Appendix A

Ice Formation in the Missouri River at Bismarck, North Dakota

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Background

Each winter a stationary ice cover forms in the reach of the Missouri River at Bismarck, ND. A significant impact caused by the ice cover is the increase in the water surface elevation (stage) of the river. The increase in stage ranges from two to six feet under constant discharge. The ice cover forms each winter during the period from early December through mid January and remains in place for about 86 days on average. The period between WY 2001 and the present was reviewed.

Summary

1. Each winter the freezeup roughly follows the same pattern with four distinct phases.
    a. The first phase is pre-freezeup open water when there is no ice or a minimal amount of ice in the reach at Bismarck.
    b. The second phase is freezeup. During this stationary ice is forming in the reach at Bismarck and having a significant impact on the stage. On average, the stage rises approximately 4.5 feet in five days.
    c. The third phase is the ice smoothing. During this phase the overall hydraulic resistance of the ice cover is declining. This is most likely due to the smoothing of the underside of the ice cover through melting and/or deposition of transported frazil ice along the bottom of the ice cover. During this stage, which can last 90 or more days, the stage slowly drops back to the pre-freezeup open water levels.
    d. The final phase is the return to open water.
2. There appears to be a rough relationship between the accumulated freezing degree days (AFDD) and the discharge observed at freezeup. In general, the greater the discharge the greater the AFDD's required before freezeup occurs.
3. Rating curves were developed for open water and ice covered conditions. There is quite a lot of scatter around the ice covered rating curve. Separate open water rating curves were developed for the pre-2011 flood and post-2011 flood conditions. The ice covered stages in 2012 were comparable to the pre-2011 ice covered stages.

Data

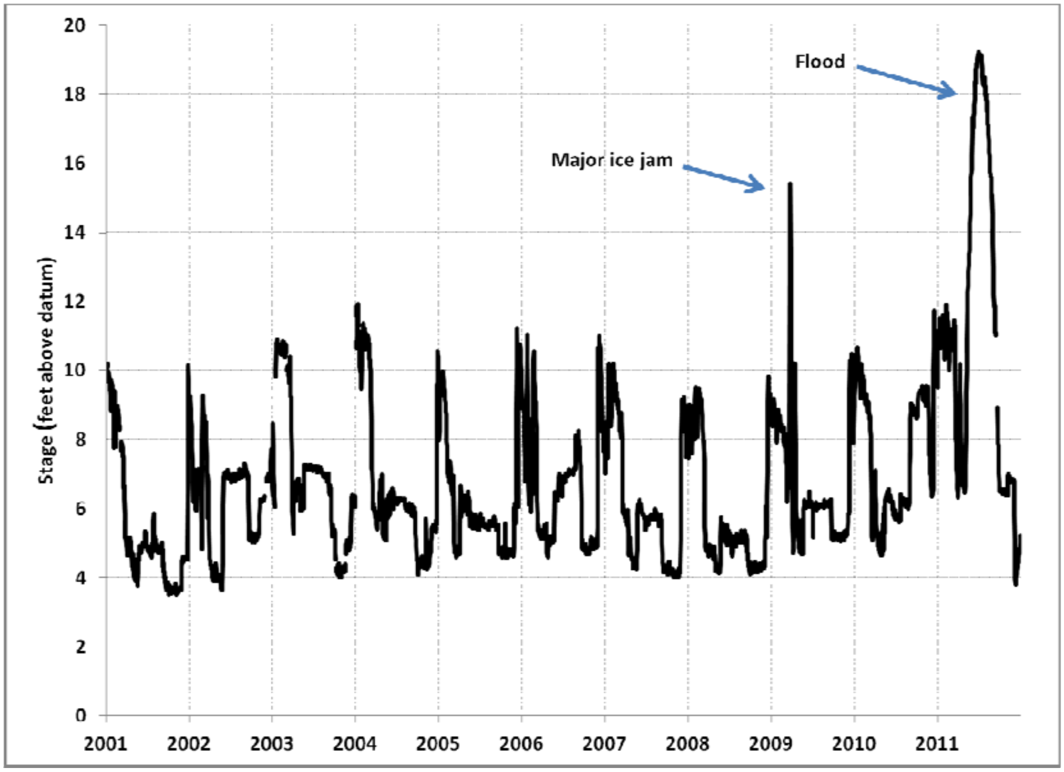

Figure 1 Observed stage at Bismarck, ND

Observed Stages

The daily average observed Missouri River stage at Bismarck, ND is shown in Figure 1. The stage and flow data was recorded at gage 06342500 (Missouri River at Bismarck, ND). The regular increase in stage that occurs each winter can be clearly seen. Beyond the regular increase in stage each winter two major events can also be seen. The first is a major ice jam that occurred in March of 2009 and the second is the major flood event that occurred during 2011.

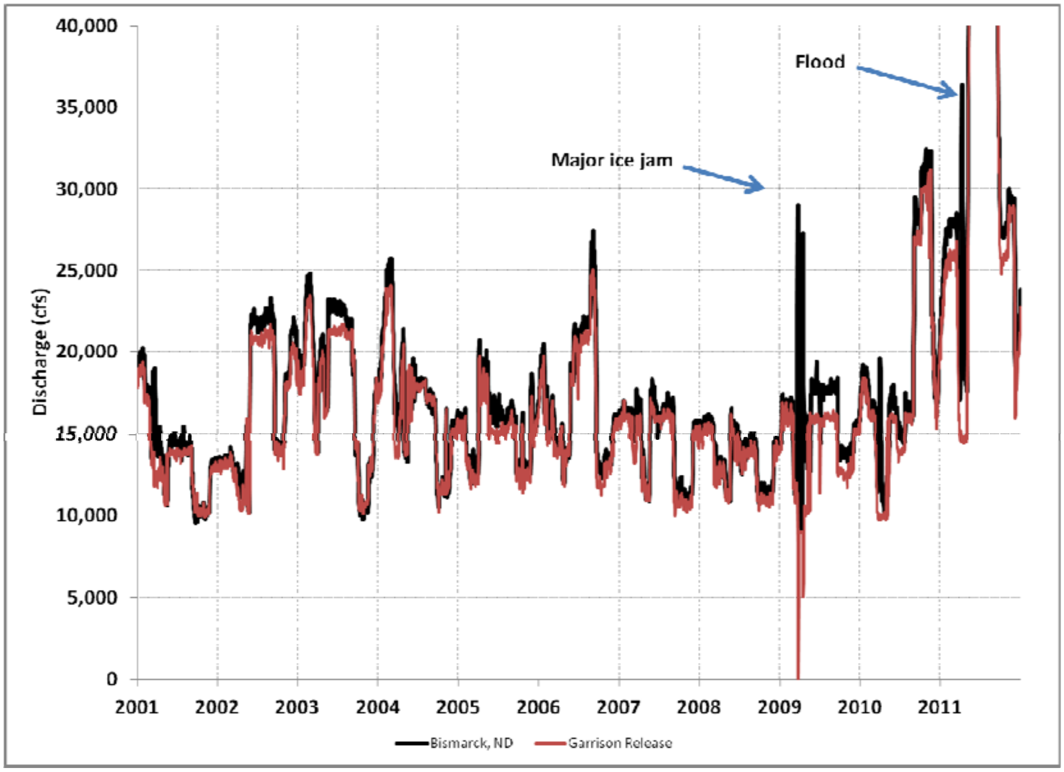

Figure 2 Observed discharge at Bismarck, ND

Observed Discharge

The daily average Missouri River flow at Bismarck, ND is shown in Figure 2. The release from Garrison Dam, located about 75 miles upstream of Bismarck is also shown. The flow at Bismarck is generally slightly larger than the Garrison Dam release, reflecting inflows into the Missouri River between Garrison and Bismarck. During the major ice jam of 2009, the Garrison Dam release was substantially reduced in order to mitigate ice jam flooding and this reduction can be seen. The discharge at Bismarck generally ranges between 10,000 and 20,000 cfs. The discharge reached a maximum of approximately 154,000 cfs (off the scale of the chart) during the major flood of 2011.

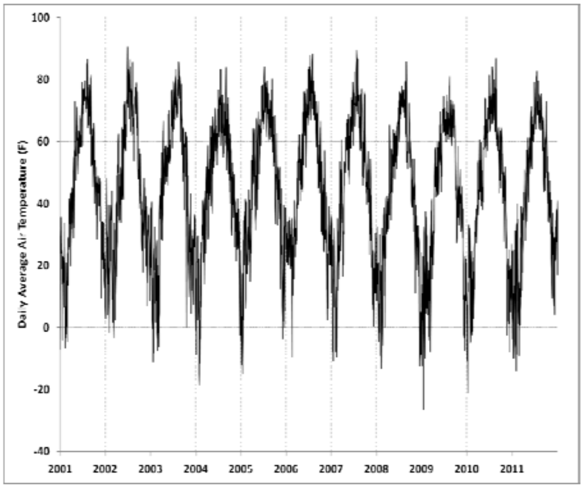

Figure 3 Daily average air temperature observed at Bismarck Municipal Airport

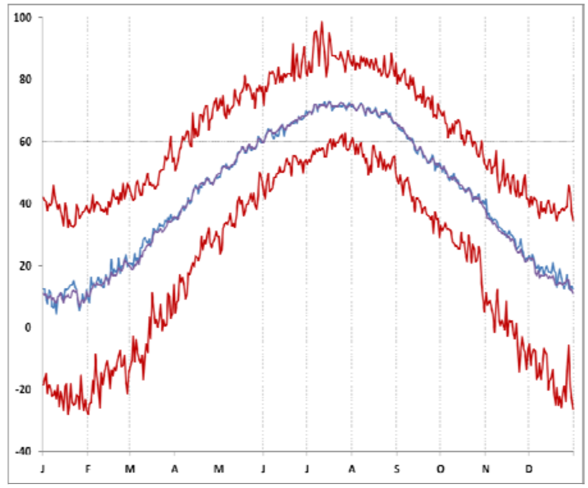

Figure 4 Maximum (red), minimum (red), average (blue) and 50th percentile (purple) daily average temperature for each day of the year (1936-2010)

Wintertime Air temperatures at Bismarck, ND

The air temperature observations were recorded at the Bismarck Municipal Airport. The daily average air temperature for the period from 2001 through 2012 is shown in Figure 3 and the statistics for each day of the year is shown in Figure 4. The daily average temperatures are often below 32F in winter and can range as low as -20F.

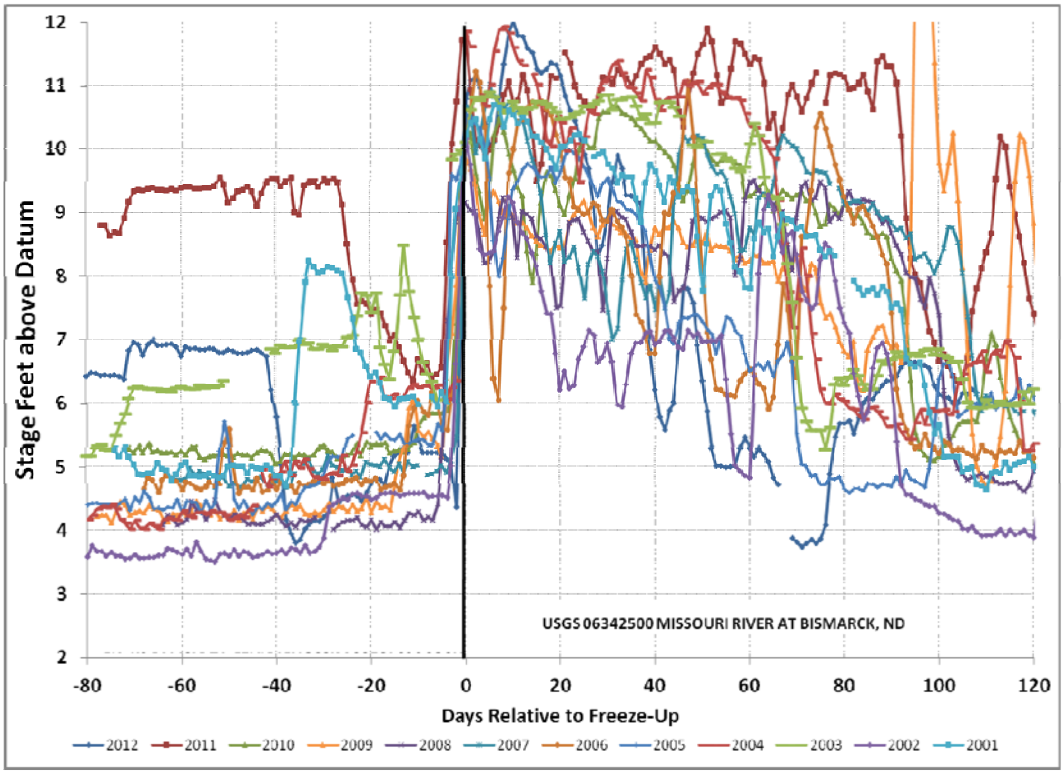

Figure 5 Stage at Freezeup observed each winter

Stage during Freezeup

The ice covered period was determined by observing the initial increase in stage. The day of freezeup was selected, somewhat arbitrarily, as the day when the initial maximum stage is reached. In some years, this is the maximum stage of the freezeup period, but in most years the maximum stage of the season occurs somewhat later. To plot the data, the days of the winter period were normalized by the date of freezeup. The day of freezeup was denoted as day 0 (zero), and the days following freezeup were denoted as 1, 2, 3,…In a similar fashion the days preceding freezeup were denoted as -1, -2, -3, ….The stages during the freezeup period for each winter are shown in Figure 5. The abrupt increase in stage that occurs at freezeup can be clearly seen. After freezeup that stages generally decline.

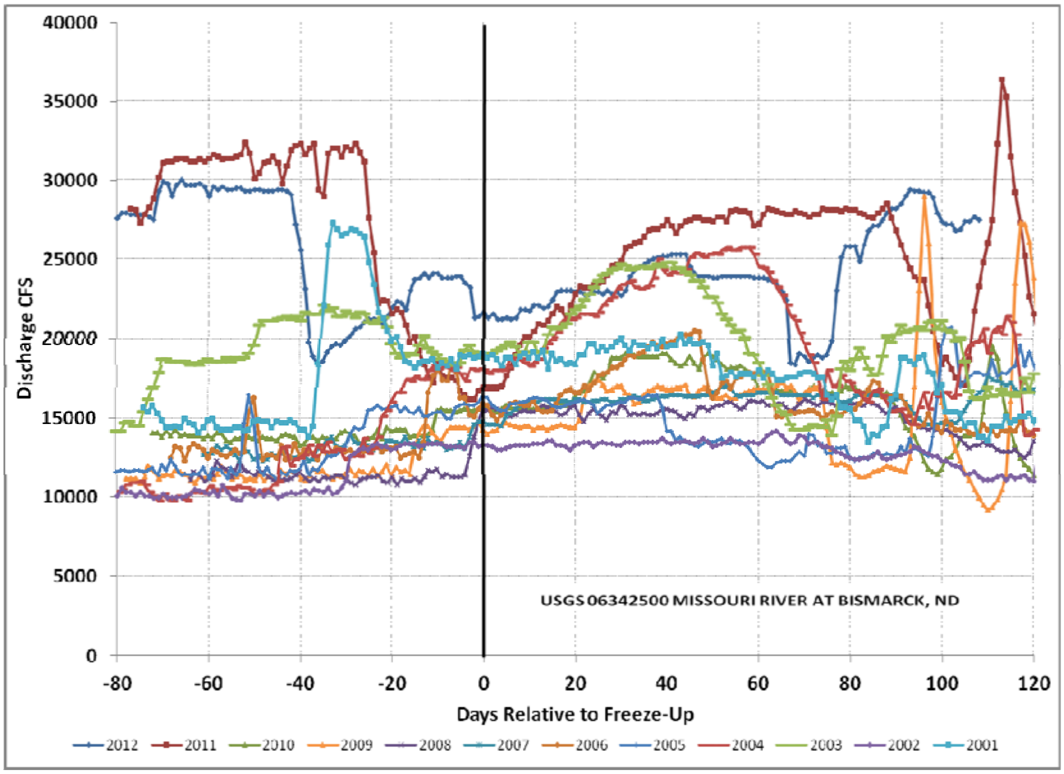

Figure 6 Discharge at Freezeup observed each winter

Discharge during Freezeup

The discharges do not show any abrupt changes at freezeup (Figure 6). Generally the discharges remain constant through freezeup, reflecting the steady releases from Garrison Dam upstream and the relatively small inflow from upstream tributaries.

Table 1 Freezeup Data

Water Year	Freezeup Date	Freezeup stage	Stage Day -5	Stage Day -10	Max Obs. Stage	Max day^	Discharge (cfs)	AFDD
2001	14Dec2000	10.21	6.18	5.98	10.7	6	19100	542
2002	27Dec2001	10.15	4.55	4.59	10.15	0	13300	294
2003	16Jan2003	10.09	-	6.99	10.89	5	18800	482
2004	02Jan2004	11.85	6.19	6.25	11.93	8	18000	527
2005	26Dec2004	10.55	5.55	5.44	10.55	0	16400	206
2006	08Dec2005	10.24	5.6	6.04	11.21	2	15900	274
2007	01Dec2006	10.66	5.03	5.03	11.01	5	14800	119
2008	04Dec2007	9.16	5.16	4.29	9.5	61	15500	190
2009	18Dec2008	9.82	5.17	5.56	15.42	97*	14300	415
2010	12Dec2009	10.29	5.84	5.65	10.67	31	15800	257
2011	17Dec2010	11.74	6.57	6.69	19.23	196**	16900	550
2012	14Jan2012	10.79	5.26	5.4	12.01	10	21600	814

*Major ice jam ** 2011 Flood ^Relative to Freezeup Date

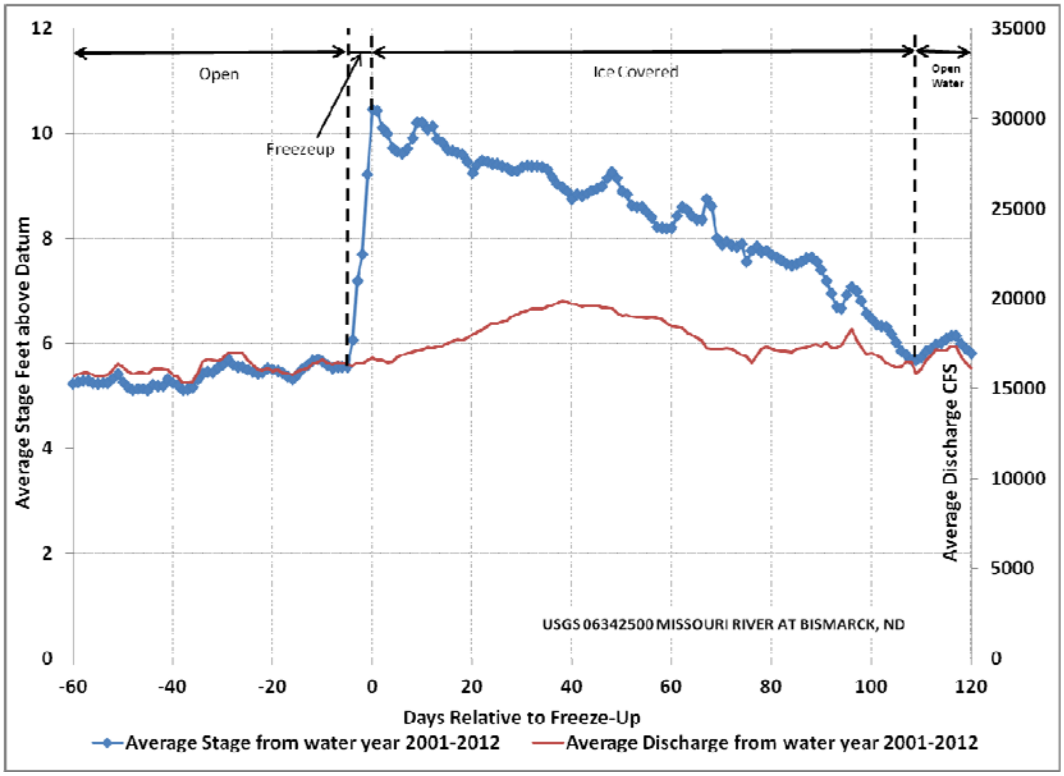

Figure 7 Average daily stage and average daily flow for each day during freezeup

Average Stage and Discharge at Freezeup

The average daily stage and average daily discharge for each day referenced to the freezeup date was determined using the observed stages and flows for the period from 2001 through 2012. This procedure clearly demonstrates the freezeup process for the Missouri River at Bismarck. There are four distinct phases.

1. The first phase is pre-freezeup open water when there is no ice or a minimal amount of ice in the reach at Bismarck.
2. The second phase is freezeup. During this stationary ice is forming in the reach at Bismarck and having a significant impact on the stage. On average, the stage rises approximately 4.5 feet in five days.
3. The third phase is the ice smoothing. During this phase the overall hydraulic resistance of the ice cover is declining. This is most likely due to the smoothing of the underside of the ice cover through melting and/or deposition of transported frazil ice along the bottom of the ice cover. During this stage, which can last over 90 days, the stage slowly drops back to the pre-freezeup open water levels.
4. The final phase is the return to open water.

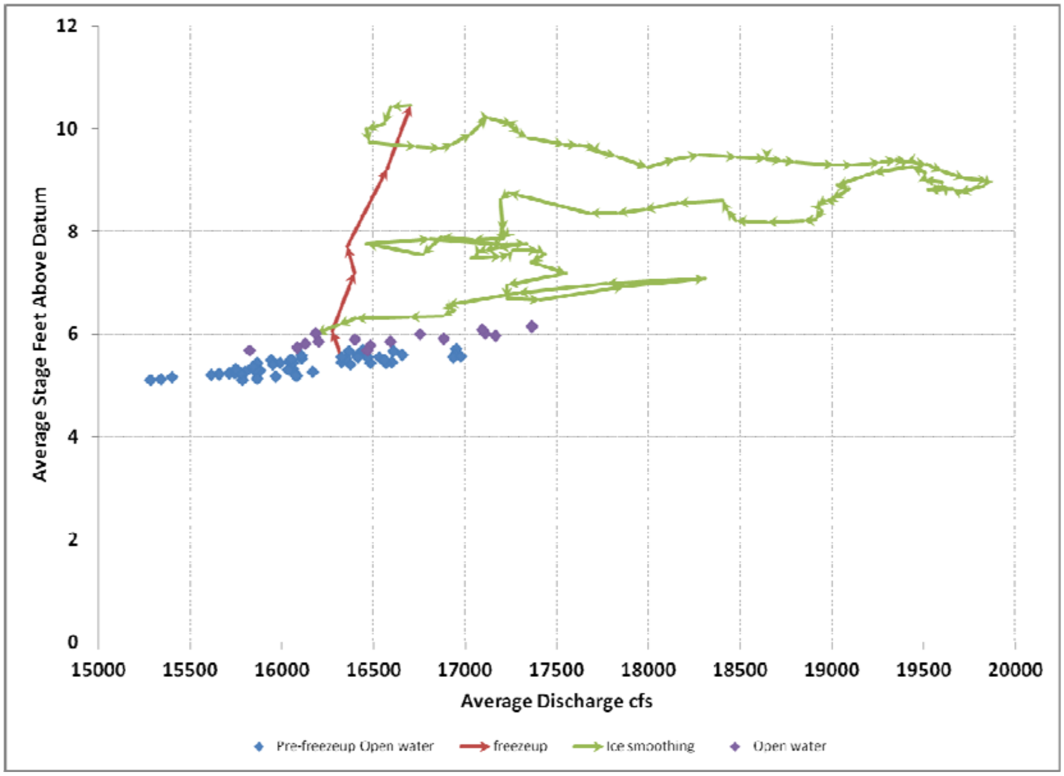

Figure 8 Rating curve for average stage and discharge during freezeup

Average Rating Curve at Freezeup

This is the rating curve for the average discharge and stage during the period shown in Figure 7. A rating curve describes the relationship between the discharge and stage at a location along a river. Under open water there is often a one-to-one relationship between the stage and flow. A one-to-one relationship can be seen for the pre-freezeup and final open water periods but the impact of ice is to make the relationship much more complicated. In general the presence of ice causes the stage to rise but the actual impact on the stage is reduced over time. This reduction is termed "ice cover smoothing." This is most likely due to the smoothing of the underside of the ice cover through melting and/or deposition of transported frazil ice along the bottom of the ice cover.

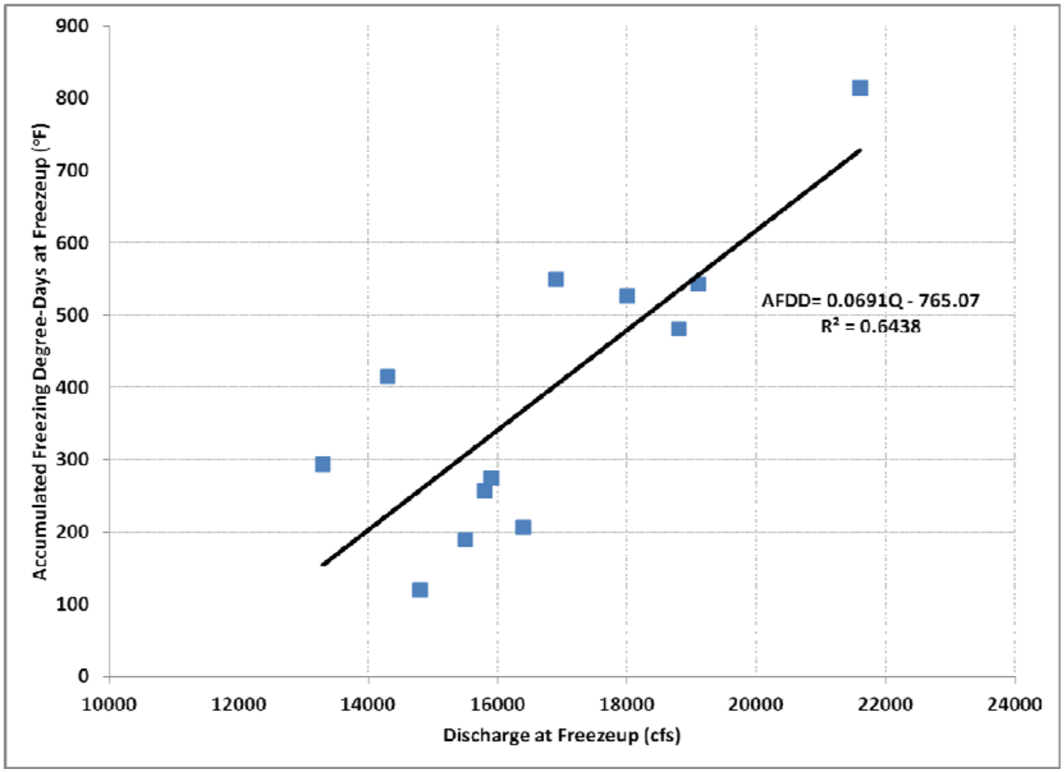

Figure 9 Accumulated Freezing Degree-Days (AFDD) at freezeup as a function of discharge

Accumulated Freezing Degree Days (AFDD) at Freezeup

The AFDD is calculated as the sum of the positive difference between freezing and the average daily temperature for each day of the winter season. (If the average daily temperature is greater than freezing, the difference is ignored.) The AFDD on any day of the winter season, U_n, represents the accumulated difference between freezing and the average daily temperature for the previous *n* days. The accumulation process starts each fall before the average daily temperature has dropped below freezing. The observed AFDD's at Bismarck on the day of freezeup is shown in Figure 9. There appears to be a rough relationship between the AFDD and the discharge observed at freezeup. In general, the greater the discharge the greater the AFDD's required before freezeup occurs. This rough relationship could be improved through further modeling of the Missouri River water temperature change from Garrison Dam downstream to Bismarck.

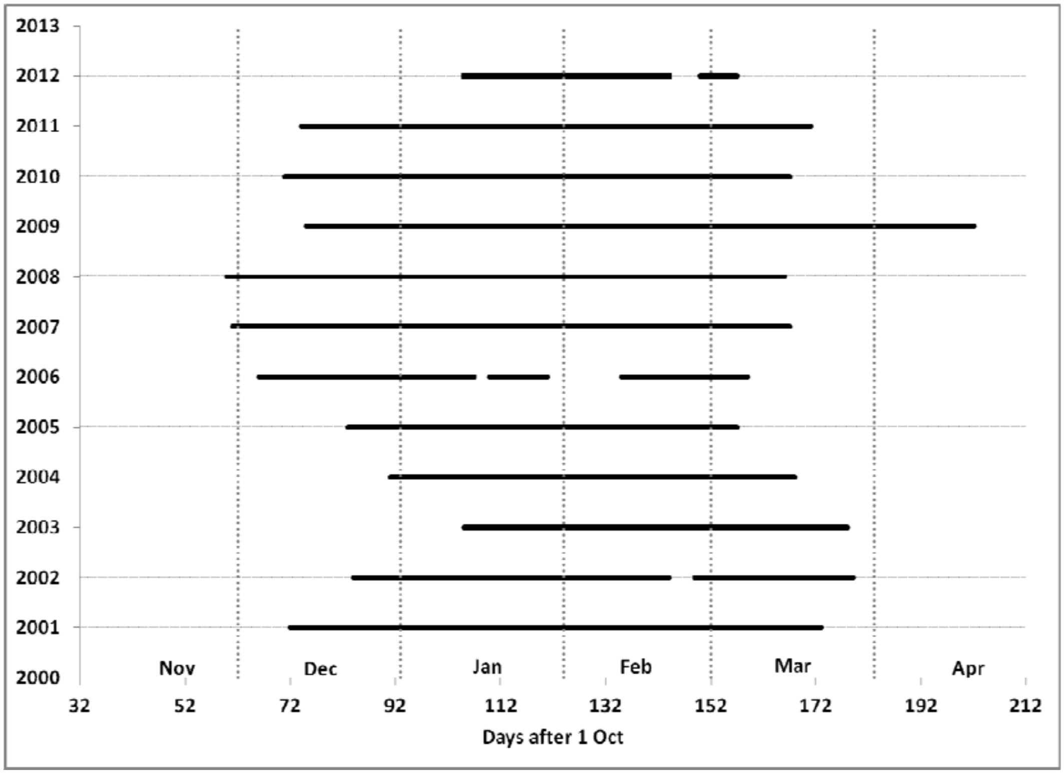

Figure 10 Ice affected flow periods in the Missouri River at Bismarck

Ice Affected Periods each Winter

The ice influenced period can be identified by plotting the combination of parameters that appear in Manning's equation. The ice covered period is then clearly identified by reviewing the value of $Q/h^{5/3}$ and also by plotting the daily observed stage vs. the daily observed discharge. The ice cover periods are shown in Figure 10 and listed in Table 2.

Table 2 Ice Affected Periods each winter

Water Year	Freezeup Date	Start of ice period	End of ice period	Additional ice periods			
				Start	End	Start	End
2001	14Dec2000	11Dec2000	22Mar2001				
2002	27Dec2001	23Dec2001	21Feb2002	26Feb2002	28Mar2002		
2003	16Jan2003	13Jan2003	27Mar2003				
2004	02Jan2004	30Dec2003	16Mar2004				
2005	26Dec2004	22Dec2004	06Mar2005				
2006	08Dec2005	05Dec2005	15Jan2006	18Jan2006	29Jan2006	12Feb2006	08Mar2006
2007	01Dec2006	30Nov2006	16Mar2007				
2008	04Dec2007	29Nov2007	14Mar2008				
2009	18Dec2008	14Dec2008	20Apr2009				
2010	12Dec2009	10Dec2009	16Mar2010				
2011	17Dec2010	13Dec2010	20Mar2011				
2012	14Jan2012	13Jan2012	23Feb2012	27Feb2012	05Mar2012		

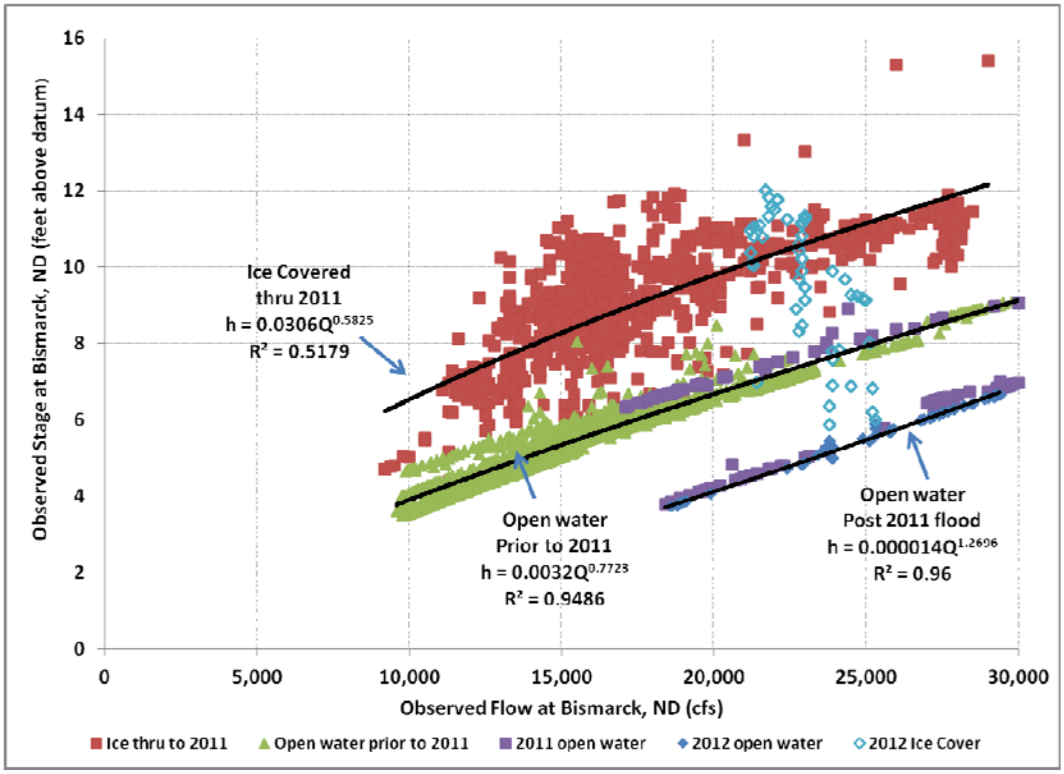

Figure 11 Open water and ice covered rating curves for period before 2011 flood and after

Open water and Ice Affected Stages

The open water and ice affected stages are plotted as a function of the discharge in Figure 11. The best-fit rating curves are also shown. There are three of four items of interest that can be seen.

- First, the increase in stage caused by the ice can be clearly seen. There is quite a lot of variation around the best fit ice covered rating curve as can be seen. This reflects the impact of the initial freezeup and then the slow decline in stage due to the ice smoothing.
- Second, there was a definite impact of the 2011 flood in changing the rating curve at Bismarck. In general, the rating curve has been lowered about two feet. The early 2011 open water data follows the pre-2011 data closely. The data at the end of the 2011 flood, the post-2011 flood data, follows the new rating curve.
- The open water data for 2012 follows the post-2011 flood data closely.
- The ice cover data for 2012 starts at the post-2011 flood rating but then rises to the same stages as the pre-2011 ice data.