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Review of Hydrologic and Hydraulic Studies and Unsteady Flow Routing of the 1993 Flood in the Upper Mississippi River System

by

Misganaw Demissie, Deva K. Borah, and David Admiraal
Office of Sediment & Wetland Studies

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Illinois State Water Survey
Hydrology Division
Champaign, Illinois

A Division of the Illinois Department of Natural Resources

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Nomenclature

A	Cross-sectional area of channel
A_o	Storage area (flow velocity considered negligible)
B	Channel top width
c	Combined channel
fp	Floodplain
g	Gravitational acceleration
h	Elevation head
i	Spatial index
j	Temporal index
K	Any variable
K_e	Expansion/contraction coefficient
mc	Main channel
n	Manning's roughness coefficient
q	Lateral inflow or outflow
Q	Discharge
R_h	Hydraulic radius
S	Bed slope
S_e	Energy slope
S_f	Friction slope
t	Time
v_x	Streamwise velocity of lateral inflow
W_f	Wind term
x	Streamwise distance
θ	Weighting factor

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Introduction

The Great Flood of 1993 has been recognized as the greatest flood experienced in the Midwest in recent history. The flood, one of the worst national disasters in the United States, has generated intense discussions about flooding and floodplain management. Fundamental questions are being asked about past and present river and floodplain regulation, land-use practices, and better management of future floods. What are the impacts of land-use changes such as enhanced drainage by ditches and tiles, drainage and conversion of wetlands, and expanding residential and industrial areas on flood peaks and heights? How do levees along rivers affect flood heights? How effective are reservoirs during major floods? Do navigational locks and dams affect flood stages? Can wetland acreage in the watershed be increased to reduce flood peaks? Can some levees be removed or set back to decrease flood heights? Can levee heights be increased to reduce flood damages? These are just a few of the questions being asked after the disastrous 1993 Flood.

Formulating answers to these types of questions requires detailed hydrologic and hydraulic modeling of the Upper Mississippi River Basin and its river system. Figure 1 shows the area covered by this 700,000-square-mile river basin and its major river system. Several agencies and groups have conducted their own hydrologic and hydraulic investigations. Study results and recommendations will have a long-term influence on flood control and floodplain management policies in the United States.

The State of Illinois has a large stake in any changes made in governmental policies and approaches to floodplain management because Illinois commerce, agriculture, navigation, and recreation all depend on the Mississippi and Illinois Rivers. Illinois is the most populous state in the Midwest, with access to more river miles (RMs) on the Mississippi River than any other state. More commodities are transported on the Illinois River than on the Upper Mississippi River. In addition, some of the most important natural areas and wildlife refuges in the state are located along the Illinois and Mississippi Rivers. Policy changes present great opportunities for

Figure 1. Upper Mississippi and Missouri River basins

state and federal governments to develop fish and wildlife habitats and provide flood relief along the floodplains of these rivers.

States in the Midwest look to Illinois to lead the discussion of river regulation and floodplain management in the Mississippi River basin. Given Illinois' current leadership role, and the opportunity to influence new federal policies and programs in these areas, it is crucial that the state independently review and evaluate the results of technical studies conducted by different federal agencies, environmental groups, and others concerning the Mississippi River and future floodplain management policy.

Such a review is also necessary because of the significant differences of opinion about the direction mat floodplain management should take following the 1993 flooding along the Mississippi, Missouri, and Illinois Rivers. Most critical decisions will be based on the hydrologic and hydraulic analyses conducted by diverse groups, which inevitably arrive at different conclusions and recommendations. A thorough and independent review of the data is required if the State of Illinois is to do more than simply endorse the position of another agency or group.

This project was initiated to enable the state to review the hydrologic and hydraulic studies conducted by federal agencies and other groups. The Illinois State Water Survey (ISWS), the state's primary data collection and research agency on water resources, proposed to conduct the technical review of studies on the 1993 Flood and future floodplain management. This report presents the ISWS' review of these hydrologic and hydraulic studies.

Different agencies and investigators have used different hydrodynamic models in their studies, and their conclusions and recommendations are based on results from these models. Therefore, it is important to compare results from different models and evaluate their predicting capabilities and relative accuracies. Another objective of this study was to evaluate several unsteady flow models for use in investigating different scenarios along the Mississippi and Illinois Rivers. However, only one model was available for use in this study. The model was used to study certain critical reaches of the Mississippi River (Lock and Dam 22-Thebes), Illinois River (Morris-Grafton), and Missouri River (Hermann-St. Louis). This report presents these Illinois State Water Survey modeling results.

The report has two major sections. The first section reviews the most significant research reports on the 1993 Flood. The second section evaluates the application of an unsteady flow routing model to examine the flood and different management scenarios. Since we were unable to obtain the other two hydraulic models from the developers, we could not conduct the comparative analyses we planned for. Therefore at this stage this study is incomplete and needs further development when the models eventually become available. Once the different modeling efforts are thoroughly analyzed and evaluated, we will prepare a comprehensive report dealing with major floods along the Mississippi and Illinois Rivers.

Acknowledgements

This study was supported by the Illinois Department of Natural Resources. Becky Howard and Dawn Amrein produced the report, Eva Kingston and Sarah Hibbeler edited it, and Linda Hascall prepared some of the figures.

Review of Hydrologic and Hydraulic Studies of the 1993 Flood

The 1993 Flood on the Mississippi River in Illinois

N.G. Bhowmik, ed. 1994. Illinois State Water Survey Miscellaneous Publication 151, Champaign, Illinois

This first-hand comprehensive report was published by the Illinois State Water Survey (ISWS) about the 1993 Flood on the Mississippi River in Illinois and the lower reaches of the Illinois River (Bhowmik et al., 1994). The report provides a background of the Mississippi and Illinois Rivers, including information on their geography, climate, previous flooding, and a history of the levees.

The geography of the Upper Mississippi River System (UMRS) is described using information published by the Upper Mississippi River Basin Commission and the Environmental Work Team in 1980 and 1981, respectively. The report includes a description of the navigation system on the Upper Mississippi and Illinois Rivers and the climate of the Mississippi River watershed, based on 30 years of record (1961-1990). A comprehensive description of the hydrology of the Upper Mississippi River covers average runoff, runoff trends, possible causes of increased flows, flooding upstream and downstream of the Missouri confluence, flooding magnitudes, and historical floods and stages. A history of levees includes complete lists and locations of Illinois Drainage and Levee Districts along the Mississippi River and along the Alton Pool of the Illinois River, and describes levee design, construction, and causes of failures.

A discussion of the synoptic basis for the 1993 Flood examines regional weather patterns prior to the flood and precipitation patterns in the entire United States, with emphasis on the Midwest. Also examined are precipitation in early 1993 and from April-September of 1993; return frequencies of rainfall events during summer 1993 (which varied from 13 years to greater than 100 years); a list of days with record rainfall amounts (the highest was July 9 with 7.9 inches); mean statewide precipitation for June, July, August, and September; and rainfall within major watersheds of the region. Soil moisture measurements taken in Midwestern states during the summer of 1993 are also presented, along with soil moisture outlooks for the fall and winter based on a simulation model.

A comprehensive chronology of the 1993 Flood describes the hydrologic conditions preceding the flood, June flooding in Minnesota and Wisconsin, July flooding in Iowa and on the Mississippi River upstream of St. Louis, and flooding in the Missouri River watershed and the Mississippi River at St. Louis. River stages at key stations along the Mississippi River during January-August 1993 are also presented and compared with record and historical stages. The duration of stages over flood stage and the impact of levee failures on river stages are briefly described. Main channel discharges along the Mississippi River are presented. The highest discharge, 1,030,000 cubic feet per second (cfs) at St. Louis, Missouri, on August 1, 1993, was

30,000 cfs less than a historical peak at Chester, Illinois. The carrying capacity of floodplains is discussed based on studies conducted at the ISWS during 1979 and 1982.

Levee breaches in Illinois along the Mississippi and Illinois Rivers during the flood are chronologically listed and described. The report gives the locations of the levee breaches and areas affected and presents a detailed investigation of the Len Small Levee breach in Illinois. This particular breach diverted a portion of the flow from the Mississippi River through the Lake Creek and Cache River diversion outlet and back to the Mississippi, cutting down its travel path. The report also discusses the consistent struggle between humans and nature to control levees, specific measures undertaken to protect levees at different locations, and the outcome.

The report also outlines the impacts of the 1993 Flood and presents a detailed discussion of the social disruption it caused. Effects on public water supplies in 17 Illinois counties are described, along with the economic impacts on agriculture (field crops and livestock), transportation (navigation, railroads, bridges, and highways), business and industry, and recreation. Accounts of residential damage and evacuations are given. An overview of the environmental impacts describes the flood's effect on floodplains, water quality (mainly due to agricultural chemicals), sediment, and ground-water supplies and quality. The report examines variations in ground-water levels at several locations from more than 40 years of records and describes an investigation of ground-water flooding in the Havana lowland area. The flood's legacies and beneficial and detrimental impacts on fish, wildlife, and vegetation are described.

Finally, this report outlines some of the lessons learned from the 1993 Flood and addresses national policy issues, government plans and policies, levee performance, effects of levees, effects of floodfighting, regulation of reconstruction, buyouts of flood-prone homes and businesses, levee degradation, flood modeling, and confusion over information dissemination. It includes a list of information gaps and research needs in the areas of hydraulics and hydrology, meteorology, sediment transport and sedimentation, surface and ground water, water quality, and levees. The report concludes with a summary and a pictorial review of the Flood of 1993.

The Great Flood of 1993: Long-Term Approaches to the Management of the Mississippi and Illinois Rivers

Illinois Department of Energy and Natural Resources, Governor's Workshop on 'The Great Flood of 1993: Long-Term Approaches to the Management of the Mississippi and Illinois Rivers, Including Lessons Learned and Information Gaps." March 1, 1994, Springfield, Illinois

These proceedings are from the Governor's Workshop on the Great Flood of 1993, which consisted of eight papers on the background and impacts of the flood, a panel discussion of the lessons learned and future policy directions, small group discussions, and reports from these small groups.

The first paper, by H.V. Knapp, Illinois State Water Survey (ISWS), describes the physical geography of the Upper Mississippi/Missouri River system and reviews the historical floods in this system, with a focus on the annual average precipitation in the basin and average annual stage and discharges on the Mississippi River at Keokuk, Iowa, and St. Louis, Missouri. The second paper, by K.E. Kunkel, ISWS, gives a climatic perspective on the 1993 Mississippi River flood and describes the much above normal precipitation in the basin from July 1992 to September 1993. The return period of the summer 1993 precipitation exceeded 200 years.

The third paper, by D.T. Braatz, National Weather Service (NWS) North Central River Forecasting Center (NCRFC), Minneapolis, Minnesota, describes the data sources and hydrologic model used by the NWS in forecasting the 1993 Flood. The hydrologic model has runoff and flow components. The runoff model, or Antecedent Precipitation Index (API) model, computes a daily index of soil moisture, accounts for any additional rainfall, and computes any possible runoff. The flow model is based on the unit hydrograph technique. The author identifies the major forecast challenge involved in obtaining a reasonably modeled sub-basin runoff value, especially given that rainfall continued for days in many cases. When record flood stages were reached, the rating curves at several points exceeded stages from previous floods. Volumes exceeded calibrated values from previous floods, testing the limits of routing procedures.

According to Braatz, the greatest challenges for hydrologic forecasters lay in simulating overtopped and breached levees and estimating the volume of flow lost from the river channel to fill backwater areas behind levees. The current method used to average basin precipitation was inadequate for Des Moines, Iowa, since the concentration of runoff was further downstream from the center of the tributary sub-basins, which led to misleading predictions of flood-crest timing. The author concludes that "Much development work needs to be done in the aftermath of this Great Flood of 1993. The NCRFC is faced with the huge task of updating and revising forecast procedures, re-calibrating models, evaluating ratings and routings, and continuing the process of enhancing data collection and forecast coordination."

The fourth paper, by N.G. Bhowmik, ISWS, focuses on hydraulic and hydrologic factors in the Flood of 1993 and is primarily based on the 1994 report by Bhowmik et al. (reviewed earlier). It presents the durations of river stages exceeding flood stage at stations along the Mississippi River during the flood, and compares the discharges during this flood with those during the Flood of 1973 at two stations along the Mississippi: Keokuk, Iowa, and St. Louis, Missouri. The 1973 Flood was a spring flood (April and May), whereas the 1993 Flood was a much more severe summer flood (July and August). Stages and discharges measured during the peak flood period at Hermann on the Missouri River are also presented.

The author makes several observations and suggestions based on the Flood of 1993. First, flood conveyance through me floodplain is an important factor that must be considered in any project related to floodplain management. Stages on the Missouri River at Hermann dropped more than 4 feet for the same discharge within a month when the river and its floodplains likely became a fully conveying channel. Approximately 50 percent of the Missouri River flow discharged directly into the Mississippi River over the St. Charles Peninsula on August 2, 1993, thus completely bypassing the main channel of the Missouri River. The failure of the Len Small Levee near Miller City allowed about 20 to 25 percent of the Mississippi River floodwater to cut across a bend. Second, formulating alternative measures to control and manage a flooding event such as the one experienced in 1993 requires thorough hydraulic and hydrologic analyses of the river floodplain system, including the use of an interactive dynamic flood-routing mathematical model with a component describing sediment transport and changes in river morphology that occur during such an event. Third, an evaluation of the impacts of wetlands, land-use changes, levees, roads, highways, and urban areas on the floodplains is also necessary.

The fifth paper, by M.J. Chrzastowski, Illinois State Geological Survey, describes the geologic factors related to the 1993 Flood in Illinois. It examines geologic controls such as topography and sediments and geologic impacts such as erosion and deposition, and describes a geologic investigation of the flood. The sixth paper, by J. Scanlon, U.S. Army Corps of Engineers, St. Louis District, describes flood management and floodfighting efforts, and presents some innovative ideas. The seventh paper, by C.S. Boruff, Illinois Department of Agriculture, discusses economic and social impacts of the 1993 Hood. The eighth and final paper, by R.E. Sparks, Illinois Natural History Survey, discusses the environmental effects of the flood. The remainder of the proceeding covers reports from the discussion groups, which provide many valuable observations, conclusions, and recommendations.

Sharing the Challenge: Floodplain Management into the 21st Century

Interagency Floodplain Management Review Committee. 1994. Report to the
Administration Floodplain Management Task Force, Washington, DC

The Interagency Floodplain Management Review Committee (1994), a committee with 31 professionals from federal agencies having responsibilities in the water resources arena and headed by Brigadier General Gerald E. Galloway, presented a report to the Administration Floodplain Management Task Force. This report is commonly referred to as the "Galloway Report." Sixteen members of the 31-member review committee were also on the Scientific Assessment and Strategy Team (SAST) chartered by the White House in November 1993 "to provide scientific advice and assistance to officials responsible for making decisions with respect to flood recovery in the Upper Mississippi River basin." SAST was incorporated into the Review Committee in January 1994 to serve as its research arm for scientific analysis. Findings of the SAST were published in a separate volume as Part V (SAST, 1994) of this report, and are reviewed separately.

The committee points out that flood damages are a national problem. During the decade ending in 1993, average annual flood damages in the United States exceeded $3 billion. Damages from the 1993 Flood were extensive, between $12 billion and $16 billion, with unquantifiable impacts on the health and well-being of the Midwestern population. Human activities in the Midwestern floodplain over the last three centuries have placed people and property at risk. Although local and federal flood damage reduction projects constructed to minimize annual risk prevented nearly $20 billion in damages during the 1993 Flood, some of these programs attracted people to high-risk areas, creating greater exposure to future damages. In addition, flood control, navigation, and agricultural activities severely reduced available floodplain habitat.

This report gives a comprehensive description of the Flood of 1993, an unprecedented hydrometeorological event given the excessive rainfall that fell throughout a significant section of the Upper Mississippi River basin. The flood recurrence interval ranged from less than 100 years at many locations to nearly 500 years on segments of the Mississippi River from Keithsburg, Illinois, to above St. Louis, Missouri, and on segments of the Missouri River from Rulo, Nebraska, to above Hermann, Missouri. At 45 U.S. Geological Survey (USGS) gaging stations, flow levels exceeded the 100-year mark, and many areas were under water for months.

Damaging effects of the rainfall included saturated grounds in upland areas and flooding conditions on floodplains. Most agricultural damage was caused by wet soil conditions and inundation in upland areas. Damage to inundated cropland in the floodplain was also quite significant, with almost total crop losses behind failed levees. Areas affected by severe erosion and deposition will suffer long-term loss of productivity. Levees may also have caused problems in some critical reaches by backing up on other levees or low-lying areas. Many levees were poorly sited and will fail again in the future. Without changes in current federal programs, some of these levees will remain eligible for post-disaster support.

During the Flood of 1993, flood damage reduction projects and floodplain management programs worked essentially as designed and significantly reduced the damages to population centers, agriculture, and industry. It is estimated that reservoirs and levees built by the U.S. Army Corps of Engineers (USACOE) prevented more than $9 billion in potential damages, and watershed projects built by the Soil Conservation Service (SCS) saved an additional $400 million. Land-use controls required by the National Flood Insurance Program (NFIP) and state floodplain management programs reduced the number of structures at risk throughout the basin. Locks and dams and other navigational structures did not raise flood heights during this flood, although navigation dikes can cause minor increases in flood heights in floods with more frequent flooding and less flow.

Impact of Wetlands

The committee describes both positive and negative impacts of human intervention. Agricultural practices, flood-control reservoirs and levees, and navigation locks and dams are the major human interventions affecting generation and flow of floodwaters in the Upper Mississippi River basin. Loss of wetlands, upland cover, and landscape modifications throughout the basin over the last 150 years significantly increased runoff. Although upland watershed treatment and restoration of upland and bottomland wetlands can reduce flood stages in more frequent floods (occurrence of 25 years and less), it is questionable whether they would have significantly altered the 1993 conditions.

The committee examines hydrologic models of four watersheds representative of distinctly different Upper Mississippi River basin terrains. Because the watersheds modeled represent only 5 of the 70 terrain types in the basin, information derived from these models has limited applicability in assessing flood flow reduction basinwide. The watersheds are:

1. Boone River near Webster City, Iowa, a central Iowa and Minnesota Till Prairie with a relatively flat 840-square-mile watershed with low relief prairie pothole terrain.

2. Whitebreast Creek near Dallas, Iowa, an Illinois and Iowa Deep Loess and Drift and Iowa and Missouri Heavy Till Plain with a relatively steep 380-square-mile watershed with well-incised drainage.

3. West Fork Cedar River near Finchford, Iowa, an Eastern Iowa and Minnesota Till Prairie with a flat 850-square-mile watershed having a well-defined drainage system.

4. Redwood River watershed above Redwood Falls, Minnesota, a Central Iowa and Minnesota Till Prairie and Loess Upland and Till Plain with high relief and low relief pothole areas in a 700-square-mile watershed.

These hydrologic models showed that floodplain wetlands reduced peak discharges by 6 percent for 1-year storm events and 3 percent for 25- and 100-year events. Wetlands are more effective in upland areas with more deeply incised potholes, such as the Redwood River watershed, where reductions were 23 percent, 11 percent, and 10 percent for 1-year, 25-year, and 100-year events, respectively. Restored wetlands in areas of shallow depressions, such as the Boone River watershed, reduced peak discharges by 9 percent, 7 percent, and 5 percent for 1-, 25-, and 100-year events, respectively. With the installation of a combination of land treatment measures and restored wetlands in the watershed, the models indicated that runoff reduction of 12 to 18 percent was possible for events of 25 years or less.

The models used the SCS runoff curve number procedure. All model runs used antecedent moisture condition II, the average annual soil condition. Antecedent moisture conditions for the 1993 Flood were actually level III, indicating near-saturated soil prior to the storm. Because the model analysis used a lower antecedent moisture condition than was actually experienced in the 1993 Flood, peak discharge reductions resulting from the model analysis were greater than what would have occurred.

Restored wetlands in the uplands can function much as small upland reservoirs. Small flood damage reduction dams are effective in the reach of stream immediately downstream, but their effect diminishes rapidly with distance. A series of small headwater dams is essentially ineffective under conditions in which major floods occur on large rivers.

A report by Demissie and Khan (1993) concluded that for certain watersheds, peak flow decreases as wetland areas increase. In very small watersheds (less than 100 square miles), peak flow rates decreased by an average of 3.7 percent for each increase in wetland area equivalent to one percent of the area of the watershed. Applicability of this report may be limited only to the study areas. While wetlands may have some impacts on peak flow in smaller watersheds during smaller storms, their effects in larger watersheds during larger events are not sufficiently documented and require further study.

An earlier study of Devil Lake in North Dakota (a closed basin) indicated reductions of peak flow rates up to 41 percent for a 100-year storm. Widely ranging results from the aforementioned studies demonstrate that alternative watershed practices produce varying degrees of success in reducing flood runoff rates depending on the magnitude and intensity of the rainfall and antecedent moisture conditions, percentage of basin treated, and basin topography.

The committee concludes that upland wetlands restoration can be effective for smaller floods but diminishes in value as storage capacity is exceeded in larger floods such as the Flood of 1993. Present evaluations of the effect of wetland restoration on peak flows for large floods on main rivers and tributaries are inconclusive.

Impact of Levees

The committee examines the storage of floodwater in flood-control reservoirs and areas protected by levees during the 1993 Flood. It refers to a modeling study using the USACOE's UNET (one-dimensional Unsteady flow through a full NETwork of open channels) model (Barkau, 1993) to ascertain the actual effect of levees on peak 1993 Mississippi and Missouri River flood stages. UNET, which analyzes unsteady state river flow conditions, was applied to river reaches where cross-sectional data were available:

1. Mississippi River between Hannibal, Missouri, and Cairo, Illinois;

2. Missouri River between Hermann, Missouri, and the mouth at St. Louis; and

3. Illinois River between Meredosia, Illinois, and the mouth above St. Louis.

The UNET modeling study used data from 1993, 1986, and 1973 floods, and developed water surface profiles resulting from the same flood flows without levees. The model was calibrated using a range of possible floodplain ground covers. The analysis suggests that without levees (other than urban levees), the peak stage at St. Louis in 1993 would have been reduced by 2.5 feet, still more than 17 feet above flood stage and almost 4 feet higher than the previous known maximum level recorded during the 1973 event. The model scenario assumes the improbable condition of a totally open floodplain covered only with bare soil or short grass cover. If one assumes that existing levees were constructed to contain all flows, peak stages at St. Louis would have increased by 2.3 feet.

A steady-state modeling study commissioned by the *St. Louis Post-Dispatch* showed that the overtopping and breaching of two levees downstream from St. Louis at Columbia and Harrisonville, Illinois, reduced peak stage at St. Louis by 1.6 feet. A physical model study conducted at the Waterway Experiment Station (WES) in 1979 by Foster and Allen showed that the removal of the trees between the river bank and levees along the Middle Mississippi River between St. Louis and Cape Girardeau would lower the stage at St. Louis about 2.5 feet for the 1973 Flood.

Further downstream along the Middle Mississippi River, the UNET model predicted a sizable local drop in river levels without levees under the most conducive flow scenario. If levees containing the river were removed at Chester, Illinois, the stage of the Mississippi River during the 1993 Flood would have been approximately 11 feet lower, but the floodplain would have been under water. The model predicted that there would be no stage reduction if the entire floodplain were covered in dense forest or brush, a scenario representing the least conducive flow condition. It is expected that a typical floodplain without levees would contain a mix of uses and associated land covers such as sloughs, side channels, forested and unforested wetlands, and agriculture.

The committee concludes that levees did not cause the 1993 Flood. During such large events, levees have minor overall effects on flood stage but may have significant localized effects. The report briefly discusses future flood potential, concluding that floods equal to or greater than the Flood of 1993 will continue to occur across the nation.

Policy Issues

The report also extensively discusses policy and organizational issues. These include a vision for the floodplain, which entails organizing floodplain management for success, avoiding vulnerability through planning, focusing on environmental enhancement, minimizing the vulnerability of existing development, and mitigating flood impacts through recovery and insurance. The committee outlines a new approach for the Upper Mississippi River basin, which entails treating the river system as a whole, reducing the vulnerability of people in the floodplain, and coordinating levee activities and ecosystem needs.

The committee supports the use of science and technology in monitoring, analysis, modeling, and development of decision support systems and geographic information systems for floodplain activities. It also recommends the establishment and continued development of a common database.

Originally the committee hoped to answer questions about flow characteristics for the entire reach of the Mississippi River from Cairo to St. Paul and for the Missouri River from its mouth to Gavins Point. However, a single model to accomplish this task does not exist. Five USACOE districts are involved in managing these river reaches, and their models differ. Additionally, the availability of topographic data is limited to certain river reaches. Furthermore, current one-dimensional models cannot satisfactorily model the complex condition of flow in large rivers where water moves into large storage areas in the overbank floodplain and where land cover varies both in the cross section and along the length of the river.

The most widely used model for flood elevation determination is HEC-2, the USACOE's Hydrologic Engineering Center model, a steady-state, one-dimensional, rigid-boundary model that cannot simulate levee breaches or take storage effects into account. UNET, the one-dimensional unsteady-flow model used by the committee to model a portion of the river reach, can assess impacts of levee breaches and associated storage effects. A systemwide, unsteady-flow model of the main stem rivers in the Upper Mississippi River basin would help evaluate the impacts of proposed structures and floodlighting, and could be used for coordinated ecosystem modeling and floodplain management decisions. Furthermore, advanced hydrologic and hydraulic models can be combined with meteorological observations and forecasts to enable better floodplain and water resources management.

The committee recommends that the USACOE, NWS, USGS, and other collaborators continue developing basinwide hydrologic, hydraulic, and hydrometeorologic models for the Upper Mississippi River system, and that federal, state, tribal, and local agencies develop coordinated estimates of flood flow frequency curves, flood elevation profiles, and floodplain maps. Overall improvement in the modeling of complex river systems will lead to advances in hydrologic prediction capabilities for both real-time forecasts of flood events and for water-resources planning. Floodplain managers should also consider one- and two-dimensional models for modeling complex areas.

Models used in determining flood heights require current estimates of flood discharges. Therefore, the committee recommends that federal water agencies, in collaboration with state, tribal, and local entities, review and update discharge-frequency relationships for streamflow gages in the Upper Mississippi River basin to reflect the 1993 Flood data, and that they assess the adequacy of the existing streamgaging network.

The National Oceanic and Atmospheric Administration's (NOAA's) Natural Disaster Survey Report (U.S. Department of Commerce, NOAA, NWS, 1994) identifies the need for improvements to real-time hydrologic forecasting and provides 106 findings and recommendations resulting from an interagency evaluation of the 1993 Midwest flood. The committee recommends that federal agencies, with coordination from the NWS and USGS, collaborate on an assessment of the effectiveness of the streamgaging network and flood forecasting during the flood.

Analysis and Research Needs

Federal programs provide for transfer of funds supporting private floodplain activities such as navigation, agriculture, flood control, and transportation. The National Science Foundation should consider funding research to fully examine the impacts of flooding on these activities.

Satellite imagery and data analyses provide evidence that some levee failures along the Missouri River coincided with historical river channels. Evidence indicates that levees were largely responsible for raising floodwaters to levels that generated the high energies necessary to overpower and blow out the levees, creating the scour holes and generating the sands that damaged the very farmlands the levees were designed to protect.

Riparian forests in many areas experienced minimal flood erosion or deposition damage. These areas commonly coincided with levees that did not fail, indicating that forested areas between levees and the river provided some protection to levees. Evidence also indicates that levees placed in high-energy zones would not hold, even if it were possible to excavate all sand from the old channel and place the levees on a clay core. This suggests that levees should not be constructed in such high-energy erosion zones, but rather should be set back to keep these zones within a designated, functioning floodway. A mix of compatible land uses, such as dry-year farming, open space, recreation, fish and wildlife habitat, could be sustained within high-energy floodways, and the committee recommends an immediate study to better define, document, and map such zones.

The federal government established the Minnesota Valley National Wildlife Refuge in the Lower Minnesota River valley to maintain the floodplain as part of a naturally functioning ecosystem and floodwater storage or conveyance mechanism, In the Upper Mississippi River valley, floodplain land uses such as green spaces and wildlife refuges have not received adequate evaluation in terms of their potential for flood control and damage reduction. Floodplain and upland areas functioning as temporary storage areas can affect flood peaks, but quantification of these impacts has not been well documented. Modern flood-control policy has not made use of natural storage areas (wetlands) for temporary storage of floodwater to decrease downstream flood heights. Additional field data are necessary to use existing models for analyses of these impacts. The administration (The White House) should request completion of these investigations as soon as possible. Wetland functions and drainage for agricultural purposes require better evaluation, and the current USACOE project in Marshall, Minnesota, offers the opportunity to further explore the effectiveness of upland treatment in reducing flood damages.

State, local, and private engineers and planners rely heavily on federal design manuals, which currently do not compare biotechnical engineering (channel or bank modification techniques that use vegetation in innovative ways) and traditional bank sloping and riprap protection. Traditional approaches typically focus only on maximizing flood conveyance, whereas biotechnical engineering techniques can be employed in engineering designs and contribute to the natural functions of floodplains. Federal agencies responsible for establishing guidelines should test and incorporate these methods into their design manuals.

Finally, the committee outlines a floodplain action plan, presents a cost analysis for the plan, and discusses perceptions, ideas, and proposals on the 21st century floodplain, emphasizing the concept of "Sharing the Challenge."

Science for Floodplain Management into the 21st Century

Scientific Assessment and Strategy Team. 1994. Preliminary Report of the Interagency Floodplain Management Review Committee to the Administration Floodplain Management Task Force, Washington, DC

This preliminary report of the Scientific Assessment and Strategy Team (SAST) is part of the Galloway Report, or the Interagency Floodplain Management Review Committee (FMRC) report to the Administration Floodplain Management Task Force (see the previous section, *Sharing the Challenge: Floodplain Management into the 21st Century).* The SAST is an interdisciplinary team composed of senior scientists and engineers from federal agencies, including 19 full-time SAST members, 6 associate members, numerous ad hoc members, and 3 project staff members. In-depth technical and scientific support is provided by the Earth Resource Observation System (EROS) Data Center (EDC) near Sioux Falls, South Dakota.

At EDC, SAST built a vast multi-layer, multi-resolution database covering the Upper Mississippi River basin (UMRB). This database includes information on historical land use and land cover, river channels, precipitation, and river flow. Data gaps were satisfied either by acquiring additional existing data or by conducting field, remote sensing, process, or modeling analyses. Database products include data, maps, illustrations, analysis results, and statistics. Developing the database was one of the major tasks of SAST, which has outlined policies on continuous collection, dissemination, and management of data.

In its report, SAST describes the natural system, including the hydrologic cycle, surface water, and ground water, and concludes that the 1993 Flood in the Midwest was caused by a persistent series of heavy summer rainstorms, following an unusually wet period from the summer and fall of 1992 through the spring of 1993. SAST summarizes the flood's meteorological characteristics from reports by the National Weather Service (1993a,b) and hydrologic characteristics from U.S. Geological Survey (USGS) reports on precipitation (Wahl et al., 1993), flood peak discharges (Parret et al., 1993), and reservoir effects (Perry, 1993).

In terms of hydrologic issues and research needs, SAST emphasizes regional hydrologic modeling of rainfall-runoff, erosion, and transport processes, and regional analysis of statistical frequency and magnitude of flood occurrence. SAST recommends that federal, state, and local agencies cooperate to: (1) develop hydrologic and hydraulic models to define flood-response characteristics, including ground-water flow and transport of water-quality constituents in river-floodplain and upland watersheds in the UMRB; (2) determine drainage-basin physiographic, land-use, and land-management characteristics affecting flood response in the UMRB, with a view toward regional-scale assessment of the effects of improved land-use and land-management practices on flood response; and (3) extend and enhance the existing observation network as needed to obtain surface water, ground-water, water-quality, and meteorological data required for development and application of hydrologic and hydraulic models.

With regard to research on flood frequency and magnitude, SAST recommends that federal, state, and local agencies cooperate to: (1) develop up-to-date coordinated estimates of statistical flood frequency-magnitude relations, including flood elevation profiles and flood-risk delineation maps, at gaged and ungaged sites, for use in floodplain planning, management, and regulation in the UMRB; (2) review and evaluate existing and proposed methodologies for statistical flood frequency estimation at both gaged and ungaged sites, and identify or develop improved methodologies, if necessary; and (3) review and evaluate the adequacy of the existing streamflow-gaging network for defining flood risk in the UMRB, and extend and enhance the network, if necessary.

Physiography

Physiographic characteristics such as topography, landscape morphology, terrain heterogeneity, soils, drainage density, wetland extent, and land cover determine storage or runoff potential and contribute to the dynamics of flood processes. Understanding and classifying the terrain provides useful information for extending the results of local analyses or for evaluating the extension of such results.

Preliminary geographic analysis shows that the UMRB can be divided into as many as 70 terrains on the basis of slope variance and aspect. Other land resource maps (Soil Conservation Service, 1981) subdivide the basin into 44 Major Land Resource Areas based on soil, topography, climate, water resources, potential natural vegetation, and land use.

SAST recommends developing a regionalization scheme (based on existing or new data), preparing hydrologic response units (HRUs), and using these HRUs to develop broad-scale hydrologic models and to evaluate the effectiveness of different potential nonstructural actions in reducing flooding.

The State Soil Geographic (STATSGO) database of the U.S. Department of Agriculture Soil Conservation Service (USDA SCS) inventories soil resources in the United States at a scale of 1:250,000. SAST used this database to develop a map of the basin showing locations of nine different slope groups. Slope groups were based on statistical clustering of the slope patterns.

Soils are an important physiographic component because they affect rates of water runoff to streams, absorption of water into the ground-water system, and vegetal land cover. Using the STATSGO database, SAST developed a map showing locations of 11 soil orders based on statistical clustering of soil properties important to hydrologic analysis. A map showing the percentages of hydric soils was also prepared.

Surface and soil profile storage of water has a major impact on excess rainfall and flooding. Using the STATSGO database, SAST estimated a total of 420 billion cubic meters of potential water storage above the ground surface and in the soil of the UMRB. This volume is equivalent to a water depth of 10 inches over the 630,000-square-mile study area. SAST presents available ponding volume and available water capacity (AWC) for the 11 states in the UMRB, a total of 52 and 529 billion cubic meters, respectively. Ponding averages 9 percent and AWC averages 91 percent of total storage. Infiltration rates are an important factor in the potential water storage of soils. Most medium-textured soils, such as those in the basin, have infiltration rates of 0.5 to 1.0 inches per hour.

While the STATSGO database is valuable for regional estimates, more detail is necessary for subregional and local planning and decision making. The SCS is conducting and coordinating an effort to obtain soils data at a much finer resolution. These data, the Soil Survey Geographic Database (SSURGO), are being collected in map and digital form. SAST recommends accelerating the production of soils data of finer resolution than the STATSGO data, e.g., SSURGO data. The SCS should maintain these data for distribution in a generally accepted format that can be easily converted to other generally accepted formats.

Wetlands

There are approximately 58 million acres of presettlement wetlands in the basin, but only about 23 million acres of wetlands remain in the basin. The loss of 35 million acres of wetlands has occurred primarily as a result of agricultural drainage, channel modification, and flood control. Percentages of presettlement and present wetlands in Illinois are 22.8 and 3.5; Iowa, 11.1 and 1.2; Minnesota, 28.0 and 16.2; Missouri, 10.9 and 1.4; North Dakota, 10.9 and 5.5; South Dakota, 5.5 and 3.6; and Wisconsin, 27.3 and 14.8, respectively.

Wetlands enhance wildlife habitat. For instance, wetlands in which the soil becomes anaerobic can remove excess nitrates from the soil and water through denitrification processes, and wetlands can reduce nitrate to nitrogen gas. Wetlands also help degrade agricultural pesticides to environmentally safer compounds, and they serve as sinks for phosphorous and as natural filters that prevent sediments from entering lakes and streams, thus enhancing surface water quality.

Closed flow systems are common in the basin. In fact, more than 1,000 square miles of the 1,760-square-mile drainage area above Jamestown, North Dakota, are still considered to be closed systems, noncontributors to runoff. The primary loss of water in these closed landscapes is through evapotranspiration and ground-water seepage. Average annual evaporation amounts are 29, 32, 39, 43, 47, and 51 inches in Milwaukee, Minneapolis, Bismarck, Havre, Kansas City, and North Piatt, respectively. A study of 135 different water regime wetlands over a six-year period (Kantrud and Steward, 1977) found that, on the average, wetlands are either dry or their water depths are substantially reduced by the time of the November freeze-up. In an average year, therefore, the depressions are available for runoff storage the following spring.

SAST recommends that the U.S. Fish and Wildlife Service complete the National Wetland Inventory. Inclusion of agricultural wetlands would improve the usefulness of the dataset in evaluating wetland areas and in planning by local and subregional entities. In addition, SAST recommends identifying the types of floodplain wetlands created, destroyed, or modified by the Flood of 1993, and analyzing their distribution, acreage, and ecology. Newly created wetlands should be reexamined periodically by remote and ground surveys over the next decade to document their morphometric changes, longevity, and ecological value. SAST also recommends further examination of historical temperature and river stage records to evaluate the temperature-river stage coupling relationship for the Mississippi, Missouri, and Illinois Rivers.

Geomorphology

Different rivers and different reaches have different flood impacts. SAST recommends that the USGS, SCS, National Biological Service, and USACOE initiate a program to conduct detailed geomorphic/hydrologic/topographic mapping of the Lower Missouri River floodplain and selected Upper and Middle Mississippi River floodplains to develop an overall geomorphic physical-process model, stratigraphic framework, and geotechnical database. The program would identify floodplain zones of variable flood risk and would include analysis of the age of floodplain zones, sedimentation rates, and the record of prehistoric floods.

Preliminary evidence suggests that levees and channel training structures have influenced water-level elevations at both low and high discharges. SAST recommends testing for possible cause-and-effect relationships between observed changes in water level at low and high discharges and factors such as river channel-floodplain modifications, measuring and estimating methods, and natural variation due to different water temperatures, sediment loads, and changes in land cover. SAST also recommends expanding depth and velocity hydraulic model simulations to the entire Lower Missouri River and determining whether or not river flow regulation has affected seasonal hydrographic, temperature, and turbidity patterns.

Ecology

SAST makes several specific recommendations on inventorying and monitoring species, communities, and habitats, as well as understanding their functional interrelationships. It also suggests developing a basinwide ecological model with the following specific objectives:

1. Define effects of sediment in runoff to streams and upland impoundments in relation to land-management and stream riparian corridors;
2. Determine effects of stream sinuosity on streamflow and flood stages;
3. Evaluate floodplain wetlands with respect to flood stream hydraulics;
4. Evaluate effects of riparian vegetation and other land covers on conveyance and storage of floodwaters and the role of riparian corridors as energy dissipaters during flooding;
5. Evaluate effects of upland restoration on stream hydraulics at both flood and low flows;
6. Determine if, and to what extent, upland and floodplain wetlands influence flood peaks;
7. Define environmental and ecological requirements of important aquatic and terrestrial river-floodplain species; and
8. Characterize the important compositional, structural, and functional interrelationships between plant and animal communities of the major Upper Mississippi River basin rivers and their floodplains.

Structural and Nonstructural Flood Control

SAST has studied the engineered system of the basin, including human activities (mainly those supporting agriculture). Agricultural practices and flood-control measures are a major part of the engineered system.

Nonstructural Methods. Nonstructural methods of flood reduction have long been encouraged in the United States. For example, the SCS has encouraged treatment of farmland to reduce runoff and erosion, both of which affect flooding in a basin. Restoration and creation of wetlands are encouraged to treat agricultural wastewater and improve water quality of streams and lakes, in addition to providing habitat for wildlife and reducing downstream flooding. The flood-control effect of wetlands depends on the volume of wetland storage relative to the flood volume, wetland location, and flood duration. Upland agricultural drainage has produced changes in surface runoff and peak flows.

The Food Security Act of 1985 (FSA) and the Food, Agriculture, Conservation, and Trade Act of 1990 (FACTA) are discussed and evaluated. These acts impose restrictions on planting of agricultural commodities on highly erodible lands or converted wetlands. The report examines such practices as residue management, reduced tillage, and conversion of croplands to grasslands, all of which reduce runoff potential and thus SCS runoff curve number values. SAST uses these values to show the total reduction of runoff in different counties within the study area. The report points out that while peak flood flow is related to flood runoff volume, further modeling is necessary to determine actual peak reductions due to the timing of runoff within the basin and the basin shape.

SAST conducted a watershed modeling study for preliminary evaluation of the role of upland land treatments, wetlands, and detention storage in reducing flood peaks. SAST applied existing models to certain watersheds. These included a calibrated SCS TR-20 model used for designing detention structures in Whitebreast Creek near Dallas, Iowa; a USACOE HEC-1 model that existed for the Boone River watershed near Webster City, Iowa; and an HEC-1 model created for the West Fork Cedar River near Finchford, Iowa, using GEOSHED software developed by the Brigham Young University Computer Graphics Laboratory. A TR-20 model was discovered for the Redwood River basin above Redwood Falls, Minnesota.

As described in the review of *Sharing the Challenge: Floodplain Management into the 21st Century*, these four watersheds represent distinct types of landscapes: a steep basin, a low relief pothole basin, a low relief basin with well-defined drainage, and a relatively high relief basin that has been drained for agriculture. Four modeling groups conducted the study: Boone River, USACOE Hydrologic Engineering Center; West Fork Cedar River, USACOE Waterways Experiment Station (WES); Whitebreast Creek, USDA-SCS, Iowa; and Redwood River, USDA-SCS, Minnesota.

The SCS curve number method was used for all studies that evaluated land-management practices. It was easier to model upland wetlands and detention basins with the TR-20 model than with the HEC-1 model. Storm durations of 24 hours were used, except for the Boone River and Redwood River basins, as a 24-hour storm would not account for the 90-hour travel time required to reach those basin outlets. The storm duration used for the Boone River was a 4-day (96-hour) storm and for the Redwood River basin the duration was a 6-day (144-hour) storm. All model runs used antecedent moisture condition II as the beginning modeling conditions.

The main modeling objective was to show the effect of various management, land-use, and storage practices on the outflow hydrographs for different types of basins. Six alternative treatments were selected for the Boone River, West Fork Cedar River, and Whitebreast Creek watersheds. Treatments and options were assumed to be applied to 100 percent of the basin to show the maximum effects. The objectives of modeling the Redwood River were to determine whether increasing wetlands would reduce flood peaks in a relatively high-relief pothole basin and, if so, to what extent. Six wetland restoration alternatives were studied. SCS land treatments were not applied. Wetlands were assumed to be restored as detention storage areas with outlets.

The models were calibrated to the largest storm event for which sufficient rainfall and flow records existed. The watersheds were evaluated for four synthetic storm events: 1-, 5-, 25-, and 100-year storms. Model results are summarized earlier in the review of the Galloway Report. Three of the watersheds showed a trend of reducing effect with increasing storm return period for the combination of all modeled alternatives, while the Whitebreast Creek model showed the opposite effect for 5-year or greater storms. This demonstrates that results from one basin cannot be directly applied to other basins. On the basis of these results, SAST made the following three recommendations:

1. Acquire higher resolution topographic data for areas of the basin where low relief potholes exist to allow more accurate determination of pothole storage volumes.

2. Conduct field trials and demonstration projects to determine the effect of various land-management practices on flood dynamics, sedimentation, soil conservation, agriculture, and habitat restoration. These studies should be conducted in a variety of physiographic regions.

3. Model additional watersheds within the basin to better estimate the flood reduction effects of upland treatment measures for other terrain types.

Structural Methods (Levees). Analysis of aerial photographs, Landsat TM images, and historical maps of the Lower Missouri River floodplain reveals that more than 90 percent of the erosional and depositional features of the 1993 Flood are associated with breached flood-control levees. Small levee scour holes are generally circular, 100 to 250 feet in diameter. Large scour holes are elongated, up to 900 to 1,500 feet wide and 3,000 feet long. Maximum depths of levee scour holes are 25 to 55 feet. Based on the 1993 Flood, SAST makes the following recommendations:

1. The USACOE in cooperation with USGS and SCS should conduct a detailed historical analysis of levee breaching to document specific levee locations and causes of high failure

rates. This study should include geotechnical data and new field studies of hydraulic and geomorphologic factors that directly affect levee erosion and failure.

2. On the basis of detailed floodplain mapping and historical levee evaluation, the USACOE in cooperation with USGS and SCS should identify alternative alignments for levees with high failure rates.

3. On the basis of new hydraulic modeling of design floods, USACOE and USGS should develop new levee designs that permit passive flooding of protected areas during major flood events to reduce levee damage and floodplain erosion and sedimentation associated with levee breaches under high head conditions.

4. The levee dataset created by SAST should be maintained by the USACOE in coordination and cooperation with the SCS and the states. The levee dataset should be kept current, and should be accessible to interested parties through the clearinghouse.

A one-dimensional unsteady flow hydraulic model was developed for a portion of the Mississippi River and its associated floodplains to test the effects of the current levee system on the Flood of 1993 and other selected floods. The mathematical model used for the analysis was the UNET model currently supported by Dr. Robert Barkau (Barkau, 1993). This unsteady flow model is suited for modeling long reaches of rivers where the dynamic effects of levee breaches, backwater conditions, bed slopes of less than one foot per mile, and varying flow rates along the river are important. The UNET model requires: (1) river cross sections, (2) Manning's roughness coefficients, (3) boundary conditions of flow and stage, and (4) observed flow and stage data for model calibration.

The UNET model was developed for the reaches of the Mississippi River from near Hannibal, Missouri (Lock and Dam 22 tailwater, RM 30.1), to Cairo, Illinois (RM 0.0); the Missouri River from Hermann, Missouri (RM 97.9), to the mouth; and the Illinois River from near Meredosia (RM 70.8) to the mouth. All major tributaries entering the Mississippi River were modeled from the last rated gage downstream to the mouth to reproduce the effects of backwater on the outflows. Cross sections used in the model were originally developed by the Kansas City and St. Louis Districts of USACOE, and are 10 to 20 years old. A total of 1,218 cross sections extending from bluff to bluff at an interval of 0.5 miles were used. The model was calibrated and analysis was conducted for three events: the 1993, 1986, and 1973 floods.

Levee effects were analyzed after calibrating the model to the Flood of 1993 with the levees as they existed prior to the flood. In the model, levees were overtopped or breached at the same time as they were during the actual flood, and the filling rate of areas protected by the levees was adjusted to match observed data where available. After the model was adjusted to accurately reflect the observed stage and flow data for river gaging stations, four levee configurations were tested.

During the 1993 Flood, the Missouri River reclaimed its floodplain and actively conveyed water through formerly leveed areas. In order to model this condition, the cross-section geometry needed extensive revision. Due to time constraints, such revisions were not made, and only the second peak of the 1993 Missouri River flood, not the third and highest peak, was reasonably simulated. The floodplain was modeled as a storage cell, rather than as a flood conveying channel.

Determination of the proper Manning's roughness coefficient was crucial for the no-agricultural-levee analysis. Areas currently inside the levees were modeled using the same "n" values that were used during calibration, and only the values behind the existing levees were adjusted. The values used were: grass meadow, 0.04; harvested cornfield, 0.08; cornfield, 0.16; forest, 0.32; dense forest, 0.64, and no overbank conveyance, 0.999.

The USDA-ARS extensively tested the Manning's n values of agricultural crops, but similar in-depth testing has not been done for shrubs and trees. Currently, research is under way at Utah State University under a contract with the USACOE-WES to determine Manning's n values for submerged shrubs, and future work is planned for trees. This work will help determine better n values to use for shrubs and trees when flood depths are not similar to those presented in the 1989 USGS report. SAST recommends more research to determine appropriate Manning's n values for use with shrubs and trees during deep flooding. In addition, the relationship between various flow depths and Manning's n values should be determined for both urban and suburban land covers.

Selection of the proper n value is affected by the model being used, the experience of the modeler, the number of inaccuracies in the model (cross section, land cover), and other factors. In effect, the selection of the n value for a reach of river is determined by how the model calibrates to the observed water surface and becomes the final device for tuning the model to give accurate results.

Model results show that with a Manning's n value between 0.32 and 0.64, there is very little change from the observed 1993 Flood elevations. This suggests that if levees were eliminated and the entire floodplain became dense forest with underbrush, flood stages would be similar to those observed for the 1993 Flood in the section of the river modeled.

The option to model no levee failures or overtopping assumed that infinitely high and strong levees were in place at existing levee locations. The results show 0.1 to 2.7 feet of increase in stage.

The original Pick-Sloan plan recommended a floodway varying in width from 3,000 to 5,000 feet for the portion of the Missouri River below Gavins Point Dam. The recommended floodway width in the portion of the river being modeled was 5,000 feet. Due to inadequate modeling, the results are not conclusive. Dr. Barkau states, however, that "given the accuracy of the model, the model shows that the Mississippi and Illinois Rivers are essentially unchanged by the Pick-Sloan Floodway," at least for the portion of the floodway that was modeled.

In an effort to approximate the pre-navigation-project active channel widths, SAST developed a hypothetical floodway for the modeled portion of the Missouri River. This involved comparing the 1879 and current river alignments and widths. This option produced no significant changes over the Pick-Sloan floodway for the reach of the river modeled.

SAST concludes that for a flood of the magnitude and duration of the 1993 Flood, levees had little systemwide impact, while locally, where failures resulted in concentrated flows, high velocities, and associated damages, overtopping or breaching of the levee often produced major effects. Use of floodways, while beneficial for local areas, could have beneficial or detrimental effects upstream and downstream and should be modeled using a model of the entire river section involved. SAST also makes the following recommendations:

1. Develop a standard set of cross sections that can be updated with local, state, and federal input for the modeling of long river reaches. Availability of a standard set would reduce the cost of modeling and facilitate the development and calibration of a basinwide model that could be used for planning, design, operations, and forecasting, if necessary. Standard cross sections must be updated when there are changes in floodplain morphology and must be available through a clearinghouse.

2. Develop, for the short term, a model capable of simultaneously handling one- and two-dimensional modeling such that two-dimensional segments can be set into one-dimensional reaches; or develop a full two-dimensional model for all river reaches with the capability to model levee breaches, river junctions, and areas with critical infrastructure to determine flow directions and velocities. For the long term, extend the two-dimensional capabilities to the entire floodplain.

3. Acquire digital elevation data of sufficient vertical accuracy and horizontal resolution to support development of a two-dimensional hydraulic model of the floodplains of the Upper Mississippi, Lower Missouri, and Illinois Rivers.

4. Continue investigating new methods for acquiring topographic data and their associated costs by testing the various technologies to determine which is most technically and economically effective.

5. Acquire detailed land-use data to support modeling on the floodplain. This should be accomplished by the USGS in cooperation with USDA, EPA, states, and tribal governments.

Strategy Recommendations

1. Produce a baseline dataset for the UMRB.

2. Establish a monitoring program to identify changes to the UMRB system. This program should link to and integrate ongoing monitoring programs for the physical, ecological, and socioeconomic sectors of the environment.

3. Conduct initial and ongoing scientific analysis of the UMRB system to improve understanding of how the various parts of the system interrelate and to provide new understanding to policy and management decision makers. This analysis should build and expand on the work initiated by SAST.

4. Develop ecologic and hydrologic models of the river basin and advanced hydraulic models of the floodways of the main stem and major tributaries. Three types of models should be expanded or developed for the river basin: (1) hydrologic, (2) hydraulic, and (3) ecological. Hydrologic models covering small areas have been developed, but no systemwide hydrologic model has been developed. Such a model would be useful to describe the impacts of various activities on the overall system.

5. Ensure that appropriate agencies manage and maintain the data under their purview according to standards and specifications that allow intercomparability and interchangeability.

6. Establish a distribution clearinghouse for data and information. This clearinghouse should be part of the National Information Infrastructure and meet the specifications of the Federal Geographic Data Committee.

7. Establish a coordinating body of scientists to review scientific research and data collection programs at various levels of government and to advise federal, state, tribal, and local governments and nongovernmental organizations on the scientific activities that are and should be conducted to support the management of the UMRB. This interdisciplinary body of scientists would serve as principal scientific advisors to the River Basin Commissions and the Water Resources Council. Additional interdisciplinary scientific bodies should be established to meet specific goals of management and disaster response in the UMRB.

The Great Flood of 1993 Post-Flood Report: Upper Mississippi River and Lower Missouri River Basins

U.S. Army Corps of Engineers North Central Division. 1994. Kansas District

This report and its five separately bound appendices describe the Flood of 1993 in the Upper Mississippi River and Lower Missouri River basins and the general involvement of the Corps in the flood-affected areas. The appendices provide detailed flood descriptions, data, and information on Corps flood-control, floodfighting, and post-flood activities. Appendices A and B (St. Paul and Rock Island Districts) cover the Mississippi River basin above Lock and Dam 22; Appendix C (St. Louis District) covers the Mississippi River below Lock and Dam 22; and Appendices D and E (Omaha and Kansas City Districts) cover the Missouri River basin.

The 1993 Flood was an unusual and significant hydrometeorological event that devastated the Midwest. It was distinctive from all other record floods in terms of its magnitude, severity, damage, and season in which it occurred. A rare combination of meteorological patterns produced a convergence zone over the upper Midwest between the warm, moist air from the Gulf of Mexico and the cooler, drier air from Canada. This weather pattern stalled in the area until the end of July, causing unusually heavy precipitation on ground already saturated as a result of a wet fall in 1992 and spring 1993 snowmelt. The additional rain went directly into runoff.

To date, estimated flood damages total $15 to $20 billion, including $6.5 billion in crop damage, 20 million acres of farmland damaged, 47 deaths, 74,000 people evacuated, 72,000 homes damaged, 39 of 229 federal levees damaged, 164 of 268 nonfederal levees damaged, and 879 of 1,079 private levees damaged. About 200 pumping stations and several water treatment plants were flooded and disabled. Corps reservoirs in Iowa reduced flood peaks by 0.9 foot in Quincy and 0.2 foot in Hannibal. Reservoirs in the Missouri River basin reduced peaks by 6 feet in Sioux City, 5 to 8 feet in Omaha, and 3 feet from Nebraska City to the mouth near St. Louis.

In response to the Flood of 1993, two different floodplain-management studies have been undertaken to examine floodplain use, floodplain management, and flood control along the Missouri and Upper Mississippi Rivers.

Floodplain Management Assessment of the Upper Mississippi and Lower Missouri Rivers and Their Tributaries

U.S. Army Corps of Engineers. 1995. Washington, DC.

The Floodplain Management Assessment (FPMA) is based on a comprehensive and systemwide study assessing flood control and floodplain management in the Upper Mississippi and Lower Missouri Rivers and their tributaries that were flooded in 1993, authorized and appropriated by the Congress. The purpose of the FPMA was further defined to assess the adequacy of current flood-control measures on the Upper Mississippi River and its tributaries.

Within the hydrologic perspective, the study was intended to focus on identifying facilities that require additional flood protection, assess the adequacy of current flood-control measures, evaluate the cost-effectiveness of alternative flood-control projects, and recommend improvements to the current flood-control system. This study complements the earlier reviewed study of the Interagency Floodplain Management Review Committee (1994) or the Galloway Report, and is a more complete and up-to-date study. The report points out four areas of caution:

1. The 1993 Flood is used as a base condition to evaluate the impacts of policy changes and structural alternatives. The FPMA does not provide a complete basis for formulating or recommending projects, because flood frequency analysis and evaluation of life cycle and cumulative benefits and costs must first be accomplished. These were beyond the scope of the FPMA.

2. Findings and conclusions are those of the five Districts and three Divisions of the USACOE.

3. Results of the hydraulic modeling of the various alternatives represent approximate values. Flood discharge-frequency estimates are based on a 1970 federal interagency agreement. There are no plans to revise these based on the 1993 Flood.

4. The report relies almost exclusively on available data. Much of the data are aggregated at a county level, and not broken down into floodplain reaches.

The report consists of a main report and five appendices. The hydraulic/hydrologic aspects of the FPMA are described in Chapter 8, entitled *Hydraulic Modeling of "Action Alternatives,"* and in Appendix A, both of which are reviewed here. The remaining chapters of the main report and the other appendices, which describe socioeconomic, environmental, cultural, and other aspects of the study, are not reviewed here.

The mathematical computer model UNET, developed and programmed by Dr. Robert Barkau, was used to perform the FPMA unsteady flow modeling. UNET is a one-dimensional, unsteady flow program that simulates unsteady flow through a full network of open channels and reservoirs. The model also simulates levee overtopping or breaching and transfer of flow from the main river into the storage area behind the levee. The levee system is simulated as storage cells defined by parameters that describe the stage-storage relationship of the protected area.

Separate UNET models were developed by each of the involved Corps Districts and linked together to provide a systemic modeling tool. UNET modeling was performed on the Mississippi River from Lock and Dam 10 at Guttenberg, Iowa (RM 615.0), downstream to Cairo, Illinois (RM 0.0). Modeling on the Missouri River extended from Gavins Point Dam (RM 811.1), downstream to the confluence with the Mississippi River. Major tributaries were included within the UNET model as routing reaches. Along the Mississippi River reach, the UNET models combine for a total of 615 main stem river miles, more than 20 tributary routing reaches with a combined length of more than 500 river miles, and more than 1,500 total cross sections. Main stem channel geometry was generally developed from existing cross-section data. Overbank geometry was taken from USGS 7.5-minute quad sheets in most cases and from additional survey data where available. Cross-section intervals within the four UNET models varied from 0.2 to 2.0 miles.

UNET model inflow consisted of USGS gaged inflows and estimated local inflows representing ungaged drainage areas. Separate tributary routing reaches were included to route tributary flow from the USGS gaging station downstream to the main stem river. Streamflow gages were used as index gages to determine streamflows for ungaged areas. Ungaged drainage basin areas were divided by the index gage drainage basin area to develop an index ratio. Streamflows for the index gage were then multiplied by the index ratio to come up with a discharge hydrograph for the ungaged area. The UNET model treated the inflow hydrographs for the ungaged tributaries as lateral inflows or uniform lateral inflows.

The UNET model developed by each district was calibrated to the 1993 Flood. The entire range of discharge experienced during the June 1-September 1 period was reproduced. Calibration parameters allowed the variation of conveyance with depth. The calibrated model, which represented the base condition for comparison of all alternatives, reproduced observed peak stages within 0.3 foot at most locations.

UNET analysis was performed on a systemwide basis for the Lower Missouri River and Middle and Upper Mississippi River basins. Stage and flow data were transferred between UNET models. Transfer locations were at Lock and Dam 22 tailwater (RM 301.1) on the Mississippi River; at St. Joseph, Missouri (RM 448.2); and on the Missouri River at Hermann, Missouri (RM 97.9). Levees in the base condition model included height added to the levee crown during floodfighting operations. Levee breaches were reproduced on the dates and times they actually occurred (where data were available). When the actual timing of levee breaching was not available, the timing was estimated based on gage data. In the alternatives modeled, levee overtopping was dependent on the relationship between the levee crown elevation and the water surface elevation of the river.

Agricultural levee alternatives included levee removal, levee setback, levee confinement to contain the flooding, and alteration of levees to provide a 25-year level of protection. Systemic upland retention/watershed measures excluded federal reservoirs and included runoff reductions of 5 percent and 10 percent. All these alternatives were systemwide and involved passing flow and stage information from upstream districts to downstream districts. For agricultural levee alternatives, the base condition of UNET models was modified to reflect geometry changes to simulate the effect of levees on conveyance within the model. Calibration parameters determined in the base condition were not altered for any alternatives.

Selection of roughness values for the flow area after the levee has been removed significantly affected the results for the levee removal alternative. The roughness values chosen for the area between the existing agricultural levees and the bluff represented a low value for agricultural conditions and a high value for natural or forested conditions. Land use between the river and the existing levee was assumed to be the same as it is now. Removal of the levee would not result in an effective flow width equal to the entire valley width. Due to numerous natural and man-made obstructions within the conveyance area, the effective flow width was much less than the cross-section width. The roughness values used in the model were adjusted to account for those ineffective flow areas. Also, rather than modifying the UNET model to accurately reflect the conveyance changes at every cross section, the effective flow width and other factors that reduce cross-section conveyance were included by adjusting the roughness values. Manning's n values were increased from 0.04 to 0.08 for agricultural land use, and from 0.16 to 0.32 for a natural floodplain. This adjustment is the same as reducing the overbank effective flow area by 50 percent.

The levee setback alternative was achieved by adjusting the minimum distance between left and right bank levees, or the bluff line, to increase the floodway width. The minimum floodway width was set at 5,000 feet or increased to 150 percent of the existing floodway. The setback levee height was maintained at the existing levee height. A variation on this alternative was modeled for the Middle and Upper Mississippi River. This variation assumed the agricultural levees were set back as described above, but were raised high enough to prevent overtopping by the 1993 Flood. This resulted in changes of stage at Lock and Dam 16 (-1.4 feet), Burlington (-0.6 foot), Quincy (1.6 feet), Hannibal (2.8 feet), Grafton (-0.5 foot), and St. Louis (-0.5 foot).

The levee confinement alternative consisted of raising all agricultural levees sufficiently so that the 1993 Flood was confined to the area between the existing levees. Levee locations or roughness values were not altered for this alternative. For the 25-year alternative, the height of all agricultural levees was set to correspond with an estimated 25-year profile based on previous hydrology. Federal levees, which are currently higher than the 25-year elevation, were notched to an elevation equal to the 25-year elevation. When flood levels exceed the 25-year level, the levee notch is eroded and the cell fills with water.

No modifications to UNET model geometry were necessary to achieve the effects of upland retention and watershed measures. Assessment was performed by adjusting inflow hydrographs to the UNET model for three scenarios: 5 percent runoff reduction, 10 percent runoff reduction, and without federal reservoirs. Based on the St. Paul District's preliminary studies of wetland storage and other upland retention measures, it was estimated that the maximum available storage with the 1993 Flood antecedent conditions would reduce the total runoff volume into the Mississippi and Missouri Rivers between 5 and 10 percent. Simulation of the no-federal-reservoirs alternative assessed the effect of reservoirs on the 1993 Flood. The no-reservoir hydrographs were computed by the reservoir control centers and were used as UNET model inflow instead of the 1993 observed hydrographs with reservoir holdouts.

Conclusions

The FPMA report concludes that "the assessment validates the view that while structural flood-control measures are an important part of an overall floodplain management program, they have limitations and floodplains are best managed through a combination of structural and nonstructural measures that fully recognize the inherent risk of occupying flood hazard areas." Some of the detailed findings and conclusions are as follows:

1. Structural flood protection performed as designed prevented significant damages.

2. Approximately 80 percent of 1993 crop damages throughout the region were caused by excessively saturated fields, unrelated to overbank flooding. These losses would not have been affected by changes in floodplain management policies. The best way to address these damages is through a rational program of crop damage insurance.

3. Flood damages in urban floodplains with inadequate or no flood protection continue to be a major problem.

4. No single alternative provides beneficial results throughout the system. Examination of many factors such as computed peak stages, discharges, flooded area extent, and depth within flooded areas is necessary to evaluate how an alternative affects performance of the flood damage reduction system as a whole.

5. Based on the results of the unsteady-state hydraulic modeling, it is clear that the hydraulic impacts must be evaluated systematically. Changes that affect the timing of flood peaks or the roughness coefficients of the floodplain can be as significant as changes in storage volume.

6. If all agricultural levees had been successfully raised and strengthened, urban flood protection would have been at much greater risk, with stages averaging 6 feet higher on the Middle Mississippi and 3 to 4 feet on the Missouri with a maximum of 7.2 feet at Rulo, Nebraska, and 6.9 feet at Waverly, Missouri.

7. Changes in flood stage due to the removal of agricultural levees are highly dependent on subsequent use of the floodplain. Given the assumption that agricultural levees are removed, hydraulic routings show that, with continued farming in the floodplain, 1993 stages would be reduced by an average of 2 to 4 feet on the Middle Mississippi River (St. Louis District). If this area had been returned to natural forested conditions, some of the system would still have shown reductions (up to 2.8 feet), but increases in stages by up to 1.3 feet in some locations. In the Lower Missouri River (Kansas City District), hydraulic modeling shows changes in stage of -3 to +1 feet for no levees with agricultural use and changes of -3 to 44.5 feet with forested floodplains.

8. Restoration of floodplain wetlands or conversion of floodplain agricultural lands to natural vegetation would not reduce stages in some locations but would marginally reduce damage payments as a result of the 1993 Rood. Agricultural use of the floodplain is appropriate when the residual damages of flood are understood and accepted within a financially sound program of crop insurance and flood damage reduction measures and when such use is compatible with essential natural floodplain functions.

9. Restoration of upland wetlands would have produced localized flood reduction and other benefits, but little effect on main stem flooding. Hydraulic modeling of 5 and 10 percent reductions in runoff from the upland watersheds predicted average stage decreases of about 0.7 and 1.6 feet, respectively, on the Upper and Middle Mississippi River and about 0.4 and 0.9 foot on the Lower Missouri River. However, wetland restoration measures alone would not have achieved this level of runoff reduction for the 1993 event because of the extremely wet antecedent conditions. There are other reasons why restoration of upland wetlands is very important, including reduced agricultural exposure to flood damage, water quality, reduced sedimentation, and increased wildlife habitat.

10. State and local floodplain zoning ordinances and regulations would be most effective in determining the siting of critical facilities with the potential for releasing toxic or hazardous elements into the environment when flooded.

11. More extensive reliance on flood insurance would better assure appropriate responsibility for flood damages.

12. Justifiably, more emphasis is being placed on flood hazard mitigation measures, particularly on acquisitions of flood-prone structures, to reduce federal disaster expenditures and other costs associated with areas of widespread and potentially significant repetitive flooding.

13. Although there are conflicting public viewpoints on uses of the floodplain, areas of potential agreement exist and need to be pursued.

14. Better adherence to existing policies is a necessary, immediate, and effective first step for better floodplain management. This includes good maintenance of the existing federal and nonfederal levee system and enforcement of land-use policies by state and local interests to ensure that new floodplain development either does not occur or is constructed to minimize damage potential (raising, flood-proofing, etc.).

15. Floods greater than the 1993 catastrophe will occur in the future, and preparation for these larger floods is necessary. As a result, smaller floods will also be more easily accommodated.

16. The FPMA produced much valuable data, including hydraulic modeling, mapping, and data inventories.

Future Direction

Following are the report's recommendations for better understanding and enhancing future floodplain management:

1. Inventory and create a spatial database of levees and other structures in the floodplain.

2. Inventory and create a Geographic Information System (GIS) database of critical facilities in the floodplain.

3. Conduct additional hydraulic modeling (unsteady state) with more detailed mapping and coverage over portions of the main stem rivers not yet modeled and for the larger tributaries. (A system model, including the Mississippi, Missouri, Illinois, Ohio, and Arkansas Rivers, is scheduled to be available by the end of Fiscal Year 1996).

4. Develop real-time unsteady state hydraulic models and tributary rainfall runoff forecasting models for predicting flood crests in future flood emergencies.

5. Update hydrologic and hydraulic data, including discharge-frequency relationships and water surface profiles.

6. Collect more extensive data and perform hydraulic modeling of upland watershed areas with the greatest potential for flood damage reduction.

7. Develop and test biological response models that are linked to existing hydraulic and hydrologic models.

8. Collect economic data, indicating specific locations and elevations of vulnerable property, to formulate a systemwide plan for flood damage reduction.

9. Maintain and update the environmental GIS database that has been developed in this effort. This database can serve as an important resource for developing floodplain management strategies in specific reaches and for developing a systemic management plan for natural resources.

Unsteady Flow Routing of the 1993 Flood Using the DWOPER Model

One of the main objectives of this project was to evaluate several unsteady flow models for use in investigating different scenarios along the Mississippi and Illinois Rivers. Three existing unsteady flow models could be used for this purpose: DWOPER [Dynamic Wave OPERational Model (Fread, 1978)] used by the National Weather Service (NWS); UNET [One-Dimensional Unsteady Flow through a Full Network of Open Channels (Barkau, 1993)] used by the U.S. Army Corps of Engineers (USACOE); and FEQ (Full Equations) Unsteady Flow Model developed by Delbert Franz (Linsley, Kraeger Associates, Ltd., 1995) and used by the Division of Water Resources, U.S. Geological Survey.

The goal of this effort was not to duplicate efforts by other agencies or groups, but rather to independently evaluate the effects of certain structural and nonstructural measures in the floodplain of the Mississippi and Illinois Rivers. The NWS was the first agency to apply the unsteady flow model in investigating the 1993 Flood, using the DWOPER model for forecasting purposes. As reviewed in this report, the USACOE used the UNET model to support the efforts of the Scientific Assessment and Strategy Team (SAST, 1994) and for its own floodplain management assessment of the Upper Mississippi and Lower Missouri Rivers and tributaries (USACOE, 1995). The Natural Resources Defense Council (NRDC) contracted with Linsley, Kraeger Associates, Ltd. to develop the FEQ model for the Mississippi River and evaluate the impact of different scenarios during the 1993 Flood.

Attempts were made to obtain all three unsteady flow models for use in evaluating the impacts of existing conditions and future alternatives on flood discharges and heights. However, at the time of this study (1995), we were only able to obtain the DWOPER model from the NWS. The USACOE planned to release its UNET model sometime in 1996, and it was not known when the NRDC would release its model of the Mississippi River. Consequently, the unsteady flow modeling results presented in this report are based solely on the NWS DWOPER model.

DWOPER, the first program used to investigate the 1993 Flood, is an unsteady flow program that predicts river stages and discharges. It can account for the effects of locks and dams, storage, tributaries, and other features. Parameters of the river system being modeled are entered into the program using an input file. For example, the input file used for this study describes parts of the Mississippi, Illinois, and Missouri Rivers, and the model predicts discharges and stages on the Mississippi between Lock and Dam 22 and Thebes, Illinois. It also predicts stages and discharges along the Illinois River from Morris to Grafton, Illinois, and along the Missouri from Hermann, Missouri, to St. Louis. Large tributaries along the Mississippi, Illinois, and Missouri Rivers are included as point discharges into the three rivers. The modeled river reaches are shown in Figure 2.

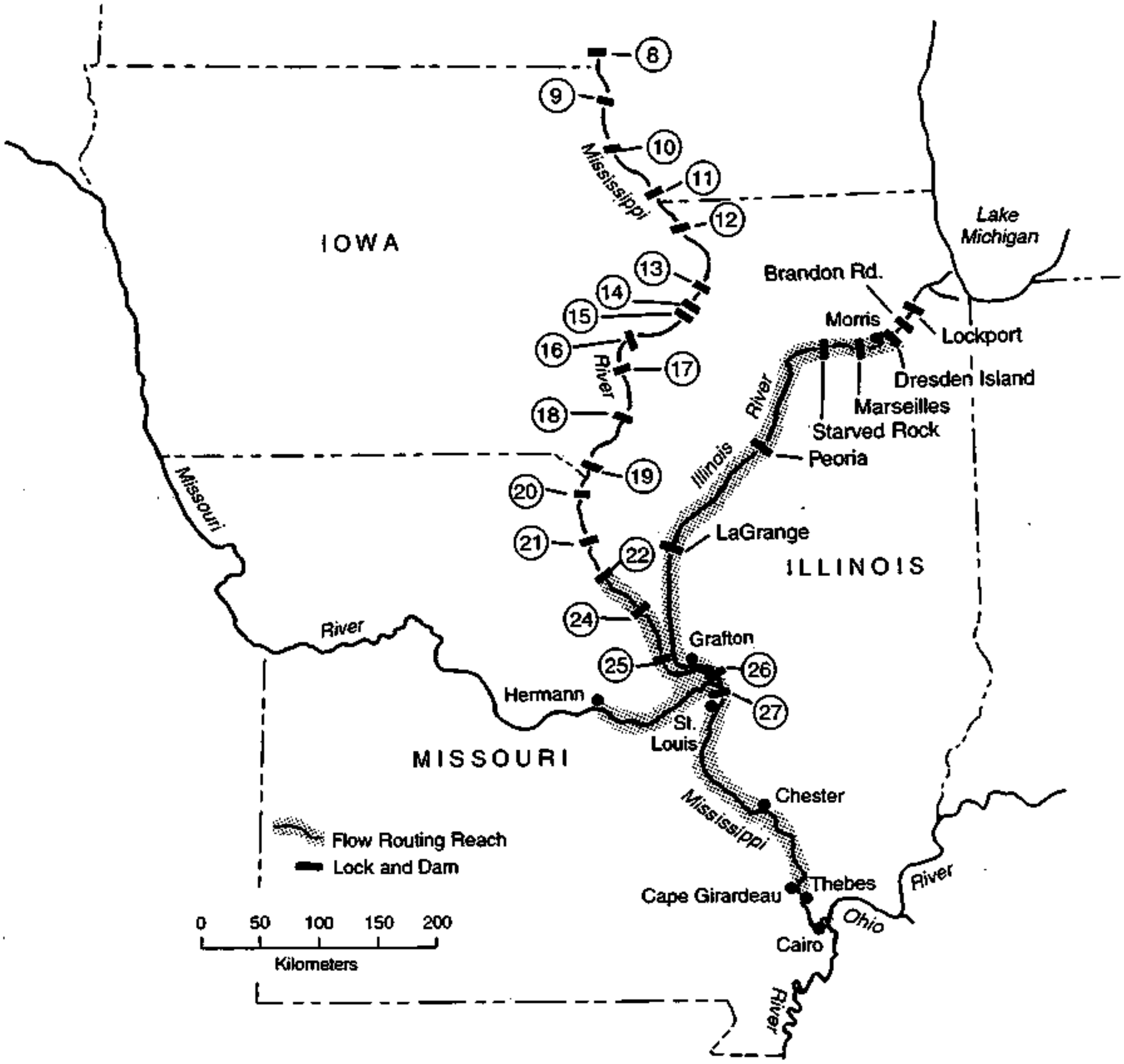

Figure 2. Unsteady flow routing reaches of the Mississippi, Illinois, and Missouri Rivers

Saint-Venant Equations

DWOPER is based on the one-dimensional Saint-Venant equations for unsteady flow. These equations have been given by Fread (1978) in his description of DWOPER. The continuity equation gives the mass balance of water for a unit segment of the river channel:

$$\frac{\partial Q}{\partial x}+\frac{\partial(A+A_o)}{\partial t}-q=0 \qquad (1)$$

where

Q = discharge,
A = cross-sectional area of channel,
A_0 = storage area (flow velocity considered negligible),
q = lateral inflow (positive) or outflow (negative),
x = streamwise distance, and
t = time.

The momentum equation is a balance of all the forces and accelerations acting on the water in a segment of the river channel:

$$\frac{\partial Q}{\partial t}+\frac{\partial(Q^2/A)}{\partial x}+gA\left(\frac{\partial h}{\partial x}+S_f+S_e\right)-qv_x+W_fB=0 \qquad (2)$$

where

g = gravitational acceleration,
h = elevation head,
S_f = friction slope,
S_e = energy slope,
v_x = streamwise velocity of lateral inflow,
W_f = wind term, and
B = channel top width.

The friction slope, Sf, in Eq. 2 is estimated using Eq. 3, and the energy slope, S_e, is estimated using Eq. 4:

$$S_f = \frac{n^2|Q|Q}{2.2A^2R_h^{4/3}} \qquad (3)$$

$$S_e = \frac{K_e}{2g}\frac{\partial\left(Q/A\right)^2}{\partial x} \qquad (4)$$

where

n = Manning's roughness coefficient,
R_h = hydraulic radius,
K_e = expansion/contraction coefficient.

The continuity and momentum equations are nonlinear and must be solved numerically for most cases. DWOPER uses an implicit finite difference scheme to solve these nonlinear equations. Derivatives with respect to time are replaced using Eq. 5, derivatives with respect to distance are replaced using Eq. 6, and undifferentiated variables are estimated using Eq. 7.

$$\frac{\partial K}{\partial t}=\frac{\left(K_i^{j+1}+K_{i+1}^{j+1}-K_i^j-K_{i+1}^j\right)}{2\Delta t} \tag{5}$$

$$\frac{\partial K}{\partial x}=(\theta)\left(\frac{K_{i+1}^{j+1}-K_i^{j+1}}{\Delta x}\right)+(1-\theta)\left(\frac{K_{i+1}^{j}-K_i^{j}}{\Delta x}\right) \tag{6}$$

$$K=(\theta)\left(\frac{K_{i+1}^{j+1}+K_i^{j+1}}{2}\right)+(1-\theta)\left(\frac{K_{i+1}^{j}+K_i^{j}}{2}\right) \tag{7}$$

where

K = any variable,
i = spatial index,
j = temporal index,
Δt = time step
θ = weighting factor, and
Ax = incremental distance.

The value of θ can vary between 0 and 1 and adjusts the implicit nature of the formulation. Fread (1975) has suggested a value of 0.55 for 6 since lower values decrease the stability of the solution, while larger values decrease the accuracy of the solution by increasing truncation error.

The complete model (initial conditions, boundary conditions, and finite difference equations) has the same number of equations and unknowns. DWOPER uses the Newton-Raphson method to solve for the unknowns after each time step. The primary reason for using the Newton-Raphson method is the rapid convergence it provides for well-behaved problems with good initial estimates.

Input Parameters

DWOPER is designed primarily for modeling river systems in which the water can follow only one path from inlet to outlet, as is the case in most natural river systems. All river systems in DWOPER consist of one main river with many tributaries. The tributaries can be modeled as either major tributaries or lateral inflows. Major tributaries are modeled like the main river and can have tributaries of their own, but lateral inflows are modeled as point discharges into the main river or major tributaries. Whether a river is modeled as a major tributary or lateral inflow depends only on whether or not stages and discharges at locations along the river are desired, and on what information about the river is available.

Only the main river can have major tributaries (i.e., major tributaries cannot have other major tributaries emptying into them). This makes it impossible to calculate the stages and discharges of any tributary that does not empty directly into the main river.

The main river and major tributaries are divided into a user-specified number of reaches. Computational points are located wherever one reach ends and the next one begins. The governing equations are solved at each computational point using the finite difference scheme. Computational reaches should be less than 20 miles in length and much shorter in locations where channel properties change rapidly. The cross-sectional area of the channel must be given as a function of water surface elevation for each computational point.

Solving the finite difference equations requires inlet and outlet conditions for the main channel, inlet conditions for each major tributary, and initial conditions for the entire river. Stage or discharge boundary conditions are required at the upstream boundaries of the main river and major tributaries, and also at the downstream boundary of the main river. Initial conditions must be given for each computational point, but may be estimated from backwater curves. DWOPER automatically smoothes out initial conditions, making the first few time steps inaccurate. This eliminates the noise introduced by faulty initial conditions, but it is inconvenient when stages and discharges near the starting time are important.

River roughnesses are determined by an autocalibration technique. Roughnesses are given as a function of either discharge or stage and are determined by comparing observed and computed stages. Once the roughnesses of a river system are known, they can be used for actual simulations. Only one value of Manning's roughness is used for each computational reach. It would be more appropriate to use different values of Manning's n for the floodplain and the main channel, but DWOPER puts all Manning's n values together into one coefficient.

Mississippi River Model

The model of the Mississippi River from Lock and Dam 22 to Thebes (Figure 2) divides the Mississippi into 64 computational points, the Illinois from Morris to Grafton into 77 computational points, and the Missouri from Hermann to St. Louis into 24 computational points. Lateral inflows from large tributaries are included for all three rivers. Four lock and dams are included for the Mississippi River, and four for the Illinois River.

Using the model, discharges and stages have been calculated. Figures 3-7 show the predicted and observed stages for five locations along the Mississippi River: Lock and Dam 22, Grafton, St. Louis, Chester, and Cape Girardeau. Figure 8 shows the discharges that were computed for Grafton, St. Louis, Chester, and Cape Girardeau, and the discharge at Lock and Dam 22 is the observed discharge required as a boundary condition.

At some locations, the model underpredicts stage by as much as 5 feet for large discharges. Since DWOPER uses an autocalibration feature to determine the best roughness values, these significant underestimates of stage may be due partly to a lack of sufficient calibration information at the large discharges. The discrepancies may also be due to inaccuracies in the estimates of tributary contributions, inadequate accounting of floodplain conveyances for high flows in the model, etc. Except for some discrepancies during the highest peak period in July and August, the model performed well during the remaining seven-month (March-September, 1993) simulation period, including the first major peak in April. In the following analysis, different parameters are altered to represent different management scenarios, and the results are compared with those of the original predictions. Although the original predictions are not exact, they provide a good baseline for examining the effects of varying different parameters. The resulting comparisons should provide a good estimate of the magnitude and direction of stage and discharge changes due to parameter variations.

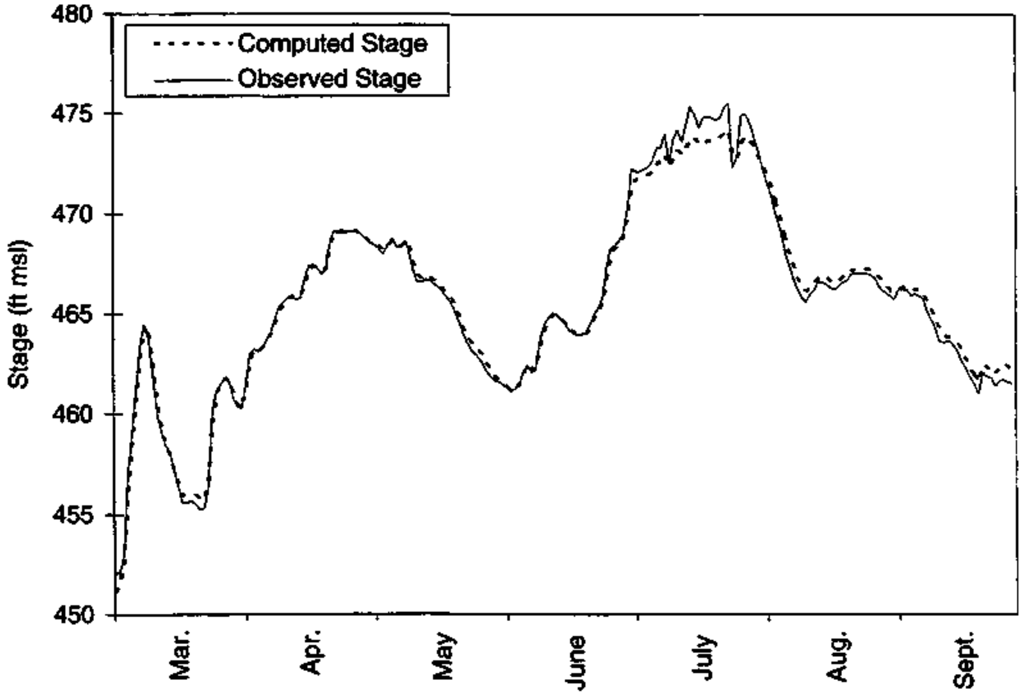

Figure 3. Comparison of computed and observed stages at Lock and Dam 22 during the 1993 Flood

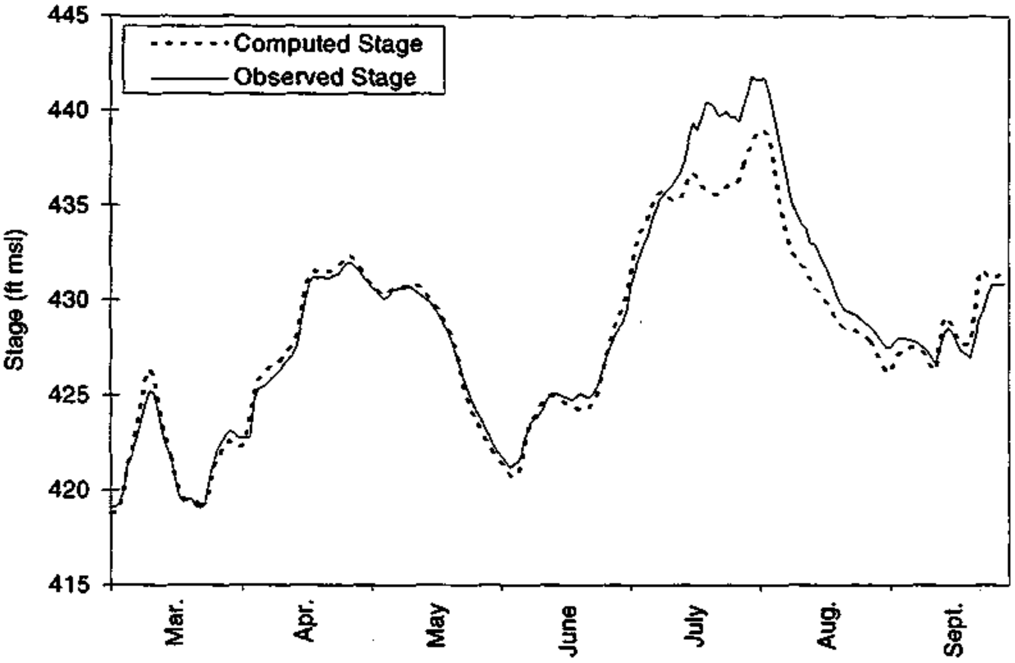

Figure 4. Comparison of computed and observed stages at Grafton during the 1993 Flood

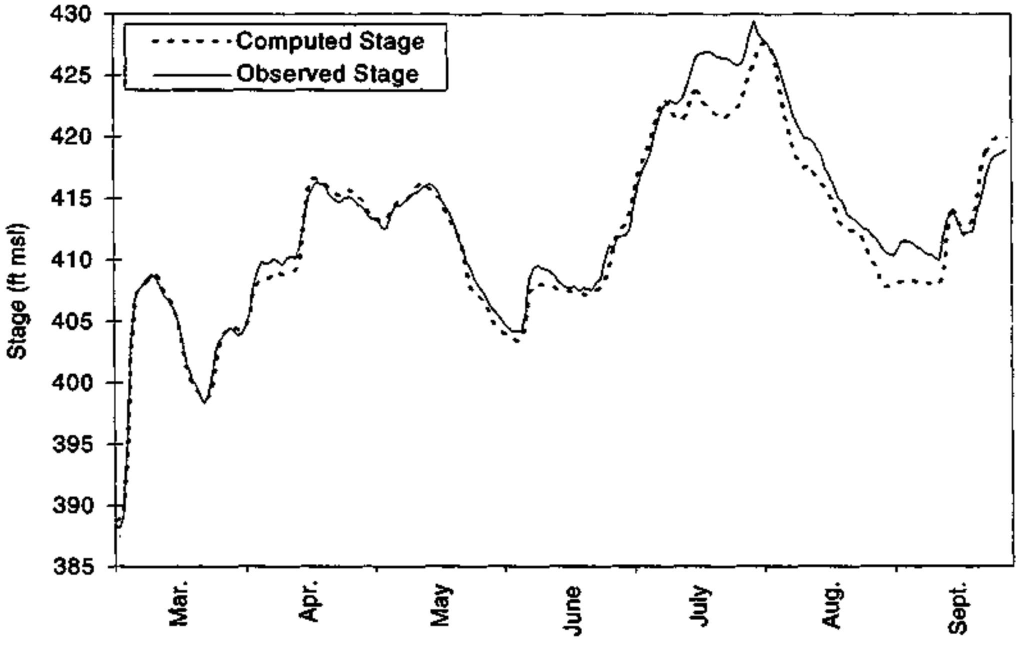

Figure 5. Comparison of computed and observed stages at St. Louis during the 1993 Flood

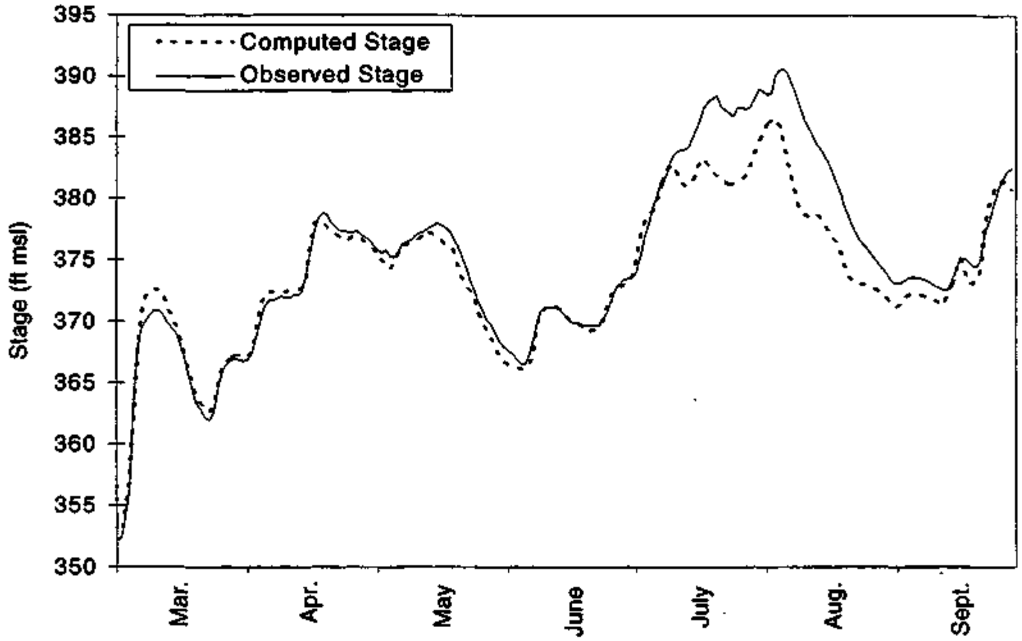

Figure 6. Comparison of computed and observed stages at Chester during the 1993 Flood

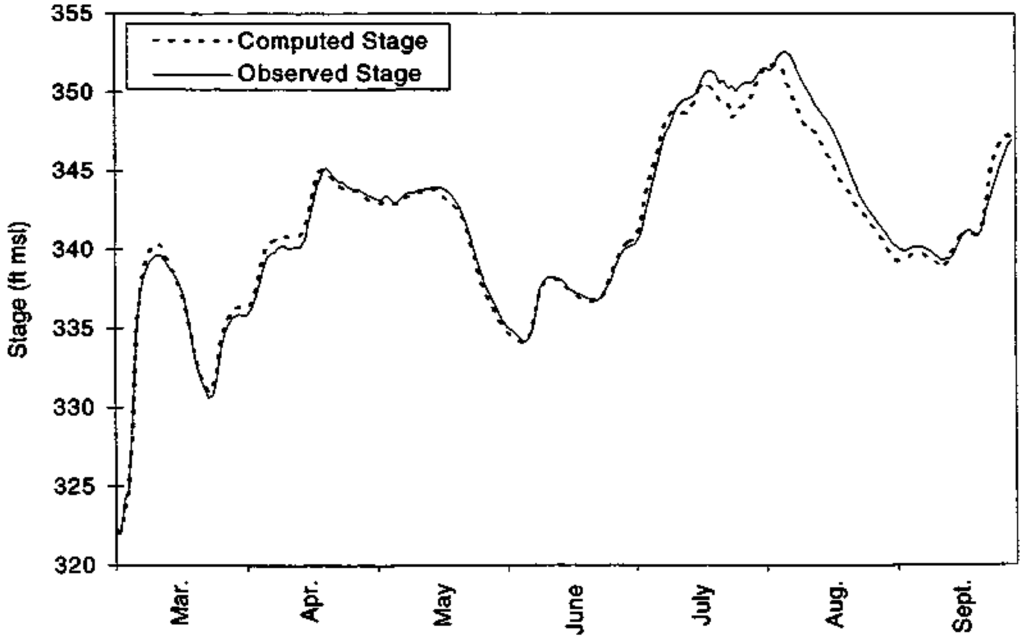

Figure 7. Comparison of computed and observed stages at Cape Girardeau during the 1993 Flood

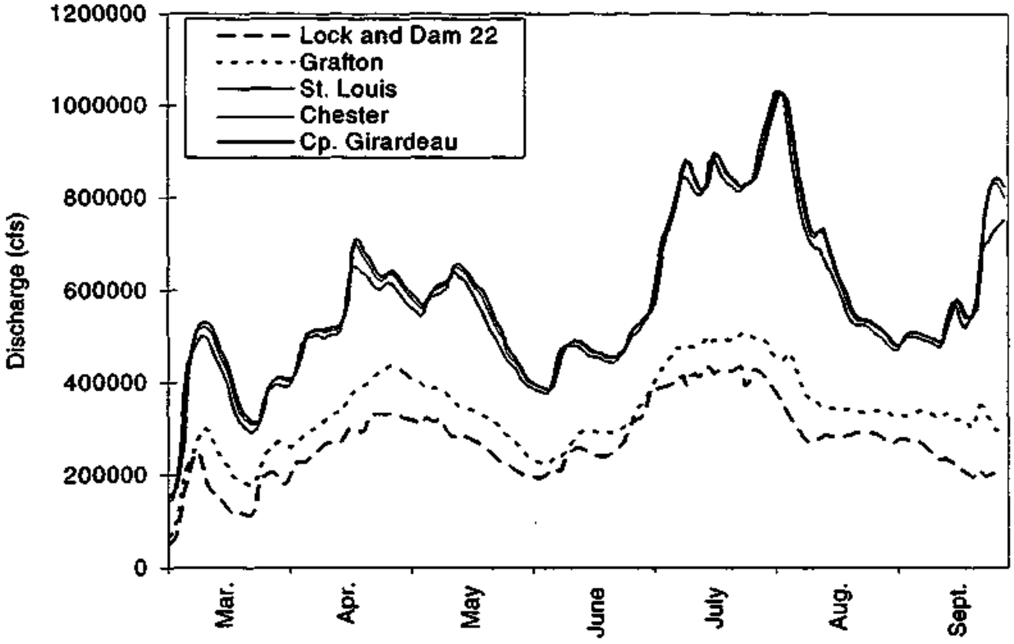

Figure 8. Discharges computed at different locations during the 1993 Flood

Effects of Locks and Dams

The effects of locks and dams along the Mississippi were investigated first. Three different scenarios were analyzed. The first scenario removed all of the locks downstream of Lock and Dam 22 and eliminated all storage. The second scenario removed the locks and allowed only the storage given in the original Mississippi River model. The third scenario removed the locks and modeled all of the floodplain as storage; this would occur if all of the levees failed but did not convey water downstream.

Locks and dams were removed from the input file. Cross sections upstream and downstream of the dam were not changed, although removal of the locks and dams could significantly change the cross sections due to erosion and deposition. Some of the scenarios required that the maximum tailwater level downstream of each dam be reduced so that DWOPER would converge. Although this yielded inaccurate stage predictions during low flows, stage predictions during the flood were not affected as much, probably because the dams did not significantly control the flow during the flood.

DWOPER's storage function uses a table of top widths versus elevations to compute off-channel storage. In the 1993 Flood model, storage is only given for elevations higher than the levee tops. Although DWOPER has a subroutine for predicting what happens when a levee is breached, it is difficult to implement for large-scale models and is not used in the Mississippi model. Instead, the storage area behind the levee is accounted for by oversizing the top width of the storage function at the top of the levee. This is not a very accurate method of modeling overtopped levee storage.

Input data for a steady water surface profile (USACOE HEC-2) model of the Mississippi River were used to get cross-sectional profiles of the floodplain for the third scenario. Profiles were converted to DWOPER format and modeled as storage area. The HEC-2 input data show where levees are located, and only the area behind the levees was included as storage.

Figures 9-12 show the effects of the different scenarios on stage at Grafton, St. Louis, Chester, and Cape Girardeau. Removal of the locks and dams has the largest effect on the stages at Grafton, which is upstream of a lock (Lock and Dam 26). Stage decreases by about 3 feet at peak discharges when the lock at Grafton is removed. Increases in stage at St. Louis, Chester, and Cape Girardeau are expected because storage behind the dams has been removed. Stages at these locations do not change, however, so the storage behind Lock and Dams 24-27 must be insignificant. Another reason for the insignificant changes in stage at St. Louis, Chester, and Cape Girardeau is that the Missouri River is a large contributor to the overall discharge at these locations, and is unaffected by removal of Lock and Dams 24-26.

Modeling the Mississippi without storage does not give significantly different results than modeling it with the originally defined DWOPER storage. However, if the whole floodplain is included as storage, the stage at Grafton drops 2 more feet over the removal of locks, but only for the first flood peak. For long-lasting floods such as the 1993 Flood, the effect of storage on peak stage is diminished. Figure 9 shows that at Grafton, the stages are attenuated by increased floodplain storage, but additional storage is insignificant at the peak stages of the flood. This is largely due to the flood duration. Increased storage causes the flood peak to occur at a later time.

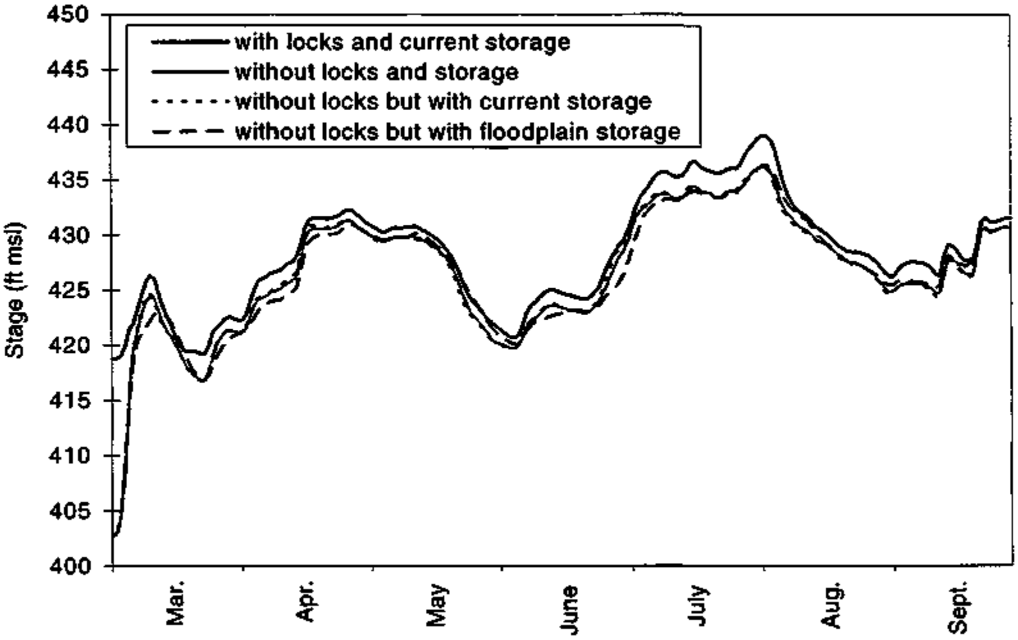

Figure 9. Effects of dam removal on stages at Grafton during the 1993 Flood

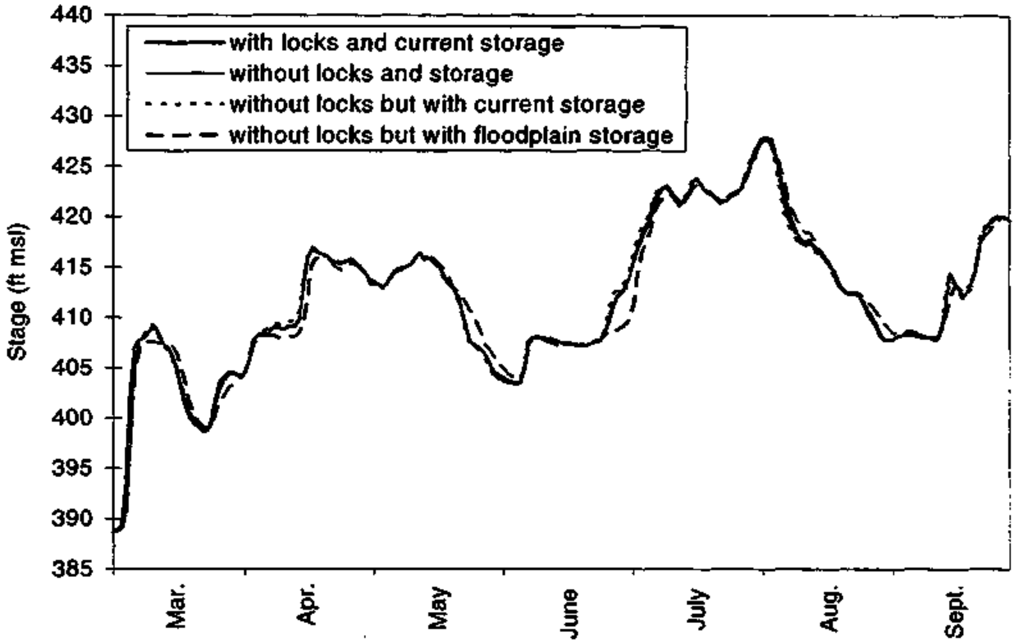

Figure 10. Effects of dam removal on stages at St. Louis during the 1993 Flood

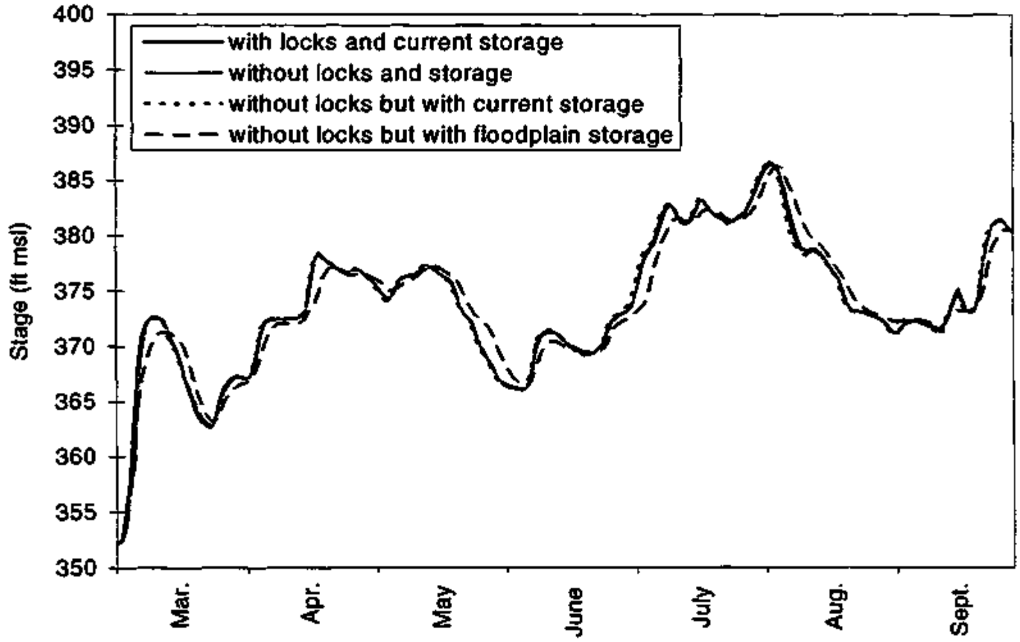

Figure 11. Effects of dam removal on stages at Chester during the 1993 Flood

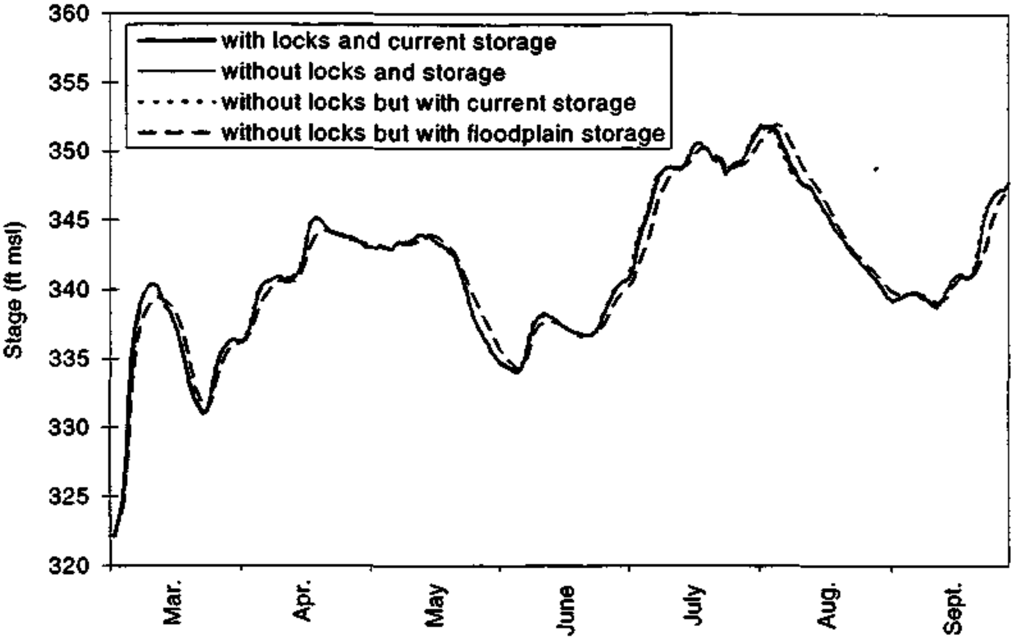

Figure 12. Effects of dam removal on stages at Cape Girardeau during the 1993 Flood

As shown by Figures 13-16, discharges are not affected much by removal of the locks and dams. Most of the changes in discharge are caused by the addition or removal of storage. Discharge is altered most when the whole floodplain is included as storage. The effect of additional storage is to attenuate the peaks of the flood wave. When the locks and dams are removed and the original storage described by the DWOPER model is used, the predicted discharges are not affected very much. This also indicates that the storage behind the locks and dams included in the model is insignificant.

Effects of Changes in Floodplain Storage

Some of the effects of storage are discussed in the section about locks and dams. In this section, the effects of levees will be examined more closely. Area behind the levees was modeled as storage; that is, it was assumed that no water was conveyed over the floodplain within the confines of the levee. The storage volume behind the levees was determined using the previously mentioned HEC-2 input data. Predicted stages are shown in Figures 17-20. Stages at Grafton and Chester drop as much as 2 feet because of the additional floodplain storage, but only when the flood wave is rapidly changing. Stage predictions shown for Cape Girardeau in Figure 20 are not reliable because Cape Girardeau is so close to the downstream boundary. The effect of the additional storage is to attenuate the flood wave, but since the 1993 Flood peaks were of such long duration, the additional storage did not substantially reduce peak stage. Since the Missouri River contributes a large percentage of the flow, changes in stage due to additional storage on the Mississippi River were not as significant at St. Louis as at Grafton. Between St. Louis and Chester, additional storage attenuates some of the Missouri River's discharge.

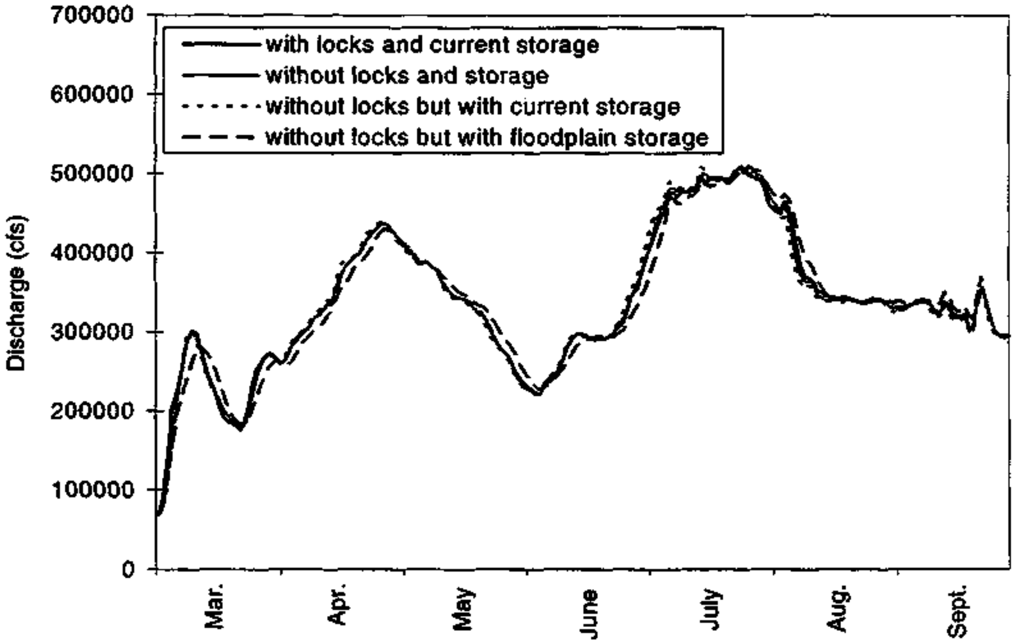

Figure 13. Effects of dam removal on discharge at Grafton during the 1993 Flood

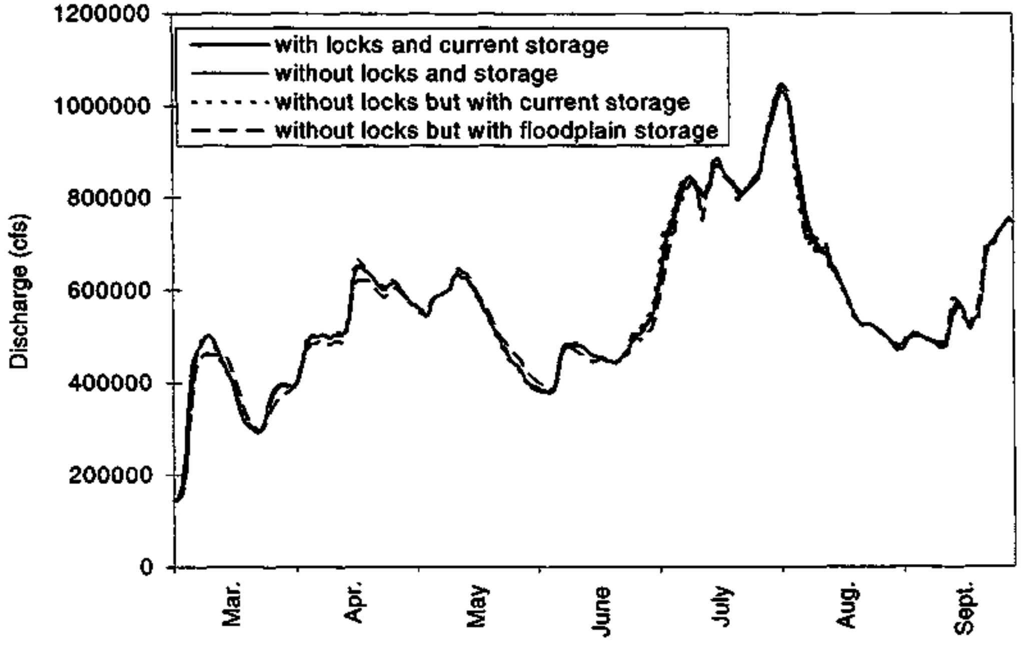

Figure 14. Effects of dam removal on discharge at St. Louis
during the 1993 Flood

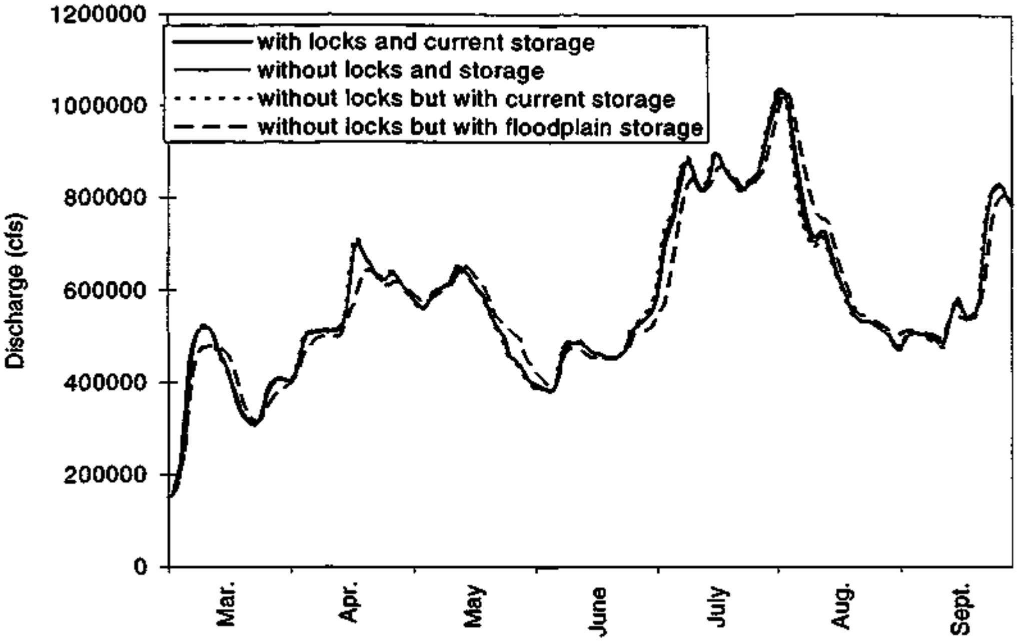

Figure 15. Effects of dam removal on discharge at Chester during the 1993 Flood

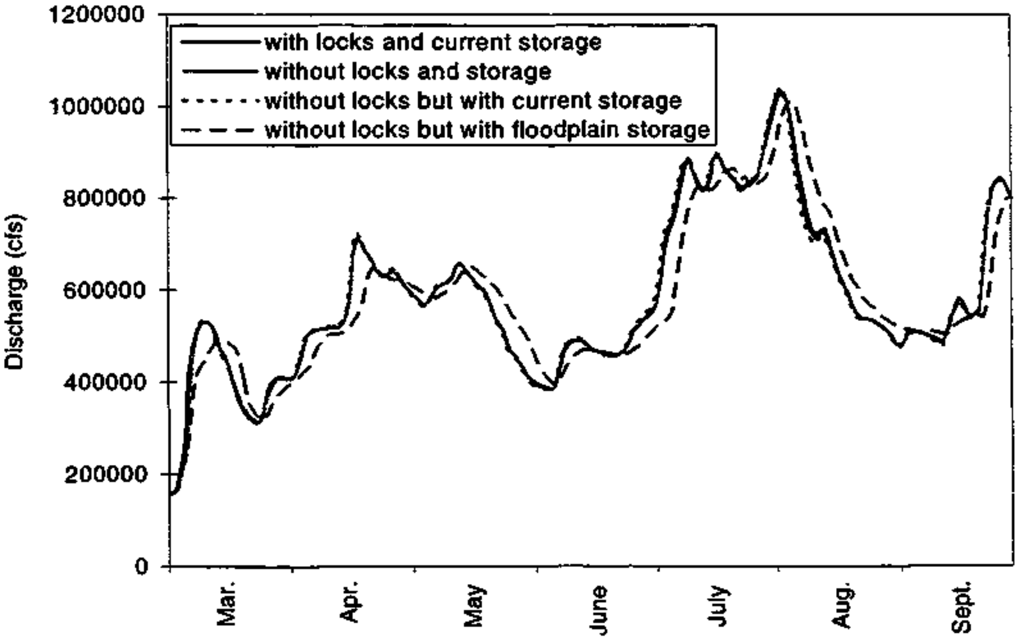

Figure 16. Effects of dam removal on discharge at Cape Girardeau during the 1993 Flood

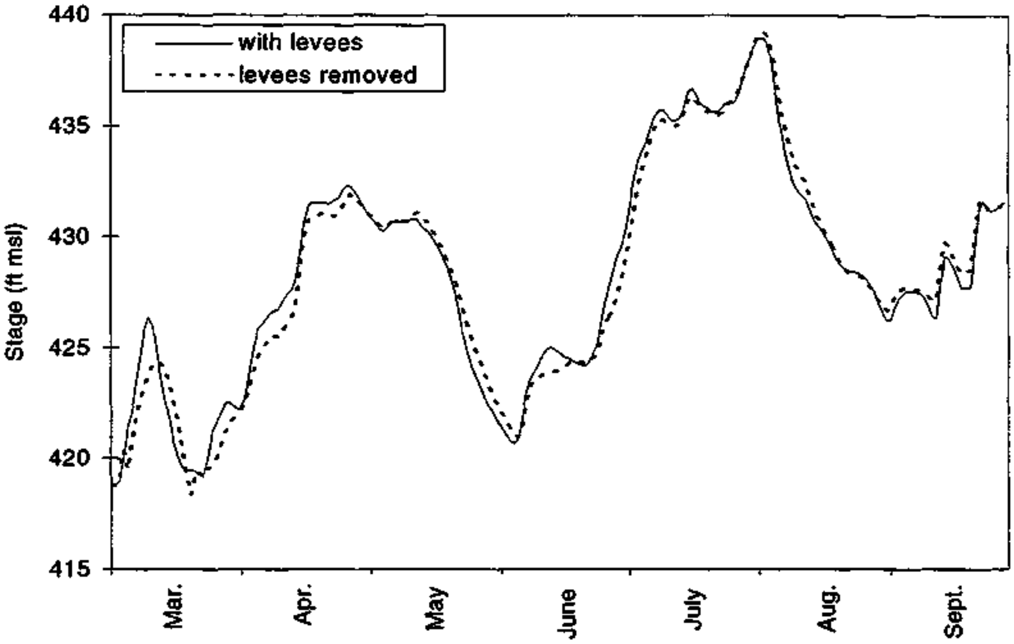

Figure 17. Effects of levee removal on stages at Grafton during the 1993 Flood

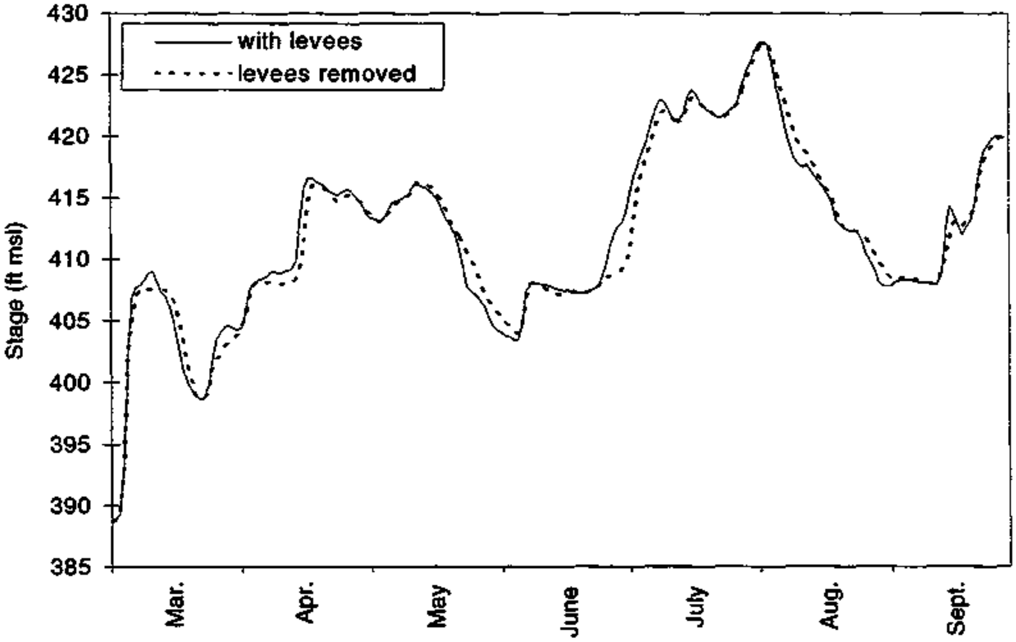

Figure 18. Effects of levee removal on stages at St. Louis during the 1993 Flood

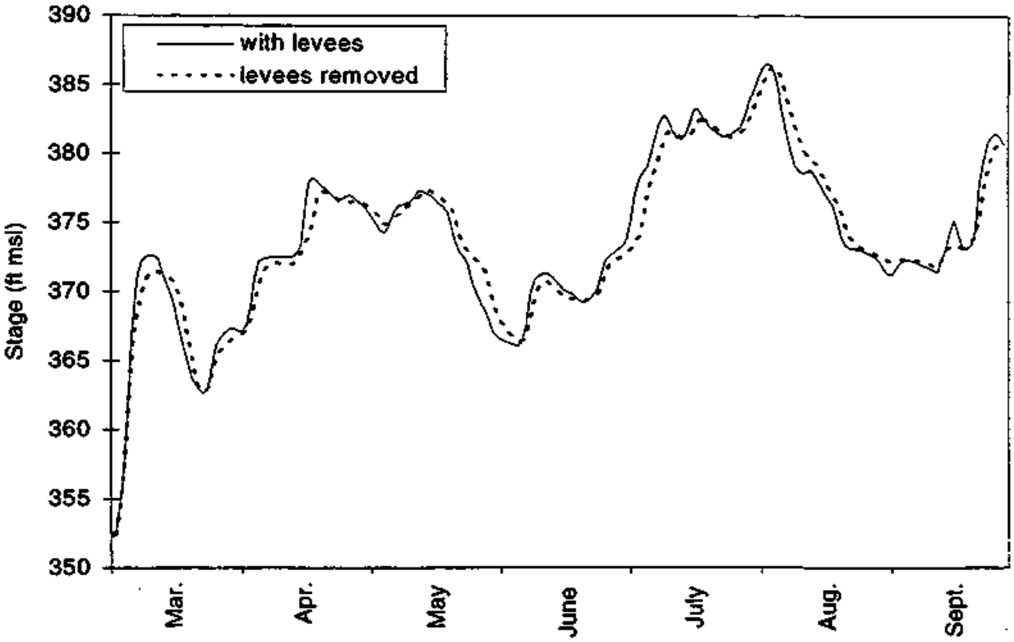

Figure 19. Effects of levee removal on stages at Chester
during the 1993 Flood

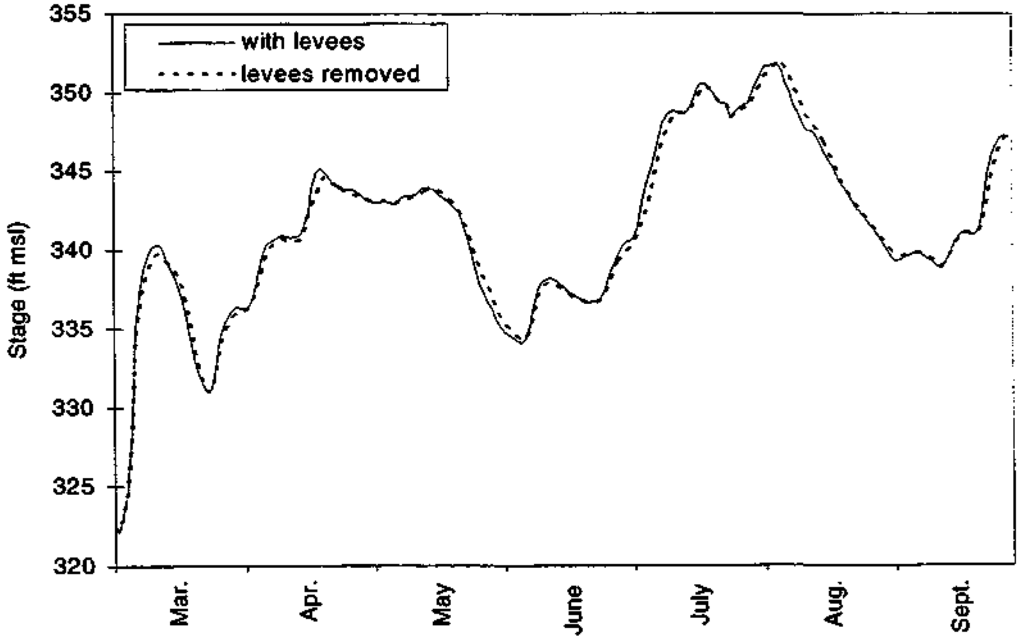

Figure 20. Effects of levee removal on stages at Cape Girardeau
during the 1993 Flood

As shown in Figures 21-24, discharges are significantly affected by changes in storage. The additional storage dampens the peak discharge and adds a time lag so that the peak discharge occurs at a later time. This is especially true of Grafton and Chester. The discharge at St. Louis is less affected because the Missouri River contributes a large fraction of the discharge. The discharge of the Missouri River is unaffected by changes in storage along the Mississippi River upstream of the confluence.

If two rivers, such as the Missouri and Mississippi, have peak discharges that arrive at a confluence at slightly different times, and additional storage is placed on the river with the earlier peak discharge, the earlier peak discharge may be delayed so that its arrival time coincides with the later peak discharge, increasing the overall peak discharge at the confluence. This is demonstrated by the peak discharges shown in Figure 22 at St. Louis.

Figure 25 shows the discharges of the Mississippi and Missouri Rivers just upstream and downstream of their confluence. The figure shows that if the peak discharge of the Mississippi at Lock and Dam 26 occurs at a slightly later time, it will more closely coincide with the peak discharge of the Missouri. When storage was added to the Mississippi upstream of the confluence, the peak discharge of the Mississippi decreased slightly, but it also occurred later in time. As a result, the overall discharge at St. Louis was larger than it would have been without the storage. If peak discharges along the two rivers occur randomly, storage will usually decrease peak discharge. However, if the two rivers drain the same region, and one river conveys the water more slowly (or over a longer route) than the other, then adding storage could regularly increase or decrease peak stages at the confluence when a rainfall event occurs.

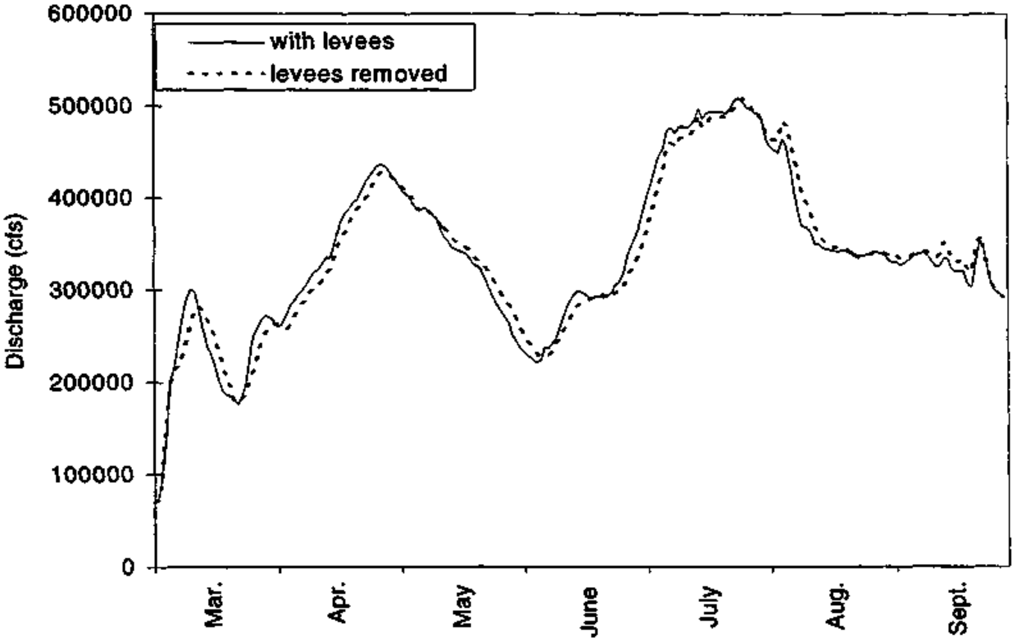

Figure 21. Effects of levee removal on discharge at Grafton during the 1993 Flood

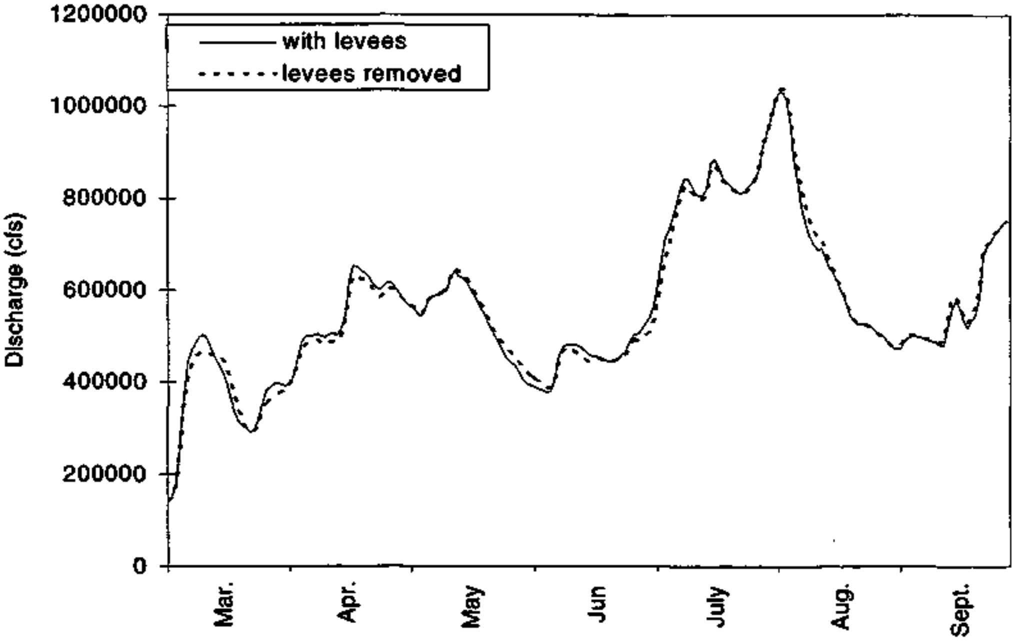

Figure 22. Effects of levee removal on discharge at St. Louis during the 1993 Flood

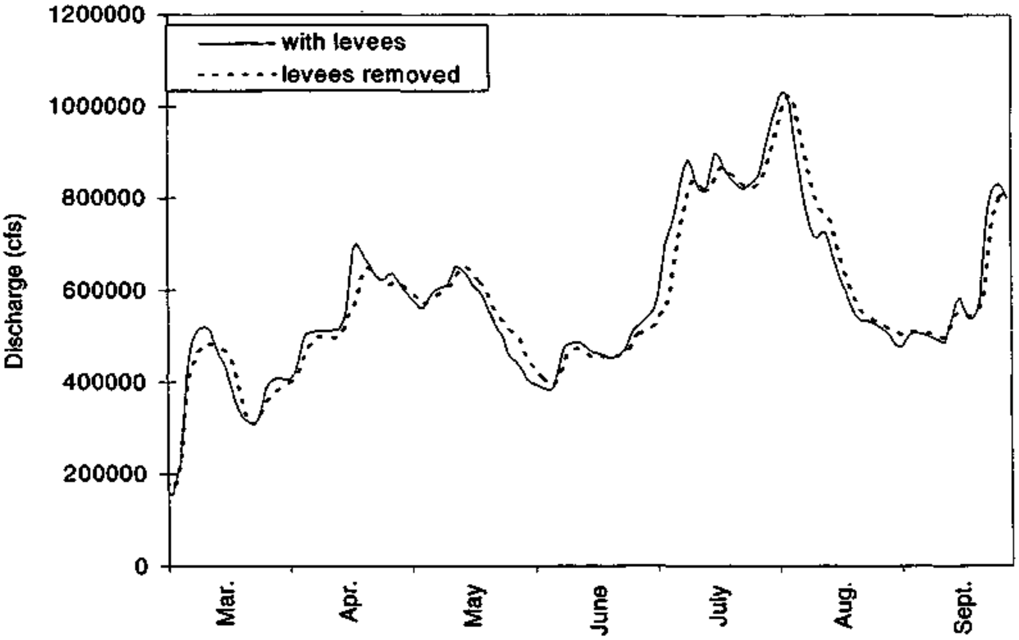

Figure 23. Effects of levee removal on discharge at Chester during the 1993 Flood

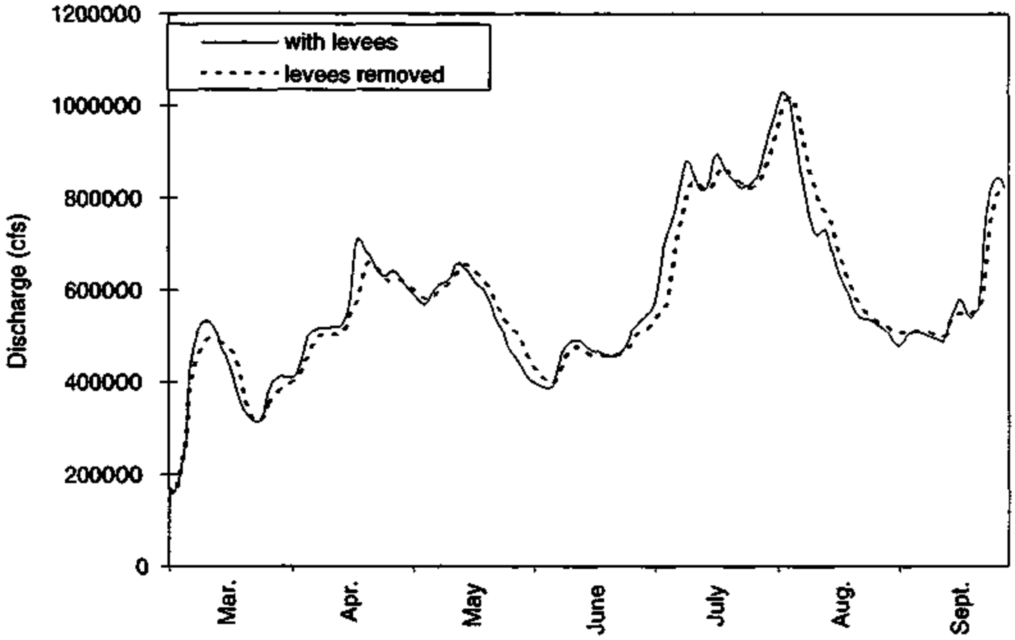

Figure 24. Effects of levee removal on discharge at Cape Girardeau during the 1993 Flood

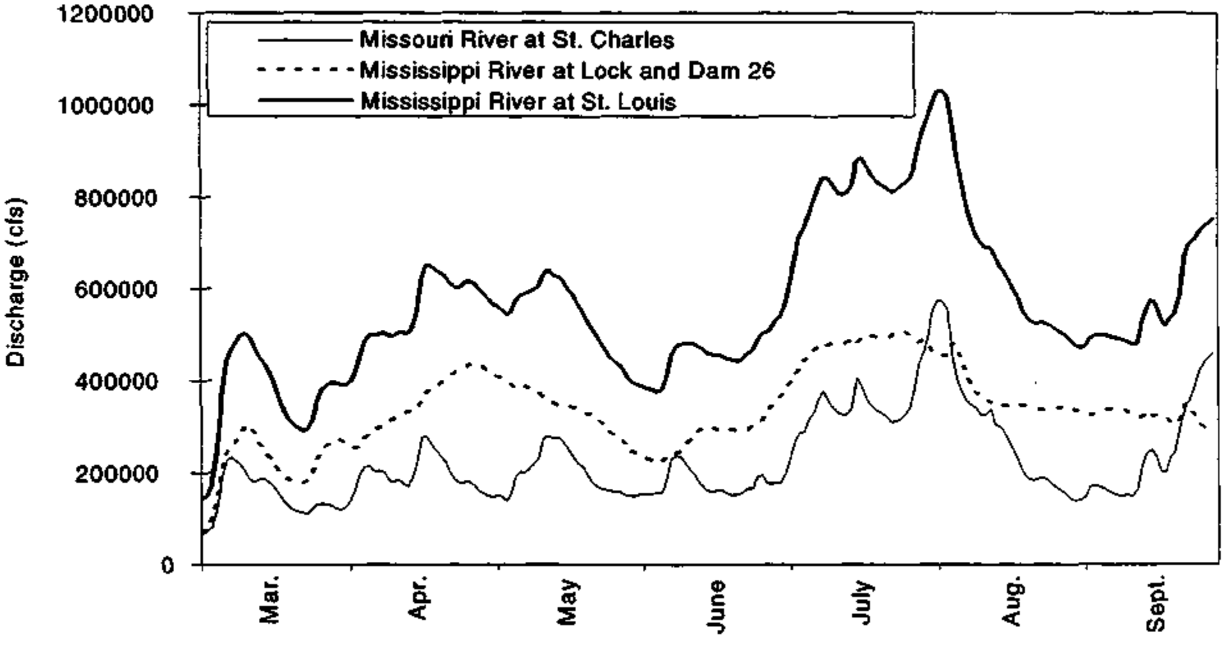

Figure 25. Discharge above and below the junction of the Missouri and Mississippi Rivers (Note: If the discharge curve at Lock and Dam 26 has a small time lag, the peak discharges upstream of the confluence will coincide more closely.)

Effects of Changes in Roughness

Changes in roughness can significantly raise or lower river stages. Changes in the effective channel roughness are caused by many factors, including wing dams, channelization, urbanization, and agricultural practices. Roughness also changes with season. The 1993 Flood was unusual because it occurred throughout the summer. Most large floods are of shorter duration and occur during the spring. Because the flood was later in the growing season, vegetation may have increased the channel roughness.

In order to demonstrate how changes in roughness affect river stages, roughnesses were changed by a constant amount for the entire model. Actual changes in roughness usually occur locally, but in this analysis roughnesses were changed uniformly for the entire river system. The roughnesses of the original DWOPER model were increased and decreased by constant amounts, 0.005 and 0.01. The effects on stage are shown in Figures 26-29.

Stages increase between 2 and 3 feet at Grafton when roughness is increased by 0.005. Changes in roughness can be even more dramatic at St. Louis and Chester, where stages can increase more than 5 feet due to a corresponding increase in roughness. Similar drops in stage occur when roughness is decreased by 0.005. When roughness is changed by 0.01, the stage changes more than 5 feet (and sometimes more than 10) at Grafton and more than 10 feet at St. Louis. Clearly, changes in channel roughness have a significant effect on stage.

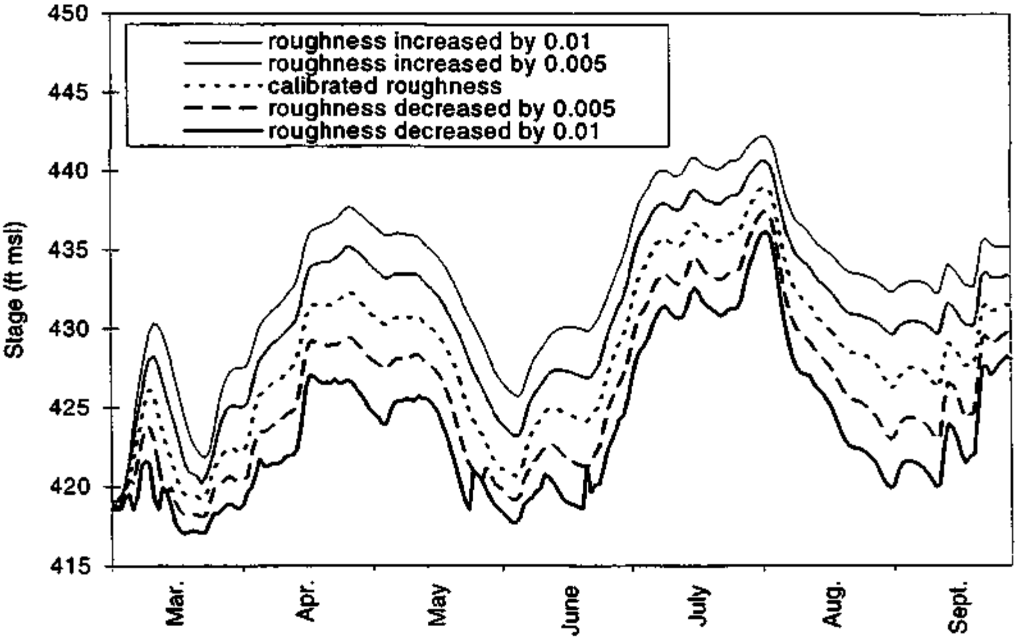

Figure 26. Effects of roughness changes on stages at Grafton during the 1993 Flood

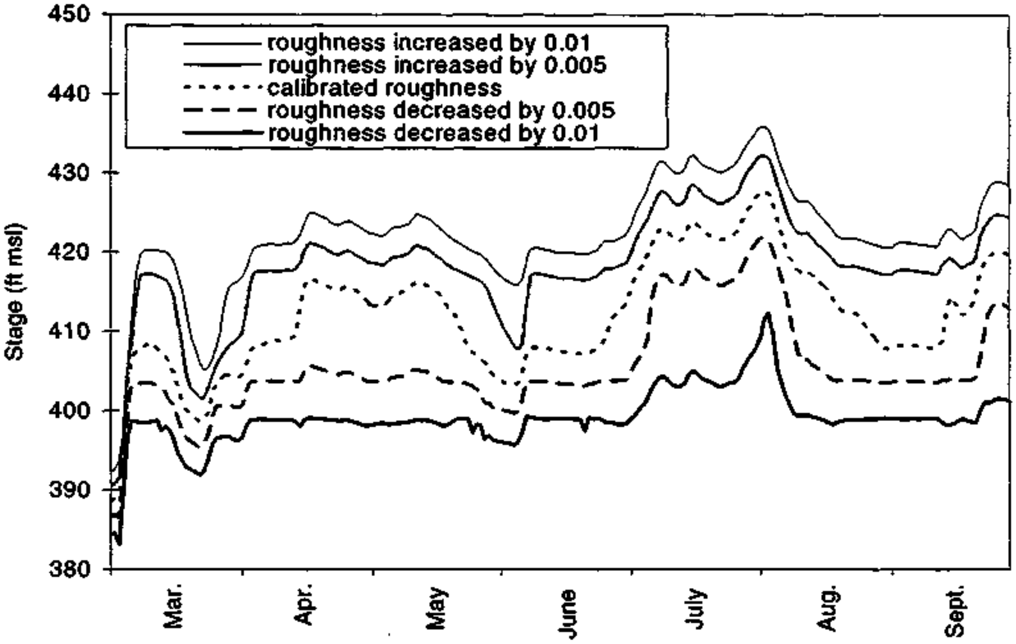

Figure 27. Effects of roughness changes on stages at St. Louis during the 1993 Flood

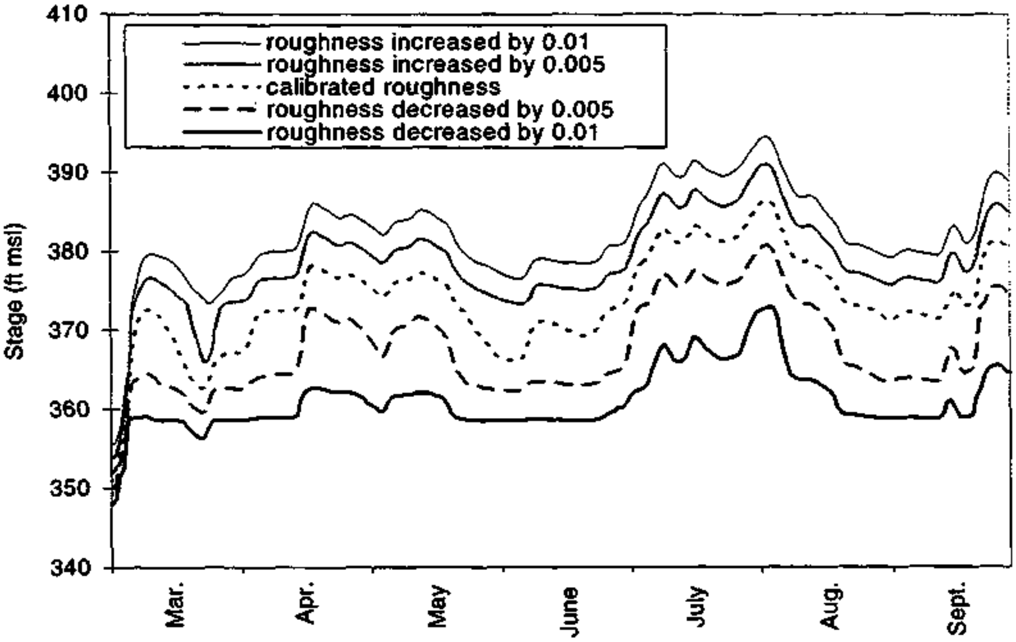

Figure 28. Effects of roughness changes on stages at Chester during the 1993 Flood

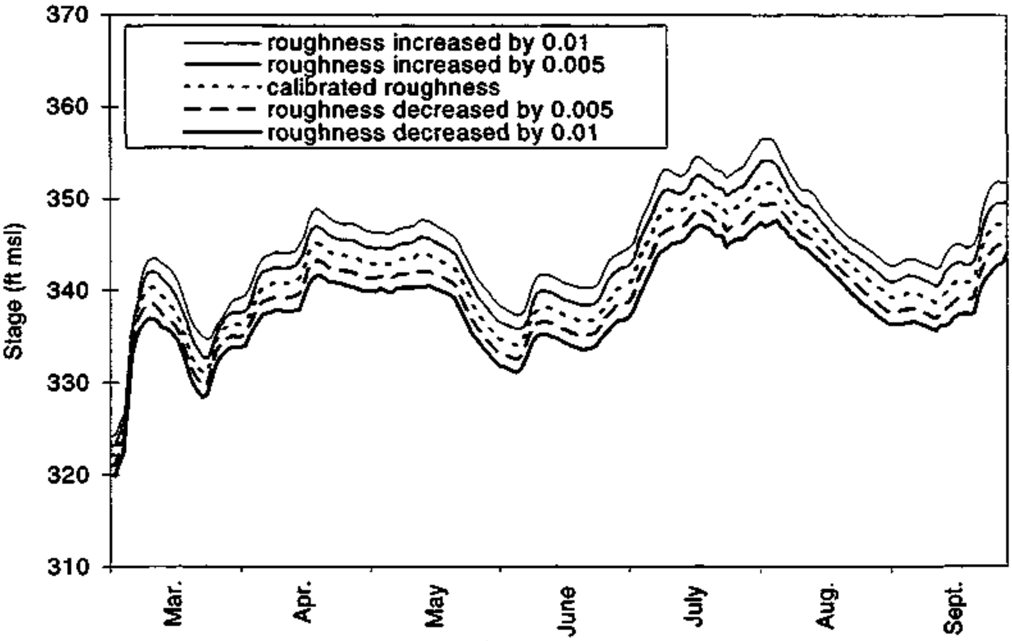

Figure 29. Effects of roughness changes on stages at Cape Girardeau during the 1993 Flood

Figures 30-33 show how discharge changes due to changes in roughness. Discharge does not seem to be significantly affected by the roughness of the channel at any of the locations. Apparently, the flood wave is not significantly attenuated by changes in channel roughness.

Stages and discharges predicted at Cape Girardeau require further explanation. One difficulty with boundary value problems such as the one being solved by DWOPER is that the boundary conditions are not always independent of the predictions being made. When roughnesses are changed, the downstream boundary condition (stage) is likely to change as well. However, a good estimate of the stage at the downstream boundary for different roughnesses was not available, so the original downstream boundary condition was used. Since the stage was fixed at the downstream boundary, stages and discharges near the boundary could not be predicted accurately. Consequently, changes in stage and discharge predicted for Cape Girardeau in Figures 29 and 33 are probably not very accurate.

Conveyance

In addition to providing storage, floodplains convey water. The Flood of 1993 occurred over a long period, and the effects of conveyance may have been more significant than those of storage. DWOPER does not have the ability to treat the floodplain separately from the main channel. The only way to include the floodplain is to include it as part of the main channel. Two things must be done to add floodplain conveyance to an existing model: first, the cross section of the channel must be modified to include the floodplain cross section, and second, the roughness of the floodplain must be accounted for by the model.

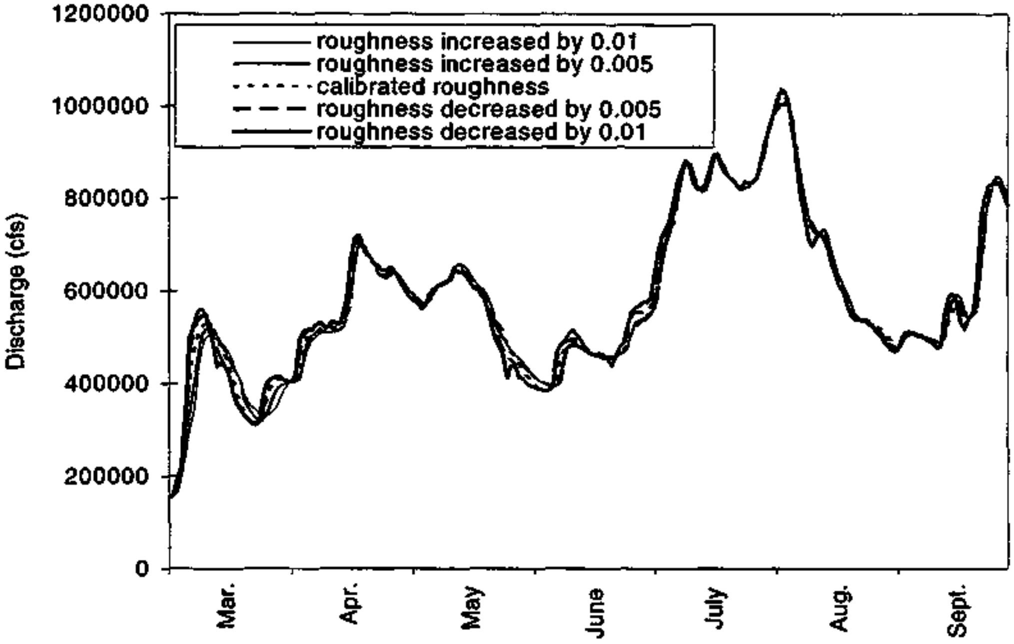

Figure 30. Effects of roughness changes on discharge at Grafton during the 1993 Flood

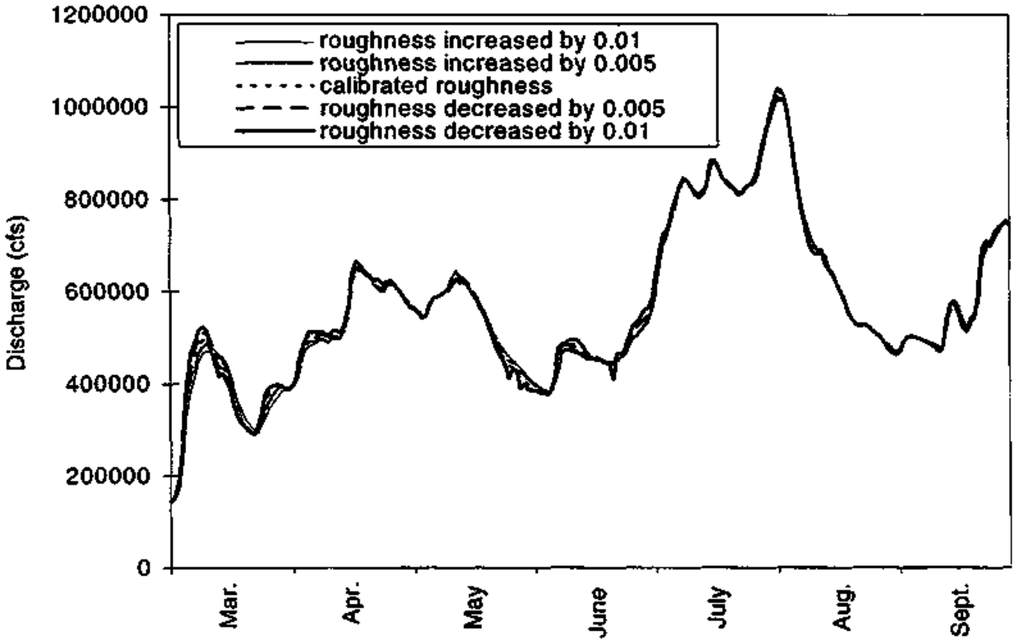

Figure 31. Effects of roughness changes on discharge at St. Louis during the 1993 Flood

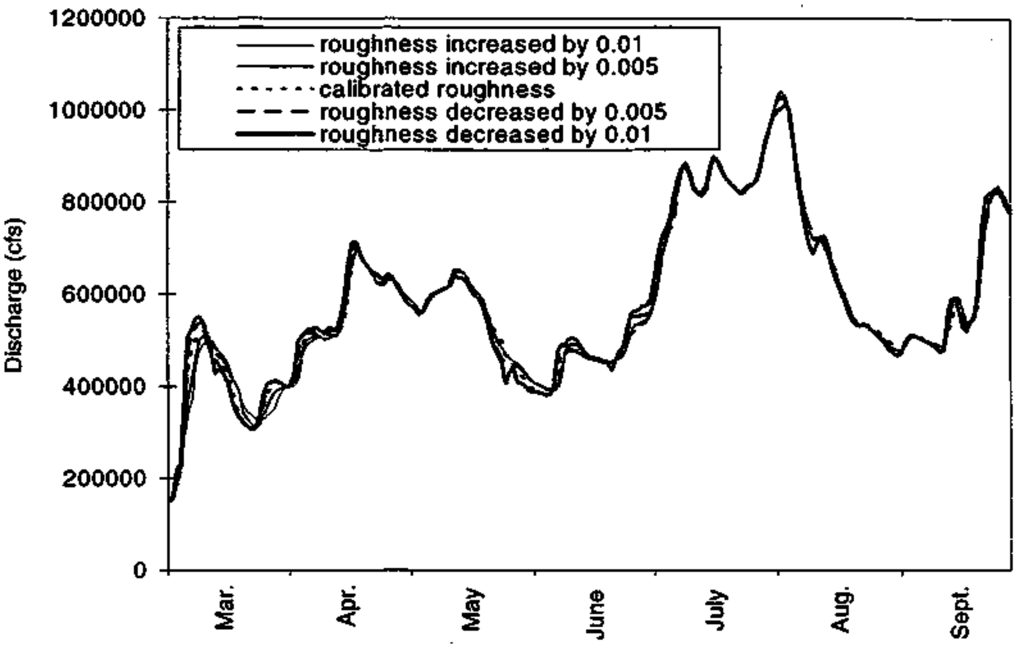

Figure 32. Effects of roughness changes on discharge at Chester
during the 1993 Flood

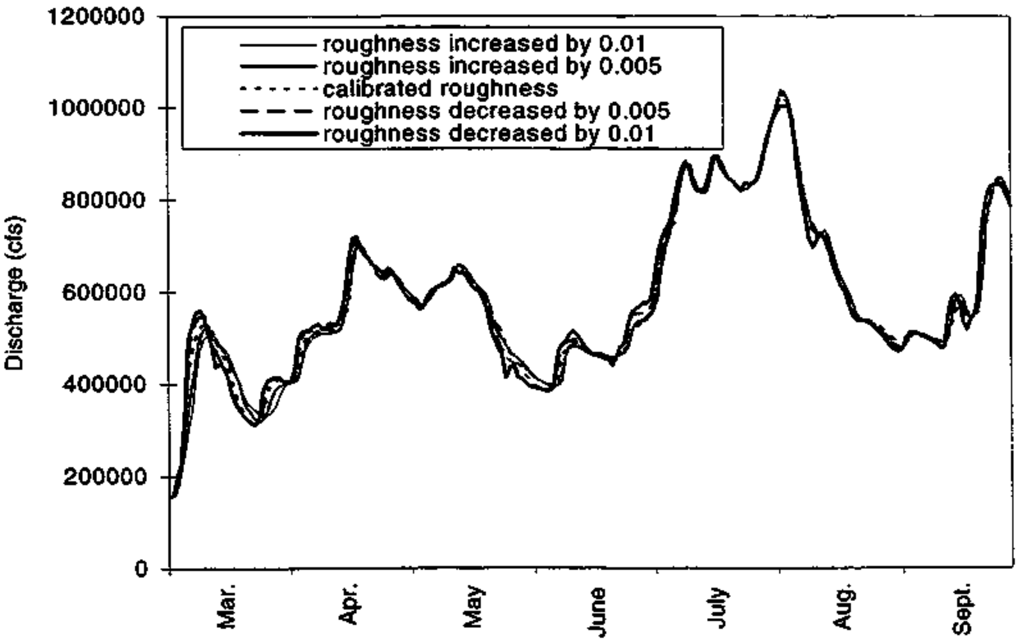

Figure 33. Effects of roughness changes on discharge at Cape Girardeau
during the 1993 Flood

For the DWOPER model, the cross section of the floodplain was included by treating all of the floodplain storage as conveyance area. At each computational point the relation between top width and depth was computed for the combined areas of the floodplain and the main channel. This relation was then entered into the DWOPER model.

Unfortunately, the change in channel roughness caused by the addition of the floodplain could not be modeled correctly by DWOPER, which uses a calibrated set of Manning's n coefficients to account for channel roughness. During program operation, the roughness coefficients are interpolated from a table that relates n to either the stage or the discharge. The river system being modeled is divided into reaches. All of the computational points within a reach use the same relation between the roughness coefficient and the stage or discharge. Neither the stage nor the discharge relation can be used to adequately model the addition of the floodplain in the Mississippi River model.

Once a floodplain is added to the model, the roughnesses in the roughness-discharge or roughness-stage tables change and must be recalculated. The model cannot be recalibrated because calibration requires observed river stages and discharges. The available observed stages and discharges do not reflect a floodplain situation, so they will not provide the proper roughness coefficients. One possible way of incorporating floodplain roughness into the model is to assume that the entire floodplain has a constant roughness and to recalculate the roughness relation for the combined channel. This may be done using the following set of equations.

By continuity, the following equation is obtained:

$$Q_c = Q_{fp} + Q_{mc} \tag{8}$$

where

c = subscript representing combined,
fp = subscript representing flood plain, and
mc = subscript representing main channel.

Flows in the floodplain, the main channel, and the combined channel can all be modeled with the Manning's equation:

$$Q_c = \left[\frac{1.49}{n} A R_h^{2/3} S^{1/2} \right]_c \tag{9}$$

$$Q_{fp} = \left[\frac{1.49}{n} A R_h^{2/3} S^{1/2} \right]_{fp} \tag{10}$$

$$Q_{mc} = \left[\frac{1.49}{n} A R_h^{2/3} S^{1/2} \right]_{mc} \tag{11}$$

where S = bed slope.

Equations 9, 10, and 11 can be substituted into Eq. 8 to yield the following:

$$\left[\frac{1.49}{n}AR_h^{2/3}S^{1/2}\right]_c = \left[\frac{1.49}{n}AR_h^{2/3}S^{1/2}\right]_{fp} + \left[\frac{1.49}{n}AR_h^{2/3}S^{1/2}\right]_{mc} \tag{12}$$

The slope is the same for each of the cross sections, so:

$$\left[\frac{AR_h^{2/3}}{n}\right]_c = \left[\frac{AR_h^{2/3}}{n}\right]_{fp} + \left[\frac{AR_h^{2/3}}{n}\right]_{mc} \tag{13}$$

Or, upon rearranging:

$$n_c = \frac{\left[AR_h^{2/3}\right]_c}{\left[\frac{AR_h^{2/3}}{n}\right]_{fp} + \left[\frac{AR_h^{2/3}}{n}\right]_{mc}} \tag{14}$$

At each computational point, the cross-sectional area and hydraulic radius of the main channel, the floodplain, and the combined channel can be determined from DWOPER's depth-top width tables for any flow depth. A constant roughness coefficient is assumed for the floodplain. In order to use Eq. 14, the roughness coefficient of the main channel must be given as a function of depth. The result will be the combined channel roughness as a function of depth.

If a roughness-discharge table is used by DWOPER for the main channel, the discharges can be converted into depths using rating curves. However, the result is a combined channel roughness coefficient that is a function of depth. Since the flow characteristics of the channel have been changed, so have the rating curves. The new rating curves are unknown, and mere is no way to convert the roughness-depth table back into a roughness-discharge table (as required by the model).

On the other hand, if a roughness-stage table is used by the DWOPER model, main channel roughness coefficients can be easily converted into combined channel roughness coefficients since it is easy to transform stages into depths and vice-versa; however, the stage-roughness coefficient table cannot be applied to the section of the Mississippi currently being studied. In order to determine the roughness-stage relation or the roughness-discharge relation, the model is calibrated using observed stage information. Each Manning's reach must have an observation station at its inlet and outlet in order to be calibrated. DWOPER cannot account for any changes in the roughness characteristics that occur between observation stations. If the river significantly drops in elevation between two observation stations (as it does for the model we are studying), the roughness-stage table does not give meaningful values of Manning's n, and converting the values for each computational point will give erroneous results. The roughness-stage table is more applicable to short reaches without much vertical drop. A more appropriate model for our application would be a roughness-depth table, a feature that DWOPER lacks.

Conclusions

While DWOPER appears to predict stages along the Mississippi between Lock and Dam 22 and Thebes fairly well, it did not predict stages as well during the highest peak discharges of the 1993 Flood, possibly because of a lack of sufficient calibration information. Removal of locks and dams affects only the stage upstream of the lock and dams. Upstream of the dams, stage is only a few feet higher than without the dams in place.

Roughness is an important factor in the determination of flood stage. Slight increases in roughness can increase stage by several feet, while slight reductions can significantly lower stage. Storage can significantly reduce peak discharge and stage for short duration flood peaks; however, if flood peaks are broad, additional storage may not be a significant factor.

DWOPER cannot be used to accurately model floodplain conveyance for the Mississippi River. Although DWOPER is a useful forecasting tool, its suitability for modeling different scenarios is somewhat limited.

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