"River Ice Jams in Iowa – Historical Evaluation, Impacts, and Predictability"

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Abstract

Ice jams are a common characteristic of Iowa winters, as it often gets cold enough for many of Iowa's river systems to freeze. There are two main types of ice jams- freeze-up and break-up. Freeze-up ice jams occur during the early winter months, and are often made of frazil ice, which is white and fine-grained. Break-up ice jams occur during the late winter months, as spring begins to emerge. Break-up ice jams pose a significant threat, as large chunks of ice tend to aggregate and cause flooding and damages to infrastructure. Current methods of predicting the likelihood of break-up ice jams uses accumulated freezing degree days to estimate the thickness of the ice as an indicator of the level of damages an ice jam could possess. Forecasters are also on the look-out for warming patterns and precipitation which could accelerate ice thaw and cause the ice to break-up, flow down river, and possibly jam. This study focuses on the meteorological and hydrological conditions that are most indicative of the possibility of a break-up ice jam by analyzing six locations in Iowa during years they experienced ice jams and years they did not. It was found that years that experienced ice jams observe not only more days below freezing (AFDD), but also more days below 20 F. It was also found that ice jam years observe more precipitation due to an increase in monthly average discharge during ice jam years as compared to non-ice jam years. Therefore, years that are colder and wetter are at the greatest risk for ice jam formation and thus break-up ice jams. Once a freeze-up ice jam occurs, it was found that certain meteorological conditions tend to support the break-up process on a shorter timescale. Warming patterns where temperatures reach at least 42 F over the span of 3 days or more along with relative humidities above 70% will cause ice to melt and break-up. This research found that along with the usefulness of AFDD to estimate ice thickness, it is also important for forecasters to evaluate the number of days where the max temperature was below 20-15 F. This temperature threshold was the largest distinction between ice jam and non-ice jam years.

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1. Introduction

Ice jams and associated ice jam floods are lesser-known forms of extreme weather in river and stream systems during the cold winter months. Ice jams present significant risks to economic and ecological systems due to the destructive flooding associated with these events.

Over 60% of the Northern Hemisphere rivers experience significant seasonal effects of river ice (**Rokaya et al. 2018**). During the early winter months, November to December, layers of ice will begin to freeze and re-freeze in distinct layers (**Figure 1**). The likelihood of the frozen layers of ice breaking apart increases between December and March as temperature patterns begin to rise and warm. During break-up ice jams, large ice sections will begin to dislodge and flow downstream once the hydraulic resistance, or the ability to resist the flow of water, of the ice is exceeded by the backup of water upstream and beneath the ice (**Figure 2**). Once the break-up occurs, large chunks of ice from the freeze-up flow downstream where they may begin to accumulate and jam as the river's ice transport capacity is met (**NWS Great Falls, MT, 2018**).

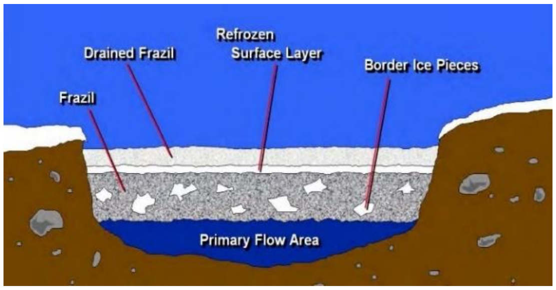


Figure 1 illustrates the cross-section of a freeze-up ice jam. Distinct layers of frazil ice and re-frozen surface layers make up the majority of the freeze-up. The primary flow area is restricted beneath the layers of ice. Here, the ice's hydraulic resistance is not exceeded, so the primary flow is contained beneath the ice. Image provided by **CRREL, 2017**.

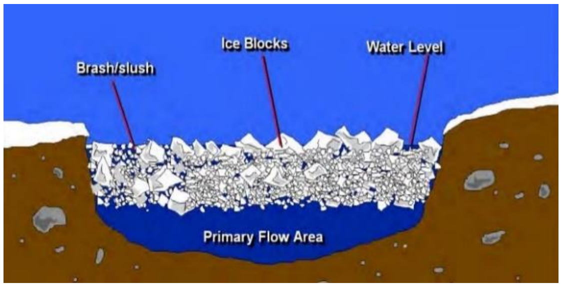


Figure 2 illustrates the cross-section of a break-up ice jam. There are no distinct layers and instead is made up of blocks of ice and slush. The ice's hydraulic resistance is exceeded by the water flow, which aided in the break-up of the ice. The primary flow is now able to rise and transport the ice downstream. Image provided by **CRREL, 2017.**

Ice jams are caused by either the freeze-up (early winter) or the break-up (late winter), as previously mentioned, of frazil and columnar ice. When the ice breaks up and flows downstream, it becomes anchored, or built up, in a river due to various hydrologic and artificial characteristics such as gentle riverbed slopes, low flow velocities, small stream sizes, and infrastructure from damns or bridges. Frazil ice, otherwise known as white ice, is fine-grained, resistant to solar penetration, and tends to occur in more dynamic and turbulent river flow. Columnar ice, or black ice, is thermally grown and will decay rapidly due to heat absorption.

As the ice thickens and increases throughout the winter, so does the likelihood of it breaking up and mobilizing downstream. Therefore, it plays a large role in the predictability of ice jams. The thickness of columnar ice can be estimated using heat transfer theory, which describes how energy in the form of heat flows from warm to cold bodies. However, frazil ice is much more common and plays a large role in anchoring river ice as described by the Granular Flow Theory, which is used to estimate the angle of frazil ice as it breaks off downstream. Accumulated Freezing Degree Days is a widely used method for anticipating break-up events affected by frazil ice. Since the thickness of frazil ice is not easily quantifiable or observed, a commonly used rule of thumb suggests that for every four days with observed temperatures below 0 degrees Celsius, one inch of ice is formed in river streams susceptible to freezing over. (**UCAR, 2006**). Therefore, rivers with a large amount of ice formed throughout the winter will pose the most significant risk of a break-up ice jam.

Once the ice jam occurs, the threat of significant flooding is expected because the primary flow of water that was initially restricted underneath the ice can now surge over the ice at higher flow velocities. Floods caused by ice jams can be considerably more devastating than most open water floods as ice aggregates and leads to increases in water level underneath and upstream from the ice accumulation. When the ice jam's hydraulic resistance is exceeded, water is forced over the ice jam. The high water levels accumulated are forced outward over a shorter temporal scale (**Rokaya et al. 2018; Beltaos 2011**). Flood levels associated with ice jams can be considerably greater than open water flood levels, even when discharge rates are equivalent or, in some cases, lower (**Rokaya et al. 2018**).

In areas prone to ice formation in rivers, necessary precautions can be taken to prevent the often catastrophic effects of break-up ice jams. Current methods to mitigate these effects include the implementation of ice motion detectors, trained observers, mechanical weakening and breaking of ice, dusting, and ice control structures. These mitigation strategies aim to increase the lead time before the occurrence of an ice jam to preserve life and property. However, these mitigation strategies are very costly and often come with increased risks and uncertainties (**CRREL, 2017**).

The prediction of ice jams is difficult and complicated due to the wide range of hydrologic and meteorological variables leading to these processes. Currently used methods to predict break-up ice jams remain highly empirical and unique to each site where an ice jam may occur (**Madaeni et al., 2020**). In other words, there is no method of predicting break-up ice jams that applies to the real world in a general sense. Many limitations, including ice jam occurrence, varying levels of severity, and timing, contributes to the challenge of forecasting and predicting break-up ice jams.

Communities along river systems are at the most significant risk for economic and ecological damage due to the ice jams and associated flooding. Thus, these locations must possess the capability to anticipate the probability of ice jam formation and, as a result, work to mitigate its effects on the surrounding communities.

This paper analyzes 30 years' worth of meteorological and hydrological data associated with six locations in Iowa. Meteorologically, maximum temperature, relative humidity, precipitation, and accumulated freezing degree days are calculated and collected. Hydrologic information includes watershed and drainage basin area, average monthly discharge for each of the ice jam affected streams. The focus of this research is to discover the conditions that are indicative of ice jam formation and break-up to provide a better method of forecasting for ice break-up. This will be done by making connections between the meteorological setup of the atmosphere and the hydrological characteristics of the streams, and analyzing these connections in search of patterns and indicators of potential ice jam formation for any given year, particularly in Iowa.

2. Data and Methods

The first steps in this research project include selecting ice jam cases that represent the spatial and temporal scales, which is, in this case, Iowa over 30 years. From here, long term meteorological and hydrological observations from November 1st to April 1st, and short term meteorological and hydrological observations preceding the event by 1-3 weeks were used to analyze the conditions indicative of break-up ice jams.

2.1. Case Selection

All of the known ice jam events in Iowa from 1990 to 2019 were organized by date, location, and river, provided by the Des Moines National Weather Service Office (**Appendix A**). Sites with six or more recorded ice jams were selected, organized, and compared by date. In the past thirty years, six locations along four different river systems in Iowa have experienced consistent and significant ice jam events- Beaver Creek in New Hartford, Des Moines River in Fort Dodge, Iowa River in Marshalltown, and Raccoon River in Jefferson, Des Moines, and Van Meter (**Figure 3**).

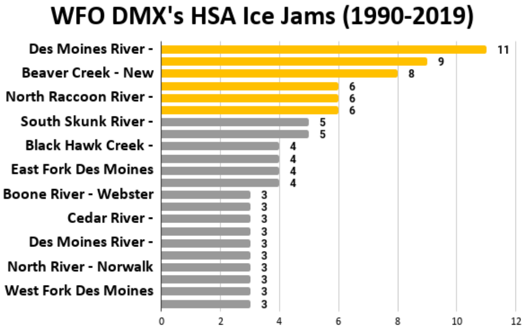
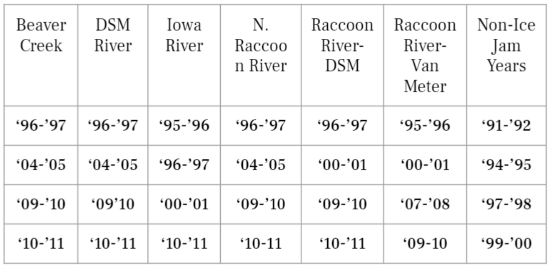


Figure 3 illustrates the number of recorded ice jam events in Iowa from 1990 to 2020. Only locations that recorded at least three ice jams are included in the figure. The gold-colored bars represent the locations analyzed in this project.

The six locations chosen experienced a break-up ice jam event during the years detailed in **Appendix A**. This project focused on consistencies in the dates of occurrence to analyze the conditions of winters that were more favorable for ice jam formation and compare them to years with no ice jam event activity, detailed in **Figure 4**. Various meteorological (see section 2.2) and hydrological (see section 2.3) variables were collected and organized by location and dates of interest to determine how certain conditions affect ice jam formation's favorability.



Beaver Creek	DSM River	Iowa River	N. Raccoon River	Raccoon River-DSM	Raccoon River-Van Meter	Non-Ice Jam Years
‘96-’97	‘96-’97	‘95-’96	‘96-’97	‘96-’97	‘95-’96	‘91-’92
‘04-’05	‘04-’05	‘96-’97	‘04-’05	‘00-’01	‘00-’01	‘94-’95
‘09-’10	‘09’10	‘00-’01	‘09-’10	‘09-’10	‘07-’08	‘97-’98
‘10-’11	‘10-’11	‘10-’11	‘10-11	‘10-’11	‘09-10	‘99-’00

Figure 4 organizes the winters analyzed for each location and the winters that observed no ice jams anywhere in Iowa. Many of the sites observed an ice jam during the same winter, indicating an especially active period.

Figure 4 organizes the winters analyzed for each location and the winters that observed no ice jams anywhere in Iowa. Many of the sites observed an ice jam during the same winter, indicating an especially active period.

To provide quality control of the data from the six locations chosen for this study, two sites were selected- Des Moines and Waterloo. These two ASOS sites and their river basins, Middle Cedar and North Raccoon, respectively, were the most representative of all of the areas in the Iowa ice jam database. The following methods were applied to both control sites as well as the six locations of interest.

2.2. Meteorological Data and Analysis

Ice jam observation data provided by the Des Moines National Weather Service office, as well as Cooperative Observer Program (COOP) meteorological data from the Applied Climate Information System (xmACIS) database and the Iowa Environmental Mesonet Automated Surface Observing System (ASOS), were primarily used to determine what the meteorological set up was during the long term and short term temporal scales before the ice jam events at the 6 locations of interest. Multiple data sites were selected to provide a broad understanding of the meteorological conditions not only at the site of the ice jam but in the surrounding region as well (**Figure 5**).

From the observational data, temperature patterns and precipitation events were used to indicate the meteorological environment that is susceptible to ice jam formation. More specifically, break-up ice jams as these are the most common and dangerous.

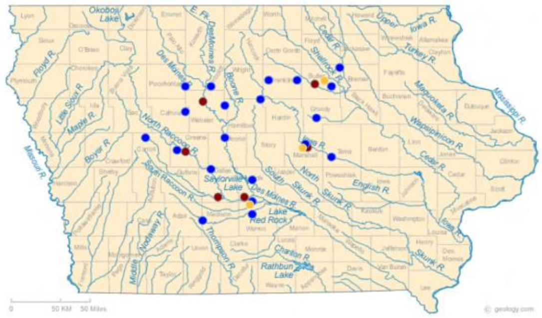


Figure 5 displays the locations of the USGS stream sites (red markers), the COOP sites (blue markers), and ASOS sites (yellow markers). The COOP and ASOS sites provide a more comprehensive view of the meteorological setup in the USGS site areas before, during, and after the ice jam event.

Three variables have been previously cited as having the most considerable impact on ice jam formation and break-up- accumulated freezing degree days, ice thickness (long term observations), and sudden warming trends (short term observations) that precede the events (**CRREL, 2017**).

Accumulated freezing degree days (AFDD) is defined as the total number of days below freezing, or 32 degrees Fahrenheit. AFDD was used to estimate the thickness of the ice at the locations in question by applying a simple calculation to the meteorological data observed from November 1st to April 1st during ice jam years and non-ice jam years. **Equation (A)** describes how the ice thickness (It) is approximated by taking the square root of the AFDD. Temperatures observed beginning November 1st preceding the event contributed to the AFDD used to calculate ice thickness.

$$I_t = \sqrt{AFDD} \qquad \textbf{(A)}$$

Ice thickness plays a large role in the severity of ice jams because the thicker the ice, the larger the chunks of ice that can be expected should a break-up ice jam occur. Once these large chunks of ice begin to anchor and jam, it will be harder to release the jam without the aid of mechanical methods. Therefore, the likelihood of flooding associated with break-up ice jams increases. On the other hand, thicker ice will require a more substantial increase in temperatures to thaw enough to lead to break-up.

Further long term meteorological observations were also collected from November 1st to April 1st during all ice jam and non-ice jam years studied. The total number of days that met the following criteria were variables of interest:

- $T_{max} \leq 20$ F
- $T_{max} \leq 0$ F

, where Tmax is the maximum temperature observed for a day. The purpose of this data is to provide other possible indicators of ice jam formation and break-up.

For short-term analysis, the temperature patterns immediately preceding an event alludes to the meteorological conditions that ultimately caused the ice to break up. More specifically, maximum temperature observations from 1-3 weeks before the event were used to determine the number of days above 42 degrees Fahrenheit. An overall warming pattern in the region of the locations will indicate possible snowmelt and runoff. Precipitation runoff into the stream system will not only increase the discharge rate behind the jam. It will also increase the rate at which the ice over the stream melts and breaks-up.

Furthermore, relative humidity observations preceding an event by one week was also recorded. Moist conditions aid in the melting of ice due to the laws of thermodynamics. As moisture is deposited on the surface of ice through condensation, heat is released, and thus the ice can melt.

2.3. Hydrological Data and Analysis

The following stream conditions were collected from the Cold Regions Research & Engineering Laboratory (CRREL) and the U.S. Geological Survey (USGS):

- Hydrologic Basin
- Drainage Area (mi^2)
- Average Monthly Discharge (cfs)

These factors were used to compare the average discharge of ice affected stream systems over the long term temporal scale for both ice jam and non-ice jam years. A change in monthly discharge, either positive or negative, provided information on how ice jams affected the streams hydrologically. Since each hydrologic basin and drainage area is not consistent between the 6 locations of interest and the two control sites, the average discharge was divided by the hydro basin area to bring the data to a scale that can be compared side by side.

Discharge rates were only evaluated over the long term temporal scale and thus were not included in the short term analysis of this study.

2.4. Ice Jam vs. Non-Ice Jam Years Analysis

Once the meteorological and hydrological setups for each ice jam event were known, they were compared to the dynamic arrangements during years when ice jams did not occur at the same locations in Iowa.

2.4.1. Long Term Analysis

A percentage difference between the meteorological and hydrological variables during ice jam and non-ice jam years was calculated at each control site and location of interest based on each variable's averages at the COOP and ASOS sites, respectively, to each area. This percentage illustrated the differences between the ice jam and non-ice jam year observations for each variable—the more significant the percentage, the greater the difference. Variables with more considerable percentage differences correlate to its effect meteorologically or hydrologically on the likelihood of ice jams.

The information analyzed between ice jam and non-ice jam years presented new variables other than AFDD and ice thickness indicative of ice jam formation on the long term temporal scale.

2.4.2. Short Term Analysis

At each control site and location of interest during ice jam years, the temperature, relative humidity, and precipitation patterns were examined.

If the maximum temperature exceeded 42 F at least three days in a row during the 1-3 weeks preceding the event, it was recorded as a factor contributing to the ice break.

Relative humidities were calculated based on the observed dew point and recorded for each event. The values for each event were compared to each other, and any significance was also a contributor to ice break-up.

To be considered a significant precipitation event, the location had to have observed more than half an inch of precipitation within three weeks preceding the event.

The results of the long-term and short-term analysis will be synthesized into preliminary guidance for predicting the likelihood of ice jams. The conditions that are the most significant during ice jam years will be used in this guidance as they will be the most useful for forecasters.

3. Results

This process revealed the main factors contributing to ice jam formations and break up for each location of interest. These factors showed consistency between each of the areas of interest and the two control sites, and therefore new guidance in the forecasting of ice jams was determined. However, it is essential to note that the ice jams in this project are a case study of Iowa. The meteorological dynamics and hydrological characteristics of river systems may be unique to that of Iowa.

3.1. Long Term Analysis Results

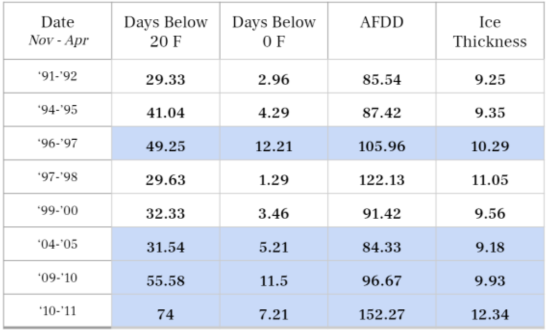
The variables collected and analyzed for the long term temporal scale (November 1st to April 1st) for both ice jam and non-ice jam years were the number of days that met the following criteria:

- Tmax ≤ 32 F (AFDD)
- Tmax ≤ 20 F
- Tmax ≤ 0 F
- Ice Thickness (in)
- Average Monthly Discharge (cfs)

3.1.1. Control Sites

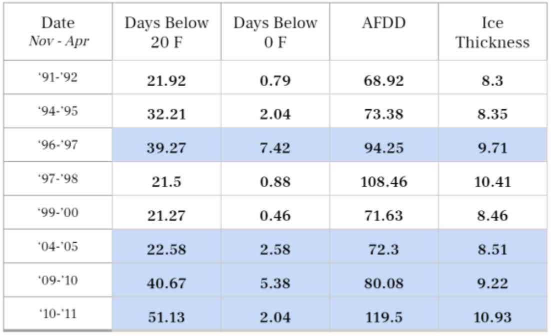
In terms of the meteorological setup, both the Waterloo and Des Moines control sites saw a positive increase in all of the variables observed during ice jam years compared to non-ice jam years (**Table 1 and 2**). During ice jam years, the magnitude of AFDD increased by 12%, which supports the CRREL forecasting method that evaluates AFDD to estimate ice thickness. Ice thickness was found to increase by 7% during years that observed ice jam events.

Table 1 displays the numerical meteorological results from the Waterloo, IA control site. The rows highlighted in blue represent ice jam years. Most of the investigated variables showed larger values during ice jam years as compared to the non-ice jam years.



Date *Nov - Apr*	Days Below 20 F	Days Below 0 F	AFDD	Ice Thickness
'91-'92	29.33	2.96	85.54	9.25
'94-'95	41.04	4.29	87.42	9.35
'96-'97	49.25	12.21	105.96	10.29
'97-'98	29.63	1.29	122.13	11.05
'99-'00	32.33	3.46	91.42	9.56
'04-'05	31.54	5.21	84.33	9.18
'09-'10	55.58	11.5	96.67	9.93
'10-'11	74	7.21	152.27	12.34

Table 2 displays the numerical meteorological results from the Des Moines, IA control site. The rows highlighted in blue represent ice jam years. Like the Waterloo, IA control site, most of the investigated variables showed larger values during ice jam yeas as compared to non-ice jam years.



Date *Nov - Apr*	Days Below 20 F	Days Below 0 F	AFDD	Ice Thickness
'91-'92	21.92	0.79	68.92	8.3
'94-'95	32.21	2.04	73.38	8.35
'96-'97	39.27	7.42	94.25	9.71
'97-'98	21.5	0.88	108.46	10.41
'99-'00	21.27	0.46	71.63	8.46
'04-'05	22.58	2.58	72.3	8.51
'09-'10	40.67	5.38	80.08	9.22
'10-'11	51.13	2.04	119.5	10.93

Furthermore, it was found that the number of days below 20 F increased by 37%, and the number of days below 0 F increased by 70%. These two variables present more drastic changes between ice jam and non-ice jam years, and therefore present essential variables to consider when forecasting for ice jams.

In terms of the hydrological setup, the most significant change in average discharge between the ice jam and non-ice jam years occurred between January and March (**Figures 6 and 7**). This observation is likely due to warmer temperatures from the onset of spring, which leads to snowmelt and runs off into the drainage basins, increasing the average discharge. The magnitude of discharge increase is larger during ice jam years. More frozen precipitation is already on the ground available to be melted, which presents another characteristic unique to years that experience ice jams.

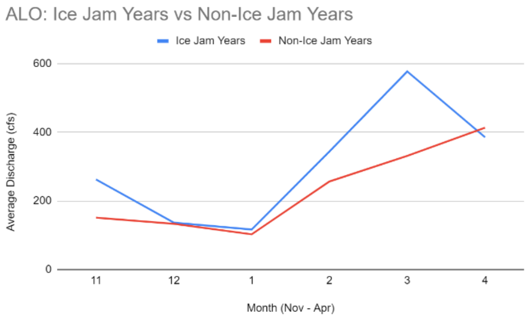


Figure 6 plots the average monthly discharge observed in the Middle Cedar Basin that encompasses the Waterloo control site. The months from November to April are plotted on the x-axis, and the average discharge for each month is shown based on the y-axis in cubic feet per second, or cfs. The red line shows the average monthly discharge trend for non-ice jam years, and the blue line describes the same for ice jam years.

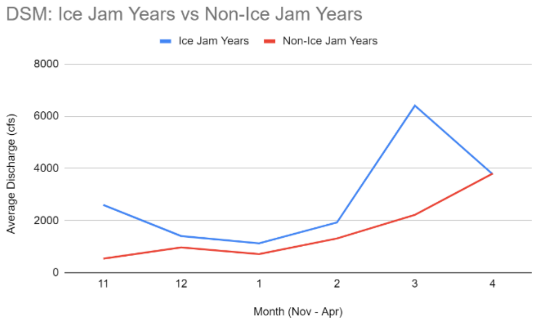


Figure 7 plots the average monthly discharge for the North Raccoon Basin that encompasses the Des Moines control site. The months from November to April are plotted on the x-axis, and the average discharge for each month is shown based on the y-axis in cubic feet per second, or cfs. The red line shows the average monthly discharge trend for non-ice jam years, and the blue line describes the same for ice jam years.

3.1.2. Locations of Interest

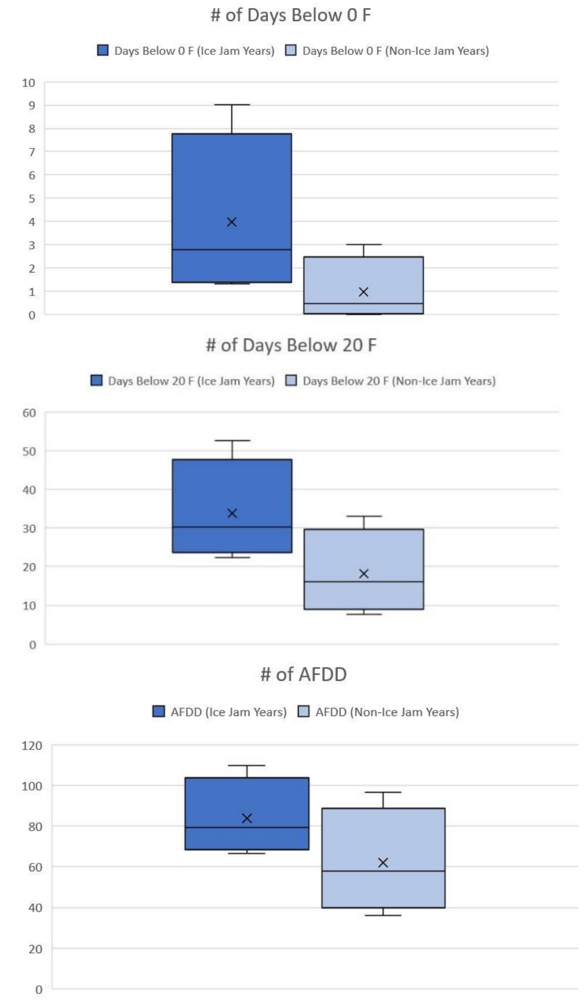
When the same analysis process used for the control sites is applied to the locations of interest, similar trends arise. **Table 3** displays the results for each meteorological variable analyzed at each area of interest in the form of a percentage difference between ice jam and non-ice jam years.

Table 3 displays the results from each location of interest (rows) for the meteorological variables (columns) analyzed in this project. The number shows represent the percentage difference between ice jam and non-ice jam years.

	# of Days $T_{max} \leq 0$ F	# of Days $T_{max} \leq 20$ F	AFDD	Ice Thickness (inches)
Beaver Creek	79.16%	43.25%	21.31%	9.90%
Des Moines River	95.19%	40.02%	21.89%	11.56%
Iowa River	91.04%	62.95%	39.92%	24.17%
N. Raccoon River	100%	50.71%	27.04%	14.60%
Raccoon River Des Moines	92.05%	55.43%	36.56%	19.53%
Raccoon River Van Meter	95.73%	61.49%	35.84%	19.82%

The total number of days below 0 F at each location is consistent with the control site results. Each area saw at least a 70% increase is the number of days below 0 F, with many of the locations exceeding this threshold by9%-30%. The same is true for the number of days below 20 F, where each area saw an increase of at least 37%, with many of the locations exceeded this threshold by 3%-26%. The number of AFDD across each of the sites saw an increase of at least 12%, and the thickness of the ice at each location also increased by at least 7% during ice jam years (**Table 3**).

There was large variability in the number of days below zero, as it was evaluated to have a broader range of values across the ice jam years studied compared to the non-ice jam years. However, the number of days below 0 F is on a small scale, so there may not be significance between the two types of years relevant to ice jams. The number of days below 20 shows a large separation between ice jam and non-ice jam years. The majority of the results during non-ice jam years falls under the median result during ice jam years. This presents a shift towards warmer conditions during non-ice jam years. The AFDD and the ice thickness, on the other hand show less variability between ice jam and non-ice jam years (**Figure 8**).



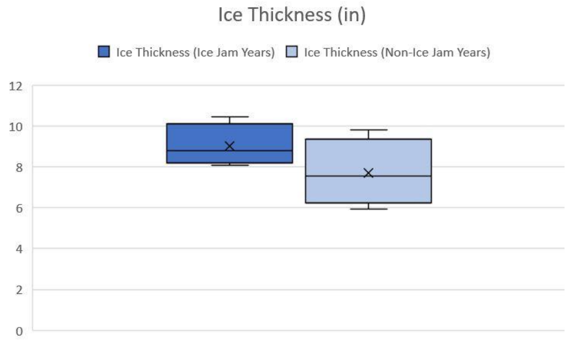


Figure 8 shows the results from the long term analysis of the locations of interest in the form of box and whisker plots. The dark blue plots represent ice jam years while the light blue plots represent non-ice jam years. The four variables compared for each location- Days below 0 F, Days below 20 F, AFDD, and Ice Thickness- are shown from top to bottom.

The number of days below 20 F showed the most considerable magnitude of difference between ice jam and non-ice jam years at the locations of interest. Therefore, it may play a larger role in the likelihood of ice jam formation and break-up than AFDD.

To further support the significance of the number of days below 20 F, a percentile distribution was plotted for temperatures during the month of January for both ice jam years and non-ice jam years. Only four of the six locations observed an ice jam during the month of January. The largest difference between the two types of years occurred in the 15 F-20 F range between the 10^{th} and 30^{th} percentiles (**Figure 9**).

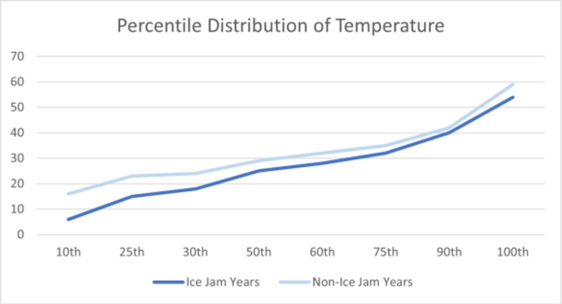
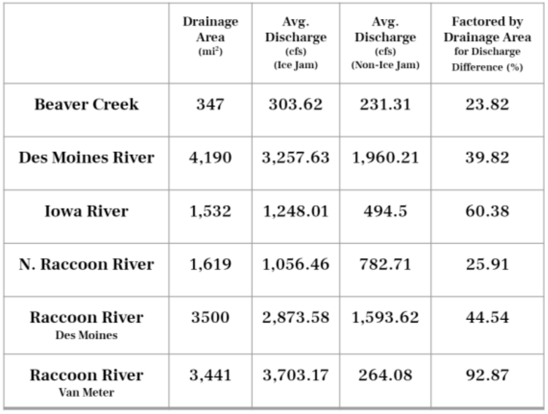


Figure 9 plots the percentile (horizontal axis) against the observed maximum temperatures (vertical axis) for both ice jam and non-ice jam years. The further apart the series lines the greater the significance. The 15 F to 20 F range between the 10th and 30th percentiles further support the importance of the number of days below 20 F and their effect on ice jams.

Table 4 shows the results for the hydrological variables analyzed at each location and their respective drainage basin. When compared to the hydrological results from the control sites, similar trends appear.

Table 4 displays the hydrological analysis results by location (rows) and their respective drainage area and average discharge (columns). The result was divided by the drainage area to scale every site, as they broadly vary in size.



	Drainage Area (mi²)	Avg. Discharge (cfs) (Ice Jam)	Avg. Discharge (cfs) (Non-Ice Jam)	Factored by Drainage Area for Discharge Difference (%)
Beaver Creek	347	303.62	231.31	23.82
Des Moines River	4,190	3,257.63	1,960.21	39.82
Iowa River	1,532	1,248.01	494.5	60.38
N. Raccoon River	1,619	1,056.46	782.71	25.91
Raccoon River Des Moines	3500	2,873.58	1,593.62	44.54
Raccoon River Van Meter	3,441	3,703.17	264.08	92.87

Each of the locations saw a positive increase in average discharge during ice jam years, with some areas showing much larger magnitudes than others. This conclusion is consistent with the control sites.

3.2. Short Term Analysis Results

The variables collected and analyzed for the short term temporal scale (up to 3 weeks preceding the event) for only ice jam years were:

- $T_{max} \geq 42$ F
- Relative Humidity
- Precipitation Amount (in) and Type

Since these variables are dependent on an ice jam event, non-ice jam years are not used in the comparison. Instead, each location is compared to each other to search for consistencies in the temperature, relative humidity, and precipitation patterns. Control sites were also not used in the short term analysis.

3.2.1. Locations of Interest

Between all six locations, there were a total of 20 cases analyzed for the short term meteorological conditions to determine the main contributors of ice break-up. The conditions preceding each case by 3 weeks were analyzed to determine if warming patterns or precipitation was evident and a possible reason for the break-up. The results of the analysis are shown in **Figure 10.**

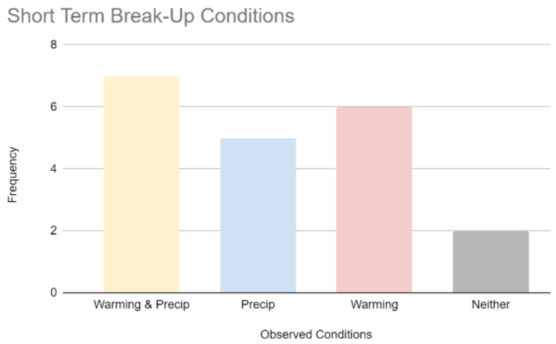


Figure 10 shows the number of cases that satisfied the observed conditions analyzed- warming and precipitation patterns.

Of all 20 cases, 35% observed both a warming trend with at least three consecutive days above 42 F and a precipitation event resulting in at least 0.5 in of rain, snow, or both. Only 30% observed a warming pattern without any precipitation, and only 25% observed a precipitation event without any warming pattern. Of the cases that followed precipitation events, 50% fell as rain, 41.7% fell as snow, and 8.33% fell as rain and snow. Finally, only 10% of the cases experienced neither a warming pattern nor a significant precipitation event.

Relative humidity may also play a role in the break-up process, especially for those locations that did not experience a warming pattern or a precipitation event. The average observed relative humidity during each event is displayed in the box and whisker plot in **Figure 11**. As described in the plot, the range is only 20%, and the majority of the observed relative humidity's are above 80%.

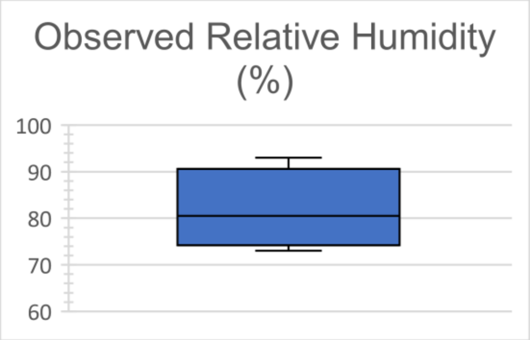


Figure 11 plots the average relative humidity observed for the 20 cases 1 week before the event. The maximum relative humidity observed was 93%, and the minimum was 73%. The small range of 20% is reflected in the box and whisker plot. The majority of the cases observed a relative humidity greater than 80%.

The two cases of the 20 analyzed from the original six locations that experienced neither a warming pattern nor a precipitation event observed relative humidity's of 80% and 73%. This result means that the air's high moisture content was the primary contributor to the ice break-up during those two ice jam events.

4. Discussion and Conclusions

When looking at all of the specified cases and years in this study, analysis of the meteorological and hydrological data reveals the following trends from November to April:

Investigated Variable	% Difference between Ice Jam and Non-Ice Jam Years
# of Days $T_{max} \leq 0$ F	92%
# of Days $T_{max} \leq 20$ F	52%
# of AFDD	30%
Ice Thickness (in)	17%
Avg. Monthly Discharge (cfs)	48%

Therefore, long term forecasting techniques for ice jams should focus more on the number of days below 0 F and days below 20 F, as they were the most significant distinction between ice jam and non-ice jam years. However, the comparison of days below 0 F revealed a high significance because most of the non-ice jam years did not experience any days below 0 F, as it is not very common for Iowa to reach that temperature threshold. Therefore, the number of days below 20 F represents a more significant distinction between ice jams and non-ice jam years. Further investigation on the low temperature threshold for ice jam formation revealed the number of days below 15 F was also a significant distinction. The months of December and January saw the largest magnitude in number of days below 20 F and 15 F. Ice jam years saw a larger number of days that meet this threshold during December and January than non-ice jam years. AFDD should not be neglected, as it is still essential to estimate the thickness of the ice. Thicker ice sheets will cause more catastrophic damage once it is affected by the short term conditions outlined below.

After analyzing all 20 cases across the 6 locations, patterns in warm temperatures, precipitation and relative humidity was discovered during the 1-3 weeks preceding an ice jam event. Warming patterns of at least three consecutive days with T_{max} above 42 F played a role in 65% of break-up jams.

Significant precipitation events resulting in at least 0.5 inches played a role in 60% of break-up jams. Relative humidity was the main factor responsible for only 10% of break-up jams. Lastly, relative humidities above 70% increase the likelihood of ice jams significantly.

The relative humidity is the commonality between all cases when analyzing contributing factors to ice break-up, and therefore holds significance.

4.1. Historical Evaluation

In this study, only 20 total cases were studied across six different locations. The small number of cases presented challenges in statistical testing. Therefore, p-tests were not conducted. A more significant number of cases meeting the same criteria outlined in this study will be required to determine if the results are statistically significant.

The use of historical data from COOP sites also presented a challenge since these sites can include missing or unreliable data. For this reason, ASOS sites were used where possible. Not all of the locations of interest were in the vicinity of an ASOS site, and therefore ASOS data was not included in the calculated statistics for that location.

4.2. Impacts

Flooding remains the primary threat of break-up ice jams. Most of the ice jams studied were associated with flooding events, some greater in magnitude than others. The risk that break-up ice jams pose is where the motivation behind this project stems. There are mitigation strategies prepared, but they are ineffective without enough lead time. The results from this study could lead to a new perspective on the variables indicative of ice jams.

It is also unclear whether any human intervention has played a role in forming ice jams in stream systems that are surrounded by populous areas. Debris and river altering can present artificial anchors and changes in flow velocity and discharge. Whether these effects hinder or help with the process of ice jam formation has yet to be investigated.

4.3 Predictability

Based on this study's results, new guidance on determining the threat of break-up ice jams was consolidated into a system of three tiers based on risk- Low, Moderate, and High. This guidance will be useful during the later winter months when break-up ice jams tend to occur. The criteria for each risk level stem from data collected during the short-term time scale analysis. It was discovered that, based on this study, warming patterns along with relative humidity's above 70% provide the most favorable conditions for break-up ice jams to occur.
Each risk level will also contain general thresholds for ice formation and long term winter conditions that present the most favorable conditions for freeze-up ice jams. However, break-up ice jam risks focus on the experimental system and assume that the freeze-up ice jams have already occurred.

The tiers are as follows:

Threat Level: **Low**

- Ice Thickness ≤ 4 inches
- No Warming Pattern expected within three weeks
  - $T_{max} < 40$ F for at least 3 consecutive days
- The Relative Humidity is expected to stay below 70%
  - Persistent Dry Conditions

Threat Level: **Moderate**

- Ice Thickness ≥ 4 inches
- Brief or Short Warming Pattern expected in the next weeks
    - $T_{max} < 42$ F for at least 3 consecutive days
- The Relative Humidity is expected to stay below 70% generally.

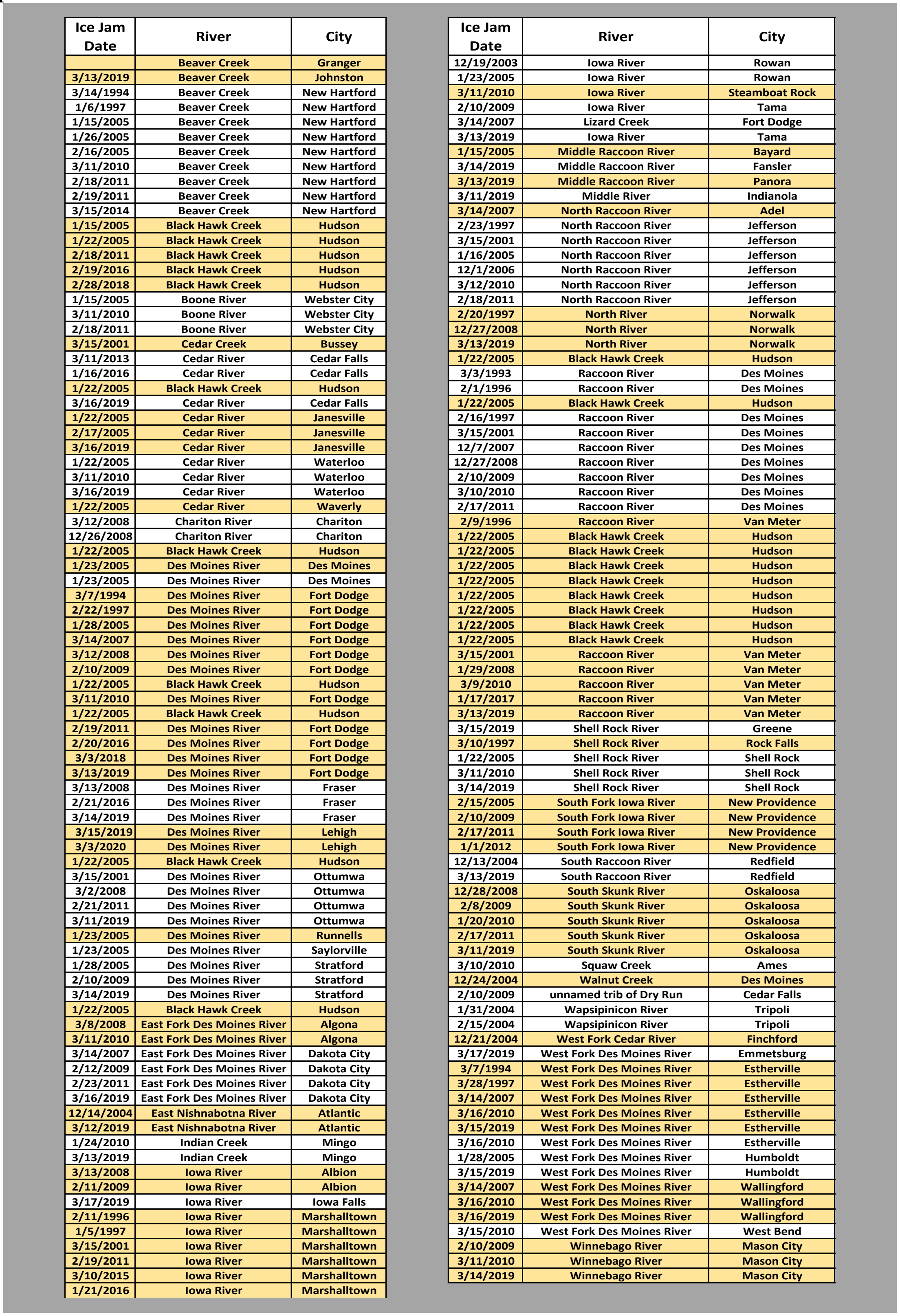
Threat Level: **High**

- Ice Thickness ≥ 4 inches
- A Significant Warming Pattern is expected in the next three weeks
    - $T_{max} \geq 42$ F for at least 3 consecutive days
- Relative Humidity is expected to exceed 70% during most of that time.

See **Appendix B** for the ‘Threat Level Guidance for Break-Up Ice Jams in Iowa’ infographic. Along with the short term forecasting guidance system, it is also important to note the climatological conditions expected for winter. In a year expecting a winter characterized by dryer and warmer than normal conditions, the threat of ice jams will be low. However, winters expected to be wetter and colder than average will have a much greater danger of ice jams. The climatological expectations for a given year can be used to determine the likelihood of a freeze-up ice jam. Freeze-up ice jams must eventually break-up, so the greater the number of rivers that freeze over, the greater the chance for break-up ice jams and any associated threats.

One final predictive factor to note is the possibility of forecasters computing real-time comparisons to the long term factors noted in this study. During the current year, it would be important to note the AFDD, the number of days below 20 F, as well as the number of days below 0 F. These values could be plotted on the box and whisker plots (**Figure 8**) to better visualize how the current year compares to the database of the ice jam and non-ice jam years. For instance, if the number of days below 20 F reached 30 by January, then the likelihood of ice jams occurring would be elevated. On the other hand, if the number of days below 20 F reached only 12 by January, the threat of ice jams is reduced.

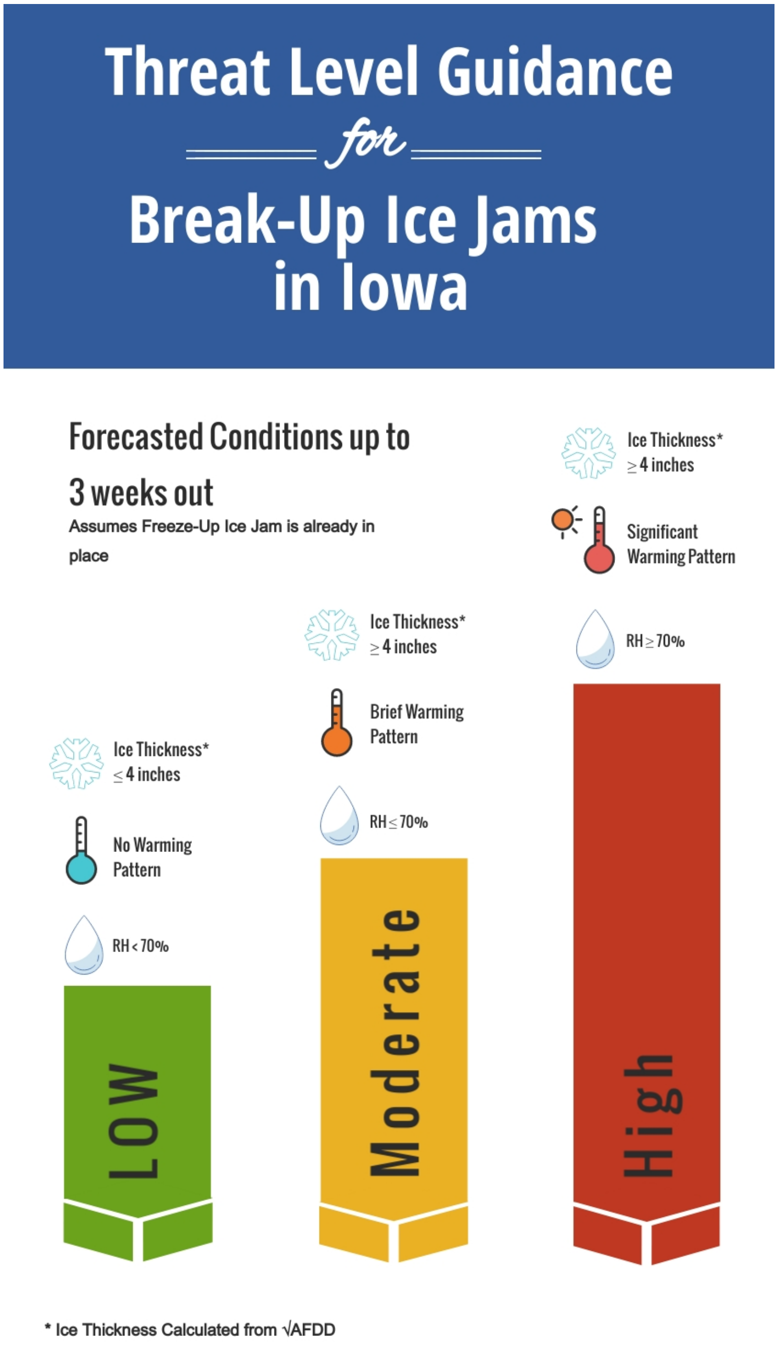
5. Appendix A



Ice Jam Date	River	City
	Beaver Creek	Granger
3/13/2019	Beaver Creek	Johnston
3/14/1994	Beaver Creek	New Hartford
1/6/1997	Beaver Creek	New Hartford
1/15/2005	Beaver Creek	New Hartford
1/26/2005	Beaver Creek	New Hartford
2/16/2005	Beaver Creek	New Hartford
3/11/2010	Beaver Creek	New Hartford
2/18/2011	Beaver Creek	New Hartford
2/19/2011	Beaver Creek	New Hartford
3/15/2014	Beaver Creek	New Hartford
1/15/2005	Black Hawk Creek	Hudson
1/22/2005	Black Hawk Creek	Hudson
2/18/2011	Black Hawk Creek	Hudson
2/19/2016	Black Hawk Creek	Hudson
2/28/2018	Black Hawk Creek	Hudson
1/15/2005	Boone River	Webster City
3/11/2010	Boone River	Webster City
2/18/2011	Boone River	Webster City
3/15/2001	Cedar Creek	Bussey
3/11/2013	Cedar River	Cedar Falls
1/16/2016	Cedar River	Cedar Falls
1/22/2005	Black Hawk Creek	Hudson
3/16/2019	Cedar River	Cedar Falls
1/22/2005	Cedar River	Janesville
2/17/2005	Cedar River	Janesville
3/16/2019	Cedar River	Janesville
1/22/2005	Cedar River	Waterloo
3/11/2010	Cedar River	Waterloo
3/16/2019	Cedar River	Waterloo
1/22/2005	Cedar River	Waverly
3/12/2008	Chariton River	Chariton
12/26/2008	Chariton River	Chariton
1/22/2005	Black Hawk Creek	Hudson
1/23/2005	Des Moines River	Des Moines
1/23/2005	Des Moines River	Des Moines
3/7/1994	Des Moines River	Fort Dodge
2/22/1997	Des Moines River	Fort Dodge
1/28/2005	Des Moines River	Fort Dodge
3/14/2007	Des Moines River	Fort Dodge
3/12/2008	Des Moines River	Fort Dodge
2/10/2009	Des Moines River	Fort Dodge
1/22/2005	Black Hawk Creek	Hudson
3/11/2010	Des Moines River	Fort Dodge
1/22/2005	Black Hawk Creek	Hudson
2/19/2011	Des Moines River	Fort Dodge
2/20/2016	Des Moines River	Fort Dodge
3/3/2018	Des Moines River	Fort Dodge
3/13/2019	Des Moines River	Fort Dodge
3/13/2008	Des Moines River	Fraser
2/21/2016	Des Moines River	Fraser
3/14/2019	Des Moines River	Fraser
3/15/2019	Des Moines River	Lehigh
3/3/2020	Des Moines River	Lehigh
1/22/2005	Black Hawk Creek	Hudson
3/15/2001	Des Moines River	Ottumwa
3/2/2008	Des Moines River	Ottumwa
2/21/2011	Des Moines River	Ottumwa
3/11/2019	Des Moines River	Ottumwa
1/23/2005	Des Moines River	Runnells
1/23/2005	Des Moines River	Saylorville
1/28/2005	Des Moines River	Stratford
2/10/2009	Des Moines River	Stratford
3/14/2019	Des Moines River	Stratford
1/22/2005	Black Hawk Creek	Hudson
3/8/2008	East Fork Des Moines River	Algona
3/11/2010	East Fork Des Moines River	Algona
3/14/2007	East Fork Des Moines River	Dakota City
2/12/2009	East Fork Des Moines River	Dakota City
2/23/2011	East Fork Des Moines River	Dakota City
3/16/2019	East Fork Des Moines River	Dakota City
12/14/2004	East Nishnabotna River	Atlantic
3/12/2019	East Nishnabotna River	Atlantic
1/24/2010	Indian Creek	Mingo
3/13/2019	Indian Creek	Mingo
3/13/2008	Iowa River	Albion
2/11/2009	Iowa River	Albion
3/17/2019	Iowa River	Iowa Falls
2/11/1996	Iowa River	Marshalltown
1/5/1997	Iowa River	Marshalltown
3/15/2001	Iowa River	Marshalltown
2/19/2011	Iowa River	Marshalltown
3/10/2015	Iowa River	Marshalltown
1/21/2016	Iowa River	Marshalltown
12/19/2003	Iowa River	Rowan
1/23/2005	Iowa River	Rowan
3/11/2010	Iowa River	Steamboat Rock
2/10/2009	Iowa River	Tama
3/14/2007	Lizard Creek	Fort Dodge
3/13/2019	Iowa River	Tama
1/15/2005	Middle Raccoon River	Bayard
3/14/2019	Middle Raccoon River	Fansler
3/13/2019	Middle Raccoon River	Panora
3/11/2019	Middle River	Indianola
3/14/2007	North Raccoon River	Adel
2/23/1997	North Raccoon River	Jefferson
3/15/2001	North Raccoon River	Jefferson
1/16/2005	North Raccoon River	Jefferson
12/1/2006	North Raccoon River	Jefferson
3/12/2010	North Raccoon River	Jefferson
2/18/2011	North Raccoon River	Jefferson
2/20/1997	North River	Norwalk
12/27/2008	North River	Norwalk
3/13/2019	North River	Norwalk
1/22/2005	Black Hawk Creek	Hudson
3/3/1993	Raccoon River	Des Moines
2/1/1996	Raccoon River	Des Moines
1/22/2005	Black Hawk Creek	Hudson
2/16/1997	Raccoon River	Des Moines
3/15/2001	Raccoon River	Des Moines
12/7/2007	Raccoon River	Des Moines
12/27/2008	Raccoon River	Des Moines
2/10/2009	Raccoon River	Des Moines
3/10/2010	Raccoon River	Des Moines
2/17/2011	Raccoon River	Des Moines
2/9/1996	Raccoon River	Van Meter
1/22/2005	Black Hawk Creek	Hudson
1/22/2005	Black Hawk Creek	Hudson
1/22/2005	Black Hawk Creek	Hudson
1/22/2005	Black Hawk Creek	Hudson
1/22/2005	Black Hawk Creek	Hudson
1/22/2005	Black Hawk Creek	Hudson
1/22/2005	Black Hawk Creek	Hudson
1/22/2005	Black Hawk Creek	Hudson
3/15/2001	Raccoon River	Van Meter
1/29/2008	Raccoon River	Van Meter
3/9/2010	Raccoon River	Van Meter
1/17/2017	Raccoon River	Van Meter
3/13/2019	Raccoon River	Van Meter
3/15/2019	Shell Rock River	Greene
3/10/1997	Shell Rock River	Rock Falls
1/22/2005	Shell Rock River	Shell Rock
3/11/2010	Shell Rock River	Shell Rock
3/14/2019	Shell Rock River	Shell Rock
2/15/2005	South Fork Iowa River	New Providence
2/10/2009	South Fork Iowa River	New Providence
2/17/2011	South Fork Iowa River	New Providence
1/1/2012	South Fork Iowa River	New Providence
12/13/2004	South Raccoon River	Redfield
3/13/2019	South Raccoon River	Redfield
12/28/2008	South Skunk River	Oskaloosa
2/8/2009	South Skunk River	Oskaloosa
1/20/2010	South Skunk River	Oskaloosa
2/17/2011	South Skunk River	Oskaloosa
3/11/2019	South Skunk River	Oskaloosa
3/10/2010	Squaw Creek	Ames
12/24/2004	Walnut Creek	Des Moines
2/10/2009	unnamed trib of Dry Run	Cedar Falls
1/31/2004	Wapsipinicon River	Tripoli
2/15/2004	Wapsipinicon River	Tripoli
12/21/2004	West Fork Cedar River	Finchford
3/17/2019	West Fork Des Moines River	Emmetsburg
3/7/1994	West Fork Des Moines River	Estherville
3/28/1997	West Fork Des Moines River	Estherville
3/14/2007	West Fork Des Moines River	Estherville
3/16/2010	West Fork Des Moines River	Estherville
3/15/2019	West Fork Des Moines River	Estherville
3/16/2010	West Fork Des Moines River	Estherville
1/28/2005	West Fork Des Moines River	Humboldt
3/15/2019	West Fork Des Moines River	Humboldt
3/14/2007	West Fork Des Moines River	Wallingford
3/16/2010	West Fork Des Moines River	Wallingford
3/16/2019	West Fork Des Moines River	Wallingford
3/15/2010	West Fork Des Moines River	West Bend
2/10/2009	Winnebago River	Mason City
3/11/2010	Winnebago River	Mason City
3/14/2019	Winnebago River	Mason City

Appendix A lists all of the recorded ice jams in Iowa, organized by date of occurrence, river, and location. This database was put together by the Des Moines National Weather Service Office.

6. Appendix B



Threat Level Guidance
for
Break-Up Ice Jams
in Iowa

Forecasted Conditions up to
3 weeks out
Assumes Freeze-Up Ice Jam is already in place

Ice Thickness* ≤ 4 inches
No Warming Pattern
RH < 70%
LOW

Ice Thickness* ≥ 4 inches
Brief Warming Pattern
RH ≤ 70%
Moderate

Ice Thickness* ≥ 4 inches
Significant Warming Pattern
RH ≥ 70%
High

* Ice Thickness Calculated from √AFDD

Appendix B illustrates the three-tiered system created from the results of this project in a consolidated infographic. The guidance featured in this infographic should be applied to short term forecasts, assuming that a freeze-up ice jam is already in place. Ice thickness is approximated using Equation **(A)**. Relative Humidity, Warming Patterns, and Ice Thickness are the three factors used to characterize each risk level.

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