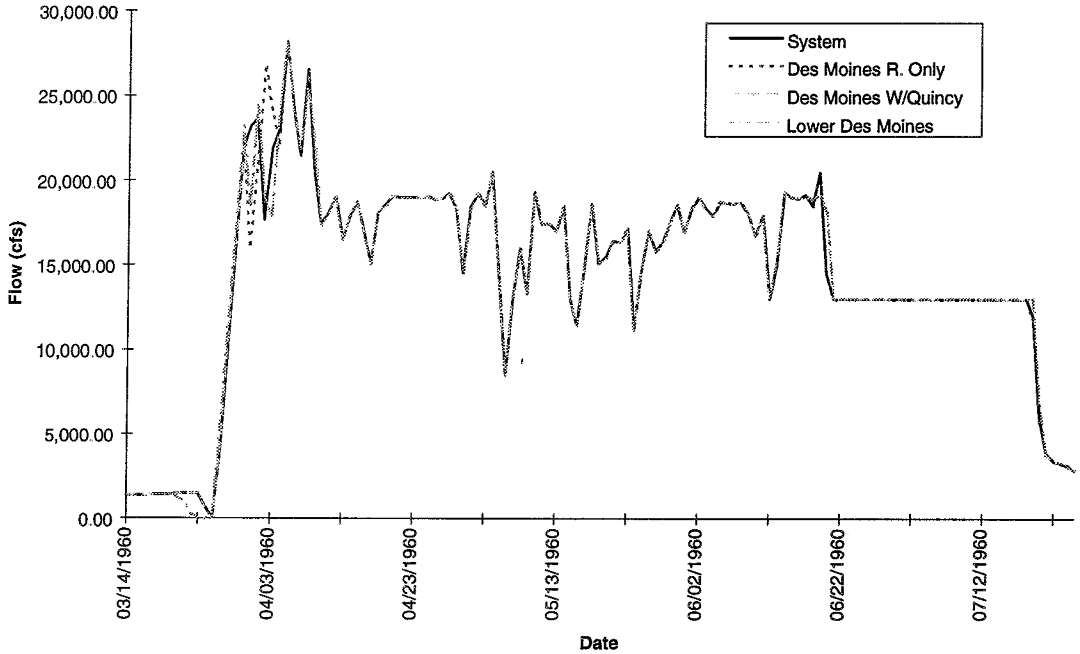

FIGURE E-3k. Hydrograph of Model Results at Tracy - Flood of 1960

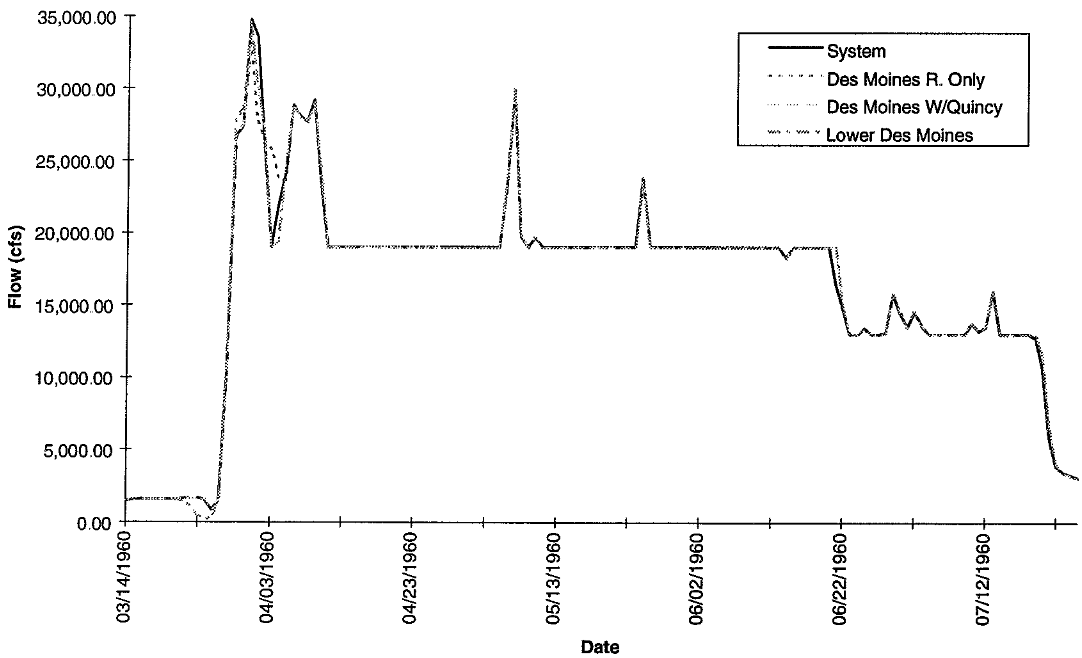

FIGURE E-3l. Hydrograph of Model Results at Ottumwa - Flood of 1960

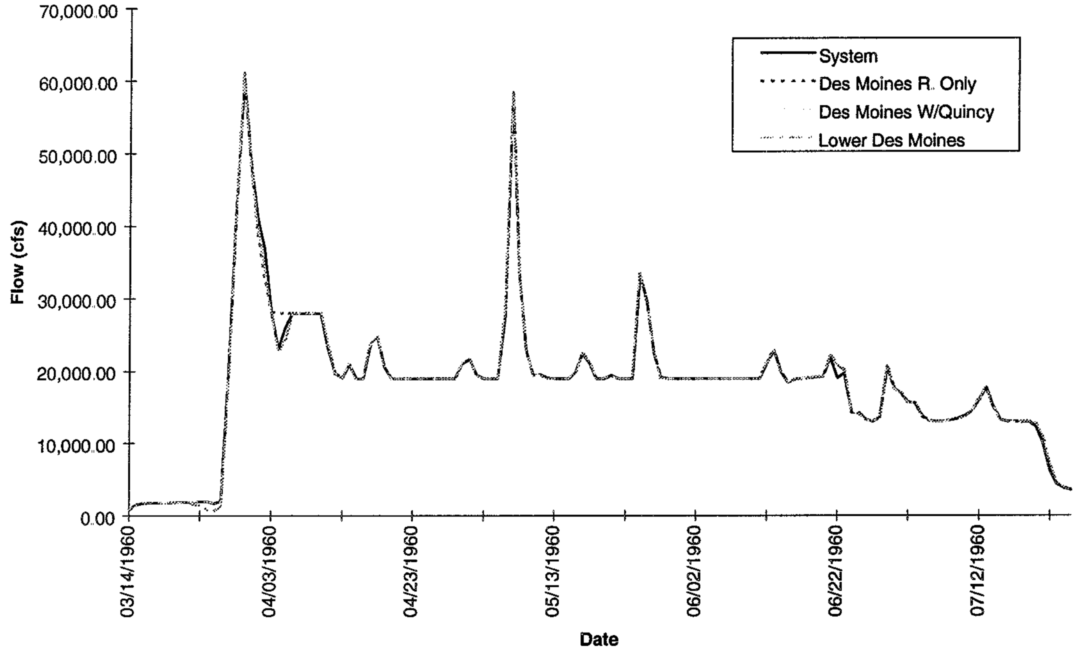

FIGURE E-3m. Hydrograph of Model Results at Keosauqua - Flood of 1960

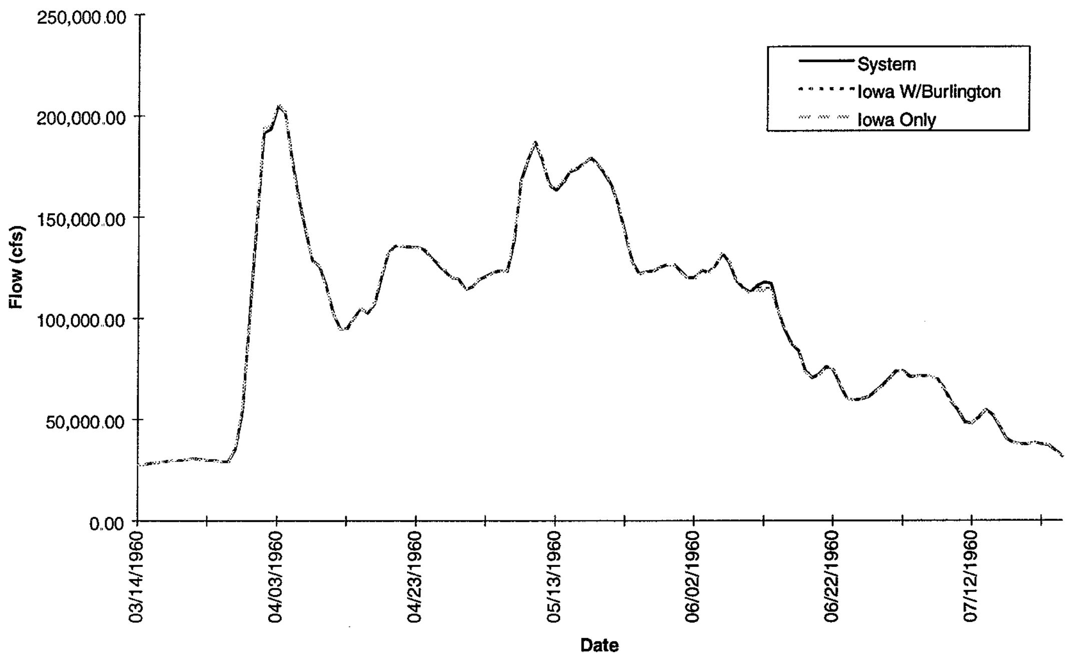

FIGURE E-3n. Hydrograph of Model Results at Burlington - Flood of 1960

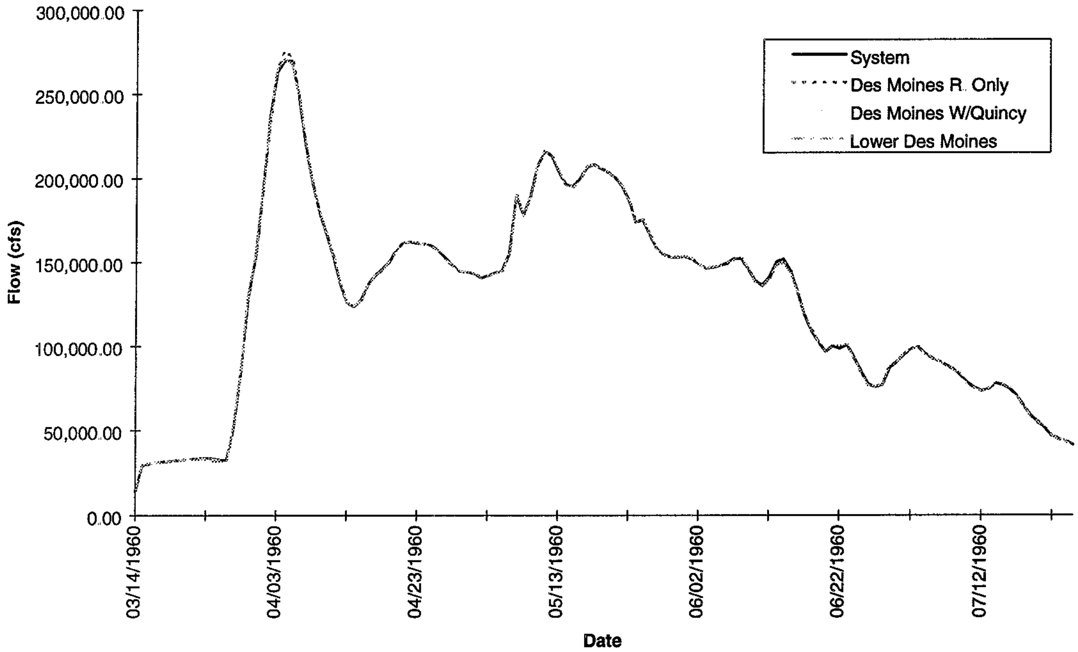

FIGURE E-3o. Hydrograph of Model Results at Quincy - Flood of 1960

1965 COMMENTARY

The flood of 1965 is one of the largest on record for the Iowa and Des Moines region. Releases made by the model vary significantly depending on the operational scheme for this event. When operating as one complete system (System A in Table E-4), releases from Coralville Reservoir cause damage at Iowa City (Figure E-4c), in order to offset flood peaks (and minimize model-computed penalties) on the Mississippi River. As illustrated in Figure E-4a, more flood control space is used when operating for Burlington, IA, than when operating only for control points on the Iowa River. This results in a savings of approximately $200,000 based on peak-flow at Burlington. However, the total damage associated with peak flow throughout the system is smaller when Coralville Reservoir does not operate for flood control at Quincy, Ill., as illustrated in Table E-4.

On the Des Moines River, releases from Saylorville Reservoir are similar for the first half of the event because the model is using its entire flood pool to reduce damage in the City of Des Moines. Draw down for Saylorville Reservoir varies under the different operating schemes in order to minimize storage penalties.

There are two main differences in how the model operates Lake Red Rock for the different system configurations. The first occurs when the Des Moines River is divided above Lake Red Rock so that the two reservoirs operate independently. Inflows into Lake Red Rock are large enough to cause damaging releases that would not occur if the reservoirs were operated in tandem, as illustrated in Figure E-4j. The other difference occurs when Quincy, Ill., is not considered. As illustrated in Figure E-4j, the peak flow at Quincy is much higher in this case, resulting in damages of more then $15 million over the case in which Lake Red Rock operates for Quincy.

TABLE E-4. Flood of 1965 Calculated Penalties

Site	Peak Flow Damage ($1000)							
	Observed	A	BD	CD	BE	CE	BFG	CFG
Iowa City	-	99	-	-	-	-	-	-
Lone Tree	74	-	-	60	-	60	-	60
Wapello	4,322	3,929	3,929	3,927	3,929	3,927	3,929	3,927
2nd Ave.	26,901	298	298	298	298	298	297	297
14th St.	-	-	-	-	-	-	-	-
Tracy	5,570	1,406	1,406	1,406	1,083	1,083	1,543	1,543
Ottumwa	12,658	1,961	1,961	1,961	1,521	1,521	2,635	2,635
Keosauqua	1,485	281	281	281	216	216	229	229
Burlington	8,415	8,316	8,316	8,509	8,316	8,509	8,316	8,509
Quincy	32,907	14,495	14,524	14,524	29,646	29,646	14,506	14,506
Total	92,332	30,786	30,714	30,965	45,009	45,259	31,455	31,706

Site	Model-Computed Flow Penalty ($1000)							
	Observed	A	BD	CD	BE	CE	BFG	CFG
Iowa City	-	320	-	-	-	-	-	-
Lone Tree	79	-	-	76	-	76	-	76
Wapello	23,601	18,900	18,699	18,219	18,699	18,219	18,699	18,219
2nd Ave.	142,433	611	611	611	611	611	601	601
14th St.	-	-	-	-	-	-	-	-
Tracy	81,567	47,227	47,227	47,227	46,252	46,252	48,357	48,357
Ottumwa	142,236	12,399	12,399	12,399	8,041	8,041	15,171	15,171
Keosauqua	14,428	626	626	626	476	476	749	749
Burlington	63,693	61,157	61,383	69,995	61,383	69,995	61,383	69,995
Quincy	180,020	90,411	93,733	93,733	149,324	149,324	93,360	93,360
Coralville		3,846	3,742	2,845	3,742	2,845	3,742	2,845
Saylorville		49,408	33,105	33,105	48,986	48,986	19,111	19,111
Red Rock		66,046	82,349	82,349	55,540	55,540	94,100	94,100
Total w/o stor.	648,056	231,650	234,678	242,885	284,788	292,996	238,321	246,528
Total w/ stor.		350,950	353,873	361,184	393,055	400,366	355,274	362,584

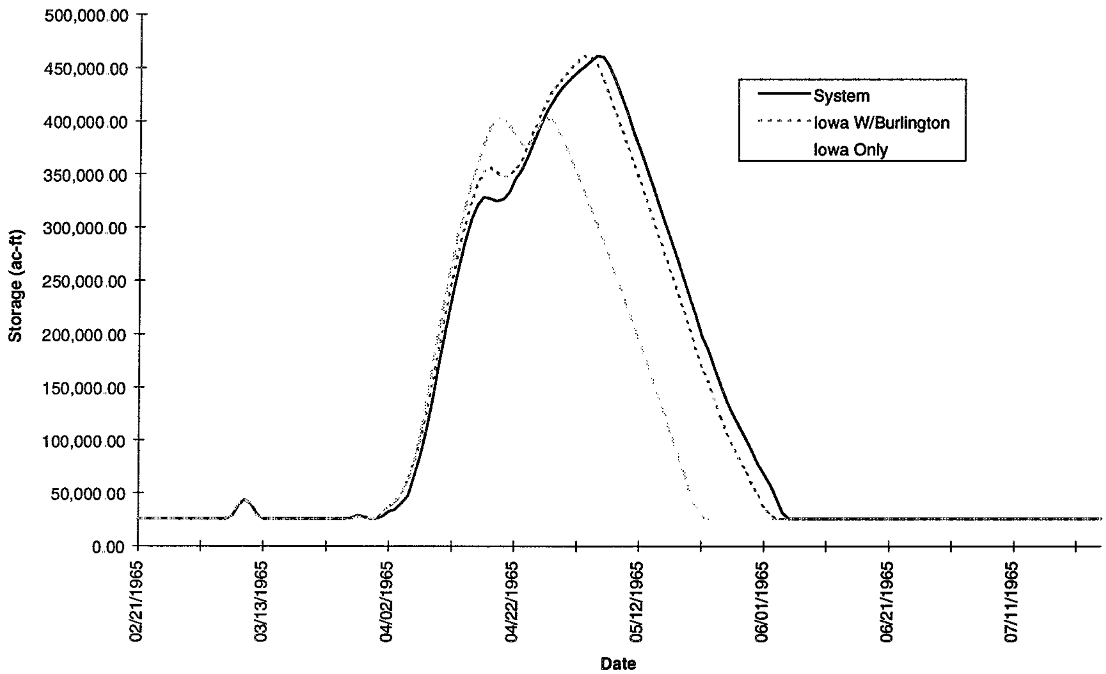

FIGURE E-4a. Model Results of Coralville Reservoir Storage - Flood of 1965

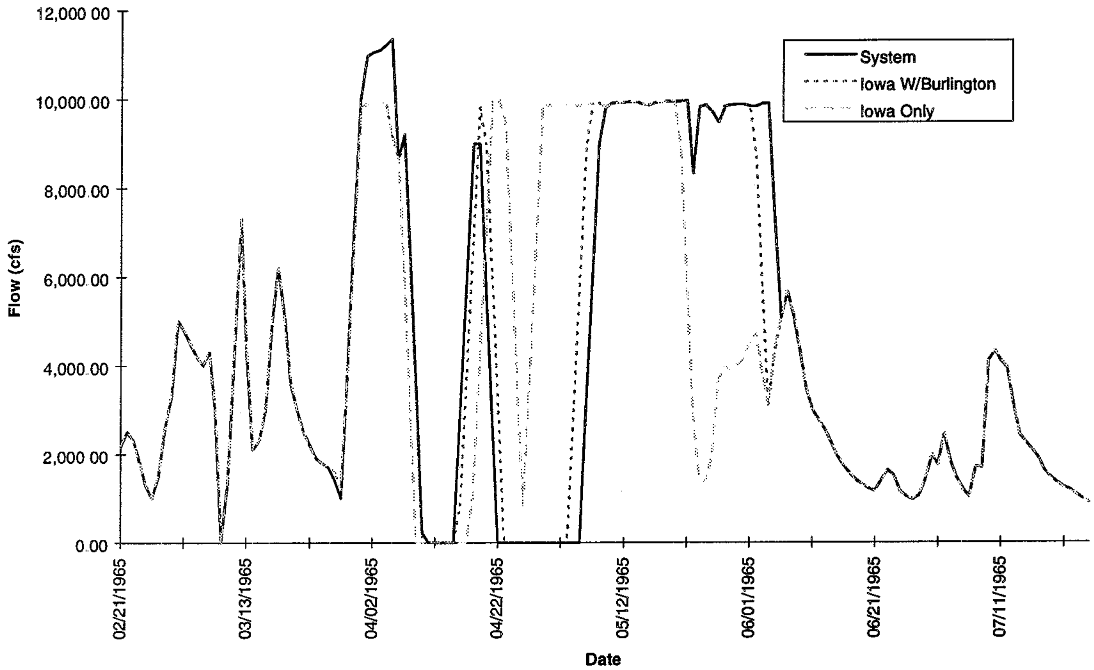

FIGURE E-4b. Model Results of Coralville Reservoir Release - Flood of 1965

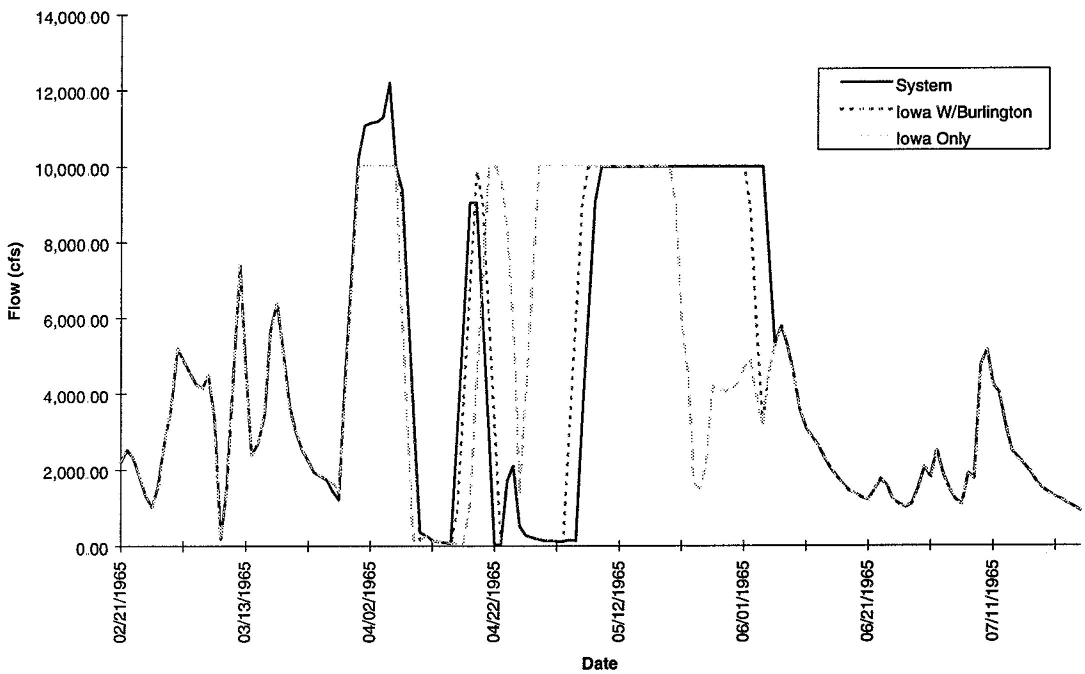

FIGURE E-4c. Hydrograph of Model Results at Iowa City - Flood of 1965

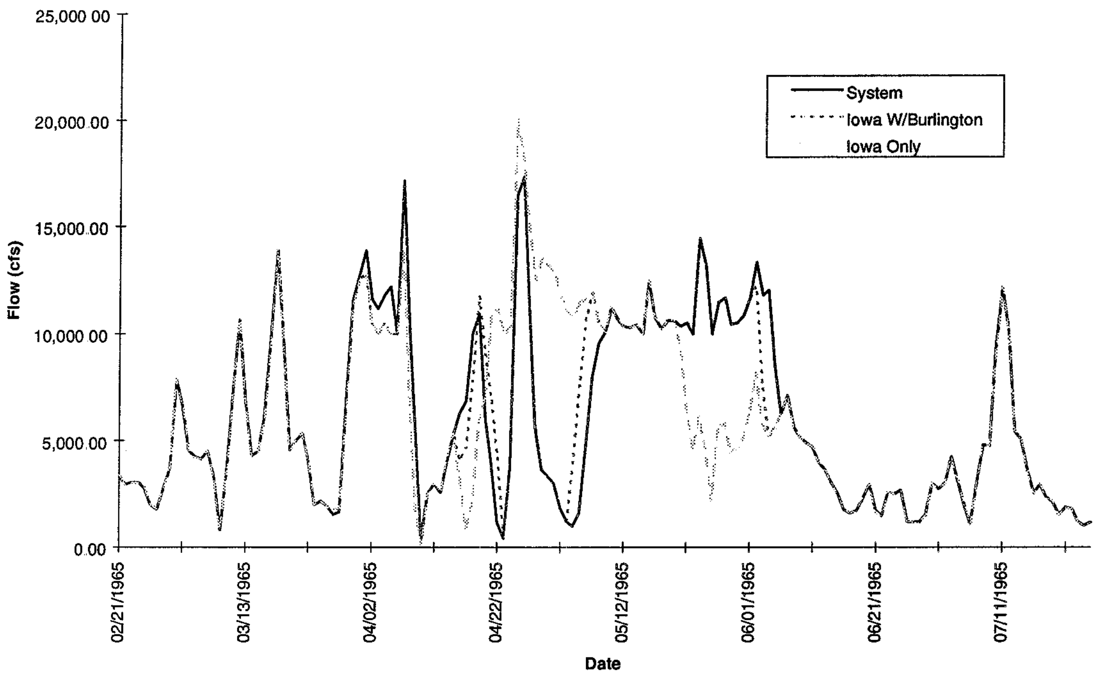

FIGURE E-4d. Hydrograph of Model Results at Lone Tree - Flood of 1965

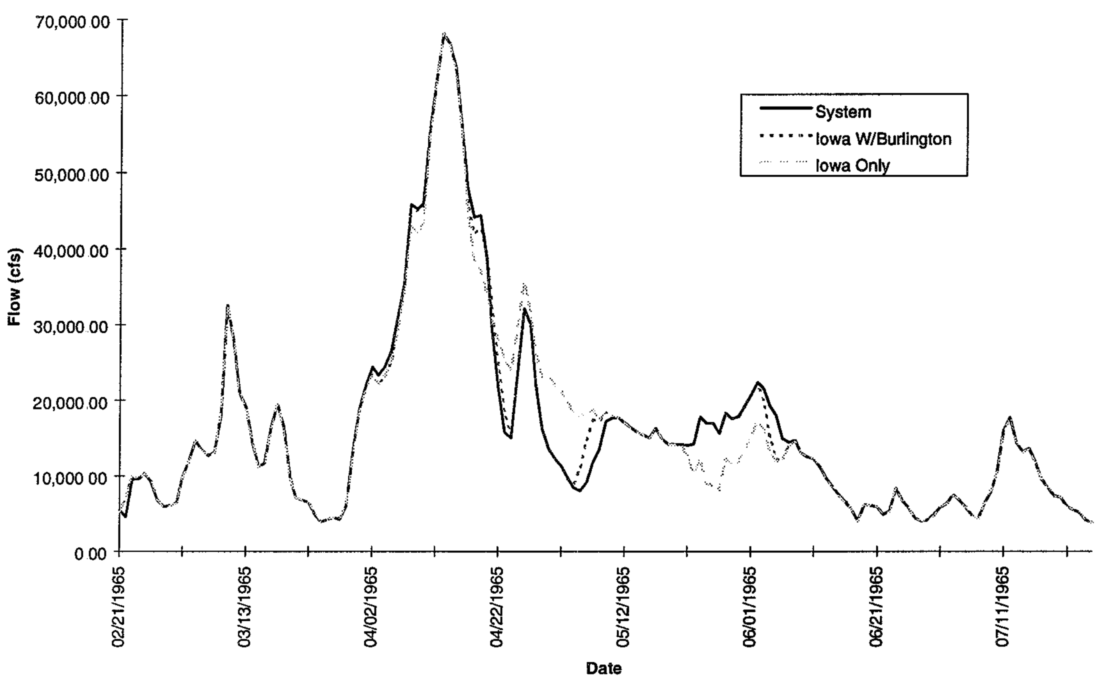

FIGURE E-4e. Hydrograph of Model Results at Wapello - Flood of 1965

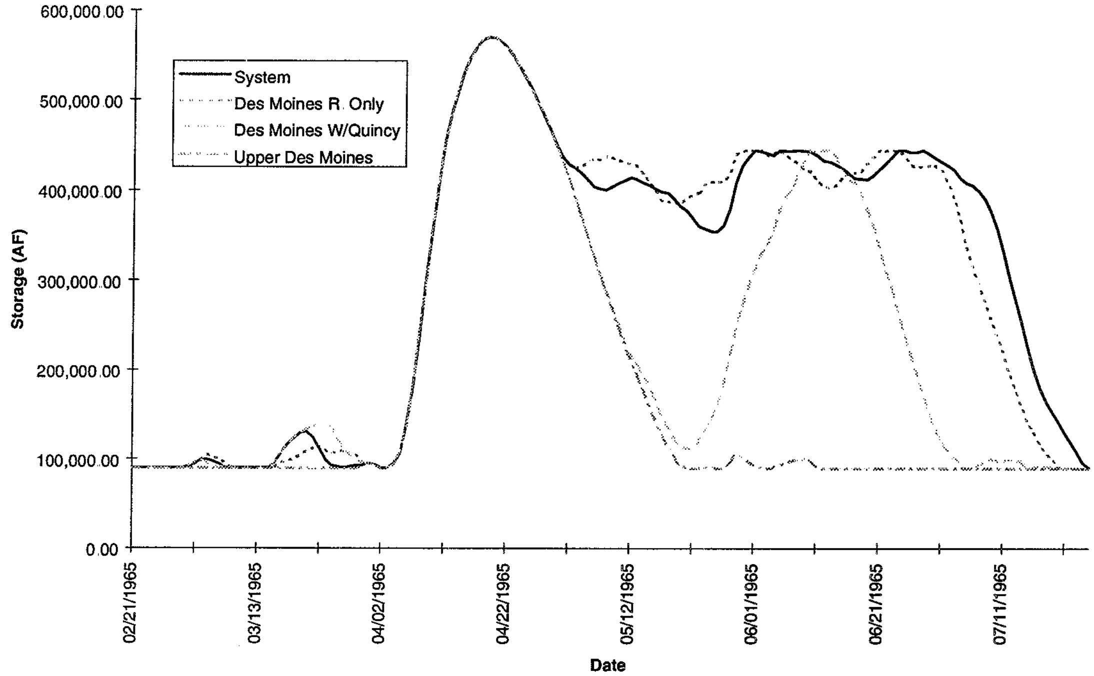

FIGURE E-4f. Model Results of Saylorville Reservoir Storage - Flood of 1965

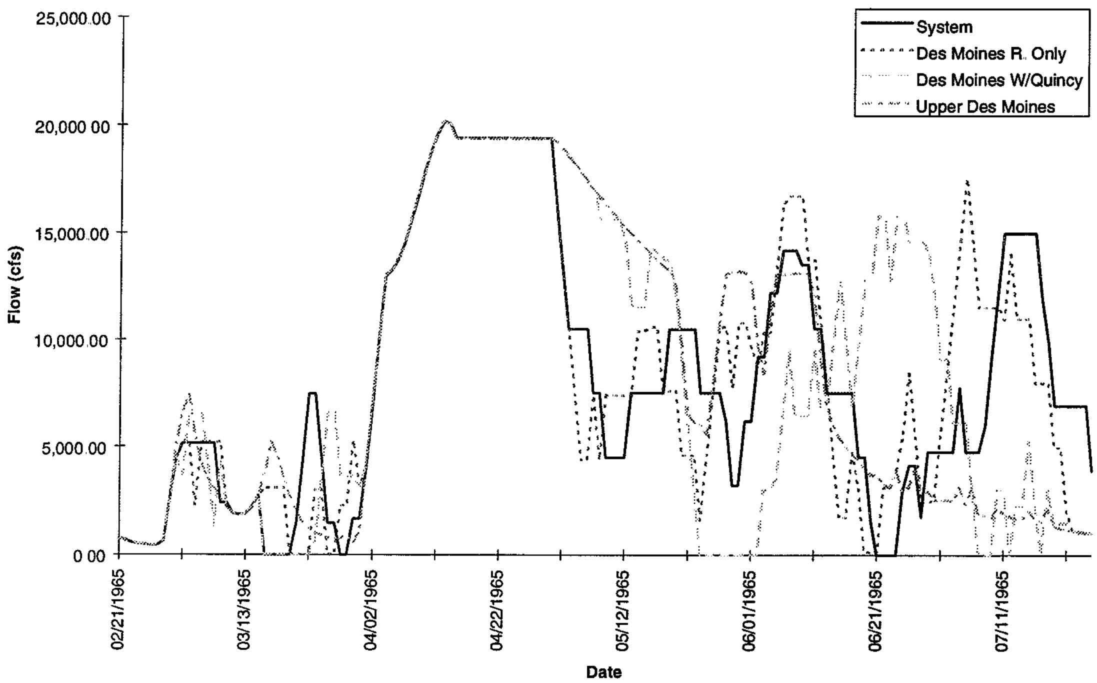

FIGURE E-4g. Model Results of Saylorville Reservoir Release - Flood of 1965

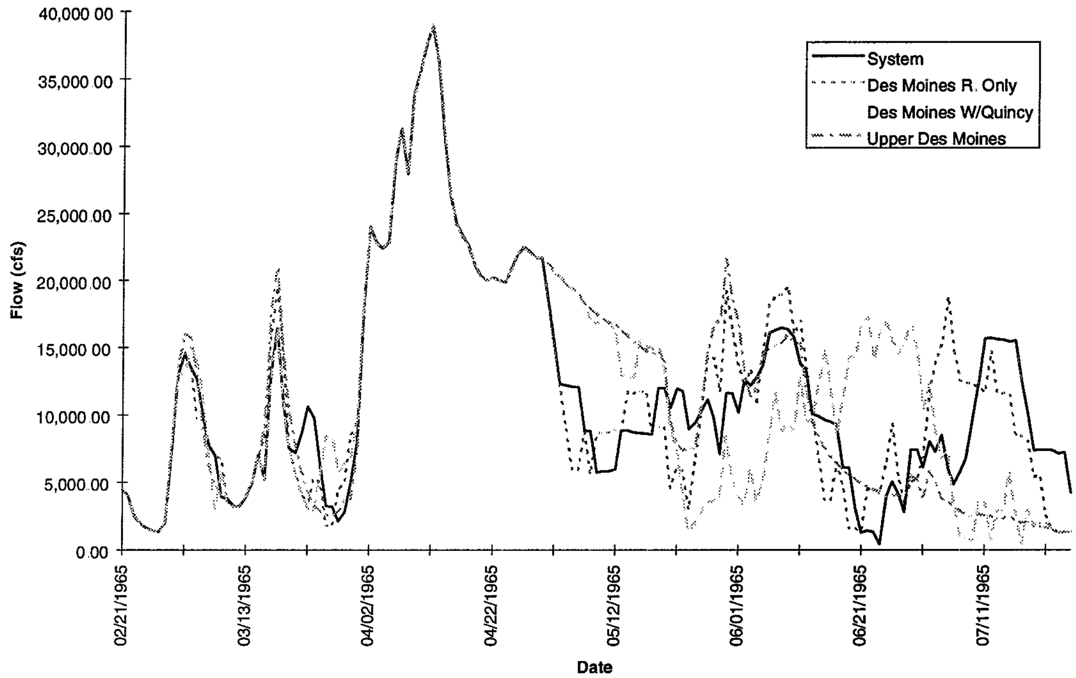

FIGURE E-4h. Hydrograph of Model Results at 14th Street - Flood of 1965

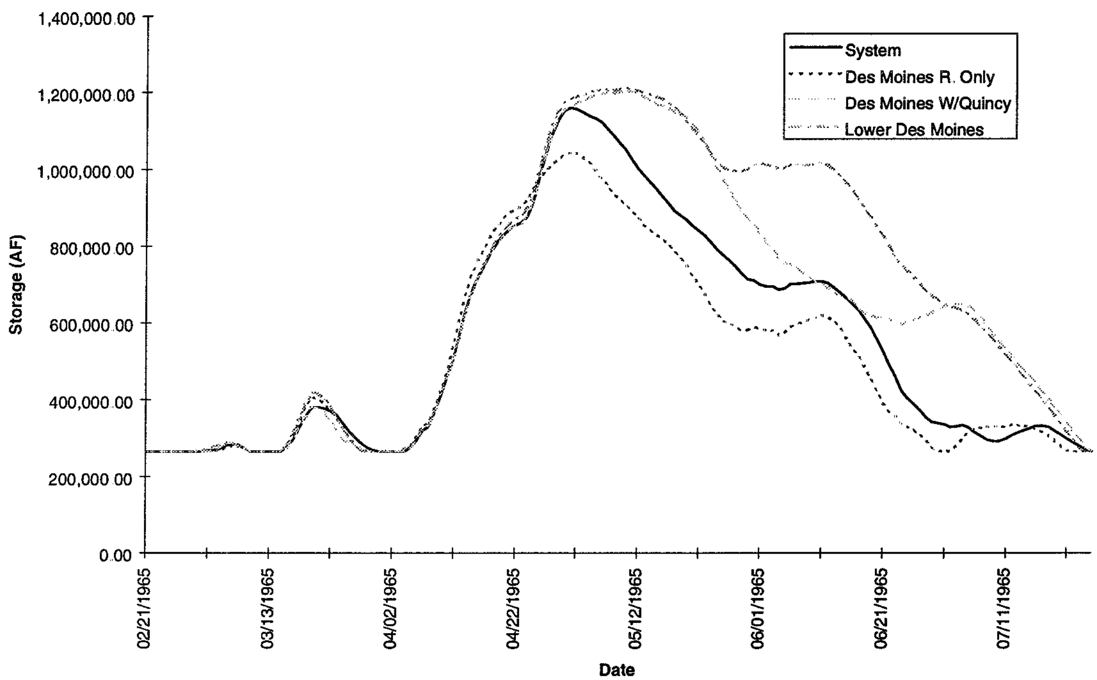

FIGURE E-4i. Model Results of Lake Red Rock Storage - Flood of 1965

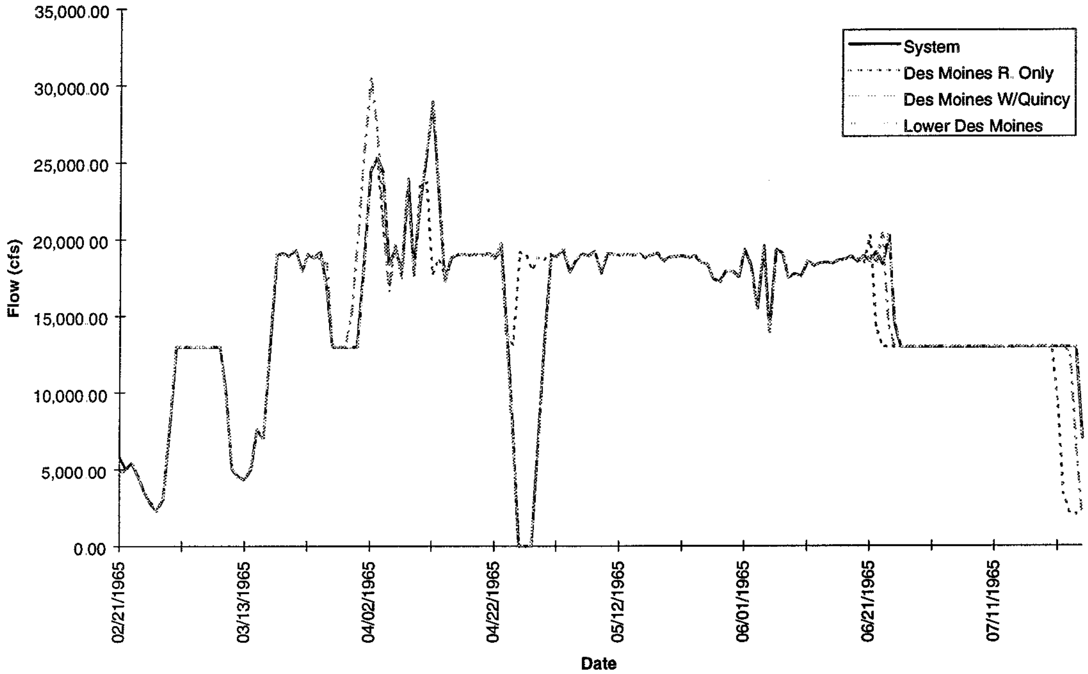

FIGURE E-4j. Model Results of Lake Red Rock Release - Flood of 1965

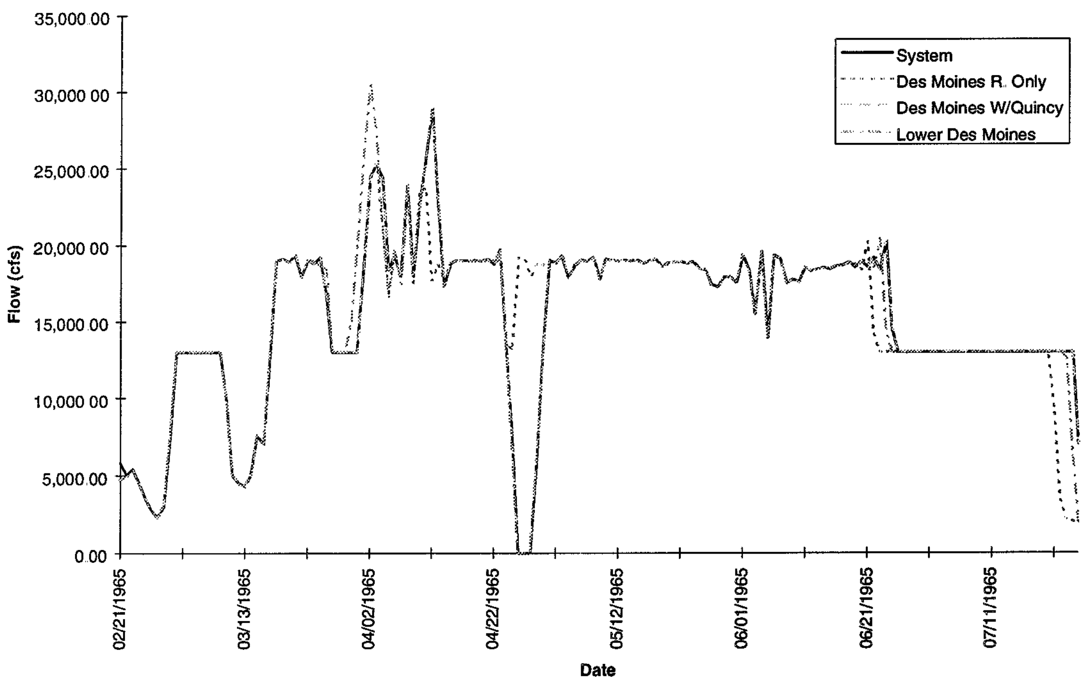

FIGURE E-4k. Hydrograph of Model Results at Tracy - Flood of 1965

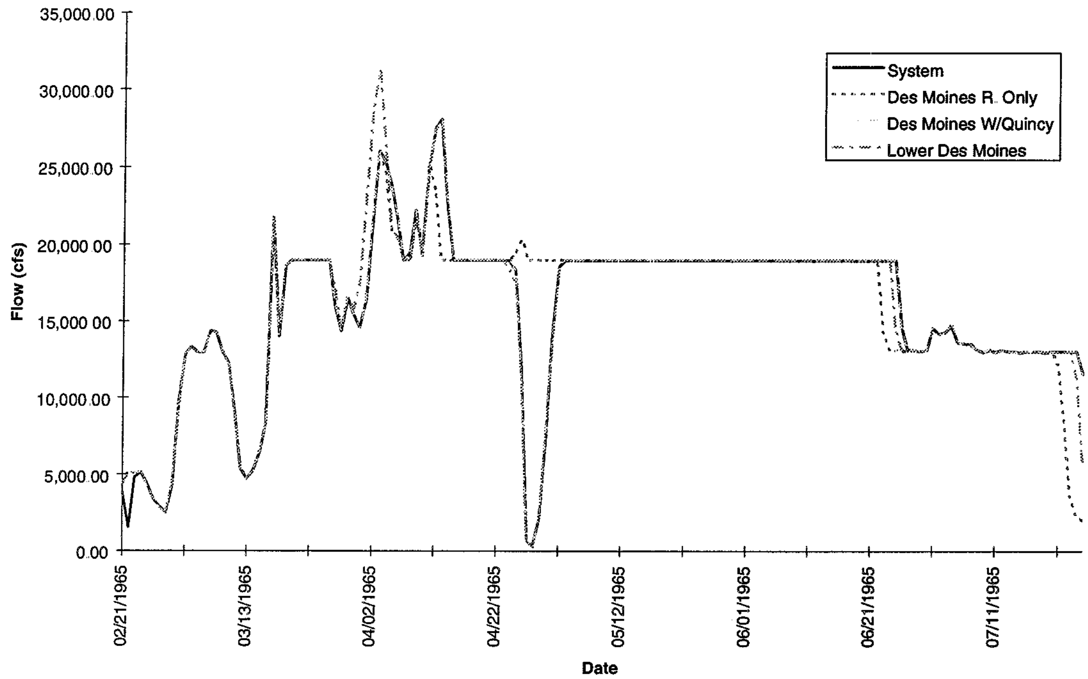

FIGURE E-4l. Hydrograph of Model Results at Ottumwa - Flood of 1965

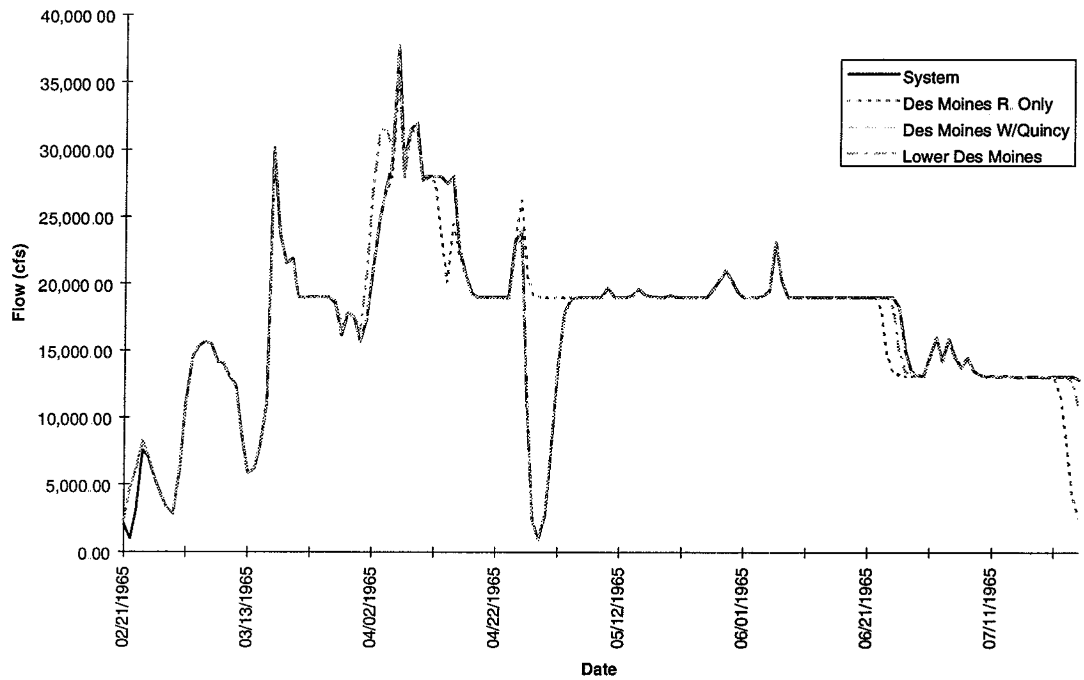

FIGURE E-4m. Hydrograph of Model Results at Keosauqua - Flood of 1965

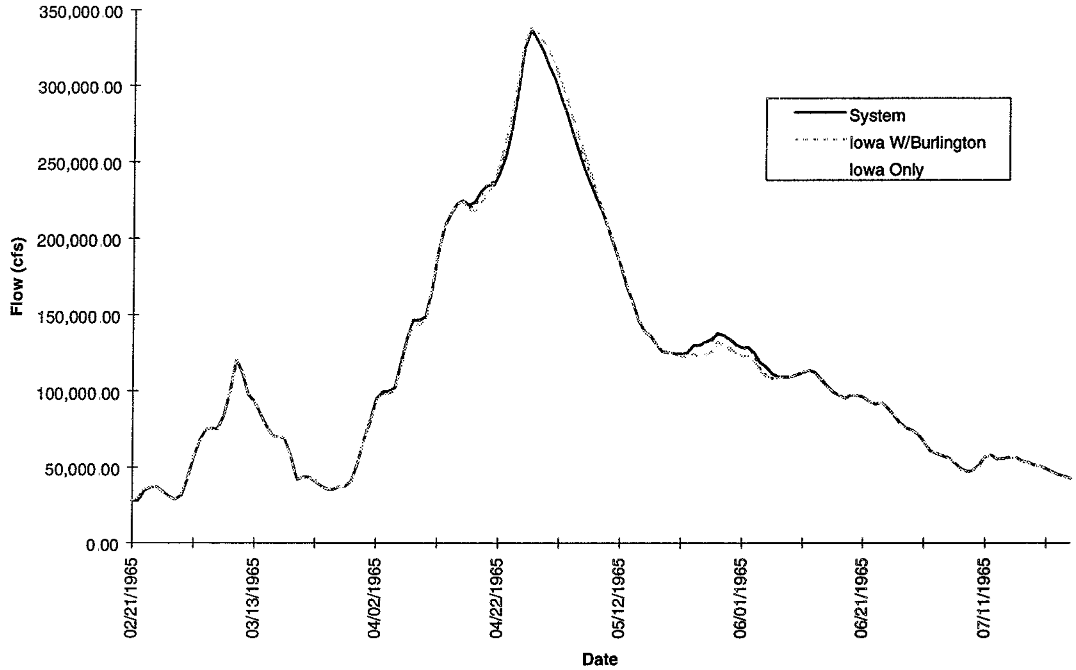

FIGURE E-4n. Hydrograph of Model Results at Burlington - Flood of 1965

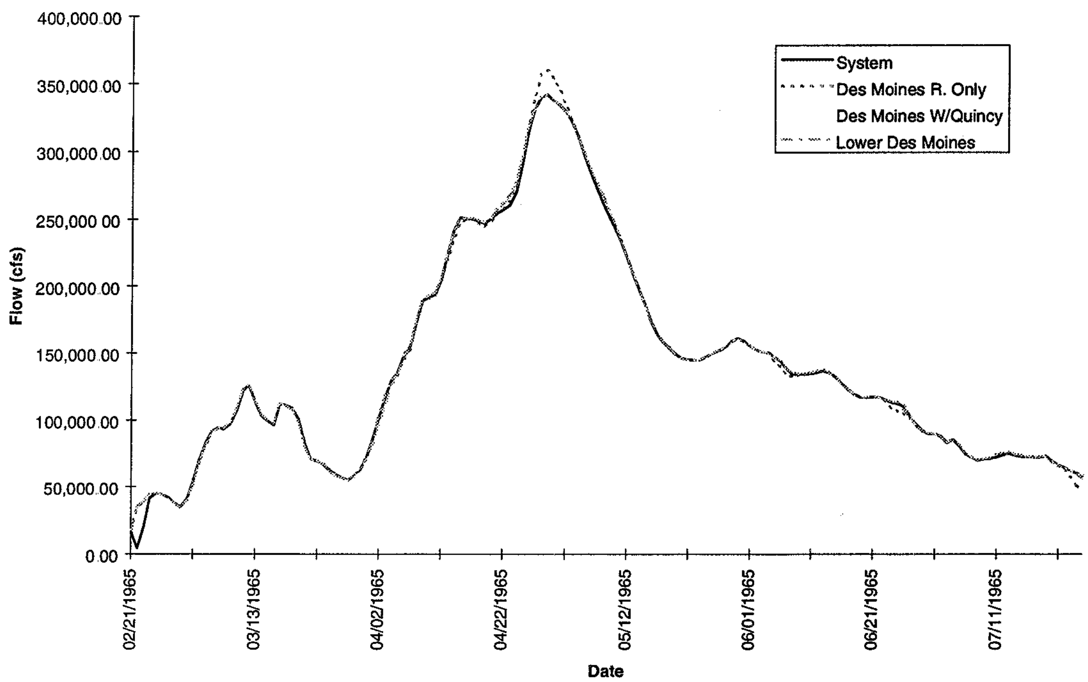

FIGURE E-4o. Hydrograph of Model Results at Quincy - Flood of 1965

1973 COMMENTARY

Model results from the flood of 1973 show peak-related damages to be practically identical on the Iowa River for the various system configurations, as seen in Table E-5. Small variations occur in how the model operates Coralville Reservoir, which lead to minor differences in the model-computed penalty.

On the other hand, there is a significant difference in damage depending on whether or not the reservoirs on the Des Moines River are operated in tandem. When Saylorville Reservoir is not operated for control downstream of Lake Red Rock, damaging releases are made from Lake Red Rock at the beginning of the event (Figure E-5j), while Saylorville Reservoir's flood pool is underutilized (Figure E-5f). When the reservoirs are operated in tandem, Saylorville Reservoir's flood pool is used more, which prevents these damaging releases.

TABLE E-5. Flood of 1973 Calculated Penalties

	Peak Flow Damage ($1000)							
Site	Observed	A	BD	CD	BE	CE	BFG	CFG
Iowa City	36	-	-	-	-	-	-	-
Lone Tree	43	34	34	34	34	34	34	34
Wapello	6,866	6,679	6,681	6,681	6,681	6,681	6,681	6,681
2nd Ave.	15,851	-	-	-	-	-	-	-
14th St.	-	-	-	-	-	-	-	-
Tracy	1,382	1,364	1,364	1,364	1,366	1,366	2,866	2,866
Ottumwa	2,808	2,103	2,103	2,103	2,040	2,040	5,545	5,545
Keosauqua	844	654	654	654	654	654	654	654
Burlington	601	596	596	596	596	596	596	596
Quincy	12,290	6,818	6,825	6,825	6,902	6,902	6,850	6,850
Total	40,721	18,249	18,257	18,257	18,274	18,274	23,226	23,226

	Model-Computed Flow Penalty ($1000)							
Site	Observed	A	BD	CD	BE	CE	BFG	CFG
Iowa City	167	-	-	-	-	-	-	-
Lone Tree	79	34	34	34	34	34	34	34
Wapello	23,394	21,392	21,329	21,990	21,329	21,990	21,329	21,990
2nd Ave.	40,017	-	-	-	-	-	-	-
14th St.	-	-	-	-	-	-	-	-
Tracy	89,487	57,897	57,872	57,872	57,767	57,767	79,158	79,158
Ottumwa	94,392	26,579	26,579	26,579	26,335	26,335	76,168	76,168
Keosauqua	6,223	3,065	3,065	3,065	3,059	3,059	7,293	7,293
Burlington	13,929	14,057	14,125	14,376	14,125	14,376	14,125	14,376
Quincy	30,173	18,859	19,559	19,693	19,853	19,988	19,805	19,998
Coralville		4,321	4,149	3,332	4,149	3,332	4,149	3,332
Saylorville		52,032	54,300	62,109	53,096	53,096	2,515	2,515
Red Rock		192,294	190,009	182,200	191,467	191,467	167,791	167,805
Total w/o stor.	297,862	141,884	142,563	143,610	142,504	143,550	217,913	219,018
Total w/ stor.		390,530	391,021	391,250	391,216	391,445	392,368	392,670

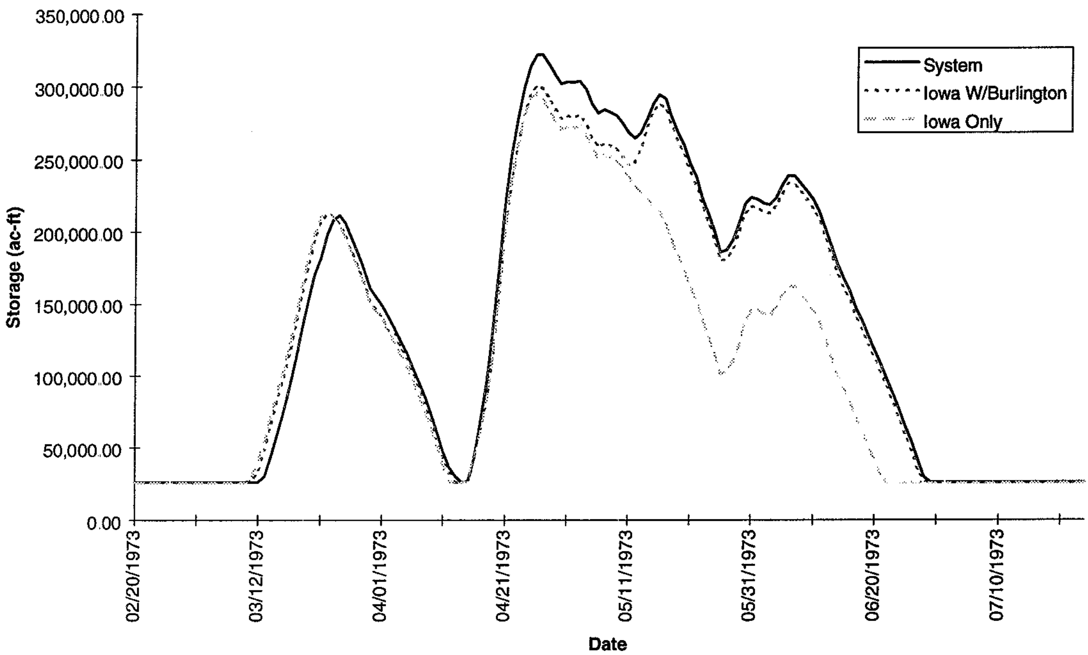

FIGURE E-5a. Model Results of Coralville Reservoir Storage - Flood of 1973

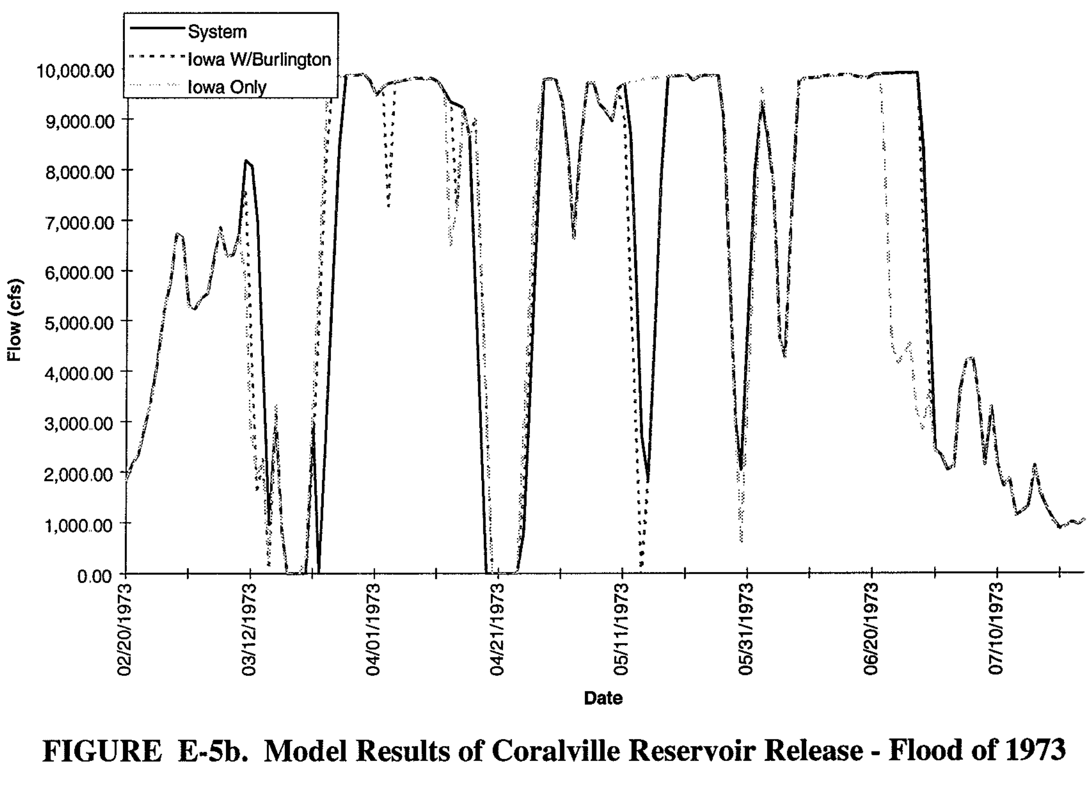

FIGURE E-5b. Model Results of Coralville Reservoir Release - Flood of 1973

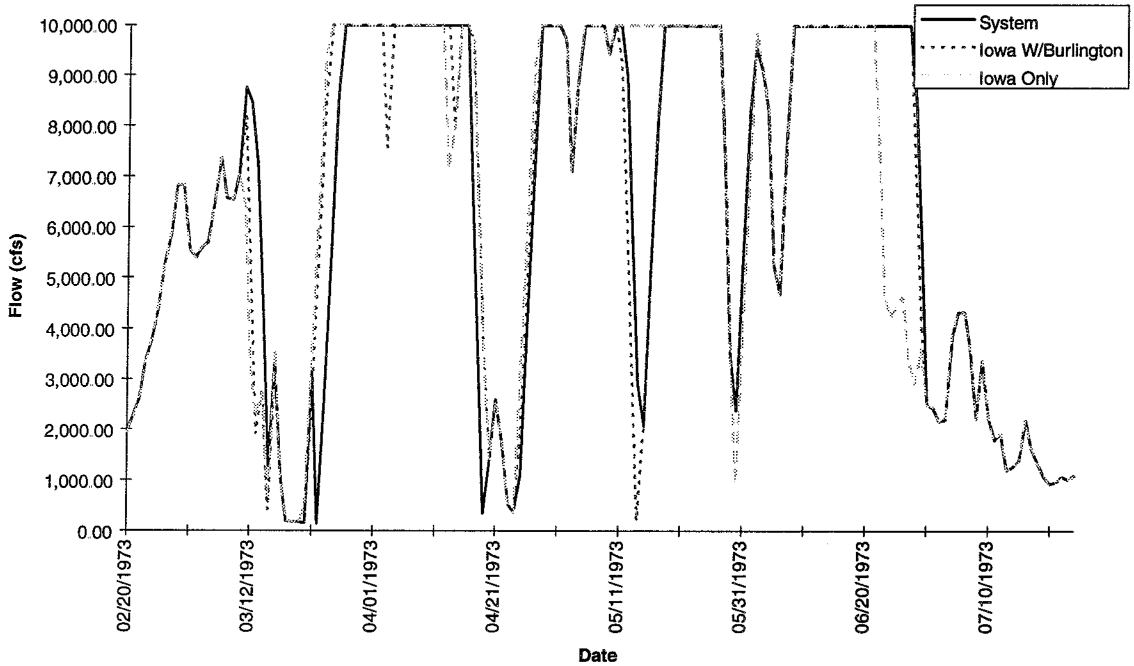

FIGURE E-5c. Hydrograph of Model Results at Iowa City - Flood of 1973

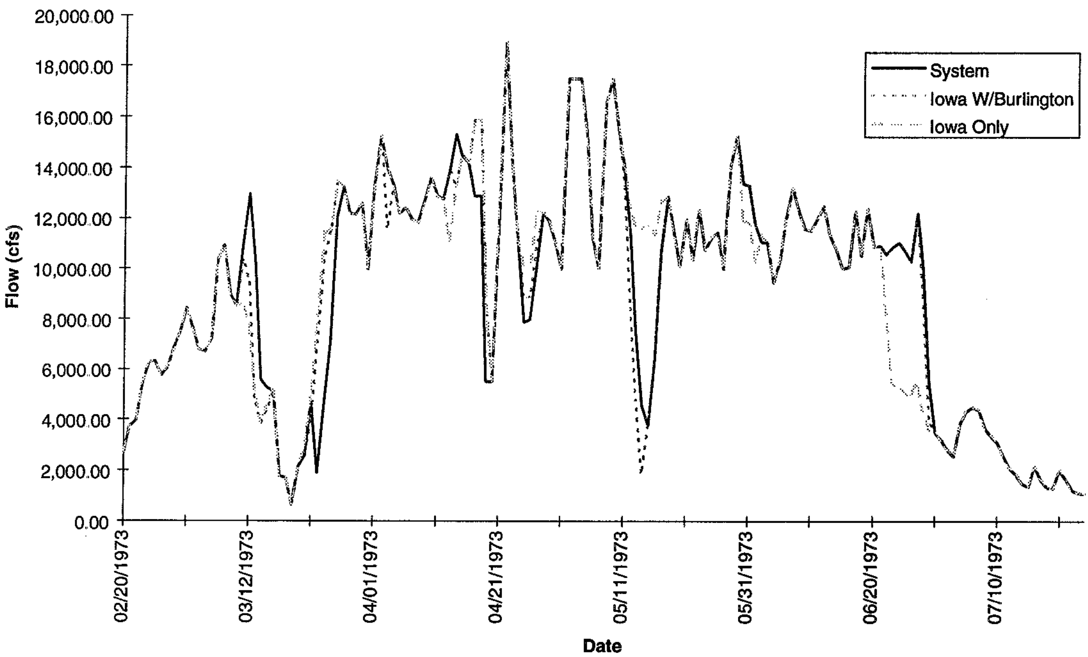

FIGURE E-5d. Hydrograph of Model Results at Lone Tree - Flood of 1973

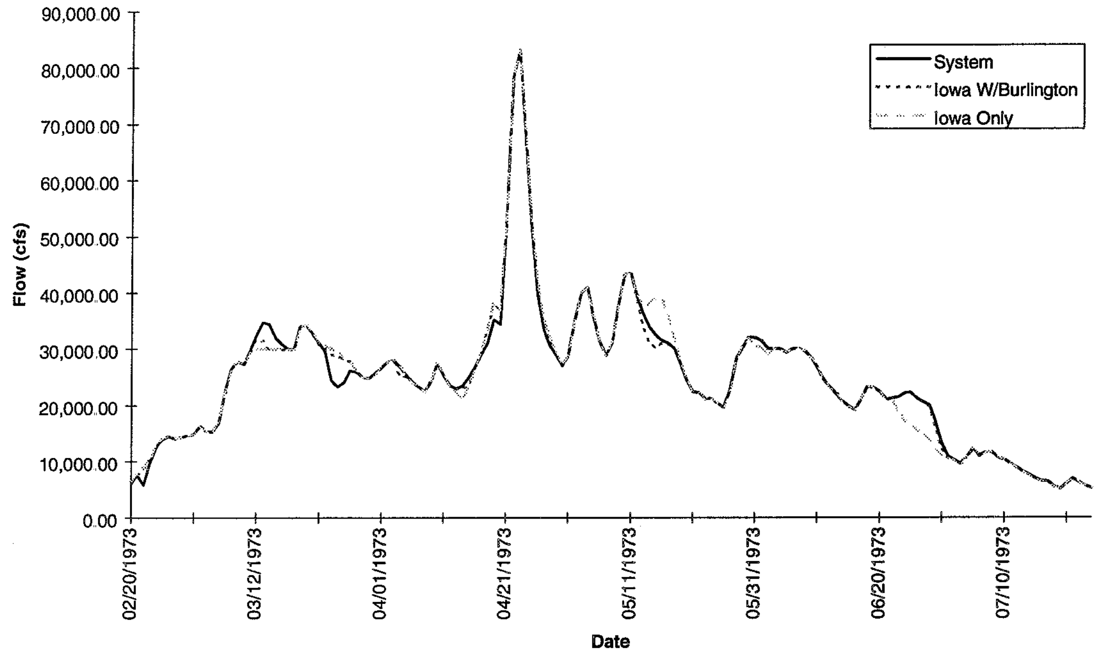

FIGURE E-5e. Hydrograph of Model Results at Wapello - Flood of 1973

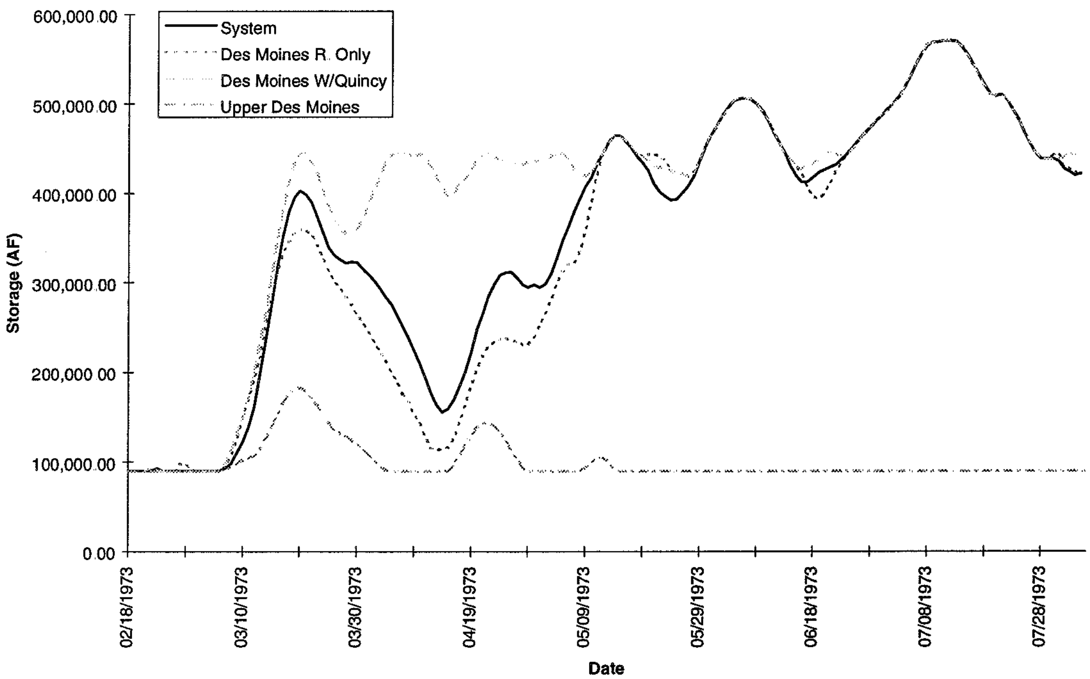

FIGURE E-5f. Model Results of Saylorville Reservoir Storage - Flood of 1973

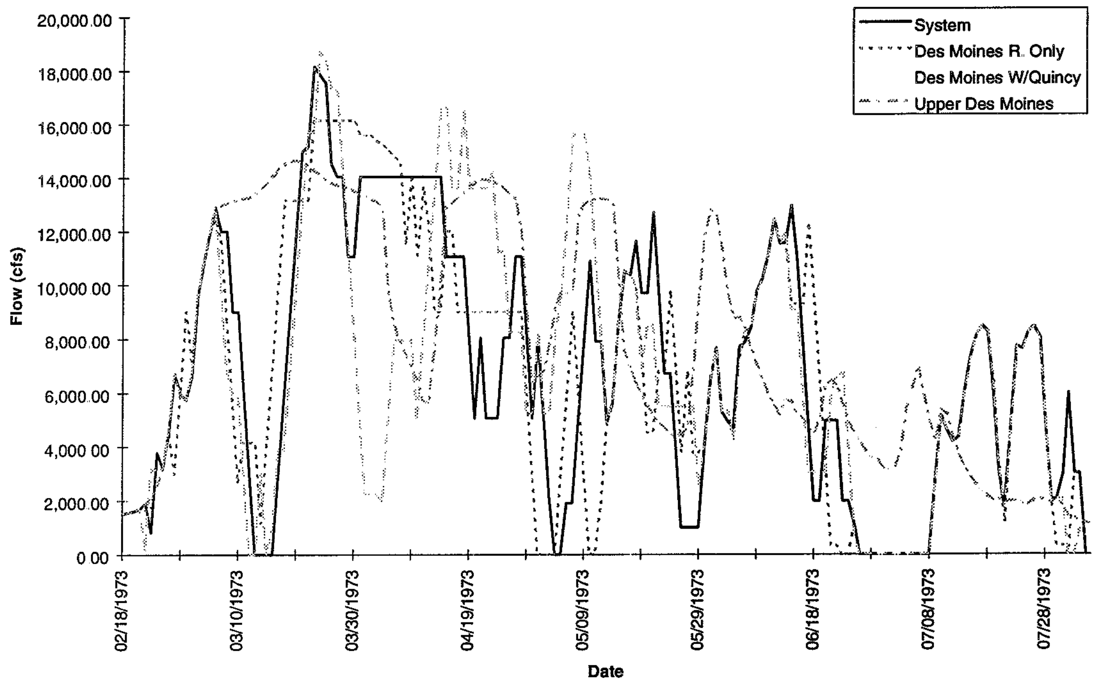

FIGURE E-5g. Model Results of Saylorville Reservoir Release - Flood of 1973

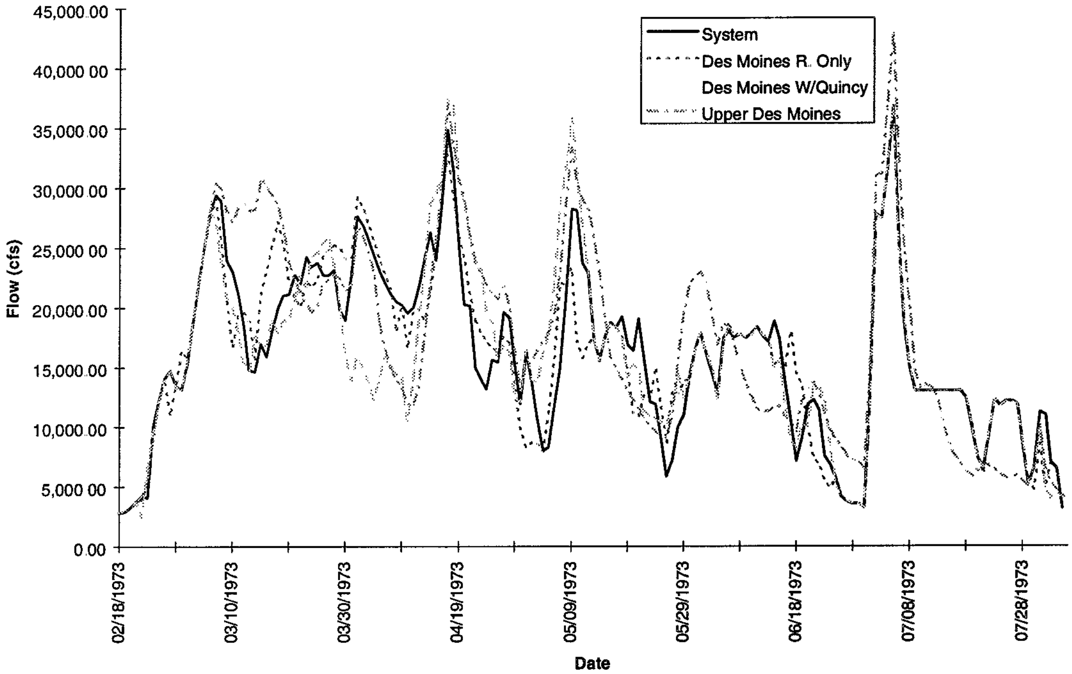

FIGURE E-5h. Hydrograph of Model Results at 14th Street - Flood of 1973

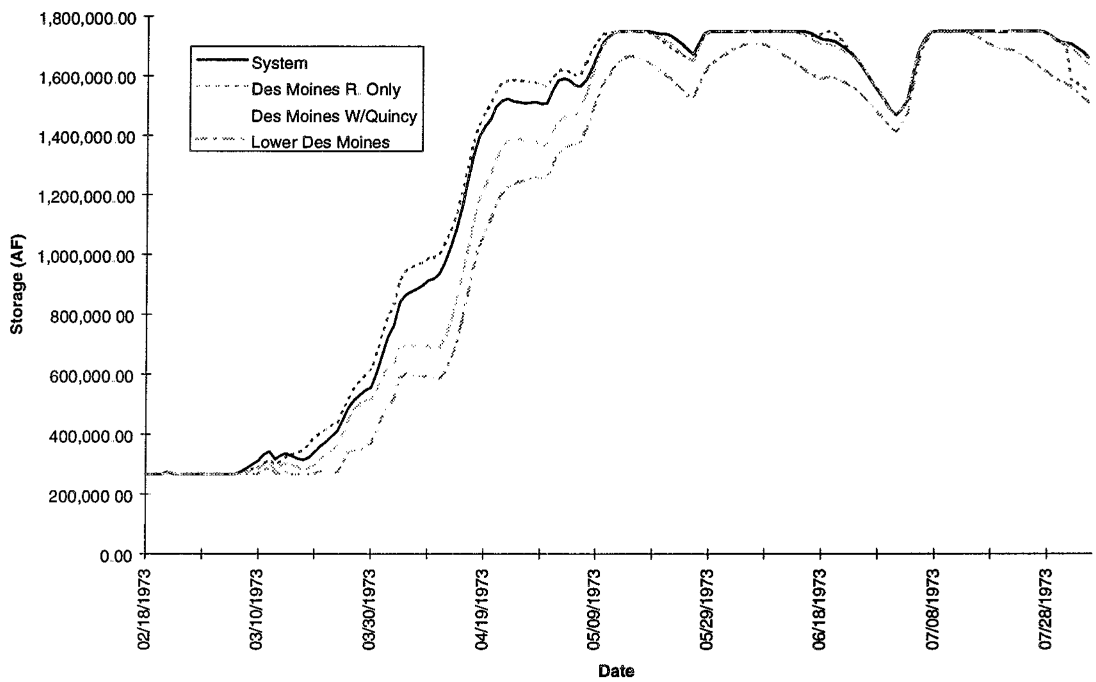

FIGURE E-5i. Model Results of Lake Red Rock Storage - Flood of 1973

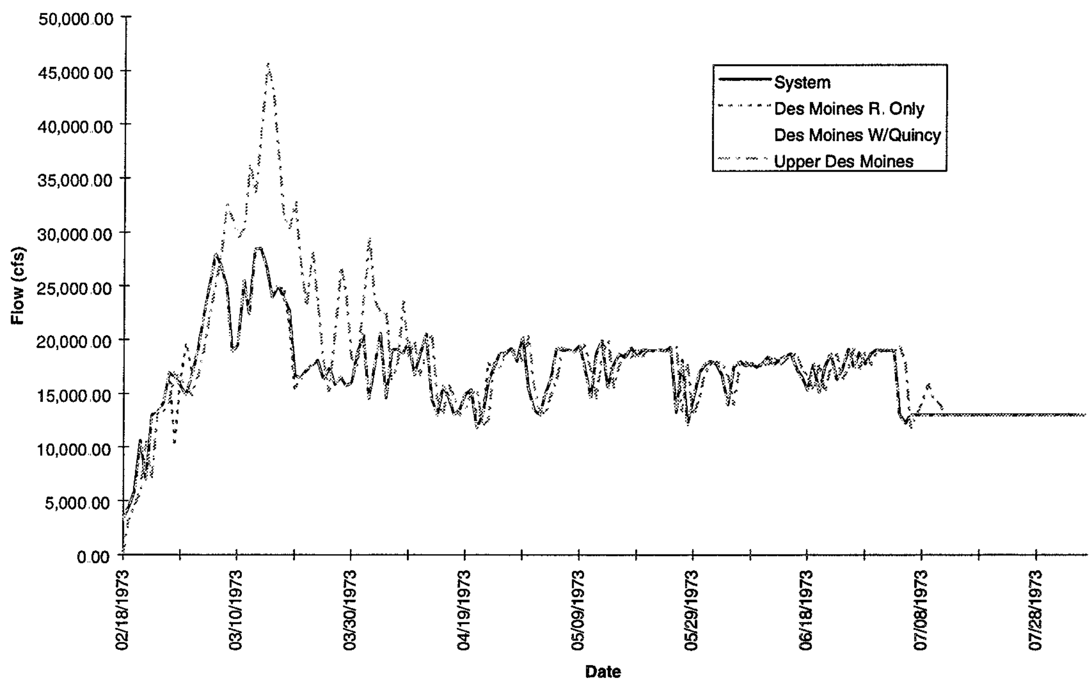

FIGURE E-5j. Model Results of Lake Red Rock Release - Flood of 1973

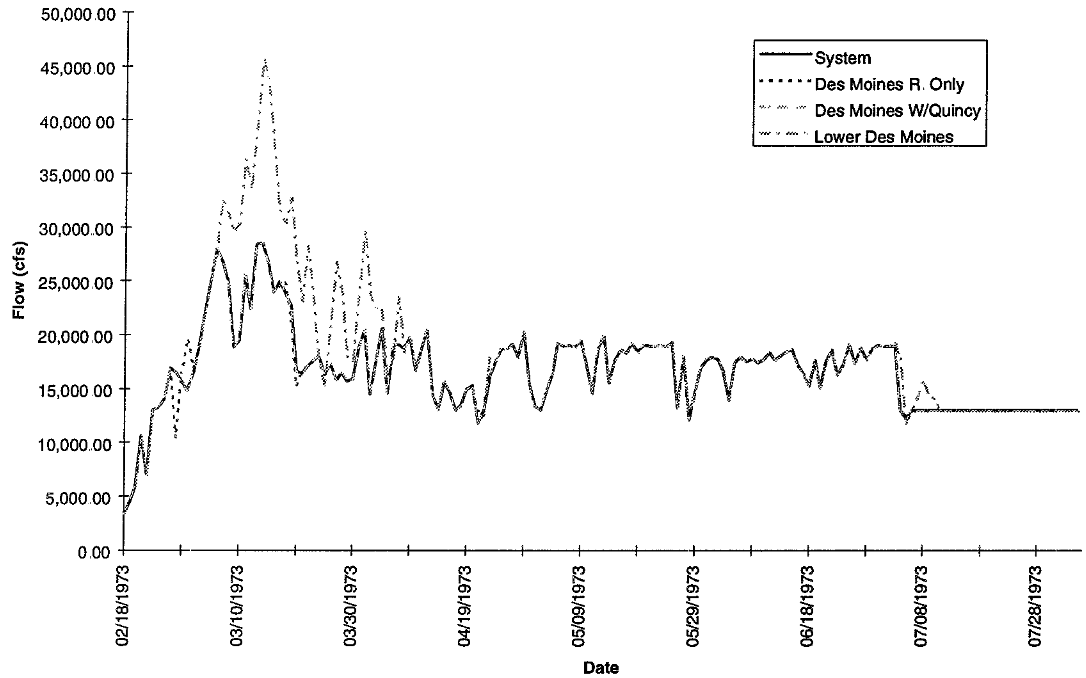

FIGURE E-5k. Hydrograph of Model Results at Tracy - Flood of 1973

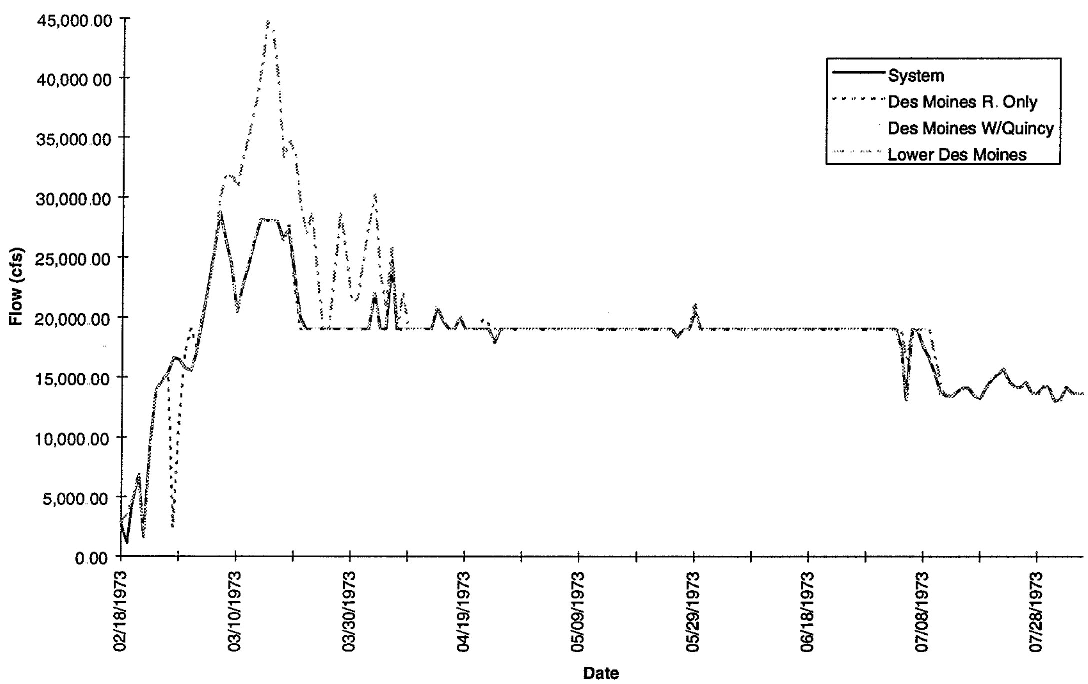

FIGURE E-5l. Hydrograph of Model Results at Ottumwa - Flood of 1973

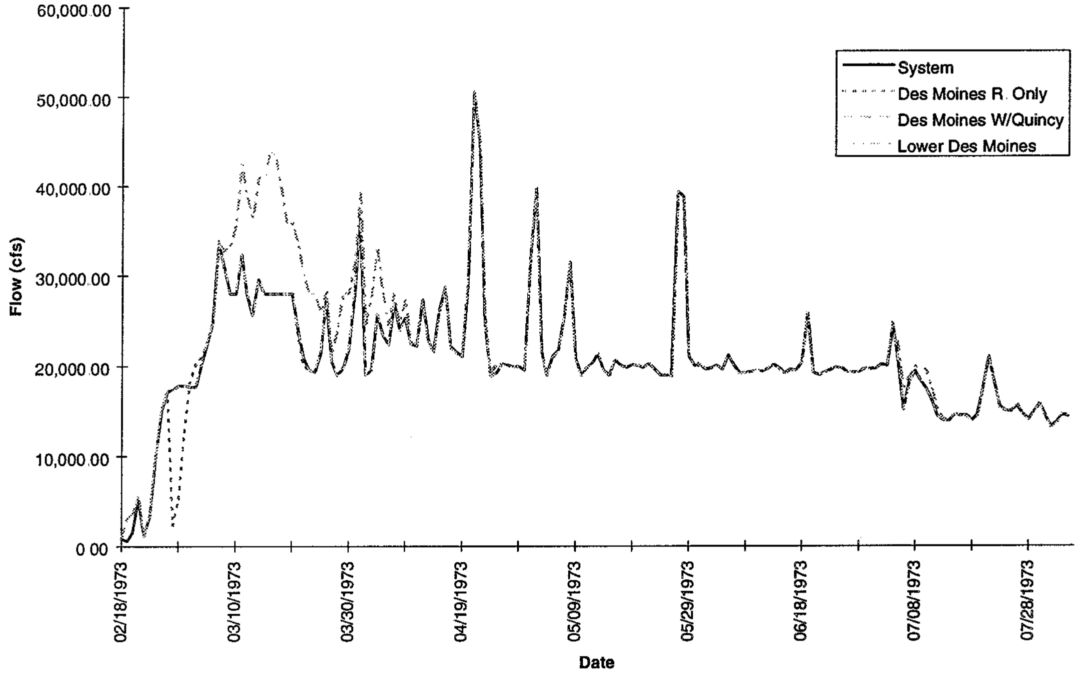

FIGURE E-5m. Hydrograph of Model Results at Keosauqua - Flood of 1973

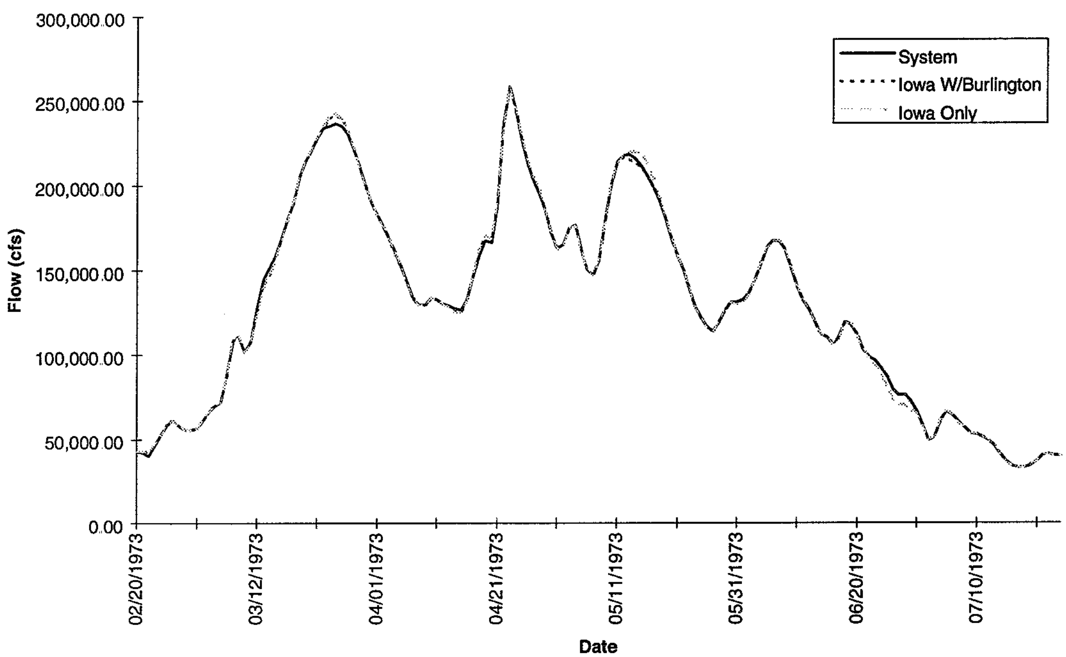

FIGURE E-5n. Hydrograph of Model Results at Burlington - Flood of 1973

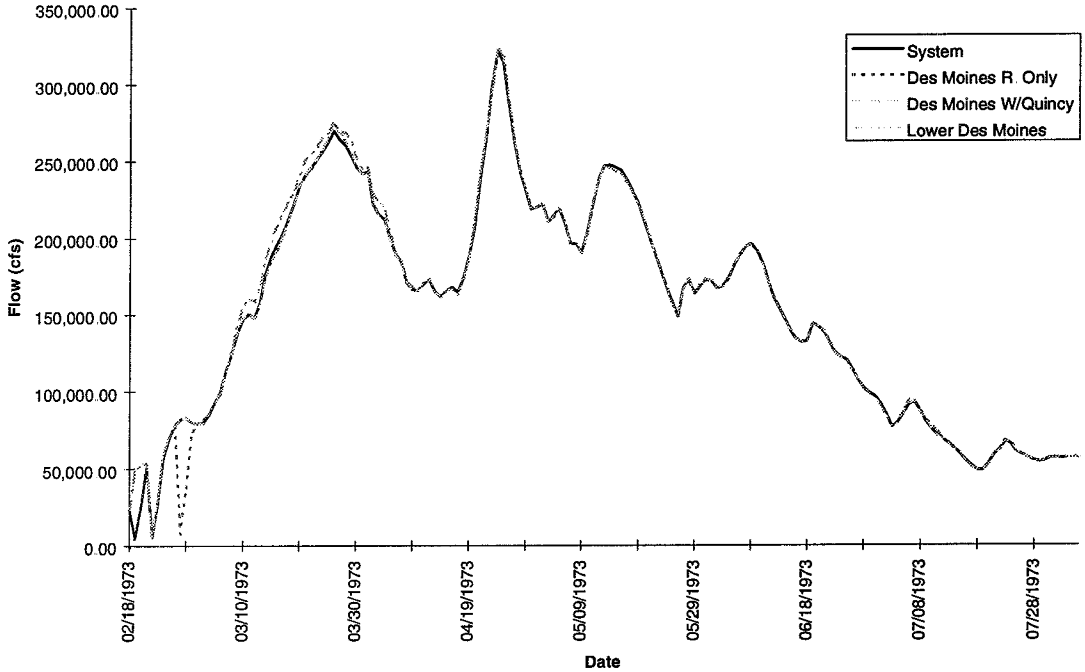

FIGURE E-5o. Hydrograph of Model Results at Quincy - Flood of 1973

1974 COMMENTARY

The flood of 1974 was one of the smaller events studied. The only difference in peak-related damage results depends on whether or not the model was operating for flood control at Burlington on the Mississippi River. This flood damage reduction is minor ($4,000), and the actual difference in operation of Coralville Reservoir is negligible, as illustrated by plots of storage and release for Coralville Reservoir (Figures E-6a and E-6b).

All flows on the Des Moines River downstream of Lake Red Rock are identical for the different operating schemes. Releases from Saylorville Reservoir vary only to minimize the persuasion penalty on storage at Saylorville Reservoir and Lake Red Rock. Differences in storage penalties are most likely an indication of multiple optimal solutions.

TABLE E-6. Flood of 1974 Calculated Penalties

	Peak Flow Damage ($1000)							
Site	**Observed**	**A**	**BD**	**CD**	**BE**	**CE**	**BFG**	**CFG**
Iowa City	54	-	-	-	-	-	-	-
Lone Tree	314	203	203	203	203	203	203	203
Wapello	5,896	5,486	5,486	5,486	5,486	5,486	5,486	5,486
2nd Ave.	-	-	-	-	-	-	-	-
14th St.	-	-	-	-	-	-	-	-
Tracy	581	658	658	658	658	658	658	658
Ottumwa	1,642	1,368	1,368	1,368	1,368	1,368	1,368	1,368
Keosauqua	191	61	61	61	61	61	61	61
Burlington	308	272	272	277	272	277	272	277
Quincy	-	-	-	-	-	-	-	-
Total	8,987	8,048	8,048	8,052	8,048	8,052	8,048	8,052

	Model-Computed Flow Penalty ($1000)							
Site	**Observed**	**A**	**BD**	**CD**	**BE**	**CE**	**BFG**	**CFG**
Iowa City	293	-	-	-	-	-	-	-
Lone Tree	694	524	524	524	524	524	524	524
Wapello	14,594	13,139	13,139	13,216	13,139	13,216	13,139	13,216
2nd Ave.	-	-	-	-	-	-	-	-
14th St.	-	-	-	-	-	-	-	-
Tracy	27,887	25,203	25,203	25,203	25,203	25,203	25,203	25,203
Ottumwa	6,955	2,039	2,039	2,039	2,039	2,039	2,039	2,039
Keosauqua	386	140	140	140	140	140	140	140
Burlington	2,236	2,023	2,023	2,048	2,023	2,048	2,023	2,048
Quincy	-	-	-	-	-	-	-	-
Coralville		4,495	4,495	4,402	4,495	4,402	4,495	4,402
Saylorville		28,224	9,114	9,114	16,608	16,608	19	19
Red Rock		38,287	57,396	57,396	49,903	49,903	66,491	66,491
Total w/o stor.	53,044	43,067	43,067	43,169	43,067	43,169	43,067	43,169
Total w/ stor.		114,073	114,073	114,082	114,073	114,082	114,073	114,082

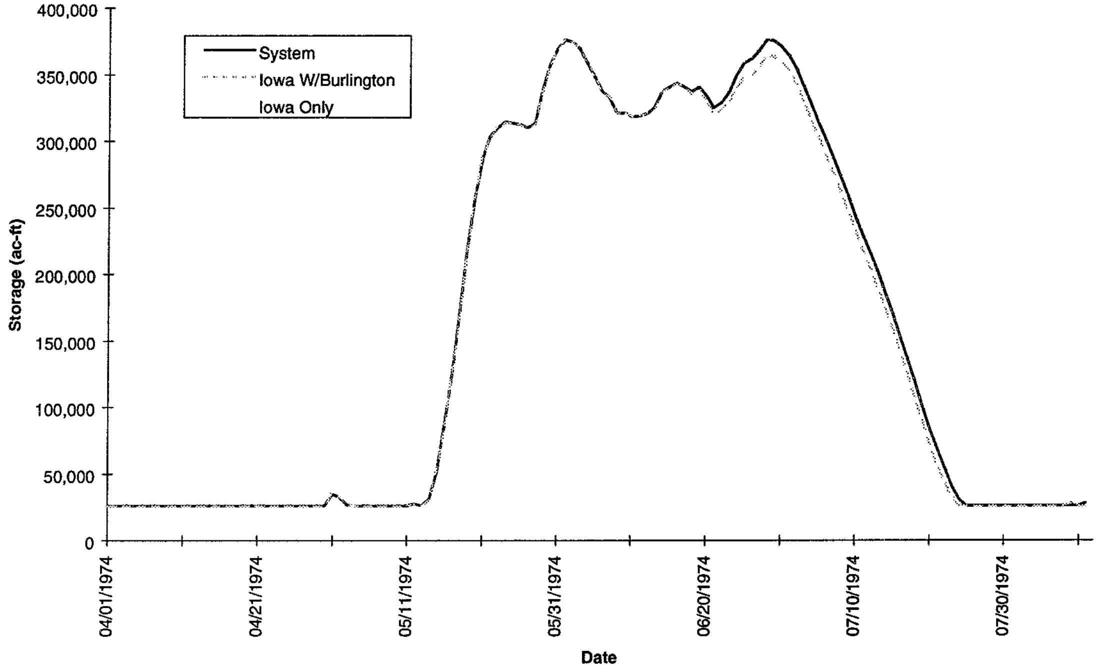

FIGURE E-6a. Model Results of Coralville Reservoir Storage - Flood of 1974

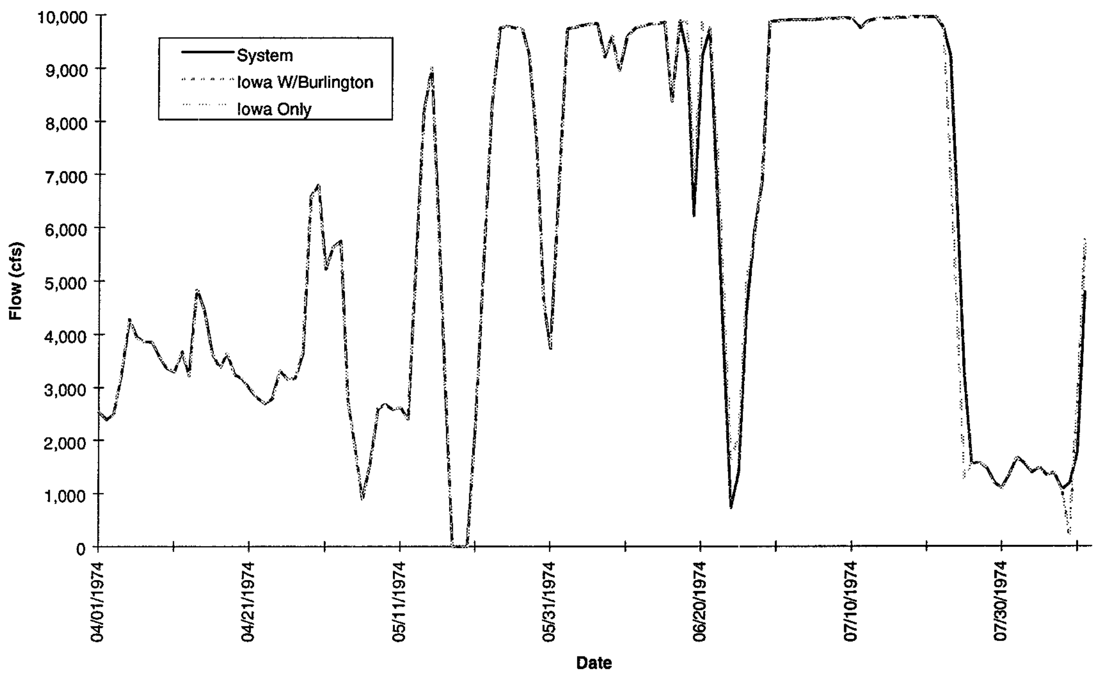

FIGURE E-6b. Model Results of Coralville Reservoir Release - Flood of 1974

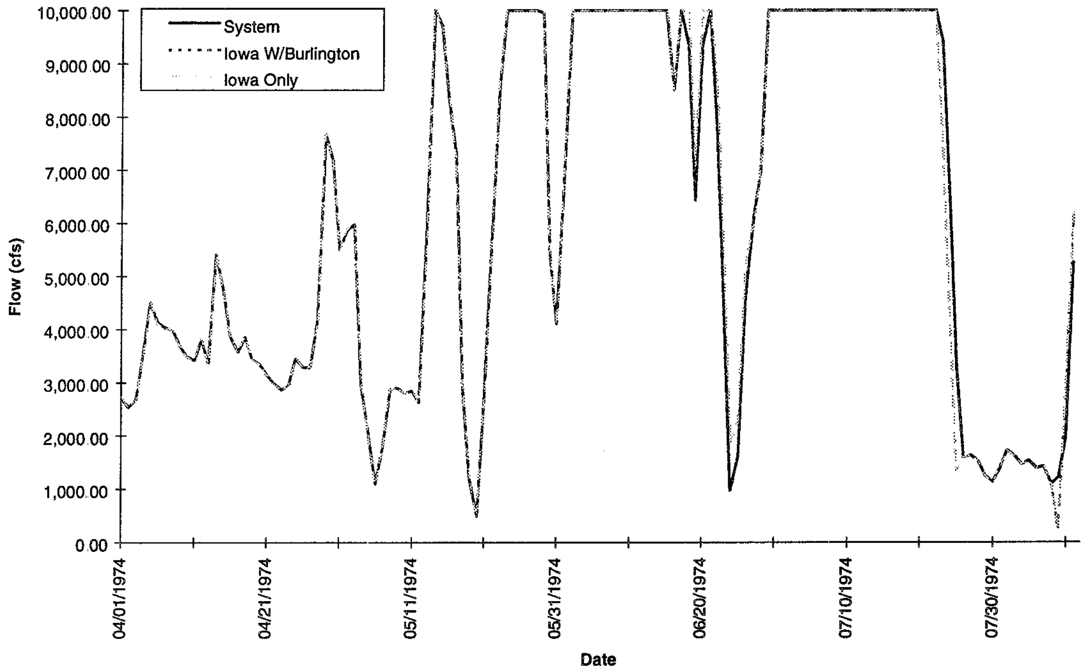

FIGURE E-6c. Hydrograph of Model Results at Iowa City - Flood of 1974

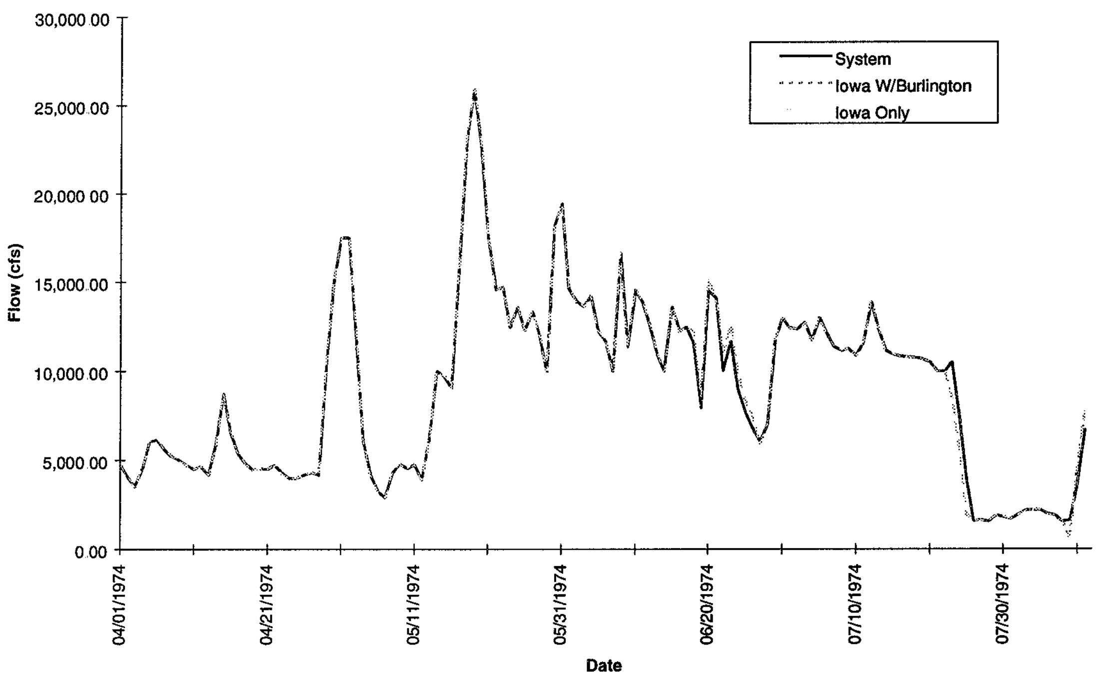

FIGURE E-6d. Hydrograph of Model Results at Lone Tree - Flood of 1974

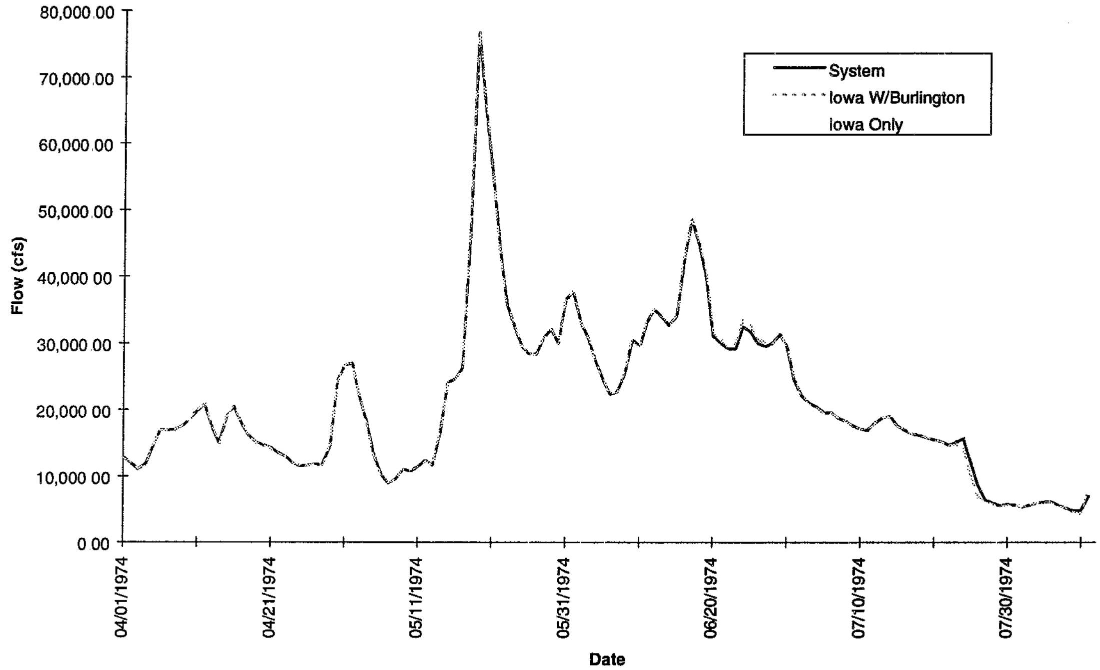

FIGURE E-6e. Hydrograph of Model Results at Wapello - Flood of 1974

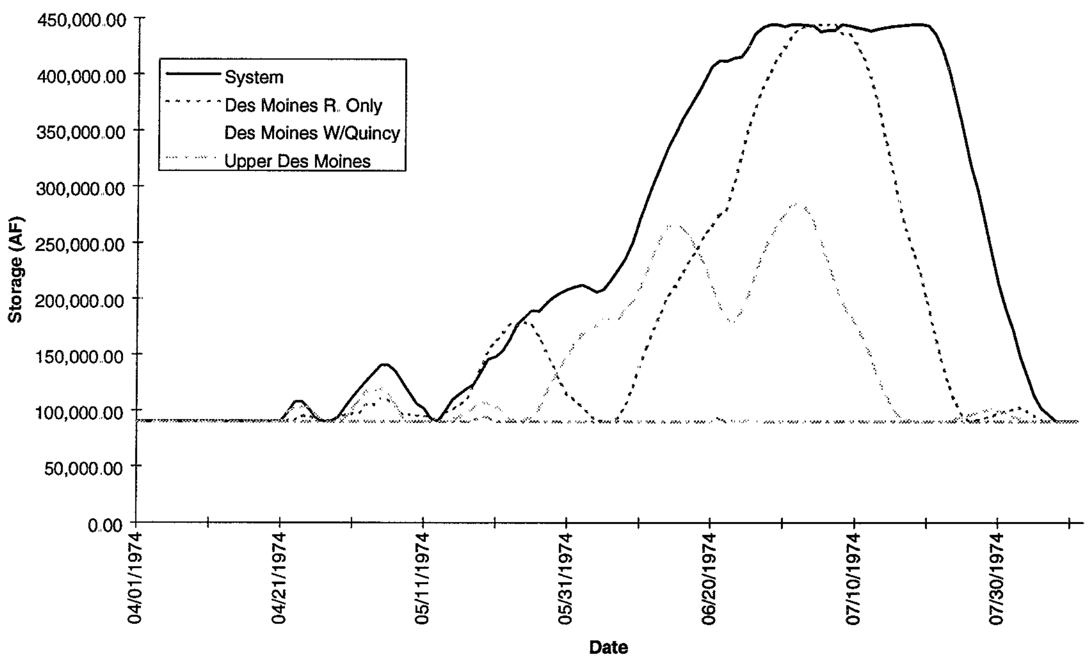

FIGURE E-6f. Model Results of Saylorville Reservoir Storage - Flood of 1974

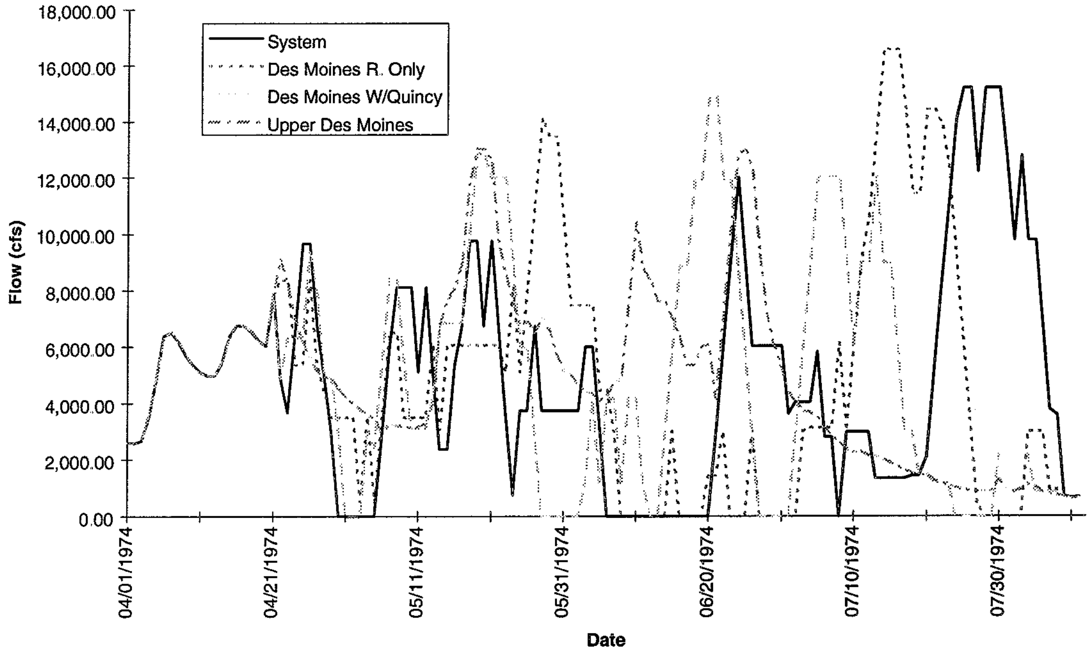

FIGURE E-6g. Model Results of Saylorville Reservoir Release - Flood of 1974

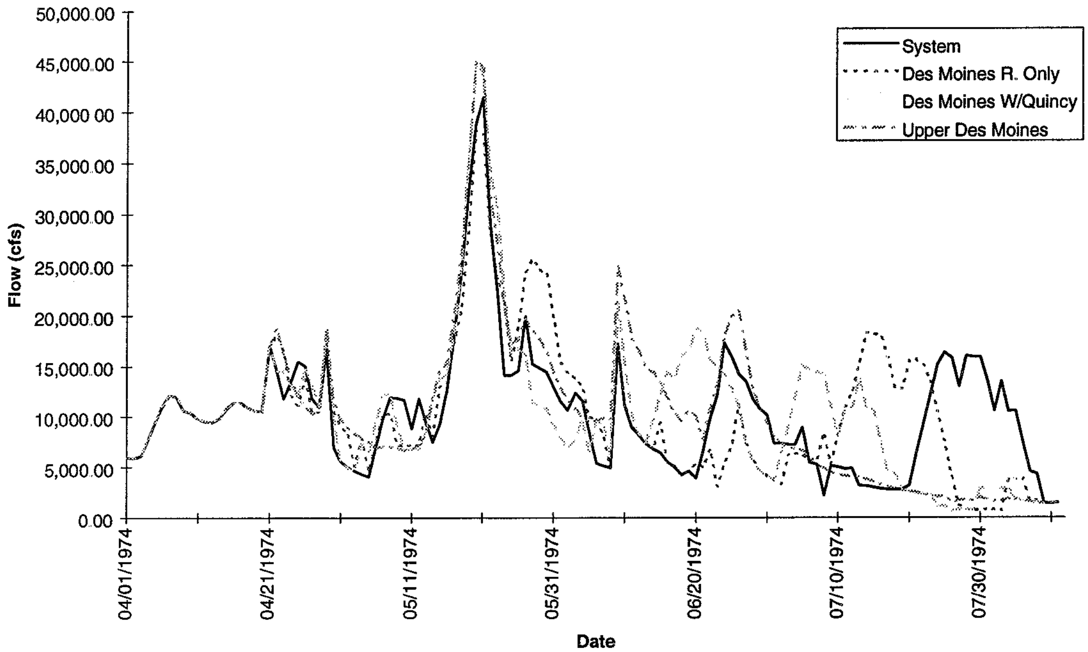

FIGURE E-6h. Hydrograph of Model Results at 14th Street - Flood of 1974

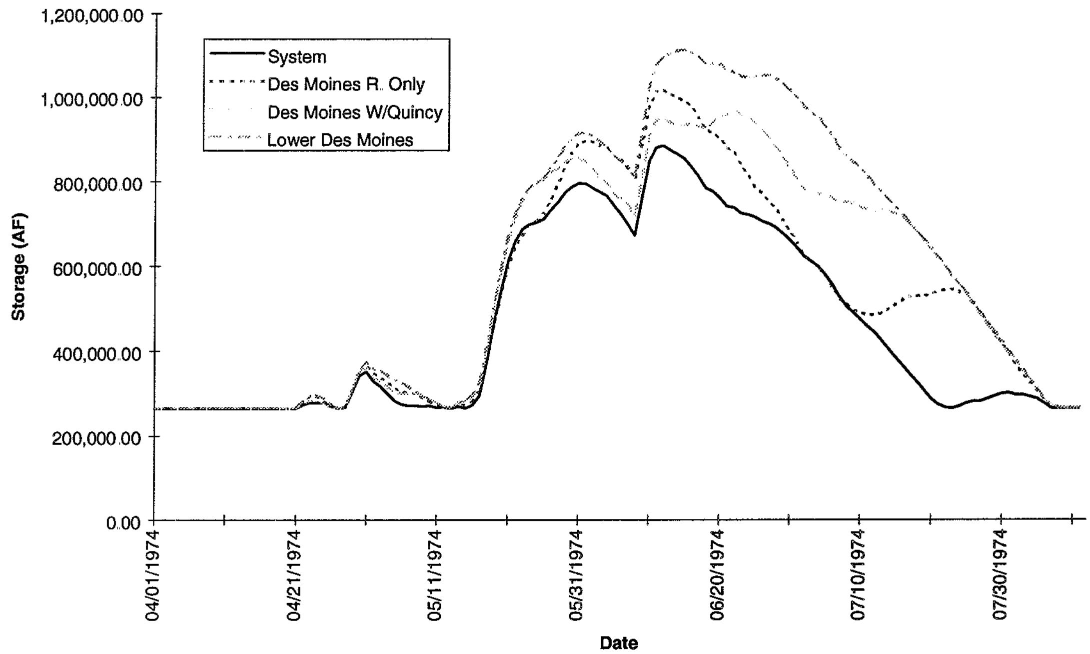

FIGURE E-6i. Model Results of Lake Red Rock Storage - Flood of 1974

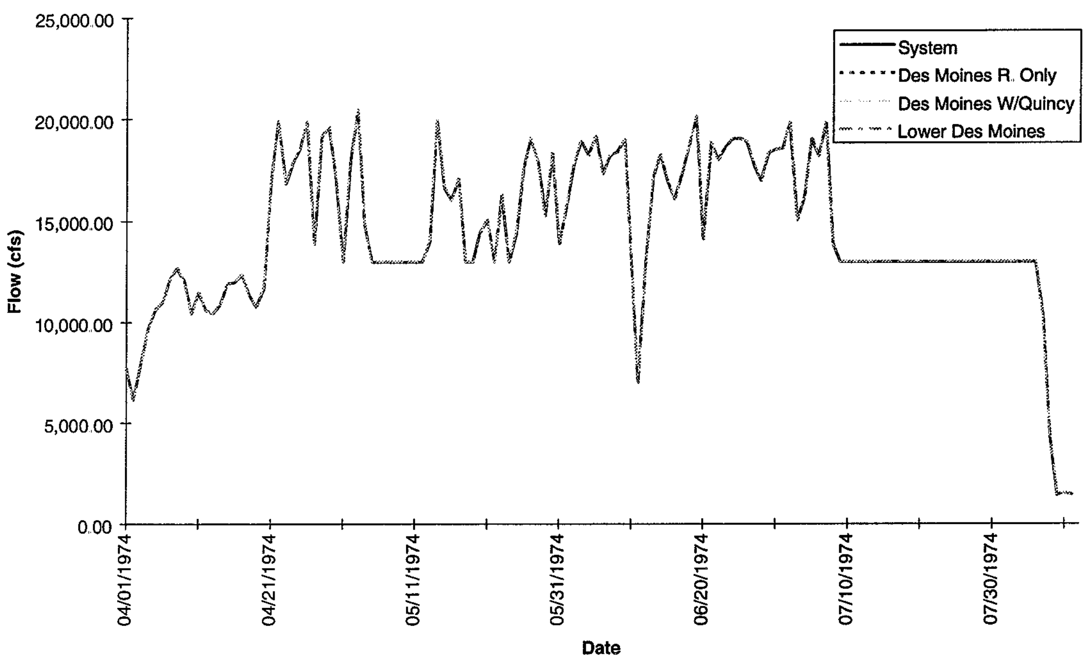

FIGURE E-6j. Model Results of Lake Red Rock Release - Flood of 1974

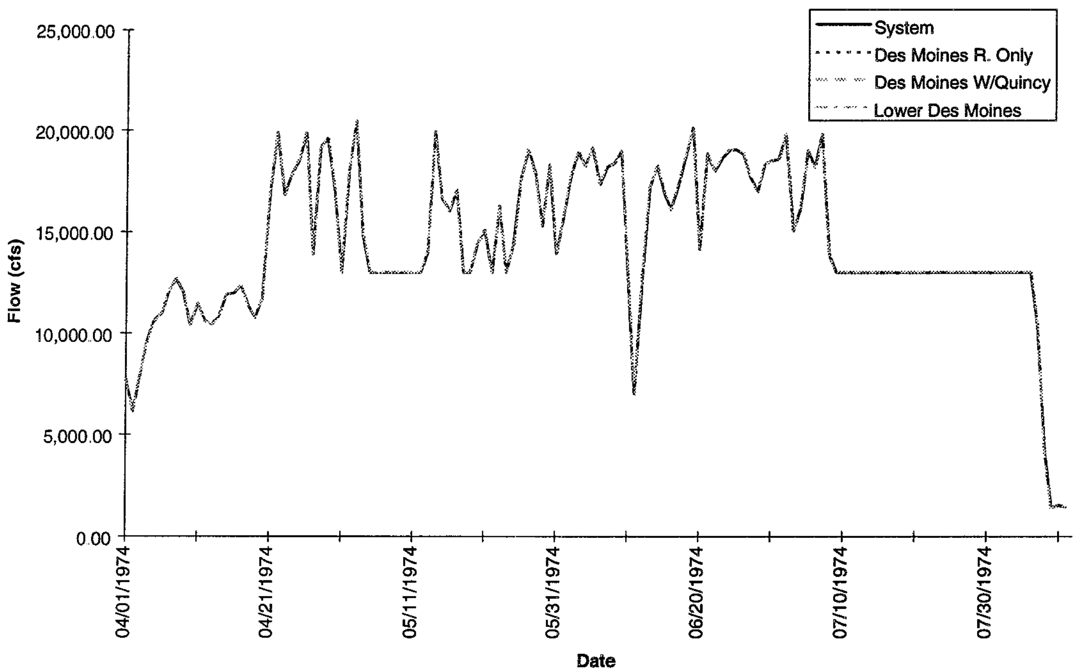

FIGURE E-6k. Hydrograph of Model Results at Tracy - Flood of 1974

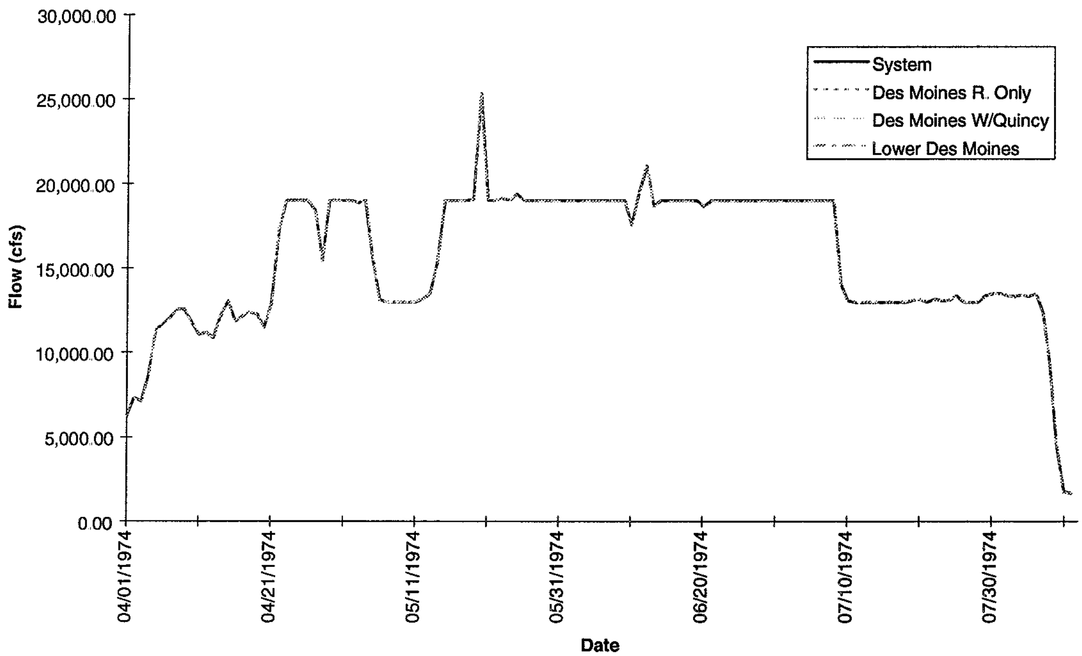

FIGURE E-6l. Hydrograph of Model Results at Ottumwa - Flood of 1974

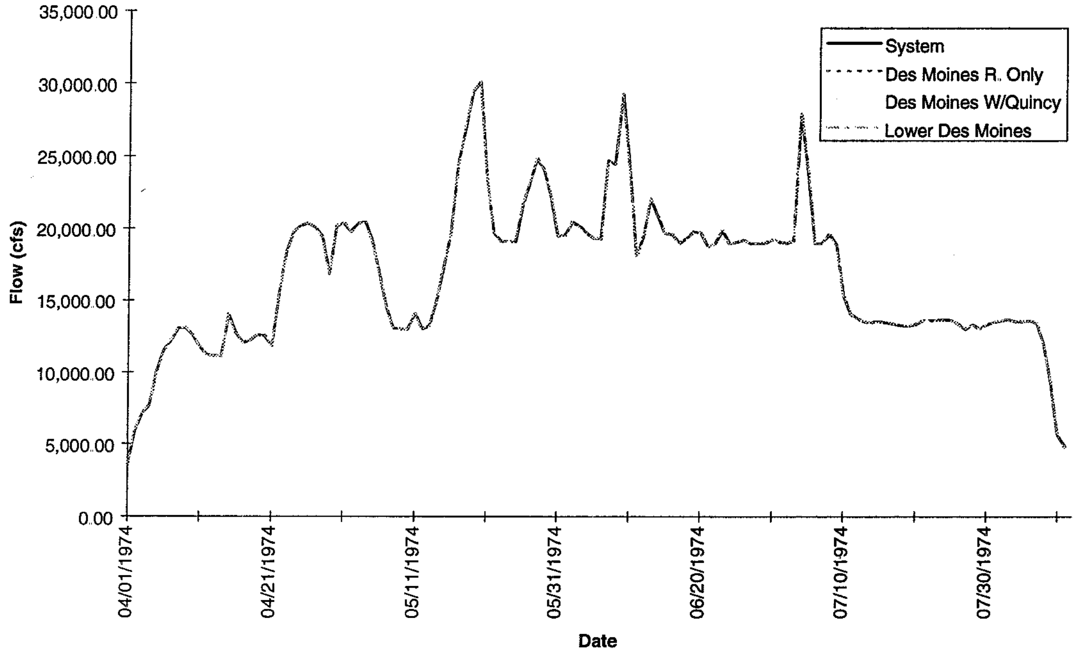

FIGURE E-6m. Hydrograph of Model Results at Keosauqua - Flood of 1974

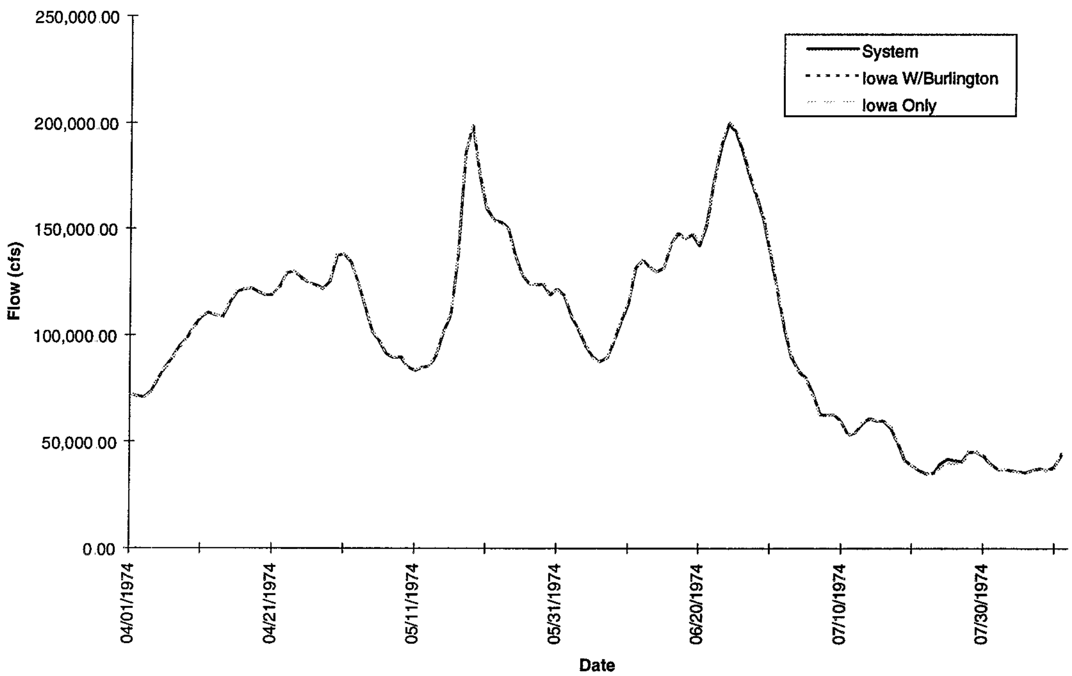

FIGURE E-6n. Hydrograph of Model Results at Burlington - Flood of 1974

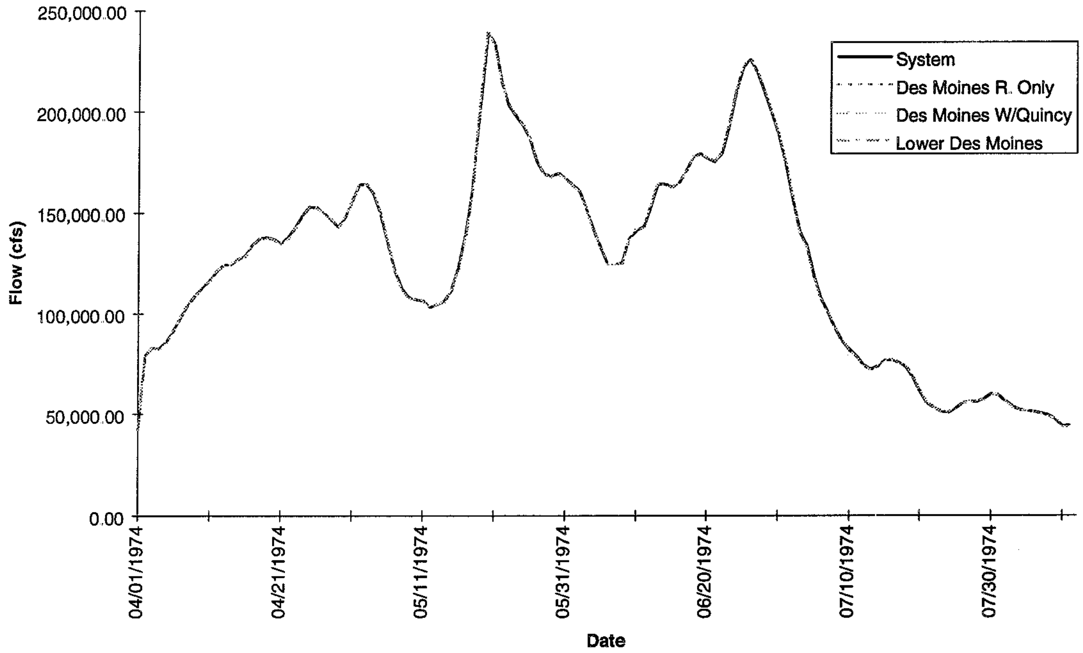

FIGURE E-6o. Hydrograph of Model Results at Quincy - Flood of 1974

1979 COMMENTARY

Figures E-7a through E-7e illustrate minor differences in storage and flow on the Iowa River depending on whether or not Coralville Reservoir is operating for flood control on the Mississippi River. As Table E-7 illustrates, these differences affect the model-computed penalty but not the damage related to peak flow.

As with the flood of 1973, when Saylorville Reservoir and Lake Red Rock are operated independently, damaging releases are made early in the event from Lake Red Rock, as illustrated by Figure E-7j. This occurs because only half of Saylorville Reservoir's flood pool capacity is used when operated independently, which leads to larger inflow into Lake Red Rock. Large releases are made from Lake Red Rock in order to minimize the storage penalties which accumulate over the course of the flood event. In contrast, all of Saylorville Reservoir's flood pool is used when the two reservoirs are operated in tandem. Among the various operating schemes, the large variance in release from Saylorville Reservoir can be attributed to a combination of the model minimizing the storage persuasion penalties and the existence of multiple optimal release schedules during periods when all flows are below flood stage.

TABLE E-7. Flood of 1979 Calculated Penalties

	Peak Flow Damage ($1000)							
Site	Observed	A	BD	CD	BE	CE	BFG	CFG
Iowa City	9	-	-	-	-	-	-	-
Lone Tree	91	-	-	-	-	-	-	-
Wapello	2,877	2,533	2,533	2,533	2,533	2,533	2,533	2,533
2nd Ave.	-	-	-	-	-	-	-	-
14th St.	-	-	-	-	-	-	-	-
Tracy	1,302	1,440	1,440	1,440	1,440	1,440	1,462	1,462
Ottumwa	3,024	3,979	3,979	3,979	3,979	3,979	3,979	3,979
Keosauqua	197	378	378	378	378	378	411	411
Burlington	290	275	275	275	275	275	275	275
Quincy	-	-	-	-	-	-	-	-
Total	7,791	8,606	8,606	8,606	8,606	8,606	8,660	8,660

	Model-Computed Flow Penalty ($1000)							
Site	Observed	A	BD	CD	BE	CE	BFG	CFG
Iowa City	36	-	-	-	-	-	-	-
Lone Tree	91	-	-	-	-	-	-	-
Wapello	14,622	11,227	11,227	11,425	11,227	11,425	11,227	11,425
2nd Ave.	-	-	-	-	-	-	-	-
14th St.	-	-	-	-	-	-	-	-
Tracy	57,772	43,034	43,034	43,034	43,034	43,034	45,050	45,050
Ottumwa	40,306	32,938	32,938	32,938	32,938	32,938	40,674	40,674
Keosauqua	377	1,106	1,106	1,106	1,106	1,106	1,518	1,518
Burlington	7,436	7,552	7,552	7,606	7,552	7,606	7,552	7,606
Quincy	-	-	-	-	-	-	-	-
Coralville		4,680	4,680	4,440	4,680	4,440	4,680	4,440
Saylorville		42,559	45,241	60,445	45,821	45,821	8,905	8,905
Red Rock		103,560	100,878	85,674	100,299	100,299	141,591	141,591
Total w/o stor.	120,640	95,856	95,856	96,108	95,856	96,108	106,021	106,273
Total w/ stor.		246,656	246,656	246,668	246,656	246,668	261,197	261,209

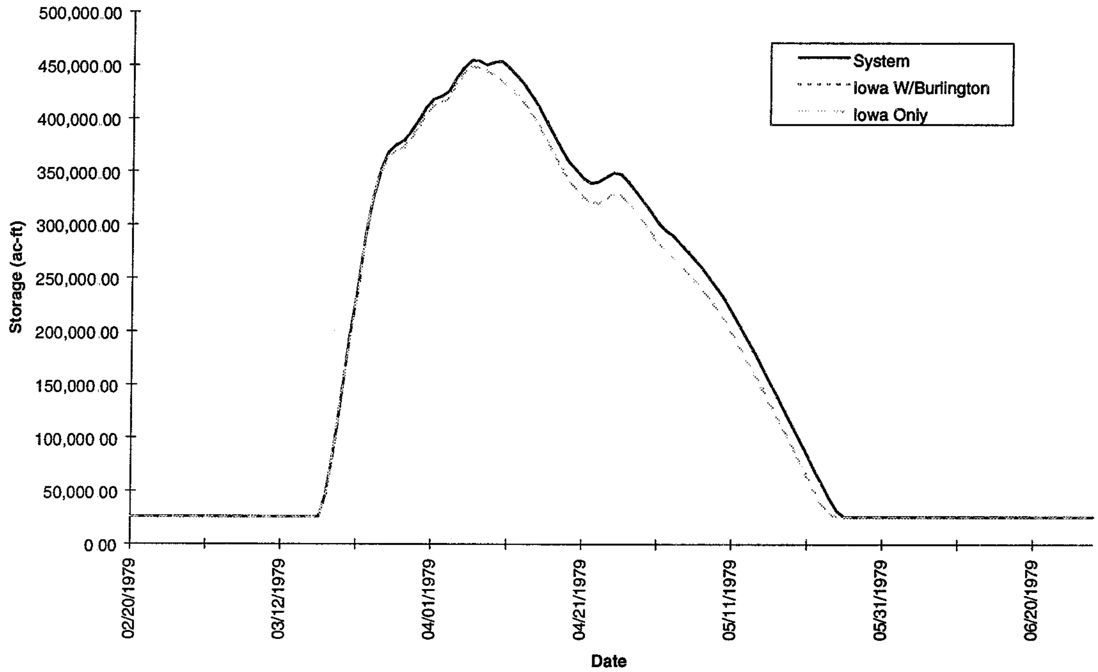

FIGURE E-7a. Model Results of Coralville Reservoir Storage - Flood of 1979

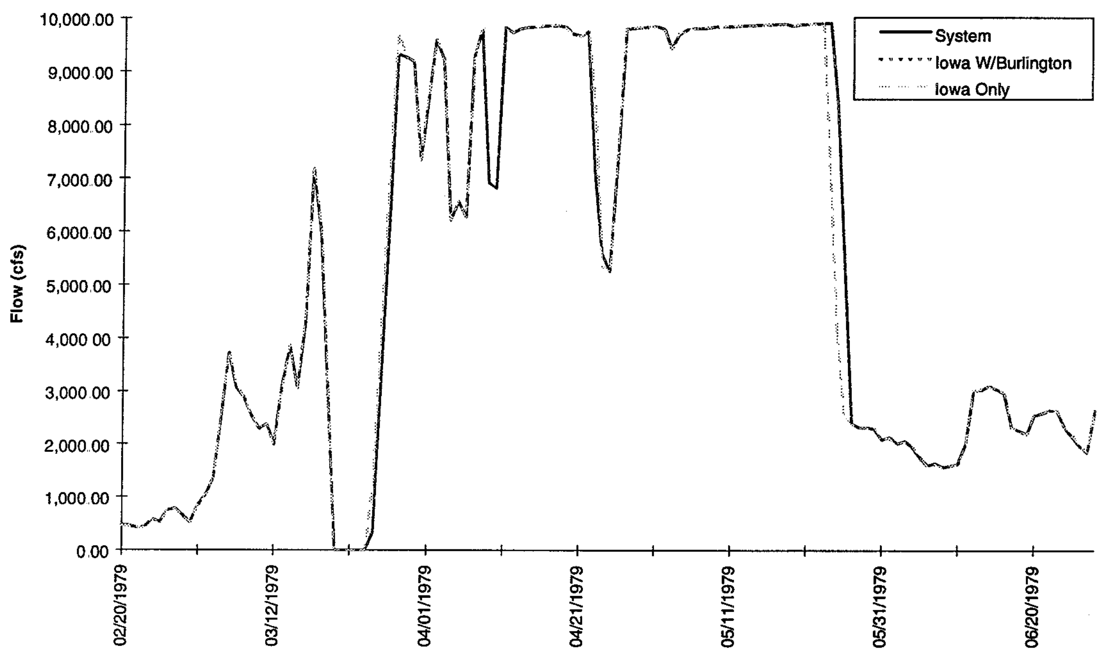

FIGURE E-7b. Model Results of Coralville Reservoir Release - Flood of 1979

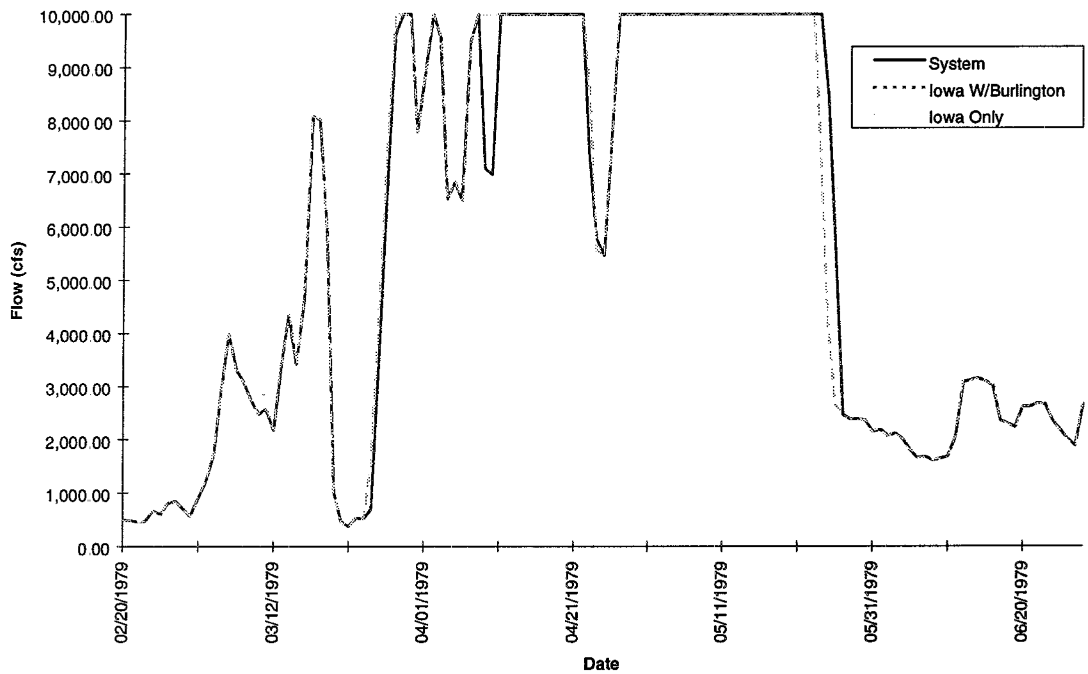

FIGURE E-7c. Hydrograph of Model Results at Iowa City - Flood of 1979

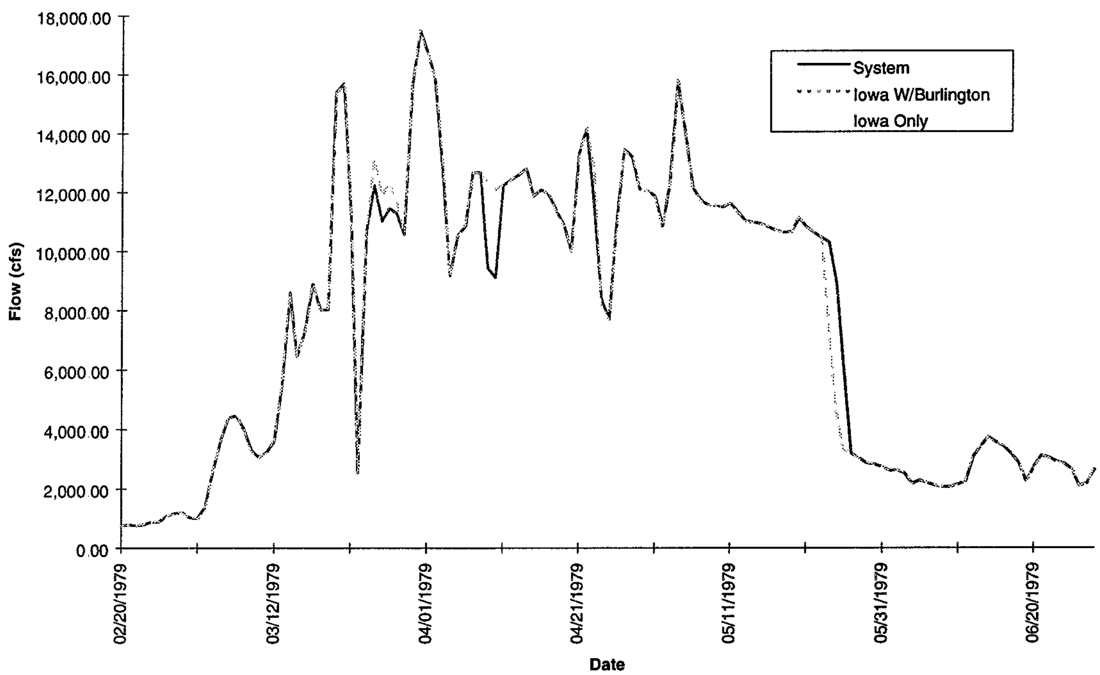

FIGURE E-7d. Hydrograph of Model Results at Lone Tree - Flood of 1979

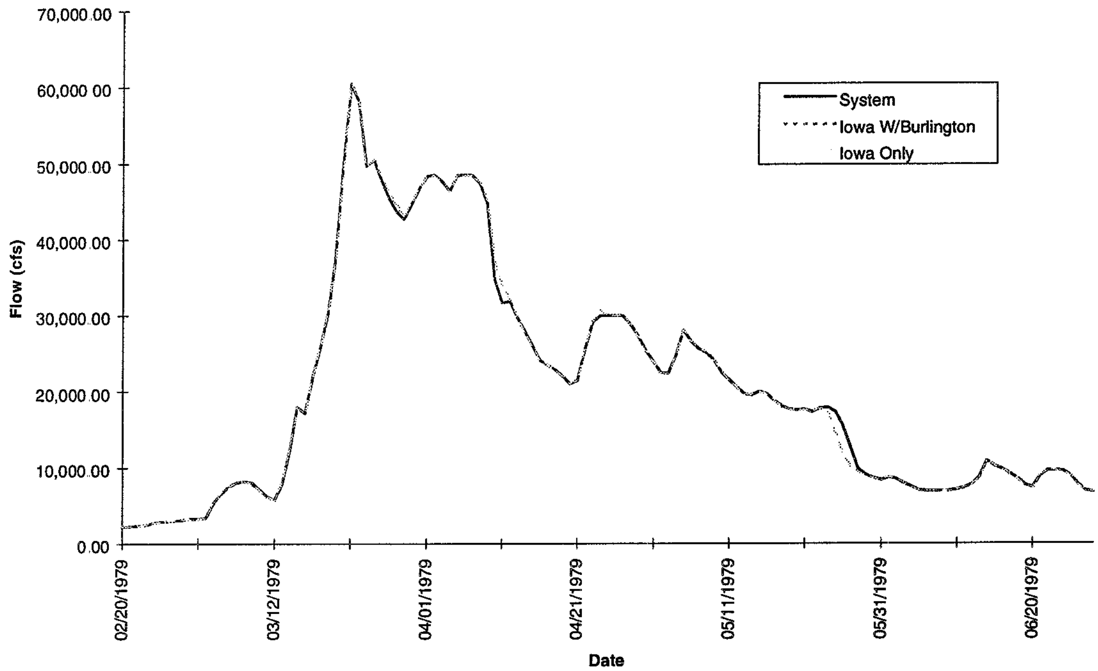

FIGURE E-7e. Hydrograph of Model Results at Wapello - Flood of 1979

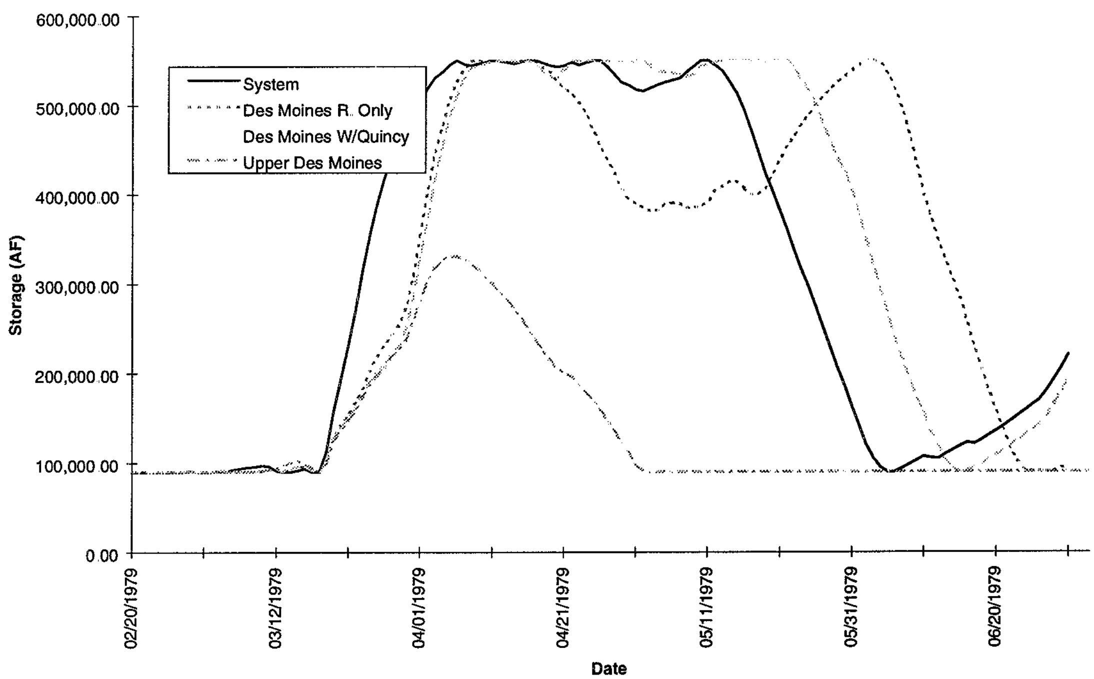

FIGURE E-7f. Model Results of Saylorville Reservoir Storage - Flood of 1979

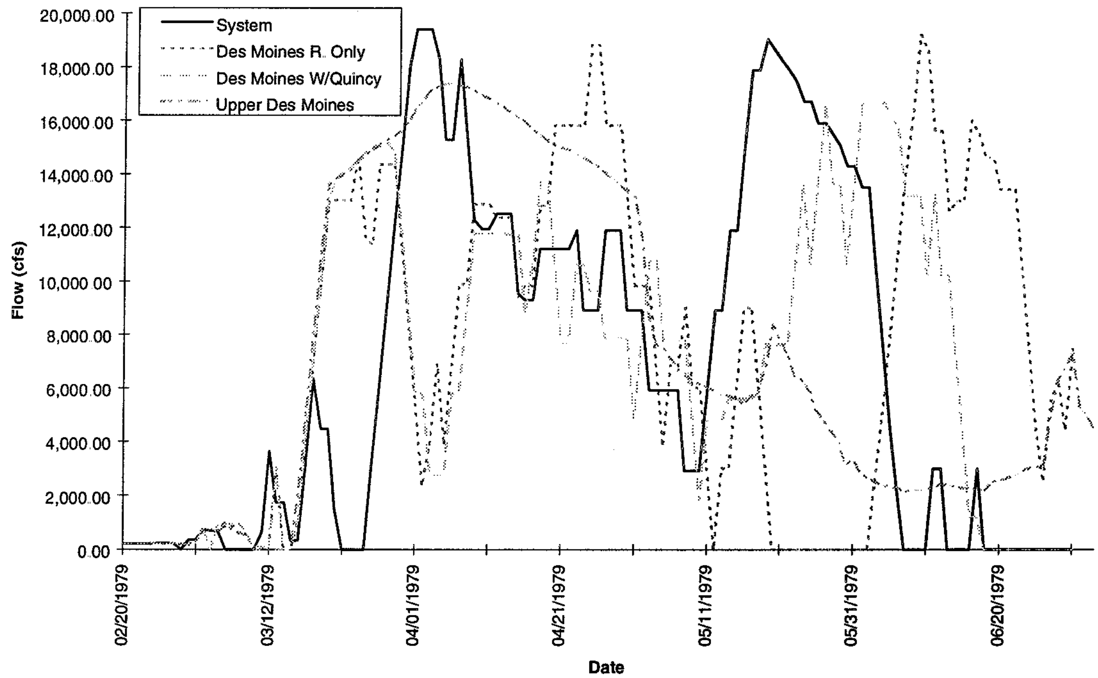

FIGURE E-7g. Model Results of Saylorville Reservoir Release - Flood of 1979

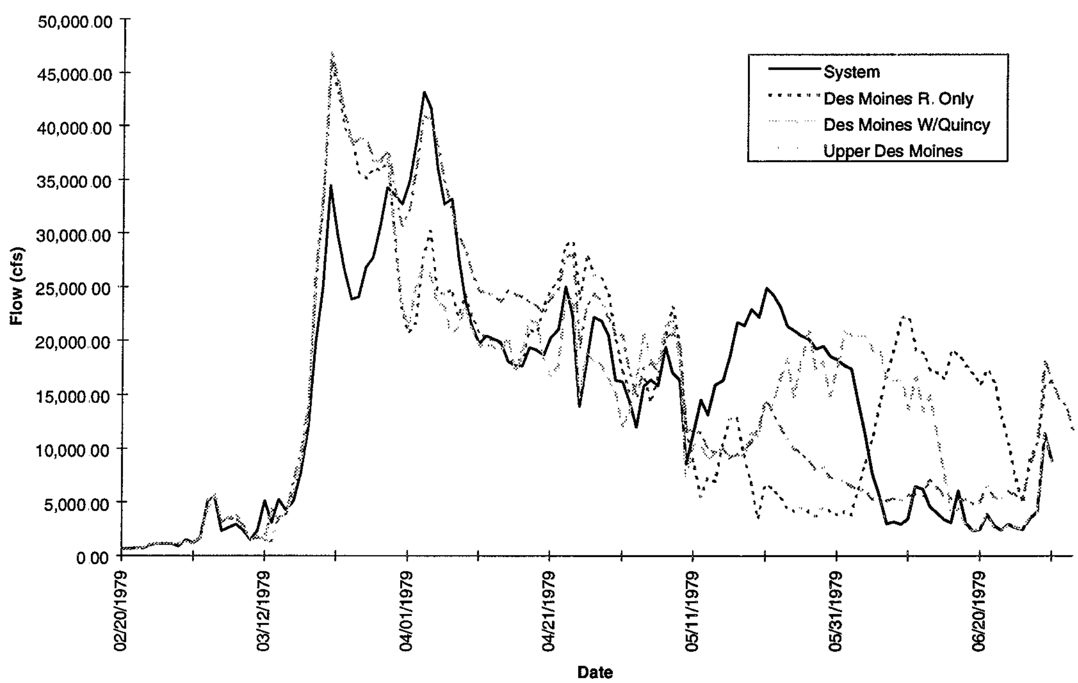

FIGURE E-7h. Hydrograph of Model Results at 14th Street - Flood of 1979

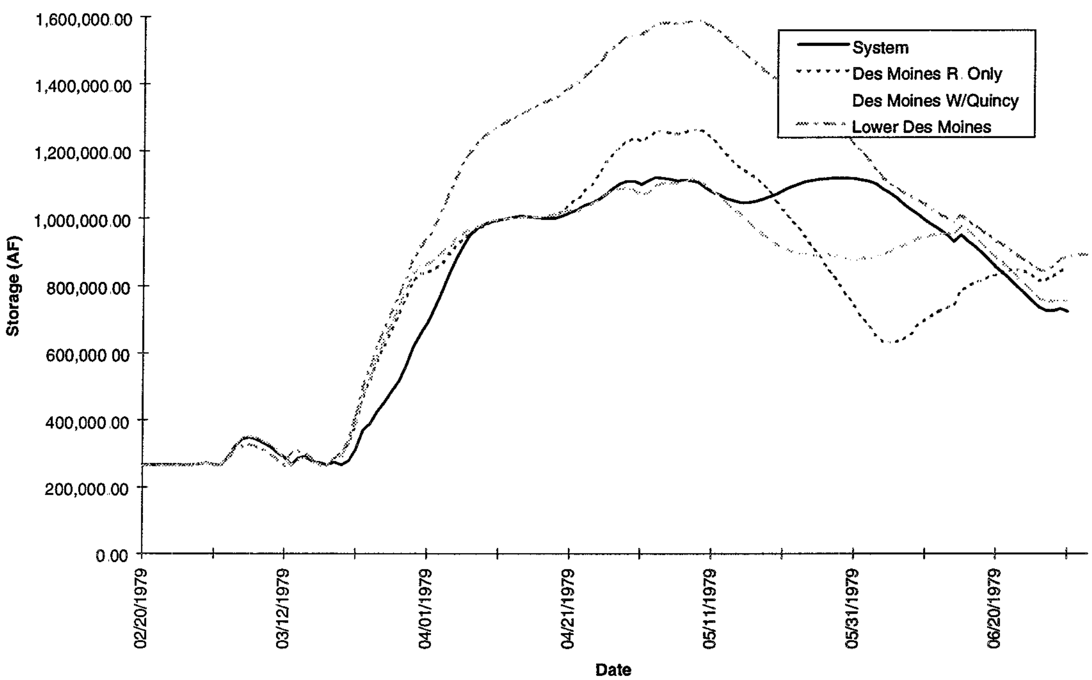

FIGURE E-7i. Model Results of Lake Red Rock Storage - Flood of 1979

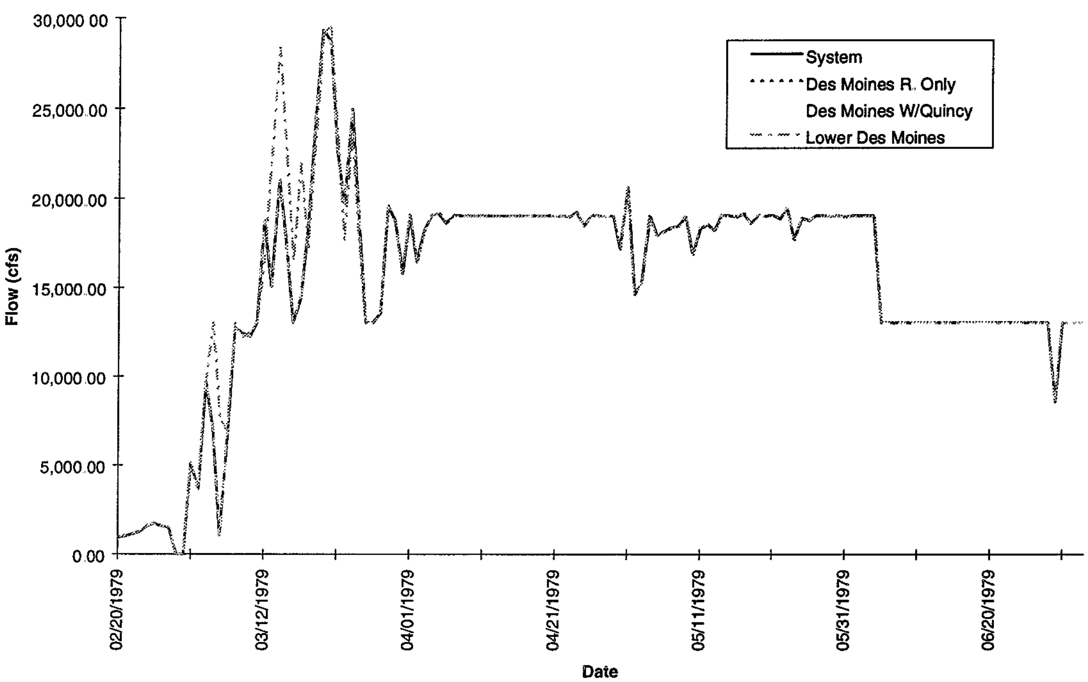

FIGURE E-7j. Model Results of Lake Red Rock Release - Flood of 1979

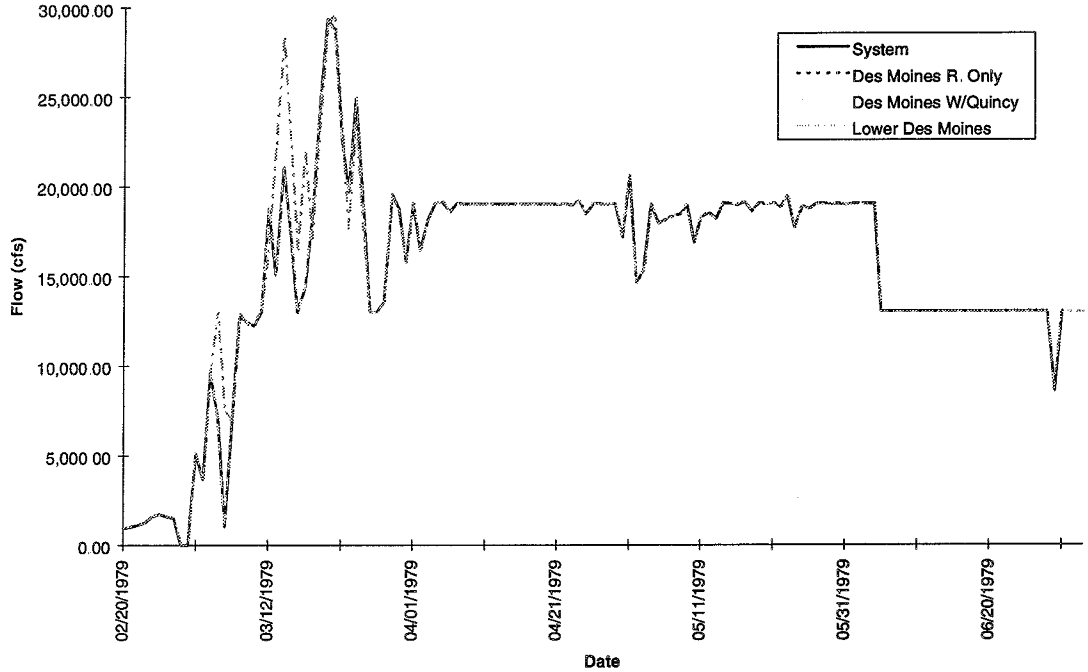

FIGURE E-7k. Hydrograph of Model Results at Tracy - Flood of 1979

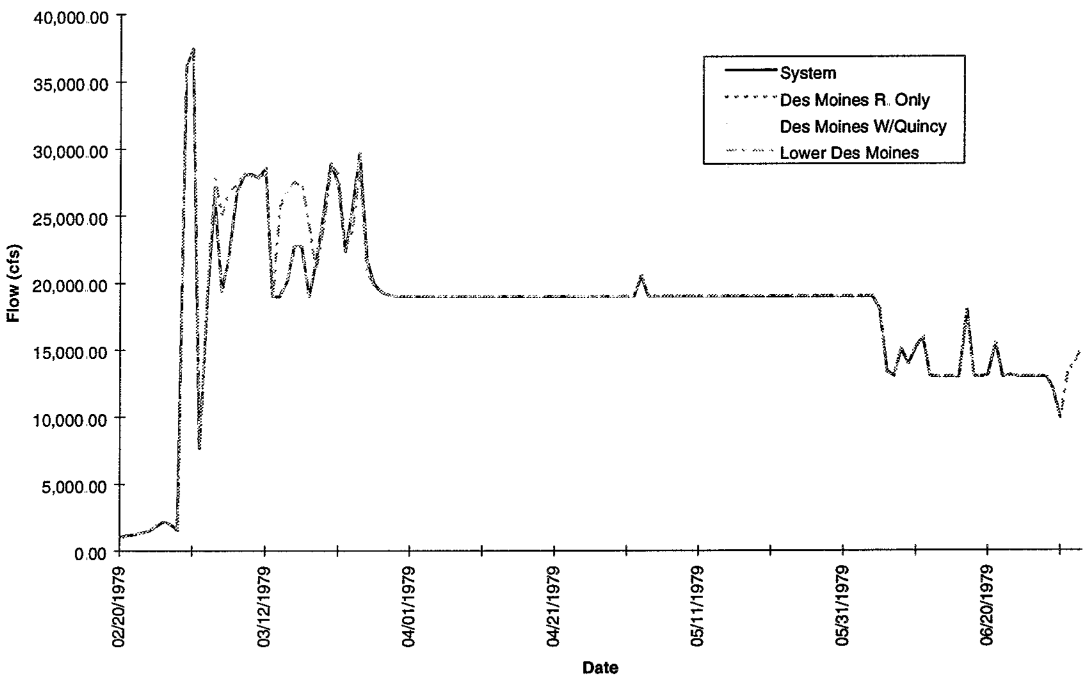

FIGURE E-7l. Hydrograph of Model Results at Ottumwa - Flood of 1979

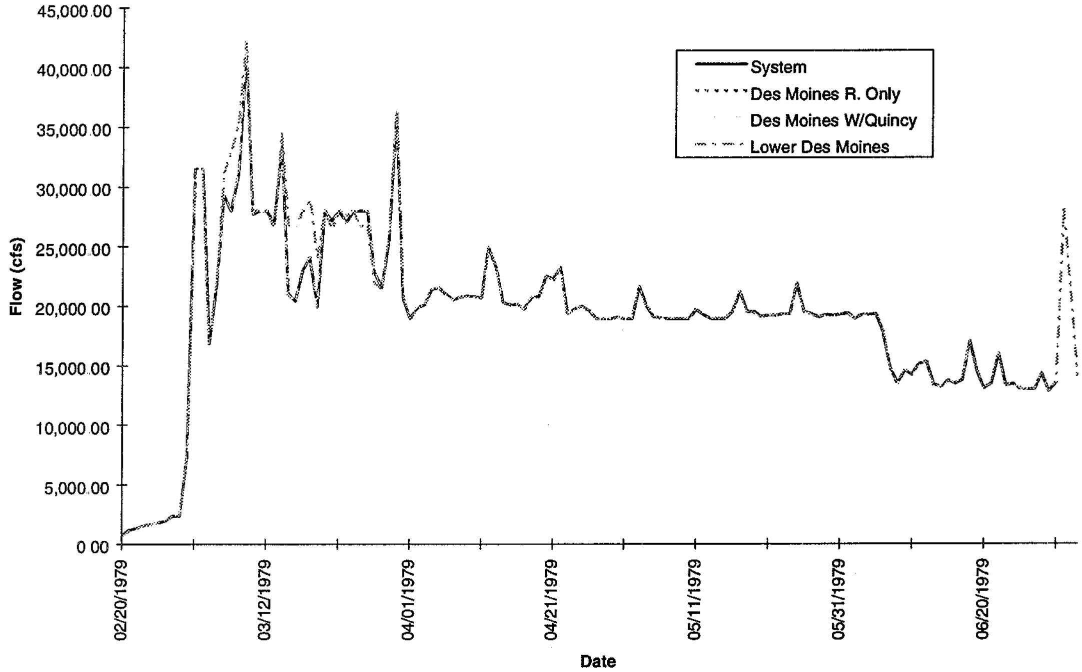

FIGURE E-7m. Hydrograph of Model Results at Keosauqua - Flood of 1979

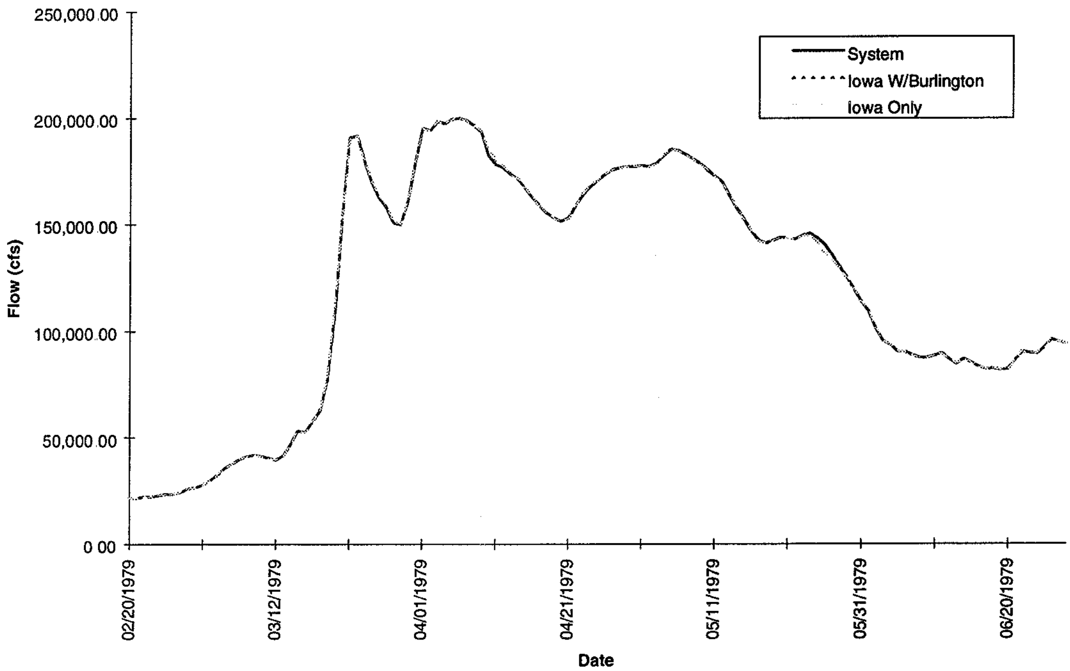

FIGURE E-7n. Hydrograph of Model Results at Burlington - Flood of 1979

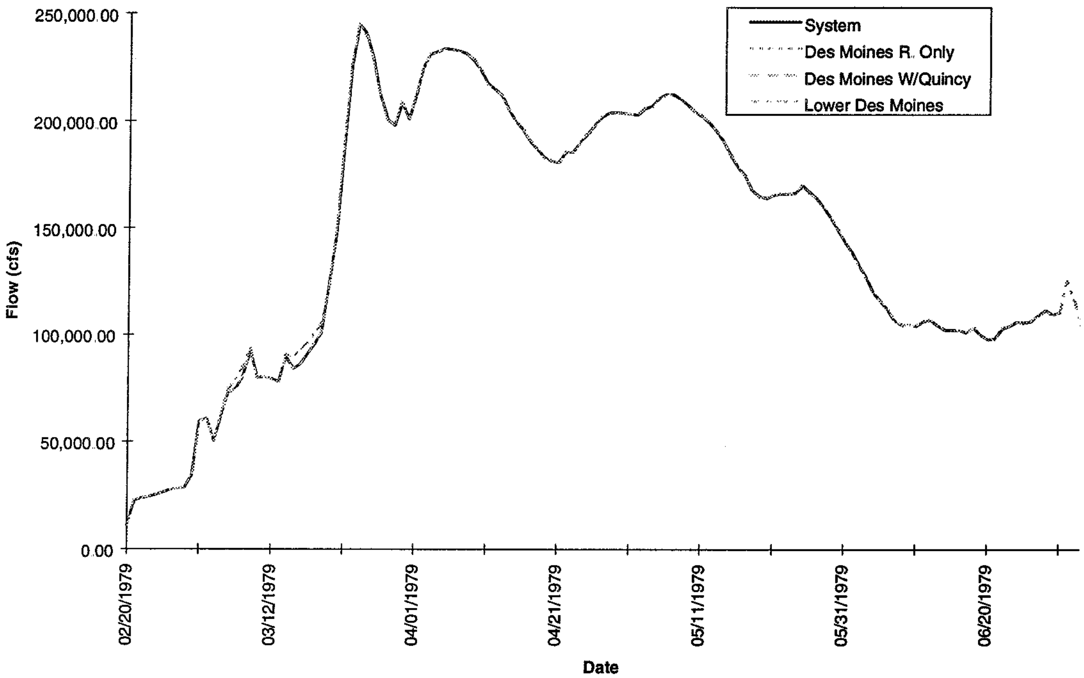

FIGURE E-7o. Hydrograph of Model Results at Quincy - Flood of 1979

1990 COMMENTARY

As with the flood of 1974, the only difference in peak-related damage results during the flood of 1990 is related to whether or not the model was operating for flood control at Burlington on the Mississippi River. Interestingly, the reduction in peak-related damage occurs at Wapello on the Iowa River even though the model is operating primarily to minimize the model-computed penalty at Burlington on the Mississippi River. This flood damage reduction is minor ($10,000), and the actual difference in operation of Coralville Reservoir is negligible, as illustrated by plots of storage and release for Coralville Reservoir (Figures E-8a and E-8b).

Once again, as Figures E-8f and E-8g illustrate, the operation of Saylorville Reservoir varies significantly depending on the operational scheme even though flows downstream from Lake Red Rock are practically identical (Figures E-8j through E-8o). This is another indication of the existence of multiple optimal solutions.

TABLE E-8. Flood of 1990 Calculated Penalties

	Peak Flow Damage ($1000)							
Site	Observed	A	BD	CD	BE	CE	BFG	CFG
Iowa City	23	-	-	-	-	-	-	-
Lone Tree	194	237	237	237	237	237	237	237
Wapello	5,366	5,532	5,532	5,522	5,532	5,522	5,532	5,522
2nd Ave.	-	-	-	-	-	-	-	-
14th St.	-	-	-	-	-	-	-	-
Tracy	889	680	680	680	680	680	693	693
Ottumwa	2,009	2,009	2,009	2,009	2,009	2,009	2,009	2,009
Keosauqua	473	482	482	482	482	482	547	547
Burlington	175	164	164	164	164	164	164	164
Quincy	-	-	-	-	-	-	-	-
Total	9,128	9,104	9,104	9,093	9,104	9,093	9,181	9,171

	Model-Computed Flow Penalty ($1000)							
Site	Observed	A	BD	CD	BE	CE	BFG	CFG
Iowa City	23	-	-	-	-	-	-	-
Lone Tree	490	459	459	459	459	459	459	459
Wapello	21,561	19,225	19,225	19,209	19,225	19,209	19,225	19,209
2nd Ave.	-	-	-	-	-	-	-	-
14th St.	-	-	-	-	-	-	-	-
Tracy	42,082	27,102	27,102	27,102	27,102	27,102	27,295	27,295
Ottumwa	39,550	4,248	4,248	4,248	4,248	4,248	4,317	4,317
Keosauqua	1,902	1,079	1,079	1,079	1,079	1,079	1,162	1,162
Burlington	1,184	1,114	1,114	1,163	1,114	1,163	1,114	1,163
Quincy	-	-	-	-	-	-	-	-
Coralville		2,506	2,506	2,492	2,506	2,492	2,506	2,492
Saylorville		30,926	40,792	40,792	33,839	33,839	1,555	1,555
Red Rock		78,566	68,700	68,700	75,653	75,653	107,974	107,974
Total w/o stor.	106,791	53,226	53,226	53,259	53,226	53,259	53,570	53,604
Total w/ stor.		165,223	165,223	165,242	165,223	165,242	165,605	165,625

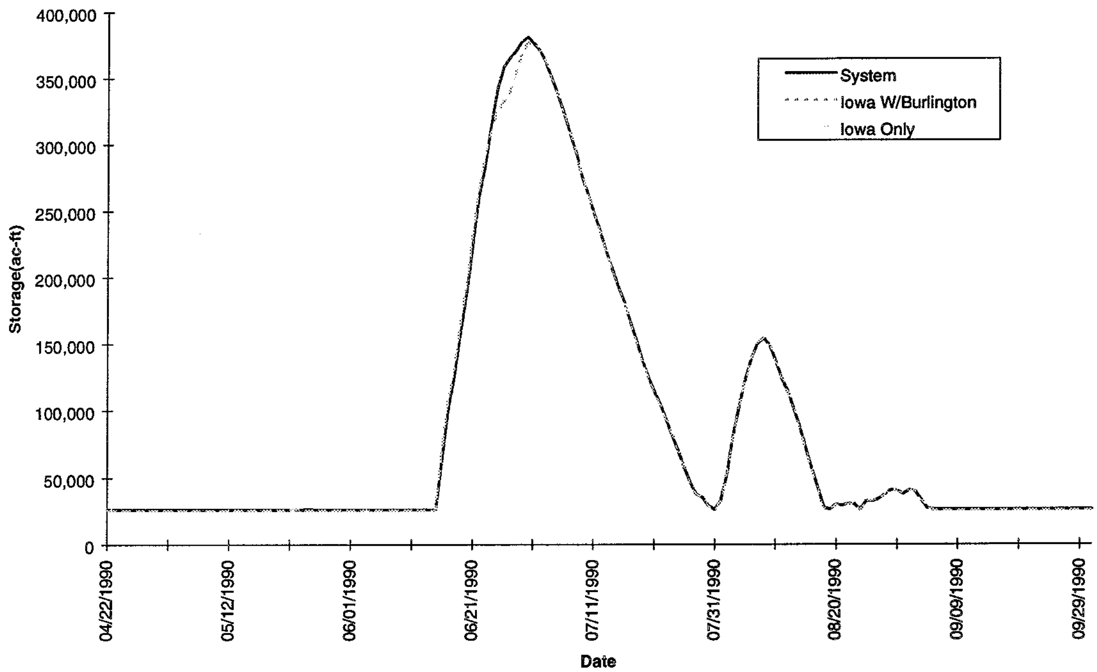

FIGURE E-8a. Model Results of Coralville Reservoir Storage - Flood of 1990

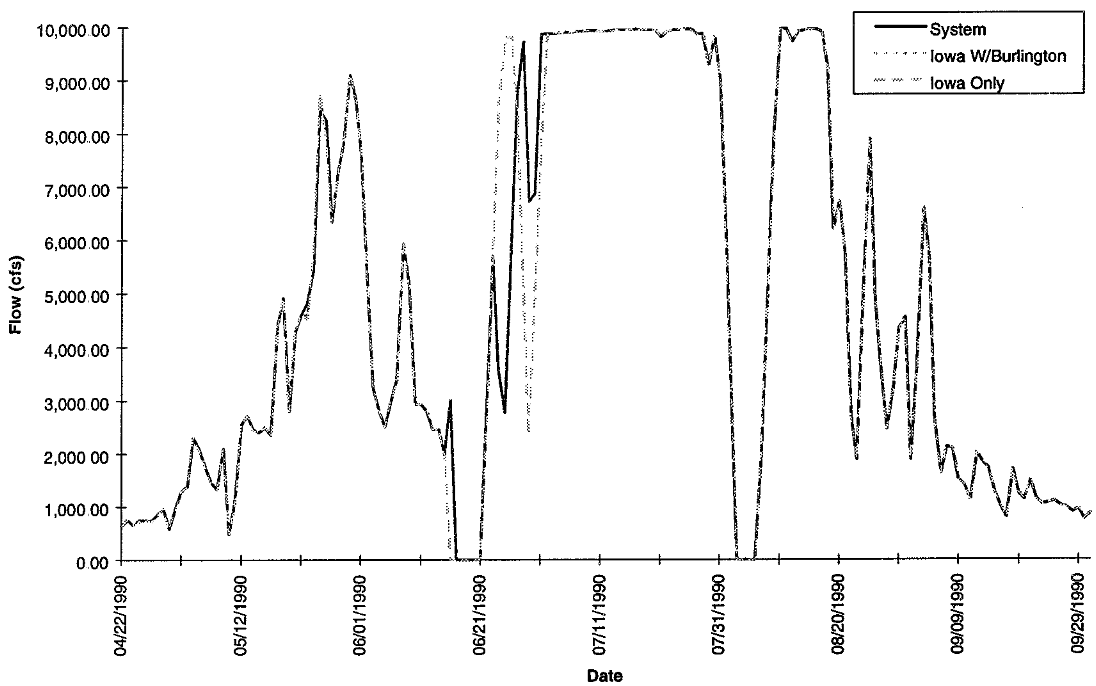

FIGURE E-8b. Model Results of Coralville Reservoir Release - Flood of 1990

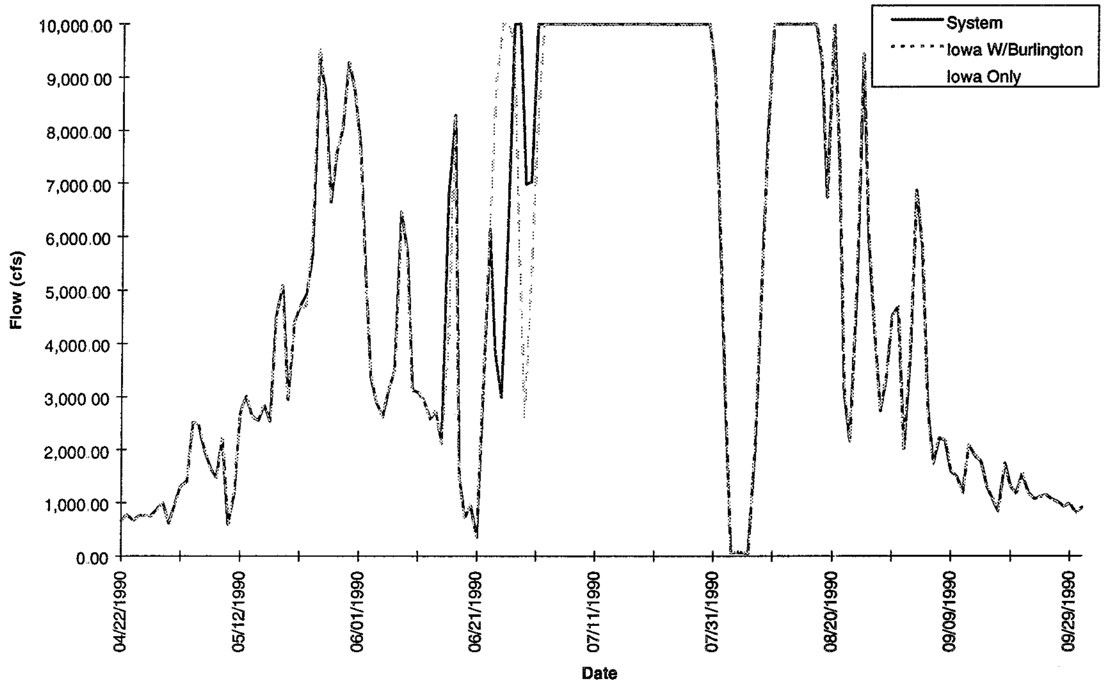

FIGURE E-8c. Hydrograph of Model Results at Iowa City - Flood of 1990

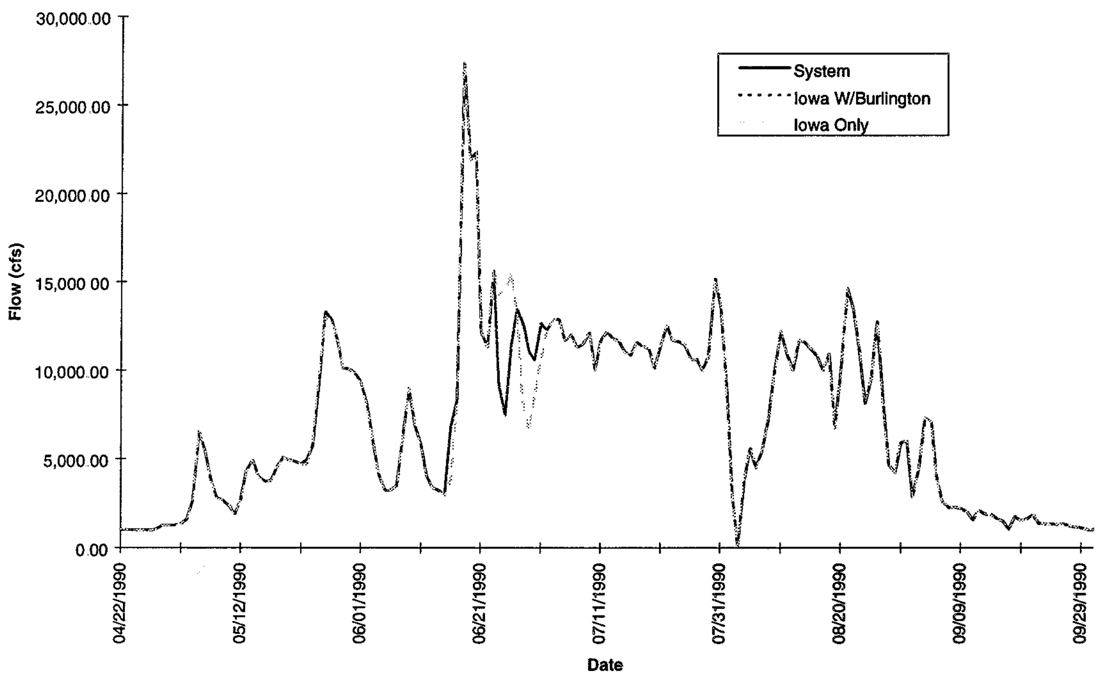

FIGURE E-8d. Hydrograph of Model Results at Lone Tree - Flood of 1990

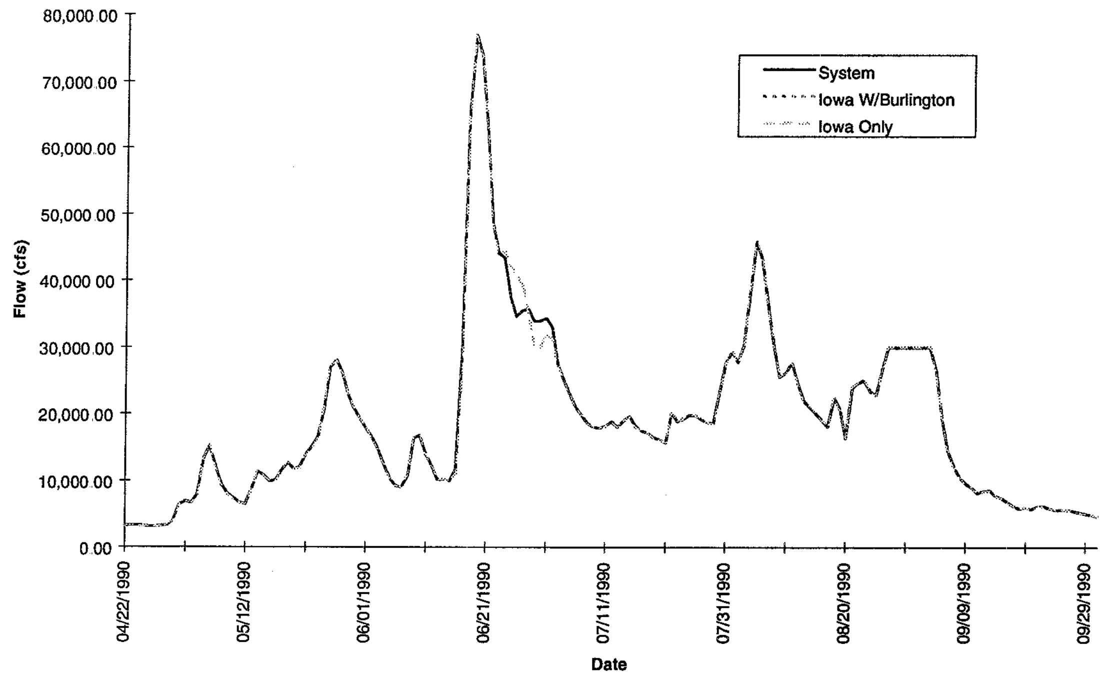

FIGURE E-8e. Hydrograph of Model Results at Wapello - Flood of 1990

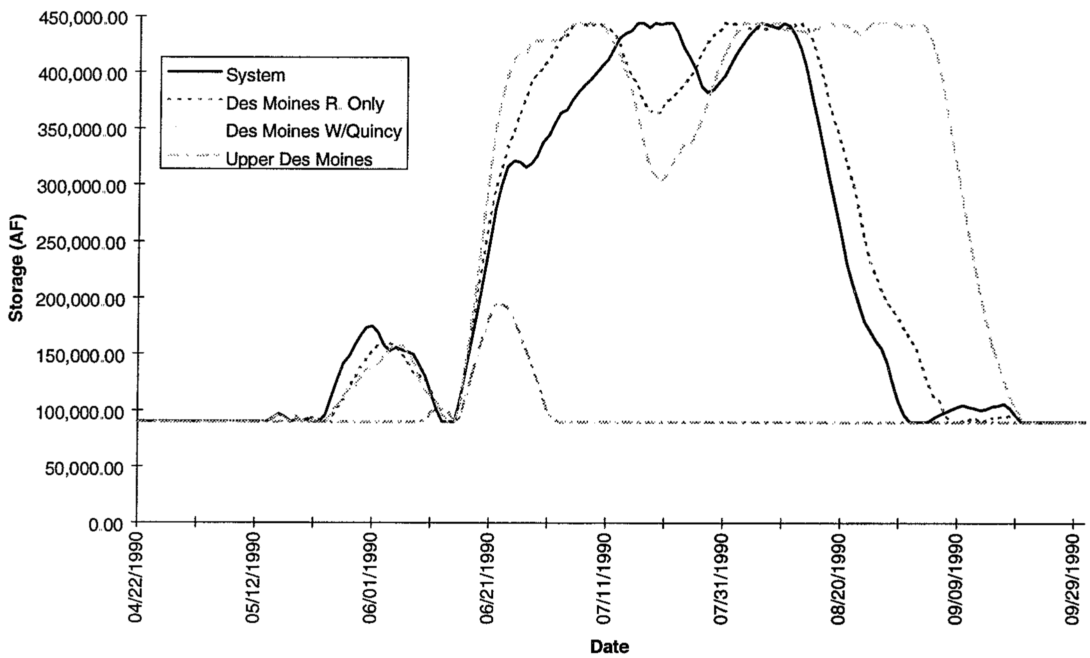

FIGURE E-8f. Model Results of Saylorville Reservoir Storage - Flood of 1990

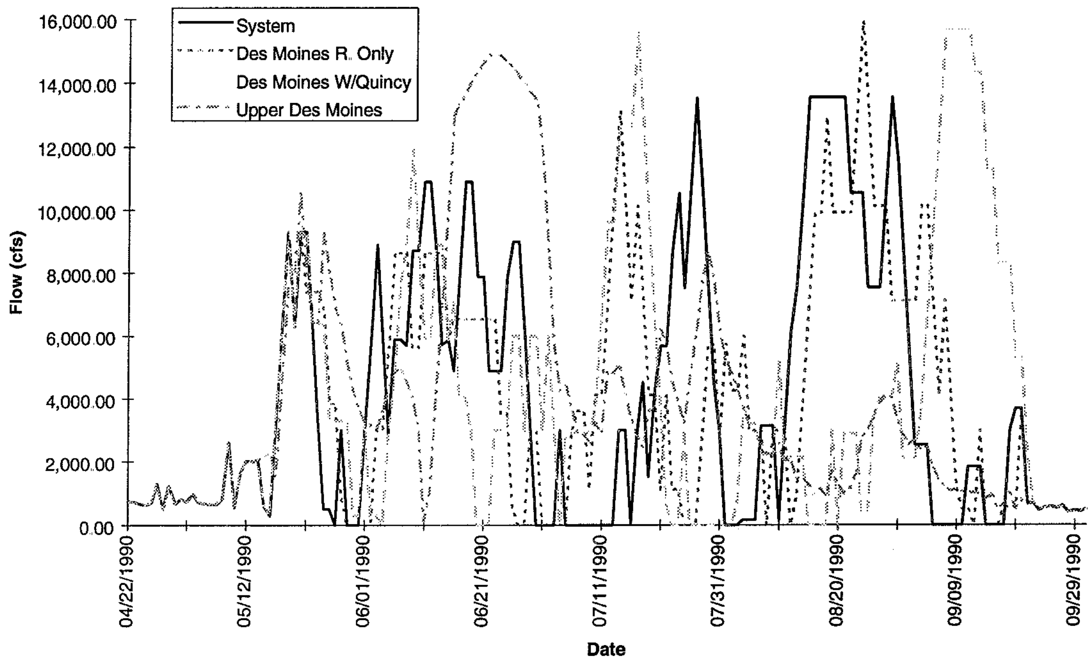

FIGURE E-8g. Model Results of Saylorville Reservoir Release - Flood of 1990

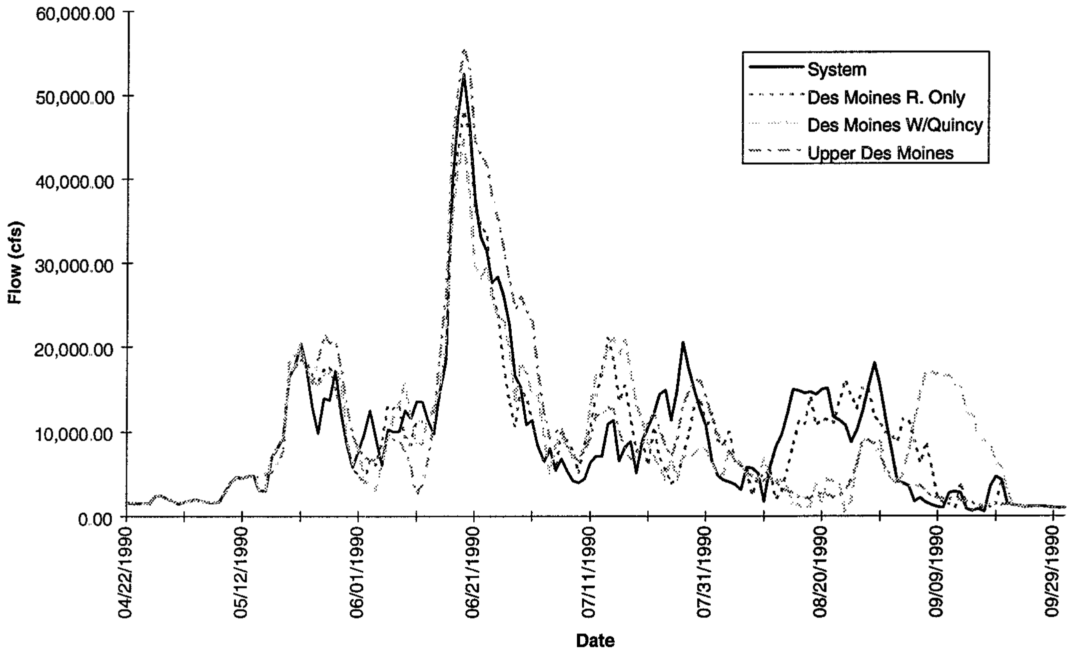

FIGURE E-8h. Hydrograph of Model Results at 14th Street - Flood of 1990

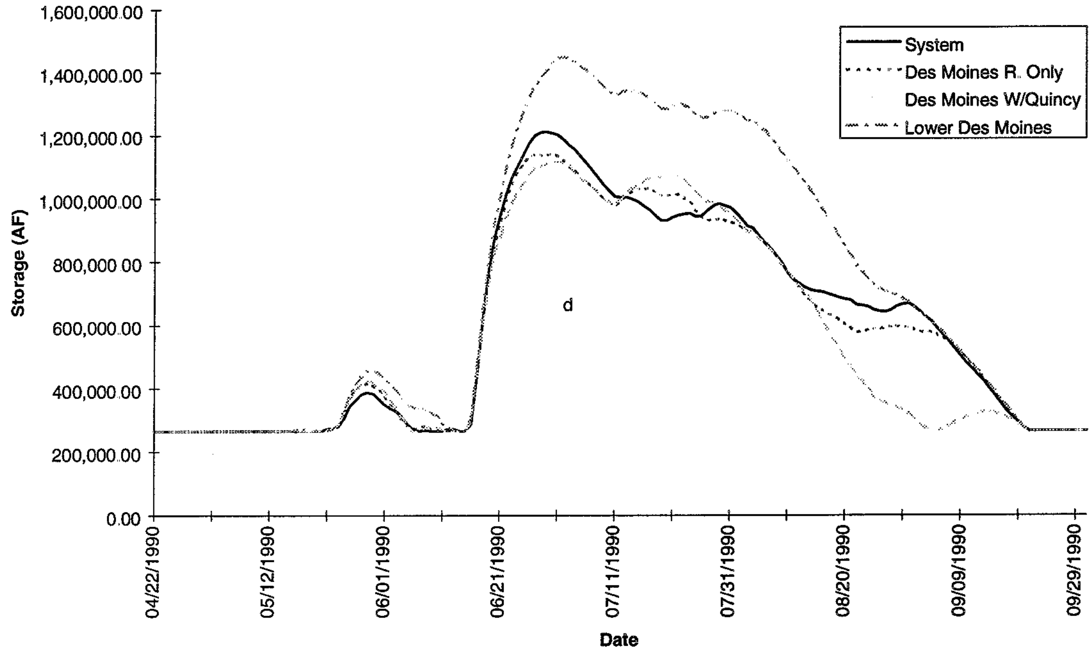

FIGURE E-8i. Model Results of Lake Red Rock Storage - Flood of 1990

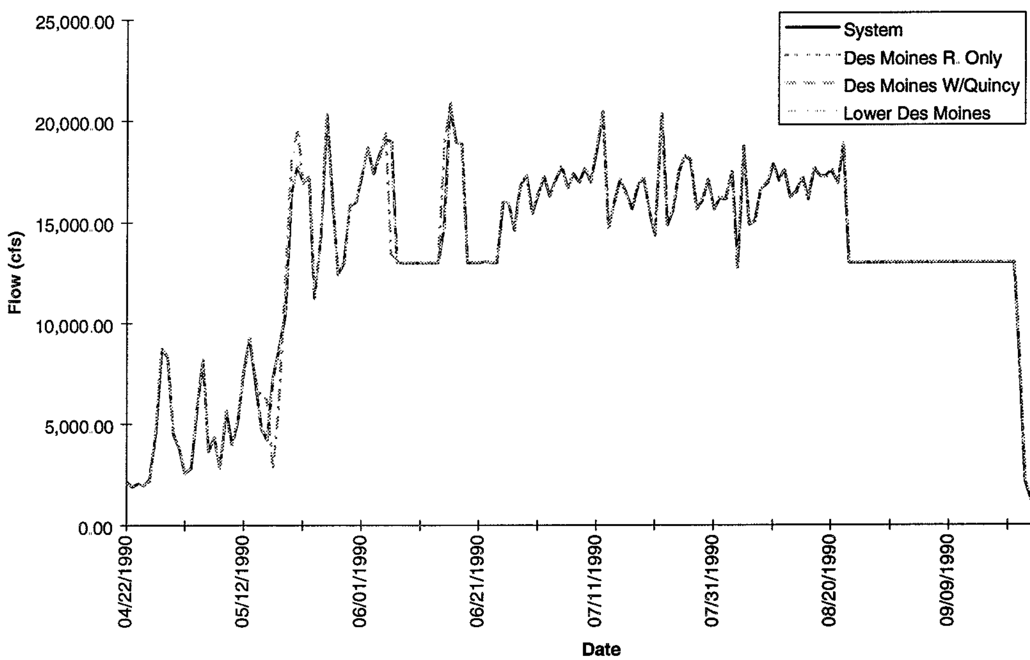

FIGURE E-8j. Model Results of Lake Red Rock Release - Flood of 1990

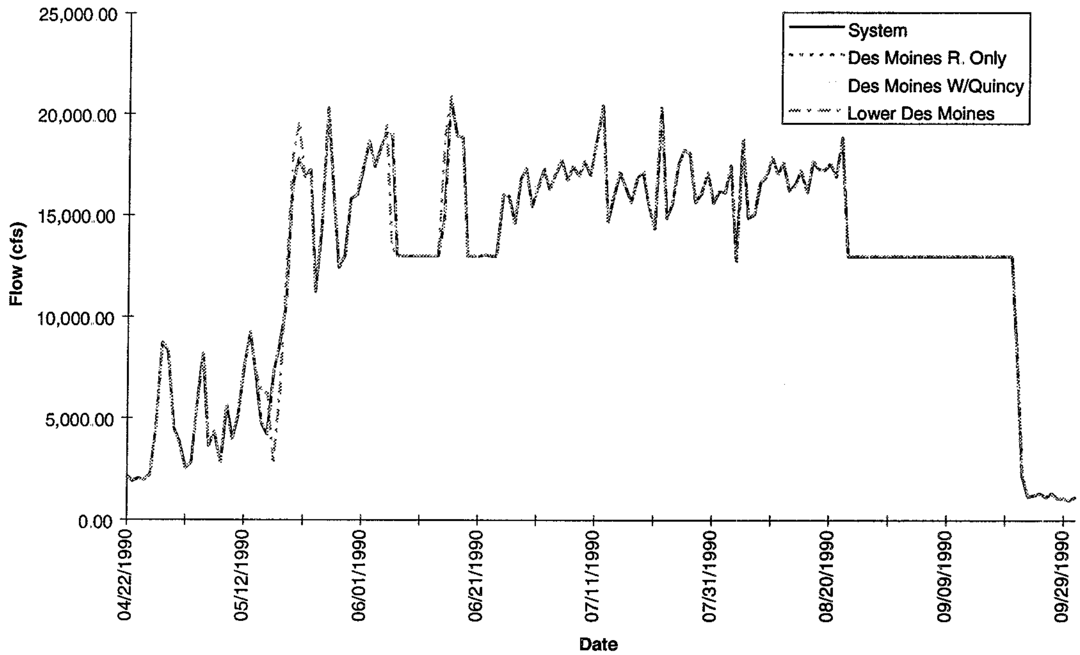

FIGURE E-8k. Hydrograph of Model Results at Tracy - Flood of 1990

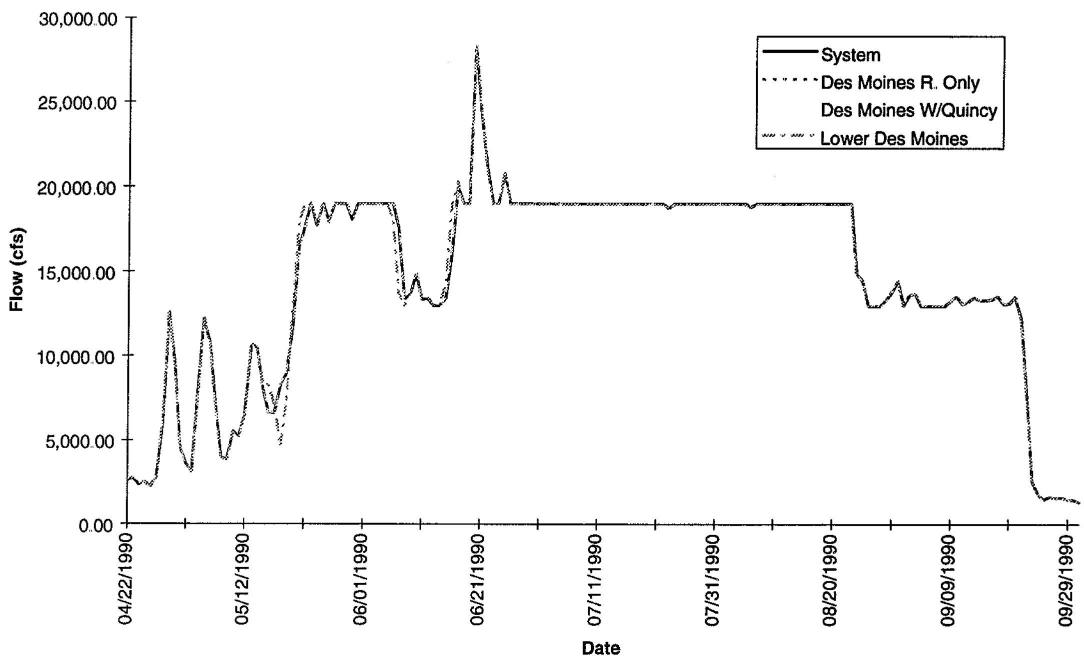

FIGURE E-8l. Hydrograph of Model Results at Ottumwa - Flood of 1990

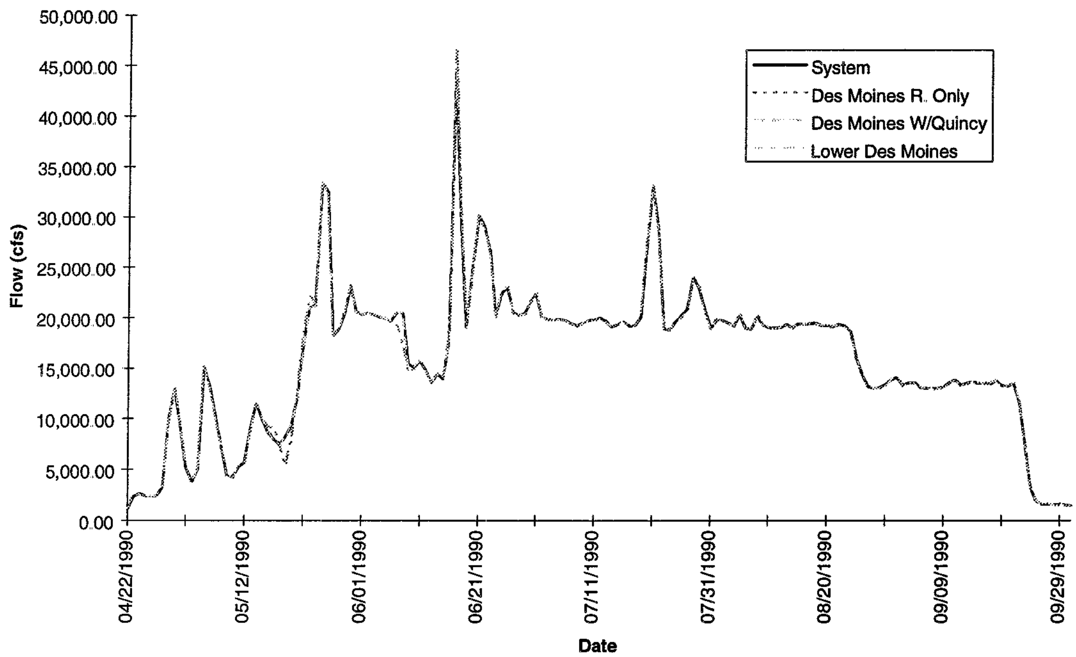

FIGURE E-8m. Hydrograph of Model Results at Keosauqua - Flood of 1990

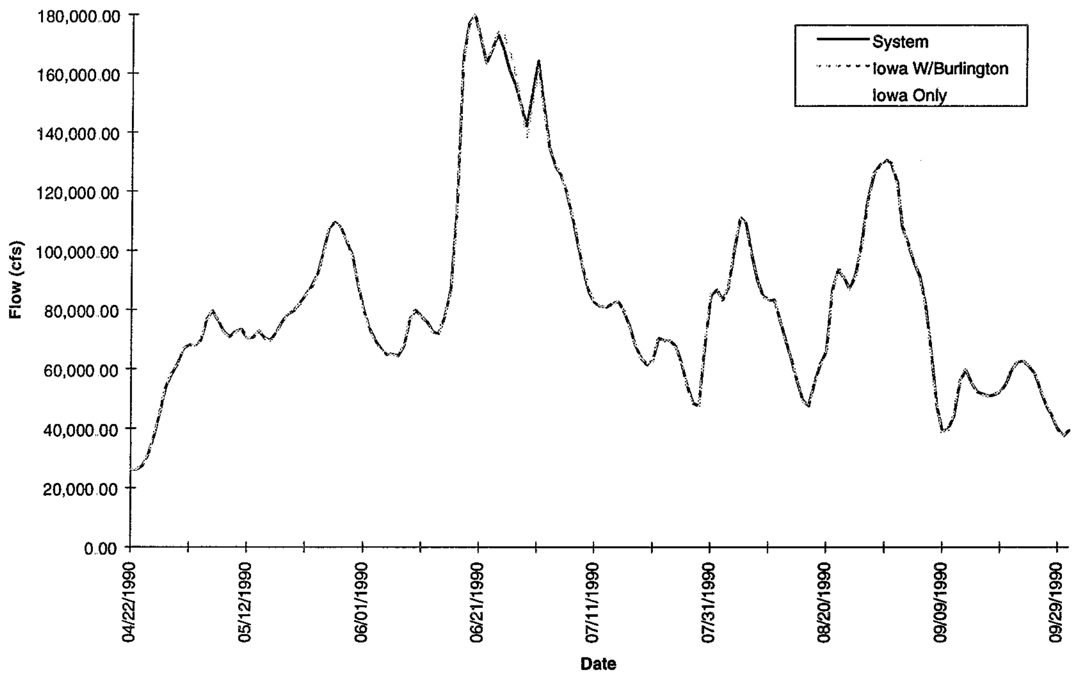

FIGURE E-8n. Hydrograph of Model Results at Burlington - Flood of 1990

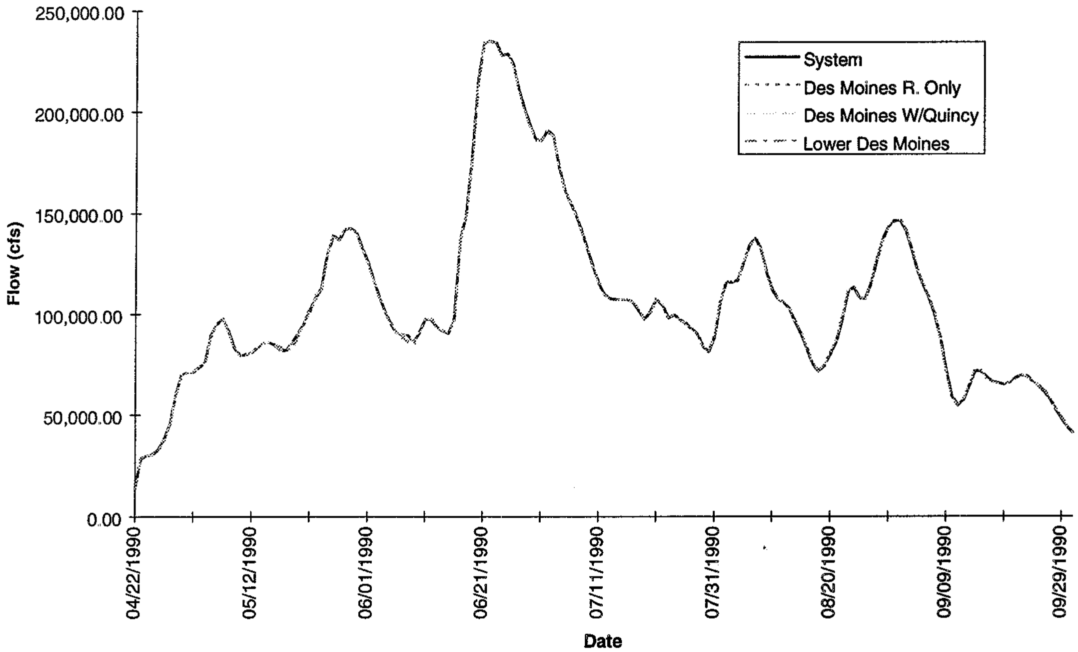

FIGURE E-8o. Hydrograph of Model Results at Quincy - Flood of 1990

1991 COMMENTARY

Model results from the 1991 flood event on the Iowa River are similar to those from the 1990 event. When the model is operating to reduce the model-computed penalty at Burlington on the Mississippi River, the reduction in peak-related damage occurs at Wapello on the Iowa River. This flood damage reduction is minor ($8,000), and the actual difference in operation of Coralville Reservoir is small, as illustrated by plots of storage and release for Coralville Reservoir in Figures E-9a and E-9b.

As with the flood of 1965, releases from Saylorville Reservoir are identical under the different operating schemes for the period in which the City of Des Moines is in danger of being flooded (Figures E-9g and E-9h). The variation in release from Lake Red Rock is relatively large depending on whether or not the reservoirs are operated in tandem. The model-computed penalty is much larger when the reservoirs are operated independently because damaging releases must be made from Lake Red Rock during periods in which Saylorville Reservoir's flood pool is not fully utilized (Figure E-9f). When operated in tandem with Lake Red Rock, Saylorville Reservoir's flood pool is used more fully, and the damaging releases from Lake Red Rock are reduced.

Table E-9 shows that tandem operation of the Des Moines River reservoirs actually increases peak-related penalty even though it reduces the model-computed penalty. This occurs because, in this case, the model-computed penalty is smaller with a higher-peak, shorter-duration flow than with a lower-peak, longer-duration flow. Nonetheless, all model runs result in no peak-flow damage or model-computed penalty at Iowa City and the City of Des Moines.

TABLE E-9. Flood of 1991 Calculated Penalties

Site	Peak Flow Damage ($1000)							
	Observed	**A**	**BD**	**CD**	**BE**	**CE**	**BFG**	**CFG**
Iowa City	135	-	-	-	-	-	-	-
Lone Tree	-	-	-	-	-	-	-	-
Wapello	443	325	325	333	325	333	325	333
2nd Ave.	2,021	-	-	-	-	-	-	-
14th St.	-	-	-	-	-	-	-	-
Tracy	1,954	3,914	3,914	3,914	3,914	3,914	4,137	4,137
Ottumwa	3,607	9,996	9,996	9,996	9,996	9,996	9,500	9,500
Keosauqua	403	1,117	1,117	1,117	1,117	1,117	1,053	1,053
Burlington	131	137	137	137	137	137	137	137
Quincy	-	-	-	-	-	-	-	-
Total	8,693	15,489	15,489	15,496	15,489	15,496	15,153	15,160

Site	Model-Computed Flow Penalty ($1000)							
	Observed	**A**	**BD**	**CD**	**BE**	**CE**	**BFG**	**CFG**
Iowa City	2,282	-	-	-	-	-	-	-
Lone Tree	-	-	-	-	-	-	-	-
Wapello	3,966	3,829	3,829	3,933	3,829	3,933	3,829	3,933
2nd Ave.	15,387	-	-	-	-	-	-	-
14th St.	-	-	-	-	-	-	-	-
Tracy	124,300	83,918	83,918	83,918	83,918	83,918	102,417	102,417
Ottumwa	156,298	102,492	102,492	102,492	102,492	102,492	135,726	135,726
Keosauqua	3,474	7,565	7,565	7,565	7,565	7,565	9,995	9,995
Burlington	1,767	1,717	1,717	1,866	1,717	1,866	1,717	1,866
Quincy	-	-	-	-	-	-	-	-
Coralville		2,350	2,350	2,169	2,350	2,169	2,350	2,169
Saylorville		16,421	16,391	16,391	15,751	15,751	10,484	10,484
Red Rock		50,921	50,951	50,951	51,591	51,591	40,946	40,946
Total w/o stor.	307,473	199,520	199,520	199,774	199,520	199,774	253,684	253,938
Total w/ stor.		269,212	269,212	269,285	269,212	269,285	307,463	307,537

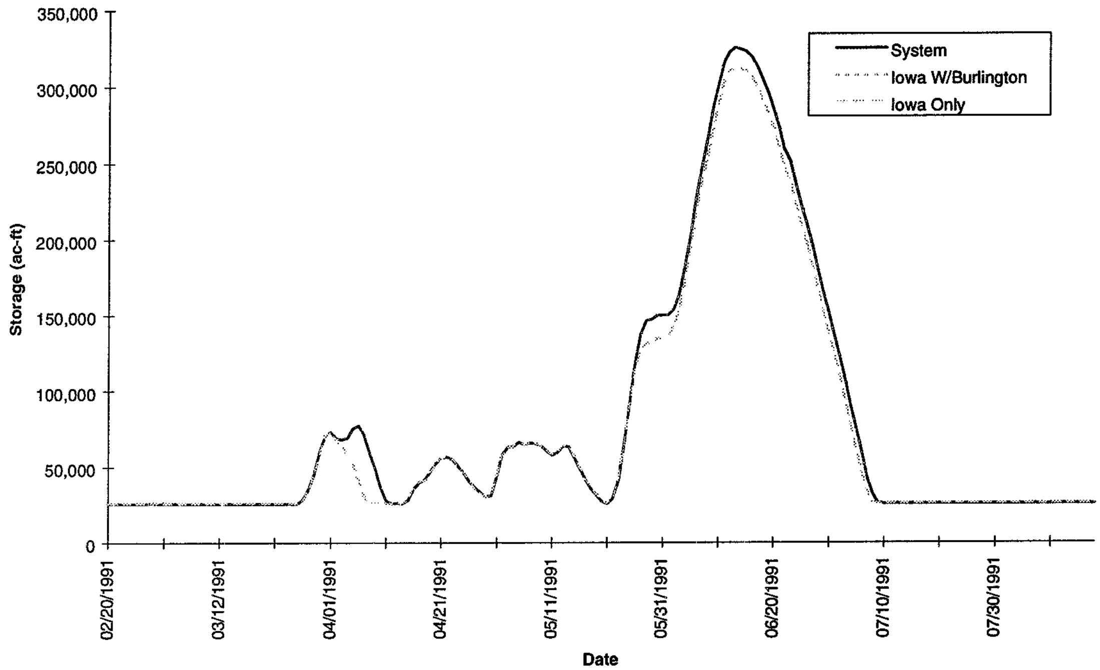

FIGURE E-9a. Model Results of Coralville Reservoir Storage - Flood of 1991

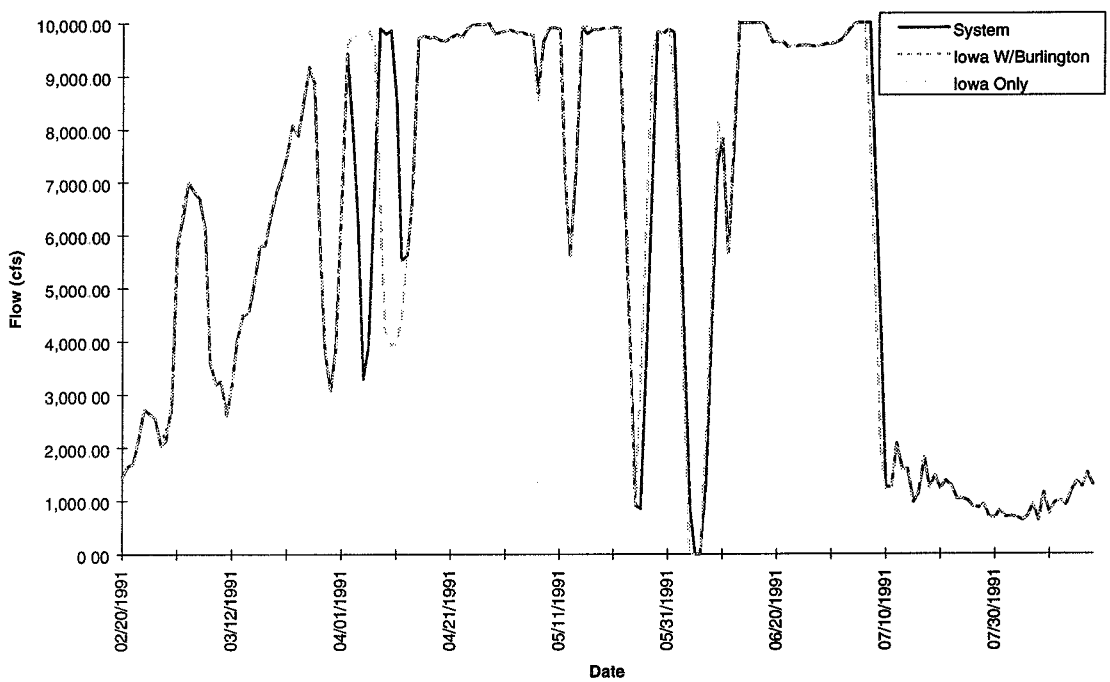

FIGURE E-9b. Model Results of Coralville Reservoir Release - Flood of 1991

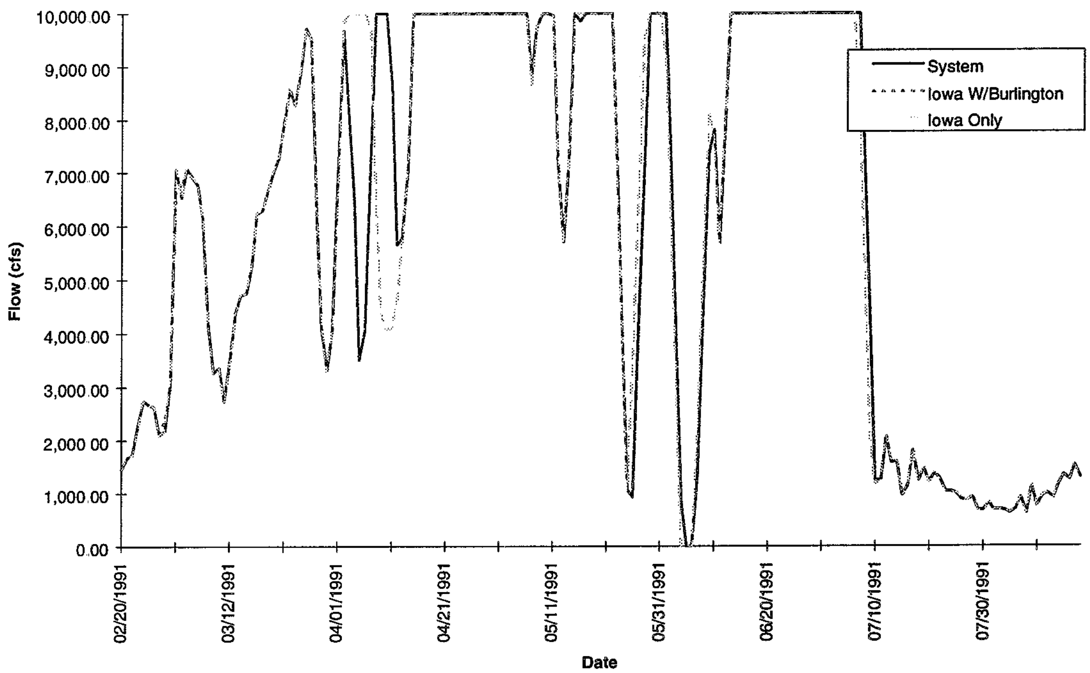

FIGURE E-9c. Hydrograph of Model Results at Iowa City - Flood of 1991

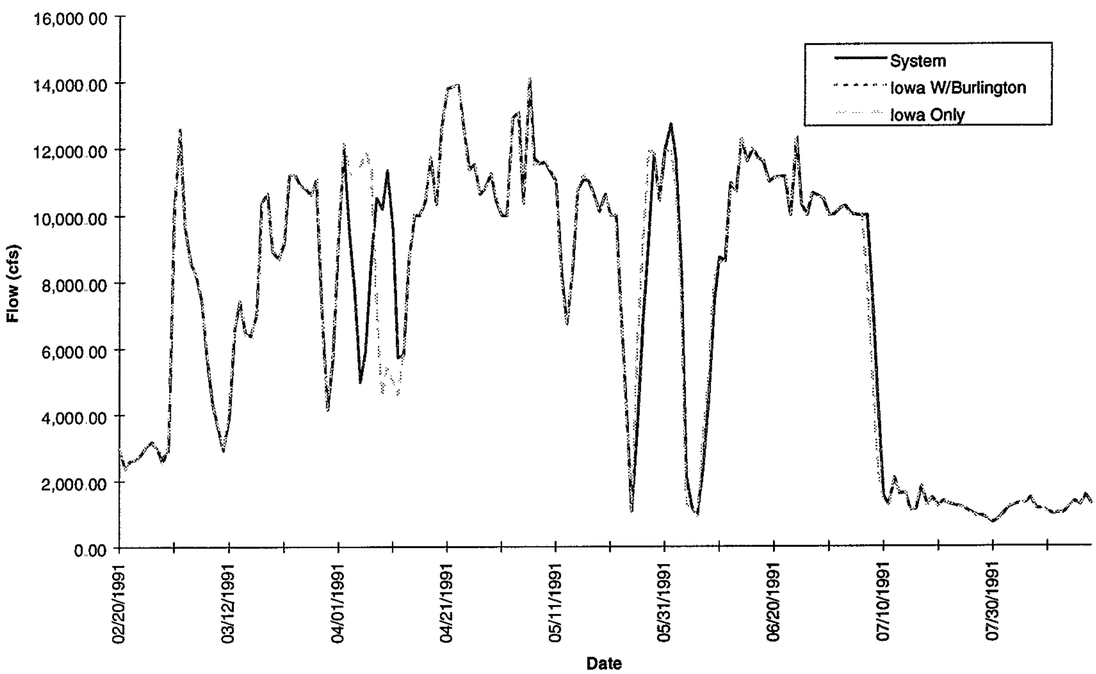

FIGURE E-9d. Hydrograph of Model Results at Lone Tree - Flood of 1991

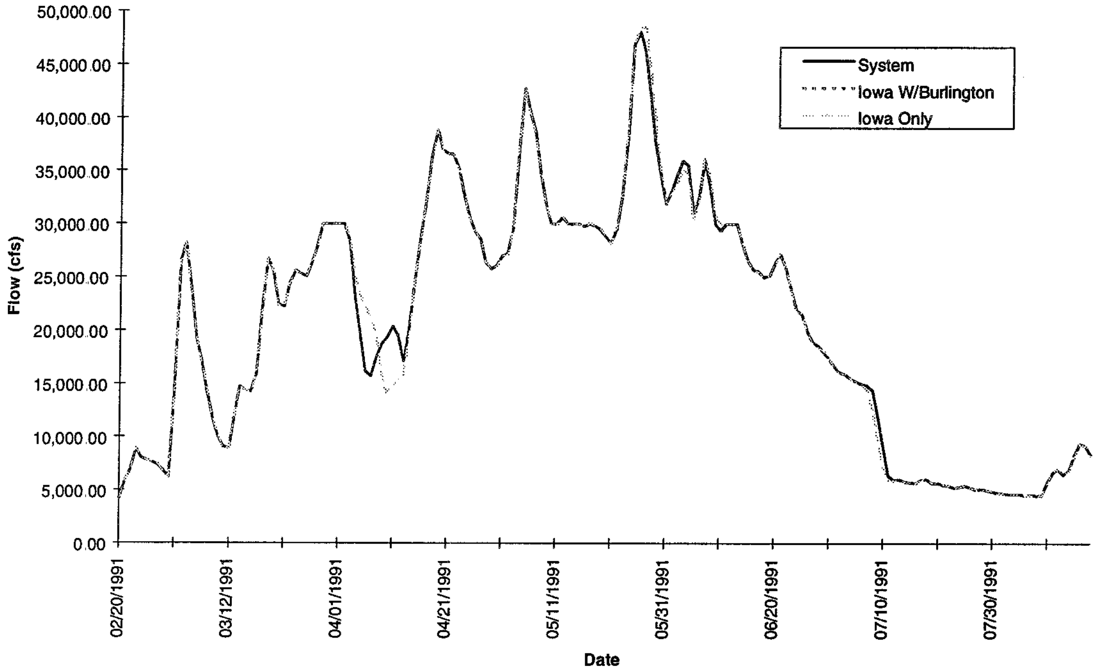

FIGURE E-9e. Hydrograph of Model Results at Wapello - Flood of 1991

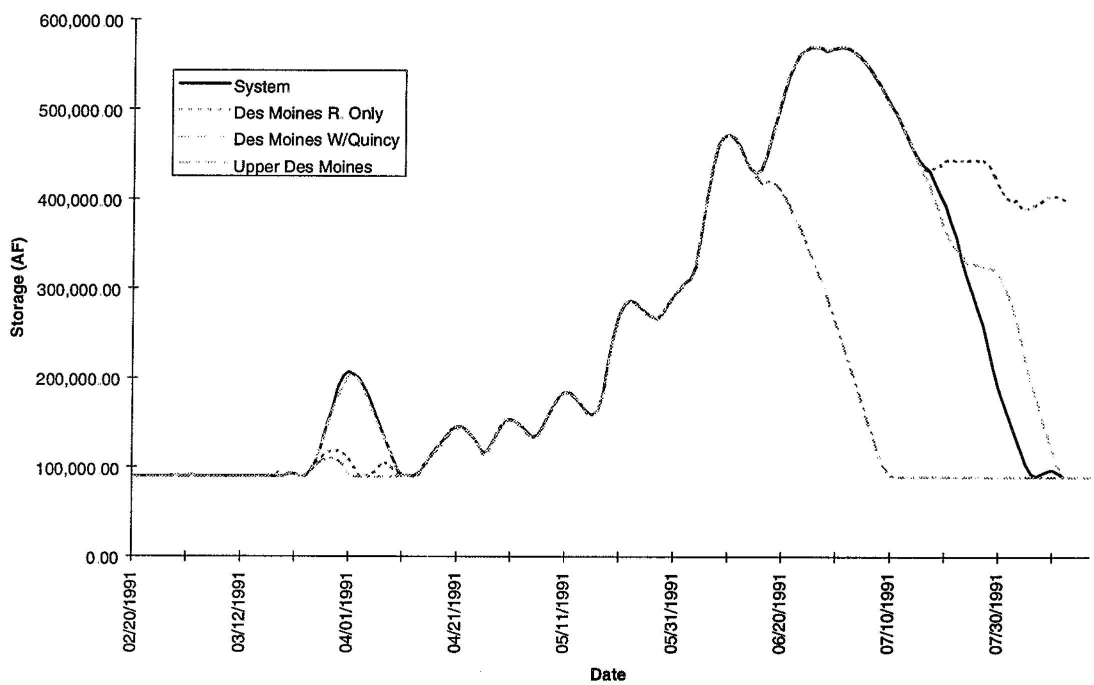

FIGURE E-9f. Model Results of Saylorville Reservoir Storage - Flood of 1991

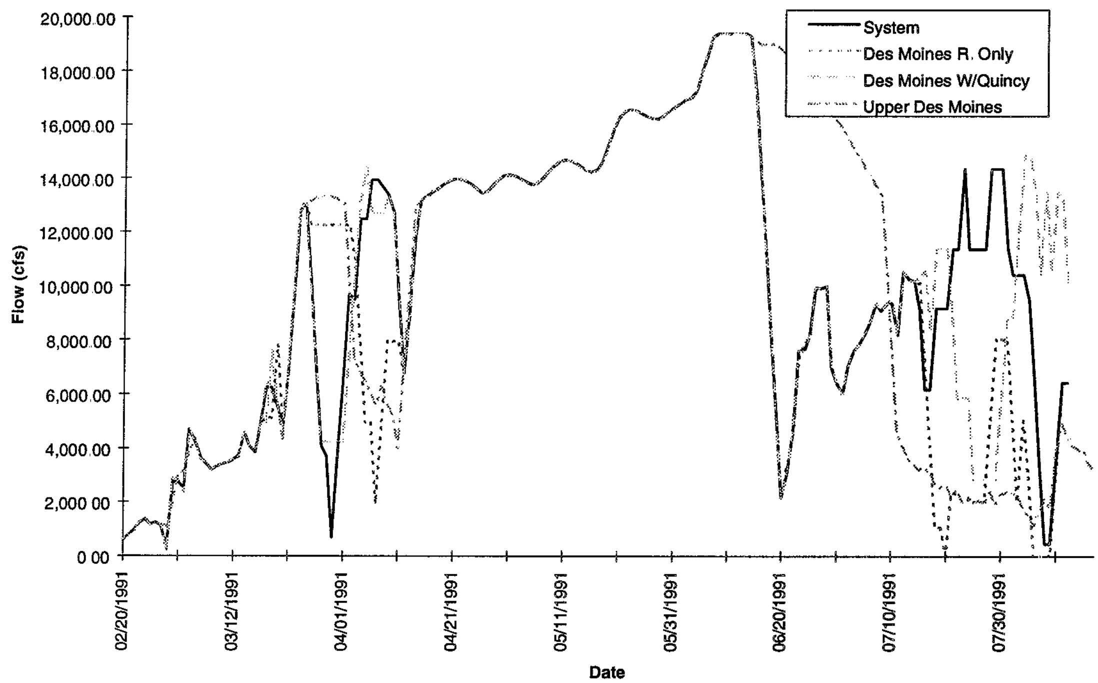

FIGURE E-9g. Model Results of Saylorville Reservoir Release - Flood of 1991

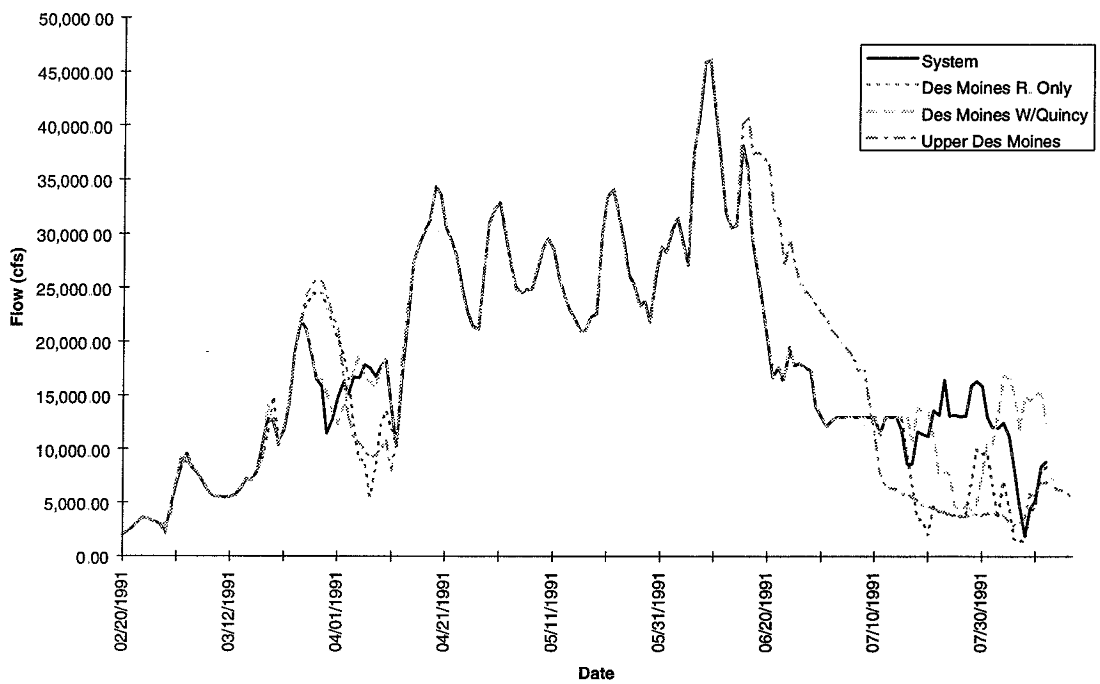

FIGURE E-9h. Hydrograph of Model Results at 14th Street - Flood of 1991

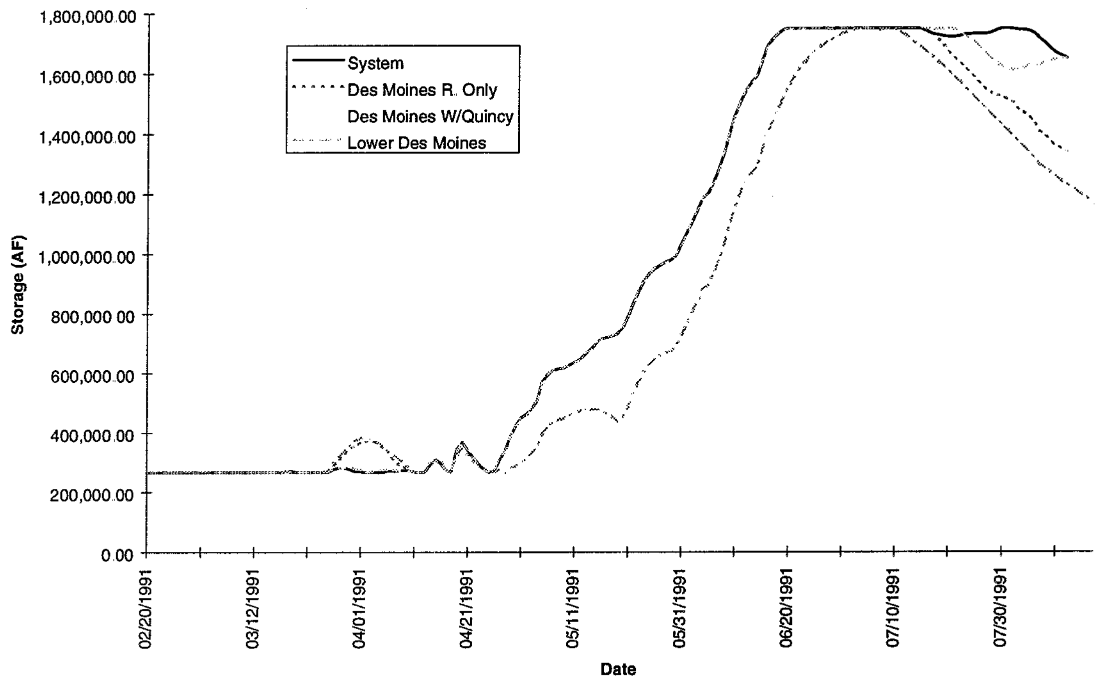

FIGURE E-9i. Model Results of Lake Red Rock Storage - Flood of 1991

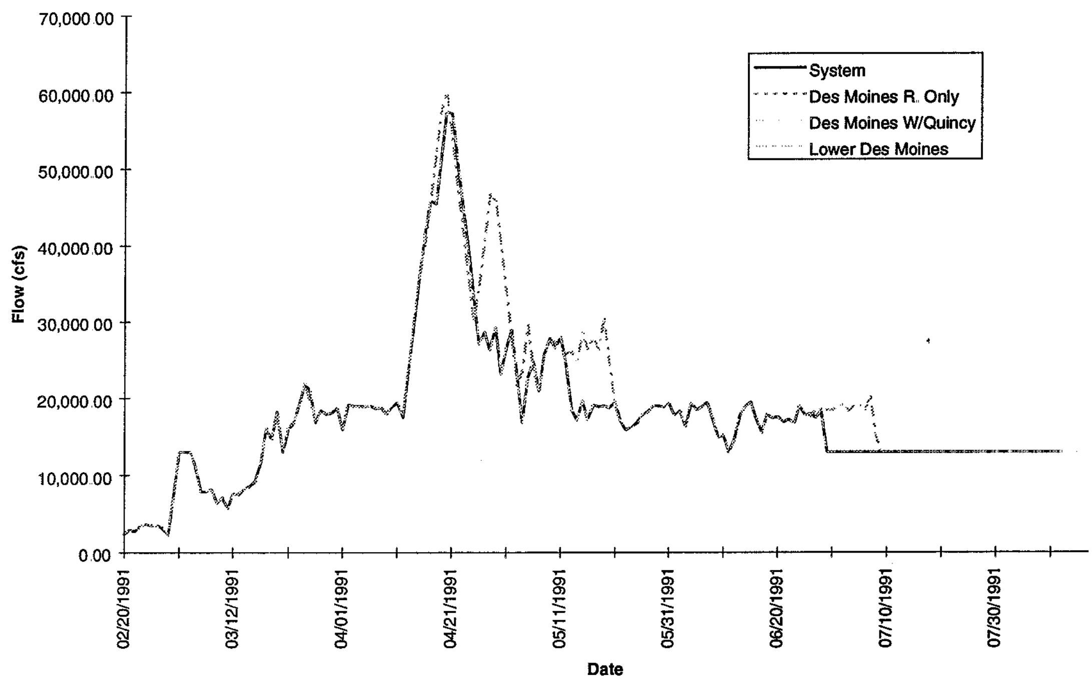

FIGURE E-9j. Model Results of Lake Red Rock Release - Flood of 1991

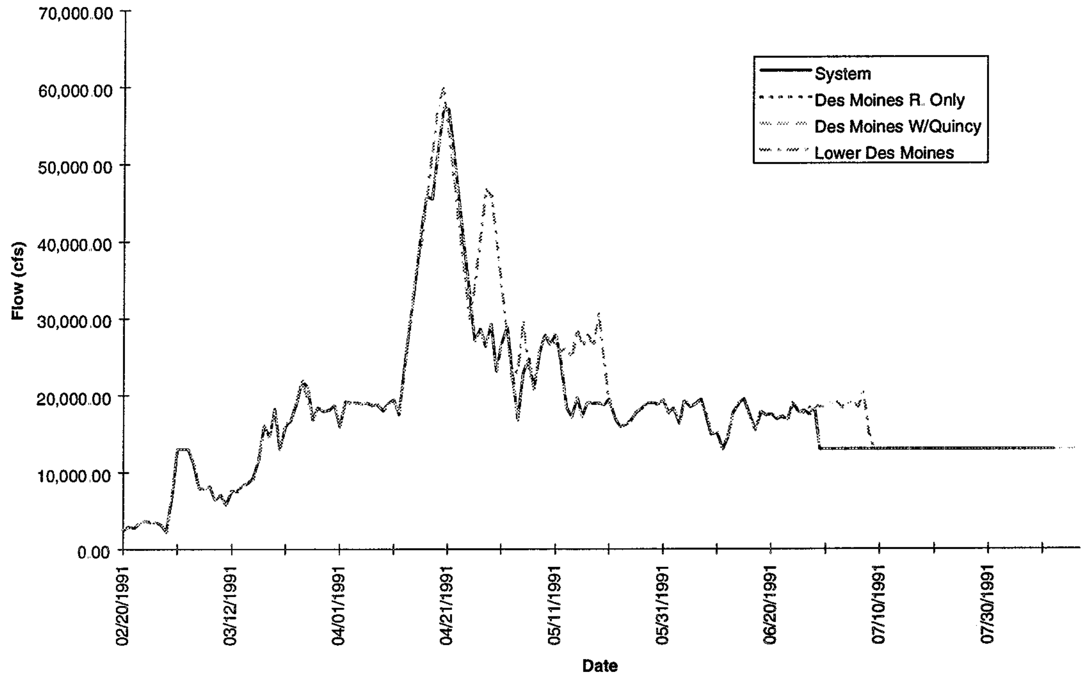

FIGURE E-9k. Hydrograph of Model Results at Tracy - Flood of 1991

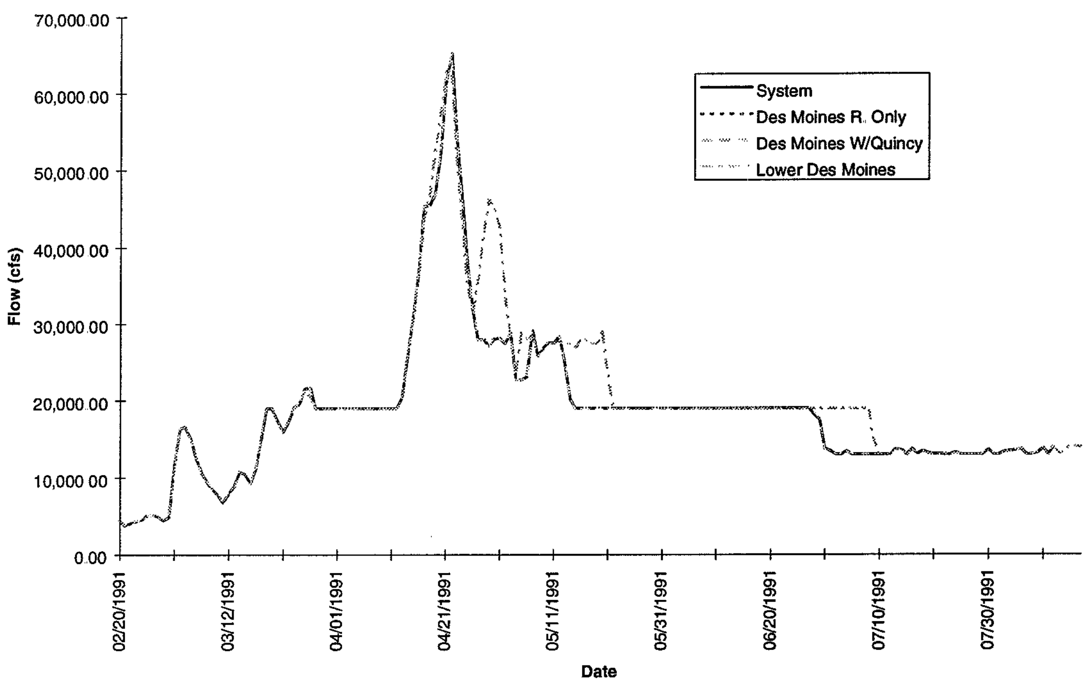

FIGURE E-9l. Hydrograph of Model Results at Ottumwa - Flood of 1991

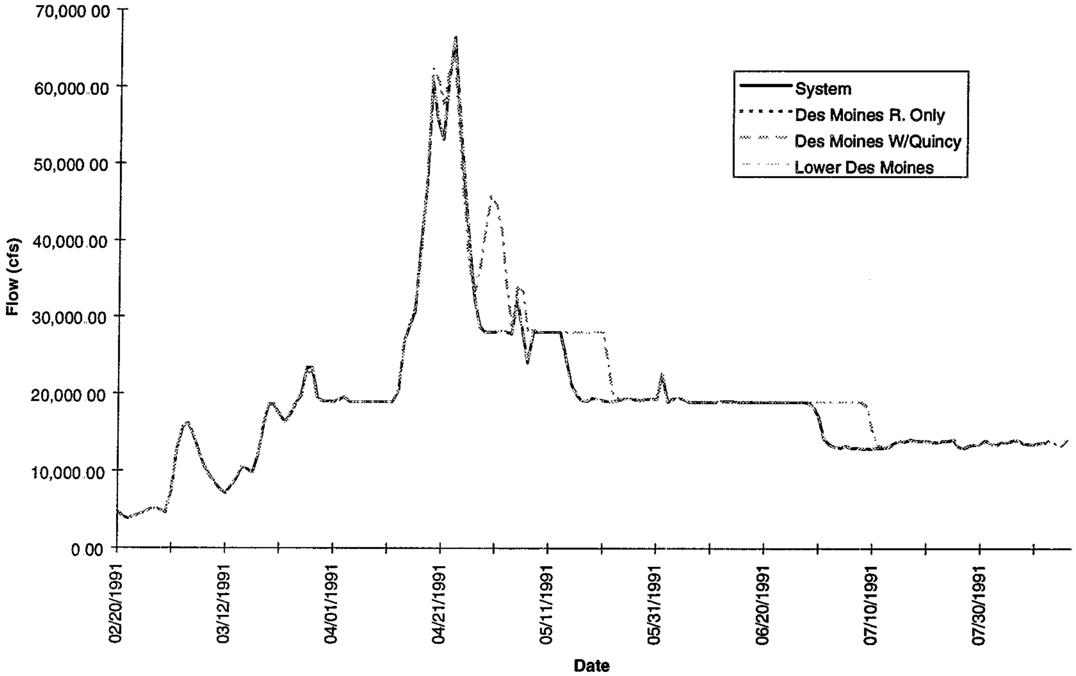

FIGURE E-9m. Hydrograph of Model Results at Keosauqua - Flood of 1991

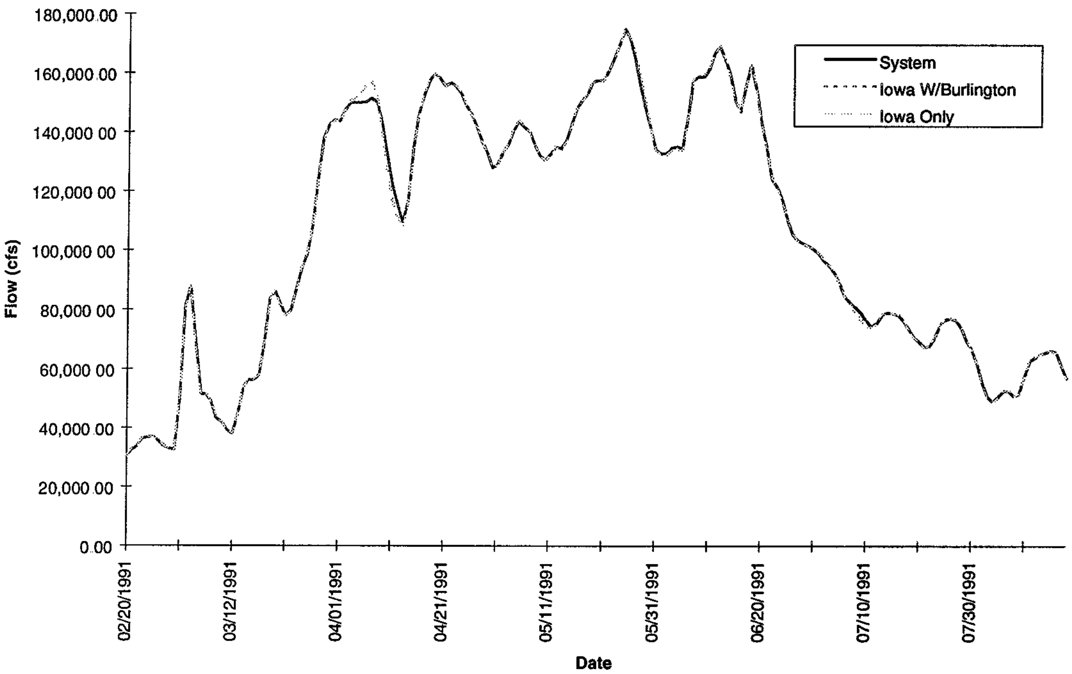

FIGURE E-9n. Hydrograph of Model Results at Burlington - Flood of 1991

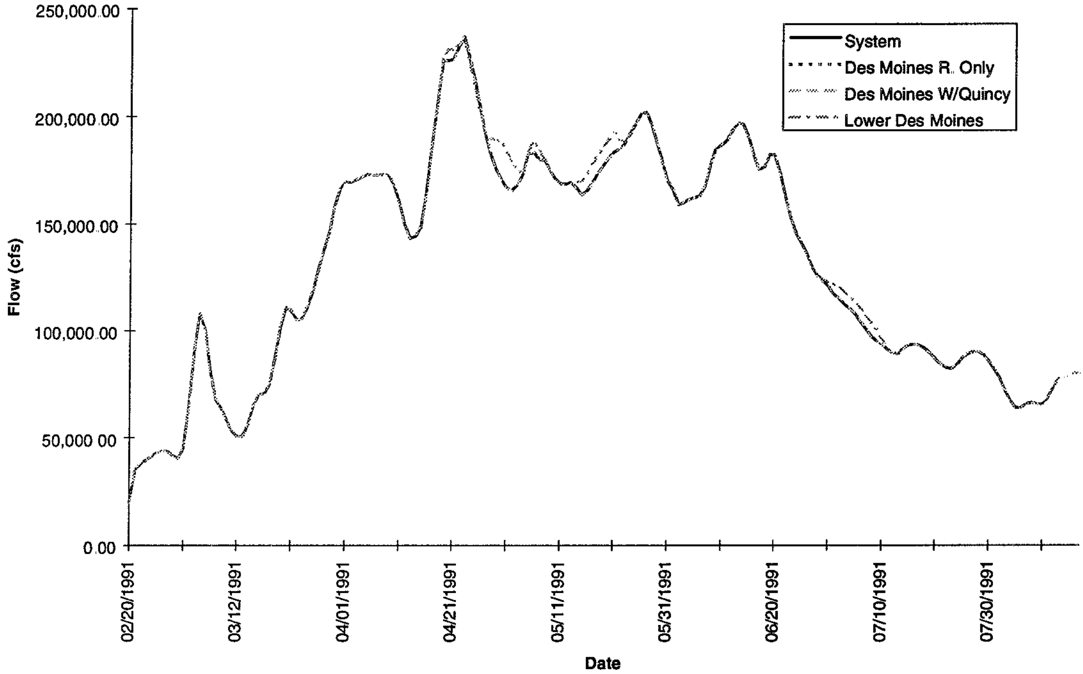

FIGURE E-9o. Hydrograph of Model Results at Quincy - Flood of 1991

1993 COMMENTARY

The flood of 1993 is by far the largest on record. As with many of the smaller floods, the variation in how the model operates Coralville Reservoir for the different system configurations has no effect on the peak-related penalty, and only a small effect on the model-computed penalty, as illustrated in Table E-10.

The operation of the reservoirs on the Des Moines River are primarily driven by two concerns. First, the model operates Saylorville Reservoir (Figures E-10f and E-10g) in order to minimize the large penalties associated with spilling which occur when reservoir storage reaches 676,000 ac-ft. Second, operation of Lake Red Rock is mainly concerned with minimizing the model-computed penalty at Quincy, Ill. Although the peak-related damage at Quincy is nearly the same for all operating schemes, the model-computed penalty is reduced by nearly 30% when Lake Red Rock operates for Quincy. This indicates that using a linear programming objective function based on peak-flow flows could lead to a significant reduction in peak-flow damage at Quincy.

TABLE E-10. Flood of 1993 Calculated Penalties

Site	Peak Flow Damage ($1000)							
	Observed	***A***	***BD***	***CD***	***BE***	***CE***	***BFG***	***CFG***
Iowa City	2,279	1,617	1,617	1,617	1,617	1,617	1,617	1,617
Lone Tree	902	953	953	953	953	953	953	953
Wapello	10,856	11,167	11,167	11,167	11,167	11,167	11,167	11,167
2nd Ave.	13,978	7,354	7,354	7,354	7,354	7,354	7,354	7,354
14th St.	-	-	-	-	-	-	-	-
Tracy	8,272	7,006	7,049	7,049	7,290	7,290	7,049	7,049
Ottumwa	18,120	15,190	15,242	15,244	18,120	18,120	15,242	15,244
Keosauqua	3,958	2,296	2,330	2,331	4,128	4,1281	2,330	2,331
Burlington	10,970	11,154	11,154	11,154	11,154	11,154	11,154	11,154
Quincy	138,979	129,982	129,983	129,983	129,998	129,998	129,983	129,983
Total	208,315	186,718	186,849	186,852	191,782	191,782	186,849	186,852

Site	Model-Computed Penalty ($1000)							
	Observed	***A***	***BD***	***CD***	***BE***	***CE***	***BFG***	***CFG***
Iowa City	68,717	33,010	30,858	30,858	30,858	30,858	30,858	30,858
Lone Tree	18,989	12,940	12,969	12,969	12,969	12,969	12,969	12,969
Wapello	312,580	277,966	278,308	278,336	278,308	278,336	278,308	278,336
2nd Ave.	211,887	147,491	147,491	147,491	147,491	147,491	147,491	147,491
14th St.	-	-	-	-	-	-	-	-
Tracy	449,979	421,968	421,968	421,968	421,968	421,968	421,968	421,968
Ottumwa	853,800	852,668	852,668	852,668	852,518	852,518	852,668	852,668
Keosauqua	102,365	89,237	89,174	89,175	96,610	96,610	89,174	89,175
Burlington	154,294	144,679	144,697	144,747	144,697	144,747	144,697	144,744
Quincy	2,207,830	1,426,780	1,429,771	1,430,582	2,005,800	2,007,361	1,429,771	1,430,582
Coralville		9,701	9,481	9,447	9,481	9,447	9,481	9,447
Saylorville		4,413,868	4,414,126	4,413,295	4,414,034	4,414,034	4,407,163	4,407,163
Red Rock		199,050	200,549	201,370	60,600	60,600	207,512	207,503
Total w/o Stor.	4,380,440	3,406,738	3,407,903	3,408,794	3,991,218	3,992,858	3,407,903	3,408,793
Total w/ Stor.		8,029,358	8,032,058	8,032,906	8,475,334	8,476,939	8,032,058	8,032,906

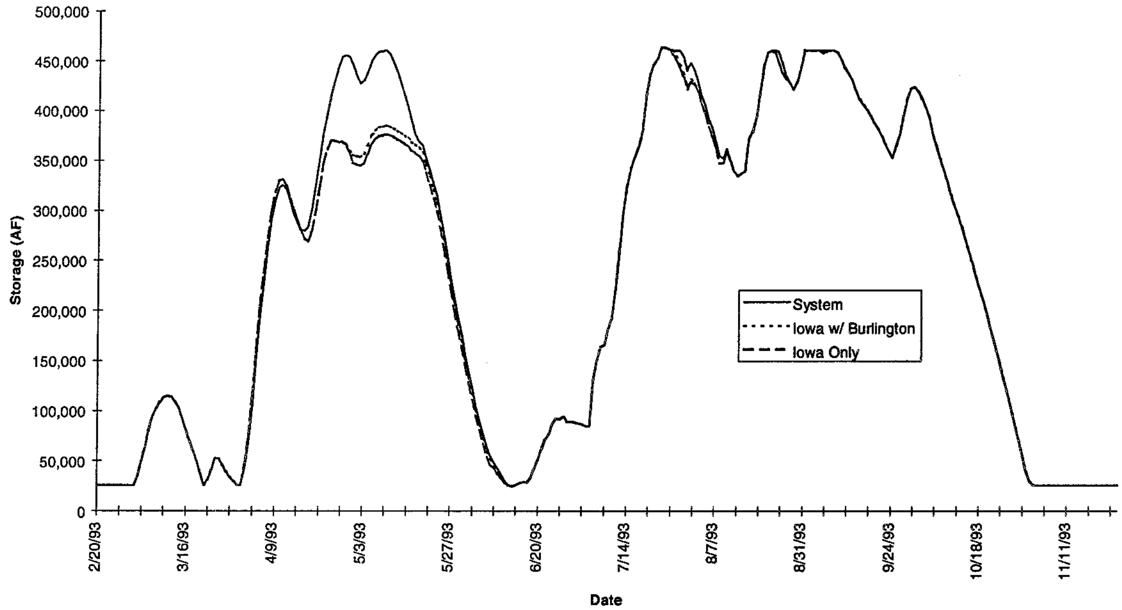

FIGURE E-10a. Model Results of Coralville Reservoir Storage - Flood of 1993

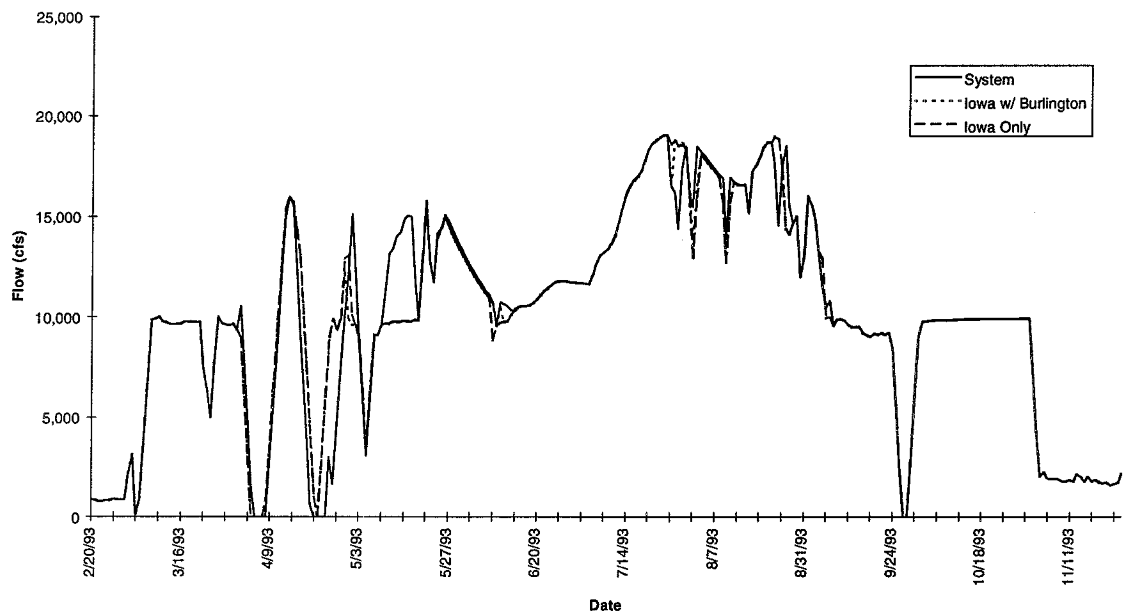

FIGURE E-10b. Model Results of Coralville Reservoir Release - Flood of 1993

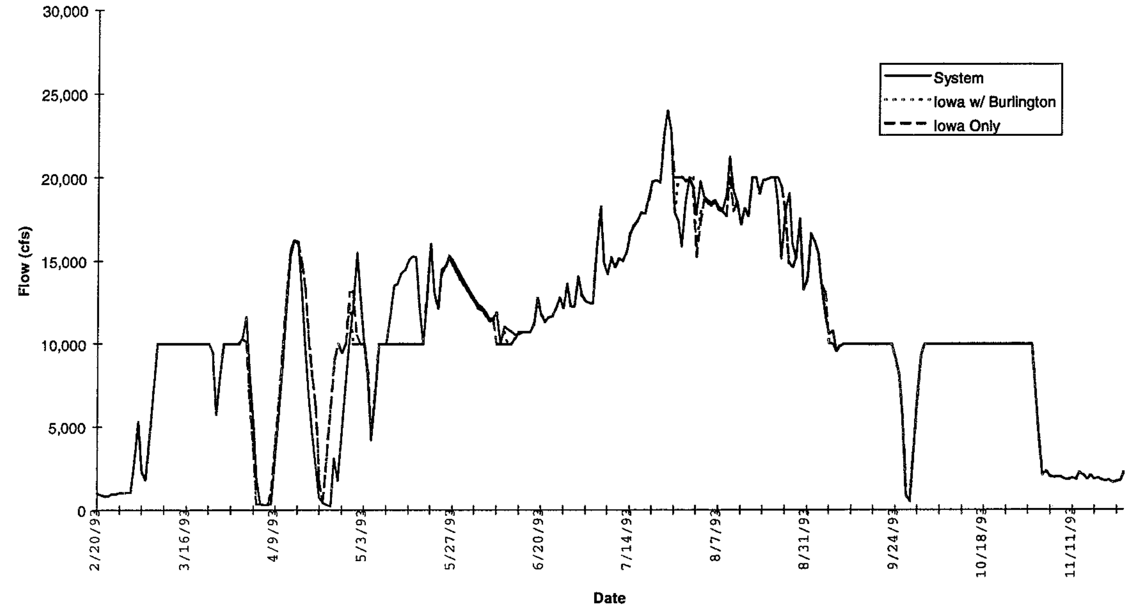

FIGURE E-10c. Hydrograph of Model Results at Iowa City - Flood of 1993

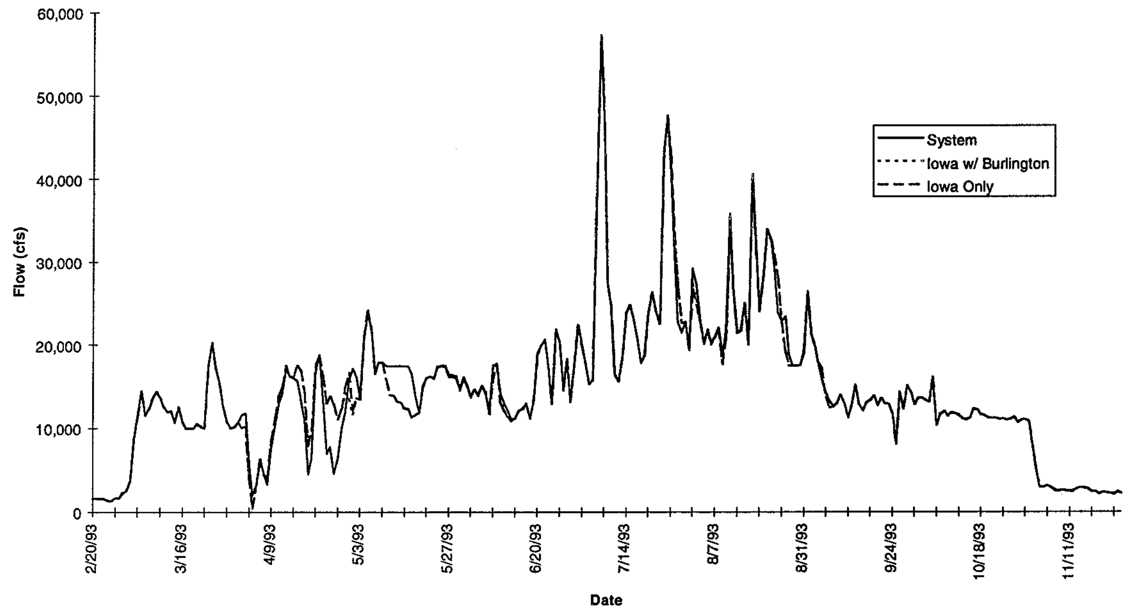

FIGURE E-10d. Hydrograph of Model Results at Lone Tree - Flood of 1993

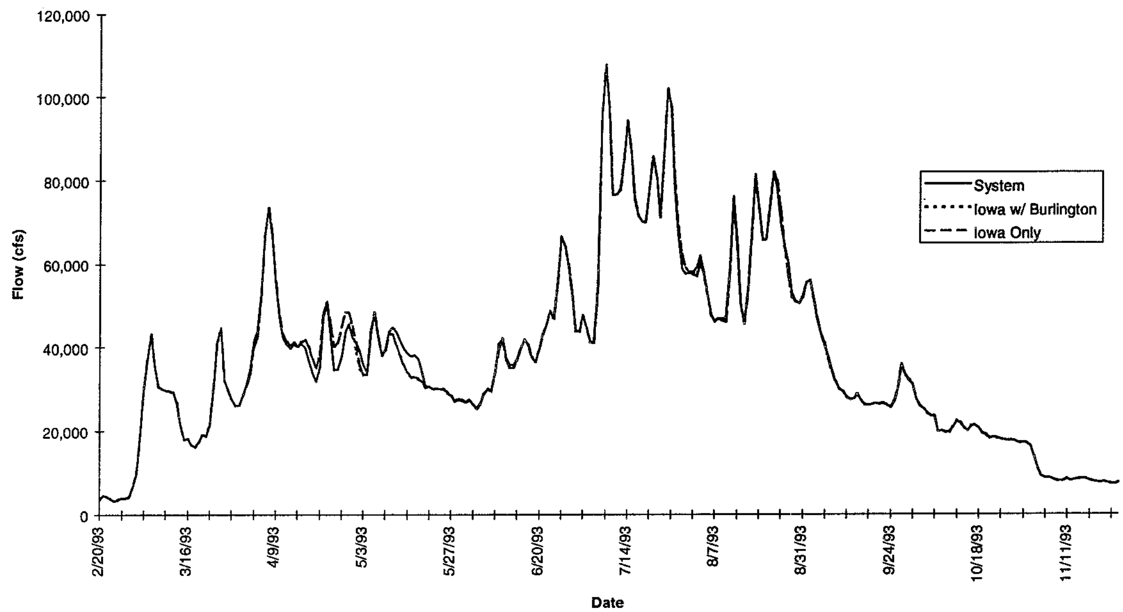

FIGURE E-10e. Hydrograph of Model Results at Wapello - Flood of 1993

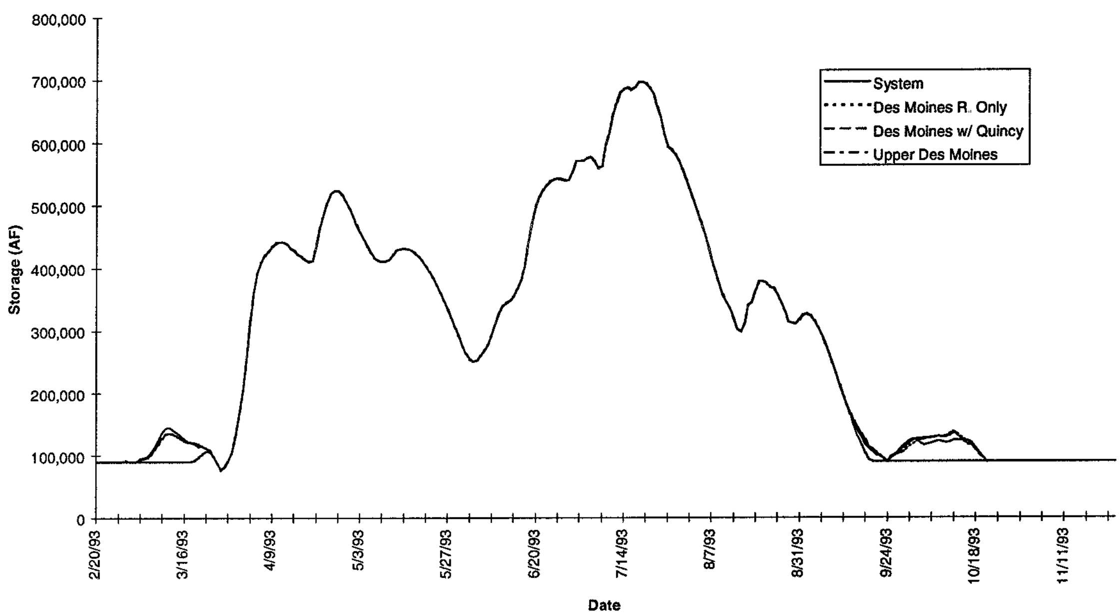

FIGURE E-10f. Model Results of Saylorville Reservoir Storage - Flood of 1993

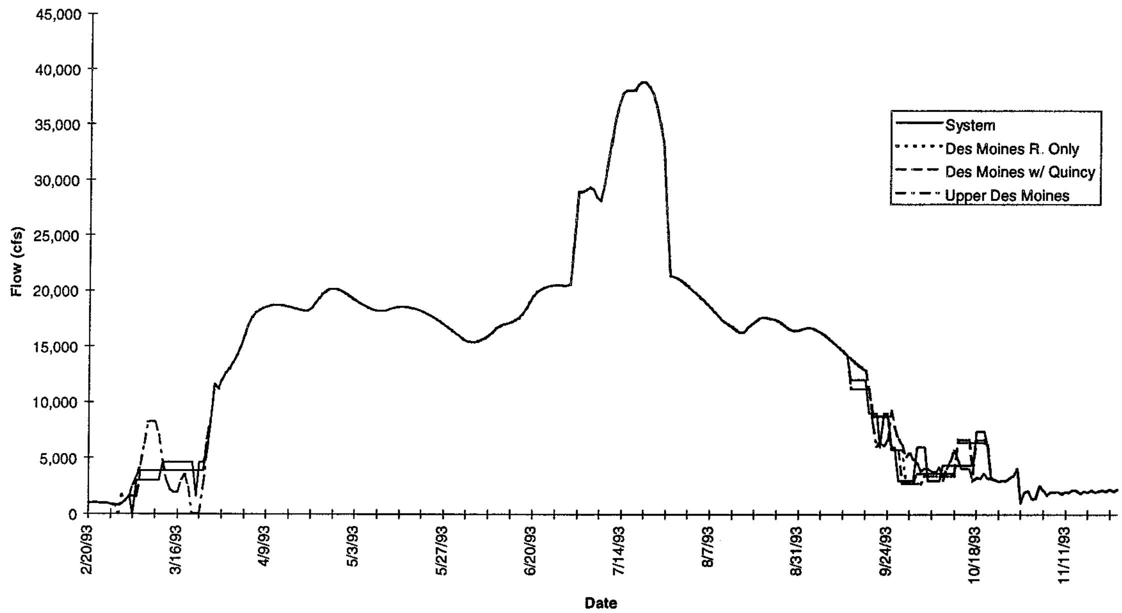

FIGURE E-10g. Model Results of Saylorville Reservoir Release - Flood of 1993

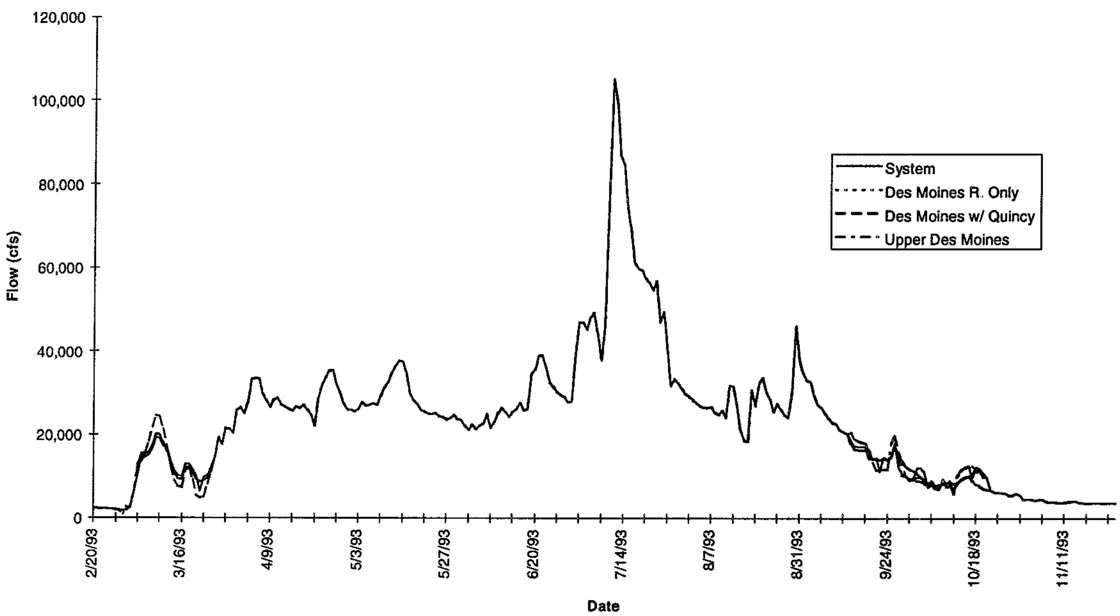

FIGURE E-10h. Hydrograph of Model Results at 14th Street - Flood of 1993

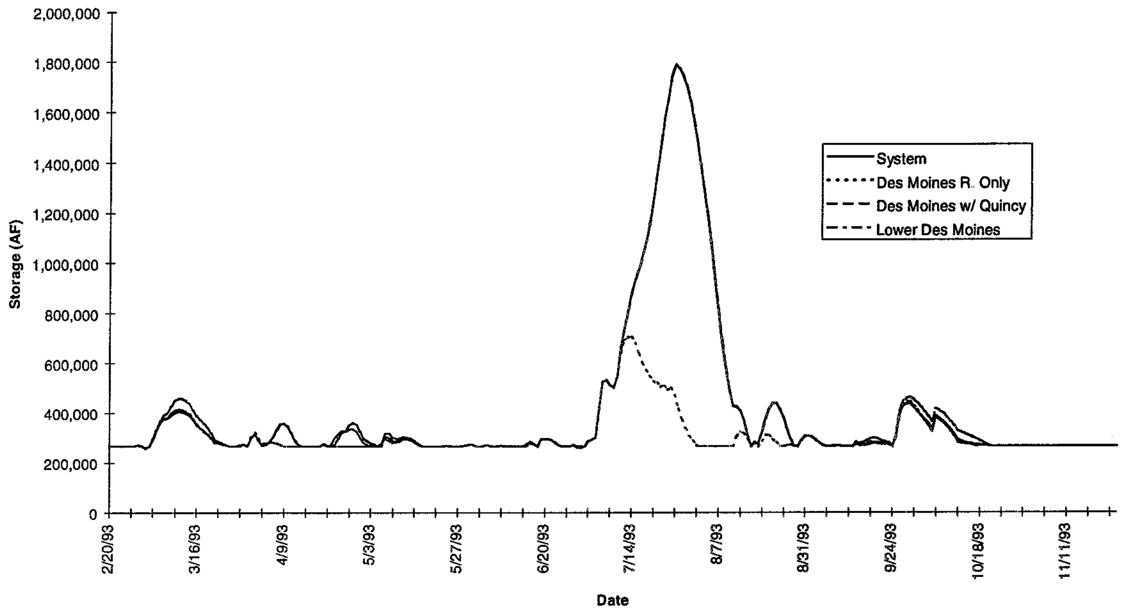

FIGURE E-10i. Model Results of Lake Red Rock Storage - Flood of 1993

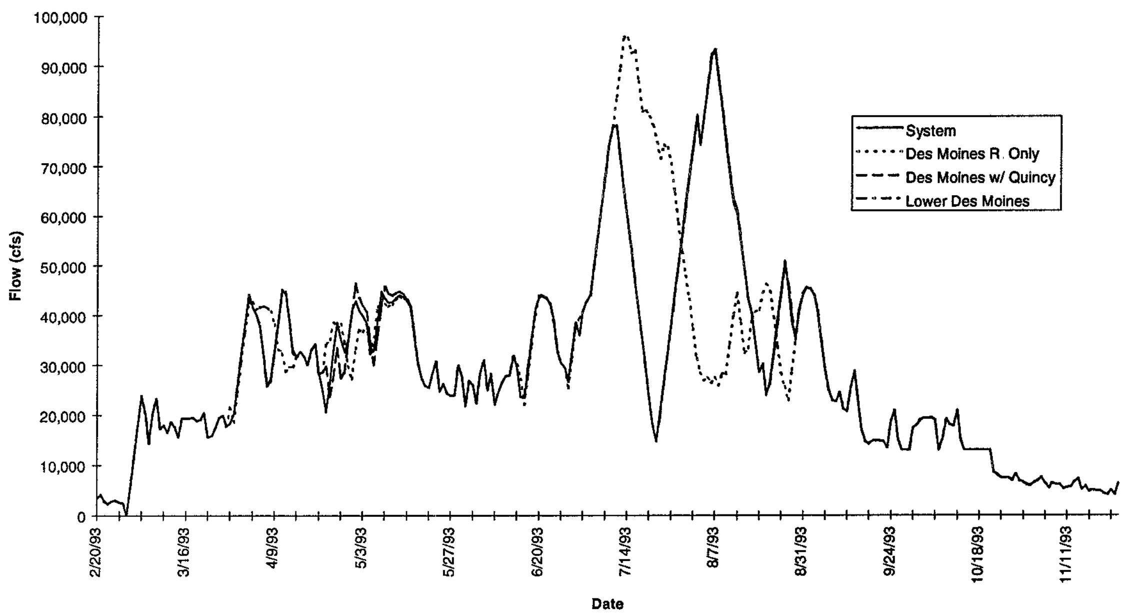

FIGURE E-10j. Model Results of Lake Red Rock Release - Flood of 1993

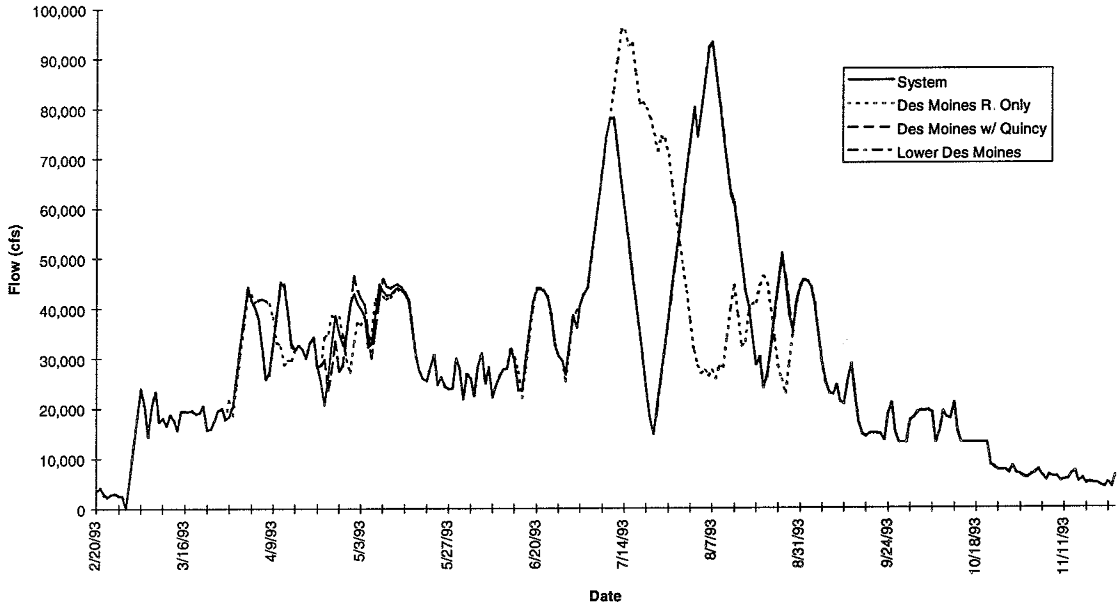

FIGURE E-10k. Hydrograph of Model Results at Tracy - Flood of 1993

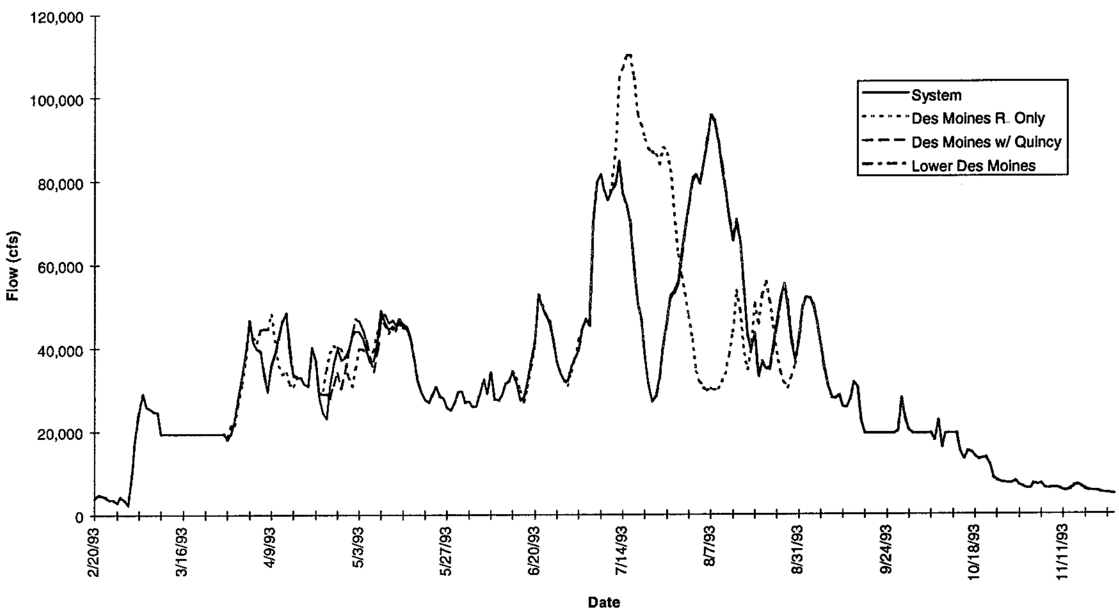

FIGURE E-10l. Hydrograph of Model Results at Ottumwa - Flood of 1993

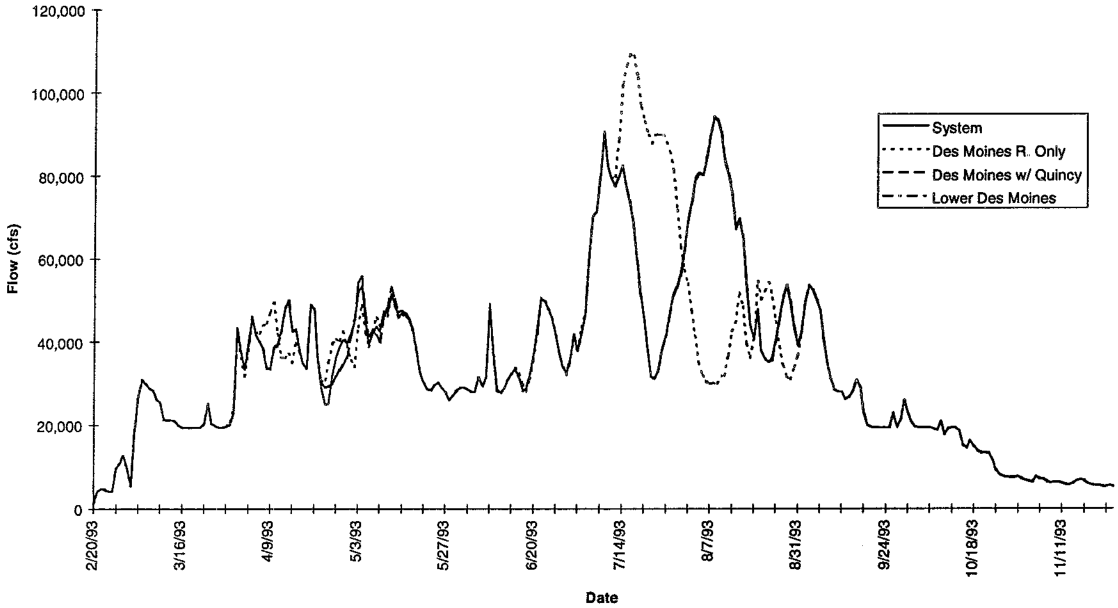

FIGURE E-10m. Hydrograph of Model Results at Keosauqua - Flood of 1993

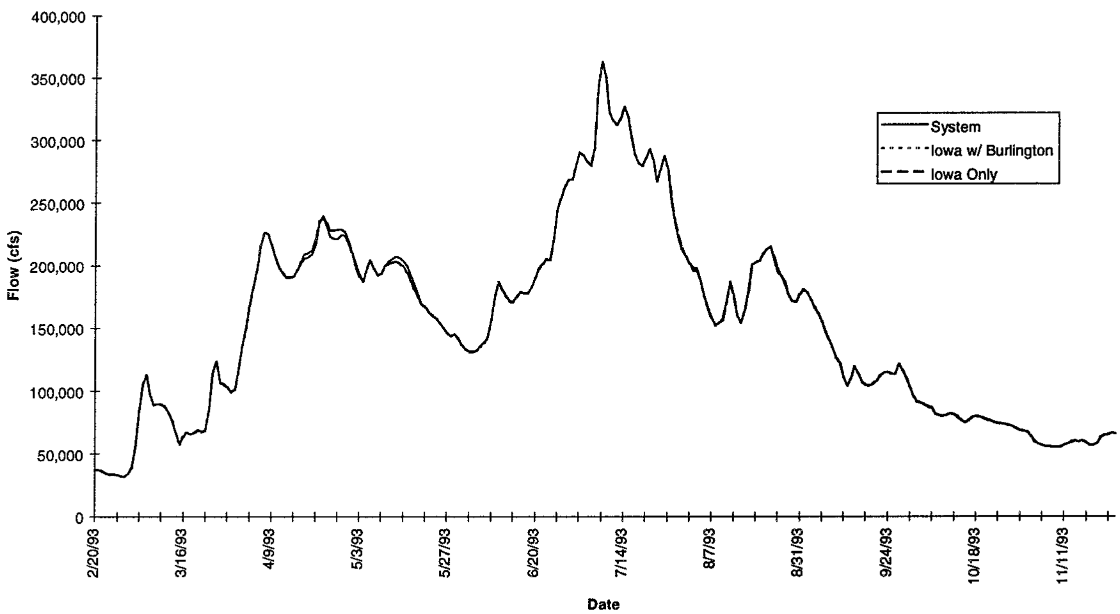

FIGURE E-10n. Hydrograph of Model Results at Burlington - Flood of 1993

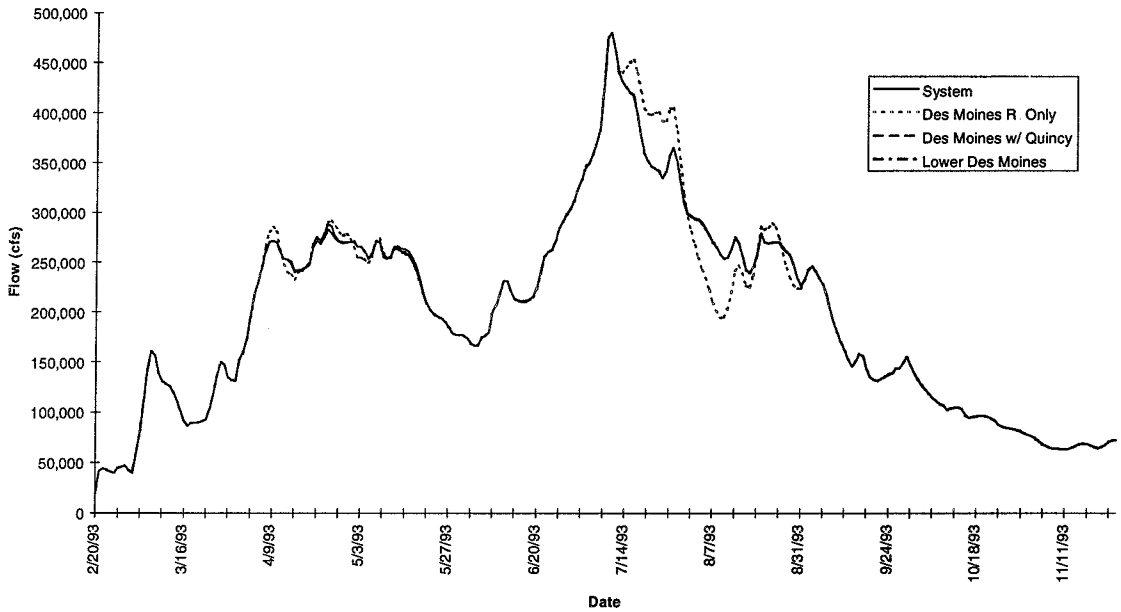

FIGURE E-10o. Hydrograph of Model Results at Quincy - Flood of 1993