Review of the Regulation of the Missouri River Mainstem Reservoir System During the Flood of 2011

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Cover: Photograph of spillway release of 140,000 cubic feet per second at Gavins Point Dam, near Yankton, South Dakota, June 24, 2011 (U.S. Army Corps of Engineers).

Contents

Figures

Tables

Acknowledgements

This was a technical review, and the review panel required a large amount of highly-detailed information over a short and intense period. The panel appreciates the considerable assistance of Kevin R. Grode and Michael A. Swenson, U.S. Army Corps of Engineers, who promptly and thoroughly fulfilled every panel request for data and information regarding the operation of the Missouri Reservoir System. Other valuable assistance from the U.S. Corps of Engineers in support of the review panel mission was provided by General John R. McMahon, Witt G. Anderson, Col. Robert Tipton, Colonel Robert J. Ruch, Captain Dan Larsen, Jody Farhat, Todd Lindquist, John Remus, and Kellie Bergman, Eric Stasch, Eric Shumate, Laila Berre, Kris Cleveland, Dave Becker, John Bartel, and Steve Daly.

The contribution of individuals and agencies who provided helpful input and comment regarding the final report is gratefully acknowledged. Contributors from the U.S. Geological Survey include: Gregg Wiche, Aldo Vecchia, Steve Robinson, Michael Slifer, Rodney Southard, Shane Barks, Timothy Cohn, Harry Lins, William Guertal, Scott Morlock, Donald Arvin, Robert Hainly, Robert Mason, Sandra Cooper, and Annette Goode. Contributors from the National Weather Service include Tom Gurss, Mike DeWeese, and Ted Apley. Other contributors include Verlon Barnes, Jan Curtis, Brian Domonkos, David Garen, John Lea, Jolyne Lea, Scott Oviatt, Tom Perkins, Mike Strobel, Rashawn Tama, Melissa Webb, and Jacquie Workman from the Natural Resources Conservation Service and David Unger with the National Oceanic and Atmospheric Administration.

During a fact-finding period, the review panel received valuable input from individuals through personal interviews and comment at public meetings in Bismarck, North Dakota; Pierre, South Dakota; Sioux City, Iowa; and St. Joseph, Missouri, including many individuals who experienced serious flood damages and losses. Although everyone the panel met could not be recognized here, all contribution were helpful and much appreciated. The panel specifically acknowledges the contributions of: Brad Lawrence, Director of Public Works, Pierre, South Dakota; Todd Sando, North Dakota State Engineer; Jason Glodt, South Dakota Governor’s Office; Lyn Beck and Mark Rath, South Dakota Department of Environment and Natural Resources; John Drew, Missouri State Hydrologist; Harold Hommes, Iowa Department of Agriculture; Charles Magaha, Director Leavenworth County Emergency Management; Tracy Streeter, Director of Kansas Water Office; Doug and Linda Larson, Larson’s Landing, Yankton, South Dakota; Jeff Dooley, Dakota Dunes, South Dakota Community Improvement District Director; Deanna Beckman, Deputy Director, Emergency Management, Dakota County, Nebraska; and Shane Goettle, former state director for U.S. Senator John Hoeven, North Dakota.

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Executive Summary

In 2011 the mainstem Missouri River Reservoir System experienced the largest volume of flood waters since the initiation of record-keeping in the nineteenth century. The high levels of runoff from both snowpack and rainfall stressed the System's capacity to control flood waters and caused massive damage and disruption along the river. As a result of its experiences during the flood, the U.S. Army Corps of Engineers (Corps) appointed a panel to conduct an independent technical review of its operations of the reservoir system during the flood event. The panel was appointed in September of 2011 and held its first meeting in early October in Omaha, Nebraska. Members of the panel represent Federal agencies with missions in water data and studies and Colorado State University. The panel's work was conducted independently from the Corps and is similar to a technical performance audit. The panel charter and members' appointment letters are included in the Appendix of the final report.

During October and November the panel reviewed documents and studies, interviewed staff of the Corps and other agencies and offices as well as members of the public, visited reservoir sites, and attended public meetings. The expertise of each member of the panel was applied to the assessment of elements of Corps' operations, and the panel members considered the full report as a group. In addition to this cross-evaluation of the panel's work, the report was subjected to independent technical peer review arranged by the U.S. Geological Survey. The Corps also was asked to respond to the draft report of the panel by checking for factual errors, breadth of coverage, and whether the report responds fully to the charter presented given to the panel. The panel considered these responses in preparing the final report.

In conducting the review of the Missouri River mainstem reservoir system during the 2011 flood, the review panel divided its findings into two areas:

- Conclusions regarding regulation of the reservoir system by the Corps during 2011 for the authorized purpose of flood control. The conclusions are summarized as answers to a set of questions that served as the starting point of the review process. The original questions posed by the Corps were supplemented by additional questions that arose during the panel investigation.
- Recommendations for actions to prevent or reduce damages from similar, or larger floods in the future.

Question 1. According to the Missouri River Master Manual and other pertinent documents, how should the mainstem reservoir system (System) and the Corps and U.S. Bureau of Reclamation (USBR) tributary reservoirs within the system have been operated, how were they actually operated, and what were the reasons for any differences in the operation?

See answer to Question 2.

Question 2. Were the water-management decisions made during the flood of 2011 appropriate and in line with the approved water control manuals?

The operation of the reservoirs must conform to guidance in the Master Manual and project manuals, and the decisions were appropriate and in line with the appropriate manuals. The Master Manual is defined to include both the System guidance and the mainstem project manuals. The tributary reservoirs of the Corps and U.S. Bureau of Reclamation (USBR) are to be operated according to their manuals, and the operations of selected USBR tributary reservoirs are subject to controls by the Corps during flood events (see the report's section on Master Manual guidance for extreme events). While the panel found that the reservoirs were operated according to the applicable manuals, it is also important to explain that during extreme flood events such as in 2011, the Master Manual does not provide a rigid formula for operational decisions. The formula-based operational procedures in the Master Manual use the concept of service levels to apply to flood conditions up to certain magnitudes, but during extraordinary flooding such as in 2011, the Master Manual requires a great deal of experience-based judgment. Here, guidance for decision-making shifts from formulas to multiple criteria based on control of floodwaters, consideration of flood damage, and the need to operate reservoirs to protect infrastructure and public safety. The panel wants to emphasize that the operators must consider the security of the infrastructure in their decisions. The serious consequences of dam failure require the operators to take precautions such as to evacuate flood waters and increase releases as they did in 2011. The panel was able to theorize about how operations might have reduced releases and increased storage, but when it considered the large volumes of water and the information the operators had at the times they had to make decisions, the panel did not see how major reductions in releases could have been made. Therefore, rather than speculate after-the-fact about differences in the required and actual operating decisions, the panel identified ways that future flood operation might be improved through lessons learned.

Question 3. Could the Corps have prevented or reduced the impact of the flood by taking other management actions leading up to the flood?

Looking at the event in hindsight, the panel and the Corps can demonstrate how more flood storage and earlier releases could have reduced the impact of the flood. However, holding more storage available carries the risk that some authorized purposes would not be met if the flood did not materialize. The Corps showed during its public presentations how it could have reduced releases if additional flood control space had been made available earlier in the season, but such actions are not authorized specifically in the

Master Manual. Barring an approved change in the Master Manual, the panel does not see how the Corps could have left substantially more storage available leading up to the flood. The panel noted that the Corps was following its guidelines and on March 1, the total system storage still had almost all of the normal flood storage remaining. The Corps took incremental flood control actions by releasing additional water as early as late March and by April 15 they had increased the service level releases by 15,000 cubic feet per second (ft^3/s). Therefore, the Corps was responding to increasing runoff forecasts, but they could not have foreseen the need to evacuate storage faster to accommodate the heavy rain that occurred during May. In summary, the Corps could have reduced the impact of the flood with more storage and higher releases before the flood, but these actions carried risks and consequences that did not seem appropriate to the Corps at the time they were required.

Question 4. Did operations for environmental or other purposes influence flood risk management operations, and if so how did they influence the operations?

Operations for System purposes other than flood control were suspended or assigned secondary priority once significant flooding started. Therefore, during the flood the Corps did not operate for environmental or other purposes in a way to influence flood risk. Prior to the flooding, they operated according to the Master Manual, which specifies operations for all eight authorized purposes.

Question 5. Were accurate and timely hydrologic and weather forecasts and other pertinent data available? What data improvements (plains and mountain snowpack information, streamflow gaging stations, and observed weather data) are warranted in light of this flood event to properly manage the system?

See answer to Question 7.

Question 6. Did the Corps properly assess basin conditions and properly forecast runoff from the plains snowpack, mountain snowpack, and precipitation? If not, what additional information and/or tools are needed to better forecast runoff?

See answer to Question 7.

Question 7. Did the Corps' long-term regulation forecasts properly account for the 2011 runoff?

In response to questions 5–7, the Corps' long-term regulation forecasts did not accurately account for the runoff volume, however, no forecasting agency accurately predicted the volume of the extreme runoff. The Corps produced its own hydrologic forecasts, which generally reflected known meteorologic and on-the-ground hydrologic basin conditions when the forecasts were made. The exception appeared to be an accurate assessment of the amount of on-the-ground plains snow, including possible increased runoff due to the antecedent conditions. The inaccuracy of the runoff forecast as it pertained to the plains snow assessment early in the runoff season possibly prevented the Corps from increasing System releases and making additional storage available. Overall,

improvements in data availability and modeling can be made. Even with improvements, leading to better assessment of conditions and forecasts, the record precipitation that fell over much of Montana, North Dakota, and South Dakota in May and June could not have been reliably predicted with currently available forecast methods, and significant flooding still would have occurred, based upon the current guidance in the Master Manual for System flood-storage allocation.

For year-ahead planning in the Annual Operating Plan, the fact that recent decades have experienced more extreme events should be considered, rather than view the entire historical record as having equally likely chances of occurrence. For within-calendar year water supply forecasting, assessment of the plains snow requires improved data infrastructure and incorporation of scientific modeling tools for determining the amount of runoff. For short-term daily streamflow and reservoir inflow forecasts of 1 to 10 days in advance, precipitation forecasts should continue to be integrated into streamflow modeling as they were in 2011. The Corps should also consider regular coordination meetings with other water supply forecasting agencies.

Refer to the section, 'Assessment of Forecasting Operations and Accuracy' and 'Effects of Climate Change on 2011 flooding' for more information.

Question 8. Did the Corps' regulation of the Missouri River mainstem system during the Mississippi River flood contribute to flooding on the Missouri River, and did it have a discernable impact on the Mississippi River flooding?

This question stems from a concern that flooding on the lower Missouri River, and flooding on the Mississippi River were factors in the Corps' decision to delay releases from the reservoirs. There was evidence of substantive communication and coordination among the Corps' water management offices in the Missouri River basin (Northwestern Division), Mississippi River basin (Mississippi Valley Division), and the Ohio River basin (Lakes and Rivers Division) during the respective floods, but actions taken did not significantly contribute to lack of available flood storage and subsequent flooding on the Missouri River. Nor did the Missouri River operations have a discernible impact on the Mississippi River flood.

Question 9. How should the flood of 2011 be characterized in terms of frequency or recurrence interval?

The range of possible interpretations of the 2011 event makes it impossible to characterize its likelihood on an exact basis, but it was clearly an extreme event with the largest volume of annual runoff on record and it was substantially larger (by greater than 20 percent) than the next largest runoff year in 114 years of record. A review by the U.S. Geological Survey (USGS) that considered an 80-percent confidence level described the recurrence interval as within a range of 50–1,070 years. Statistical analysis by the Corps characterized the annual runoff as approximately a 500-year event (annual 0.2 percent probability), which is in the middle of this range. Therefore, the recurrence interval is not

known exactly, but the 500-year designation might be a reasonable approximation of the extreme nature of the flooding.

Question 10. Does the Master Manual adequately address reservoir operations during extreme flood events? Does Plate VI-I of the Master Manual adequately address the hydrologic conditions like those experienced during 2011? Do the downstream flood control constraints adequately balance flood risk in the upper and lower basins?

The Manual addresses reservoir operations during extreme events, but its procedures can be improved. The unprecedented size of the 2011 runoff event mandates a re-evaluation of the Manual's guidance about how to handle such extreme events. The Manual is based on statistical analyses of hydrologic events, but behavior of the system is difficult to analyze or predict statistically during such large-scale flood events. More definite and specific procedures to respond to emergency scenarios can be included in the Manual, which currently leaves a large degree of discretion to the Corps' Missouri River Basin Water Management (MRBWM) and the Division and District Commanders during flood events. While this discretion is appropriate and needed, the possible consequences of an event such as in 2011 or larger are of such magnitude that a fresh 360-degree look at all aspects of the emergency might lead to additional procedures and technical resources to improve preparedness and reduce consequences of future events.

Plate VI-1 is effective during lower-magnitude flood events, but it does not apply directly during periods of extraordinary flooding such as in 2011. In particular, it does not apply well when both storage and runoff are high, which was the case in 2011. Plate VI-1 did not address how to manage the system once the extreme flooding began in 2011. The combination of mainstem and tributary storage and forecasted inflow was unprecedented and gave no guidance for "service level" or "target flows." Also, Plate VI-1 does not address the schedule for drawdown, especially for an extreme event such as the 2011 flood.

Question 11. Did climate change play a role in the record runoff during 2011? Should future regulation of the reservoir system be adjusted to account for climate change? If so, what types of additional studies would be required to integrate climate change planning into the system regulation?

Although climate change is not fully understood and how it might have affected the flooding is beyond the scope of this report, given that more extreme runoff events have occurred in recent decades compared to the data on record, the panel recommends re-examining the Missouri River System planning that is based on the entire historical record dating back to 1898. In addition, the panel recommends studying the incorporation of greater flexibility in operating the System to adapt to varying climatic extremes.

Question 12. What role did floodplain development play in the operation of the reservoir system prior to and during the event?

During the 2011 event, the Corps considered floodplain development but was unable to protect all properties and facilities due to the extreme volume of runoff to be passed through the System. The Master Manual identifies vulnerable areas where floodplain development has occurred, and the panel perceived that many floodplain residents thought that the dams provided more protection than they did. Prior to the event the System operators were following the Manual, which provides for downstream protection. During the period when the flood levels were increasing rapidly, there were episodes where the Corps took certain actions to protect downstream entities, such as in the March 15–28 period when Garrison releases were reduced from 26,000 ft^3/s to 15,000 ft^3/s to provide downstream channel capacity for inflows from plains snowmelt. When peak inflows were experienced and releases had to be increased, the System operators made some short-term decisions to delay the increase in releases so as to enable levee construction to be completed. The MRBWM received news from multiple sources and was aware of many local needs, but in many cases the travel time of flood waters and the inflows below the System prevented the Corps from controlling flooding in the vulnerable areas. Ultimately, when inflows became so large due to the combination of snowmelt and record rainfall, the priority shifted to emergency releases for dam safety and to maintain some storage capacity for the eventuality that much larger inflows would be experienced. In this emergency situation, the Corps was considering floodplain developments but was focusing on emergency actions to respond to the greatest risks.

Question 13. How much flood-control storage was needed on March 1 (or earlier) to control the flood? Or, what releases should have commenced on March 1 (or earlier) to control or reduce damages caused by the flood?

The panel noted that different combinations of storage and releases could be shown to reduce damages from the flood (see answer to Question 2 above). While it did not conduct exhaustive studies to determine the combinations of storage and/or releases that would have reduced the damages, the panel agrees with the general conclusions of the Corps staff that additional storage of 4.6 million acre-feet (MAF) could have limited the releases at Gavins Point to 100,000 ft^3/s. However, it is important to also note the necessity that the release rate of 100,000 ft^3/s would have to have been maintained into November.

Question 14. Were there System infrastructure-related factors that contributed to poor flood response?

After studying the system infrastructure and visiting sections of it, the panel judged that infrastructure condition did not materially affect the Corps' capability to manage the flood. However, there were situations where concern about infrastructure restricted the Corps' options, such as concern about the spillway and use of surcharge storage at Oahe Dam. In answering this question, the panel was acutely aware of the unprecedented magnitude of the flood volume and the large-scale nature and difficulty of maintaining the infrastructure in perfect condition. Therefore, the answer to the question "Was the condition of the project infrastructure a factor in operation of the system reservoirs?" is: "Yes, infrastructure condition was a factor in operation of the reservoirs, and with such

massive and high-risk structures it will always be a factor in such extreme events." It is imperative that the facilities be maintained at high levels of readiness and monitored and protected during the heat of operation while extreme events are in progress. The panel believes that the Corps did an impressive job of using the infrastructure and that the absence of major, or even catastrophic failures is evidence of performance that should be acknowledged and appreciated. The other lesson is that adequate funding and guidance for future maintenance of the infrastructure are required and all concerned should guard against complacency about the need for strategic investment to maintain a high level of System readiness.

Question 15. Were peak releases managed effectively? Could maximum releases have been reduced in order to lessen downstream flood damages?

Given the System storage conditions and rate of runoff into the System during peak inflow conditions in early June, the panel concluded that the System reservoir capacity was utilized almost to capacity. Downstream releases were minimized while still accomplishing necessary flood-water evacuation from the reservoirs to manage the safety of the system. Given the rapid increase in release rates, there could have been improvements in communication to all emergency managers about the MRBWM's awareness of conditions and plans for high releases from the reservoirs.

Question 16. Is a multi-year operation plan, taking into consideration climate cycles, worth considering?

The panel believes that recognition of climate cycles might enable the Corps to sustain the management of the eight congressionally mandated purposes while focusing more on flood control during wet cycles. It is clear that the basin experiences varying periods of dry and wet weather. While there is no guarantee that these will continue in the future, recognition of them might provide the Corps with opportunities to increase regulatory flexibility of the System. During dry periods the Corps could try to maximize storage in the System while reducing storage during a wet period. The panel realizes the difficulty of predicting the runoff for the following year and deciding which path to follow. Such actions might be taken only after well-defined periods of dryness or wetness are evident. For example, 2011 was the fourth year in a row of above average runoff after 7 years of drought. Had different patterns of regulation of the System started after the second year of above normal runoff, additional storage may have lessened, but not necessarily prevented the 2011 flooding . In sum, the Corps needs to be given the flexibility to manage to changing, wetter conditions but also needs to be removed from reproach, if, after successive wet years, the following year turns out dry.

Question 17. Was reservoir (mainstem and tributary) storage utilized effectively? Did storage capacity go unused? What changes are needed to better utilize storage for future flooding?

The System reservoir storage for flood control comprises the annual flood control and multiple use zone, the exclusive flood control zone, and possibly some of the surcharge storage zone. Also, some of the tributary reservoirs have enough flood control storage to affect overall System releases. The answers to the questions are "yes, the storage was utilized effectively," and also "some storage did go unused." It would not be prudent to use 100 percent of all storage because there would be no remaining capacity for the contingency of additional runoff and it would not be prudent to use 100 percent of surcharge storage because that action might increase risk to infrastructure to an unacceptable level.

Recommendations for Future Management of the Missouri River Mainstem Reservoir System

The panel makes the following recommendations:

1. **Support for a program of infrastructure enhancement to ensure all flood release spillways and tunnels are ready for service and that all levees are in good condition. One of the main functions of the Corps is to maintain the water-resources infrastructure that was constructed in the past. The panel would like to emphasize the importance of adequate funding and direction for a program of infrastructure repair and rehabilitation to ensure that all flood-release spillways and tunnels are ready for service as soon as possible.**

2. **Hydrologic studies to update the design flood with new probabilities. The panel recommends re-examining the Missouri River System planning that is based on the entire historical record and adjusting to the recent decades of varying climatic extremes. In addition, the Corps should be given the flexibility to manage the System storage depending on anticipated dry and wet cycles. This modification to the Master Manual procedures might be controversial and require collaborative development with state and Federal agencies.**

3. **A review of the System storage allocations, based upon the 2011 flood event. The unprecedented inflow volume tested the reservoir system more than ever before. The panel recommends a review of the System storage allocations, to include the flood-control storage needed for floods like 2011 or larger. The panel noted that the Corps is already considering a storage allocation study such as this.**

4. **The panel recommends improved future cooperation and collaboration with the National Weather Service (NWS), and its already-established forecast systems as well as with USGS,**

possibly through the Integrated Water Resources Science and Services (IWRSS) initiative. Coordination meetings should be held with the other agencies that produce water supply forecasts, specifically the NWS and the Natural Resources Conservation Service (NRCS), to help alert the Corps to potential trouble spots. State, local, city officials, and other emergency managers, such as Federal Emergency Management Agency (FEMA) and Sheriff's departments, should be included in these meetings during periods of heightened flood risk. Communication systems for awareness of other agency forecasts and distribution of current conditions, forecasts, and planned releases for the System to all local officials and emergency managers.

5. **Studies to enhance data collection, forecasting, and resulting runoff from plains snow. Suggested activities include establishment of additional permanent plains snow measurement stations (using already established snow measurement standards), focused on the development of improved historical record at permanent stations; and research on the effects of prairie soils, geomorphology, and hydrology on snowmelt runoff. Also, the Corps should work to improve collaboration with other groups that collect and analyze snow data, for example, the Community Collaborative Rain, Hail, and Snow (CoCoRaHS) network.**

6. **A decision support system to include real-time status information on tributary reservoirs and inflows and linked to a modern interactive graphic forecast system. In noting the complexity of the communication systems required to manage the mainstem reservoirs, while considering the status of weather, downstream flooding, inflows, and storage in tributary reservoirs, the panel observed that a program of modernization is needed to create an effective decision support system linked to a modern interactive graphic forecast system.**

Introduction

During March through July 2011, a record amount of runoff (48.7 million acre-feet) from melting snowpack and heavy rains entered the Missouri River, far exceeding the flood storage capacity of the dams and reservoirs, overwhelming the floodplains, saturating and overtopping levees, and forcing hundreds of homeowners, farmers, and business owners to evacuate. In the states affected by the Missouri River flooding (Montana, North Dakota, South Dakota, Nebraska, Iowa, Kansas, and Missouri) the cost of direct flood damages and response and repair activites borne by the U. S. Army Corps of Engineers (Corps) are expected to total about $1 billion (McMahon, 2011). The total cost of direct and indirect damages to homes, buildings, farms, businesses, and public facilities will be far greater and has not yet been estimated.

The Northwestern Division of the Corps operates the reservoir system and supports flood control efforts such as flood fighting by levee construction and repair. Overall regulatory control is by the Missouri River Basin Water Management (MRBWM) and operation of individual reservoirs and related flood-fighting is by the Corps' District offices. The flood-fighting activities were extensive and conducted in cooperation with numerous groups and individuals along the river.

The Corps' MRBWM maintains records of Missouri River basin runoff volumes dating back to 1898. During 2011, the annual runoff into the Missouri River Reservoir System (upstream of Sioux City, Iowa) was estimated at 60.8 million acre-feet (MAF). In comparison, the previous greatest annual runoff volumes were 49 million acre-feet in 1997 and about (roughly estimated) 50 MAF in 1881. The System flood-control storage allocation (16.3 MAF) and flood-control management was patterned after the 1881 flood event, during which an estimated 40 MAF of runoff was produced during March–July. During 2011, the March–July runoff was 48.7 MAF, greatly exceeding the previous record of 36.6 MAF in 1997 (figure 1). The 2011 annual runoff volume of 60.8 MAF equates to an average daily rate of about 83,980 cubic feet per second (ft^3/s) over a 12-month period.

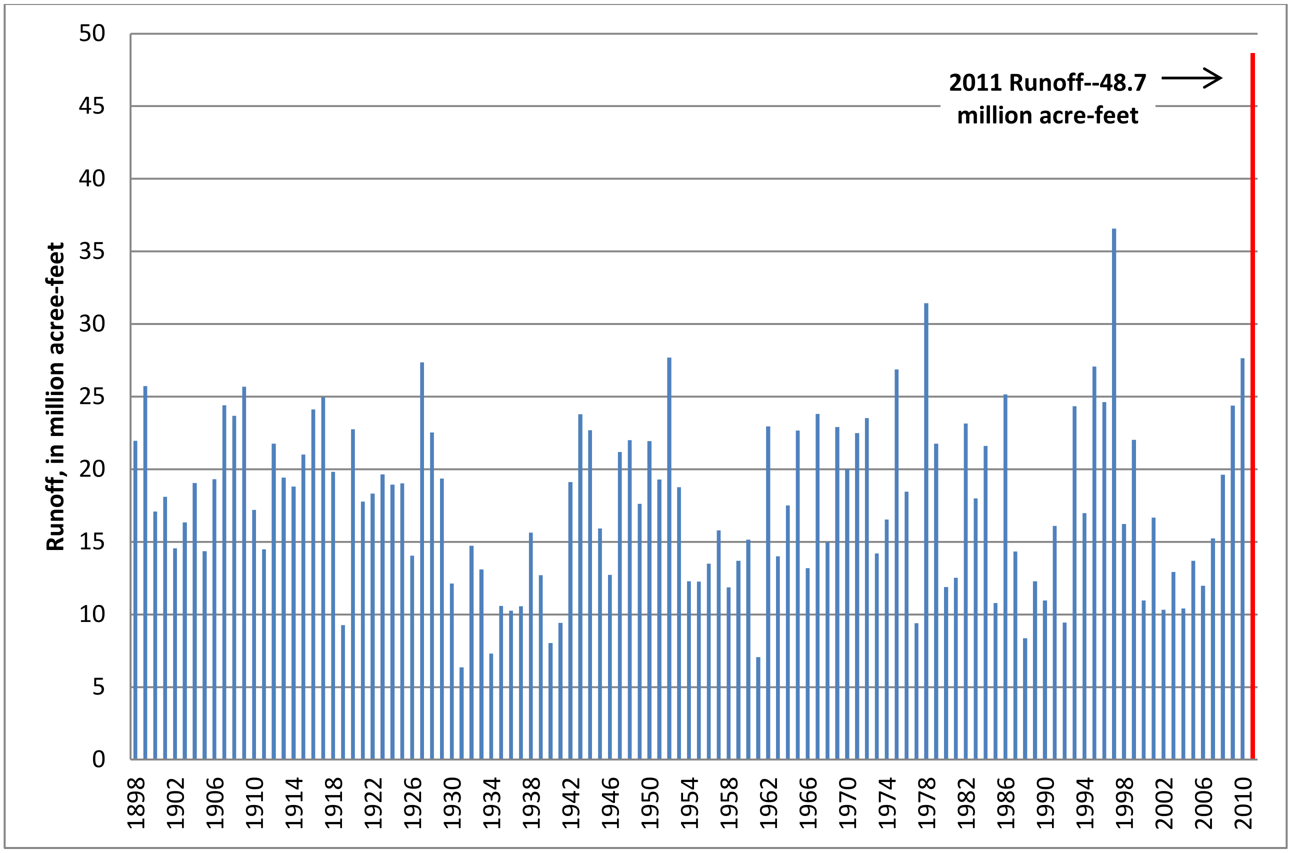

Figure 1. Annual March–July runoff, Missouri River basin, upstream of Sioux City, Iowa, 1898-2011

In September 2011, the Corps appointed a technical panel to assess the Corps' operation of the six Missouri River mainstem dams and reservoirs and any appropriately related dams and reservoirs, prior, during, and after the 2011 sequence of flooding, for the purpose of gaining lessons learned and recommendations to improve future operations. The panel is independent of the Corps and was expected to assess Corps operations objectively by studying the flood, the decisions, and the consequences, including collection of information from outside groups.

The review panel was requested by the Corps to review, analyze, and assess any information it determined necessary, and that was relevent to pre-flood, flood, and post-flood operations, in order to reach findings regarding the planning and execution of reservoir operations as they might have been affected by hydrologic conditions, operational constraints, and other conditions in the Missouri River basin. Relevant information such as the Missouri River Mainstem Reservoir System Master Water Control Manual (Master Manual), Annual Operating Plan (AOP), hydrologic forecasts and forecast methods, real-time chronology and decisions, coordination and communication with other reservoir operators and agencies was considered. The panel charter and members' appointment letters are included in the report Appendix.

As a beginning outline for the review, the Corps provided the following list of 12 questions for the review panel:

1. According to the Missouri River Master Manual and other pertinent documents, how should the mainstem reservoir system and the Corps and U.S. Bureau of Reclamation (USBR) tributary reservoirs within the system have been operated, how were they actually operated, and what were the reasons for any differences in the operation?

2. Were the water-management decisions made during the flood of 2011 appropriate and in line with the approved water control manual?

3. Could the Corps have prevented or reduced the impact of the flood by taking other management actions leading up to the flood?

4. Did operations for environmental or other purposes influence flood risk management operations, and if so how did they influence the operations?

5. Were accurate and timely hydrologic and weather forecasts and other pertinent data available? What data improvements (plains and mountain snowpack information, streamflow gaging stations, and observed weather data) are warranted in light of this flood event to properly manage the system?

6. Did the Corps properly assess basin conditions and properly forecast runoff from the plains snowpack, mountain snowpack, and precipitation? If not, what additional information and, or tools are needed to better forecast runoff?

7. Did the Corps long-term regulation forecasts properly account for the 2011 runoff?

8. Did the Corps regulation of the Missouri River mainstem system during the Mississippi River flood contribute to flooding on the Missouri River, and did it have a discernable impact on the Mississippi River flooding?

9. How should the flood of 2011 be characterized in terms of frequency or recurrence interval?

10. Does the Master Manual adequately address reservoir operations during extreme flood events? Does Plate VI-I of the Master Manual adequately address the hydrologic conditions like those experienced during 2011? Do the downstream flood control constraints adequately balance flood risk in the upper and lower basins?

11. Did climate change play a role in the record runoff during 2011? Should future regulation of the reservoir system be adjusted to account for climate change? If so, what types of additional studies would be required to integrate climate change planning into the sytem regulation?

12. What role did floodplain development play in the operation of the reservoir system prior to and during the event?

Because of the short review period (approximately two and a half months from early October to mid December 2011), the panel's scope was focused on technical answers to the original questions posed by the Corps and did not extend to broader questions of policy or to detailed technical studies. During the review, several additional questions were added by the panel to amplify and extend the original list:

13. How much flood-control storage was needed on March 1 (or earlier) to control the flood? Or, what releases should have commenced on March 1 (or at other times) to control, or reduce damages caused by the flood?

14. Were there factors related to the infrastructure of the System that contributed to poor flood response?

15. Were peak releases managed effectively? Could maximum releases have been reduced in order to lessen downstream flood damages?

16. Is a multi-year operation plan, taking into consideration climate cycles, worth considering?

17. Was reservoir (mainstem and tributary) storage utilized effectively? Did storage capacity go unused? What changes are needed to better utilize storage for future flooding?

The review panel (comprising authors of this report) was composed of independent (non-Corps) persons with expertise in meteorology and forecasting, hydrology and hydraulics, and dam and reservoir system operations and regulation. The panel reviewed the Master Manual and AOP to determine the consistency of the established water control procedures and the actual System operations. As part of this process, the panel reviewed data and records that documented reservoir system conditions and timelines of Corps operational decisions and actions. The panel also consulted local, state, and other Federal agencies and entities. In addition, the panel members attended public meetings and interviewed private citizens affected by flooding. Finally, the panel examined, to a limited extent, public comments related to reservoir system operations and consequences.

Description of Missouri River Mainstem Reservoir System

The Missouri River is the longest river in the United States, extending 2,619 miles from its source at Hell Roaring Creek and 2,321 miles from Three Forks, Montana where the Jefferson, Madison and Gallatin Rivers converge in southwestern Montana, near the town of Three Forks (figure 2).

The Missouri River flows generally east and south about 2,321 miles to join the Mississippi River just upstream from St. Louis, Missouri. The Missouri River basin has a total drainage area of 529,350 square miles, including about 9,700 square miles in Canada. That part within the United States extends over one-sixth of the Nation's area, exclusive of Alaska and Hawaii. The basin includes all of Nebraska; most of Montana, Wyoming, North Dakota, and South Dakota; about half of Kansas and Missouri; and smaller parts of Iowa, Colorado, and Minnesota (U.S. Army Corps of Engineers, 2006, section 3-01).

Figure 2. Map of Missouri River basin

Regulation and Management of the Missouri River Mainstem Reservoir System

The Missouri River mainstem reservoir system, authorized by the 1944 Flood Control Act (Missouri River Authorized Purposes Study, 2010), consists of six dams (and reservoirs) constructed on the Missouri River—Fort Peck Dam (Fort Peck Lake), Garrison Dam (Lake Sakakawea), Oahe Dam (Lake Oahe), Big Bend Dam (Lake Sharpe), Fort Randall Dam (Lake Francis Case), and Gavins Point Dam (Lewis and Clark Lake). The locations of these projects, as well as major tributary reservoirs in the basin, where regulation is coordinated and integrated with mainstem regulation, is shown in figure 1. Statistics and characteristics of the six mainstem projects are listed in table 1.

Table 1. Specifications of Missouri River Mainstem Flood Control and Reservoir System Projects

Project	Construction Period [1]	Drainage Area (square miles)	Storage Capacity (thousand acre-feet) [2]	Generating Capacity (kilowatts)
Fort Peck	1933–40	57,500	18,463	185,000
Garrison	1946–55	181,400	23,821	583,000
Oahe	1948–62	243,490	23,137	786,000
Big Bend	1959–64	249,330	1,798	493,000
Fort Randall	1946–53	263,480	5,418	320,000
Gavins Point	1952–55	279,480	450	132,000

[1] Dates from beginning of construction to project operation

[2] Storage capacity at maximum operating pool elevation (U.S. Army Corps of Engineers, 2010)

The mainstem projects are operated for the congressionally authorized purposes of flood control, irrigation, navigation, hydroelectric power generation, water supply, water quality, recreation, and fish and wildlife enhancement. The combined storage of all six System reservoirs is reported to be 73.1 million acre-feet (MAF)(U.S. Army Corps of Engineers, 2011a). System storage is about three times the average annual runoff into the System upstream of Sioux City, Iowa. The System storage capacity is divided into four unique zones, for regulation purposes (figure 3). The bottom 25 percent, 17.9 MAF, of the total System storage comprises the permanent pool designed for sediment storage, minimum fisheries, and minimum hydropower heads. The largest zone, 53 percent or 38.9 MAF, is the carryover-multiple use zone, which is designed to serve all authorized project purposes, though at reduced levels, through a severe drought like that of the 1930s. The annual flood-control and multiple-use zone, 16 percent or 11.6 MAF is the desired operating zone of the System. Ideally, the System is at the base of this zone at the start of the spring runoff season. Spring and summer runoff is captured in this zone and released throughout the remainder of the year to serve project purposes, returning the reservoirs to the base of this zone by the start of the next runoff season. The top 6 percent, 4.7 MAF, of the System storage capacity is the exclusive flood-control zone. This zone is used only during extreme floods and evacuation of flood water is initiated as soon as downstream conditions permit. In addition, surcharge storage is provided and freeboard storage above that. These storage areas normally are not used, although surcharge storage may be used with reservations during extreme events. Freeboard storage is an additional dam safety feature of reservoirs but is not used for water control purposes.

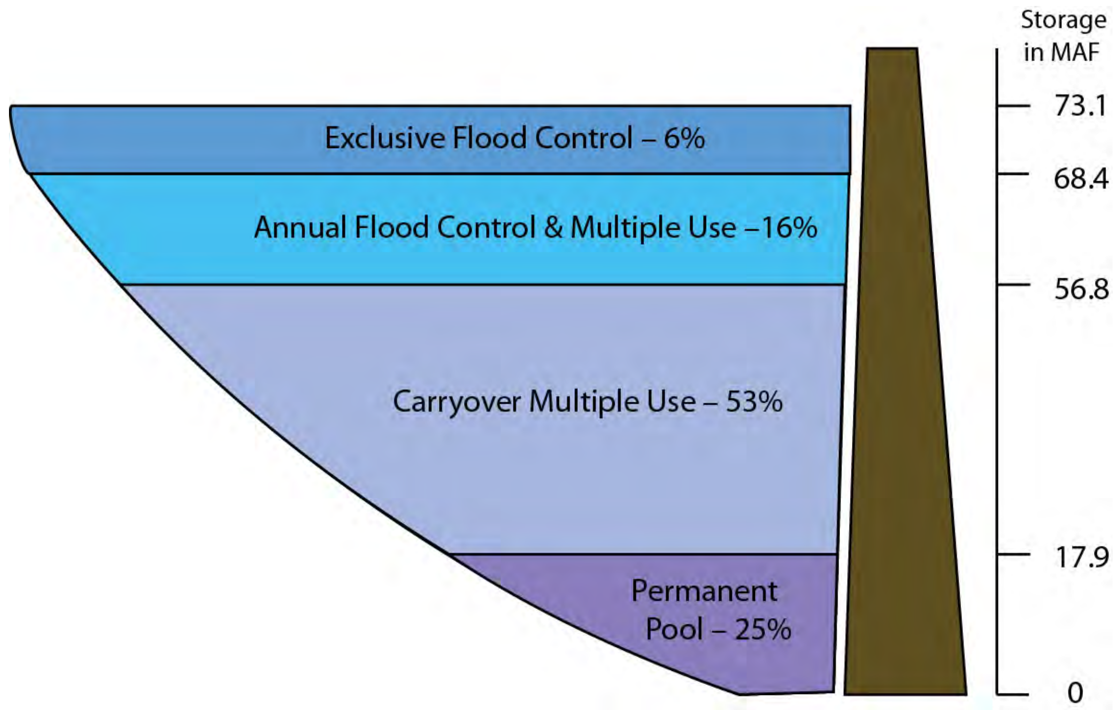

Figure 3. Missouri River Reservoir System storage zones and capacity

Master Manual

The operation of the Missouri River Mainstem Reservoir System (System) is guided by information presented in master water control manuals, which comply with engineering standards as outlined by the Corps' series of engineering regulations (labeled as ER reports). To achieve the maximum multi-purpose benefits for which the mainstem reservoirs were authorized and constructed, the System must be operated as a hydraulically and electrically (in regards to power generation) integrated system. The Missouri River Mainstem Reservoir System Master Water Control Manual (Master Manual) is the controlling document to present and coordinate the basic operational objectives and plans to obtain maximum multi-purpose benefits with supporting data. The individual project (dam and reservoir) manuals for the System serve as part of the Master Manual and present aspects of project usage not common to the System as a whole.

The Master Manual describes the water control plan for the System. The plan consists of the water-control criteria for the management of the System for the full spectrum of anticipated runoff conditions that could be expected to occur. According to Corps Regulation (ER) 1110-2-240 (U.S. Army Corps of Engineers, 1994),"Throughout the life of the project, it is necessary to define the water control criteria in precise terms at a particular time, in order to assure carrying out the intended functional commitments in accordance with the authorizing documents.” Annual water management plans (Annual Operating Plans, or AOPs) are prepared each year, based on the water-control criteria contained in the Master Manual, in order to detail reservoir regulation of the System for the current operating year. Because the System is so large, it can respond to extreme conditions of longer than one-year duration. The AOP document also provides an outlook for planning purposes in future years.

The Corps is responsible for operation of the System. The Corps’ MRBWM, located in Omaha, Nebraska, oversees the day-to-day implementation of this water control plan. The Omaha District of the Northwestern Division has staff located at each of the System’s projects to carry out the day-to-day operation (based on the water management orders received from the MRBWM) and maintenance of the mainstem projects. All of the mainstem dams provide hydropower as an authorized function and, therefore, are automated into a system called the Power Plant Control System (PPCS) for regulation of hydropower production and project releases. The Western Area Power Administration (Western) uses the mainstem projects as an integral part of the Midwest power grid. Project Power Production Orders, reflecting the daily and hourly hydropower limits imposed on project regulation, are generated by the MRBWM and sent to each mainstem project on a daily basis, or more frequently, as required. Also during critical periods, coordination between project personnel and MRBWM staff is conducted on an as needed basis to assure that expected releases rates are achieved.

A detailed explanation of the current Missouri River Mainstem Reservoir System Water Control Plan (WCP) is found in section VII of the Master Manual.

History of Master Manual Revisions

The Master Manual, which was first published in 1960 and subsequently revised during the 1970s, was revised in 2004 to include more stringent drought conservation measures and again in 2006 to include technical criteria for a “spring pulse” (high water release to simulate a typical seasonal flood) from Gavins Point Dam to benefit endangered species. Periods of adjustment to the original Master Manual storage zones that were made prior to 1960 are explained in Appendix A of the Manual. The System currently includes regulation provisions for three species protected under the Endangered Species Act: the endangered interior least tern, the threatened piping plover, and the endangered pallid sturgeon. The 2004 revision of the Master Manual represented the culmination of a review that began in 1989 during the first major drought the Missouri River basin experienced since the System first filled in 1967. The purpose of the review study was to identify a water-control plan that would serve the congressionally authorized project purposes, comply with current environmental laws, and meet Corps trust and treaty obligations to the Federally recognized Tribes. A 2006 revision was a result of the U.S. Fish and Wildlife Service (USFWS) 2003 Amendment to the 2000 Biological Opinion on the Operation of the Missouri River Mainstem Reservoir System. The 2003 Amendment presented the USFWS opinion that regulation of the System would jeopardize the continued existence of the pallid sturgeon.

History of System Flood-Control Storage Allocations

The current version of the Master Manual states that "*The System flood control storage allocation has been examined and confirmed as adequate by numerous long-range regulation studies and the study for this Master Manual update.*" Early history of the determination of flood-control storage allocation for the System is discussed in the 1979 version of the Master Manual (U.S. Army Corps of Engineers, 1979) and Appendix A (section A-06) of the current version of the Manual.

In 1943 and 1944, studies were made of flood control storage requirements in the mainsstem reservoirs as units in the basin program. No Standard Project Floods were developed; the relatively conservative design inflows to the system utilized in these studies were based on past flood history. Great emphasis was placed on the reconstructed 1881 flood for which records are sparse and not subject to refined analysis. At the time, no detailed techniques for flood control regulation had been selected. Operation studies were based on not exceeding specified release rates, rather than on consideration of the potential downstream effects of these releases. As a consequence, the storage required for the control of flood flows varied over a range from about 15 to 21 MAF, depending upon criteria and assumptions utilized. It was recognized in these studies that as a result of continued basin water resource development (tributary dams and irrigation), the required flood control storage space in the mainstem system would decrease (Master Manual, section A-06.6).

The first detailed long-range operation study of the main-stem system, which attempted to systematically reflect the progressive growth of irrigation depletions and the loss of storage to sedimentation, was published in 1956 (Master Manual section A-06.12). For those studies, it was assumed that 20.7 MAF of combined exclusive and seasonal flood-control storage space (near the maximum level determined in preliminary studies of flood control requirements) was required under the 1949 level of basin water resource development and that due to future basin development and depletions, the flood control requirements would be reduced to 15 million acre-feet (the minimum requirement developed in preliminary studies) by the year 2010 (Master Manual, section A-06-12).

Long-range System regulation studies that were conducted in 1958 in connection with cost allocation studies were based on the streamflow depletions that had developed prior to 1949. These studies considered the effects of depletions on historical runoff into the System. They also assumed a System flood control storage capacity of about 17 MAF for the early years of System regulation, with this value reduced to about 15 MAF by the year 2010 to reflect continued water-resource development in the basin (Master Manual, section A-06-12).

Storage allocations have gone through a long history of analysis and have changed relatively little. The present CWCP flood-control storage (16.3 MAF) is consistent with historical allocation studies. However, the developers of System regulation practices recognized that System storage allocations might need to be reevaluated. The Master Manual states (section H-08): "*Future studies… are necessary not only for the definition of total System flood control storage at locations, but also for the optimal distribution of the total flood control storage included in the reservoirs comprising the System*". and in section H-10: "*With the detailed analysis of design flood inflows to the System and permissible releases from the System during the inflows, the storage required for control of the design flood could be re-examined. Such determination will take into account allocations for both seasonal and* *exclusive flood control functions and their corresponding differing regulation criteria. This could lead to the redistribution of the storage space between the Permanent Pool Zone and the base of required surcharge storage in each System reservoir*."

Previous Floods

The Master Manual (Appendix A) provides a history and description of numerous major Missouri River floods beginning with the 1844 flood (1844, 1881, 1903, 1908, 1923, 1927, 1943, 1944, 1947, 1951, 1952, 1960, 1967, 1975, 1984, 1986, 1987, 1993, 1994, 1995, 1996, 1997, and 1999). The Master Manual discussion of major floods also includes estimates of flood elevations and discharges for several of the largest floods that occurred prior to regulation of the System (1844, 1881, 1908, 1943, 1951, and 1952). Some floods were accompanied by peak discharges that were greater than the 2011 flood, which was a record in terms of volume but not always in terms of peak discharge. A discussion of actual historic System regulation for flood control is provided for major flood events that occurred since the System reservoirs have been regulated as a completely integrated System (1967, 1972, 1975, 1978, 1993, and 1997). Following the 1975 and 1997 floods, regulation practices were evaluated and summary System regulation reports were prepared for future reference (U.S. Army Corps of Engineers, 1975, 1998).

All major floods experienced in the upper basin except one have occurred in the March-July season, with snowmelt as an important flood component. The one exception occurred in 1923 when a large September rainstorm in southern Montana and northern Wyoming resulted in an early October Missouri River flood. Estimated crest discharges during this flood exceeded 100,000 ft^3/s at Pierre, South Dakota and all upstream locations to the mouth of the Yellowstone River. In the lower Missouri River basin, floods have tended to follow the same seasonal pattern observed in the upper basin; however, damaging floods have occasionally occurred prior to or following the normal March-July flood season, due mainly to rainfall over the downstream drainage areas.

System regulation prior to 2011 did not completely eliminate flood damages during major floods. Flood damages on the Missouri River downstream of the reservoir System occurred in 1952, 1967, 1975, 1993, 1996, 1997, and 1999. However, in likely all cases, regulation reduced flood stages in all downstream reaches, resulting in substantial flood-damage reduction. The exception is 1952 when only Fort Peck Dam had been constructed.

The 1952 flood established record flows throughout the basin and was a result of exceptional runoff from snowmelt. At the end of March, one of the heaviest snow covers, on record, was present on the upper plains. In April, a peak discharge of 500,000 ft^3/s occurred at Bismarck, North Dakota, compared to 2011 levels of about 150,000 ft^3/s as a result of releases from Garrison Dam. Although peak discharges were recorded along most of the Missouri River reaches, peak flows generally decreased downstream because most of the runoff originated upstream in Montana, North Dakota, and South Dakota as a result of snowmelt.

During the 1967 flood, System regulation eliminated all flood damage that would have otherwise occurred between Fort Peck Dam to the mouth of the Platte River. At Sioux City, the effect of

System regulation resulted in a crest discharge reduction of almost 200,000 ft^3/s. However, total actual flood damages along the Missouri River downstream of the Platte River amounted to over $125 million.

During the 1993 flood, record stages occurred on the Missouri River from St. Joseph to the mouth and near record stages occurred from Nebraska City to Rulo. Flooding downstream of the System resulted in damages of about $12 billion. The mainstem reservoir regulation was not a factor in the 1993 flooding as most of the flooding resulted from inflows downstream of the System.

The 1997 System annual runoff volume (above Sioux City) was the highest on record—49.0 MAF (compared with 34.2 MAF in 1952). System releases also set records—70,100 ft^3/s at Gavins Point, compared to the previous high release of 61,100 ft^3/s (in 1975). However, downstream flooding was minimal because heavy downstream rains did not occur during the reservoir evacuation period. The effects of the System regulation on runoff during years with substantial snowpack accumulation can be seen between 1952 and 1997. The 2011 event combined heavy snowpack accumulations, similar to 1997, with heavy rains in May and June, which were not a component of the 1952 and 1997 flooding.

Summary of 2011 Flood Conditions, Consequences, and Damages

This section of the report summarizes the sequence of flooding and consequences of the overall event. While it is not feasible to provide detailed accounts of local situations as they developed during the event, the panel wanted to review the overall incident so it could assess Corps operations as they affected the flooding and consequences.

Flood Conditions

The 2011 Missouri River flood was the largest on record for the entire basin in terms of volume of water, and record peak flows were also experienced in some reaches. River stages and peak flows are difficult to summarize because stages vary with channel conditions and flows are different in historical and post-regulation time frames. Chronologies of basin hydrology, forecasting and reservoir regulation are presented later, with detailed explanations of the causes of flooding and the responses by the Corps.

In summary, the unprecedented runoff occurred from record rainfall over portions of the upper basin, along with plains and mountain snowmelt, led to the following record peak releases from the System dams: 65,000 ft^3/s at Fort Peck, 150,000 ft^3/s at Garrison, 160,000 ft^3/s at Oahe, 166,000 ft^3/s at Big Bend, 160,000 ft^3/s at Fort Randall, and 160,000 ft^3/s at Gavins Point.

The high releases resulted in high stages. Flood stages varied markedly along the river and with time. As an example, figure 4 shows the river discharge and stage at Bismarck, North Dakota during April–August, 2011. The peak discharge was 151,000 ft^3/s on June 26 and the peak stage was 19.25 ft on July 1. For comparison to historic peak stages prior to construction of Garrison Dam (completed in 1953), the peak flood stage for the 1881 flood (31.9 ft) and 1952 flood (27.9 ft) also are shown on the graph.

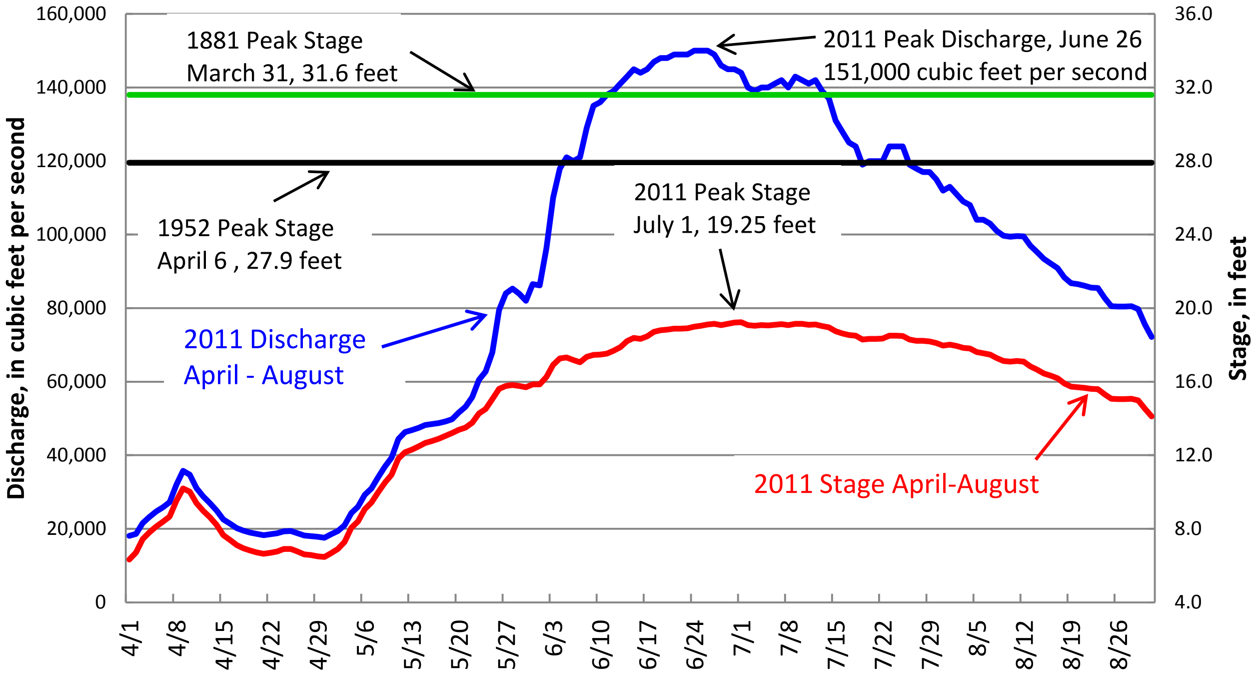

Figure 4. Discharge and stage at Missouri River at Bismarck, North Dakota, April–August, 2011, compared with previous historic stages

Downstream from Oahe Dam, at Pierre, South Dakota, the river stage reached an average daily level of 1,433.98 ft at a streamflow rate of about 160,000 ft^3/s on June 21, 2011. This was the highest stage since the dam was completed in 1958 (MacPherson, 2011). Although the 2011 flood is the largest flood of record in overall volume, earlier floods have had higher peak flow rates and stage levels. Prior to construction of Garrison and Oahe Dams, the Missouri River at Pierre reached a peak stage of 1439.6 ft on April 6, 1952 at a streamflow rate of 440,000 ft^3/s.

Downstream of Gavins Point Dam, the peak flood stage at Sioux City, Iowa was the highest since construction of the dams. The stage on July 21, 2011 was 35.25 ft, or over four feet higher than the next highest, which occurred in 1984 (figure 5). Prior to regulation, the stage at Sioux City reached 44.26 ft at a streamflow of 441,000 ft^3/s.

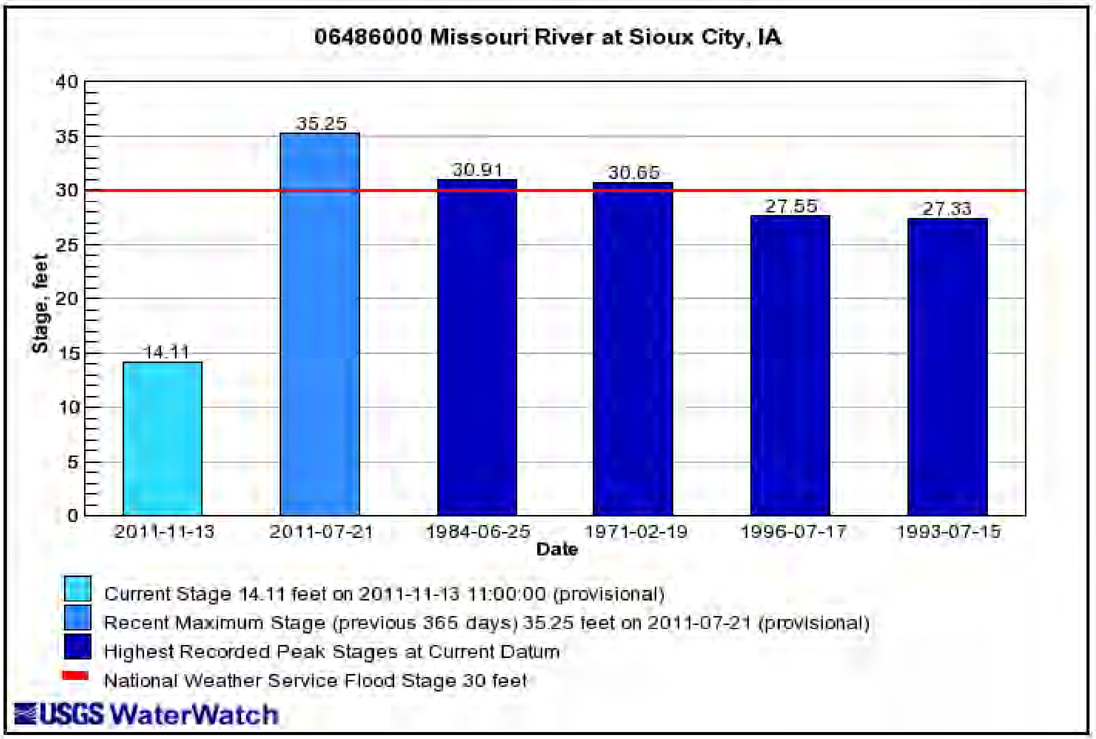

Figure 5. River Stage at Sioux City, Iowa for selected historical flood events

Flood stages further downstream in Iowa, Nebraska, Kansas, and Missouri also were high (figure 6). St. Joseph, Missouri experienced the second highest flood stage on record (exceeded only during the 1993 flood) and considerable damage. Missouri River floods prior to System regulation have resulted in higher flood stages, but continued floodplain development has led to successively more damage at lower stages.

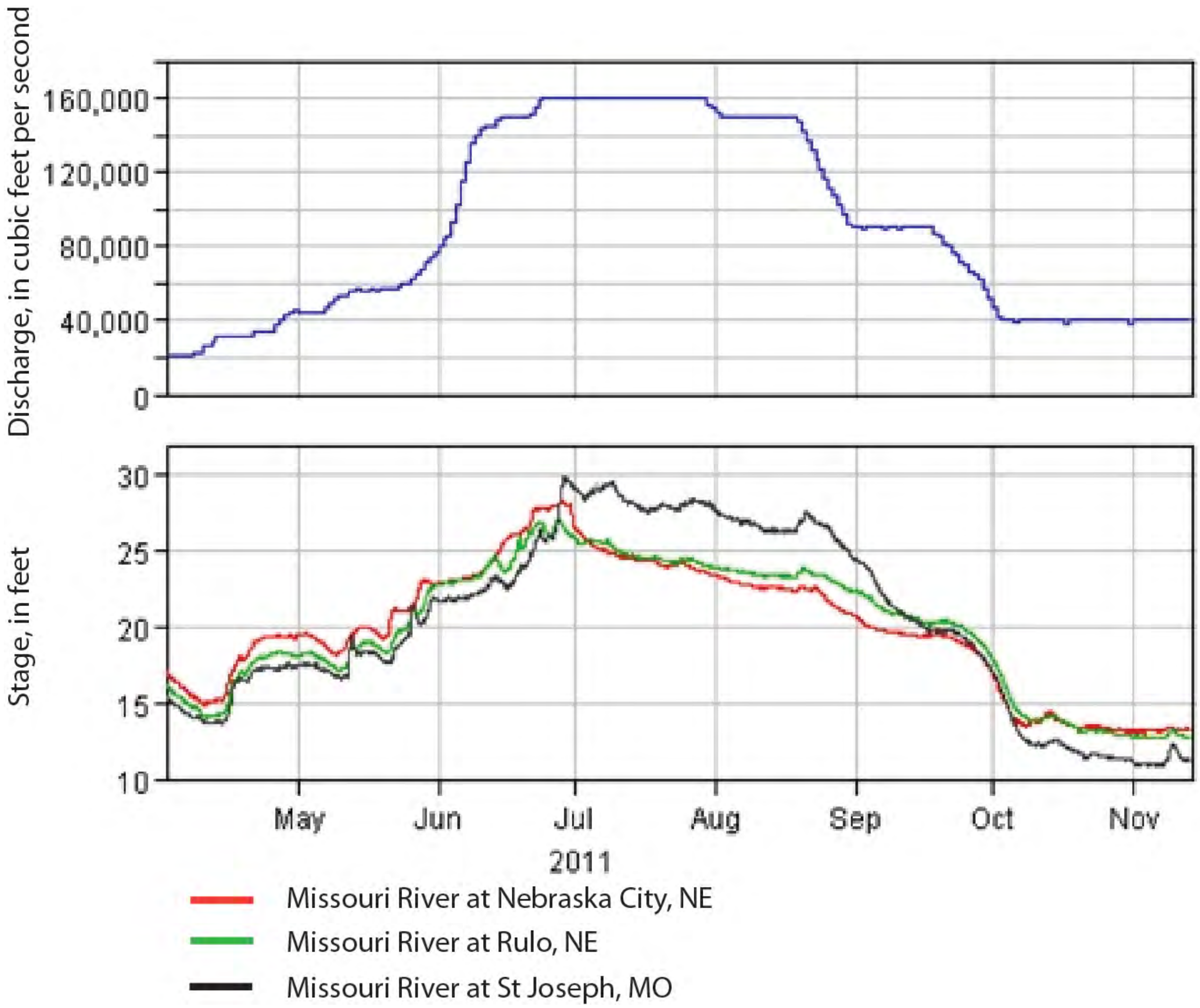

Figure 6. Discharge from Gavins Point Dam and river stages at selected downstream locations, April–November, 2011 (U.S. Army Corps of Engineers, 2011)

Consequences

The high water caused extensive and extraordinary damages along a number of reaches. All damages have not been totaled yet, but the flood clearly caused substantial disruption, economic losses, and suffering.

To gain an understanding of the types of damage along the river, the panel referred to the reaches defined in the Master Manual (chapter 4), which include:

Reach	Approximate river miles
Fort Peck Dam to Lake Sakakawea	204
Garrison Dam to Oahe	87
Oahe Dam to Lake Sharpe	5
Fort Randall Dam to Lewis and Clark Lake	44

Gavins Point Dam to Sioux City*	79
Sioux City, Iowa to Omaha	116
Omaha to Kansas City	250
Kansas City to Mouth of Missouri River	366

* Includes the National Recreation River Reach (a protected 59-mile reach); the Kensler's Bend Reach (17 miles with bank stabilization), and the Missouri River Navigation Channel Reach (3 miles with bank stabilization). The channelized reach extends to the confluence with the Mississippi River.

Figure 7, taken from Plate III-1 of the Master Manual, shows the key features of the river. The reaches outlined in the Master Manual have been added to the map.

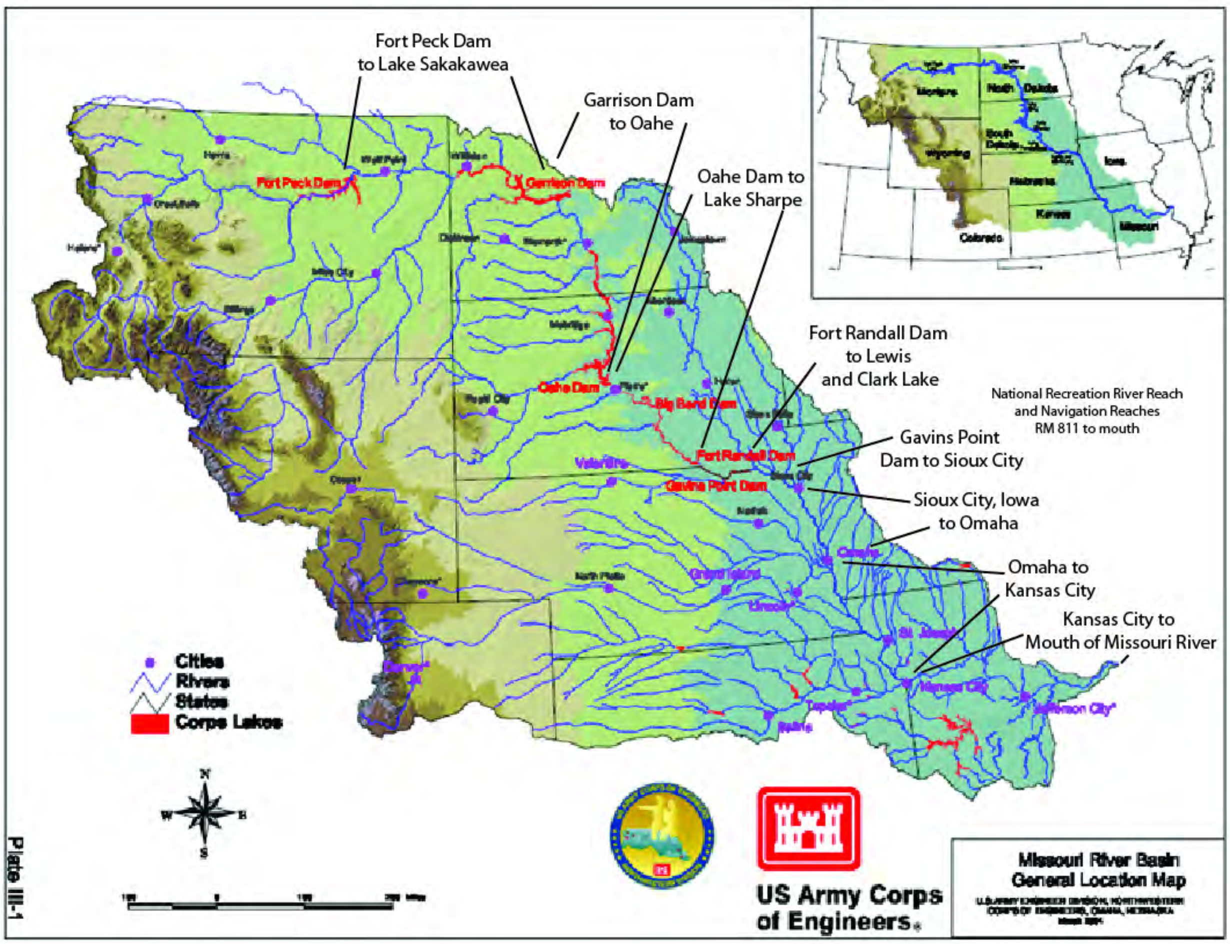

Figure 7. Missouri River basin and major river reaches

The fact that damages were anticipated is evident from the Master Manual, which outlines the potential for damages in the reaches. Of course, it was not possible to anticipate all of the damages for insertion in the Manual, but it provides a general picture of the categories to expect. The following list of potential damages is summarized from the Master Manual:

Fort Peck Dam to Lake Sakakawea	Most floodplains consist of croplands, pastures, and hayfields, with 100,600 acres subject to flooding. Flood damages begin at 30,000 ft^3/s. For flows ranging from 50,000 ft^3/s in the upper portion to 70,000 ft^3/s in the lower reach, damages are relatively minor.
Garrison Dam to Oahe	Includes cities of Bismarck and Mandan , North Dakota. Reach contains 34,600 acres of agricultural land subject to flooding. History shows that stages at Bismarck below 13 feet do not result in significant damages. Capacity has decreased from about 90,000 ft^3/s to about 50,000 ft^3/s. During 1997, a release of 59,000 ft^3/s resulted in a stage of 14 feet and created minor damage. Floodplain development has occurred in the Bismarck and Mandan area. The area most subject to flooding is the urban area near Bismarck. Expensive homes in the bottomlands are subject to flooding during the winter as well as during releases greater than 60,000 ft^3/s from Garrison. Floodplain construction during the past 25 years is of concern. Damage expected to be very high with higher project releases.
Oahe Dam to Lake Sharpe	Urban flooding in the Pierre-Fort Pierre area has been a recurring problem since 1979. The urban areas are subject to high potential damages if high releases are required from Oahe Dam.
Fort Randall Dam to Lewis and Clark Lake	This reach was capable of flows in excess of 150,000 ft^3/s prior to construction of the Fort Randall dam, but releases of 35,000 ft^3/s now result in flood problems. The reach contains about 2,200 acres of agricultural land and 62 residential buildings subject to flooding.
Gavins Point Dam to Sioux City	Prior to construction, capacity was over 100,000 ft^3/s. In 1997, flows of 70,000 ft^3/s in this reach caused no significant damage. The reach contains approximately 1,900 acres of agricultural land and some 4,000 buildings subject to flooding.
Sioux City, Iowa to Omaha	During recent years, there has been considerable encroachment on the channel. Boat docks have been constructed and low areas are now cropped. Flows of 65,000 ft^3/s in 1975 and 70,000 ft^3/s in 1997 flooded cropland and some marinas. The reach contains about 415,000 acres of agricultural land and about 18,500 buildings subject to flooding.
Omaha to Kansas City	River flows exceeding 90,000 ft^3/s will flood Nebraska City, Rulo, and St. Joseph. Complaints are received from farmers at 2 ft below flood stage. The reach contains about 360,000 acres of agricultural land and about 2,650 buildings subject to flooding.
Kansas City to Mouth of Missouri River	Flows of about 150,000 ft^3/s cause only minor agricultural damages in this reach. The reach contains about 472,000 acres of agricultural land and about 4,800 buildings subject to flooding.
Systemwide	About 1.4 million acres of agricultural land are subject to flooding, with 90 percent downstream of Gavins Point Dam. Corn, soybeans, and wheat are the major crops. Some 42,800 acres of Tribal lands are subject to flooding, mostly on the Fort Peck Reservation. Some 30,395 residential buildings worth approximately $1.9 billion are located within flood hazard areas. Also, some 5,345 non-residential buildings are subject to flooding, with a total value of approximately $15.7 billion. Floods greater than a 25-year flood event have the potential to adversely affect navigation. The estimated accumulated flood damages prevented by the System are $24.8 billion from 1938 to 2001, or $393.7 million annually.

Damages

The panel members visited several areas and tracked reports of flood damages to be aware of their seriousness and long-term effects on many people. No comprehensive survey of flood damages has been completed yet, but when direct and indirect damages are computed, they are likely to amount to billions of dollars.

Damages occurred all along the river, from Montana to the the confluence with the Mississippi River at St. Louis, Missouri. The event was covered extensively in the media and, for an overview, the Omaha World-Herald (2011) maintained an interactive floodplain map, which gathered reports from county emergency managers to provide up-to-date information on damages, transportation routes, and other response and recovery matters. The map extends in Nebraska from Boyd County (just below Lake Francis Case) along the river to Richardson County (in the extreme southeastern corner of the state). The map includes Iowa counties beginning with Woodbury on the north to Fremont County south of Council Bluffs.

The devastation and disruption on a county-by-county basis (shown on the map) were massive, and the reports indicated that many homes were destroyed; levees were built and removed, transportation arteries and bridges were disrupted and/or damaged, farms were damaged, and other general disruptions occurred.

As an example, Otoe County, Nebraska, did not have homes evacuated, but it received evacuees from Iowa, mainly Fremont County and the towns of Hamburg and Percival. Highway 2, a major economic corridor, suffered severe damage. The Omaha Public Power District had a generating plant that was threatened, but survived the flood. As another example, Woodbury County, Iowa, did not suffer major damage to homes or public facilities, but large amounts of sand piled up in farm fields, which was a topic reported at the Sioux City public meeting.

The flood had differential effects on economic activities. In Brownsville Nebraska, south of Omaha, the River Inn Resort was empty all summer. However, in Otoe, Nemaha and Richardson Counties in southeastern Nebraska, traffic increased greatly due to the closure of Interstate 29. Some convenience stores and restaurants had much higher sales than normal, but other retailers lost customers from Missouri. The Highway 2 bridge remains closed, as well as the U.S. 136 bridge further south (Duggan, 2011).

A tremendous scale of flooding occurred below Gavins Point. Many witnesses reported on the flood incidents and a series of 150 aerial photos on the Internet shows the scale of flooding of farmland and cities (Geiger, 2011). The U.S. Geological Survey (USGS) in a series of 213 photos (U.S. Geological Survey, 2011) illustrates some of the hydraulics issues and infrastructure damages of the flood.

Urban damages

Urban flood damages are anticipated in the Master Manual, and they occurred in cities from Montana to Missouri. Cities and areas affected include Bismarck, Pierre, Dakota Dunes (South Dakota), South Sioux City, Sioux City, Omaha, Kansas City, and Jefferson City. Panel members attended public meetings in four of these cities and heard first-hand from people about the damages and pain suffered. The first larger city where flood damages were significant was Bismarck, North Dakota. Low-lying areas in Bismarck were being affected by the increased Garrison Dam releases before the heavy rains in May (average Garrison releases in May were 49,000 ft^3/s). Ultimately, many homes in the outlying county areas suffered severe damage or total loss, and high groundwater levels (caused by high river stages) affected many additional homes in the city.

Pierre and Fort Pierre lie just below Oahe Dam. The scale of the urban damage is not yet known, but at the public meeting in Pierre a number of homeowners and farmers rose to tell personal stories of great losses.

In the Sioux City area, damages were experienced at Dakota Dunes (in South Dakota a separate developed community), at South Sioux City, and at Sioux City. One panel member met with officials from Dakota Dunes and attended the public meeting at Sioux City where once again many residents reported their severe losses.

Urban damages were also evident in the cities of Omaha, Kansas City, and Jefferson City. A panel member attended the St. Joseph, Missouri, public meeting and the panel received a report about the Omaha meeting. Many people spoke at both meetings about the personal suffering they experienced.

Industrial and Utility Damages

In addition to urban damage, many industrial areas were flooded. Highly-visible issues included flooding at the site of the Fort Calhoun nuclear plant in Nebraska and threats to the Cooper nuclear station belonging to Nebraska Public Power District and located near Brownsville. Steam generating plants along the river also were affected.

Industries and utilities were affected, including wastewater treatment plants, water supply plants, and industries located in the floodplain. At Omaha, the main airport was threatened with closure.

Agricultural Damages

Farmland flooding was particularly devastating. In the upper reaches, land uses are mostly agricultural and undeveloped lands and a number of small communities are located between Fort Peck and Garrison Dams. As anticipated by the Master Manual, damages in the upper reaches focus on agricultural losses and flooding in smaller urban areas, along with disruption of transportation routes. Further downstream of Garrison Dam many farms were devastated.

Transportation

Bridges that were closed caused tremendous disruption to transportation routes. A list of bridges affected between Omaha and Kansas City included many main routes that people depend on for work and other essential travel. For example, the Interstate 680 bridge connecting Nebraska and Iowa was still closed when a panel member passed through in early November. The bridge reopened on about November 3.

Chronology of 2011 Events: Meteorology, Hydrology, and System Regulation

A chronological history of hydrologic conditions and forecasting prior to and during the 2011 flood event follows. This history includes a summary of the conditions and regulation leading into the 2011 season as well as documentation of meteorological forecasts and runoff estimates during 2011. An unusual meteorological series of events led to the worst flooding to occur on the mainstem Missouri River system since the reservoir System was fully implemented in the late 1960s. What started out as a forecast for a slightly above average runoff year changed rapidly during the late spring and led to unprecedented volume runoff and the highest storage ever experienced by the System since dam regulation.

Antecedent Conditions and System Storage

The Missouri River basin experienced drought conditions for much of the 2000–08 period. The total storage of the reservoir system fell to its lowest point since 1967 by 2006. At this time, storage had fallen to less than 35 MAF (figure 7). The first substantially wetter than normal year since 1999 occurred in 2009. Year 2010 was even wetter, finishing the third highest in the 1898–2010 record. The above normal precipitation in 2009 and 2010 allowed the reservoir system to recover to an operating range not seen since 2000.

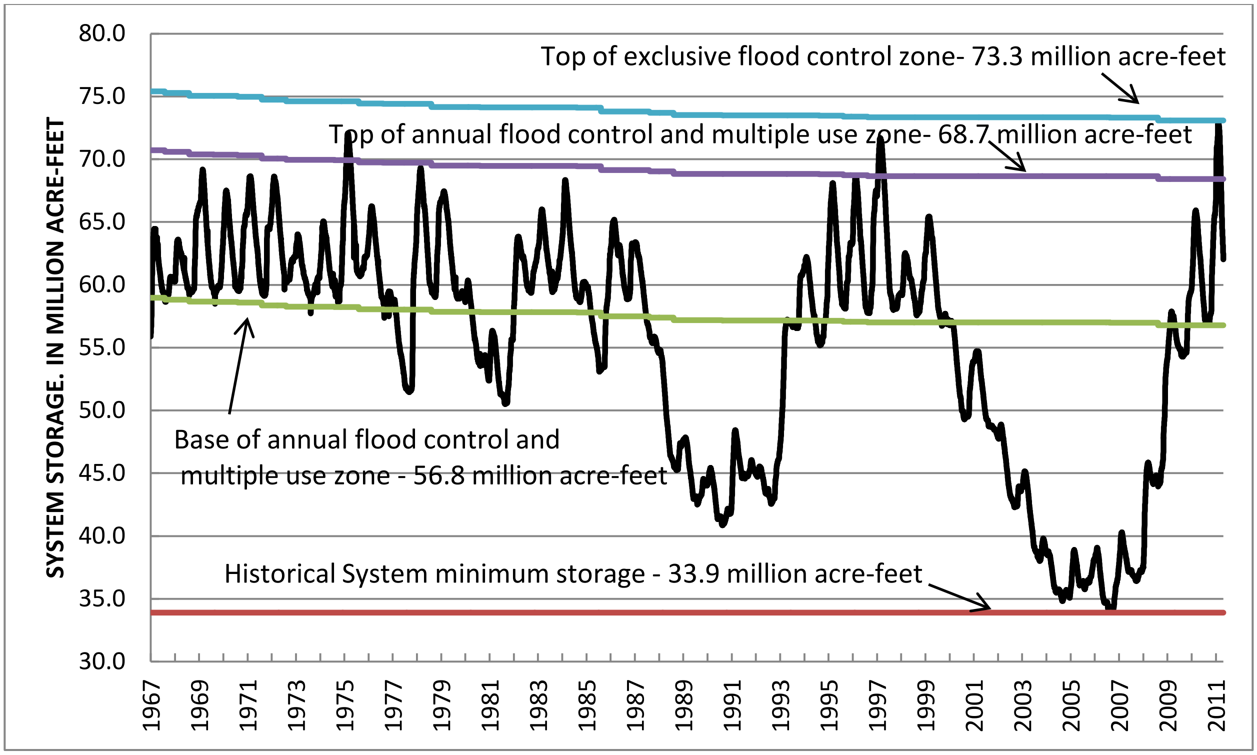

Figure 8. Missouri River mainstem system storage, 1967–2011

Even though the 2010 water year was very wet, the Corps was on target to bring storage of the reservoir down to the base of the Annual Flood Control and Multiple Use Zones by March 1, 2011.

According to the Master Manual, the desired total storage of the System, in preparation for the remainder of the year, is 56.8 MAF on March 1. The system is evacuated to this level "to provide adequate storage capacity for capturing runoff during the next flood season." (Master Manual, page VII-6).

The Omaha MRBWM followed the Master Manual and evacuated the 2010 flows, and on January 28, 2011, the total System storage was down to 56.8 MAF. An early season warm spell in late January gave an early start to the plains snowmelt, and runoff from this brought System storage amounts up slightly in February.

Winter Forecasts and La Niña

The winter of 2010–11 was controlled mainly by "La Niña" conditions occurring in the Pacific Ocean. This La Niña event has been ranked as moderate to strong, but was not characterized as the strongest La Niña event of the past 60 years (Heureux, 2011). A La Niña event is characterized by cooler than normal ocean waters in much of the tropical Pacific Ocean. This normally results in wetter and cooler weather across the northwest corner of the U.S. during the winter months. The upper half of the Missouri River Basin is contained within this area, thus colder and wetter weather were expected across much of Montana and northern Wyoming. Long range forecasts from the Climate Prediction

Center issued in November 2010 bore out this message with a 3-month winter forecast of above normal precipitation for much of Montana, and below normal temperatures for much of North Dakota and parts of Montana (figure 9). However, it is important to note that much of the basin (North Dakota, South Dakota, and Nebraska) had equal chances of above or below normal precipitation. Going into the winter, it appeared that there was a strong chance of above normal snow in the mountainous headwaters of the basin, but little indication of significant deviations from normal elsewhere.

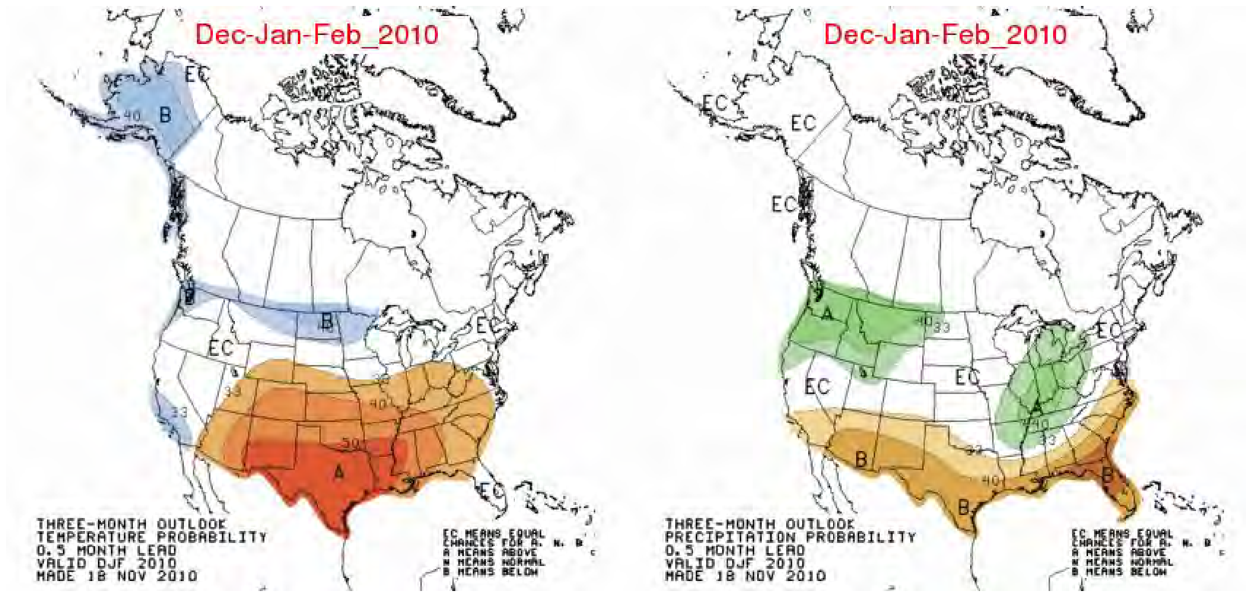

Figure 9. Climate Prediction Center 3-month (December 2010–February 2011) outlook for North America precipitation and temperature, issued November, 2010

Weather, Streamflow, and System Regulation, December 2010–February 2011

As the winter ensued, much of the long-range forecasts for a La Niña winter were realized. Precipitation across the basin during the winter months of December, January, and February was well above normal. The Missouri River Basin's precipitation during the winter months was the 112th driest in the last 116 years, or fifth wettest (figure 10). It was also colder than normal, so most, if not all of the precipitation fell in the form of snow. It is important to note however, that normal precipitation amounts for the winter months are relatively low. Outside of the mountains, most areas normally receive water equivalents of less than 2 inches during the entire winter season.

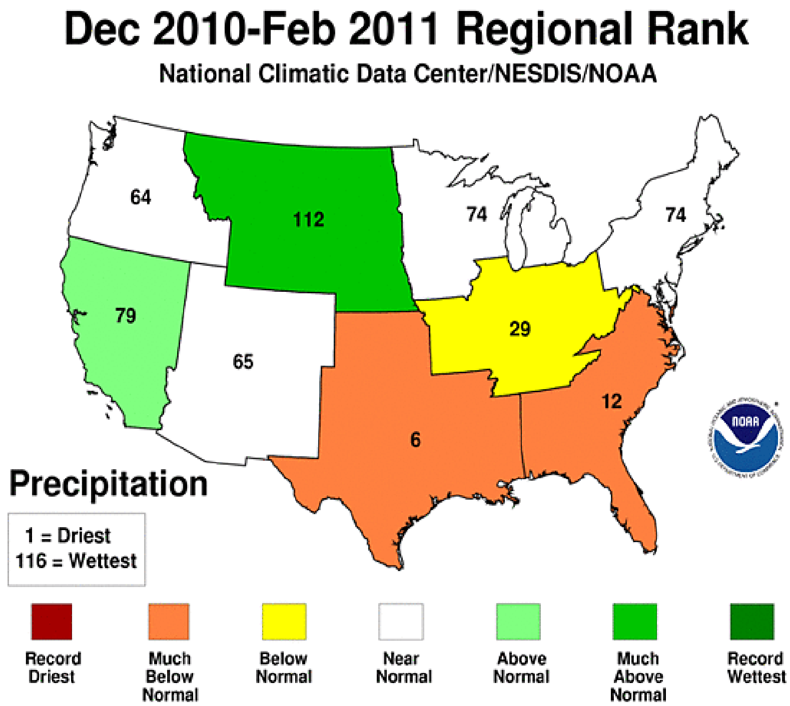

Figure 10. December 2010–February 2011 winter precipitation ranking for period 1895–1896 to 2010-2011

The December runoff volume for the Missouri River above Sioux City was 140 percent of average. Starting the first of the year, antecedent conditions indicated high soil moisture conditions in much of the upper basin. Conditions remained wet. January volume runoff at Sioux City finished 8th highest on record, approximately 170 percent of normal flows. February runoff at Sioux City also was above normal, at over 200 percent of average. Due to the high runoff, as of March 1, the System storage was up slightly to 57.6 MAF, but still near the bottom of the Annual Flood Control and Multiple Use Zone.

January 1 mountain snowpack was modestly above average, overall, just over 110 percent of average in both the Missouri and Yellowstone River Basins. As the snow accumulation season continued, the snowpack at the beginning of February and then again in March continued at about the same percent of average, on the whole, just over 110 percent of average snowpack.

By March 1, plains snow varied across the basin. Snow was heaviest in the Milk River Basin, upstream of Garrison Dam, and in the Dakotas.

The Corps' annual volume runoff forecasts from the beginning of January through the beginning of March remained nearly constant, starting at 112 percent of normal for the Missouri River upstream Sioux City, Iowa, up slightly to 114 percent of normal in February, and then back to 112 percent of normal by the beginning of March.

Weather, Streamflow, and System Regulation, March 2011

March 2011 continued the pattern established over the winter of above normal precipitation over much of Montana, North Dakota, South Dakota and northern Wyoming (figure 11). The eastern half of Montana was particularly wet. However, drier than normal conditions prevailed on the lower parts of the basin, specifically southern South Dakota, much of Nebraska, Iowa and northern Kansas. Overall, the basin averaged near normal precipitation (figure 12).

Temperatures were below normal over North Dakota and South Dakota, and near normal elsewhere. The colder than normal temperatures over the Dakotas tended to slow the snowmelt on the plains, while normal temperatures in the mountains prevented any early spring snowmelt. Most precipitation that fell over northern areas was in the form of snow. There existed a substantial plains snowpack at the end of the month, especially over Montana and North Dakota.

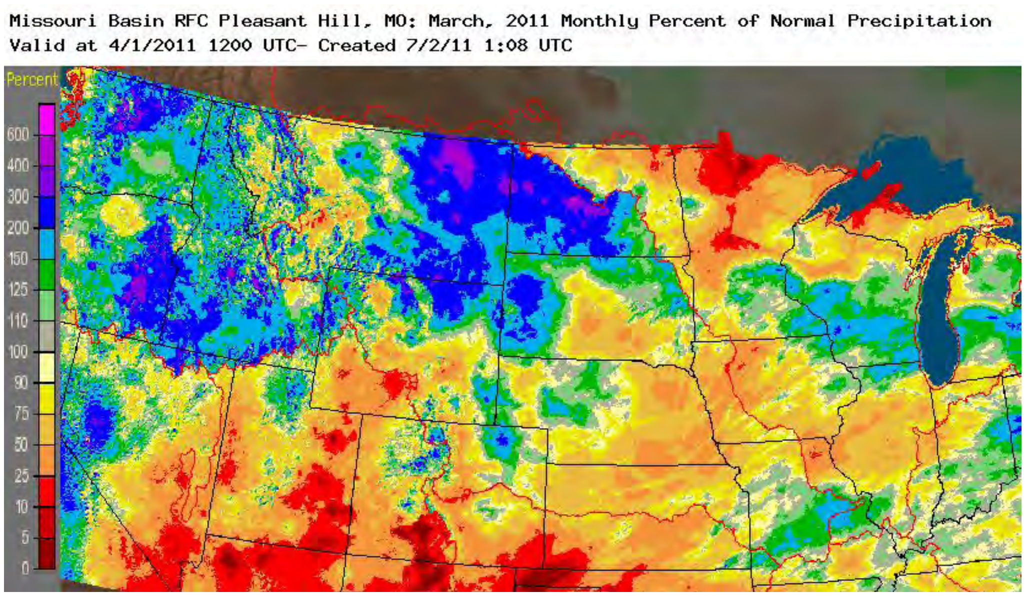

Figure 11. March 2011 percent of normal precipitation

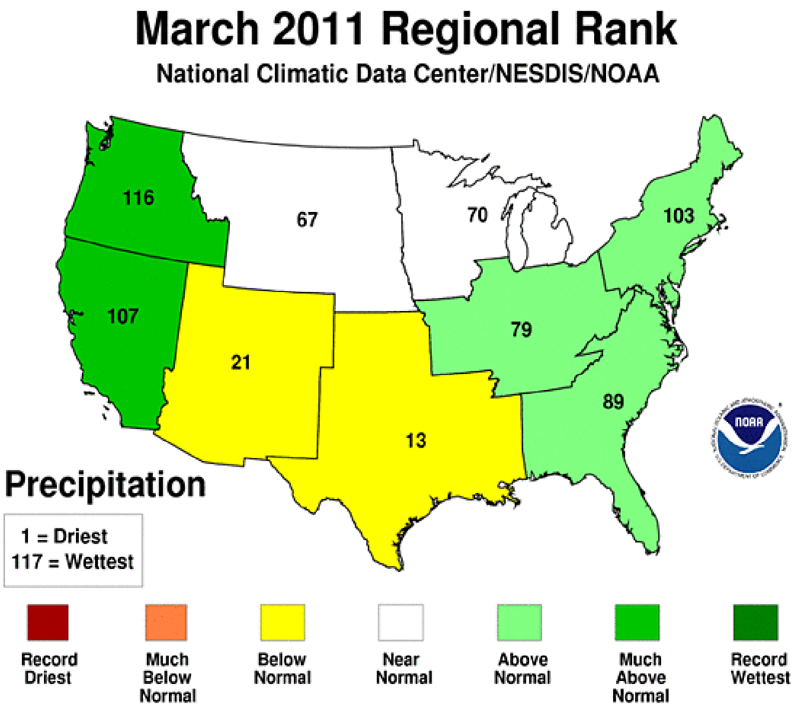

Figure 12. March 2011 regional precipitation ranking, for period 1895–2011

Long range forecasts made in March for the 3-month period of April, May and June indicated a continuation of the colder than normal temperatures, but showed most of the basin with equal chances of above or below normal precipitation. There was a small area centered over North Dakota where the forecast was for above normal precipitation (figure 13). Even though the long range outlook was for above normal precipitation over North Dakota, the forecast gave no indication how far above normal the precipitation might be.

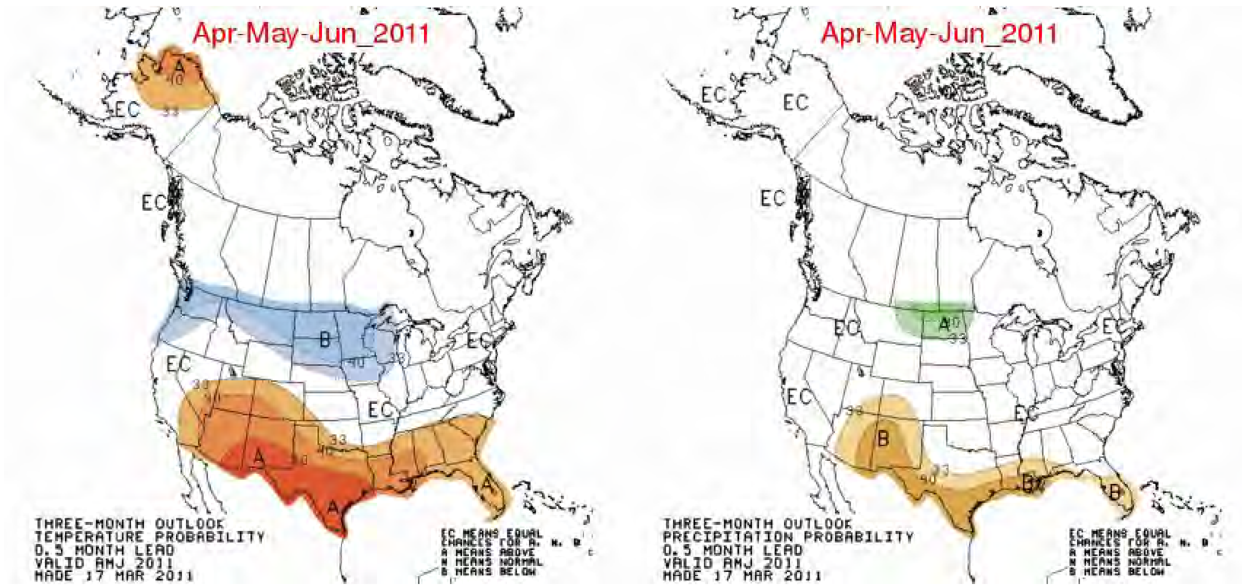

Figure 13. Climate Prediction Center three-month outlook (April 2011–June 2011) outlook for North America temperature and precipitation, issued March 2011

Into March, runoff continued to be high. The March runoff volume at Sioux City was approximately 230 percent of average. In the period March 15–28, the release from Garrison Dam was reduced from 26,000 ft^3/s to 15,000 ft^3/s to free up downstream channel capacity for anticipated runoff from plains snowpack, which was above normal. In late March, the navigation season started, and it looked like it would be a normal year of operations that fit well into the Master Manual plan. On March 28, the planned Gavins Point pulse for the pallid sturgeon was cancelled because river flows were high.

By the end of March, mountain snowpack had increased slightly from March 1 but was still under 120 percent of average. Although above average, these amounts were not unusually high, nor excessive when compared with snowpacks at the same date in previous years.

Weather, Streamflow, and System Regulation, April 2011

As of April 1, the Corps annual runoff forecasts for upstream of Sioux City, Iowa, went up to 136 percent of normal, or 33.8 MAF. The Corps went into flood control operation and the “service level,” or target flows, were raised to 45,000 ft^3/s for flood water evacuation.

During April 2011, precipitation was above normal across almost the entire basin with the exception of areas in central Kansas (figure 14). During April, normal rainfall increases quite rapidly from the normally drier winter months. Normal precipitation ranges from less than an inch in extreme northern Montana up to more than 4 inches in central Missouri. Eastern Montana was the area with the largest departure from normal during April, and also an area that had the sixth month in a row with above normal precipitation. Overall, the basin ranked as the 94th driest (23rd wettest) April out of 117 years (figure 15).

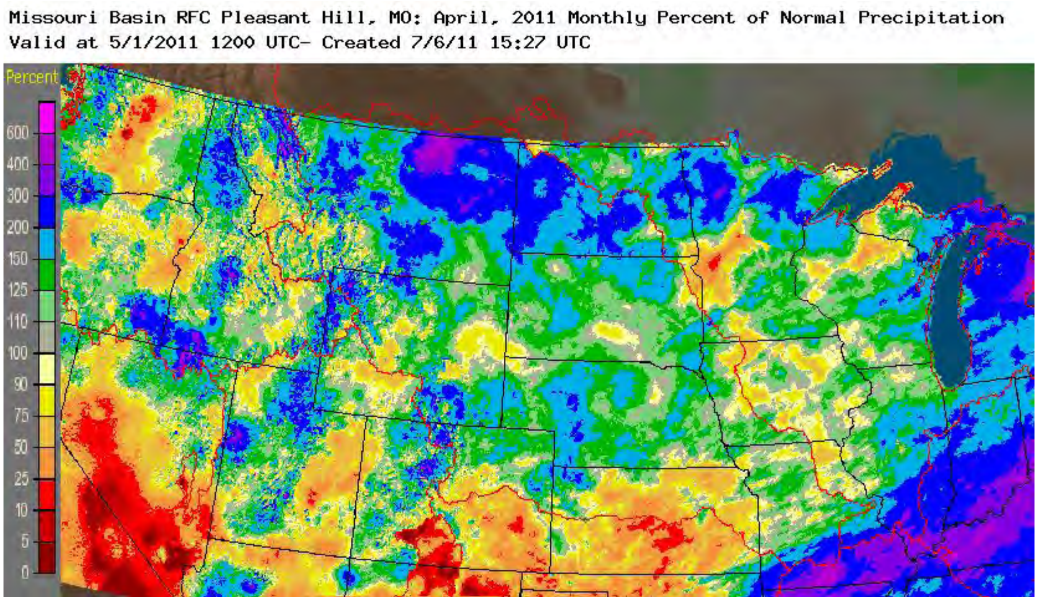

Figure 14. April 2011 percent of normal precipitation

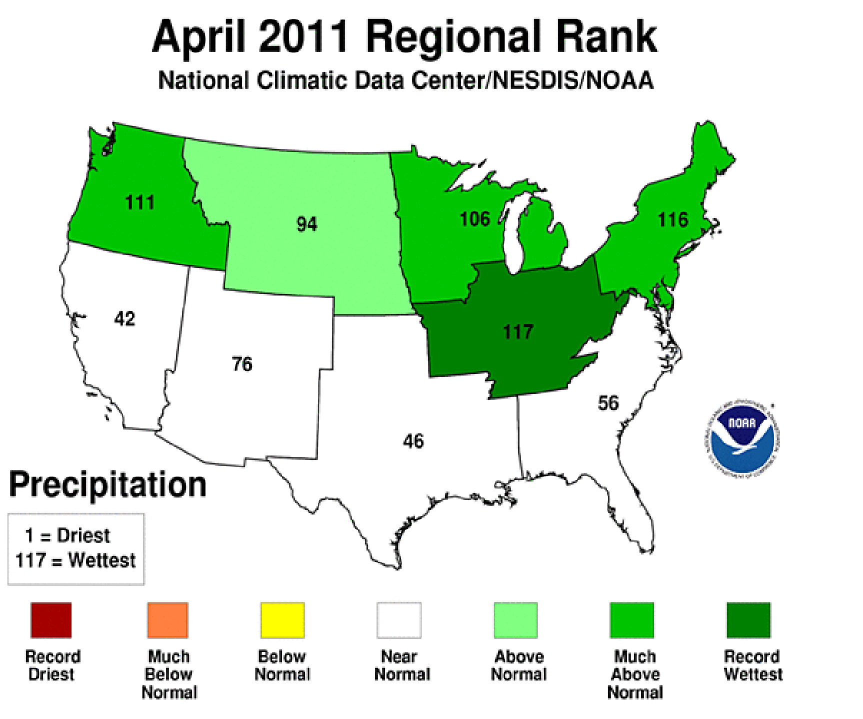

Figure 15. April 2011 Regional rank of precipitation, showing above normal precipitation over the basin as a whole.

In April, long range meteorological forecasts used by the Corps continued to indicate a weak signal for above-normal precipitation over the next 3 months in much of North Dakota and now extending into northeast Montana. Another area of above normal precipitation was predicted further south from eastern Kansas into Missouri. The remainder of the basin, including much of Wyoming, South Dakota and Nebraska had equal chances of above or below normal precipitation (figure 16). Again, these forecasts gave no indication of how far above normal the rainfall might be, and there was no overwhelming signal of the record breaking precipitation deluges that would actually occur during the forecast period.

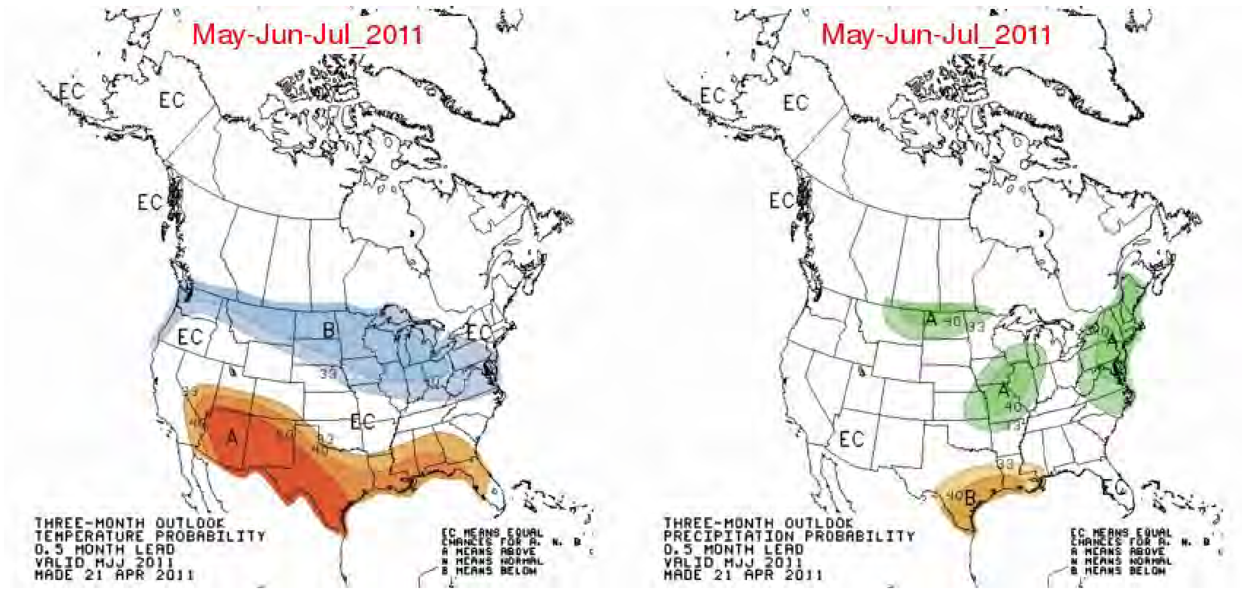

Figure 16. Climate Prediction Center three-month outlook (May 2011–July 2011) for North America temperature and precipitation, issued mid April, 2011

It was during April that hydrologic conditions went from an upper quartile year to an upper decile runoff year. On April 15, for flood evacuation, the service level was increased 5,000 ft^3/s up to 50,000 ft^3/s, which was 15,000 ft^3/s above the full service level. On April 25, the USFWS was notified that there would be no operation for least terns and piping plovers.

As a result of greater than forecasted precipitation in April, the Corps' May 1 annual runoff volume forecast upstream of Sioux City went to 44 MAF, which would amount to the second highest monthly runoff volume in 114 years of record and amounts to 178 percent of average runoff for May. The service levels were increased to 60,000 ft^3/s, an addition of 10,000 ft^3/s of flood water evacuation.

The March–April runoff volume upstream of Sioux City finished third highest on record. By the end of April, some snow measurement sites in the mountains had started to break records. Data from Natural Resources Conservation Service (NRCS) SNOTEL (SNOw TELemetry) sites reported mountain snowpack was approximately 150 percent of average overall in the Missouri and Yellowstone River basins. The Corps reported snowpack values to be 141 percent and 135 percent of average upstream of Fort Peck and Garrison Dams, respectively, because the Corps compared values to April 15 readings.

Weather, Streamflow, and System Regulation, May 2011

May 2011 can be characterized as having record shattering precipitation amounts across a large portion of the basin. Monthly totals were in excess of 300 percent of normal (figure 17) across almost the entire eastern half of Montana (an area larger than the state of Georgia) as well as northern Wyoming. This area of excessive rainfall stretched east covering much of western North Dakota and western South Dakota, as well as western Nebraska and northeastern Colorado. Normal rainfall was much higher in May than previous months, ranging from almost 2 inches in northern Montana to over 5 inches in parts of Missouri. Actual rainfall during May was over 4 inches in most of the basin, upwards to almost 20 inches in parts of southeast Montana. May 2011 ranked as one of the wettest Mays on record in the five states of Montana, Wyoming, North Dakota, South Dakota and Nebraska (figure 18). This was an unusually large area to experience such a degree of wetness and was caused by an unusually strong area of low pressure aloft in the atmosphere that persisted over the northwest sections of the continental United States. This re-occurring low pressure system brought round after round of excessive rain. The eastern half of Montana, and portions of northern Wyoming were pounded by four intense storms during the month of May. The first storm occurred May 9–11 and dropped between 3 and 4 inches of rain over much of the area. The second storm followed extending from May 20-24, dropping 3 to 7 inches of rain. Another storm followed quickly on the May 25 and dropped up to an additional 3 inches of rain. Finally, the month ended with another intense storm on May 30–31, which dropped another 1 to 3 inches of rain. New May monthly records of 9.36 inches and 6.97 inches of rain were set at Miles City, Montana and Glasgow, Montana respectively. Billings, Montana, set an all-time monthly rainfall record of 9.54 inches. It is also interesting to note that Glasgow exceeded their maximum annual rainfall by August 2011, only 8 months into the calendar year. This is an indication of how wet the 2011 calendar year was across eastern Montana.

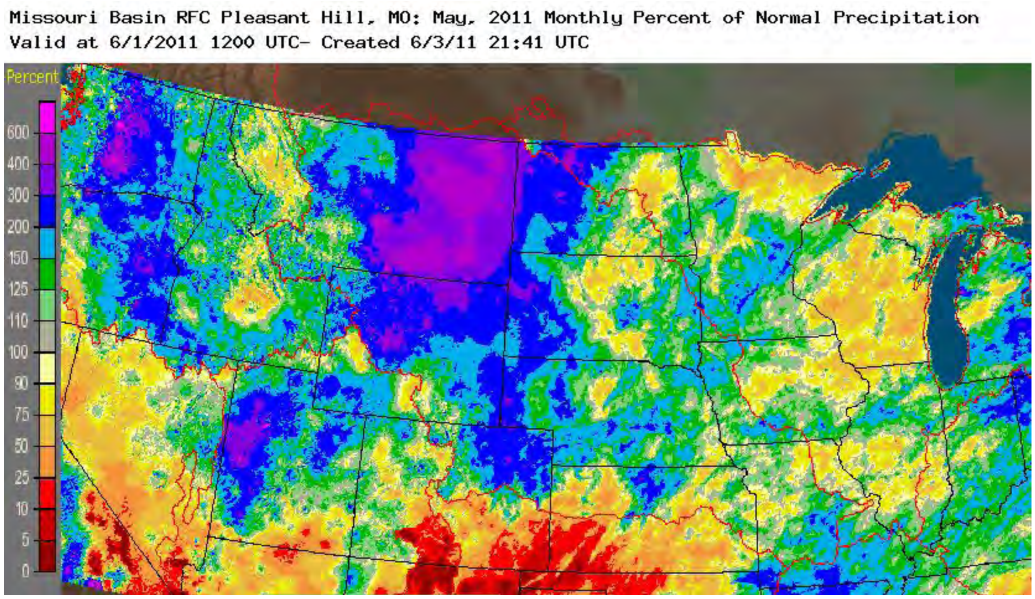

Figure 17. May 2011 percent of normal precipitation

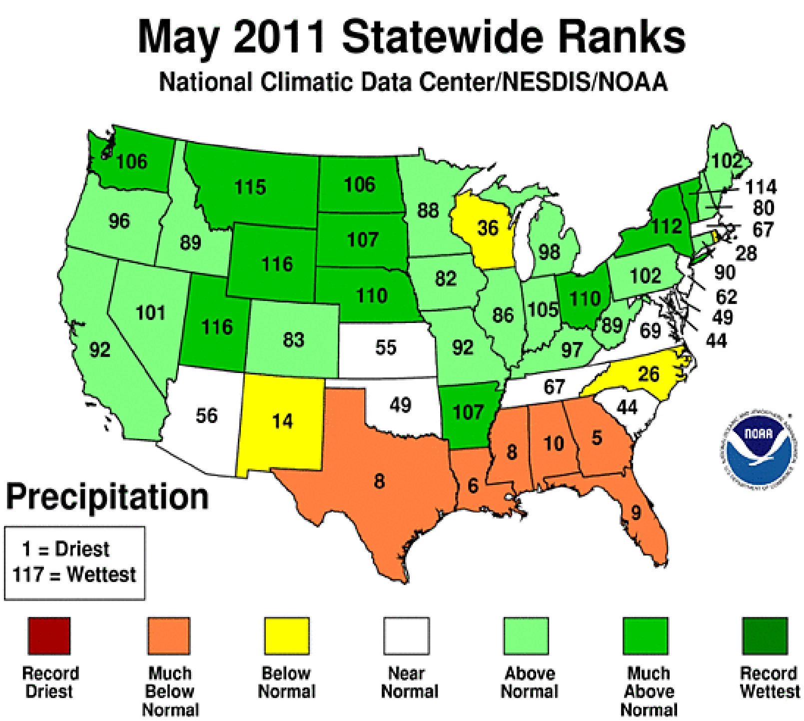

Figure 18. May 2011 state rank of precipitation

May is also normally the month that mountain snowpack begins to melt in earnest, but this was generally not the case in May 2011. This month experienced below to much below normal temperatures, especially in the mountainous areas of Wyoming and Montana. The persistent clouds, rain and low pressure resulted in temperatures well below normal, especially in western parts of the basin. Many of the larger storms dropped significant snow, not rain on the higher elevations of Montana and Wyoming. This had the twofold effect of delaying the normal beginning of the snowmelt season as well as augmenting the current mountain snowpack. The normal date of maximum snowpack in the mountains is approximately April 15. This year, the snow water equivalent in the mountains peaked on May 2. After May 2, the snowpack started to melt, but with continued storms, the pack melted and then was resupplied several times throughout the month of May. By June 1, mountain snowpack was still much higher than the average peak of April 15.

On May 23, the Corps announced that releases from Garrison Dam and Gavins Point Dam would go up to 75,000 ft^3/s. The next day, that number was raised to 85,000 ft^3/s. On May 26, the Corps announced in a Congressional Delegation call that releases from the five lower dams would increase to between 110,000 ft^3/s and 120,000 ft^3/s. After re-evaluation of inflow forecasts from the National Weather Service (NWS) Missouri Basin River Forecast Center (MBRFC), the Corps announced on May 28 that releases from the five lower dams would reach 150,000 ft^3/s. Note that during these increased releases the last 10 days of May, three heavy precipitation storms brought record-breaking rain and snow, in the higher elevations, to the basin upstream of Garrison Dam.

The precipitation in May was so high that the May volume runoff of 10.5 MAF on the Missouri upstream of Sioux City, Iowa, greatly exceeded the previous record of 7.2 MAF. Total runoff volume during May was approximately 320 percent of normal.

The mountain snowpack by the end of May continued to be extremely high for that time of year. As mentioned previously, the snowpack started to melt in May, but with continued storms, the snowpack was resupplied several times throughout the month of May and melt was delayed. Figure 19 shows an index summary of snow water equivalent, daily precipitation, and cumulative precipitation for mountain SNOTEL sites in the Upper Missouri basin upstream of Fort Peck and Garrison Dams. Incremental, that is daily, precipitation is shown in red, the cumulative precipitation is shown in green, the mountain snow is shown in blue. Incremental precipitation below a quarter inch is not shown. Average cumulative precipitation is the dotted black line and average snow water equivalent is the solid black line. The large amount of precipitation, particularly towards late May, was mostly snow at higher elevations.

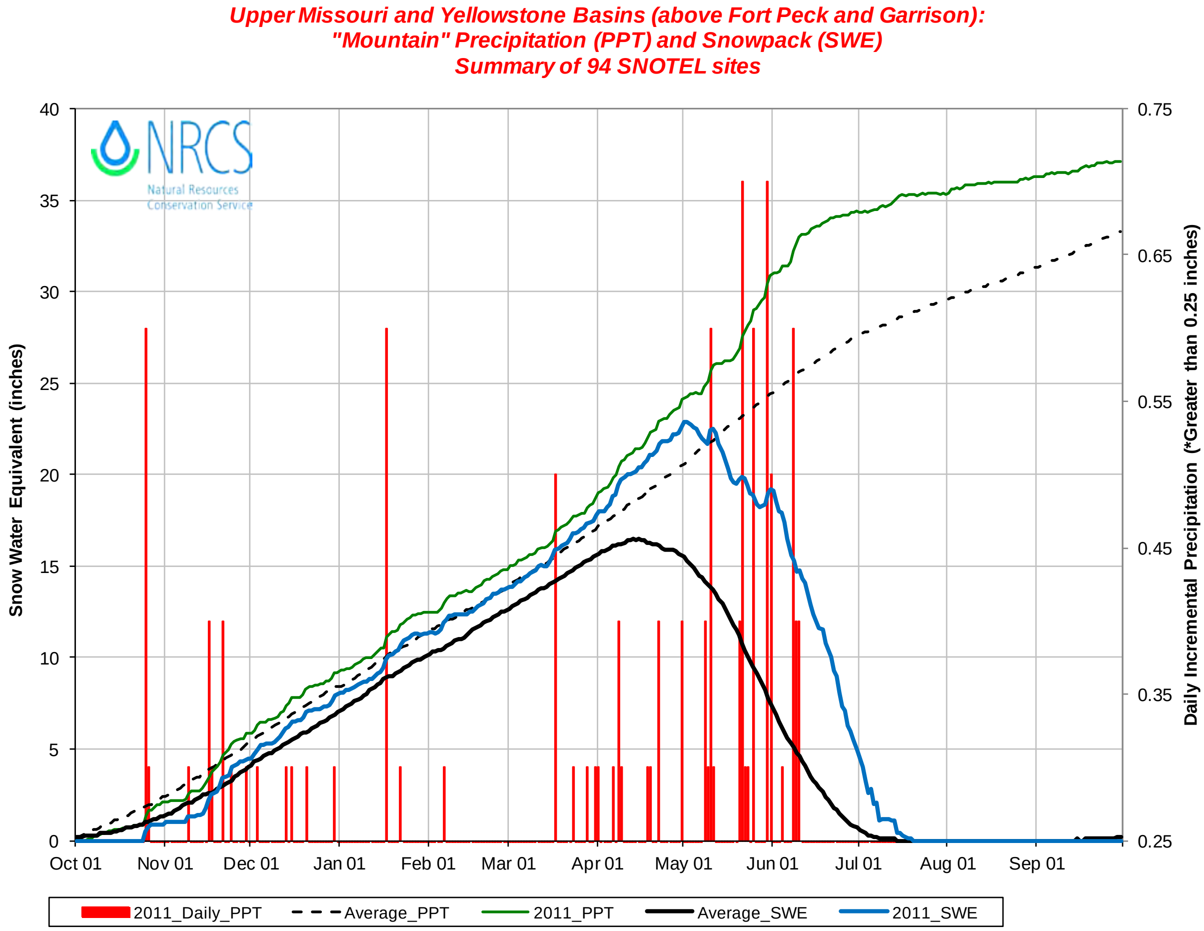

Figure 19. Precipitation and snowpack snow water equivalent summary from 94 snowpack monitoring stations in the upper Missouri and Yellowstone River basins, October 2010–September 2011

Weather, Streamflow, and System Regulation, June 2011

On June 1, the annual runoff forecast above Sioux City was raised to 54.6 MAF, or 220 percent of normal. System storage on June 1 was 70.4 MAF.

Extensive, above normal rains in June 2011 only compounded the flooding situation on the Missouri River (figure 20). Once again, rainfall was well above normal in much of Montana, Wyoming, South Dakota and Nebraska. June is normally the wettest month of the year across the plains of the upper basin, with normal rainfall between three-quarters of an inch in central Wyoming ranging up to more than 3 inches across most of the plains. Mountainous areas of Montana also normally receive at least 3 inches. Actual rainfall during June 2011 amounted to over 5 inches across most of the plains with a few places along the South Dakota-Nebraska line exceeding 10 inches. Montana was not left out with over half of the state recording over 4 inches. There were small areas around the basin that had below normal precipitation, but this was not the rule. Temperatures continued to run below normal over Montana and Wyoming during June. This had the continued effect of slowing the snowmelt in mountainous areas.

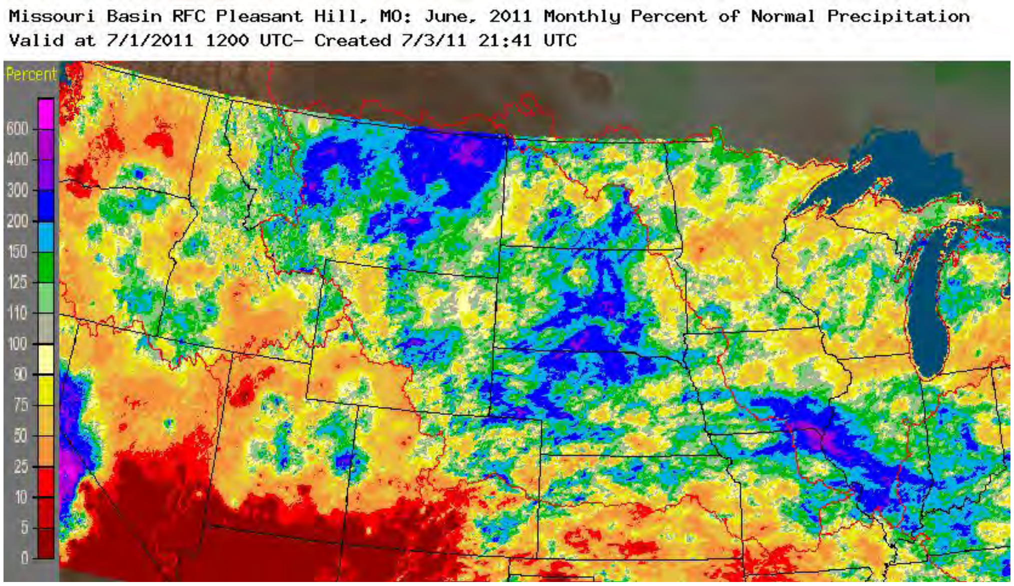

Figure 20. June 2011 percent of normal precipitation

Due to the combination of high June precipitation and mountain snowmelt, the June volume runoff above Sioux City, Iowa, was the highest ever on record for any single month. Releases from Gavins Point Dam were increased to 160,000 ft^3/s on June 21. Simulations by the MRBWM indicate that unregulated flows (without the dams) at Gavins Point Dam (Yankton, South Dakota) during June would have exceeded 250,000 ft^3/s, with an increase in stage of about 5 ft over actual, regulated conditions (Michael Swenson, U.S. Army Corps of Engineers, written commun., 2011).

Weather, Streamflow, and System Regulation, July 2011

By the beginning of July, the annual runoff forecast above Sioux City, Iowa, had increased to 57.7 MAF.

July was another wet month, especially for North Dakota and South Dakota and Nebraska. Montana and Iowa had near normal rainfall, while Wyoming, Kansas and Missouri were below normal. Figure 21 shows percent of normal rainfall for the month. Heavy rains in July tended to follow the crests of the flood waves downstream into North Dakota and South Dakota, running off already saturated soils. July was the ninth month in a row with above normal rainfall at Bismarck, North Dakota.

Hot summer conditions finally arrived to Montana and Wyoming in July with most spots swinging to well above normal temperatures after a very cool spring. This had the effect of rapidly melting the mountain snowpack during a condensed season. In a normal spring, the snowmelt occurs over the 3-month period of May, June, and July. In 2011, due to the excessively cold conditions that were observed in May, most of the snowmelt occurred in late June into July. This shortened melting season only further served to increase the runoff volumes and increase flooding flows into the reservoirs downstream.

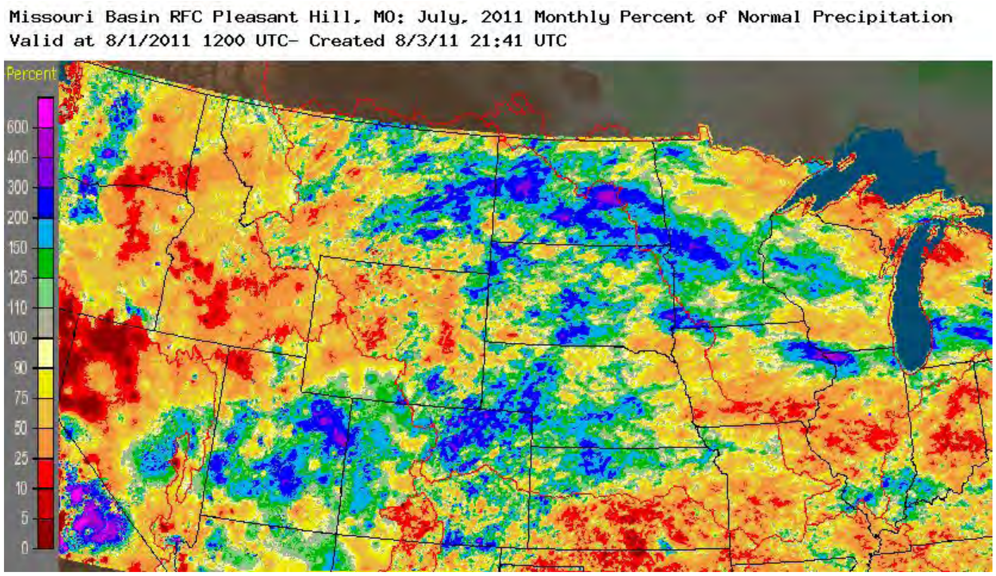

Figure 21. July 2011 percent of normal precipitation

July runoff upstream of Sioux City was over 300 percent of normal. With records dating back to 1898, the combined May–July volume runoff of 34.3 MAF exceeded the previous high volume of 20.9 MAF (in 1997).

Runoff during the 5-month period of March through July 2011 was estimated at 48.7 MAF, or more than 20 percent higher than the design storm of 1881, which had 40.0 MAF of runoff during the same 5-month period. Whereas the design storm of 1881 led to the allocation of 16.3 MAF of flood control storage that would limit peak releases to 100,000 ft^3/s from Fort Randall Dam, during the 2011 event the System storage crested at 72.8 MAF and peak releases from Gavins Point Dam reached 160,000 ft^3/s.

Releases from Gavins Point Dam remained at 160,000 ft^3/s into late July and were reduced to 40,000 ft^3/s by early October.

Review of Possible Factors Affecting the 2011 Flood and System Regulation

Assessment of Forecasting Operations and Accuracy

One of the largest contributors to the flooding along the Missouri River in 2011 was the unprecedented record rainfall that fell over much of Montana, North Dakota, and South Dakotas in May and June.

Meteorologic and hydrologic forecasts were utilized by the Corps during the 2011 events. However, no forecast accounted for the record precipitation and ensuing streamflows, including the Corps' long-term regulation forecasts. Accurate prediction of precipitation more than a week into the future is beyond the current state of science. The mountain snowpack was accumulating throughout the cool, wet spring but the real excessive amounts at many sites did not occur until May, too late for an advanced prediction of the record high volume of runoff.

However, advancements could be made. Plains snowpack could be better quantified. Internal forecasting procedures at the Corps could use some improvement, but even if modeling is improved upon, the Corps should work in closer cooperation with other forecasting and data collection agencies. During extreme events such as those in 2011, the Corps may want to consider contingency weather forecasts. All of these potential improvements could have contributed to better communication, earlier preparedness, and possibly a slight reduction in releases, but given the current state of science, none would have prevented the 2011 circumstances.

Assessment of Conditions

Use of Long Range Forecasts

Long range precipitation forecasts available from the National Oceanic and Atmospheric Administration's (NOAA) Climate Prediction Center (CPC) for the combined months of March, April, and May, available by mid-February, did not show a chance of above normal precipitation, instead indicating equal chances of above or below normal precipitation over much of the upper Missouri River Basin.

By mid-March, the CPC forecast did indicate above normal precipitation over much of Montana and North Dakota during April, but indicated that only North Dakota would receive above normal precipitation for the 3-month period of April, May, and June. Finally, by mid-April, the CPC forecast did indicate above normal precipitation for May over Montana and North Dakota, with a smaller area of above normal precipitation anticipated for the 3-month period of May, June and July centered again over North Dakota and northeastern Montana.

An important note is that the CPC long-range forecasts do **not** indicate the quantitative amount of precipitation, rather the forecasts indicate the simple odds of precipitation being above normal, near average, or below normal. Also, the signal present on these forecasts was "moderate" at best, and the CPC had difficulty zeroing in on the unprecedented precipitation that would occur in the next 1 to 2 months.

According to the CPC, this situation is not particularly unusual, because long range precipitation forecasts are "extremely unpredictable." During the entire 2011 spring, the CPC never had higher than 40 percent chances of above normal precipitation indicated over the upper Missouri River basin. Note this 40 percent chance is in contrast to the 33 percent equal chance of above, normal, or below. The CPC sometimes forecasts as high as 60 percent chances of above normal precipitation, but this is rare, and only for certain physical locations. A 50 percent forecast is termed a "strong" signal, whereas a 40 percent forecast is termed "moderate". The "state of the science" holds that long-range forecasting of precipitation is improving, but forecasting actual amounts more than 5 to 8 days in advance is nearly impossible. The panel agreed that there was no scientific evidence that the Corps should have expected record rains and mountain snowpack during the late spring and early summer months over the upper Missouri basin.

Although CPC forecasts do not predict precipitation amounts, the Corps included the CPC predictions in their decisions. The Corps incorporated the CPC's above normal precipitation forecasts, along with previous months' streamflows, and assessment of soil conditions, in their estimation of inflow forecasts into Oahe for the months after the traditional plains snowpack runoff. That is, the Corps' forecasts made in March, April, May, and June for the months of May, June, and July were above normal. The signal from CPC was not particularly strong and the monthly values used for runoff in the months after plains snowmelt, for Oahe of 110 percent to 140 percent seems reasonable to the panel. These numbers were a reasonable effort to account for the above normal precipitation even though predictions fell far short.

Plains Snow and Antecedent Plains Conditions

The Corps was aware of the increased plains snowpack and organized a network of volunteers to make manual measurements. These measurements were used by NOAA's National Operational Hydrologic Remote Sensing Center (NOHRSC), as input into their Snow Data Assimilation System (SNODAS) model, to produce snow water equivalent (SWE) snow cover maps.

Beginning in January, the Corps noted that the snow was above normal in the northern plains. By February, the Corps characterized most areas as "Moderate". In March, assessment varied across the basin from "Light" to "Heavy". The Corps characterized the snow and then placed this characterization in a ranking of other years to determine a March-April forecast runoff. The 2011 March–April volume runoff for the Missouri River at Sioux City, Iowa. ended up the third highest in the 114 years of record.

The Corps has been criticized for not accurately determining the volume of water in the plains snow in 2011. The Corps Update to the MRBWM Technical Report D-96 (U.S. Army Corps of Engineers, 2011d) states, "There is no defined empirical mathematical method or regression for forecasting plains snowmelt runoff based on snow water equivalent, temperature, soil moisture content, and other hydrologic factors that influence runoff."

Runoff on the prairie from plains snow is difficult to assess with blowing snow, sublimation, and pothole depressions that can hold water but release when filled. (Fang, and others, 2007) Even so, it appears that the Corps substantially underestimated the volume of water in the plains and the plains snow in their forecasts.

December, January and February all had above normal precipitation amounts and above normal runoff over much of Montana, North Dakota, and South Dakota. With the above normal precipitation and colder than normal temperatures in the winter months, much of the precipitation fell as snow.

Soils were extremely wet. Throughout the winter and spring months, the Corps examined antecedent conditions and assessed that many areas experienced wetter than normal soil moisture. However, determining excess runoff from very wet prairies still appears to be difficult and requires additional data and further study.

Figure 22 shows the Corps' forecasts for inflow into Oahe reservoir (between Garrison and Oahe Dams) for March 2011 inflows and compares the January, February, and March forecasts to average and adjusted observed values. The Corps' forecast was too low on January 1 and the forecast trended in the wrong direction as time progressed. Meteorological temperature records confirm an 8-day melt period in mid-March with no rainfall. When precipitation did fall during the month of March over the Oahe runoff basin, it fell in the form of snow, mitigating the chance that rain running off during the month resulted in the abnormally large observed value.

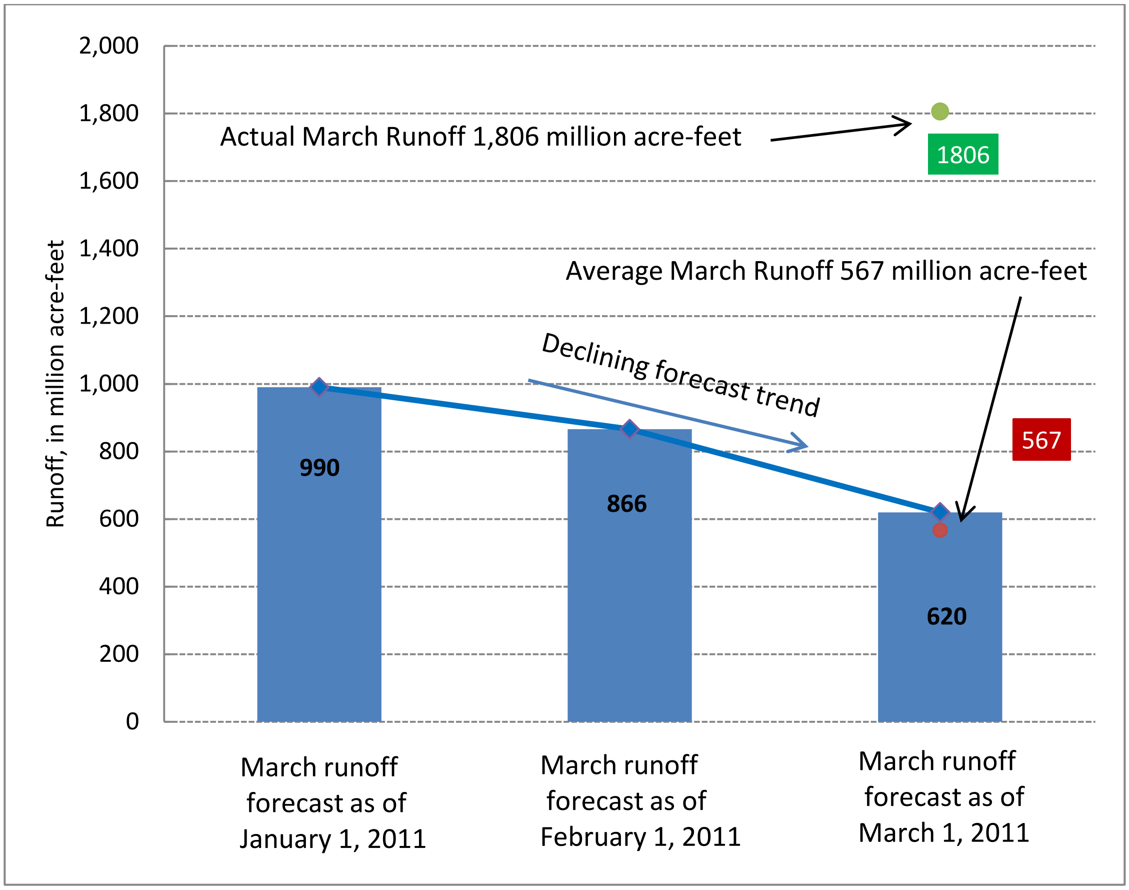

Figure 22. January 1, February 1, and March 1 forecasts of March Inflow to Oahe Reservoir, 2011, compared with average March and actual March inflow.

The underestimation of plains snow and associated wet antecedent conditions, might have created a level of confidence that there would be enough storage capacity available in the upper three reservoirs come late spring to handle runoff from mountain snowpack. This was the apparent scenario in 2011 when the plains snow runoff was greater than anticipated, filling the storage levels higher than expected by April.

A time-wise analysis (figure 23) shows how an underestimate of plains snowmelt can lead to major problems later. If plains runoff is underestimated, there may be little consequence in a subsequent normal or below normal precipitation pattern, however if compounded with high rainfall and mountain runoff, problems can develop. The figure shows zones of alternative outcomes. If plains snow runoff is underestimated but an over-prediction of mountain snowmelt and rainfall follows, the operations are self-correcting and no problems develop. If the difference between actual and anticipated runoff is negative, there might be drought problems with reduced service. The problem that occurred in 2011 was one of underprediction of plains snowmelt followed by high mountain snowmelt and rain.

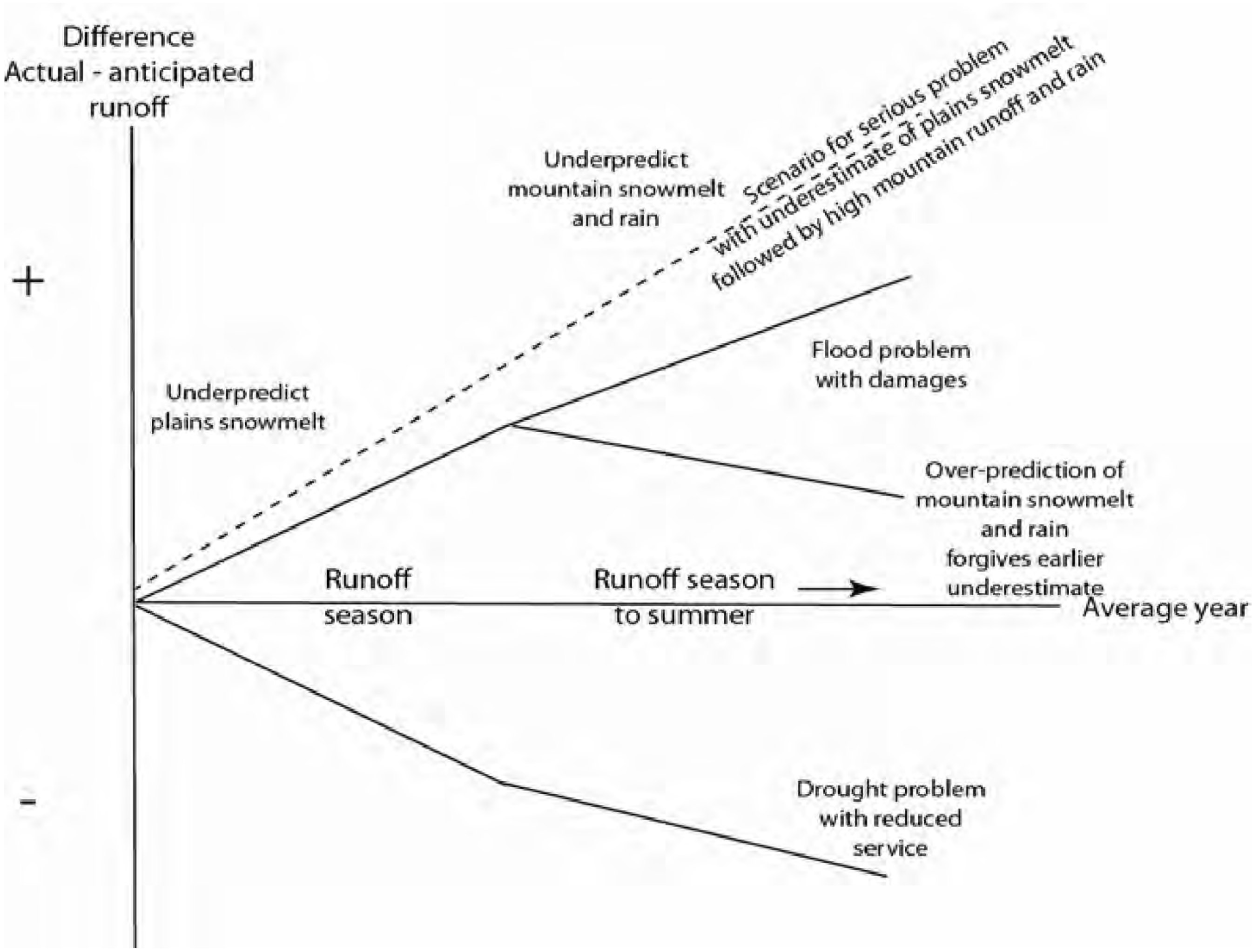

Figure 23. Problems associated with under- or over-prediction of runoff

If the plains snow runoff had been more accurately forecasted, the Corps might have increased releases in March and April, but there still would have been flooding. The Corps' underestimation of plains snowmelt was a part of a bigger picture that included late-building, high mountain snowpack, and late spring, record precipitation, all contributing to the extreme runoff. However, the panel notes that the Corps' plains snow evaluation procedures could use additional study and improvement. See 'Suggested Improvements' below. It is also important to recognize that over-prediction with increased reservoir releases can exacerbate drought problems later.

Mountain Snow

The mountain snowpack hovered at above average throughout the winter and early spring. Starting around the beginning of April, circumstances began changing. The snowpack increased due to a combination of additional accumulation and cool temperatures moving from a modest above average to well above average by forecasting standards.

Note the conditions of the SNOTEL snow measuring sites located in the upper Missouri River Basin in Montana and Wyoming. A snowpack summary for the combined areas of the Missouri River upstream of Fort Peck and the Yellowstone River Basin upstream of Garrison Dam are shown below (figure 24). The black line is average, the green line is 1997, and the blue line is 2011.

On April 1, SNOTEL sites were not in record territory, by the beginning of May sites began breaking records and records continued to break throughout May. Overall, about a quarter of the sites hit all-time maximum snow water equivalent peaks.

Again note, early season snowpack was above average but significantly increased after April 1. The Corps monitored the snowpack and has similar graphs. Also, note that 2011 did not start off as in 1997 when high early season snows provided an alert to System Managers to increase releases. Also, unlike 1997, the 2011 snowpack was much higher throughout May as melt was delayed and there was additional snow accumulation.

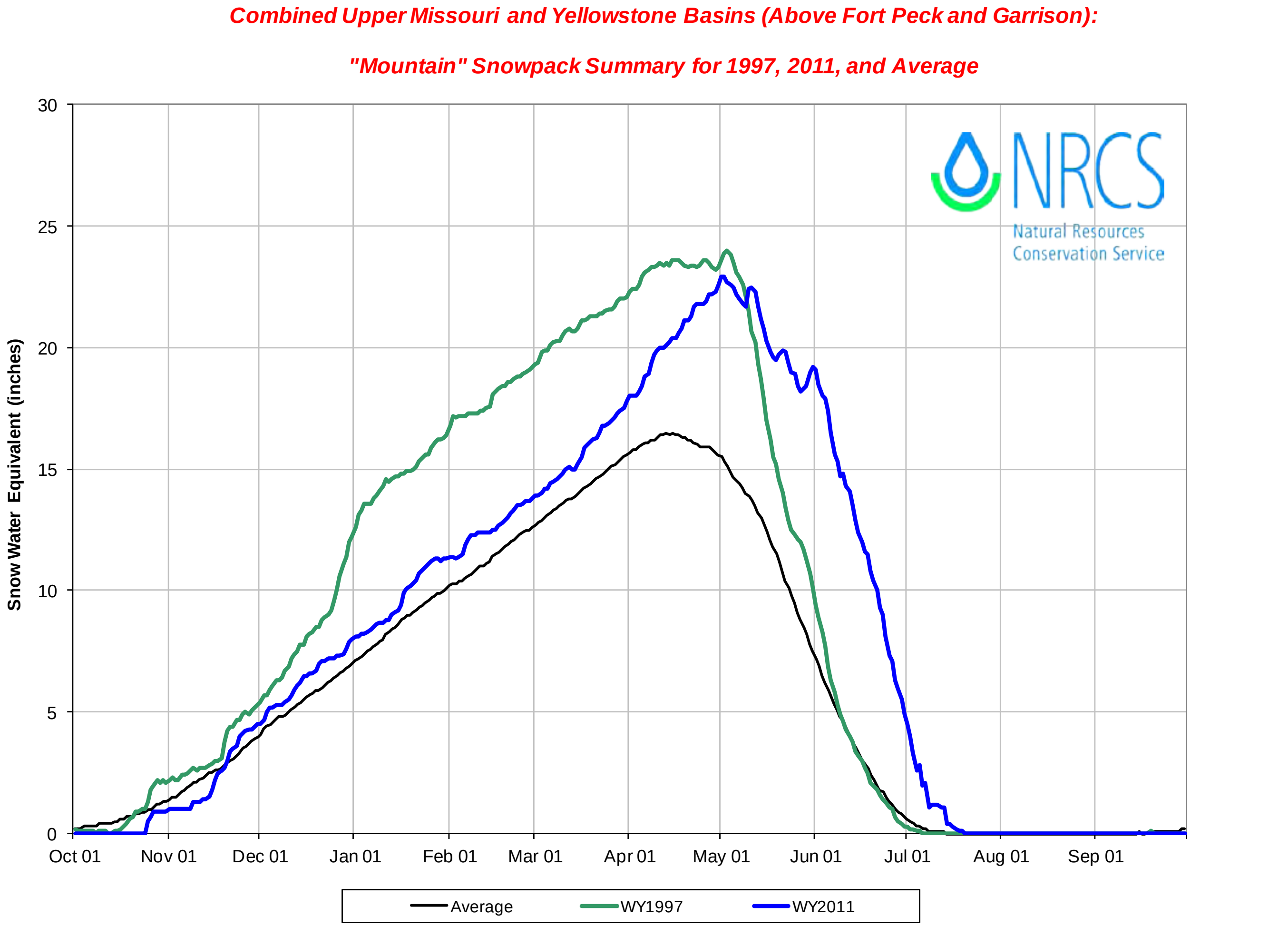

Figure 24. Mountain Snowpack Summary for Upper Missouri River and Yellowstone River Basins, 1997, 2011, and Average Year.

Mountain snow-based runoff forecasts are produced by the NRCS and the NWS for areas in the upper basin above and into Fort Peck and Garrison reservoirs. Forecasts from these agencies produced at the beginning of January, February, March, April, and even May were underestimated.

The Corps' forecasts for flows into Fort Peck and Garrison fit the same pattern. As the snowpack increased and as the rain fell, the forecasts rose but did not predict the record precipitation and runoff. Even as late as May 1, the predicted runoff volume for May through July into Garrison, based on a regression equation using peak mountain snow-to-runoff volume relationship, was "only" expected to be the tenth highest since 1898. However, the May–July flows into Garrison broke the record. The Corps regression-based forecasts for mountain snow-affected areas properly assessed on-the-ground conditions, but the forecasts cannot and did not predict the May, June, and July above normal precipitation.

During May, the mountain snowpack started to melt, but additional precipitation that came as snow actually increased the snowpack again several times during the month (figure 24).

Streamflow Gages and Forecasts

Although some USGS automated streamflow gaging stations that are used by the Corps to assess streamflows and inflows to the reservoirs malfunctioned or were damaged during the high flows, the Corps worked extensively with the USGS to get updated stage and flow measurements. The USGS made numerous field measurements of stage and streamflow during the flooding. (Jody Farhat, U.S. Army Corps of Engineers, oral commun., 2011).

The Corps used meteorological websites to assess the weather forecast and subjectively incorporate the forecast into river management. The Corps historically, and during 2011, used forecast products from the NWS MBRFC, including river forecasts without, and with quantitative precipitation forecasts (QPF). In May, the NWS MBRFC began providing daily reservoir inflow forecasts (specific reservoir inflow forecasts being distinct from streamflow forecasts) for Fort Peck Lake, Lake Sakakawea (Garrison), and Lake Oahe, saving the Corps considerable manpower that had been previously used for computing the reservoir inflows. After peak flows occur, the Corps uses historic recession rates to adjust their forecasts for points downstream not still affected by the mountain snowmelt. Although the Corps took into account the antecedent high streamflows, and pushed their predictions upward, the forecasts were too low due to the continued much above normal precipitation in May and June.

Suggested Improvements

Plains Snow

Runoff from plains snow is difficult to determine. Complications arise in point measurements where wind can cause drifts and scour, in assessment of frozen ground and soil moisture, in sublimation as a result of blowing wind, and in previously glaciated areas where areas of depression can hold water, which may or may not reach the river in a given time period.

Nevertheless, the Corps' procedures for forecasting plains snow could use more study with the intent of leading to improved modeling techniques in the future. The panel recommends a literature search on research that is being conducted concerning the soils and geomorphology of the plains, return flow periods, effects of antecedent conditions on runoff, and related rainfall-snowmelt runoff modeling of the plains.

An increased network of soil moisture probes should be considered to develop an historical record of soil moisture for quantitative use in modeling. Greater than expected runoff as a result of wet antecedent conditions needs to be studied. The same amount of snow may produce varying runoff due to the complexities of water retention.

Also, an expanded network of plains snow data is recommended and an historical record needs to be developed at permanent stations. Measuring of snow needs to be done according to an established and internationally recognized methodology (Scott Oviatt, Natural Resources Conservation Service, oral commun., 2011). Given that plains snow is not present every year, a volunteer network of permanent stations may be difficult to maintain, therefore, installation of automated snow monitoring devices should be considered. In reference to the use of snow measurements by the NWS as well, Jon Lea, Natural Resources Conservation Service, Oregon Data Collection Office Supervisor noted, “There is a very big opportunity here for a great cooperative process.” (written commun., 2011)

Although not the Corps’ responsibility, vegetation management throughout the basin should be examined, as management of the plains soils in the past century has significantly affected the plains snowmelt, reducing infiltration and increasing runoff (Verlon Barnes, Natural Resources Conservation Service, oral commun., 2011).

Finally, in combination with the literature search suggested previosuly, the Corps should explain their needs to the NOHRSC, MBRFC, NRCS, and the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) and ask for possible assistance.

The panel notes that the Corps’ post-flood assessment report on the 1997 flood recommends in its final conclusion that, “The forecasting procedure for the plains snowpack part of the annual runoff needs to be evaluated” (U.S. Army Corps of Engineers, 1998, p. 17). In the panel’s assessment, the Corps needs to continue to apply resources toward quantifying runoff from the plains snow.

Cooperation with Forecasting Agencies

The panel recommends that the Corps continue to use reservoir inflow forecasts, produced by the NWS MBRFC, on a regular basis. These forecasts would have aided the Corps in the days leading up to the determination of the high releases. Also, the panel recommends that the Corps continue to use the NWS forecasts that incorporate the Quantitative Precipitation Forecast to the degree of confidence as recommended by the meteorologists at the NWS, particularly when reservoir systems are nearing full capacity. The NWS also has the ability to run contingency forecasts of various weather scenarios. This procedure should be considered during extreme events.

In addition, the panel recommends that the Corps request long-range Ensemble Streamflow Prediction (ESP) forecasts from the MBRFC, for side inflow volumes between reservoirs. ESP forecasts use current estimated conditions and run an ensemble of future possible scenarios based on precipitation and temperatures that have occurred in the past. These forecasts may help in determination of the amount of plains snow volume runoff. 2011 would not have been captured in ESP, although results could have led the Corps closer to actual streamflow outcomes.

Finally, the panel suggests the Corps have regular coordination meetings with the other agencies that produce water supply forecasts, including the NWS and the NRCS, to help alert the Corps to potential trouble spots. State, local, city officials, and other emergency managers, such as FEMA and Sheriff’s departments, should be included in these meetings. Understanding the circumstances leads to increased awareness and preparedness and reduced blame.

Utilization of Available Flood-Control Storage

Mainstem Reservoir Storage

During the 2011 flood, the mainstem reservoir System storage reached a historic record of 72.8 million acre-feet (MAF) on July 2, 2011. The combined System maximum storage allocation, with each reservoir at the peak operating pool elevation is 73.1 MAF. Prior to the 2011 flood, the previous System storage peak was 72.1 MAF in 1975. During the 1997 flood, storage peaked at 71.7 MAF. Of the total System storage of 73.1 MAF, 16. 3 MAF of storage is authorized for annual flood control and exclusive flood control. The utilization of flood storages for each of the mainstem reservoirs, as well as the entire system, during 2011 is listed in table 2 (Michael Swenson, U.S. Army Corps of Engineers, unpublished data, 2011).

Table 2. Missouri River mainstem reservoir peak flood-control storage during the 2011 flood

Project	Designated Flood-Control Storage Capacity[1] (acre-feet)	Peak Flood-Control Storage in 2011 (acre-feet)	Peak Flood-Control Utilization in 2011 (percent)	Reservoir Discharge during Peak Storage Condition (cubic feet per second)	Date of Peak Flood-Control Storage in 2011 (percent)
Fort Peck	3,675,000	4,226,000	115[2]	65,000	June 16
Garrison	5,711,000	5,882,000	103[2]	150,000	July 2
Oahe	4,303,000	4,131,000	96.0	160,000	July 1
Big Bend	177,000	84,000	47.5	166,000	June 22
Fort Randall	2,294,000	2,191,000	95.5	160,000	July 7
Gavins Point	143,000	95,000	66.4	160,000	June 22
Combined System	16,303,000	16,060,000	98.5	160,000[3]	July 2

[1] Includes combined annual and exclusive flood-control storage

[2] Indicates surcharge storage conditions

[3] Discharge from Gavins Point Dam

Fort Peck reservoir was operated at a peak level of 2.3 ft above the maximum exclusive flood-control zone, into a level of storage referred to as surcharge storage. Surcharge operations represent a reservoir condition when the normal maximum flood-control storage is full and continuing (extreme) inflows must be passed though the System. Fort Peck Reservoir remained in surcharge condition from June 3 through July 6. During this period, the average release from the reservoir was about 55,000 ft^3/s.

Lake Sakakawea behind Garrison Dam was operated in surcharge mode from June 20 through July 12. During this period of surcharge storage, the reservoir was less than 1 ft into surcharge level, reaching a peak storage on July 1. In case of additional rainfall (which did not occur), the System operators were prepared for use of additional surcharge capacity, as a contingency measure (Michael Swenson, U.S. Army Corps of Engineers, written commun., 2011).

Lake Oahe reservoir was operated within 1 foot of surcharge level during June 21 through July 18, reaching peak storage on June 26, at about 0.3 ft below the surcharge level. Lake Sharpe, upstream of Big Bend Dam, provides little flood-control storage, compared with the three upstream reservoirs. The reservoir was operated near the lower level of the exclusive flood-control zone during most of the flooding.

Lake Francis Case, upstream of Fort Randall Dam, was operated well into the exclusive flood-control zone, reaching a maximum elevation of less than 1 ft from the maximum operating pool elevation and achieving about 96 percent of exclusive flood control storage.

Similar to Lake Sharpe (Big Bend), Lewis and Clark Lake, upstream of Gavins Point Dam, provides little flood-control storage, compared with the three large upstream reservoirs. During the flood, the reservoir was operated almost exclusively within the annual flood control zone. The peak storage occurred on June 22 at an elevation of 1208.32 ft, slightly above the base elevation of exclusive flood control, 1208.0 ft.

As a system, the reservoirs achieved a peak utilization of about 96 percent of available storage on July 2. Individually, Fort Peck and Garrison reservoirs actually achieved greater utilization than the overall System by operating in surcharge mode for extended lengths of time, 34 days and 23 days, respectively.

Tributary Storage

The U.S. Bureau of Reclamation (USBR) operates a system of tributary dams and reservoirs upstream of the mainstem System projects that contain authorized flood control storage. Section 7 of the 1944 Flood Control Act gives regulation authority to the Corps when these projects store water in their authorized flood control pools. During the 2011 flood, these projects were operated to integrate available flood-control storage into overall regulation of the Missouri River System (John Remus, U.S. Army Corps of Engineers, written commun., 2011). Table 3 lists the major tributary projects, including designated flood-control storage compared with peak flood-control storage during 2011 (Kellie Bergman, U.S. Army Corps of Engineers, written commun., 2011). A number of smaller dams and reservoirs operated by USBR and Corps are limited in the capability to provide sustained flood-control storage and are not listed in table 3. Typically, for these smaller dams, the base of the designated flood-control zone is coincident with the crest of an ungated spillway. Although these smaller projects do not significantly contribute to designated flood-control storage, they were operated at, or above the maximum normal pool elevation during 2011, in coordination with System flood-control operations (John Remus, U.S. Army Corps of Engineers, written commun., 2011).

Table 3. Missouri River tributary dam and reservoir flood-control storage during the 2011 flood

Project	Location	Designated Flood-Control Storage Capacity (acre-feet)	Peak Flood-Control Storage in 2011 (acre-feet)	Peak Flood-Control Utilization in 2011 (percent)
Canyon Ferry	Missouri River, Montana	101,089	90,204	89.2
Clark Canyon	Beaverhead River, Montana	79,075	53,630	67.8
Tiber	Marias River, Montana	403,074	379,351	94.1
Boysen	Wind River, Wyoming	150,632	57,406	38.1
Yellowtail	Bighorn River, Montana	258,331	224,710	87.0
Total		992,201	805,301	81.2

For the major tributary projects listed in table 3, about 81 percent of the available 0.99 MAF flood-control storage was utilized during the peak storage conditions during the middle of July, leaving about 0.18 MAF of unused storage. Boysen reservoir was unable to store water in the top 0.8 MAF of its flood control pool under this year's conditions due to the nature of the outlet structure. As the pool elevation rises the gates are opened to maintain safe freeboard, which increases the release from the reservoir. Boysen's inflows this year would not have sustained storage in the flood control pool at higher pool levels. Clark Canyon's flood control storage was limited by irrigation releases that were consumed before the flows reached Canyon Ferry reservoir. Storage was limited in Yellowtail's flood control pool due to the flashy nature of thunderstorms that pass through Bighorn Canyon and the need to provide local flood control capability downstream of the dam.

The values for peak flood-control storage and percent utilization of available storage provide a general indication of the effectiveness of the tributary projects during the 2011 flood-control operation. Other factors, such as timing and duration of tributary storage, also have an effect on inflows and available storage at the downstream mainstem System reservoirs. Also, the total available flood-control storage of the major tributary projects listed in table 3 amounts to about 0.99 MAF compared with 16.3 MAF of storage available from the main-stem projects. Unused tributary storage (available during peak storage conditions) amounted to about 1 percent of total System storage (mainstem plus tributary flood-control storage).

2011 Runoff Frequency Estimates

Using 113 years of available hydrologic data from 1840, 1881, 1898–2010, and preliminary estimates of 2011 runoff, the Corps MRBWM performed preliminary calculations to estimate the probability of the 2011 runoff inflows to the Missouri River System. The probability estimates (expressed as recurrence periods, in years) were calculated for annual inflows and for several multi-month periods, including March–April (plains snowmelt period), May–July (mountain snowmelt period), and March–July (dominant upper basin runoff period). The purpose of the calculations is to help characterize the rare nature of the 2011 runoff event by assigning a probability to the occurrence of annual and seasonal runoff volumes during 2011. The Corps' runoff frequency analyses are summarized in table 4. Details of the frequency analyses, as completed by MRBWM were provided by the Corps to the review panel (Michael Swenson and K. Stamm, U.S. Army Corps of Engineers, written commun., 2011).

Table 4. Summary of frequency analyses of the 2011 Missouri River mainstem System runoff.

Period	Runoff volume (thousand acre-feet)	Computed probability (percent)	Recurrence period (years)	Weibull probability (percent)
Annual	60,500	0.20	500	0.58
March–April	14,365	1.38	70	3.03
May–July	34,653	0.26	385	0.87
March–July	49,018	0.17	590	0.87

The runoff data and Corps statistical calculations were reviewed by the USGS (Timothy Cohn, U.S. Geological Survey, written commun., 2011) resulting in a recommendation to use non-parametric statistical methods to estimate a return interval for the 2011 annual runoff. Given the magnitude of the uncertainty, it would be more appropriate to express the recurrence period as a probable range. The 66 percent confidence interval for the nonparametric return period estimate of the greatest annual runoff in 113 years extends from 64 to 607 years. The corresponding 80-percent confidence interval extends from 50 to 1,070 years.

Effects of Climate Change on 2011 Flooding

The question of whether climate change played a role in the historic flooding along the Missouri River in 2011 is beyond the scope of this report. However, given that more extreme runoff events have occurred in recent decades compared to the data on record, the panel recommends re-examining the Missouri River System planning that is based on the entire historical record dating back to 1898. In addition, the panel recommends studying the possible allowance of greater flexibility in operating the System to adjust for varying climatic conditions.

Presently, the Corps considers all years of runoff on record (through 2006, until updated next year) in its streamflow statistics for determining the upper decile, upper quartile, median, lower quartile, and lower decile numbers for planning in the Annual Operating Plan. However, streamflow data records indicate that extreme events are becoming bigger and more frequent. The 2011 annual flow volume for the Missouri River at Sioux City is nearing 61 MAF. Including 2011, 9 out of the top 10 years in the historical record beginning in 1898 have occurred from 1975 to present. Note the red line in figure 25 demarcating the top 10 years.

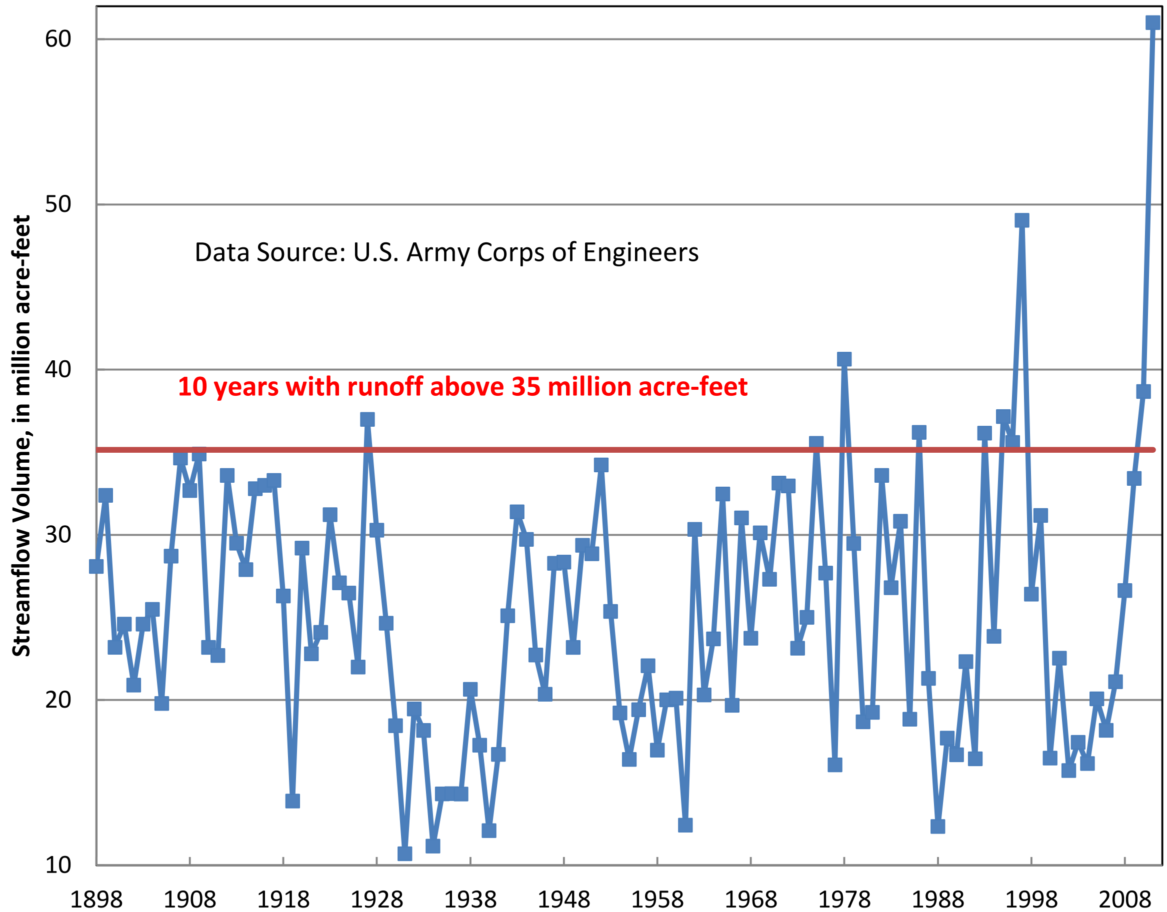

Figure 25. Missouri River Mainstem System Annual Runoff upstream of Sioux City, Iowa, 1898–2011

It is beyond the current state of meteorological science to predict events with certainty more than a week or two in advance. It is impossible to predict with certainty these extreme years. However, in 2011, the amount of precipitation broke records, and the annual runoff from 2011 is expected to exceed the previous record by greater than 20 percent. Although not predictable, and regardless of the cause, climatic conditions, compared to the period of record, have been changing, with more variability and extremes. Again, an examination of the Missouri River mainstem streamflow record points to increased variability with a positive skewness, indicating larger outlier events in recent years (David Garen, Natural Resources Conservation Service, written commun., 2011).

Future System operation should be focused on the possibilities of extreme precipitation amounts and new "normals". Also, given that consecutive years on record can be grouped as "wet" or "dry" periods, persistence, which can be determined from statistical lagged correlation, should be given consideration, although much uncertainty still exists in predicting the next year. Finally, any other completed research looking into the paleohydrology or reconstruction of streamflows could be investigated, to assess past precedence of such large events. These proposals do not imply a limitation on other climatic studies but do suggest the need for further investigation. The results of these suggested studies should be incorporated into future reservoir operating plans.

With non-stationarity as a rule (Milly, and others, 2008), consideration should be given to allowing the Corps to move beyond the rigid structure of the historical record, along with providing the Corps greater flexibility to incorporate emerging climate information and conditions into System management.

Master Manual Guidance and Extreme Events

Question 10 includes these two sub-questions: "Does the Master Manual adequately address reservoir operations during extreme flood events?" and "Does Plate VI-1 adequately address the hydrologic conditions like those experienced this year?" Both of these questions are addressed by how reservoir regulation decisions were made during the 2011 flood.

How does the Master Manual address regulation during extreme flood events?

The Master Manual (Manual) addresses flood control as one of eight authorized purposes of the System. During significant flood events, the flood control purpose becomes dominant (Manual, Section 7-07). During extreme events, the focus on using System storage to prevent damage is emphasized more (Sections 7-04.20, 27). The 2011 flood seemed to be significant and extreme, although these terms are not defined specifically in the Manual and it is not clear whether the original System planners envisioned a large flood such as in 2011. For example, the Manual states that "Regulation provided by the System, augmented by upstream tributary reservoir storage, has virtually eliminated significant flood flows on the Missouri River in this reach" (Fort Peck to Omaha, see Section 3-06.2). The Manual also states that the Exclusive Flood Control Zone (EFCZ) is to be used only for extreme or unpredictable events (Section 7-03.1.1). It is also envisioned that surcharge space will provide flood reduction during extreme flood events (In addition to project safety, see Section 7.04.3).

The panel agrees that the terms significant and extreme are used in the Manual to refer to large floods that require a shift of priority to flood control and away from the other seven purposes and that as the magnitude of flooding increases, the Manual envisions that the floods become "extreme," even though the terms are not defined precisely.

Current Corps practice is to consider a Standard Project Flood in project design, but in explaining how the System was planned, the Manual states "What is now referred to as a Standard Project Flood was not yet developed; the relatively conservative design inflows to the System used in these studies were based on past flood history" (Section A-06.6). The Manual also states that "Sufficient surcharge storage, freeboard space, and spillway capacity are provided at each project to pass the maximum probable flood for each System project while maintaining the individual integrity of the System and its individual projects" (Section A-06.4). The panel's conclusion is that the designers intended for the System to have the capability to pass any flood that could occur without compromising safety and to reduce damage to the extent possible, depending on a range of conditions that includes storm intensity, antecedent storage and soil moisture, and other determinants of flood severity.

Guidance for System operation is provided for all months of the year. The concept is to achieve a desired System storage on March 1 of 56.8 MAF, which is equivalent to each reservoir at the base of its Annual Flood Control and Multiple Use Zone (7-04.6). The 2011 operations achieved this for the most part, although by March 1 snowmelt runoff had filled the storage to the 57.6 MAF level. Then, the Annual Flood Control and Multiple Use Zone will be allowed to fill through the flood season at a rate and volume determined by hydrologic conditions. The goal here is to meet the objectives of the Current Water Control Plan for all purposes (7-04.6.1). It should be emphasized that the Manual requires that judgment and experience are required to assess current and anticipated hydrologic conditions to enable operators to respond to unforeseen conditions.

When flood storage has been used, the method to evacuate flood storage during downstream flood episodes relies on the "service level" and "target flow" concepts (7-04.12). Selecting the service level for flood storage evacuation above the full-service level requires analysis of anticipated runoff, depletions, storage in the System and major tributary reservoirs, and evaporation (7-04.13).
The governing control for System storage during the year is Plate VI-1 from the Manual, shown in figure 26 (see 7-04.13.4).

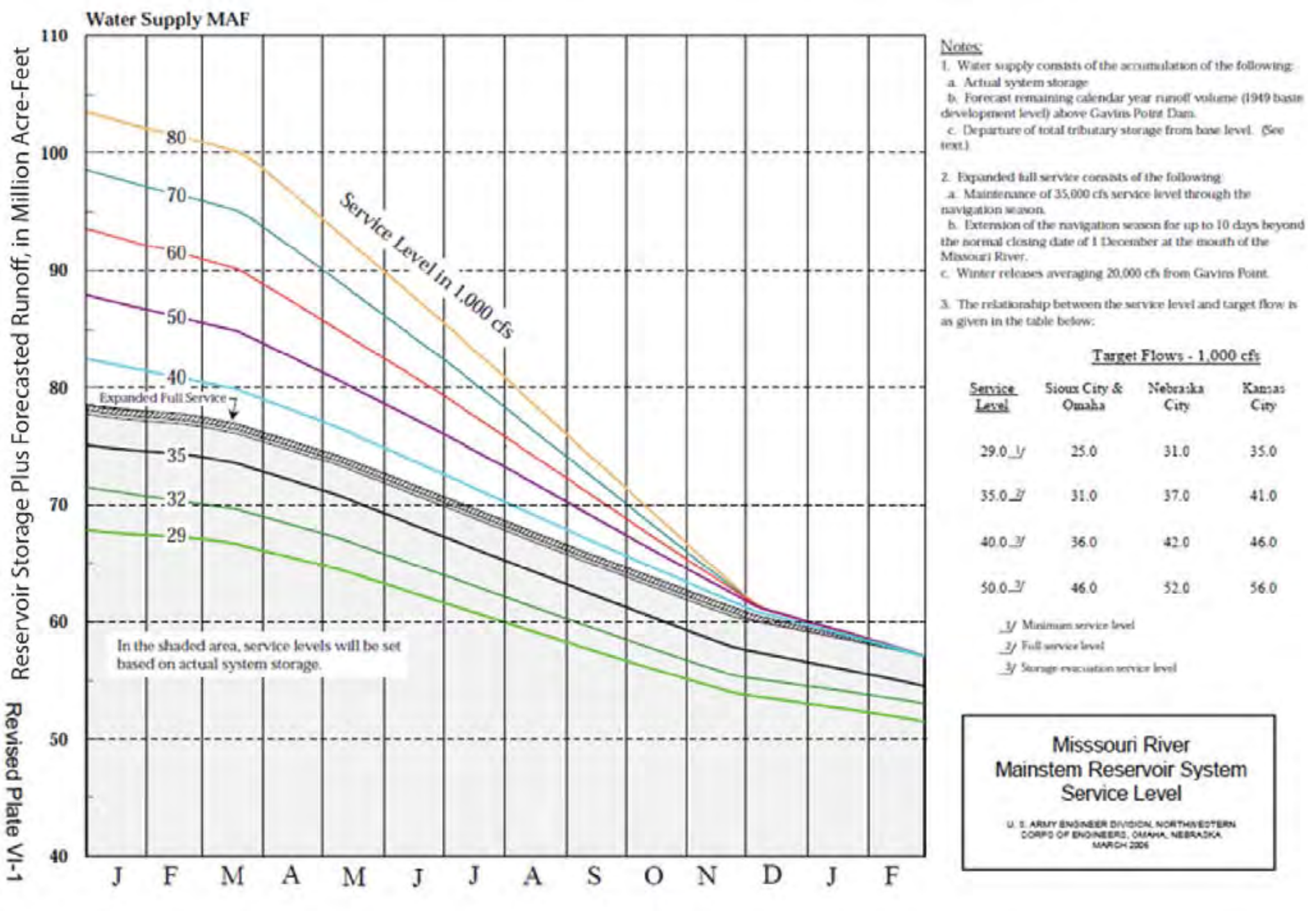

Figure 26. Missouri River mainstem reservoir system service level (cfs refers to cubic feet per second)

Plate VI-1 is used to determine the service level for flood control evacuation (see 7-04.13.4). The concept is to schedule releases to result in the evacuation of the System to the base of the Annual Flood Control and Multiple Use Zone by March 1. Use of the graph is complex, but it can be explained this way. The excess or deficiency of current tributary storage is computed and then added to or subtracted from the System storage. The result is added to forecasted remaining annual runoff into the System to obtain the current water supply value, which is the vertical axis on the graph.

This water supply value is projected horizontally over to the current date to determine the service level. For example, say the total water supply is 80 MAF on July 1. This might occur from (as an example) 60 MAF in storage, +3 MAF in tributary excess storage, and 17 MAF projected runoff for the rest of the year. The service level would then be read from the graph as about 62,000 ft^3/s. This would be in the "full service" range. A safety factor in favor of flood control is provided by a provision for limitation of service level prior to July 1 (see 7-04.13.4). As is evident from Plate VI-1, computed service levels such as those that occurred in 2011 are off the scale and the Plate could not be used to guide releases..

The 35,000 ft^3/s service level is considered as a "full-service level" to meet all eight System purposes. If this level is increased for flood storage evacuation, it is designated as an “expanded full-service level” and enables the extension of the navigation season.

The System service level is coordinated with target flows at Omaha, Nebraska City, and Kansas City. Values are presented in Table VII-7 to reduce target flows when the anticipated downstream flows exceed the current service level flow values by indicated amounts.

Does the Master Manual adequately address reservoir operations during extreme flood events?

It is the opinion of the panel that the Manual does adequately address reservoir operations during extreme events, but with some reservations.

The panel’s first reservation is that the definition of "extreme events" is vague in the Manual, and the unprecedented size of the 2011 runoff event mandates a revisit to the Manual's guidance about how to handle such an event. The Manual is based on statistical analyses of hydrologic events and on studies of how the actual 1881 flood could be handled by the System. As explained elsewhere in this report, behavior of the System is difficult to analyze or predict during such large-scale flood events, and the panel believes that either the Manual should be revised to take into account the 2011 experience or supplemental guidance should be issued.

The panel’s second reservation is that more definite procedures to respond to emergency scenarios may be required in the Manual. The Manual leaves a large degree of discretion to the MRBWM and the Division and District Commanders to decide on reservoir operations during flood events, and this is appropriate, given that many different scenarios may occur. However, the probable consequences of an event such as in 2011 or a larger event are of such magnitude that emergency drills might help the Corps prepare to include a range of technical resources, as well as normal emergency response forces. The idea here is to recognize that it may not be possible to anticipate and prepare for all scenarios in the Manual but procedures can be included to involve the best minds and resources to decide what to do when extreme events do occur. For example, more definite explanations might be included of the roles of the Division versus District and project offices, how the NWS would be engaged in forecasting, communications with USBR, how the capabilities of the USGS would be used to document current streamflow conditions, and coordination with emergency management agencies for the dissemination of flood warning information.

Does Master Manual Plate VI-1 adequately address the hydrologic conditions like those experienced this year?

Question 10 includes this query: "Does Plate VI-1 adequately address the hydrologic conditions like those experienced this year?" Plate VI-1 relates a concept of "service level" to total water volume and time of year. It provides a guide for System releases to meet project purposes and downstream flow targets under different conditions of total System and tributary storage and anticipated additional runoff. The Manual's explanation is: "Quantitatively, this service level approximates the water volume necessary to achieve a normal 8-month navigation season with average downstream tributary flow contributions" (7-03.2).

The concept of service level applies to flood water evacuation as well. It aims to do this by establishing service levels greater than 35,000 ft^3/s, which is the "full service level" that will meet all System purposes. Plate VI-1 has been prepared to provide the guidance over the full range of flow conditions to be expected.

Section 7-04.13.4. (Determining the Service Level for Flood Control Evacuation) explains the use of Plate VI-1 for flood water evacuation. It identifies the releases that will evacuate the System storage to the base of the Annual Flood Control and Multiple Use Zone by March 1, providing that scheduled winter releases can be maintained.

While Plate VI-1 provides guidance, the Manual also specifies additional measures for flood response to enable System operators to respond in a timely manner. For example, (see 6-02.3.1.) the Manual notes that "the sooner a significant flood event can be recognized and the appropriate pre-release of flows scheduled, an improvement in overall flood control can be achieved" (referring mostly to snowpack runoff) and that "System storage … from significant rainfall events must be evacuated following the event and as downstream conditions permit…" Another statement is "Also critical is the quick response in scheduling System release changes. This makes the small amount of flood control storage available in Fort Randall important as it is used to absorb these changes for a short period of time. Thus, the System has an effective regulation plan to optimize downstream flood control, which is one of the authorized project purposes. Flood control carries the highest priority during significant runoff events that pose a threat to human health and safety …"

As an example of how this works, consider the critical date of June 1, 2011. At the time, System storage was 70.4 MAF, anticipated additional runoff above Gavins Point was 23.4 MAF, and the adjustment for tributary storage was -0.8 MAF. This results in a total "Water Supply" to enter Plate VI-1 of 93.0 MAF and would indicate a service level above the highest curve of about 83,000 ft^3/s. This indicates that when total water supply is that high at that time of the year, it is out of the range of the indicated service level curves on the Plate.

The provisions of Section 7-03 guide the MRBWM in determining releases during normal and flood periods. When flooding is experienced, it specifies that "The above sequence (a normal sequence of flow determination) is altered slightly if the System water supply is above normal or if the System is performing a major flood control action. In that case, the service level is determined as often as required (Plate VI-1) based on actual System storage and forecasted water supply so that the System release rate can be scheduled to minimize downstream flood risk and reduce flood damages." This would be the case when the storage is filling up with snowmelt runoff and there is a need for more frequent updating of release plans. However, when sudden increases occur such as during late May 2011, the Plate cannot be used on a routine basis.

In all cases, releases from Gavins Point are modified to consider the relationships among service levels and target flows at the four locations (Sioux City, Omaha, Nebraska City, and Kansas City are shown on Table VII-1).

During 2011, as the remaining year runoff forecast increased toward 60 MAF, the indicated service level would have been rising rapidly to a point above the service level curves on Plate VI-1 and the System would have been beyond the range that was envisioned for the use of the graph. When this occurred, the System operators would turn to the use of models and direct computations to make decisions about releases.

The panel's conclusion is that Plate VI-1 is effective during periods with the magnitudes of flood runoff in the ranges that occur frequently but it does not apply directly during periods of extraordinary flooding. Because the graph includes both anticipated runoff and System storage, the main situation where it does not apply well appears to be when both storage and runoff are high, which was the case in 2011.

The Manual envisions situations such as this. For example, the Manual states (7-04.27.1.): "During extremely large foods that may use all of the flood control storage zone capacity provided in any of the individual System projects, regulation will primarily be based on conditions affecting that particular project rather than the System as a whole. Examples of regulation during this type of flood are, consequently, not included in this manual."

Another issue that limits the applicability of Plate VI-1 during extraordinary flood events is the need to work with downstream entities to plan flood releases to minimize damage, which is a different objective than those used to create Plate VI-1 (to organize the navigation season and evacuate storage by the next flood season).

In conclusion, Plate VI-1 did not address how to manage the system this year once the extreme flooding began. The combination of mainstem and tributary storage and forecasted inflow was unprecedented and gave no guidance for "service level" or "target flows." Also, Plate VI-1 does not address the schedule for drawdown.

Floodplain Development Along the Missouri River

This section of the report addresses question 12, "What role did floodplain development play in the operation of the reservoir system prior to and during the event?" In operating a system of reservoirs for flood control, decisions normally take into account the capacity and vulnerability of the downstream river segments. This goal is inherent in the guidance provided in the Manual. This section describes the extent to which floodplain development in the segments downstream of the mainstem reservoirs affected or did not affect flood control operations.

In the context of this report, floodplain development means the installation of structures or land use changes and associated facilities in flood-prone areas along the mainstem of the Missouri River. These flood-prone areas are generally known as floodplains and are mapped under the U.S. floodplain management program, which is under the National Flood Insurance Program (Federal Emergency Management Agency, 2011). The FEMA mapping program has produced floodplain maps for the U.S., and they can be purchased from the agency's mapping provider. Many other resources are available to identify floodplain areas. For example, the state of South Dakota created a website with mapping features called "disasterrecovery.sd.gov" and it has mapping to show flood limits at selected discharges, with the goal to advise residents about flood fighting and recovery. The Corps issued flood plain maps below reservoirs to show the probable extent of flooding (see news release at: *http://www.nwd.usace.army.mil/pa/news/shownews.asp?rn=NR053011d*).

Land use management and regulation of development within designated floodplain areas is the responsibility of state and local governments and in general no single information resource is available to identify the full extent of floodplain development. However, the Master Manual identifies areas of concern that were evident when it was prepared. These are:

Fort Peck Dam to Lake Sakakawea	Most floodplain consists of croplands, pastures, and hayfields.
Garrison Dam to Oahe	Floodplain development has occurred in the Bismarck and Mandan areas. Expensive homes in the bottomlands are subject to flooding. Floodplain construction during the past 25 years is of concern.
Oahe Dam to Lake Sharpe	Urban flooding in the Pierre-Fort Pierre area has been a recurring problem since 1979.
Fort Randall Dam to Lewis and Clark Lake	The reach contains about 2,200 acres of agricultural land and 62 residential buildings subject to flooding.
Gavins Point Dam to Sioux City	The reach contains approximately 1,900 acres of agricultural land and some 4,000 buildings subject to flooding.
Sioux City, Iowa to Omaha	During recent years, there has been considerable encroachment on the channel. Boat docks have been constructed and low areas are now cropped. The reach contains about 415,000 acres of agricultural land and about 18,500 buildings subject to flooding.
Omaha to Kansas City	The reach contains about 360,000 acres of agricultural land and about 2,650 buildings subject to flooding.
Kansas City to Mouth of Missouri River	The reach contains about 472,000 acres of agricultural land and about 4,800 buildings subject to flooding.

These parts of the Manual show that the Corps has been continually aware of floodplain development, which proceeds incrementally with time. During the visits, the panel members noted many instances where residents expressed frustration that they were not protected by the dams or did not have enough advance information or warning to enable them to buy flood insurance on a timely basis. It seemed to the panel that in cases like this, their overall long-term risk was unknown to them. This would not be an operational issue specific to the 2011 flood but would be an issue of overall risk assessment by the Corps and related flood agencies, especially FEMA and the National Flood Insurance

Program. It would also involve local and state agencies, who sponsor flood maps and communicate with residents about hazards.

There are many specific examples of floodplain developments with great significance. For example, the Fort Calhoun nuclear facility, operated by the Omaha Public Power District, was completed in 1979. During the flood, the facility was like an island when a temporary dam burst and water filled in around the plant to a depth of more than 2 ft. The threats to the facility were serious enough to draw a visit by the head and staff of the Nuclear Regulatory Agency and congressional representatives (Gaarder and Womack, 2011). Fortunately, no nuclear emergency occurred as a result of the flooding.

Use of target flows and service levels

To address the specific instances of floodplain development and how it factored into reservoir operational decisions, the panel considered that it includes all types of land uses, such as residential and commercial structures, industries, utilities, and farm operations. At the detailed level, there are so many vulnerable locations and properties that the Corps could not consider them all individually, but the panel noted that the concept of the downstream flow targets on which the Manual is based recognizes floodplain development.

In fact, part of Question 10 directed to the panel includes this query: "Do the downstream flood control constraints adequately balance flood risk in the upper and lower basins?" MRBWM staff clarified that this refers to the downstream flood targets at Omaha, Nebraska City and Kansas City referred to in the Manual, Section 7-04.16 and Table VII-7. The flow targets described in this section of the Manual refer to full service conditions and the situation where “large amounts of tributary inflow are forecasted between Gavins Point Dam and the downstream flow target control points.” This is the basic way that the regulation decisions consider floodplain development and related flow constraints.

Section 7-04.15 explains the general approach to the target flows, which is that the difference between service level and target flows at downstream control points will be the same for flood evacuation as for normal releases. System releases should be adjusted to sustain the full-service level but not exceed flow constraints at these downstream control points. The reasoning is that it is necessary to take into account changes in flow due to tributary inflows, losses, and other hydrologic changes.

This is clarified in (6-02.4), which states: "**…** the System is regulated based, primarily, on discharge or flow with downstream flow targets for both flood control and other multi-purpose regulation." Further clarification in (6-03.2.2) states: "The scheduling of releases … throughout the open-water season is based on maintaining prescribed flows at downstream control points on the Missouri River referred to as “target locations” at: Sioux City, Iowa; Omaha, Nebraska; Nebraska City, Nebraska; and Kansas City, Missouri." Also, "The proper scheduling of System releases requires… accurate forecasts of the inflows…."

Table VII-1 from the Manual presents the relations of target discharges to service level:

Relation of Target Discharges to Service Level

Control Point Location	Flow Target Discharge Deviation from Service Level
Sioux City	- 4,000 ft^3/s
Omaha	- 4,000 ft^3/s
Nebraska City	+ 2,000 ft^3/s
Kansas City	+ 6,000 ft^3/s

Section 7-03.2.1 explains that a full-service level of 35,000 ft^3/s results in target discharges of 31,000 ft^3/s at Sioux City and Omaha, 37,000 ft^3/s at Nebraska City and 41,000 ft^3/s at Kansas City. Also, a minimum service level of 29,000 ft^3/s indicates target values of 6,000 ft^3/s less than the full-service levels. Sections 7-04.12.1 and 1.2 explain that the minimum open-water level to sustain the navigation purpose is 29,000 ft^3/s, and that for the full-service level 35,000 ft^3/s is required.

As an example (see Section 7-04.15), a 40,000 ft^3/s service level might indicate a target flow of 42,000 ft^3/s at Nebraska City. This might be controlling if Sioux City, Omaha, and Kansas City had forecasted flows greater than their targets of 36,000, 36,000, and 46,000 ft^3/s.

This section also states: "When target flows at the non-controlling locations approach critical levels from a flood damage standpoint, the service level-target flow concept is modified to emphasize System regulation for downstream flood control instead of navigation support or System storage evacuation."

Section 7-04.16 provides guidance for target flows at the full-service level. The section states: "As a flood control measure, the normal relationship between service levels and target flow levels may be modified when large amounts of tributary inflow are forecasted between Gavins Point Dam and the downstream flow target control points."

Criteria for the modifications are presented in Table VII-7 from the Manual.

Criteria for Modifying Target Flows – Full Service

Target flows will be reduced to those consistent with the full-service level of 35,000 ft^3/s when one or more of the anticipated downstream flows exceed the current service level flow values by more than:	
6,000 ft^3/s at Omaha	Target flow plus 10,000 ft^3/s
12,000 ft^3/s at Nebraska City	Target flow plus 10,000 ft^3/s
36,000 ft^3/s at Kansas City	Target flow plus 30,000 ft^3/s

As an example, for a full-service level of 40,000 ft^3/s, System releases would be reduced if it was necessary to maintain flows at or below 46,000 ft^3/s at Omaha. This is computed as 40,000 ft^3/s (service level) + 6,000 (Table VII-7). The note that says "target flow plus 10,000 ft^3/s " refers to the target flow in Table VII-1 (-4,000) + 10,000 that has been established as the limit for the downstream control point at Omaha.

This section also allows to modify the target flows by up to 5,000 ft^3/s due to antecedent, current, and projected hydrometeorological conditions. The section also envisions situations where during "conditions during large runoff years similar to 1997" …"the above criteria must be replaced with a System regulation approach that will result in the best flood control for the lower river."

This provides the possibility that "The progressive increase in System releases must be evaluated against the approach of taking some small flood risk over a longer period of time and providing a slightly higher System release initially."

Returning to the basic question, "Do the downstream flood control constraints adequately balance flood risk in the upper and lower basins?"

The downstream flow constraints refer to the flow targets that are featured prominently throughout the Manual as a way to guide releases from Gavins Point for various service levels while coming close to the required flows at the downstream locations and avoiding flood damage.

The guidance for flow targets (Table VII-1 for basic operations and Table VII-7 for full-service when large inflows are expected below Gavins Point) recognizes the range of conditions from minimum to full-service and higher, as well as conditions when large inflows are expected below Gavins Point. The guidance is based on analysis and experience with actual channel conditions, and it recognizes the multiple purposes of reservoir regulation. The panel believes that the Manual is adequate to handle most levels of flooding, but it does not offer adequate guidance needed for large, extraordinary floods such as 2011.

The Manual considers the circumstances when the target flow approach will not work adequately. For example, Section 7-04.16 allows the MRBWM to change the approach during "conditions during large runoff years similar to 1997" when "…the above criteria (target flows) must be replaced with a System regulation approach that will result in the best flood control for the lower river."

The adherence to these guidelines can be seen in the Corps tracking of downstream conditions as they developed. This is evident from the Corps' summary of decisions and the timelines. It shows that by March 15 the Corps was following the observed flows, which were at that time: Sioux City, 29,000 ft^3/s; Omaha, 34,000 ft^3/s; Nebraska City, 44,000 ft^3/s; and Kansas City, 55,000 ft^3/s. The Corps continued to track these conditions, indicating awareness of flow constraints, until the need for releases to protect the infrastructure and maintain capacity for possible additional flooding overwhelmed the service level approach.

In conclusion related to Question 10, the Manual approach seems adequate, provided it is fully recognized that the target flow approach must give way to an approach to achieve "the best flood control for the lower river" (7-04.16).

Conclusions to discussion of floodplain development

The answer to Question 12 ("What role did floodplain development play in the operation of the reservoir system prior to and during the event?") has several parts. The first part is to note that prior to the event, the Corps was following the Manual and using the service level approach. This procedure embodies several complex issues into a few simple rules that enable the System operators to balance across the eight purposes while protecting downstream areas and preparing for flood events. So, prior to the event the System operators were following the Manual, which provides for downstream protection.

During the period when the flood levels were increasing rapidly, there were episodes where the Corps took certain actions to protect downstream entities, such as in the March 15–28 period when Garrison releases were reduced from 26,000 ft^3/s to 15,000 ft^3/s to provide channel capacity for plains snowmelt. In those periods they were not always certain what would happen next, and decisions were being made on a case-by-case basis, which was appropriate.

Later, when peak inflows were being experienced and releases had to be increased even more, the System operators made short-term decisions to delay the increase in releases so as to enable levee construction to be completed. However, when flows became so large the priority shifted to emergency flood control for dam safety and the goal of maintaining some capacity for the eventuality that much larger flows would be experienced. In this emergency situation, the Corps considered floodplain developments but took the emergency actions that were required in their judgment.

Effects of Missouri River System Releases and Flooding on the Lower Missouri and Mississippi Rivers

The Master Manual (section 7-04.18) provides guidelines for coordination and management of Missouri River Mainstem Reservoir System releases during downstream flooding on the lower Missouri and Mississippi Rivers. At Kansas City, the farthest downstream control point used for scheduling System releases, control of streamflow is also provided by tributary reservoirs located in the Kansas River basin. According to the Master Manual section 7-04.19: *"If System release reductions will not result in missing flow targets and hydrologic forecasts indicate that System release reductions will result in flood damage reductions below Kansas City, a reduction in System releases will be scheduled. This should not be attempted if it will significantly impact System or tributary reservoir flood storage evacuation."* In other words, reduction of System releases to help alleviate flood conditions on the lower Missouri River are permitted, unless such releases would hinder System flood storage evacuation.

Regarding System operation to reduce flood-damage on the Mississippi River, according to the Master Manual, section 7-04.19, "*Requests for coordinated flood storage evacuation from the System due to flooding on the Mississippi River have occurred in the past.*" **and**, " *If System regulation changes can be accomplished without significant adverse affects, they should be attempted.*"

In the case of the 2011 flooding, internal Corps emails during late April (Kevin Grode, U.S. Army Corps of Engineers, written commun., 2011) indicate that some consideration of management of releases to help downstream flooding, on both the lower Missouri and Mississippi, was weighed against the need to evacuate Missouri River mainstem System flood storage. During April 29–May 6, releases at Gavins Point were held at 45,000 ft^3/s. During May 7–13, releases were incrementally increased to 56,000 ft^3/s. A concern that has been raised about the April 29–May 6 level of release (Kevin Grode, U.S. Army Corps of Engineers, written commun., 2011) is that increased releases during this period would have provided more System storage and thus would have prevented some flood damage on Missouri River reaches. The Corps responded that even if System releases had been raised to 56,000 ft^3/s during April 29–May 6, the additional System storage available later when releases had to be increased to the 160,000 ft^3/s level would only have accounted for a reduction of peak releases for about 14 hours out of the 65 days of releases at 160,000 ft^3/s (Kevin Grode, U.S. Army Corps of Engineers, written commun., 2011).

System Operation Considerations Regarding Threatened and Endangered Species During the 2011 Flood

In addition to the congressionally authorized System purposes of flood control, navigation, hydropower, water supply, water quality, irrigation, recreation, and fish and wildlife, the Endangered Species Act of 1973 (Public Law 93-205, as amended in Public Laws 95-632, 96-159 and 97-304) (U.S. Senate Committee on Environment and Public Works, 2002) states that the policy of Congress is for all Federal departments and agencies to seek to conserve endangered and threatened species and to utilize their authorities in furtherance of the purposes of the Act. The purposes of the Act are to provide a means whereby the ecosystems upon which endangered and threatened species depend may be conserved and to provide a program for the conservation of such endangered and threatened species. Section 7 of the Act states that all Federal departments and agencies shall, in consultation with and with the assistance of the Secretary of the Interior, ensure that any actions authorized, funded, or carried out by them are not likely to jeopardize the continued existence of any endangered or threatened species or result in the destruction or adverse modification of habitat determined by the Secretary of Interior to be critical unless an exception has been granted by the Endangered Species Committee. The U.S. Fish and Wildlife Service (USFWS) of the Department of Interior administers consultation procedures. The System has both threatened and endangered species and has, therefore, operated for the continued existence of these species in coordination with the USFWS.

System Regulation for Endangered and Threatened Species—Terns and Plovers

While the Missouri River provides habitat for a wide variety of wildlife species, the endangered least tern and threatened piping plover are of particular importance. They depend on unvegetated sandbars and islands in the river for nesting and are directly affected by water-level changes. These birds typically nest in colonies on river sandbars, sandy shorelines of reservoirs, or in sandpits along the river. Important nesting reaches are below Fort Peck, Garrison, Fort Randall, and Gavins Point Dams, and on Oahe and Garrison reservoirs. River hydrology and channel characteristics influence the composition and distribution of tern and plover habitat along the river. Seasonal river flow and water-level patterns dictate the frequency and duration of habitat flooding and the scouring of sandbar vegetation. Bank erosion and sediment movement in the riverbed also affect the creation and removal of sandbar and island habitat. Declining reservoir levels result in exposed bare shoreline increasing nesting habitat. Specific System regulation criteria used in the past for endangered species nesting is discussed in the Master Manual (chapter VII, paragraphs 7–10).

The 2010–11 AOP (section V, part F) provides a more specific plan for the management of System operations during 2011 in support of tern and plover nesting habitat. An excerpt from section V, part F is included below:

Based on 2003 through 2009 nesting season results with the Steady Release – Flow to Target (SR-FTT) regulation (Master Manual, section 7-10.3.4) *and planned habitat development activities, it is anticipated that sufficient habitat will be available above the planned release rates for Median or below runoff to provide for successful nesting. All reasonable measures to minimize the loss of nesting threatened and endangered bird species will be used. These measures include, but are not limited to, such things as a relatively high initial steady release during the peak of nest initiation, the use of the Kansas River basin reservoirs, moving nests to higher ground when possible, and monitoring nest fledge dates to determine if delaying an increase a few days might allow threatened chicks to fledge. The location of navigation tows and river conditions at intakes would also be monitored to determine if an increase could be temporarily delayed without impact. Cycling releases every third day may be used to conserve water early in the nesting season if extremely dry conditions develop. In addition, cycling may be used during downstream flood control regulation. It is anticipated that for Upper Decile and Upper Quartile runoff scenarios a Steady Release scenario will be implemented due to the need to evacuate flood water. A SR-FTT release scenario will be implemented for Median and below runoff scenarios. A full description of these two release scenarios can be found in the Master Manual.*

The Gavins Point pool will be regulated near 1206.0 feet msl in the spring and early summer, with minor day-to-day variations due to inflows resulting from rainfall runoff. Several factors can limit the ability to protect nests from inundation in the upper end of the Gavins Point pool. First, because there are greater numbers of threatened and endangered bird species nesting below the Gavins Point project, regulation to minimize incidental take usually involves restricting Gavins Point releases, which means that the Gavins Point pool can fluctuate significantly due to increased runoff from rainfall events. Second, rainfall runoff between Fort Randall Dam and Gavins Point Dam can result in relatively rapid pool rises because the Gavins Point project has a smaller storage capacity than the other System reservoirs. And third, the regulation of Gavins Point for downstream flood control may necessitate immediate release reductions to reduce downstream damage. When combined, all these factors make it difficult and sometimes impossible to prevent inundation of nests in the upper end of the Gavins Point reservoir. The pool will be increased to elevation 1207.5 feet msl when it is determined that there are no terns or plovers nesting along the reservoir."

On April 25 the Corps notified the USFWS that flow management operations in support of tern and piper nesting habitat were suspended because of high runoff conditions and the need to evacuate flood-control storage.

System Regulation for Endangered and Threatened Species—Pallid Sturgeon

A native Missouri River fish of primary concern is the endangered pallid sturgeon. The historic range of the pallid sturgeon encompassed the middle and Lower Mississippi River, the Missouri River, and the lower reaches of the Platte, Kansas, and Yellowstone Rivers. Because the pallid sturgeon was not recognized as a distinct species until 1905, little is known about its abundance and distribution prior to this date. They have always been uncommon. Hybrids of the shovelnose and pallid sturgeon have been collected and may be common in the lower Missouri River. Some surveys suggest a probable decline in the abundance of pallid sturgeon from former levels. According to the Pallid Sturgeon Recovery Plan (U.S. Fish and Wildlife Service, 1993), modification of the natural hydrograph, habitat loss, migration blockage, pollution, hybridization, and over harvesting are possibly all responsible for this decline (Master Manual, section D-02.2.4.).

In 2003, the USFWS issued an Amended Biological Opinion (2003 Opinion) (U.S. Fish and Wildlife Service, 2003) on the Corps Missouri River System operations. Among other actions, the 2003 Opinion called for bimodal spring pulse releases from Gavins Point Dam for the benefit of the listed pallid sturgeon. Working with the USFWS, Tribes, states, and other basin stakeholders, the Corps has developed technical criteria for the bimodal spring pulse releases which, under the terms of the 2003 Opinion, were to be implemented by March 2006. Details of the somewhat extensive release plan are described in greater detail in the Master Manual (sections I-03.2 and I-03.3).

The 2010–11 AOP (table III) included plans for the bimodal (March and May) spring pulse releases to benefit the pallid sturgeon. As of March 1, 2011 System storage was at 57.6 MAF, above the 56.8 MAF target level for base of flood-control storage and satisfying the criteria for implementation of the March spring pulse. However, on March 28 the Corps announced the cancellation of the March spring pulse because of high flows on the James and Missouri Rivers. On April 6 the Corps announced that the May spring pulse also would be cancelled because of excessive runoff conditions.

The review of the System conditions and management (storage and releases) as well as guidelines for management operations related to support of threatened and endangered species indicate that decisions related to storage and evacuation of spring runoff were not influenced or affected by consideration of threatened or endangered species. In fact, as the potential for large runoff volumes became evident in March and April, operational considerations for threatened and endangered species became somewhat irrelevant (because of high runoff conditions), even before the heavy rains (and greatly increased concern for flood-control operations) in May.

Effects of Project Infrastructure Conditions on System Regulation

The issue of project infrastructure components and their condition was added by the panel to the original list of questions as a result of meetings held at the Omaha offices of the Corps' Northwestern Region on October 4-6, 2011. It was clear that the condition and operating status of spillways, gates, and storage structures were factors in operating decisions. This added question is: "Was the condition of the project infrastructure a factor in operation of the system reservoirs?"

As is evident from the extent of flooding in 2011 and the massive nature of Missouri River basin projects, it is clear that maintaining the system infrastructure is a critical requirement in flood risk preparedness. This section of the report identifies the main system facilities and presents brief information about their condition and performance. The conclusion of the section is an answer to the question of the extent to which the condition of project infrastructure was a factor in operation and/or flood damages.

Mainstem Reservoirs

Information about the Missouri mainstem dams and reservoirs is available in the Master Manual and from other Corps publications, and the table below provides brief information (summarized from the Manual Chapter 2) as it relates to their operation during flood events.

	Closure	**Flood control data and experience in Chapter 2**
Fort Peck Dam	1937	Exclusive flood control zone (EFCZ) storage space was first used in 1969, and then again in 1970, 1975, 1976, 1979, 1996, and 1997. In 1975, a maximum level of 2251.6 ft mean sea level (msl), 1.6 ft above the top of the EFCZ, occurred.
Garrison Dam	1953	EFCZ storage space was used in 1969, 1975, 1995 and 1997. During 1975, all flood control space was filled and the maximum reservoir level was 0.8 ft above the top of the EFCZ, elevation 1854.8 ft msl.
Oahe Dam	1958	The EFCZ was used in 1975, 1984, 1986, 1995, 1996, 1997, and 1999. The maximum elevation was on June 25, 1995, at 1618.71 ft msl, when the pool occupied 1.7 ft of the 3-ft EFCZ.
Big Bend Dam	1963	Run-of-the-river reservoir. A maximum level at elevation 1422.1 ft, was 0.1 ft into the EFCZ, occurred in June 1991.
Fort Randall Dam	1952	The maximum level to date was in July 1997, when 1372.2 ft occurred, 2.6 ft below the top of the EFCZ. The maximum mean daily release of 67,500 ft^3/s occurred in November 1997.
Gavins Point Dam	1955	Similar to Big Bend, Gavins Point is a run-of-the-river reservoir and provides little flood-control storage. During the 2011 flood, the reservoir reached a peak elevation 0.3 ft above the base EFCZ elevation of 1208.3 ft

Flood Control Infrastructure Facilities

Information in this section is summarized from the Master Manual (chapter 4) and from current information collected by the panel. The six mainstem reservoirs contain about 73.1 MAF of storage capacity. The six dams are regulated for the eight authorized purposes of flood control, navigation, hydropower, water supply, water quality, irrigation, recreation, and fish and wildlife. The reservoir operations manual explains operation of the flood control features of the system. Of particular concern to the panel was the condition of emergency and service spillways and tunnels, gate systems, operating controls, and geotechnical factors that might limit flood control use of facilities and surcharging.

Fort Peck Dam

The Fort Peck spillway is about 3 miles east of the dam. It has a crest elevation of 2225 ft msl and discharge capacity at the maximum operating pool elevation of 2250 ft msl is 230,000 ft^3/s. Past spillway discharges have affected the discharge channel, and there is concern about future sustained releases that might erode around the west wing wall or uplift the floor slabs.

Fort Peck has outlet works and flood control tunnels (#3 and #4), which were designed for emergency releases. Total capacity of these tunnels at 2250 ft msl is 45,000 ft^3/s. The tunnels have not been used in some years and should not be operated at rates above 5,000 ft^3/s per tunnel without an evaluation from the Corps Omaha District. Since 1975, supplemental releases above the power plant capacity were made over the spillway.

Referring to a 1996 Fort Peck spillway engineering reconnaissance study by R.W. Beck and Associates, a Corps Omaha District report (U.S. Army Corps of Engineers, 2000) summarized experience with damages to Fort Peck facilities and threats when high releases are sustained. There has been past damage to the spillway, tunnels and gates, and caution is advised in future operation during extreme flood events.

Garrison Dam

The spillway is along the left abutment and separated from the main embankment by about 800 ft. The crest is at an elevation of 1825 ft. The concrete discharge chute extends 2,600 ft downstream to the stilling basin. Discharge capacity at maximum operating pool (elevation 1854 ft) is 660,000 ft^3/s. An unlined pilot channel is designed to erode and guide flows to the Missouri River channel.

Garrison has eight tunnels with #6, #7, and #8 for flood control and with a combined discharge capacity of 98,000 ft^3/s at a pool elevation 1854 ft. These tunnels discharge into a stilling basin and a discharge channel extends to the Missouri River channel.

Oahe Dam

Oahe Dam has outlet works tunnels in the right abutment. The top of dam elevation is 1660 ft. The spillway is located about 1 mile from the right abutment of the dam with an unlined approach channel. The spillway crest elevation is 1596.5 ft. The spillway has never been used, even during 2011. An unlined discharge channel extends approximately 2 miles downstream. Spillway operating criteria are established to reduce unpaved discharge channel erosion rates. The discharge capacity of the spillway is 80,000 ft^3/s at maximum operating pool.

The outlet works include an approach channel and six tunnels, with supporting structures. The six flood control tunnels have a combined discharge capacity of 111,000 ft^3/s at a pool elevation 1620 ft. A discharge channel approximately 9,000 ft long returns flow to the Missouri River.

The panel asked whether the flood magnitude downstream could have been reduced if the Oahe spillway had been used during the flood. The Corps advised that they were reluctant to use the spillway due to safety and damage concerns. See the later section about surcharge and dam safety.

Big Bend Dam

Big Bend Dam has a spillway at the left abutment. The spillway is 376 ft wide and has a crest elevation at 10 ft above the bottom of the approach channel. The discharge capacity is 268,000 ft^3/s at a pool elevation 1,423 ft. Big Bend has no outlet works structures for flood control, and releases must be made through the power plant or the spillway.

Fort Randall Dam

Fort Randall Dam includes a spillway section near the left abutment. The top of dam elevation is 1395 ft. A large ravine and some unlined excavation form the approach channel. The spillway has a crest elevation of 1346 ft. A paved chute connects the spillway weir to the stilling basin. Discharge capacity at the maximum operating pool elevation, 1375 ft, is 508,000 ft^3/s.

The outlet works include eight tunnels for the powerplant and four tunnels (9 through 12) for supplemental releases. A fine regulating gate in Tunnel 10 failed in 1975 and was not replaced. Flood control tunnels 9 through 12 are 22 ft in diameter. The discharge capacity of the flood control tunnels is 128,000 ft^3/s.

Gavins Point Dam

Gavins Point Dam has an embankment crest at elevation 1234 ft. The spillway crest structure located with the embankment has a 560-ft-long concrete weir and a capacity of 345,000 ft^3/s at a maximum operating pool of 1,210 ft.

Missouri River Channel, Floodway, and Levees

The river system of concern extends from Fort Peck to the confluence with the Mississippi River at St. Louis. The highest flow that can pass through a reach without damage varies with channel capacity, degree of encroachment, and improvements such as levees and channel modifications. Other factors such as ice cover affect some reaches.

In the reach from Fort Peck Dam to Lake Sakakawea, flow is in an unchannelized river. There are many sandbars, islands, and side channels. Above Brockton, Montana (RM 1660), the floodplain is about 4 miles wide and is bordered by rolling grasslands, dry-land crops, and rangelands. Downstream, the floodplain narrows to a 1-mile-wide valley surrounded by badlands. Most of the floodplain in this reach consists of croplands, pastures, and hayfields.

Flood damages begin with open-water flows of 30,000 ft^3/s. For flows varying from 50,000 ft^3/s (upper reach) to 70,000 ft^3/s (lower reach), damages are relatively minor and limited mainly to pasture and other unimproved lands. Channel capacity is reduced when ice cover is present.

Below Garrison Dam to Oahe, the Missouri River passes through Bismarck and Mandan, North Dakota. The river has one main channel in this reach and few side channels, old channels, or oxbow lakes. Historical regulation shows that stages at Bismarck up to 13 ft do not cause significant flood damages. Prior to construction of Garrison Dam, this occurred at about 90,000 ft^3/s but by 1997 the channel had deteriorated to where 13 ft occurs at about 50,000 ft^3/s (Master Manual, section A-03.2). The primary cause for the loss in channel capacity is likely due to floodplain encroachment and possible aggradation of sediment material. Floodplain development has occurred in Bismarck and Mandan. Expensive homes in the bottomlands along the River are subject to flooding during winter as well as during releases greater than 60,000 ft^3/s from Garrison Dam. Floodplain development in the Bismarck area is of concern and damage in the floodplain is expected to be high during high releases.

From Oahe Dam to Lake Sharpe is a relatively short reach. Flooding in the Pierre-Fort Pierre area has been a recurring problem since 1979. High Oahe Dam releases and river ice caused water to flood street intersections. It is expected that the urban areas of Pierre and Fort Pierre will experience high potential damages from high Oahe Dam releases for flood storage evacuation.

The Fort Randall Dam to Lewis and Clark Lake reach is in an unchannelized river. Originally, this reach could pass flows of over 150,000 ft^3/s but now, Fort Randall releases of 35,000 ft^3/s result in flood problems.

The Gavins Point Dam to Sioux City reach has three sub reaches, the Missouri River National Recreational River, Kensler's Bend, and the Missouri River Navigation Channel. In 1997, flows of 70,000 ft^3/s in this reach caused no significant damage.

The Sioux City to Omaha reach had original channel capacities prior to construction of more than 100,000 ft^3/s. However, encroachment on the channel and other factors have reduced the capacity. Flows of 65,000 ft^3/s in 1975 and 70,000 ft^3/s in 1997 flooded cropland and interrupted access to some marinas.

The Omaha to Kansas City, Missouri reach indicates that flows above 90,000 ft^3/s will exceed flood stage at Nebraska City, Rulo, and St. Joseph.

From Kansas City to the mouth of the Missouri River flows of about 150,000 ft^3/s cause only relatively minor agricultural damages.

Many levees and river control structures are in place below Gavins Point. Damage to many levees with resulting flooding occurred during the flood.

Tributary Flood Control Reservoirs

A number of tributary reservoirs serve to control local floods and, to some extent, mainstem flows. Figure 27 shows these projects, as they are owned by the Corps, USBR, and other entities, including local water management organizations. The USBR reservoirs, which the Corps controls for flood operations during emergencies, are called Section 7 Reservoirs after the 1944 Flood Control Act. The Section 7 Reservoirs evaluated by the panel (under jurisdiction of the Corps Omaha District) are:

- Above Fort Peck: Clark, Canyon Ferry and Tiber
- Above Garrison: Boysen and Yellowtail
- Above Oahe: Shadehill, Pactola, Heart Butte and Keyhole
- Below Gavins Point: Glendo and Jamestown

In addition, another 11 Section 7 reservoirs are under jurisdiction of the Corps' Kansas City District. These are tributary to the Kansas River, which discharges into the Missouri River at Kansas City.

The Corps MRBWM does not control these during flooding, but it can direct them to provide navigation flow support from Tuttle Creek, Perry, and Milford during drought (Kevin Grode, U.S. Army Corps of Engineers, oral commun., 2011).

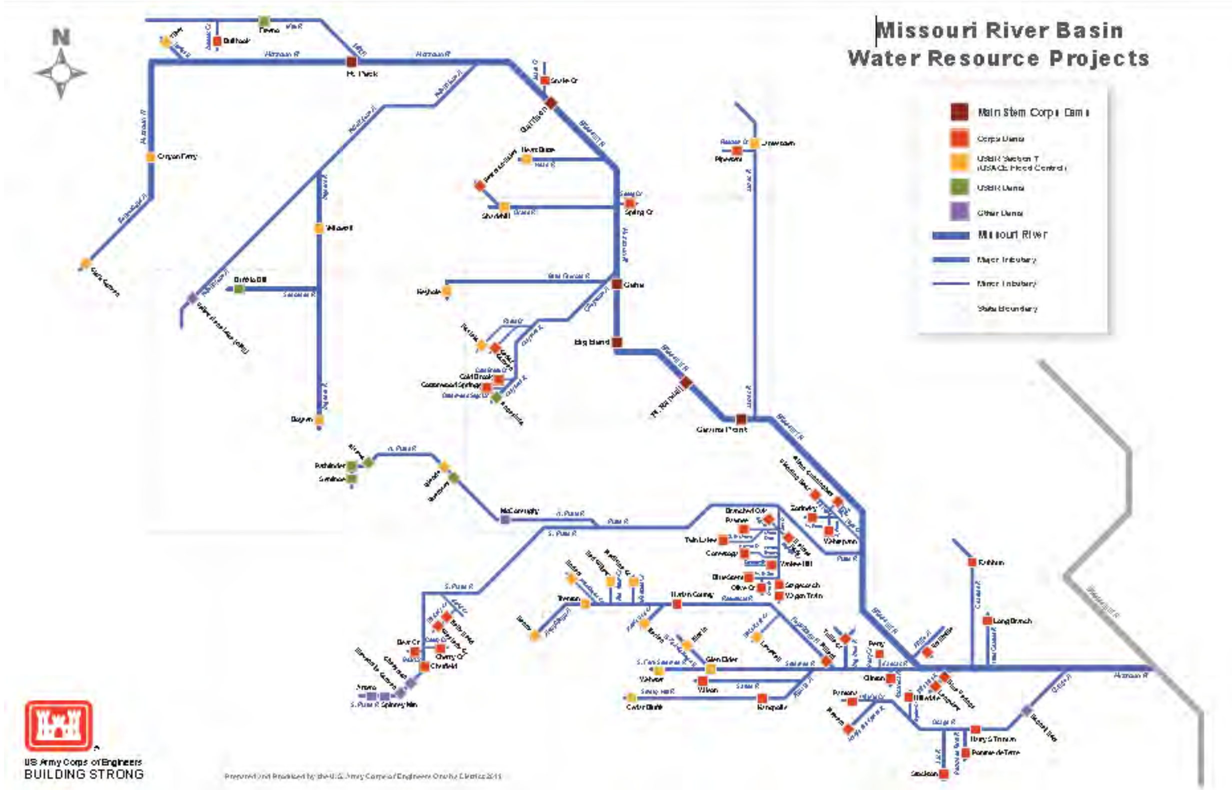

Figure 27. Missouri River Basin Water Resource Projects

Surcharge Storage and Dam Safety Factors

The panel evaluated the constraints placed on the Corps operations as a result of infrastructure condition and was briefed or learned about several important issues that affect operations. In an ideal sense it is easy to speculate that long-term use of the Exclusive Flood Control Zone and short-term use of all surcharge storage might have enabled the Corps to reduce peak flows and downstream damages, however, this view must be tempered by the reality of infrastructure condition and concerns about dam safety.

During its October meetings in Omaha, the panel was briefed by Northwestern Division Dam Safety Manager Laila Berre, who advised panel on a number of important issues, concerns and constraints. The major issues are risk of dam failure and constraints on use of emergency spillways and tunnels.

The Corps has had to maintain vigilance in monitoring dam conditions and assessing threats using boards of consultants and experts. Dam failure beginning at Fort Peck would cause a catastrophic disaster of unprecedented magnitude. It would probably lead to failure of downstream dams and cause heavy loss of life and property all the way into the Mississippi River system. Such a disaster cannot be risked, even if it means that the reservoir storages are not used to the maximum levels.

Constraints on use of emergency spillways and tunnels occur because of past damage, lack of funding for rehabilitation, and infrequent use and lack of experience with use of the facilities at extreme flows. For example, some emergency facilities, such as the Oahe spillway, have never been used. Consequently, it is not feasible for the dam operators to take storage levels to maximum surcharge quickly to manage a sudden event such as the one that occurred beginning in late May. It is also not feasible to leave the reservoirs in the EFCZ or in surcharge for very long because the dams are at greater risk of failure at those levels than at normal operating levels. Finally, it is important during extreme flood events to not lose the capability to capture future extreme runoff, such as that which might have occurred in June if additional heavy rains developed.

2011 Damage to Infrastructure

The general infrastructure challenges facing the Corps were described by Katie Schenk (U.S. Army Corps of Engineers, 2011c). These challenges include declining past and future budgets, aging infrastructure, increased regulations and requirements, and 2011 flood-related damages. She explained how the high releases at mainstem projects used spillways that had never been used before and created challenges due to the length of time on some structures. The projects performed as they were designed, but there were questions about what was hidden under the water and whether spillway repairs would be needed. Damage included the erosion at Fort Peck of a spillway plunge pool, collapse of concrete slabs downstream and along the right spillway of Fort Randall, flooded project offices (Missouri River Project Office in Nebraska), erosion behind flood tunnel stilling basin walls, downstream bank erosion and possible tunnel damage at Oahe, wingwall damage at Bend, spalls on spillway slab and possible flood tunnel damage at Garrison.

Conclusions on Flood Infrastructure Effects on 2011 Flood

The flood control infrastructure performed well during the 2011 event, but a good bit of damage occurred and will require timely repair to prepare for future events. Most facilities operated near their maximum capabilities and water levels at Fort Peck and Garrison entered the surcharge zone. The Exclusive Flood Control Zone storage at Oahe was utilized fully, but its reservoir did not enter the surcharge zone, to some extent due to infrastructure condition. After looking at all of the events, the panel judged that infrastructure condition did not materially affect the Corps' capability to manage the flood, but it is clear that infrastructure condition is a major issue of concern and will require concerted attention in the future. The answer to the question "Was the condition of the project infrastructure a factor in operation of the system reservoirs?" is as follows. Yes, infrastructure condition was a factor in operation of the reservoirs, and with such massive and high-risk structures it will always be a factor in such extreme events. It is imperative that the facilities be maintained at high levels of readiness and equally imperative that they be monitored and protected during the heat of operation while extreme events are in progress. The panel believes that the Corps did an impressive job of using the infrastructure and that the absence of major failures is evidence of that.

Effects of May Rainfall

The heavy rains in May 2011 were the main factor contributing to excessive inflows to the reservoir System and the need for the Corps to release record flows from the System reservoirs. To help illustrate the effects of the rainfall in May 2011, rainfall and runoff for the Yellowstone River basin are compared for the flood events of 1997 and 2011. Since 1898, the 1997 runoff was the previous highest annual total before 2011. The 1997 flood event, like the 2011 event, was centered upstream of the reservoir System. System-wide runoff volumes during March–April also were similar between the 1997 and 2011 events. Runoff was 15,860 acre-feet and 14,365 acre-feet in 1997 and 2011, respectively. The 1997 and 2011 March–April runoff volumes rank second and third greatest since 1898 (exceeded during the 1952 flood). Figure 28 shows rainfall and runoff during April–May during 1997 and 2011. Rainfall was measured at the NWS station at Miles City, Montana. Daily streamflow (runoff) was measured at the USGS streamgaging station on theYellowstone River at Sydney, Montana. The Sydney station measures runoff from about 68,400 square miles at a point upstream of the confluence with the Missouri River and downstream from Fort Peck Dam. These stations within the Yellowstone River basin were judged to generally represent rainfall and runoff conditions in the upper Missouri basin, upstream of Fort Peck, Garrison, and Oahe reservoirs, during the two flood events.

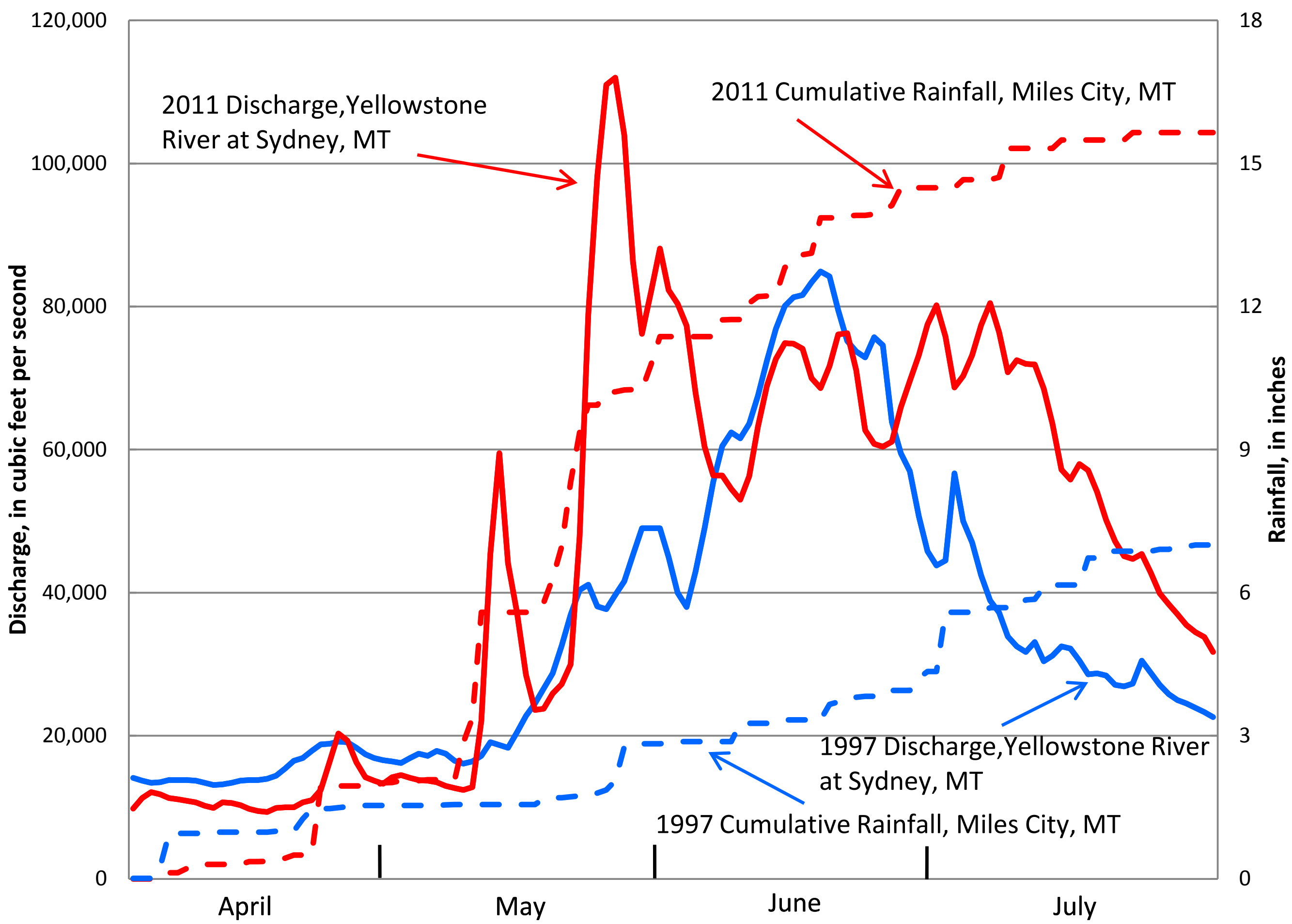

Figure 28. Comparison of 1997 and 2011 rainfall and runoff during April–July, Yellowstone River basin

Figure 28 shows that up to early May, runoff conditions during 1997 and 2011 were similar, with 1997 streamflow being slightly greater than in 2011. From May 7–10, 2011, about 3.5 inches of rain were recorded at Miles City. Daily mean streamflow at Sydney responded with an abrupt rise to about 60,000 ft^3/s on May 12. During May 18–22, 2011, additional heavy rain fell across the basin, registering 4.1 inches of rain at Miles City. Daily mean streamflow at Sydney rose to about 112,000 ft^3/s on May 25. The resulting May streamflow peak and volume in 2011 greatly exceeded those in 1997. Similar timing and volume of runoff across the upper Missouri basin in May resulted in rapid filling of available flood-control storage. Interestingly, Yellowstone River streamflows in mid June of 1997 and 2011 were similar, with the 1997 volume modestly greater. However, 1997 streamflow receded, beginning in late June, wheaeas during 2011, much greater runoff volumes were sustained through mid July before beginning to recede.

Alternative Storage and Release Scenarios

Questions asked by the panel also included: What flood-control storage would have been required on March 1 (or earlier) to control the flood? Or, what releases should have commenced on March 1 (or at other times) to control, or reduce damages caused by the flood? The Corps provided results of model simulations of two alternative storage and release scenarios to help answer these questions. Figure 29 shows actual releases from Gavins Point Dam compared with results of the alternative scenario simulations. The first scenario shows simulated releases if the System storage allocation (some combination of annual and exclusive flood control storage) provided an additional 4.6 million acre-ft of flood storage. The first scenario also simulates actual System monthly releases up to the time when Gavins Point releases were increased to 160,000 ft^3/s. However, for this scenario releases were limited to 100,000 ft^3/s. The 100,000 ft^3/s release rate had to be maintained through October to evacuate the flood storage by March 2012.

The second scenario assumed no additional flood-control storage and also simulated January through May releases at the maximum historical monthly rates. This scenario resulted in a peak discharge of 130,000 ft^3/s released from Gavins Point, compared with 160,000 ft^3/s .

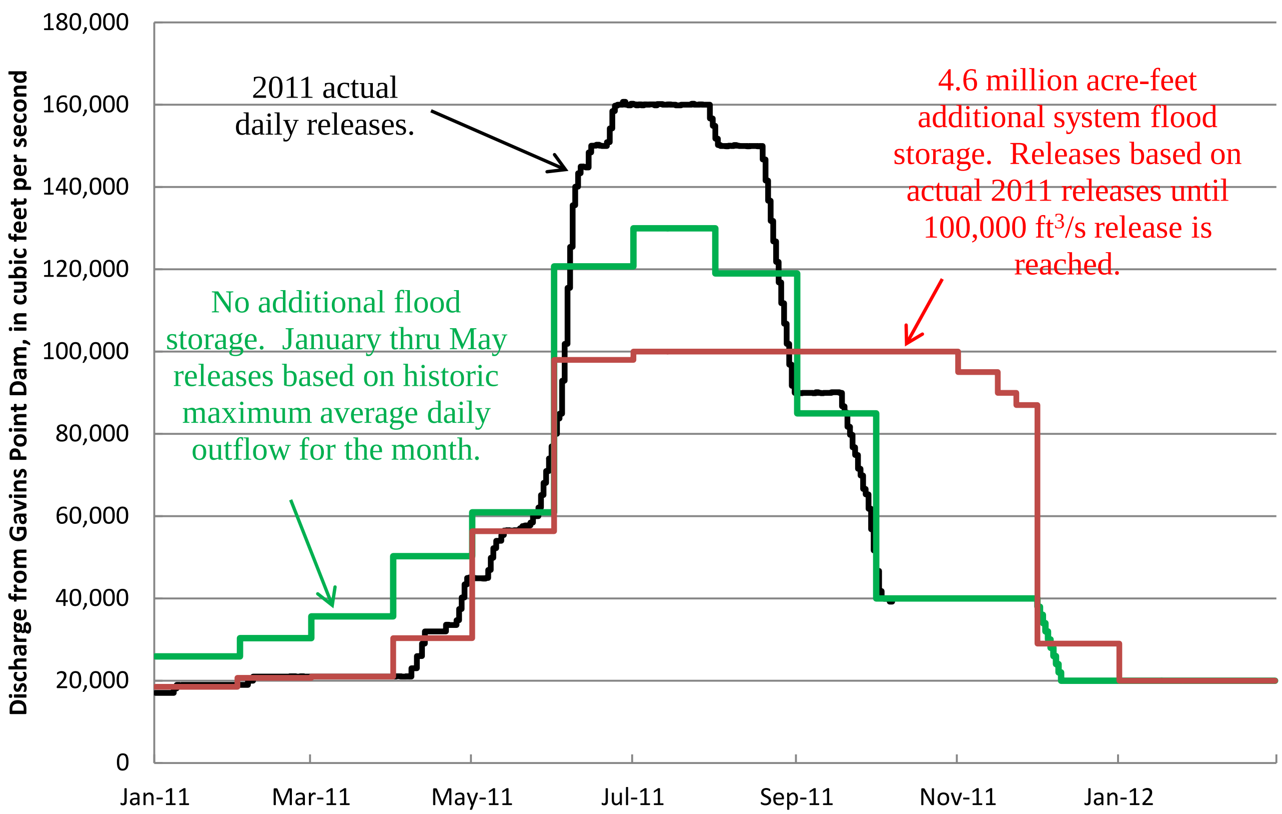

Figure 29. Comparison of actual Gavins Point Dam releases with simulated releases for alternative reservoir system management scenarios, January 2011–February 2012

Either scenario would still have resulted in record releases from Gavins Point and would have caused flood damage to some extent. However, flood damage would have been greatly reduced.

Decisions on Peak Releases

The panel questioned the Corps on how peak release rates at various projects were determined and whether the evacuation of flood water could have been accomplished by different scenarios of release rates. For example, instead of a peak release rate of 150,000 ft^3/s for 10 days, could the same volume of flood water have been evacuated at a lower rate, for example, 100,000 ft^3/s for 30 days, with a possible result of greatly reduced flood damage? These questions focus on the period in June and July when the System dams experienced maximum inflows and the Corps raised the dam releases to the maximum levels.

Communities near Bismarck, North Dakota, experienced severe flood damage from releases from Garrison Dam that reached a maximum rate of about 150,000 ft^3/s as shown in figure 30. From around June 5–18, the Corps increased releases from about 115,000 ft^3/s to 150,000 ft^3/s and maintained a release rate of about 150,000 ft^3/s for 9 days before stepping down the releases to 110,000 ft^3/s by the end of July.

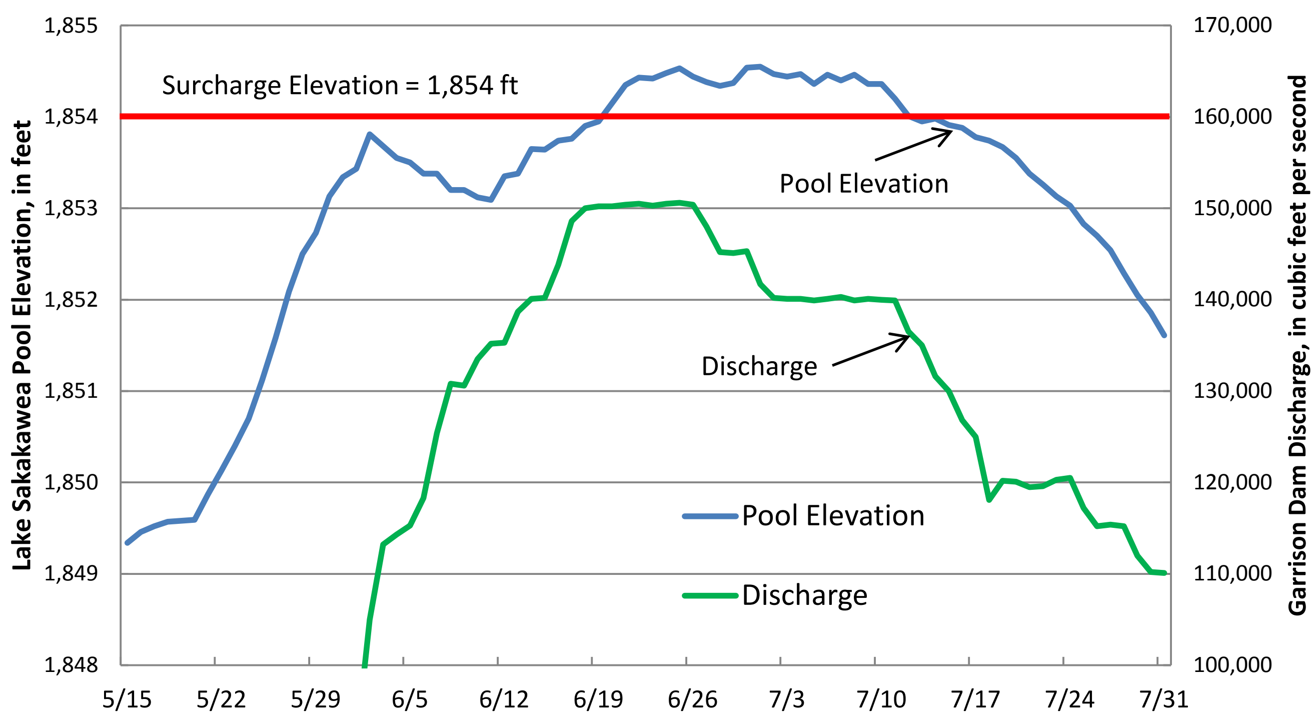

Figure 30. Lake Sakakawea elevation and Garrison Dam discharge, May 15–July 31, 2011

Lake Sakakawea reached surcharge levels on June 20 and remained in surcharge condition until July 13. However, the Corps began reducing releases on June 27, balancing releases with inflows while allowing the project to remain in surcharge mode for 16 days. Not raising the peak release to 150,000 ft^3/s would have allowed the reservoir elevation to rise further into the surcharge zone, jeopardizing dam safety. Also, the decision process needed to consider the inflow forecast and possible additional rainfall. In addition, Fort Peck reservoir was in surcharge condition at this time and could not reduce releases and would have had to increase releases in case of additional rainfall. So, in the example of Garrison Dam releases, during the period of peak inflows, the Corps appears to have operated the project optimally, minimizing the peak release rate and quickly stepping down releases.

Communities near Pierre, South Dakota, experienced flood damages from Oahe Dam releases that peaked at 160,000 ft^3/s. Figure 31 shows Lake Oahe elevation and Oahe Dam discharge during May 15–July 31. The Corps avoided surcharge conditions at Oahe because that would have required using, and damaging, the unlined spillway channel. Release discharges were increased from about 87,000 ft^3/s on June 2 to about 150,000 ft^3/s on June 8, peaked at 160,000 ft^3/s on June 20, and then were maintained at about 150,000 ft^3/s until July 11. Reservoir elevation was maintained within 1 ft of the surcharge zone for 28 days until July 19. So, similar to Garrison Dam, Oahe Dam was operated near capacity to accommodate peak inflows and releases were stepped down as soon as possible as inflows receded.

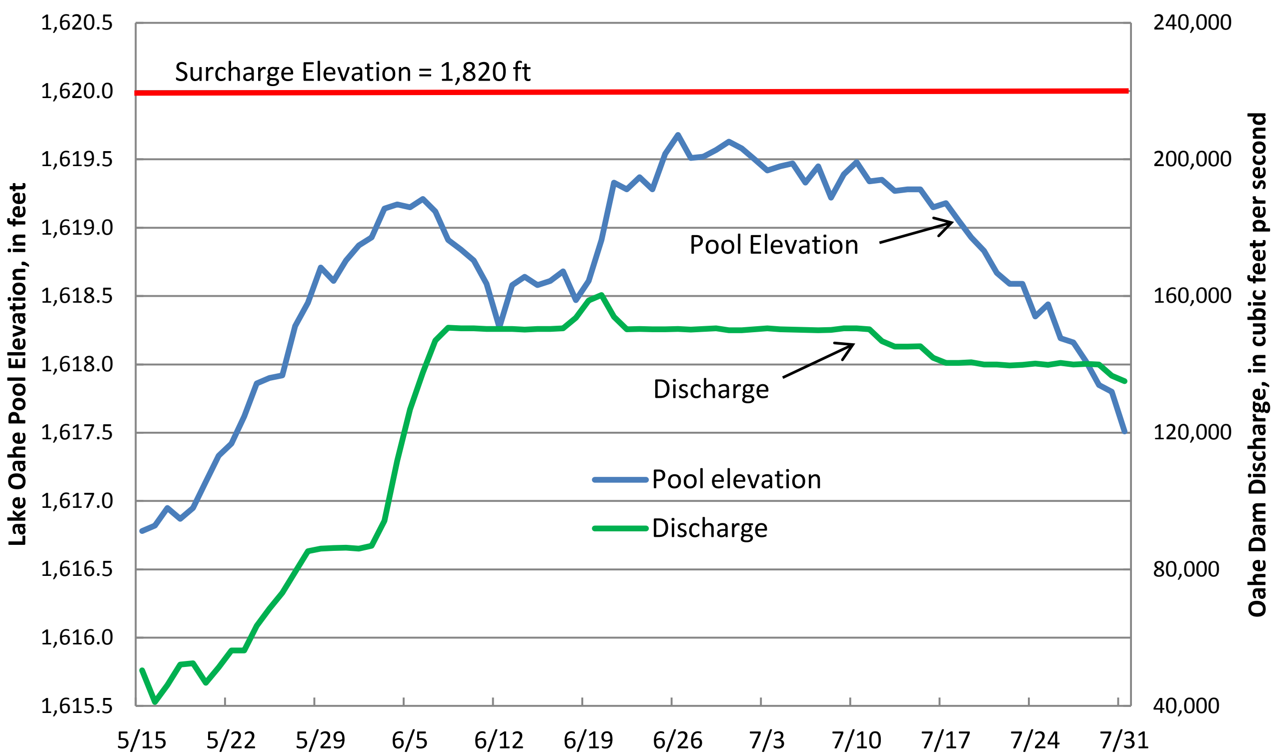

Figure 31. Lake Oahe elevation and Oahe Dam discharge, May 15–July 31, 2011

Releases from the most downstream dam, Gavins Point, depend largely on releases from the three large upstream dams. In addition, Fort Randall, which includes about 14 percent of the System storage, also is critical for flood operations because the reservoirs directly upstream (Big Bend) and downstream (Gavins Point) have essentially no flood-control storage. Peak releases from Gavins Point Dam were maintained at a level of 160,000 ft^3/s for 35 days, from June 25–July 29. The panel asked the Corps about the implications of limiting the Gavins Point release to 140,000 ft^3/s. Model simulations for such a scenario were performed by the Corps (Michael Swenson, U.S. Army Corps of Engineers, written commun., 2011). Results indicated that to limit Gavins Point releases to 140,000 ft^3/s, peak releases also would have to have been reduced at Garrison and Oahe. Reduction of those releases would have required that Oahe Dam be operated in surcharge mode and Garrison Dam would have to have been operated at an even higher surcharge level. Such a condition places the dams at greater risk of failure and eliminates any remaining flexibility to manage possible future runoff events.

After review of the Corps' decisions regarding peak dam releases, the panel concludes that given the conditions at the time when peak inflows were occurring in June (regardless of earlier decisions related to evacuation of storage leading up to June's peak inflows), the Corps appears to have managed peak releases as well as possible. It also should be noted that the Oahe spillway condition (the need to avoid spillway releases in order to avoid damaging the unlined spillway channel) limits the use of surcharge storage. Without this constraint, the Corps might have utilized additional storage at Oahe and might possibly have been able to reduce peak releases, slightly, at Oahe and Gavins Point.

Communications

Decisions about reservoir operations require communication between the Corps and various agencies and the public. The panel sought to understand how the effectiveness of communications might contribute to decreased or increased flood damages as well as to public understanding and adaptation. Communication is a key factor in reducing public mistrust and initiation of rumors, as referenced in the 1997 report. Without information regarding the meteorological and hydrologic situations throughout the basin and how problems in one part of the basin affect other parts, misunderstanding of the Corps operations will occur.

During this investigation, the panel noted as a minimum the following categories of communications:

	Examples of required communication
Corps NorthwesternDivision with Corps Districts	The Districts have responsibility for projects, and MRBWM communications with them must take into account operational and safety considerations. MRBWM requires information from Districts about status of tributary reservoirs.
Corps Districts with USBR	The Districts operate tributary reservoirs and have responsibility to guide USBR in operation of Section 7 reservoirs.
Corps with NWS	Routine forecasts follow established patterns, but extraordinary conditions such as in 2011 require frequent and intense coordination of information and forecasts.
Corps with state governments	State water managers require accurate and timely information to be able to discharge their duties relating to public information and

	other functions of state government agencies and political leaders.
Corps with emergency managers at different levels	Emergency managers at the Federal, state, and local levels have duties to work with the public and communities for flood awareness and response, and they expect and require timely and accurate information.
Corps with local officials for flood fighting	Local officials require timely and accurate information to build levees and evacuate citizens. These duties overlap with emergency management but in some cases the mayors and public works directors will expect direct communications themselves.
Other coordination and communication	The above listing may not capture all communication requirements. For example, one project manager related how work was required with Federal agencies, State Water Commission, Bismarck and Mandan city engineers, private consultants from Bismarck, the National Guard, the State Emergency Operations Center, the NWS, and other Corps personnel.

It was beyond the scope of the panel review to study all of these communication requirements, but as citizens, state officials, and project staff were interviewed, the panel heard continually about communications. The panel sought to interpret what was heard in the context of the questions that were asked and to formulate suggestions for lessons learned.

The panel's first impression about communications was to note that it seems impossible to satisfy everyone's expectations to be notified promptly and accurately about every decision and eventuality. Officials along the river in various roles should take part of the responsibility for communciations, as they do in other public emergencies. The Corps' Omaha District established a Joint Information Center, which was announced on May 30 (U.S. Army Corps of Engineers, 2011b). The panel was briefed about the operations of the Joint Information Center and heard positive feedback about it from a number of sources. The news release that announced the Center showed that Corps officials were issuing the best information they could. Jody Farhat (U.S. Army Corps of Engineers, Northwest Division) was quoted to say: "We continue to receive precipitation in the upper basin" and "Each day we update the reservoir forecast with new rain and snow runoff information. When changes to the inflow forecasts occur, which they often do, it is necessary for us to make adjustments… at the mainstem reservoirs to balance the impacts of changing conditions." She reported that "The sooner we reach these maximum release rates, the less risk there is that we'll have to go higher. Once we have evacuated some storage in the reservoir system, we will have more flexibility to respond to changing conditions." The Corps' Brigadier General John McMahon was quoted to say "We are working closely with state and local emergency management teams to identify potential flood areas, provide residents with the most current information and help protect vital public infrastructure."

Communication in the weeks leading up to the flooding was limited compared to the information that was disseminated once the Joint Flood Information Center was established.

The simultaneous occurrence of the rapidly-changing decisions about flow increases and the establishment of the Joint Information Center shows how difficult it would have been to inform all stakeholders about the situation. Conditions were changing rapidly, but local emergency managers expected timely and accurate information, which would have alleviated some of the reported confusion and frustration. This is what county emergency managers and state officials told the panel, but it seems like a formidable task for the Corps to be responsible for all of the communication requirements. Even so, the Corps did well once the Joint Information Center was established, although communication in the months leading up to the flooding seemed less effective.

The panel believes that there is a lesson to be learned about emergency communication during a rapidly-changing flood event such as this, but making this recommendation is beyond the scope of this panel.

Lessons have been learned in the past. For example, the Summary Report of the 1997 Flood states exactly what works: "Public confidence in the Corps of Engineers remained high, because of a clear explanation of the expected release and pool rises provided by the MRBWM staff. The distribution of this information to the public was provided in a concise up-front matter, which also helped alleviate rumors" (U.S. Army Corps of Engineers, 1998, p. 16).

Once the high releases were imminent, communication improved significantly. The Corps notified the Governors of the states, and then proceeded to hold weekly conference calls with the states that proved valuable.

Summary and Conclusions

The Missouri River flood of 2011 was the largest of the period of record in terms of runoff volume and it stressed the mainstem reservoir system and its operators as never before. The flood caused massive damage and disruption that affected farms, homes, businesses, industries, public infrastructure, and transportation networks. Many people were dismayed that such a damaging event could occur, in spite of the flood control reservoir system.

The flooding was a result of unprecedented runoff from a combination of heavy plains and mountain snowpack and extreme, widespread rainfall in the upper reaches of the basin. After a wet year in 2010, the storage in the system was back at the base of the planned annual flood control and multiple use capacity as defined in the U.S. Army Corp of Engineers (Corps) Master Manual. However, during the 2011 runoff season, the authorized flood control storage was inadequate to handle such large volumes of runoff from snowmelt and rainfall, so that record dam releases were required to safeguard the system and to ensure that storage capacity was available in the case of additional rainfall and runoff into the reservoirs.

To assess the effectiveness of the Corps' operations during the flood, an independent investigative panel was charged to answer a set of questions pertaining to the operation of the System. The approach used to answer these included an assessment of the Master Manual and whether it provides adequate guidance for extreme flood events. Another set of questions concerned the effectiveness of operations to include an assessment of how the mainstem and tributary reservoirs were operated, whether decisions were appropriate and in line with water control manuals, and if storage was utilized effectively. These questions included whether opportunities to prevent or reduce flood impacts were missed and what flood-control storage would have been needed to control the runoff. Along the same lines, the panel also considered whether infrastructure-related factors contributed to the losses, such as the inability to use a reservoir's flood control features, for example. During the event, flooding was also experienced in the Mississippi River System, and the panel was asked to evaluate whether any consideration of that flooding exacerbated losses on the Missouri System, as well as whether operations for environmental or other purposes contributed to the losses. Finally, the panel probed whether floodplain development influenced operating decisions.

Forecasting of runoff from snowmelt and rainfall is an essential element in planning System operations, and the panel was asked if accurate and timely hydrologic and weather forecasts were available and what data improvements are needed to enable the Corps to assess basin conditions and properly forecast runoff, including long-term regulation forecasts. Additionally, the panel considered issues relating to climate change, including climate cycles and variability, the frequency of the 2011 event, and whether hydrologic knowledge is adequate to provide effective guidance to control such extreme flooding.

The individual questions are answered in the main report and in the Executive Summary. The panel found that the decisions of the Corps were appropriate and in line with the appropriate manuals, but both the manuals and the decision-making process can be improved. During extreme flood events, such as in 2011, the Master Manual does not provide a workable formula for operational decisions and during extraordinary flooding experience-based judgment along with repetitive quantitative analysis must be used. Operators must and did consider a great deal of information in their decisions, including the security of the System infrastructure. Earlier releases to provide additional flood storage could have reduced the impact of the flood, but these actions carry the risk that later in the year some authorized purposes would not be satisfied if the flood had not occurred. Without knowledge of the impending precipitation in the late spring, higher releases would have been (and were) called into question.

The panel found particular weakness in addressing runoff from melting plains snowcover where increased data infrastructure and improved data gathering and modeling techniques are needed. Recommendations are made for needed improvements in forecasting.

The panel's findings lead to a set of recommendations that begins with the fundamental need to support a program of infrastructure enhancement to make sure all flood release spillways and tunnels are ready for service and that all levees are in good condition. To assess how the infrastructure should be used to control floods, hydrologic studies are needed to update the design flood with new probabilities given the widely fluctuating and more extreme runoff experienced in the last several decades. Also studies should consider managing the system differently within recognized wet and dry cycles examining persistence between years of annual flows, although a strong relationship does not necessarily predict the following year. The panel recommends a review of System storage allocations for floods like 2011 and possible modification of Master Manual procedures to take into account different storage amounts for dry and wet periods and to adjust to varying climatic extremes. The panel also found that its own recommendations regarding plains snow data and forecasting closely mirror conclusions from the 1997 post-flood assessment report. Also similar to the 1997 report, the panel observed that clear information dissemination to the public was invaluable. It is imperative that these recommendations be implemented to help prevent or lessen the impact of such future flooding disasters.

Given the importance of forecasting, the panel recommends studies to enhance data collection, forecasting, and modeling of snow pack and resulting runoff, especially from plains snow. As other agencies are also involved in forecasting and data collection, improved communication and data-sharing systems with other agencies are recommended.

By combining improved data and forecasting systems with operational procedures and more flexible control of flood storage space, a System-wide decision support system is recommended to include status information on tributary reservoirs and inflows and linked to a modern interactive graphic forecast system.

The record runoff of 2011 created high stress on the mainstem reservoir system and placed demands on the Corps to manage the flood waters to protect public safety and minimize downstream damage. The Corps ultimately had to balance the cost of elevated reservoir releases and the accompanying losses versus dam safety and the implications of a dam break. The panel heard testimonies about the destruction and witnessed devastating losses as a result of the high releases. After studying the conditions, the panel believes the Corps had few options. The panel found no evidence that Corps personnel were attempting to do anything other than to operate the system using the best available methods and to minimize the overall negative consequences. The flood in 2011 was a record-breaking event with unprecedented levels of runoff that could not be predicted in advance, and the Corps responded well to a difficult test of historic dimensions.

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Appendix

Charter and Panel Member Appointment Letters For 2011 Missouri River System Operation Post Flood Review

Missouri River System Operation 2011
Post Flood Review – Charter

PURPOSE: This independent review is intended to assess USACE operation of the six Missouri River mainstem reservoirs (Fort Peck, Garrison, Oahe, Big Bend, Fort Randall, Gavins Point), and any appropriately related dams and reservoirs, prior, during and after the 2011 sequence of flooding, for the purpose of gaining lessons learned and recommendations to improve future operations.

PANEL: The review panel is composed of non-USACE independent experts in hydrology and/or dam and reservoir system operations and regulation. USACE staff will provide all available data, records and other information that the panel deems relevant to its review, but will not serve directly on the panel. The panel may choose to select a Chairman and assign duties and responsibilities among its members as it deems appropriate.

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SCOPE: The panel is charged to review, analyze, and assess any and all information it determines necessary and that is relevant to pre-flood, flood, and post-flood operations in order to reach findings regarding the planning and execution of reservoir operations as they may have affected, or been affected by hydrologic conditions, operational constraints, and other conditions in the Missouri River basin. Relevant information such as the Annual Operating Plan, hydrologic forecasts and forecast methods, real time chronology and decisions, coordination and communication with other reservoir owners/operators and agencies shall be considered. The panel shall review the Missouri River Master Manual to determine the consistency of the AOP and the actual operations. In its review, the panel shall consider consistency of the operations with system authorized purposes from a technical, but not legal perspective. The panel is encouraged to reach out to external agencies and entities for information and input.

The panel shall address, but is not limited to, the following questions:

1. According to the Missouri River Master Manual and other pertinent documents, how should the mainstem reservoir system and the Corps and U.S. Bureau of Reclamation (USBR) tributary reservoirs within the system have been operated, how were they actually operated, and what were the reasons for any differences in the operation?
2. Were the Water Management decisions made during the Flood of 2011 appropriate and in line with the approved water control manual?
3. Could the Corps have prevented or reduced the impact of the flood by taking other management actions leading up to the flood?
4. Did operations for environmental or other purposes influence flood risk management operations, and if so how did they influence the operations?
5. Were accurate and timely hydrologic and weather forecasts and other pertinent data available? What data improvements (plains and mountain snowpack information, river gages, and observed weather data) are warranted in light of this flood event to properly manage the system?
6. Did the Corps properly assess basin conditions and properly forecast runoff from plains snowpack, mountain snowpack, and precipitation? If not, what additional information and/or tools are needed to better forecast runoff?
7. Did the Corps' long-term regulation forecasts properly account for the runoff?
8. Did the Corps' regulation of the mainstem system during the Mississippi River flood contribute to flooding on the Missouri River, and did it have a discernable impact on the Mississippi River flooding?
9. How should the Flood of 2011 be characterized in terms of frequency or recurrence interval?
10. Does the Master Manual adequately address reservoir operations during extreme flood events? Does Plate VI-1 adequately address the hydrologic conditions like those experienced this year? Do the downstream flood control constraints adequately balance flood risk in the upper and lower basins?
11. Did climate change play a role in this year's record runoff? Should future regulation of the reservoir system be adjusted to account for climate change? And if so, what types of additional studies would be required to integrate climate change?
12. What role did flood plain development play in the operation of the reservoir system prior to and during the event?

<u>REPORT, FINDINGS AND RECOMMENDATIONS:</u> The panel shall prepare a report that presents the scope of its investigation; methods used; data and information cited; contacts and other sources of information; and its assessment including any findings and recommendations for USACE to consider.

<u>SCHEDULE:</u> The panel shall initially convene in person no later than the week of 26 September 2011 and complete it work with its report no later than 2 December. Meetings and means of coordination and communication subsequent to the initial meeting is at the panel's discretion.

DEPARTMENT OF THE ARMY
CORPS OF ENGINEERS, NORTHWESTERN DIVISION
PO BOX 2870
PORTLAND OR 97208-2870

REPLY TO
ATTENTION OF

SEP 1 2 2011

Programs Directorate

Neil Grigg, PhD
Professor (retired)
Colorado State University
Department of Civil Engineering
1372 Campus Delivery
Fort Collins, CO 80523-1372

Dear Dr. Grigg:

Thank you for agreeing to serve on the Missouri River post flood water management technical review panel. This letter confirms your appointment to the review panel per your discussion with Mr. Kevin Grode, Reservoir Regulation team leader, Missouri River Basin Water Management Division. A copy of this letter has been provided to your supervisor, Dr. Luis Garcia, for his situational awareness.

The purpose of the independent technical review is to assess U.S. Army Corps of Engineers' operation of the six Missouri River mainstem reservoirs (Fort Peck, Garrison, Oahe, Big Bend, Fort Randall, and Gavins Point), and any appropriately related dams and reservoirs, prior, during and after the 2011 sequence of flooding, for the purpose of gaining lessons learned and recommendations to improve future operations.

The enclosed charter outlines the intended purpose, panel composition, scope (including charge questions), expected products, and schedule of the post flood technical review. The panel is empowered to make changes to the charter based on their findings. We anticipate this review will entail approximately four weeks labor for each panel member and at least one face-to-face meeting. The Corps will provide travel funds, per diem, and salary for each panel member if necessary. We request the panel commence work no later than the week of 26 September 2011 and provide the final report to the Corps by 2 December 2011.

Again, thank you for agreeing to serve on the review panel. If you have any questions, please feel free to contact Mr. Kevin Grode, at (402) 996-3870, or me at 503-808-3730.

Sincerely,

Witt Anderson

Witt Anderson
Director, Programs

Encl

DEPARTMENT OF THE ARMY
CORPS OF ENGINEERS, NORTHWESTERN DIVISION
PO BOX 2870
PORTLAND OR 97208-2870

REPLY TO
ATTENTION OF

SEP 1 2 2011

Programs Directorate

Cara McCarthy
Senior Forecast Hydrologist
Natural Resources Conservation Service
National Water and Climate Center
1201 NE Lloyd Blvd, Suite 802
Portland, OR 97232-1274

Dear Ms. McCarthy:

Thank you for agreeing to serve on the Missouri River post flood water management technical review panel. This letter confirms your appointment to the review panel per your discussion with Mr. Kevin Grode, Reservoir Regulation team leader, Missouri River Basin Water Management Division. A copy of this letter has been provided to your supervisor, Mr. Tom Perkins, for his situational awareness.

The purpose of the independent technical review is to assess U.S. Army Corps of Engineers' operation of the six Missouri River mainstem reservoirs (Fort Peck, Garrison, Oahe, Big Bend, Fort Randall, and Gavins Point), and any appropriately related dams and reservoirs, prior, during and after the 2011 sequence of flooding, for the purpose of gaining lessons learned and recommendations to improve future operations.

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Again, thank you for agreeing to serve on the review panel. If you have any questions, please feel free to contact Mr. Kevin Grode, at (402) 996-3870, or me at 503-808-3730.

Sincerely,

Witt Anderson

Witt Anderson
Director, Programs

Encl

DEPARTMENT OF THE ARMY
CORPS OF ENGINEERS, NORTHWESTERN DIVISION
PO BOX 2870
PORTLAND OR 97208-2870

REPLY TO
ATTENTION OF

September 15, 2011

Programs Directorate

Mr. Bill Lawrence
NOAA/NWS Arkansas-Red Basin RFC
10159 E 11th Street, Suite 300
Tulsa, Oklahoma 74128-3050

Dear Mr. Lawrence:

Thank you for agreeing to serve on the Missouri River post flood water management technical review panel. This letter confirms your appointment to the review panel per your discussion with Mr. Kevin Grode, Reservoir Regulation team leader, Missouri River Basin Water Management Division. A copy of this letter has been provided to your supervisor, Mr. Bill Proenza, for his situational awareness.

The purpose of the independent technical review is to assess U.S. Army Corps of Engineers' operation of the six Missouri River mainstem reservoirs (Fort Peck, Garrison, Oahe, Big Bend, Fort Randall, and Gavins Point), and any appropriately related dams and reservoirs, prior, during and after the 2011 sequence of flooding, for the purpose of gaining lessons learned and recommendations to improve future operations.

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Again, thank you for agreeing to serve on the review panel. If you have any questions, please feel free to contact Mr. Kevin Grode, at (402) 996-3870, or me at (503) 808-3730.

Sincerely,

Witt Anderson
Director, Programs

Enclosure

DEPARTMENT OF THE ARMY
CORPS OF ENGINEERS, NORTHWESTERN DIVISION
PO BOX 2870
PORTLAND OR 97208-2870

REPLY TO
ATTENTION OF

SEP 12 2011

Programs Directorate

Darwin Ockerman
Hydrologist
U.S. Geological Survey
Office of Surface Water
12201 Sunrise Valley Drive, M/S 415
Reston, Virginia 20192

Dear Mr. Ockerman:

Thank you for agreeing to serve on the Missouri River post flood water management technical review panel. This letter confirms your appointment to the review panel per your discussion with Mr. Kevin Grode, Reservoir Regulation team leader, Missouri River Basin Water Management Division. A copy of this letter has been provided to your supervisor, Mr. Bob Hainly, for his situational awareness.

The purpose of the independent technical review is to assess U.S. Army Corps of Engineers' operation of the six Missouri River mainstem reservoirs (Fort Peck, Garrison, Oahe, Big Bend, Fort Randall, and Gavins Point), and any appropriately related dams and reservoirs, prior, during and after the 2011 sequence of flooding, for the purpose of gaining lessons learned and recommendations to improve future operations.

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Again, thank you for agreeing to serve on the review panel. If you have any questions, please feel free to contact Mr. Kevin Grode, at (402) 996-3870, or me at 503-808-3730.

Sincerely,

Witt Anderson

Witt Anderson
Director, Programs

Encl