ICE JAM PROCESSES AS INFLUENCED BY CLIMATIC VARIABILITY AND HYDROPOWER OPERATIONS: LOUP RIVER

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Abstract: The Loup River is the largest tributary of the Platte River and drains approximately 15,200 square miles in the State of Nebraska. Like many rivers in the region, the basin is subject to flow regime changes due to reservoirs and diversions for irrigation and hydropower. The Loup Power District operates one such hydropower plant, with flows diverted from the Loup River near Fullerton, NE, through a 35-mile canal with return flows to the Platte River downstream of the Loup River confluence. Approximately 69-percent of the annual Loup River flow is diverted for hydropower purposes in an average year.

Operational experience dictates canal flows cease when the river carries any quantity of floating ice during cold periods, to allow the canal to form a smooth ice cover and prevent entrainment of ice floes which would reduce the canal's conveyance capacity. During such periods, all flow is allowed to pass downstream through the natural river channel, carrying large quantities of ice. This operational constraint has led to the perception among local residents that these operations lead to an increased flood risk due to ice jam formation. During a recent relicensing process, FERC asked the Loup Power District to demonstrate what impact their operations may have on downstream interests, including ice processes.

Loup Power District asked the U.S. Army Corps of Engineers, Omaha District, to evaluate the impact of project hydropower (Project) operations on ice jam flooding due to any changes in hydrology, sediment transport and channel morphology on the Loup and lower Platte Rivers related to the operation of the hydropower plant. The methodology utilized included a review of flood histories, a statistical overview of climatic data, and hydraulic modeling of the study area. The statistical overview of climatic data included evaluation of temperature, snowfall, snow depth and precipitation for multiple weather stations within the study area covering a period in excess of 110 years. The climatic data was evaluated for accumulated freezing degree days (AFDD) to assess initiation of ice processes, formation of intact ice cover, thickness and quantity of ice prior to breakup and any correlation to history of ice jam flooding. Temporal trends and variability in AFDD were also assessed, as well as any correlation between snowfall depths and rainfall with occurrence of ice jams. Results of the flood history and statistical analyses of climatic data were utilized to assist in appropriate parameters for one-dimensional (1-D) hydraulic modeling of ice jam formation during freezeup and breakup periods. Two-dimensional (2-D) hydraulic modeling utilizing DynaRICE validated many of the results of the 1-D hydraulic modeling.

Results of the analyses and hydraulic modeling indicate that hydropower operations have not significantly changed the ice regime of the Loup River, nor contributed to an increased risk of

damaging ice jam flooding. The results also indicate that subtle trends in climatic variability and floodplain development may lead to an increased flood risk due to ice jams over time.

INTRODUCTION

Goals and Objectives: The goal of the study of ice jam flooding on the Loup River was to evaluate the impact of Project operations on ice jam flooding on the Loup and Platte Rivers between Fullerton, Nebraska, and North Bend, Nebraska. The study also was to develop an ice jam and/or breakup predictive model (limited to examination of Project effects), as well as identify operational or structural measures to mitigate or minimize Project effects on ice jam formation and subsequent flooding, if it was demonstrated that operation of the Project materially impacts ice jam formation on the Loup and Platte Rivers (Kay, et al, 2011).

Study Area: The study area includes the Loup River from Fullerton (approximately 7 miles upstream of the Loup Power Canal Headworks) to the confluence with the Platte River (the Loup River bypass reach), the Platte River from just upstream of the confluence of the Loup and Platte rivers to North Bend, and the Loup Power Canal from the Headworks to the Tailrace Canal confluence with the Platte River below the Loup-Platte confluence (Figure 1).

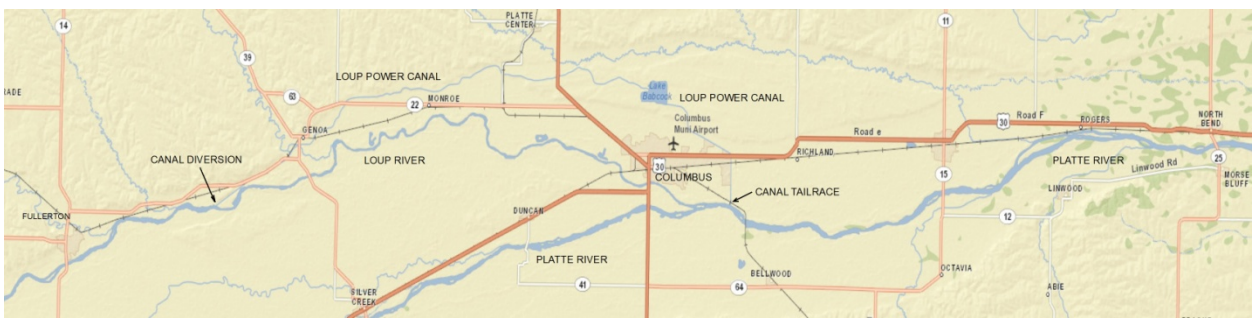

Figure 1 Study Area near Columbus, NE.

Methodology: Several methods were employed to determine if the operation of the Loup Power Canal contributes materially to the formation of ice jams along the study reach. These methods included a review of flood history, a statistical overview of meteorological data, and hydraulic modeling of the study area.

DATA COLLECTED

Flood History: A review of all available records was conducted to determine when significant flood events occurred along the study reach. The flood history was heavily influenced by Nance County Journal articles, which were some of the only records of floods before the 1930's.

Significant Floods in Lower Loup Basin: Significant floods were defined as those that resulted in loss of life and/or significant property damage. Significant floods were noted as occurring in March of either 1848 or 1849, March 1881, May 1904, February 1905, February 1907, March 1910, June 1923, April 1935, March 1936, February 1941, June 1947, February 1948, March 1960, August 1966, March 1969, February 1971 and March 1993. The 1904, 1923, 1935, 1947,

and 1966 floods were not ice-affected however. The 1960 event is not documented as being ice-affected on the Loup River, but was a significant ice-affected flood on the Platte and Elkhorn Rivers in Nebraska. For purposes of this paper, the March 1960 event is not considered an ice jam event on the Loup River.

Other Ice Related Floods: Other ice-affected floods were those that were noted as either causing low-land flooding in various records or as noted in USGS records as stage readings influenced by backwater caused by ice. There were 17 separate ice-affected flood events noted in records. USGS gaging station at Genoa indicated 32 years where the peak stage was due to backwater caused by ice; however, records prior to 1962 did not indicate the cause of backwater-influenced peak stages, so there may be as many as 10 additional years where the peak stage was influenced by ice. It was noted, however, that not all ice-affected peak stages resulted in flood stage being exceeded (Kay, et al, 2011).

Flow and Ice Thickness Measurements: The USGS maintains a network of stage-discharge gages throughout the Loup River basin. Data from two stations, listed in Table 1 below, were compiled for flow data.

Table 1 USGS Gaging Stations with Flow Data, Loup River.

Station ID	Station Name	Period of Record
06792500	Loup River Power Canal near Genoa, Nebr.	December 1936 – Present
06793000	Loup River near Genoa, Nebr.	August 1928 – June 1932, October 1943 – Present[1]

[1] Monthly Data Only, October 1953 – April 1955

Thirty sets of ice thickness measurements covering 60 years at four stations (North Loup River at St. Paul, NE; Middle Loup River at St. Paul, NE; Loup River at Genoa, NE; and Loup River at Columbus, NE) were provided by the USGS. Most ice thickness measurements were from years with below average air temperatures.

Meteorological Data: Applicable meteorological information near the study area was used, with data gathered from NOAA's National Climatic Data Center (NCDC). Temperature, snowfall, snow depth and precipitation data were collected for five stations listed in Table 2. Columbus and Genoa were selected as the primary stations for data computations, as both stations are at similar latitudes, and both have the same number of complete water year observations. Although within the study basin, St. Paul was a secondary station as its latitude is south of Columbus and Genoa, and the station has a shorter period of record. Madison and David City records were used primarily to synthesize missing daily temperature data at the two primary and one secondary station through use of multiple regression techniques.

Table 2 Climate Data Stations.

Climate Station	Period of Record
Columbus 3NE, NE	1894 – 2010
Genoa 2W, NE	1893 – 2010
St. Paul 4N, NE	1900 – 2009
Madison, NE	1895 – 1994
David City, NE	1897 – 2010

Bathymetric Data: Bathymetric surveys were collected between bank lines at 110 georeferenced cross-sections located from just downstream of the Loup Power Canal Headworks to just upstream of the Union Pacific Railroad (UPRR) bridge west of Columbus. These cross-sections were then overlain on a digital elevation model (DEM) and extended in ArcGIS to include potential overbank flow areas. HEC-GeoRAS was used to cut new cross-sections based on the extended cross-section alignments, and the surveyed cross-sections were then merged into the newly cut cross-sections and saved to a new geometry in HEC-RAS. The HEC-RAS geometry with the combined surveyed and extended cross-sections were then merged with an existing georeferenced hydraulic model geometry extending from approximately one mile downstream of the Platte-Loup confluence to upstream of the UPRR bridge west of Columbus to create a geometry extending from the Platte River at the Loup Canal Tailrace upstream to the Loup River at the Loup Power Canal Headworks Diversion. The bathymetric data, in conjunction with the DEM was also used to create a two-dimensional grid for modeling ice transport and jamming processes near the Loup Power Canal Headworks and near Columbus.

ANALYSIS

Statistical Analysis of Climatic Data: Freezing degree days (FDD) are a measure of daily average air temperature departure from freezing (32°F/0°C), with temperatures below freezing resulting in a positive FDD value and temperatures above freezing resulting in a negative FDD value. FDD can be cumulatively summed through the winter season, providing accumulated freezing degree days (AFDD), which can be used as a measure of a winter's severity. Statistical analysis of AFDD, coupled with physical measurements of ice, snow and rain, were performed to determine if the frequency and/or severity of ice jam formation has changed since commencement of Project operations.

Statistical Analysis of AFDD: The Project must cease diversions through the canal when moving ice is present on the Loup River, so the AFDD required to initiate ice production (and hence movement) in the Loup River were computed based on dates when Project flows, as recorded by USGS at Station 06792500, dropped to near zero. The AFDD required to form a stable ice cover on the Loup River (hence cessation of ice movement and resumption of Project operations) was also determined and was based on dates when Project flows returned to near normal. The annual peak AFDD value ($AFDD_{max}$), changes in AFDD during the months of January, February and post-February (referred to as $AFDD_{month}$), the change in AFDD in the 21 days preceding $AFDD_{max}$ ($AFDD_{-21}$), and the change in AFDD in the 7 days following $AFDD_{max}$ (MDD_{+7}, or melting degree days), as well as relationship between $AFDD_{max}$ and increases in Loup River discharge following $AFDD_{max}$ were all compiled as well.

Temporal Trends in AFDD: Trend analyses were performed to determine if AFDD data has changed over time, looking at annual $AFDD_{max}$ values, annual $AFDD_{month}$ values, cyclical changes in $AFDD_{max}$ over periods of 5, 10 and 30 years, annual $AFDD_{-21}$ values, annual MDD_{+7} values, and the change and variability in the Julian date of $AFDD_{max}$ (JD_{max}, where JD=1, or JD_1, is October 1 of each Water Year).

Ice Thickness Computations: Measured ice thicknesses and AFDD data from the nearest climate station were used to back-compute the coefficient for the modified Stefan equation.

Estimate Ice Thickness for Historic Ice Jams: Ice thickness values for each year just prior to breakup were estimated based on the $AFDD_{max}$ for each year, as well as a range in modified Stefan equation coefficients as determined from the statistical review of actual ice measurements.

Relationship Between Snow Cover and/or Rain and Ice Jams: Snow depth (measured on-ground depth) and snow accumulation (accumulated seasonal snowfall depth) data at Genoa and Columbus were compiled, and temporal relationships between snow cover and temperatures were analyzed, as well as any relationships between snow accumulations and $AFDD_{-21}$ and MDD_{+7} (limited to years with documented ice jams).

<u>HEC-RAS Modeling</u>: The HEC-RAS model was calibrated to the most recent rating curve at the Genoa gage for open water flows up to 3,000 cfs to determine the channel n-value. Higher flows were then used to calibrate overbank n-values to the Genoa gage rating curve. Flows for with- and without project hydrology were provided from the Loup Power study report (Loup River Public Power District, 2012).

Ice Formation and Freezeup Jam Formation: Flows representing the 10-, 25-, 50-, 75-, and 90% by duration flows for the months of November, December, and January (typical months for an ice cover to form) were modeled in conjunction with an ice cover. The ice n-value and thickness varied with channel velocity based on previous observations by the author and experience. Multiple iterations were needed to evaluate velocities and adjust ice n-values and thicknesses to achieve a stable ice cover consistent with velocity results.

The ice cover geometry was then adjusted to allow jamming at all cross-sections with the 10% exceedance flow to identify the most likely locations for freezeup jams to form based on available channel flow area, ice thickness, profile increase and constrictions and bends in the river. Nine potential jam locations were identified in this manner. Areas that consistently had velocities too high to allow stable ice cover formation were identified as well.

Ice Breakup and Breakup Jam formation: In order to model breakup ice jams accurately, an estimate of the volume of ice in the river prior to breakup must be known. Two single layer ice thicknesses were modeled, based on results of AFDD computations with the modified Stefan equation for average AFDD and 1-standard deviation above average AFDD at breakup to determine the initial volume of ice available at initiation of breakup. Ice jams were allowed to form at the previously identified 9 locations, with 4 locations adjusted either upstream or downstream to allow for more realistic ice jam shape and size. The upstream extent of each ice

jam was determined based on the volumes of ice previously computed and reduced by 50% to allow for broken ice pieces that are pushed into overbanks and ice that melts during transport into the jam location. Flows modeled for breakup jams were the 0.5-, 0.2-, 0.1-, 0.05-, and 0.02% ACE event assuming both current operations and no canal diversions allowed.

DynaRICE Modeling: Modeling the transport of ice floes is beyond the capabilities of a one-dimensional model such as HEC-RAS. Therefore, the two-dimensional DynaRICE ice-hydraulic numerical model was used to simulate ice transport in the Loup River, as well as ice jam initiation. The primary purpose of the DynaRICE modeling was to determine if there were any differences in ice formation and ice jamming processes with and without diversions into the Loup Power Canal. The model was calibrated against UGSG data and highwater marks from the 1993 flood near Columbus.

Two flow conditions representing 3,400 and 2,000 cfs (flows exceeded 25% and 50% of the time during freezeup conditions) were modeled for freezeup conditions near the headworks; lower flows were not modeled as the bathymetry was too coarse to accurately model shallower flows. Two historic breakup ice jams, 1969 and 1993, were simulated at Columbus as well.

RESULTS OF ANALYSES

Some of the more significant results are summarized in the following section. A more complete record of results may be found in Kay, et al (2011).

Frequency and Severity of Flooding: The record indicates 12 significant ice jam related floods and 6 open water floods along the Loup River between Genoa and Columbus between 1848 and 2010. However, records prior to the late 1800's are inconsistent, and it is possible that there are undocumented flood events during this period. Table 3 below compares the number of floods during the known period of record, including pre-Project and post-Project operations.

Table 3 Occurrence of Documented Significant Floods Before and After 1937.

Period of Record	**Number of Documented:**		**Annual Probability of:**	
	Ice Jam Floods	*Open Water Floods*	*Ice Jam Floods*	*Open Water Floods*
1848 – 1936 (88 years)	7	3	0.0795	0.0341
1893 – 1936 (43 years)	5	3	0.1163	0.0698
1937 – 2010 (73 years)	5	3	0.0685	0.0411

As can be seen, the annual probability of ice jam related flooding appears to be higher in the years preceding Project operations. The decrease in probability of ice jams cannot be credited towards Project operations, but it does discount the idea that Project operations have increased the frequency of significant ice jams. It is notable that in every year that a significant Loup River ice jam has occurred since Project operations commenced, one or more significant ice jams occurred on other Nebraska streams of similar characteristics, such as the Platte and Elkhorn Rivers. This tends to support the occurrence of ice jams as regular natural process, given the right set of ice and meteorological conditions preceding the ice jam event, irrespective of Project operations.

The occurrence of ice jams relative to meteorological conditions was also examined. Although an $AFDD_{max}$ of 1000 has about a 20% annual chance of occurrence (see Figure 2), 70% of the documented ice jams since 1905 occurred in years with $AFDD_{max}$ exceeding 1000. However, the flood of 1907, which caused four fatalities in Columbus, occurred in a year with near average $AFDD_{max}$. An $AFDD_{max}$ exceeding 1000 does not constitute a certainty of having an ice jam; less than one-third of years with $AFDD_{max}$ exceeding 1000 experienced a significant ice jam. It is noted that $AFDD_{max}$ is consistently greater at Columbus than the other stations. Since ice growth and thickness is directly correlated to FDD, it is possible that ice thickness is greatest at Columbus, which may lead to a greater risk of breakup ice jam formation at Columbus, as greater force would be required to lift, break up and transport a thicker intact ice cover.

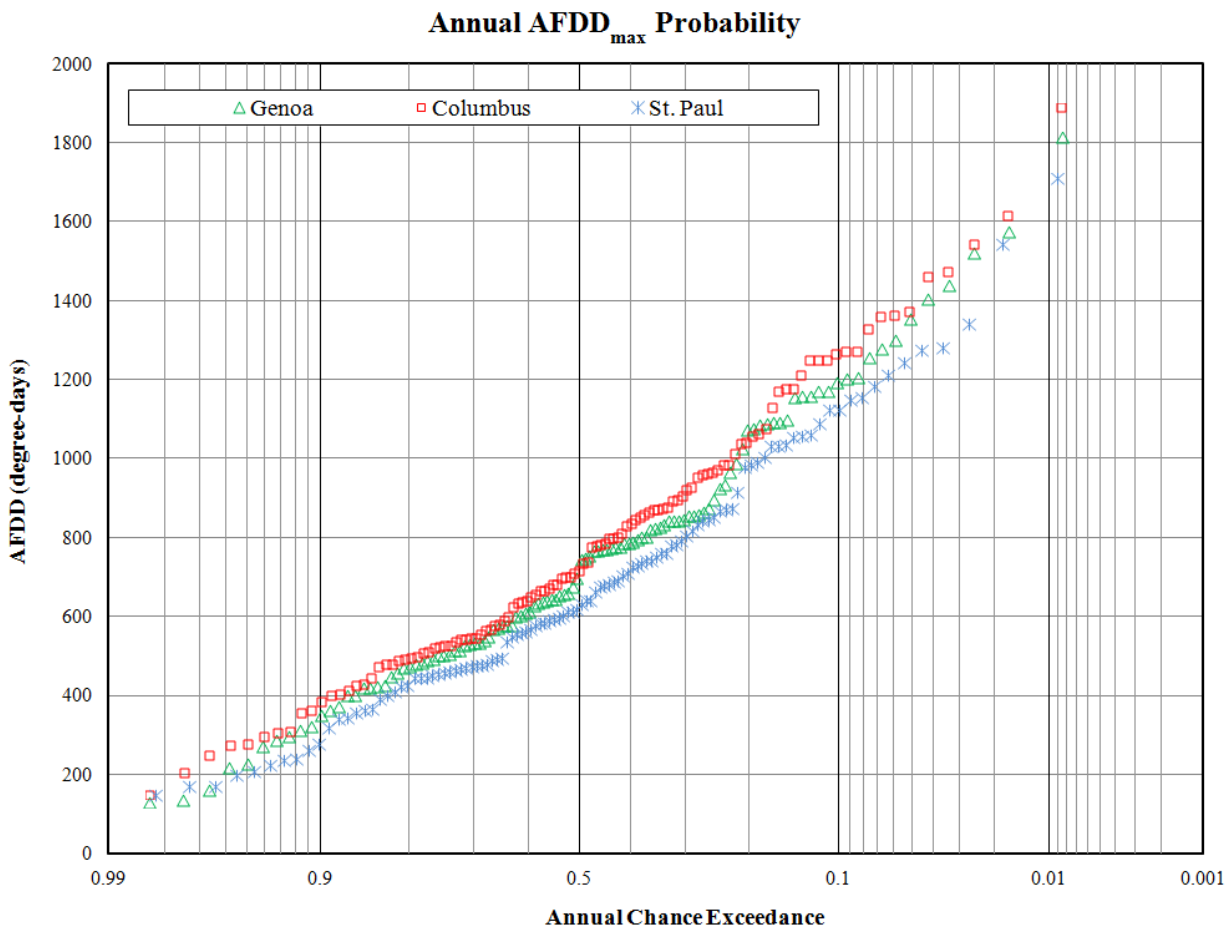

Figure 2 Annual $AFDD_{max}$ Probability at Genoa, Columbus and St. Paul.

The $AFDD_{-21}$ values may be an indicator of ice jam occurrence. Kay (2007) notes that more MDD are needed to initiate ice cover breakup on the Platte River in years with higher $AFDD_{-21}$ values. This is presumably due to greater ice growth (and hence less ice deterioration) immediately preceding ice breakup, leading to an ice cover with greater strength and therefore higher probability of resulting in jam formation. Sixty percent of the documented significant ice jams occurred in years with above average $AFDD_{-21}$. When the occurrence of $AFDD_{max}$ is

coupled with above average $AFDD_{-21}$, only 2 years, 1918 and 1893, had no documented significant flood; all other years with this combination of $AFDD_{max}$ and $AFDD_{-21}$ had significant ice jam flooding.

Likewise, higher values of MDD_{+7} may also indicate a greater likelihood of ice jam formation. White and Kay (1996) discuss that thawing degree days may be indicative of the rapidity of snowmelt but was weakly correlated with stage (i.e., severity of flooding) on the Platte River in Nebraska. Kay (2007) notes that MDD_{+7} is correlated with the increase in discharge in the 2 days preceding the peak discharge associated with an ice breakup event on the Platte River at North Bend, Nebraska. For the Loup River, 70% of the documented significant ice jams occurred in years with above average MDD_{+7}. A combination of $AFDD_{max}$ exceeding 1000 and above average MDD_{+7} results in a 50% chance of significant ice jam formation.

A review of precipitation data indicates that years with a high snow accumulation generally correlate with high discharges on the Loup River, although there was no correlation between snow accumulation and discharge with the occurrence of ice jams. However, it was noted that 80% of ice jams occurred in years with above average snowfall, and 60% of the significant ice jams occurred with snowfall in the 20th percentile or higher. Only 1 significant ice jam formed in a year with a below average $AFDD_{max}$, and that was due to a rainfall event occurring on top of an existing snowpack, which indicates that rainfall may increase the probability of ice jam formation.

Although no factors point to Project operations contributing to ice jam severity, floodplain development may be a significant contributor to the severity of ice jam flooding along the lower Loup River. Floodplain development at Columbus that may impact stages include a levee along the left bank of the Loup River, highway and railroad embankments crossing the right overbank, as well as a residential development in the right overbank surrounded by a ring levee. Notable backwater under ice-affected conditions in the vicinity of the residential development and Highway 81 road crossing were noted by USACE (1994), as well as a reduction in floodplain conveyance due to these right overbank developments (USACE, 1996).

Temporal Climatic Trends: Trend analyses were performed on $AFDD_{max}$, $AFDD_{-21}$, MDD_{+7} and $AFDD_{month}$ at each of the three climate sites. It is noted that the value in any particular year is random, as a year with low $AFDD_{max}$ may be followed by a year with high $AFDD_{max}$. None of the data shows an obvious trend when looking at the entire record, as each data set exhibits a very low correlation coefficient due to the year-to-year variability. The trends over the period of record for the various parameters noted above are shown in Table 4.

Table 4 Annual Rate of Change of Key Climate Data Related to Ice Jam Formation.

Parameter	**Annual Change in Value over Period of Record at:**		
	Columbus	*Genoa*	*St. Paul*
$AFDD_{max}$	-0.34	-1.21	-0.24
$AFDD_{-21}$	-0.69	-0.32	-0.30
MDD_{+7}	+0.01	-0.04	-0.10
$AFDD_{Jan}$	+0.21	-0.13	-0.01
$AFDD_{Feb}$	-0.86	-1.15	-0.81
$AFDD_{Mar}$	+0.06	+0.07	+0.27

The general trend in data points to slight warming with time, although the magnitude of this increase varies with parameter and location. Two of the strongest trends are in $AFDD_{-21}$ and $AFDD_{Feb}$; both of these are significant in regards to ice breakup, as ice breakup tends to occur in late February or early March, so both $AFDD_{-21}$ and $AFDD_{Feb}$ would be indicative of ice growth just prior to breakup. The warming trend shown for both $AFDD_{-21}$ and $AFDD_{Feb}$ would indicate that breakup ice jams in the future may be less severe on average, as the ice would tend to be slightly thinner and weaker with less AFDD prior to $AFDD_{max}$ occurring. It may also indicate, however, that the ice cover will break up more readily, leading to more frequent ice jams. This may also indicate that the average ice breakup date may occur earlier on average; however, this may be offset by the slight cooling shown for $AFDD_{Mar}$ and MDD_{+7}. $AFDD_{max}$ also shows a downward trend at all three sites, which would also tend to indicate that ice jams may become slightly less severe in the future, as ice thickness would be slightly reduced, on average.

$AFDD_{max}$ does not just exhibit a downward trend, as a review of 5-, 10-, and 30-year averages of $AFDD_{max}$ indicate a cyclical nature with $AFDD_{max}$ trending up and down on a 25-35 year cycle. The Figure 3 below shows the 5-, 10- and 30-Year $AFDD_{max}$ averages at Columbus over the period of record. Similar trends were noted at both Genoa and St. Paul, although the cyclical nature of the data is not as pronounced at St. Paul. It is likely that the cyclical nature of the data will continue into the future, which would indicate that the next 10 years should likely be a period of higher $AFDD_{max}$.

A comparison of the 30-year average in $AFDD_{max}$ with the occurrence of significant ice jams can be seen in Table 5. It appears from this data that the occurrence of significant ice jams is decreasing in frequency. This data also indicates that ice jams are twice as likely to occur, on average, during periods of higher $AFDD_{max}$ than periods of lower $AFDD_{max}$. This is likely due to the high $AFDD_{max}$ periods having about a 30% probability of $AFDD_{max}$ greater than 1000, while the low $AFDD_{max}$ periods have about a 10% probability of $AFDD_{max}$ greater than 1000. This would indicate that ice jams should occur about three times more frequently during periods of high $AFDD_{max}$ as opposed to low $AFDD_{max}$, if $AFDD_{max}$ greater than 1000 was the sole indicator of ice jam formation. Since the record seems to indicate that periods of high $AFDD_{max}$ are only twice as likely to have ice jams than periods of low $AFDD_{max}$, it is apparent that there are factors other than high AFDD that determine the likelihood of an ice jam occurring.

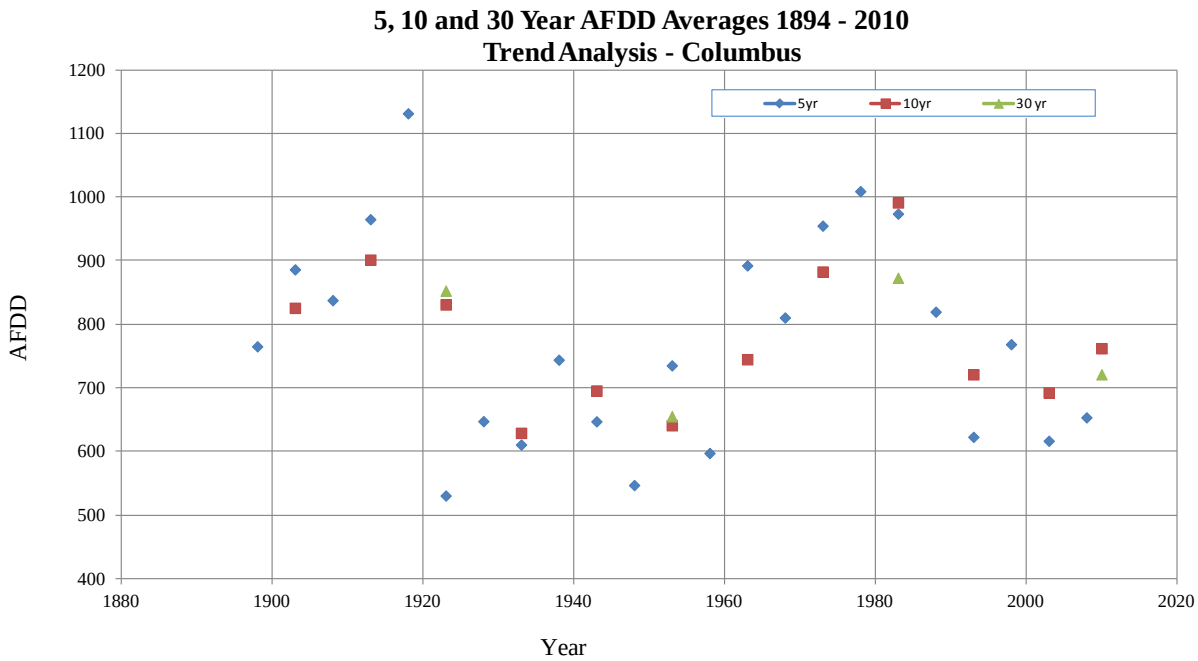

Figure 3 Average $AFDD_{max}$ Over Various Periods of Time.

Table 5 30-Year Average $AFDD_{max}$ and Ice Jam Occurrence.

	Genoa	Columbus	St. Paul	Number of Significant Ice Jams
1894 – 1923	822	853	-	4
1924 – 1953	656	655	614	3
1954 – 1983	831	872	809	2
1984 - 2010	636	721	600	1

A final trend analyzed was the Julian Date of $AFDD_{max}$ (JD_{max}), assuming JD_1 corresponded with the start of the water year on October 1, JD_2 with October 2, etc. Generally, the date of $AFDD_{max}$ is a good precursor to determining when the river ice will breakup, although in some years, most noticeably 1993, the breakup occurred prior to $AFDD_{max}$ being achieved. A review of JD_{max} over the period of record indicates that JD_{max} is occurring between 0.8 to 1.4 days earlier per decade, depending on location. This is consistent with the trends shown in Table 4 as well, as warmer temperatures will on average lead to $AFDD_{max}$ being reached at an earlier date. When the JD_{max} and $AFDD_{max}$ are averaged by decade, both show the same general cyclical trends noted in Figure 3 and shown in Table 6. However, the standard deviation of JD_{max} shows a marked increase during the past 20 years, while standard deviation of $AFDD_{max}$ does not. The reason for this significant increase in variability in JD_{max} is not readily apparent. However, it may be indicative of a more variable weather pattern with more sustained warming periods, generally occurring earlier, which would be consistent with the inter-decadal change in JD_{max} occurring earlier, as well as the decreases in $AFDD_{-21}$ and $AFDD_{Feb}$ noted earlier in this paper.

Table 6 Trends in $AFDD_{max}$ and Julian Date of $AFDD_{max}$ (JD_{max}) by Decade.

	Genoa				**Columbus**				**St. Paul**			
	Average:		*St. Dev.*		*Average:*		*St. Dev.*		*Average:*		*St. Dev.*	
	JD	*AFDD*	*JD*	*AFDD*	*JD*	*AFDD*	*JD*	*AFDD*	*JD*	*AFDD*	*JD*	*AFDD*
1890s	164	929	14.3	268	161	842	13.2	365	n/a	n/a	n/a	n/a
1900s	146	793	11.9	308	146	841	11.7	336	146	634	11.9	284
1910s	157	875	14.3	389	158	987	11.5	412	157	803	14.3	331
1920s	138	624	16.8	229	141	647	15.7	237	136	649	24.1	264
1930s	144	668	16.6	436	143	641	16.0	418	138	626	21.6	393
1940s	163	643	12.2	267	153	648	19.7	251	157	573	17.1	264
1950s	151	682	18.0	250	147	662	17.1	248	141	671	21.0	252
1960s	153	816	14.6	279	154	863	13.8	266	154	824	14.5	273
1970s	147	967	14.9	398	147	1036	14.1	400	146	988	14.6	425
1980s	141	704	14.5	329	142	759	15.6	329	142	759	15.6	329
1990s	136	597	32.9	329	136	652	37.8	317	134	638	38.0	338
2000s	141	628	22.0	313	149	766	15.5	335	139	539	23.6	261

Hydraulic Modeling: Results of the HEC-RAS modeling indicate 9 locations where freezeup jams are most likely to occur between Columbus and the Loup Power Canal Headworks. These results also show that stages are higher in the Loup River when all flows are passed down the Loup River; however, this is due strictly to the higher flows, rather than any change in ice regime. Perhaps somewhat surprisingly, there was no difference between no-diversion and diversion flows in producing stretches of river where velocities are too great to sustain a stable ice cover (except via upstream progression of a downstream ice cover increasing dynamically from upstream ice transport). This indicates that regardless of Project operation, there are certain reaches of the river that can, under the right circumstances, produce significant volumes of frazil ice, which would materially impact the potential for ice jams to occur, as the volume of the ice cover can greatly increase.

The HEC-RAS modeling also indicates 8 locations where breakup jams are most likely to form, all of which correlate with historic accounts of various ice jams of varying severity. There was one historic location, however, that the HEC-RAS model did not predict as forming an ice jam, which was just downstream of the Highway 81 bridge at Columbus, where the 1969 and 1993 ice jams formed. This may be due to a lack of detailed channel bathymetry in this location, rather than an issue with the HEC-RAS ice routine.

The DynaRICE modeling showed a freezeup jam occurring in the bend just downstream of the Genoa gage, with a thin ice cover progressing upstream towards the Canal Headworks with Loup River flows of 2000 cfs or greater, which correlated very closely with ice jam locations predicted in the HEC-RAS modeling for similar discharges. Although HEC-RAS cannot presently simulate the dynamic growth of an ice cover or ice jam, the DynaRICE modeling appears to validate the location of ice jam formation selected by the HEC-RAS modeling. The results of both modeling efforts seem to indicate slightly greater volumes of ice produced in the Loup River between the Canal Headworks and Columbus, although this slight increase in volume does not appear to contribute to a significant stage increase during ice cover formation, nor does it contribute significantly to the volume of ice available at breakup to form an ice jam.

CONCLUSIONS

A review of flood history shows that the occurrence of significant ice jam flooding has not increased since the Loup Power Canal commenced operations. A lack of historical data precludes a similar comparison of minor ice-affected flooding; however, a thorough review of climatological data and use of hydraulic models does not show a difference in the occurrence of minor ice-affected flooding due to operation of the Loup Power Canal. Other factors, such as climatic variability and floodplain developments may lead to an increased flood risk during an ice jam; however, as these factors are often subtle over time, they may be overlooked as a cause of increased flood risk. It is the opinion of the author that the Loup Power Canal has not significantly changed the ice regime of the Loup River between the Headworks and its confluence with the Platte, nor has it increased the risk of significant ice jam flooding.

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