AN INVESTIGATION OF WATER OBSTRUCTIONS AND RELATED WEATHER CONDITIONS FOR NEBRASKA ROADWAYS

FINAL REPORT

Mark R. Anderson and Logan R. Bundy

Department of Earth and Atmospheric Sciences

University of Nebraska-Lincoln

Lincoln, NE 68588-0340

Sponsored By

Nebraska Department of Transportation and U.S. Department of Transportation Federal Highway Administration

May 2022

NEBRASKA
Good Life. Great Journey.
DEPARTMENT OF TRANSPORTATION

UNIVERSITY OF Nebraska Lincoln

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FY21(001)	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle AN INVESTIGATION OF WATER OBSTRUCTIONS AND RELATED WEATHER CONDITIONS FOR NEBRASKA ROADWAYS		**5. Report Date** May 2022 **6. Performing Organization Code** 26-0514-0211-001
7. Author(s) Mark R. Anderson and Logan R. Bundy		**8. Performing Organization Report No.**
9. Performing Organization Name and Address University of Nebraska-Lincoln 2200 Vine Street, PO Box 830851 Lincoln, NE 68583-0851		**10. Work Unit No.** **11. Contract** FY21(001)-No. 26-0514-0211-001
12. Sponsoring Agency Name and Address Nebraska Department of Transportation Research Section 1400 Hwy 2 Lincoln, NE 68502		**13. Type of Report and Period Covered** Final Report July 2020 - May 2022 **14. Sponsoring Agency Code**
15. Supplementary Notes		

16. Abstract

Roadway resilience across the 10,000 miles of road and 3,500 bridges in Nebraska is critical to the economic success of production and logistics. In a state where historical flooding scenarios, such as the one in March 2019 that caused $150 million in damage, could potentially be increasing, it has become essential to understand the spatial and temporal distribution of high-frequency water obstruction areas on roadways. Therefore, in order to further investigate these areas, the main objectives of this research were to perform statistical and spatial analyses to quantify the relationship between water obstructions and their associated meteorological conditions, and identify the potential linkages between water obstructions and climate patterns. Nebraska Department of Transportation (NDOT) historical water obstruction data were obtained for June 2016 through August 2021 to formulate 298 total unique water obstructions, of which 174 came from March 2019, and 225 in total came from 2019 alone. While 2019 was an outlier year, on a median basis, the state experiences 13 water obstructions annually and these occur primarily in the summer season. A key finding in this analysis was that water obstructions over the study period were closely related with 30-year climatological data, which can then be used for water obstruction risk assessment on a seasonal and annual basis. Groundwater, ice jamming, and long- and short-duration precipitation obstructions occurred most frequently in the northern and eastern domains of Nebraska. There is a greater risk of water obstructions reoccurring given the exposure to weather-related hazards on average, and the higher density of roadways exposed to rivers such as the Elkhorn and Platte. In addition to identifying specific high-frequency water obstruction locations, there is a predictable relationship between weather, climate, and roadway water obstructions. A fundamental understanding of the water obstruction spatiotemporal climatology, knowledge of where water obstructions have occurred the most, and identifying the precursor and future meteorological conditions, a more proactive approach can be taken in the onset of potential water obstructions. Further, the identification of the high-frequency water obstruction locations can be considered for mitigation efforts to increase the resiliency of travel from water obstructions.

<table>
<tr><td colspan="2">17. Key Words
transportation; risk; weather; climate; floods</td><td colspan="3">18. Distribution Statement
No restrictions. This document is available through the National Technical Information Service.
5285 Port Royal Road
Springfield, VA 22161</td></tr>
<tr><td>19. Security Classification (of this report)
Unclassified</td><td colspan="2">20. Security Classification (of this page)
Unclassified</td><td>21. No. of Pages
127</td><td>22. Price</td></tr>
</table>

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. The contents do not necessarily reflect the official views or policies neither of the Nebraska Department of Transportations nor the University of Nebraska-Lincoln. This report does not constitute a standard, specification, or regulation. Trade or manufacturers' names, which may appear in this report, are cited only because they are considered essential to the objectives of the report.

The United States (U.S.) government and the State of Nebraska do not endorse products or manufacturers. This material is based upon work supported by the Federal Highway Administration under SPR-FY21(001). Any opinions, findings and conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the Federal Highway Administration.

Acknowledgments

The authors thank the members of the Technical Advisory Committee for their guidance and input throughout this study. The authors are thankful for the help received from the NDOT Research Division with all aspects of this research project.

Table of Contents

TECHNICAL REPORT DOCUMENTATION PAGE i
Disclaimer iii
Acknowledgements iv
1 Introduction 1
2 Background 3
3 Data and Methods 12
3.1 Data 12
3.1.1 Water Obstruction Data 12
3.1.2 Meteorological and Climatological Data 15
3.2 Methods 20
3.2.1 Determining Root Weather-Related Cause 20
3.2.2 Statistical Analysis 22
3.2.3 Spatial Analysis 23
4 Results 25
4.1 Roadway Water Obstructions 25
4.1.1 Overview of Water Obstructions 25
4.1.2 Temporal Distribution of Water Obstructions 30
4.1.3 Spatial Distribution of Obstructions 36
4.1.4 Frequency Analysis 43
4.2 Nebraska Climate 50
4.2.1 Temperature and Precipitation 50
4.2.2 Palmer Indices 56
4.2.3 Ice Jamming 59
4.2.4 Summary of Nebraska Climate 61
4.3 Study Period Conditions 62
4.3.1 Temperatures and Precipitation 62
4.3.2 Palmer Indices 65
4.3.3 Ice Jamming 68
4.4 Associated Meteorological Conditions 70
4.4.1 Precipitation 70
4.4.2 Precipitation Characteristics 83
4.4.3 Palmer Indices 89
4.4.4 Water Gage Data 92
4.4.5 National Weather Service Information 96
4.5 Top Water Obstruction Locations 100
4.5.1 NE 5 in Thayer County, Nebraska 100
4.5.2 US 183 in Rock County, Nebraska 102
4.5.3 US 275 in Cuming and Dodge County, Nebraska 103
4.5.4 US 136 in Nemaha County, Nebraska 105
4.5.5 Other High-Frequency Water Obstruction Locations 107
5 Summary and Conclusions 110
References 114

List of Figures

Figure 2.1 Framework of factors that contribute to a damaging flood. 5
Figure 3.1 Study area with NDOT district labels. 12
Figure 3.2 Study area with county outlines. 13
Figure 3.3 Study area with state and federal highways. 13
Figure 3.4 Study area with Nebraska's major river network. 14
Figure 3.5 Research framework. 15
Figure 3.6 NOAA Atlas 14 precipitation estimates (inches) example. 18
Figure 3.7 Framework for determining root weather-related cause. 21
Figure 4.1 Distribution of water obstruction by root weather-related cause. 25
Figure 4.2 Number of obstructions that resulted in a road closure. 28
Figure 4.3 Number of miles impacted by each water obstruction. 29
Figure 4.4 Number of obstructions by cause annually. 31
Figure 4.5 Number of obstructions by cause monthly. 33
Figure 4.6 Number of obstructions by cause for each month and year. 35
Figure 4.7 Locations of obstructions by season. 37
Figure 4.8 Locations of obstructions by year. 38
Figure 4.9 Water obstructions in 2019 and March 2019. 40
Figure 4.10 Locations of water obstructions in the study period. 41
Figure 4.11 Locations of water obstructions by root weather-related cause. 42
Figure 4.12 Kernel density results of obstructions by cause. 44
Figure 4.13 Kernel density results of obstructions by cause (without March 2019). 44
Figure 4.14 River reference map with line density results of obstructions. 48
Figure 4.15 Average seasonal temperature (°F) averages by county. 52
Figure 4.16 Seasonal temperature trends (°F per decade) by county. 53
Figure 4.17 Seasonal precipitation averages (inches) and by county. 54
Figure 4.18 Seasonal precipitation trends (inches per decade) by county. 55
Figure 4.19 Seasonal PDSI averages by climate division. 57
Figure 4.20 Seasonal PHDI averages by climate division. 57
Figure 4.21 Seasonal PDSI trends (PDSI per decade) by climate division. 58
Figure 4.22 Seasonal PHDI trends (PHDI per decade) by climate division. 59
Figure 4.23 Monthly sum of observed river ice jams by county. 60
Figure 4.24 Seasonal temperature and precipitation rankings by year. 62
Figure 4.25 Annual averaged daily temperature anomalies for each year. 64
Figure 4.26 Annual averaged precipitation anomalies for each year. 65
Figure 4.27 Seasonal PDSI and PHDI rankings by year. 66
Figure 4.28 Annual PDSI values for each year for each climate division. 67
Figure 4.29 Annual PHDI values for each year for each climate division. 68
Figure 4.30 River ice jam totals by month in Nebraska. 69
Figure 4.31 River ice jam locations over the study period. 70
Figure 4.32 NOAA Atlas 14 reoccurrence intervals for obstructions. 71
Figure 4.33 Precipitation totals per water obstruction event by cause. 73
Figure 4.34 Precipitation accumulation intervals prior to obstruction. 75
Figure 4.35 Precipitation totals intervals prior to obstruction (no March 2019). 76
Figure 4.36 Precipitation timing with respect to the water obstruction occurring. 78
Figure 4.37 Precipitation data for each water obstruction event. 79

Figure 4.38 Precipitation data for month prior to each obstruction. 81
Figure 4.39 Precipitation data for month prior to each obstruction (no March 2019). 82
Figure 4.40 Convective and stratiform precipitation obstruction locations. 84
Figure 4.41 Number of obstructions cause and by precipitation mode. 84
Figure 4.42 Precipitation totals and duration by precipitation mode. 85
Figure 4.43 Water obstruction locations by respective system type. 86
Figure 4.44 Precipitation totals and duration by system type. 88
Figure 4.45 PHDI data for month prior to obstruction. 90
Figure 4.46 PHDI data for month prior to obstruction (no March 2019). 91
Figure 4.47 River water gage departures for each obstruction by month. 93
Figure 4.48 River water gage departures for each obstruction by cause. 94
Figure 4.49 Water gage information near obstruction occurrence. 95
Figure 4.50 Percent of obstructions without an NWS Watch/Warning/Advisory. 99
Figure 4.51 Obstruction segments in Thayer County along NE 5. 101
Figure 4.52 Obstruction segments in Rock County along US 183. 103
Figure 4.53 Obstruction segments in Cuming and Dodge County along US 275. 104
Figure 4.54 Obstruction segments in Nemaha County along US 136. 106

List of Tables

Table 4.1 All multi-obstruction events in study period. 27
Table 4.2 NDOT district obstruction totals by cause and season. 37
Table 4.3 NDOT district obstruction totals. 43
Table 4.4 Number of obstructions by river. 47
Table 4.5 Number of obstructions by highway. 49
Table 4.6 Number of obstructions by county and highway. 51
Table 4.7 Number of obstructions by system type and cause. 87
Table 4.8 Number of obstructions with NWS information by cause. 96
Table 4.9 Number of obstructions with NWS information by system type. 98
Table 4.10 Top ten water obstruction locations. 109

1 Introduction

State and federal roadways are essential paths for the transportation of goods and people among states, thus, they require robust infrastructure designed to withstand stresses from weather-related hazards (Pedrozo-Acuna et al. 2016). Roadway resilience has become essential for cities and states as they support the safety and wealth of the economy, especially within the context of a global economy that has become increasingly reliant on the mobility of goods, information, and people (Rodrigue and Notteboom 2013). This is especially true for Nebraska, as the transportation system consisting of 10,000 miles of road and over 3,500 bridges are the backbone of the state's economy (Jamshidi 2021). On an annual basis, 19.4 billion miles are traveled in Nebraska, and this contributes to a non-trivial portion of the $229 billion worth of commodities shipped to and from the state annually (National Transportation Research Nonprofit (TRIP) 2022). Since the start of the 21st century, surface transportation mileage has increased 17% while the state's population increased 13%. Safety, cost, travel time, and regularity of service are valued in reliable surface transportation systems (Koetse and Rietveld 2009). Furthermore, maintaining constant traffic flow volume and limiting disruptions is critical for production and logistics (Jenelius et al. 2006).

Flooding can impact reliability, sustainability, and production of a roadway in a number of ways. This includes both direct impacts, such as physical damage to transportation infrastructure, and indirect impacts such as disruption to traffic flow, business interruptions, and increased emissions (Walsh et al. 2012; Hammond et al. 2015; Brown and Dawson 2016). The historic flooding events during March of 2019 across central and eastern Nebraska, along with the major flash flooding in the summer of 2019 across central Nebraska, continues to highlight the need to understand roadway water obstructions (which will be referred to as water obstructions herein) and their frequencies more completely. Recognition of the significant economic impacts of disruptions in the transportation sector have attracted increased interest in such analyses due to the threat to human safety and infrastructure impacts of extreme flooding events (Pregnolato et al. 2017). Expected changes in climatic conditions, including increased frequency and intensity of precipitation will further complicate the water obstruction challenge.

This research presents a unique analysis using Condition Acquisition Reporting System 511 (CARS511) data providing specific insight into problem areas for roadway water obstructions in Nebraska that may prove critical for stakeholders. The CARS511 historical dataset, stored within the Nebraska Department of Transportation (NDOT), provides when and where water obstructions have occurred in Nebraska since June 2016. To reduce economic and infrastructure losses, it is necessary to utilize various datasets, like the CARS511 dataset, and methods that guarantee both highway safety and minimization of damages associated to service interruptions. Determining water obstruction patterns prior to any water over the pavement situation can produce valuable information regarding road vulnerability (Kalantari and Folkeson 2013). The main objective of this investigation is to further the awareness of water obstructions on federal and state highways across Nebraska. In addition to the locations of the water obstructions, meteorological information was investigated for a specific weather-related cause of each water obstruction. Once the obstructions and their root weather-related causes are identified, increased knowledge of these roadway water obstruction situations will be better understood and could lead to some different forms of mitigation. Overall, this research will produce a better understanding of 1) where water obstructions have taken place for the study period, 2) the weather conditions associated with each water obstruction, and 3) how closely related water obstructions are to climate patterns across Nebraska.

2 Background

Flooding and flash flooding, which are attributed to longer and shorter duration precipitation events, respectively, are the predominant causes of weather-related disruptions to surface transportation (Brown et al. 2014) and are expected to continue into the future (Dawson et al. 2016). Water obstruction events may lead to numerous direct and indirect damages and societal impacts derived from even a single closed road (Lwin et al. 2014). Water obstructions impact roadway production, logistics, and economics through direct impacts, for example, physical damage to roadway infrastructure and indirect impacts, for example, disruptions to traffic flow, business interruptions, increased emissions (Walsh et al. 2012; Hammond et al. 2015; Brown and Dawson 2016). These impacts include the direct costs associated with water obstructions involving public agencies and utilities providing emergency management or any repairs needed to restore roads (Chang et al. 2011). The direct costs could include bridges, culverts, drainage repairs, pavement resurfacing or replacement, signs, guardrails, striping, landscaping, as well as repairs to public utility infrastructure (Chang et al. 2011).

In addition, water obstructions can create a hazardous situation for drivers as more people are killed each year in the United States by flash floods than by any other weather-related hazard (Boselly 2001). A majority of these deaths have been noted to be on roadways (Boselly 2001). From 2015 through 2019, 1170 people died on Nebraska's highways, an average of 234 annual fatalities. Nebraska's traffic fatality rate of 1.17 fatalities per 100 million vehicle miles of travel is higher than the national average of 1.11 (TRIP 2022). It only takes 18–24 inches of moving water on pavement to move a truck, while only six inches are needed to move a small car (Das et al. 2020). Existing approaches to assess the disruptive impact of water obstructions typically do not capture the dynamics and complex interactions between floodwater and surface transportation (Pregnolato et al. 2016). While rainfall intensity creating flooding and flash flooding scenarios have repeatedly been shown to be a factor in transport disruption, the correlation is not always strong (Pregnolato et al. 2016). However, measuring only rainfall at a weather station does not take into account the spatial distribution of the falling precipitation, the surface puddling and subsequent runoff movements, which frequently makes these hazardous situations occur on such a local scale that it is difficult to forecast (Boselly 2001).

Highway water obstruction causes can be classified into natural causes (e.g, rainfall, groundwater, ice jamming), social causes, and human related impacts, although the meteorological conditions generally induce water on pavements (Ou-Yang et al. 2014). Figure 2.1 illustrates the complex interactions between natural causes, and damaging floods in general, that could result in water obstructions and damages to the roadway (Pielke Jr. and Downton 2000; Polemio and Lollino 2011). For natural causes, current meteorological conditions and past climate scenarios both contribute to water obstructions, while social and human-related causes can be grouped into three additional categories: 1) intensifying flood conditions from land use and land cover changes, 2) policies such as the current structural and non-structural mitigation implemented, and 3) floodplain occupancy, meaning properties and people at risk within the floodplain. Since natural causes are the primary inducers to water obstructions, it is critical to understand how precipitation event placement and total rainfall production affects the obstruction. Moreover, the sensitivity of select hydrological basins to flooding varies considerably and depends on a variety of the human and non-meteorological factors relating to local topography (Peters and Roebber 2014). Thus, the same precipitation may cause flooding in hydrological basins that are more susceptible to flooding, while having negligible effects on other basins.

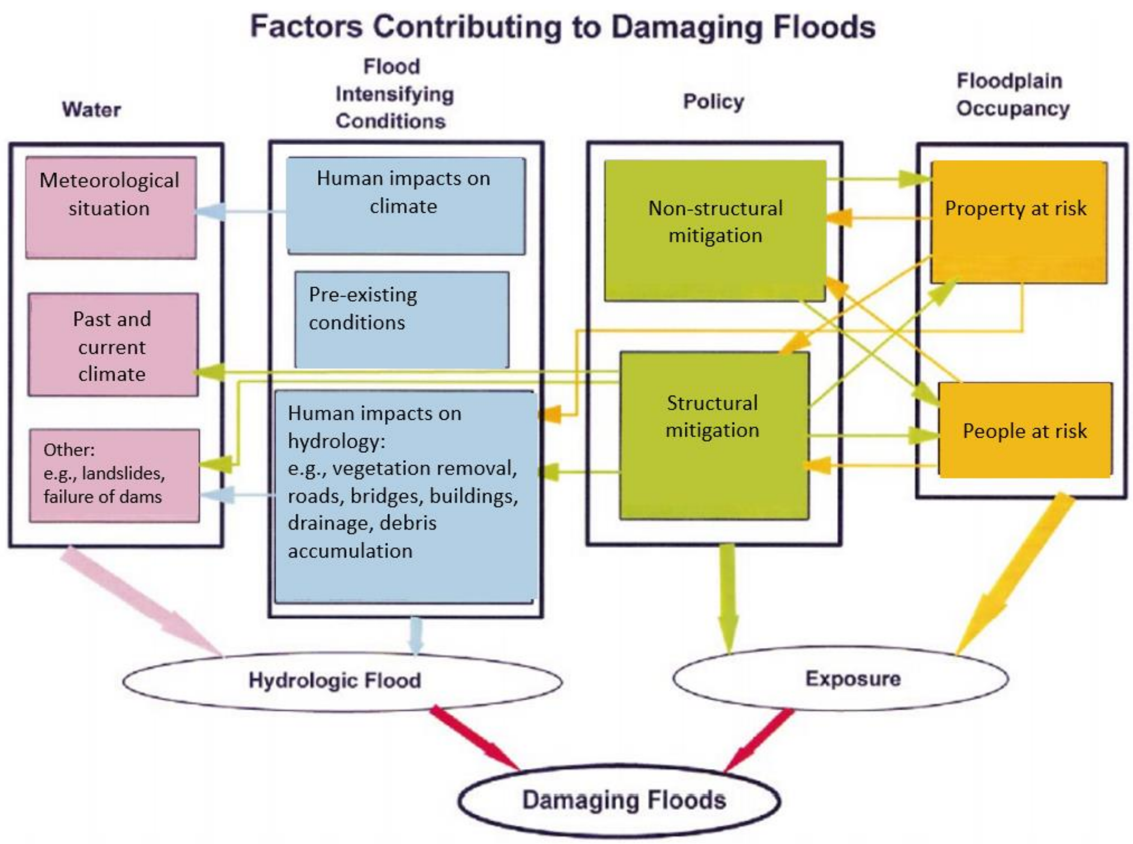

Figure 2.1 *Framework of factors that contribute to a damaging flood (Source: Pielke and Downton 2000).*

Nebraska's climate allows for a wide array of meteorological and hydrological factors to influence the onset of a water obstruction scenario. One scenario is severe convective storms, or thunderstorms in general, which can occur at any time of the year, though are more frequent during spring and summer in Nebraska. These thunderstorm conditions can cause infrastructure damage (e.g., lane submersion, debris on roads), and reduce the productivity of road maintenance crews, (e.g., impaired paving) which ultimately lead to some degree of disruption on the roadway (Pisano et al. 2002). Extreme rainfall events can be separated into five general types: mesoscale convective systems (MCSs), high-precipitation supercells, tropical, terrain forced, and synoptic scale systems such as extratropical cyclones (Schumacher and Johnson 2005). A substantial percentage of these extreme rainfall events, especially in Nebraska, result from the organizations of deep convection, or heavy rainfall in MCSs, which causes a rather slow or repetitive storm motion over a particular area (Moore et al. 2003; Schumacher and Johnson 2005, 2006). In addition, high rainfall totals often occur when thunderstorm cells organize into an ‘‘echo training’’ event, or convective training, which is recognized as the movement of convective echo returns on radar over the same location (Doswell et al. 1996; Davis 2001). In other words, the training refers to the storm motion as it becomes tangent to the line of storms and redevelopment downstream continues, thus, an increase in the total rainfall occurs. Synoptic scale extratropical cyclones (ETCs), especially the ones that form around Colorado and have a mean track favoring Nebraska for frontal precipitation (Fritzen et al. 2021) and have been known to produce heavy and extreme precipitation events (e.g., March 2019 historical flooding).

Ice jams can cause substantial damage to highways and bridges annually as they are often attributed to very damaging flood events (Shattuck 1988; Healy and Hicks 2006). Ice jams pose a significant threat to human safety and property and represent one of the most dynamic of river ice processes (Healy and Hicks 2006). The occurrence of ice jamming is highly dependent on the hydrometeorological conditions, which is also the primary cause for the severity of each ice jamming event. Breakup ice jams are associated with rapid runoff, usually due to a combination of rapid melt and heavy rain (Shattuck 1988). Hydrodynamic forces in a river are adequate to lift and break the ice cover before substantial and widespread thermal deterioration of large blocks can occur. The main cause of breakup ice jam formation is a barrier of the downstream movement of ice blocks by stagnant ice cover segments, resisting the movement of the ice blocks downstream (Shattuck 1988). While an ice jam can form anywhere on a river, there are certain geomorphic features highly conducive to jamming which includes sharp bends and abrupt reductions in slope or flow velocity in the river. In addition, ice jams are also known to most commonly occur at bridge locations (Shattuck 1988).

Another contributor to roadway water obstructions is groundwater flooding. For Nebraska, the most groundwater obstructions are likely to occur in the Sandhills region because of the Ogallala Aquifer, also commonly known as the High Plains Aquifer. Groundwater provides a freshwater source that is relatively reliable, and contributes towards the security and sustainability of irrigated agriculture in the state (Steward and Allen 2016). The regionally extensive groundwater flooding scenario can be caused by the water table in an aquifer rising above the land surface due to precipitation (Macdonald et al. 2008). Precursor river basin conditions predetermine the likelihood and severity of a flood (Kundzewicz et al. 2014). When water storage is limited in basins because groundwater levels elsewhere are above normal and soil moisture is at maximum capacity, then even low to moderate rainfall totals can initiate a water obstruction (Kundzewicz et al. 2014). On the other hand, very dry soils after a prolonged period can also rapidly convert rainfall to runoff resulting in a potential water obstruction, which then would not be groundwater related (Kundzewicz et al. 2014).

There are several case studies documented across Nebraska where each of the primary weather-related causes as defined by this project have historically created flooding and water obstruction issues. In recent time, the most notable and perhaps most historical event to date was the flooding on March 13-15, 2019 across a large portion of the state. The event was the combination of meteorological, climatological, and hydrological conditions leading to largescale flooding across the Nebraska region (Flanagan et al. 2020). These conditions included: 1) precursor soil moisture conditions from a warmer and wetter early winter relative to February and March, 2) above normal runoff in river systems prior to significant freezing in the river system in February which allowed for above normal river ice depths, 3) above normal precipitation with frozen soils which did not allow for infiltration of moisture from melting snow, 4) rapid surface cyclogenesis of a synoptic scale extratropical cyclone that produced prolonged rainfall and blizzard conditions on March 13-15, and 5) rapid snow and ice melt due to warm air advection from the synoptic system resulting in substantial ice jamming and historical flooding. As a result, 104 cities, 81 counties, and 5 tribal nations in Nebraska received State or Federal Disaster Declarations due to the flood events (Nebraska Department of Natural Resources 2021). The Federal Emergency Management Agency (FEMA) declared a major disaster for both Nebraska and Iowa, with a preliminary damage estimate of at least $3 billion. Other events include September 2013 flooding which resulted in record water gage heights for the time in the Platte River, the May 2015 record rainfall, which caused cities in southeastern Nebraska to evacuate due to the fear that some levees may be overtopped, and the July 2019 extreme rainfall in and around Kearney, Nebraska that resulted in evacuations and record water gage levels on the Wood River.

There have been several studies that have investigated weather impacts on road networks, including research that considered aspects of the relationship between surface transportation and weather/climate hazards (e.g., Koetse and Rietveld 2009; Jaroszweski et al. 2014; Faturechi and Miller-Hooks 2015; Hammond et al. 2015; Kramer et al. 2016; Martínez-Gomariz et al. 2016). However, fewer research has been conducted on the performance of transportation-related infrastructure such as culverts and bridges exposed to future weather extremes (Kalantari et al. 2014). In addition, when financial resources for flood risk management are restricted, it is crucial to understand where the impacts of water obstructions occur most often to prioritize investment decisions with the most informed analyses (Pregnolato et al. 2016). At the national level, there is a $786 billion backlog in needed repairs and improvements to roads and bridges across the United States. Consequently, it has been recommended by the Department of Transportation to increase the nation’s current $105 billion investment in roads and bridges by 29% to $136 billion annually (FHWA 2020). The Infrastructure Investment and Jobs Act (IIJA), signed in November of 2021, will provide $2.43 billion in state funds for highway, bridge, and transit investments in Nebraska through 2026. Therefore, future highway development and or improvement in the transport system for specific areas across Nebraska will need an integrated approach for mitigation design that is reliable and resilient against extreme weather (Pedrozo-Acuna et al. 2016).

In terms of mitigation on roadways that flood frequently, non-structural options may include passive and active warnings used to warn drivers of water over a roadway (Boselly 2001). The implementation of passive warnings involves warning signs that indicate a location on the road may flood or that there might be standing water during heavy rain events, while active devices require a sensor to determine if water is over a roadway before triggering flashing lights on signs to warn drivers (Boselly 2001). As for structural mitigation, these come at a higher cost; they may be worth implementing in some of the most flood prone areas to increase resilience and reduce risk of water obstructions. These may include a lift in the roadway, deeper culverts and ditches, drainage pipes, levees, and dikes to mitigate against ice jamming, river flooding, and water obstructing the roadway. Furthermore, land use planning is likely to focus on prevention and flood-risk/water obstruction mitigation that the parties affected may need to consider long-term protection of open space in floodplains or areas thought to be a cause of water obstructions on roadways (Chang et al. 2011).

A related issue is that there is potential for drivers to misunderstand the potential or real danger of entering a location where there is an ongoing water obstruction (Boselly 2001). Furthermore, even if the location is known for a potential hazard, there is often no way for drivers to know whether the roadway condition is or is not a hazard which may cause the driver to venture onward into a difficult situation. Therefore, the availability for driver education to learn about these situations in the form of an online course or facts sheet may prove beneficial, especially if never encountering these situations in the past. In addition, research has suggested that the National Weather Service (NWS) and other public warning agencies need to focus education efforts on ensuring that the public understand watches, advisories, and warnings, the importance of paying attention to these, and the dangers inherent in driving on a roadway with water obstructions (Drobot et al. 2007).

The Transportation Research Board (TRB) put forward three key climate factors that can challenge the surface transportation system in the United States: rising sea levels, increases in intense precipitation, and increases in hurricane intensity (National Research Council et al. 2008). For Nebraska, increases in weather-related hazards are what makes research involving transportation and understanding these weather-related hazards to further assess mitigating the societal and economic impacts essential. There is high confidence that heavy precipitation events in most parts of the United States have increased in both intensity and frequency since 1901 (Easterling et al. 2017; Flanagan and Mahmood 2021). The central United States, including Nebraska, has experienced an increase in MCSs, which are a main mechanism for warm season precipitation (Easterling et al 2017). In addition, the precipitation amounts associated with MCSs have increased, and the frequency and intensity of heavy precipitation events are projected to increase under both lower and higher CO2 emission scenarios (Easterling et al. 2017). Increased precipitation events include the intensity of synoptic scale ETCs, such as the one experienced in March 2019. As a result of increasing extreme precipitation and soil moisture content, water tables are likely to increase, leading to more frequent flooding and water obstructions in locations already frequently affected by precipitation and groundwater (Chang et al. 2011).

In total, 18% of Nebraska's major roads are in poor or mediocre condition (TRIP 2022). Meanwhile, 42% of the state's bridges are at least 50 years old, while 8% of bridges in the state are rated in poor condition (TRIP 2022). Conditions on the surface transportation system are deteriorating, as the need for transportation improvements far outpaces the amount of state and federal funding available. While there are specific locations where water obstructions have occurred frequently, these locations may not be documented and are often only known to highway agencies and not to the local traveling public (Boselly 2001). Therefore, reemphasizing the importance of this project's analysis as it aims to quantify a spatiotemporal water obstruction climatology across Nebraska to better understand flooding and associated meteorological conditions. This project targets the high-frequency water obstruction locations to implement structural or non-structural mitigation strategies and to improve the predictability of the onset of potential future water obstructions on state and federal highways.

3 Data and Methods

3.1 Data

3.1.1 Water Obstruction Data

Raw historical water obstruction data from the CARS511 historical archive were obtained from the Nebraska Department of Transportation (NDOT) for the period June 2016 through August 2021 (NDOT 2021). The study domain for this analysis is Nebraska, and obstruction data were summarized by NDOT district (Figure 3.1), by county (Figure 3.2), for all state and federal highways (Figure 3.3), and by river (Figure 3.4). These aforementioned figures are to serve as reference throughout the manuscript. Raw water obstruction data consisted of the event ID, date and time of obstruction, route designator, route mile marker of start and end of obstruction, latitude/longitude of the start and end of obstruction, link direction, and the level of obstruction (water on pavement, lane closure, or complete closure). The end date of the water

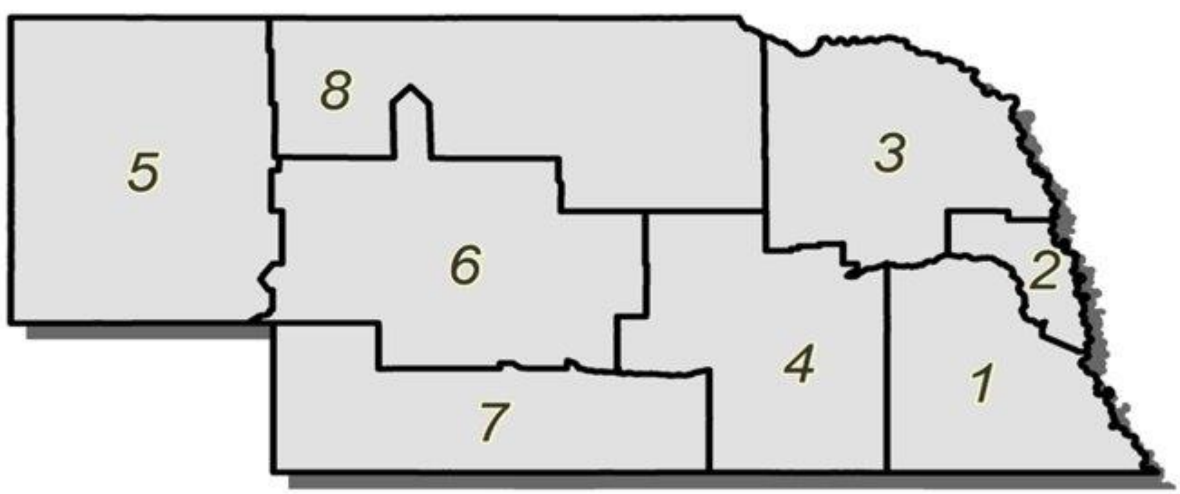

Figure 3.1 *Study area with NDOT District labels.*

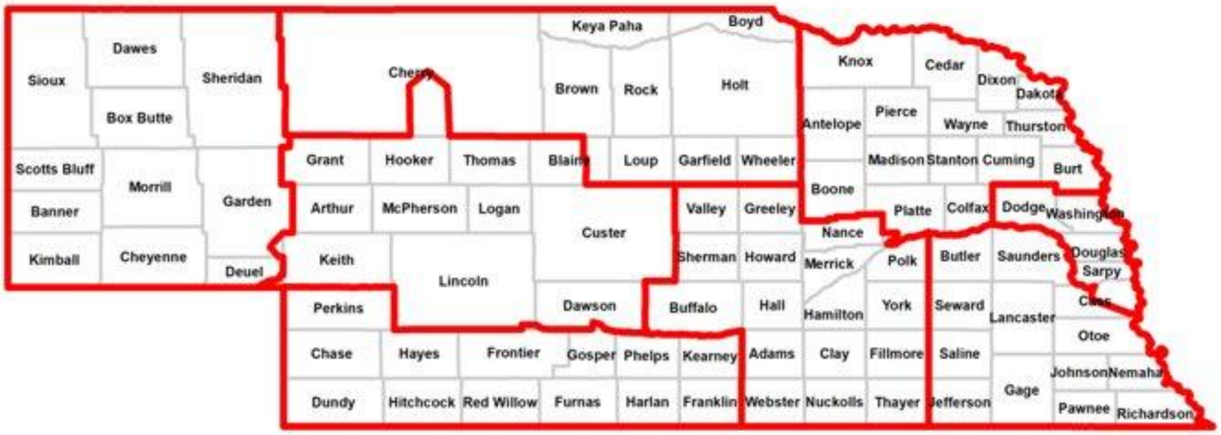

Figure 3.2 *Study area with county outlines (gray) and labels along with NDOT district outlines (red).*

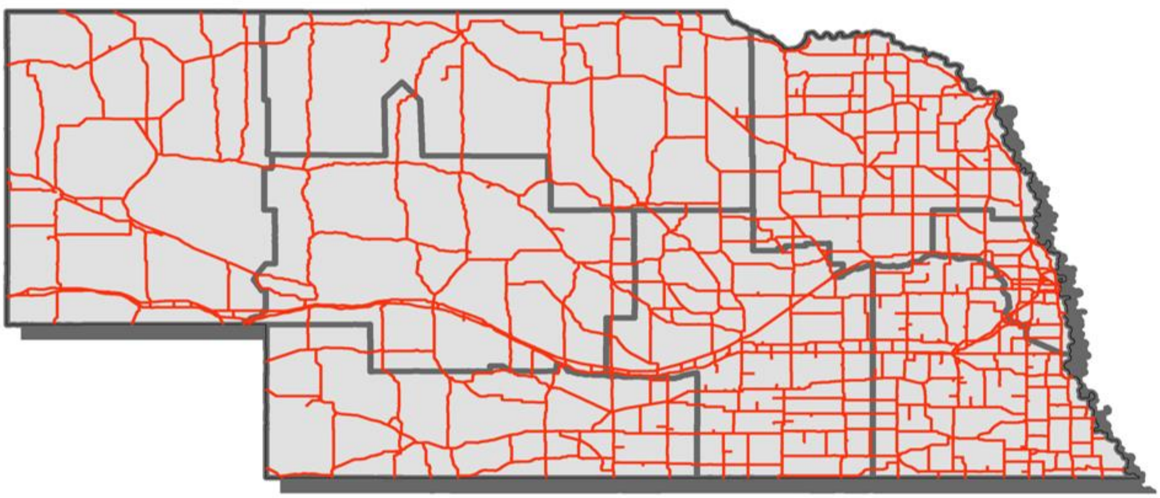

Figure 3.3 *Study area with all state and federal highways examined.*

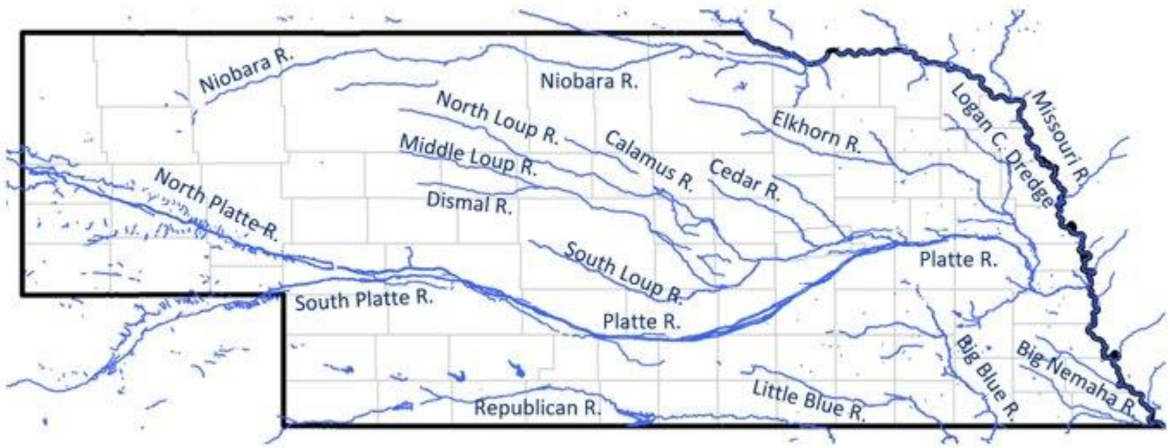

Figure 3.4 *Study area with the Nebraska major river network.*

obstruction was also included in the obtained dataset; however, due to data reliability and uncertainty, the end dates were not considered in the analysis. Ending dates were illegitimate, or unrealistic, with respect to the starting date of the water obstruction in many cases. Furthermore, the ending dates for a majority of events were set to 12/31/2020 no matter the starting date, thus making these unusable for the analysis. In addition, many event IDs were repeated in the dataset if an obstruction was reduced or expanded in mileage due to improving or worsening conditions. Therefore, any events that were duplicated were removed from the analysis to avoid potential spatial bias. In other words, only the first unique event ID is considered per water obstruction event, which resulted in 298 unique roadway water obstruction events over the 2016–2021 period. For the ending points to the water obstruction latitude and longitude points, there were a significant number of events that had “NULL” instead of the actual latitude and longitude. Thus, only the starting point latitude and longitude points along with the starting and ending highway mile markers were used. Other information for each water obstruction event including the respective county, NDOT district, and obstruction distance were also obtained and incorporated into the analysis.

3.1.2 Meteorological and Climatological Data

To understand the occurrence of roadway water obstructions, better precursor weather and climatic conditions were assessed. With the given information in the water obstruction dataset, meteorological and climatological data were extracted (Figure 3.5). For the climatological analysis, which acts to “set the stage” for the deeper analysis in the water obstructions, data from the National Centers for Environmental Information (NCEI) Climate at a Glance were gathered from 1991-2021 (NCEI 2021). Climate data consisted of monthly average temperatures, precipitation, Palmer Drought Severity Index (PDSI), and Palmer Hydrological Drought Index (PHDI) values. The PDSI was chosen because the index attempts to measure the duration and intensity of the long-term drought-inducing circulation patterns (Palmer 1965).

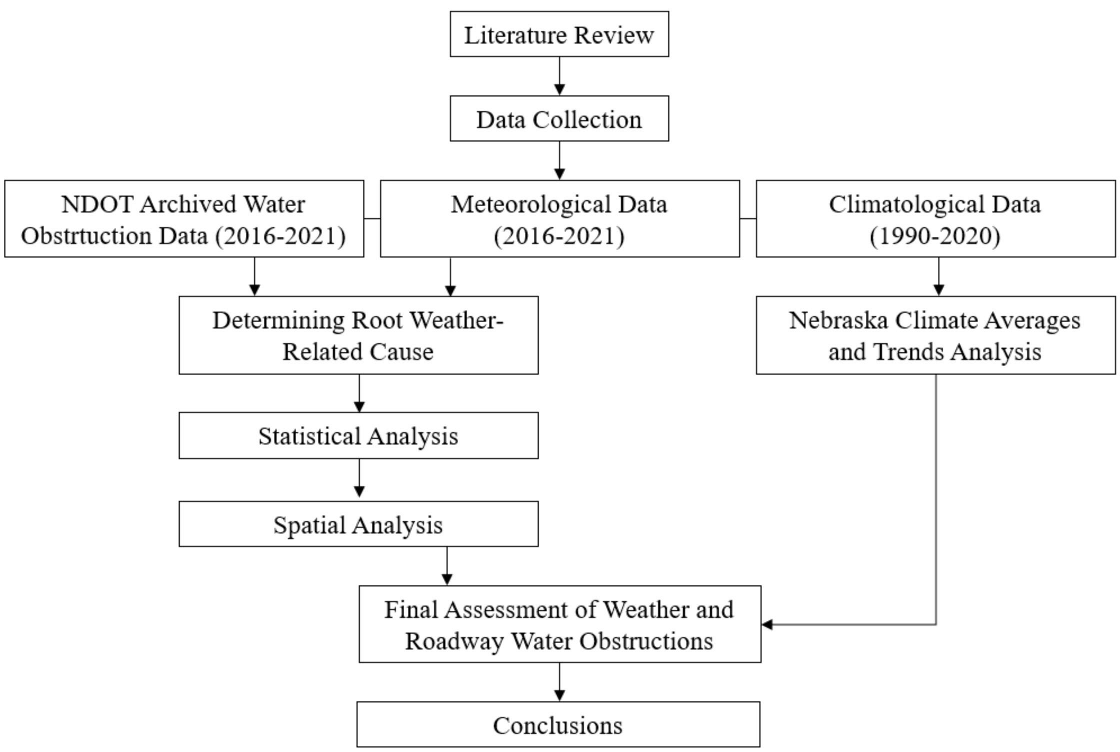

Figure 3.5 *Research framework.*

Long-term drought is cumulative, so the intensity of drought during the current month is dependent on the current weather patterns plus the cumulative patterns of previous months (NOAA 2021). The reverse can be said for the non-drought (moist) periods of time when the soil is saturated. The PHDI also measures hydrological impacts of drought and moisture surplus scenarios (e.g., reservoir levels, groundwater levels, river levels) which take longer to develop and longer to recover from (Palmer 1965). This long-term drought index was developed to quantify these hydrological effects, and it responds more slowly to changing conditions than the PDSI. From here, the 30-year average (1991–2020) was computed to understand the baseline means for each county across the state. The climatological data were collected for each county and were informed by meteorological season: winter (current year's December, following year's January and February); spring (March, April, May); summer (June, July, August); and fall (September, October, November). More specifically on the winter season, if the winter of 2019 was being examined, then December 2019, January 2020, and February 2020 were considered. The PDSI and PHDI were the only variables that could not be informed by county, thus, were displayed by each climate division in Nebraska. For all climate variables, the 127-year seasonal and annual rankings were collected at Nebraska state-level aggregation to compare how the study period (2016-2021) and climatological period (1991-2020) compared with the entire climatological record (1895-2021). In addition, groundwater level percentiles were gathered for each of the prospective groundwater obstruction events to aid in the confirmation process (NDMC 2022). These 0.125 gridded cell units were based on the 1948 through 2014 period for the United States.

Meteorological data were also collected with respect to the date and time of each roadway water obstruction. First, NWS advisory data were assembled to assess if there was a flood or flash flood watch/warning or related advisory ongoing during or prior to the water obstruction (ISU 2021). Archived radar imagery was assessed to determine if there was precipitation ongoing or within seven days prior to the water obstruction, and if so, then what the duration of the precipitation was prior to the obstruction, start and end times, and if the precipitation return was convective or stratiform. Convective precipitation is defined as a radar return greater than 45 dBZ located 0–250 km out from the radar site, and greater than 35 dBZ when the rainfall return is greater than 250 km from the radar site (Qi et al. 2013). Any precipitation not meeting these radar-return requirements is classified as stratiform precipitation. The categorization of storm's precipitation type was determined by the initial precipitation over the water obstruction location. In other words, if a storm had convective precipitation followed by stratiform, then that storm was classified as convective. Precipitation assessed by radar was also categorized by storm mode or storm type. These storm type categories were subjectively assigned from radar analysis using guidance from Schumacher and Johnson (2005), as either being a part of a synoptic scale extratropical cyclone (ETC; which is a Colorado-Low in this case having a mean track from the southwest direction), an Alberta-Clipper system (mean storm track from the northwest direction), mesoscale convective system (MCS), supercell, multi-cluster cells, or convective training.

Automated surface observing system (ASOS) precipitation data from the nearest observing location to the water obstruction were obtained at 1-hour, 3-hour, 6-hour, 12-hour, 1-day, 2-day, 7-day, and 30-day intervals for each water obstruction (ISU 2021). These data are different than the already collected precipitation data for the climatological analysis since these are actual precipitation amounts for a specific location and time, while the climate precipitation data were summarized by county, month, season, and year by the NCEI. The closest ASOS station to the obstruction was used, and these data along with the NWS advisory and radar imagery were obtained through the Iowa Environmental Mesonet website (ISU 2021).

National Oceanic and atmospheric Administration (NOAA) Atlas 14 precipitation frequency and recurrence intervals were obtained for each water obstruction location based on the precipitation duration prior to the water obstruction (HDSC 2005). The NOAA Atlas 14 database consists of precipitation frequency estimates with associated confidence limits for any given location in the United States where the nearby weather observing station has at least 20 years of data for (NOAA 2008). Thus, there is not a definitive period of record the NOAA Atlas 14 uses for daily, hourly, and sub-hourly durations. So long as the station has at least 20 years of data, there could have been upwards of 150 years examined. Though, the average length of data used for stations were 68 years for daily station durations, 41 for hourly station durations, and 26 for sub-hourly station durations (NOAA 2008). For reference, Figure 3.6 shows the precipitation totals in a 24-hour period that would be representative of a 50-year reoccurrence precipitation event.

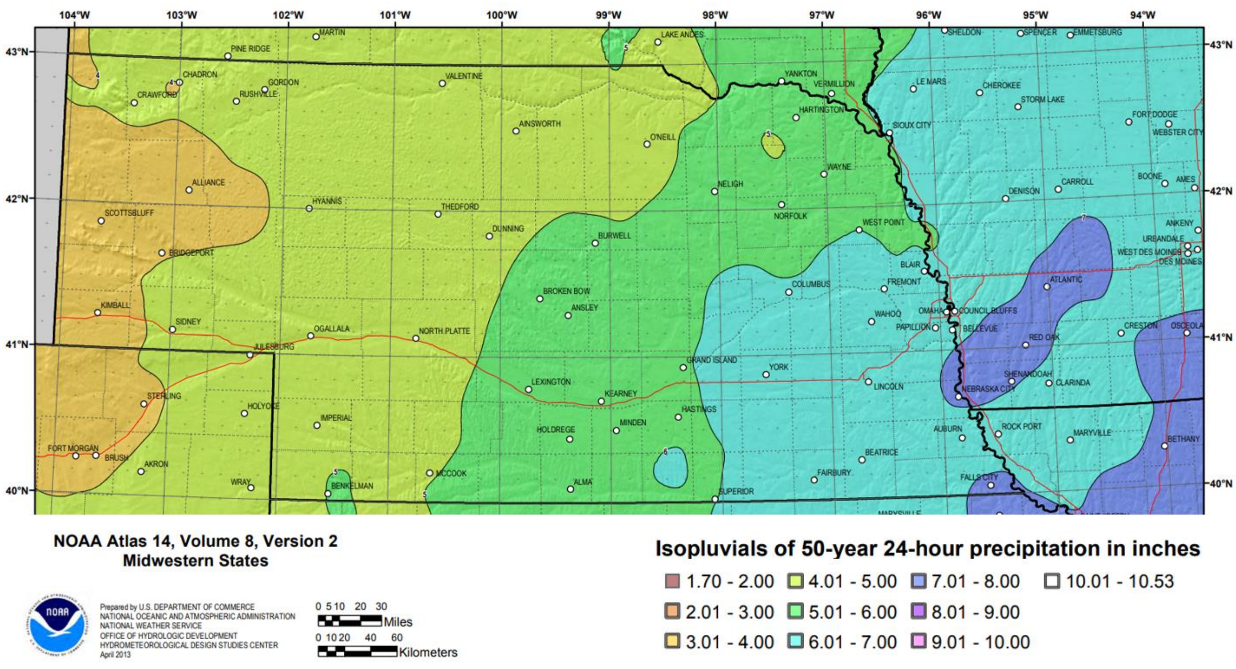

Figure 3.6 *NOAA Atlas 14 precipitation estimates (in) for a 24-hour period that is considered a 50-year precipitation event in Nebraska (Source: NOAA 2008; HDSC 2005).*

The Atlas provides these estimates for 5-minute through 60-day durations at average recurrence intervals of 1-year through 1000-years (NOAA 2008). Therefore, the duration of the precipitation event prior to the water obstruction being documented is what was used to determine the duration. For example, 3 inches of precipitation may have fallen over the course of 1 hour prior to the water obstruction, which translates to a 10-year reoccurrence precipitation event according to the NOAA Atlas 14 for the selected location in Nebraska.

In addition, Nebraska river ice jam data from 1991–2021 were gathered from the Cold Regions Research and Engineering Laboratory, or CRREL (CRREL 2021). These data include the name of the water body, the city and state where the ice event took place, the month, year, and date of the ice event, the ice event type (if known), a brief description of damage (if known), the names of the Corps personnel familiar with the event or site (points of contact), latitude and longitude, and United States Geological Survey (USGS) gage number (if available). This database is especially useful, not only for the historic records of river ice jam events, but also for potential applications using this information including the identification of potential ice jam stages, problem areas, and mitigation areas (White and Eames 1999). An important note with the CRREL ice jam database is that the USGS gaging station records consist of about 80% of the historical information in the database, while the National Weather Service (NWS) is the primary source since near-real-time monitoring began in the mid 1990's. Both rely in large part on hydrometeorological gages, making them highly reliable data sources and making the ice jam database reliable (White et al. 2007). Nebraska ice report summaries were collected, if available, to increase the confidence if an ice jam event was taking place (NDNR 2022).

Streamflow conditions in the form of river gage levels and river discharge were obtained via the USGS and Nebraska Department of Natural Resources (NDNR 2021; USGS 2022). Thus, the data on streamflow were compiled using both USGS and NDNR stream gage sites.

Streamflow data were obtained before, during, and after the time of the obstruction to understand if river levels or river discharge increased due to the precipitation, contributing to the roadway water obstruction. If there were no stream gage sites near the water obstruction (within ~5 miles), then data were not collected for that specific roadway water obstruction. The stream gage data for each qualifying water obstruction were then subtracted from the daily 40-year median for that gage height and discharge number to form the departure at that time.

Finally, climatological data in the initial analysis were also used with respect to the occurrence of each water obstruction event. This includes the values, means, and anomalies of average temperature, minimum temperature, precipitation, PDSI, and PHDI for the month when the water obstruction occurred and for the month prior to the water obstruction. River ice jam data gathered for the climate analysis were also used with respect to potential ice jam-induced water obstructions.

3.2 Methods

3.2.1 Determining Root Weather-Related Cause

The next step in the research framework was to use the NDOT water obstruction data and the meteorological data to determine the root weather-related cause for each roadway water obstruction event (Figure 3.7). To determine the root weather-related cause for each roadway water obstruction, a combination of location and precursor meteorological conditions were used to make the most accurate judgement. The types of flooding most prominent in Nebraska highlighted in Section 2 were used as the four root weather-related causes for this analysis. Throughout this analysis, these root causes are displayed alphabetically in each of the figures. Thus, they were not formatted by importance or relevance. For each water obstruction, the method for determining the root weather-related cause is highlighted in Figure 3.7 and summarized below:

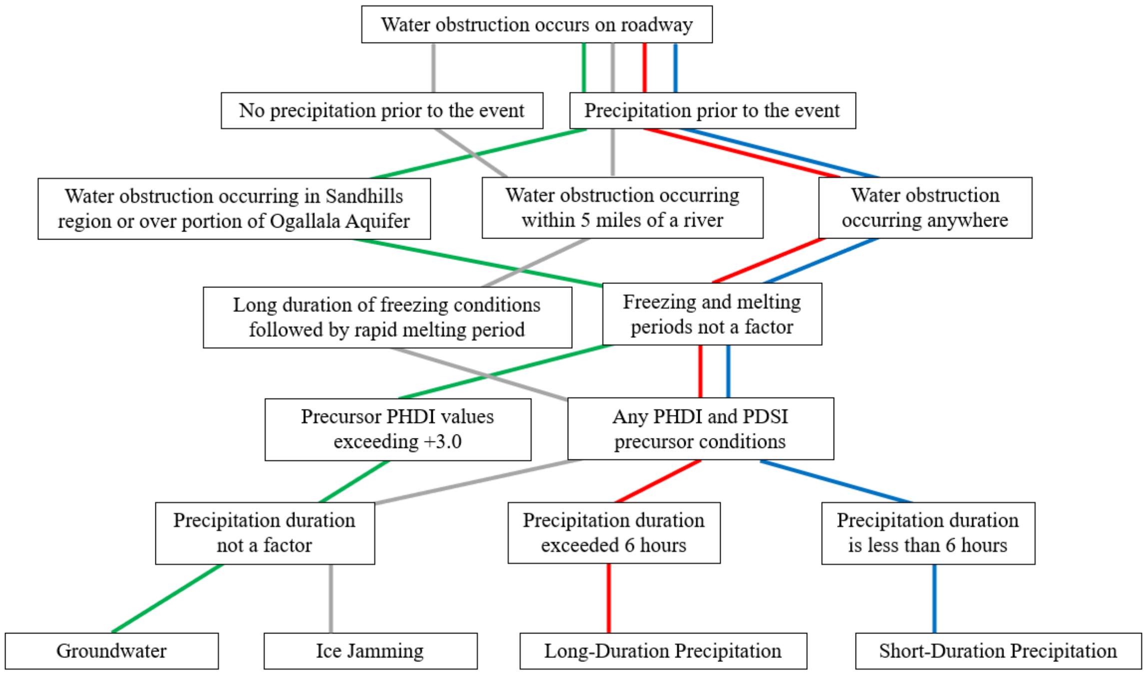

Figure 3.7 *Framework for determining root weather-related cause. Green path represents groundwater induced obstructions; gray path represents ice jamming induced obstruction; red path represents long-duration precipitation induced obstructions; blue path represents short-duration precipitation induced obstructions.*

- *Groundwater* – PHDI values exceeding +3.0 (very moist conditions) were observed. Precipitation does occur prior to the water obstruction, though precipitation duration did not matter. Locations of groundwater-induced water obstructions need to be over the Ogallala Aquifer, generally located in the Sandhills region of Nebraska. Archived groundwater level percentiles were also used to confirm the occurrence of groundwater flooding.
- *Ice Jamming* – A combination of below freezing (<32°F) temperatures for at least a 10-day duration, followed by a rapid warming of temperatures to above freezing

(>32°F) temperatures. Confidence of the ice jam increased when the rapid warming was associated with either short- or long-duration precipitation. Location of water obstruction needs to be within 5 miles of a waterway. CRREL ice jam data and Nebraska ice report summaries were also used to aid in this assessment.

- *Long-Duration Precipitation (LD Precip)* – Typically associated with flood warnings, which is defined as longer, more gradual flooding usually beginning after 6 hours of excessive rainfall (NWS 2017). Therefore, obstructions were flagged as long-duration precipitation if the precipitation prior to the water obstruction was 6 or more hours in duration (if the possibility of groundwater or ice jamming have been eliminated).
- *Short-Duration Precipitation (SD Precip)* – Typically associated with flash flood warnings, which is defined as short-duration (less than 6 hours), intense flooding resulting from torrential rain (NWS 2017). In other words, precipitation events that were less than 6 hours in duration prior to the water obstruction were flagged as short-duration precipitation (if the possibility of groundwater and ice jamming have been eliminated).

While these may be the root *weather-related* cause to each water obstruction, it is important to understand there are likely other physical processes contributing to these obstructions, including land-use, infrastructure, etc., as highlighted in Section 2. In addition, each analysis was performed with and without March 2019 to avoid potential bias since the aforementioned March 2019 historic flooding event was responsible for 171 (58%) of the total roadway water obstructions from June 2016–August 2021.

3.2.2 Statistical analysis

Given the information in the CARS511 historical dataset, other information was extracted using a merge geoprocessing technique. In other words, the point locations of each water obstruction were tagged to its respective county and NDOT district. Thus, summary statistics were able to be computed to inform the number of water obstructions that occurred in each county and NDOT district. Furthermore, summary statistics were computed on a monthly, seasonal, and annual basis by county, NDOT district, and for Nebraska as a whole. For climate averages, a simple mean was computed over the 30-year period to inform county, climate division, or state-wide averages. In order to assess trends in climate variables, Theil-Sen slope analysis was chosen due to its efficient computation and insensitivity to outliers (Wilcox 2010). Kendall's τ was used to assess the statistical significance of the trend to the 95% confidence level. In addition, for all box and whisker plots presented in the analysis, Tukey HSD ("honestly significant difference") multiple comparison test was computed at the 95% confidence level. Tukey HSD determines if the relationship between two sets of data is statistically significant in terms of their difference in sample means (Ott and Longnecker 2015). In other words, it is a way to quantify the statistical differences between each box and whisker plot in each chart. Furthermore, each box and whisker plot presents a six number summary: whiskers represent the 1.5x multiple of the interquartile range; outliers (values outside the 1.5x multiple of the interquartile range); the boxes represent first quartile (25^{th} percentile) and third quartile (75^{th} percentile) values; black line horizontal within boxes represent the median value; white squares represent the average value.

3.2.3 Spatial analysis

ArcMap (ESRI 2019a) was used to perform all spatial analyses for this study. This allowed for in-depth assessments of specific water obstruction spatial patterns and causes. All water obstruction events, along with their respective meteorological observations and root weather-related causes, were imported into ArcMap using the "Add Route Events" tool. Water obstruction hot-spots were identified by using the Line Density and Kernel Density tools, which calculate a magnitude-per-unit area from point features that fall within a neighborhood around each cell (ESRI 2019b, c). Only the lines (road segments) within the neighborhood are considered when calculating the density, then returning a density raster for the output. Kernel densities were calculated on a seasonal and annual basis by root weather-related cause, and also when the four primary causes and all years in the study were compiled together. Line densities were used for a finer analysis when examining obstruction overlap in specific areas identified as hot-spots with the Kernel Density tool.

4 Results

4.1 Roadway Water Obstructions

4.1.1 Overview of Water Obstructions

Over the study period June 2016 through August 2021, long-duration precipitation and ice jamming water obstructions are the most common in occurrence and account for 71% of all water obstructions (Figure 4.1a). With March 2019 possessing 58% of the water obstruction total in the study period, it is no surprise that long-duration precipitation and ice jamming account for over two-thirds of the obstructions (Figure 4.1a). However, the distribution of water obstruction root weather-related causes shows distinct differences when March 2019 is removed from the dataset (Figure 4.1b).

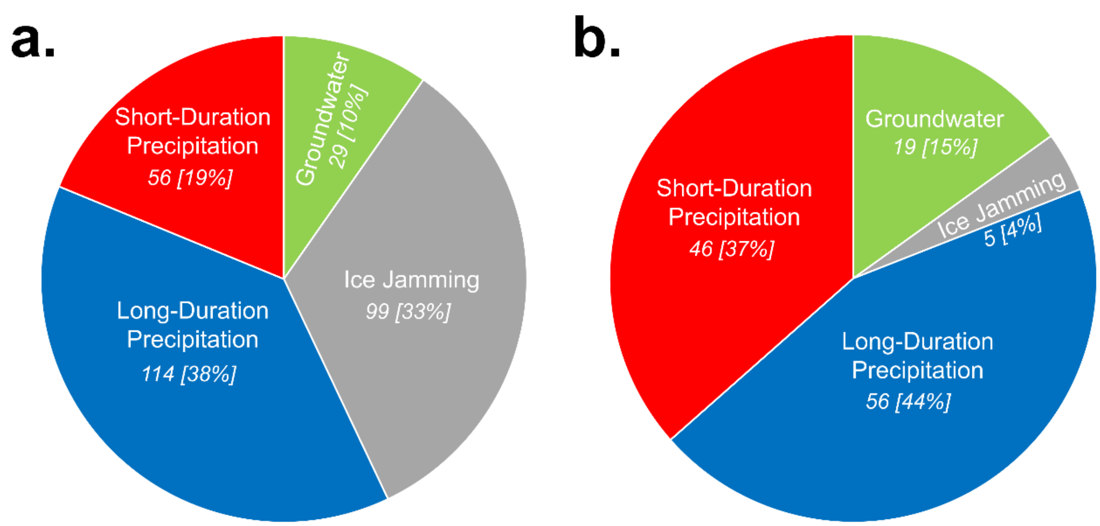

Figure 4.1 *a) Distribution of water obstruction by root weather-related cause. First number represents the total number of obstructions while percent in brackets signify the distribution of 100% (2016-2021); and b) is the same as (a), without March 2019 obstructions.*

Without March 2019 in the dataset, the distribution of long-duration precipitation and ice jamming water obstructions decrease to only 48% of the total water obstructions, with most of this new distribution being accounted for by long-duration precipitation. Overall, long-duration and short-duration precipitation are the two leading causes for water obstructions in Nebraska between June 2016 and August 2021, which consist of 80% of the water obstructions in Nebraska when March 2019 is removed. With the removal of the extra summer in the dataset, whether it is summer 2016 or summer 2021, long- and short-duration are still the two leading causes. The prevalence of groundwater water obstructions remains relatively consistent when considering March 2019, as the range of the distribution is on the magnitude of only 5%. When all is considered, the order of frequency in which these causes lead to water obstruction is as follows: 1) long-duration precipitation, 2) short-duration precipitation, 3) groundwater, 4) ice jamming. With March 2019 in the dataset, ice jamming takes the number 2 spot while short-duration moves to 3 and groundwater move to 4.

Over the study period, there are 19 total multi-obstruction events, which are defined as having at least two or more roadway water obstructions associated with the event (Table 4.1). These multi-obstruction events can include both long- and short-duration precipitation water obstructions along with groundwater and ice jamming obstructions. The non-trivial role these 19 multi-obstruction events play in the overall distribution warrants further examination, as not only do they contribute to the overall distribution, the events also contribute to the monthly and annual water obstruction climatologies. The March 2019 event has the most water obstructions (171), which leads to the highest number of accumulated miles impacted (1334), and the most obstructions that resulted in a road closure (121 out of 171; 71%). Over 88% of those closures are due to ice jamming and long-duration precipitation, which occurs during a time of year when ice jamming occurs frequently and when/where extratropical cyclones indicative of

***Table 4.1** All multi-obstruction events (≥ 2 obstructions) with 1) the total mileage that closed and remained open within the roadway water obstructions, and 2) the root weather-related cause associated with each event.*

Precipitation Event	Obstructions	Roadway Status			Distance	Weather-Related Cause			
	Count	Water on Pavement	Lane Closure	Full Road Closure	Obstructed Miles	Groundwater	Ice Jamming	L.D. Precip.	S.D. Precip.
March 2019 ETC Precipitation Event	171	44	6	121	1334	10	93	58	10
May 2019 Precipitation Event	15	5	1	9	45			13	2
July 2019 Central NE MCS Event	14		2	12	54	1		13	
June 2018 Northeast NE Precipitation Event	12	1		11	135			10	2
August 2017 Central NE Convective Training Event	7	6	1		11			3	4
September 2016 Northeast NE Convective Training Event	6	4		2	8			5	1
July 2020 Southern NE MCS Event	4	2	1	1	17				4
August 2021 Eastern NE MCS Event	3		1	2	3				3
July 2019 Northern NE MCS Event	3	3			3	2			1
June 2016 Eastern NE MCS Event	3			3	5			2	1
June 2020 Eastern NE Convective Training Event	3		1	2	3			2	1
May 2017 South and Eastern NE MCS Event	3	3			3			1	2
August 2021 Southeast NE Severe Storms Event	2			2	2				2
July 2017 Northern NE Convective Training Event	2			2	2				2
July 2017 Southeast NE Convective Training Event	2	2			4			2	
June 2017 Eastern NE Convective Training Event	2	2			2				2
May 2017 Eastern NE ETC Precipitation Event	2	2			2				2
May 2019 Southeast NE MCS Event	2			2	5			1	1
September 2019 Northern NE MCS Event	2	1		1	6	1			1
Other (single obstruction events)	40	23		17	68	15	6	4	15
Total	298	98	13	187	1712	29	99	114	56

long-duration precipitation events occur frequently (more on this climatology in Section 4.2). No other multi-obstruction event over the 5-year period caused ice jamming water obstructions in Nebraska. In other words, all other ice jamming water obstructions contribute to the single obstruction case total, in which ice jamming accounts for 6 of the 40 total single obstruction cases. Two months following the March 2019 historic flooding event, the next highest water obstruction event (or multi-obstruction event) occurred in May 2019 across central and eastern Nebraska with 15 total obstructions, nine of them leading to a road closure from long-duration precipitation. Not even two months later, the July 2019 central Nebraska long-duration multi-obstruction event caused 14 total obstructions, 12 of these leading to a road closure. In summary, the top three multi-obstruction events, in terms of total water obstructions in Nebraska since June 2016, occur within a five-month period in 2019. However, the second and third leading multi-obstruction events do not possess the highest number of accumulated miles impacted (Table 4.1). The June 2018 multi-obstruction event in northeast Nebraska has the second most mileage impacted behind March 2019 with 135 obstructed miles, with most of these obstructions being caused by long-duration precipitation further leading to 92% of the obstructions causing a road closure. Otherwise, there are 15 other multi-obstruction events where short-duration precipitation is the dominant cause of the obstructions, and 40 total single obstruction cases where groundwater and short-duration precipitation are the primary causes over the 5-year study period. Overall, every year in the study period (2016–2021) has at least one multi-obstruction event: 2016 with two; 2017 with six; 2018 with one; 2019 with six; 2020 with two; and 2021 with two.

Multi-obstruction events and single water obstruction cases alongside their root weather-related cause may contribute to whether or not a road closure or lane closure is in place (Figure 4.2). Over 80% of the ice jamming water obstructions cause either a lane closure or a full road closure. With the removal of March 2019, all ice jam water obstructions result in a full closure. Long-duration precipitation events also cause a larger number of roadways to have a lane closure or a full closure accounting for 74% (84 of 114) of long-duration precipitation water obstructions. Thus, 25% (30 of 114) of long-duration precipitation obstructions result in water on

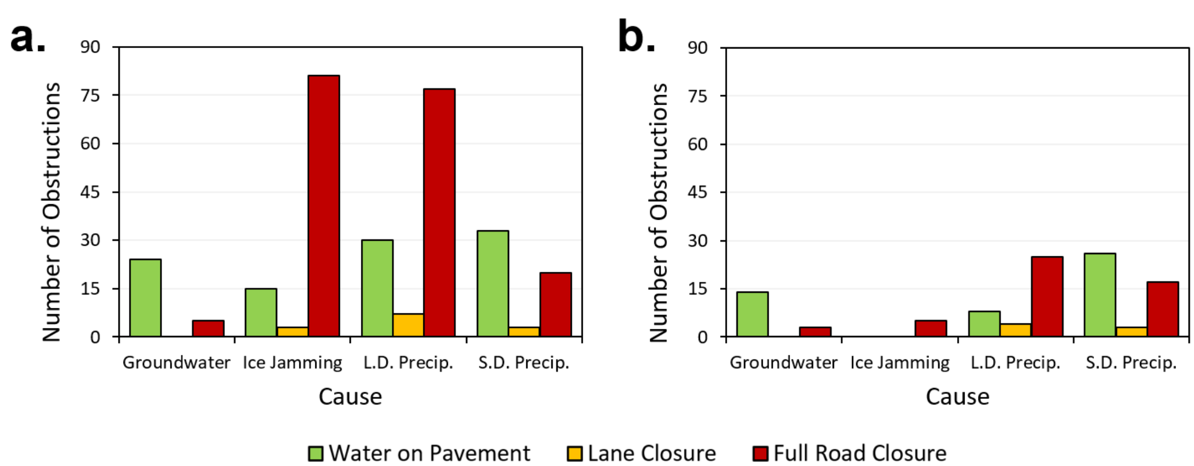

Figure 4.2 *Total number of water obstructions that resulted in just having water over a roadway (no closures), lane closure, or full road closure (a) with March 2019 and (b) without March 2019 from 2016-2021.*

The pavement and no lane or full closure recorded. However, this is not the case for short-duration precipitation water obstructions as only 41% (23 of the 56 short-duration water obstructions) of these events result in a lane closure or full road closure. The same can be said with groundwater water obstruction events as only 17% (5 of 29 groundwater obstructions) of these events result in a lane or full road closure.

Accumulating the number of miles impacted by each water obstruction, ice jamming and long-duration precipitation water obstructions cause the highest number of miles impacted by an obstruction on average at 10 and 6 miles, respectively (Figure 4.3a). Without March 2019, the averages drop slightly to 7 miles and 5 miles respectively, with both causes still having the highest number of miles impacted (Figure 4.3b). Also, miles impacted by ice jamming and long-duration precipitation are statistically significant differences than short-duration and groundwater water obstructions to the 95% confidence level (when excluding March 2019). In other words, the less frequent ice jamming and the more frequent long-duration precipitation water

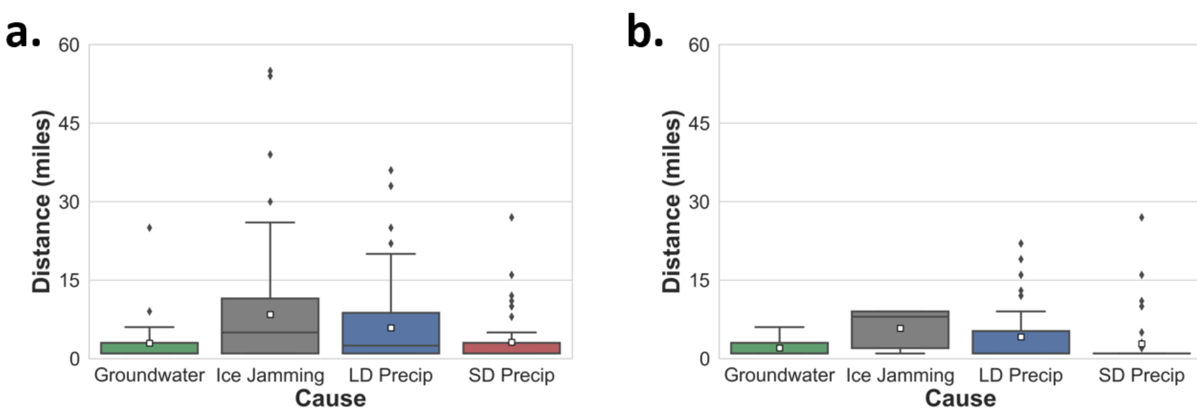

__Figure 4.3__ Box and whisker plots of distance (miles) impacted per water obstruction event by each obstruction's root weather-related cause (a) with March 2019 and (b) without March 2019 from 2016-2021.

Obstructions tend to not only result in road closures; they also impact a higher number of miles that close. However, when excluding March 2019, it is the short-duration precipitation induced water obstructions that have the most outliers, with distances of obstructions up to 29 miles impacted since June 2016. This suggests that short-duration precipitation obstructions tend to not close roads and to not impact as many miles as the other weather-related causes (average of 3-4 miles impacted). There are short-duration precipitation obstructions causing outlier events that impact more extreme mileage than any other weather-related cause (Figure 4.3b). Groundwater obstruction miles show similar results with short-duration precipitation in terms of the average number of miles typically impacted; however, there are not any outliers when excluding March 2019. This increases confidence in determining the number of miles impacted during the onset of a groundwater water obstruction, ranging from 1 to 6 miles impacted (when excluding March 2019). An important caveat, and likely a larger contributor to some of the water obstructions than the meteorology, is the number of miles impacted per obstruction event is dependent on the location of the obstruction, thus impacting the detour of the route which can also be considered a direct impact of water obstructions. This is likely the case for obstructions that occur in a sparser road network, such is the case in the central and western portions of Nebraska (Figure 3.3). With less state highway options, the mileage on an obstruction detour may need to be much longer than the roadway segment being impacted by the obstruction. Where these obstructions occur and the density of the road networks cannot be controlled for; however, the mileage information provided in Figure 4.3 may still aid in where potential mitigation efforts could take place.

4.1.2 Temporal Distribution of Water Obstructions

The top three events causing the most water obstructions occur within a five-month span in 2019. The year 2019 alone has 225 water obstructions, which accounts for 76% of the total dataset (Figure 4.4a). Even when excluding March 2019, the year still has at least 25 more water obstructions than any other year (Figure 4.4b), further justifying that while 2019 is an outlier year in terms of obstructions, these years can continue to happen. Each year, except for 2021, has at least 13 or more water obstructions. While 2021 still has two multi-obstruction events, the events only cause a combined five water obstructions while all other years either have more multi-obstruction events, or more water obstructions per event. For example, 2018 only has one multi-obstruction event; however, that one event is responsible for 12 obstructions. When

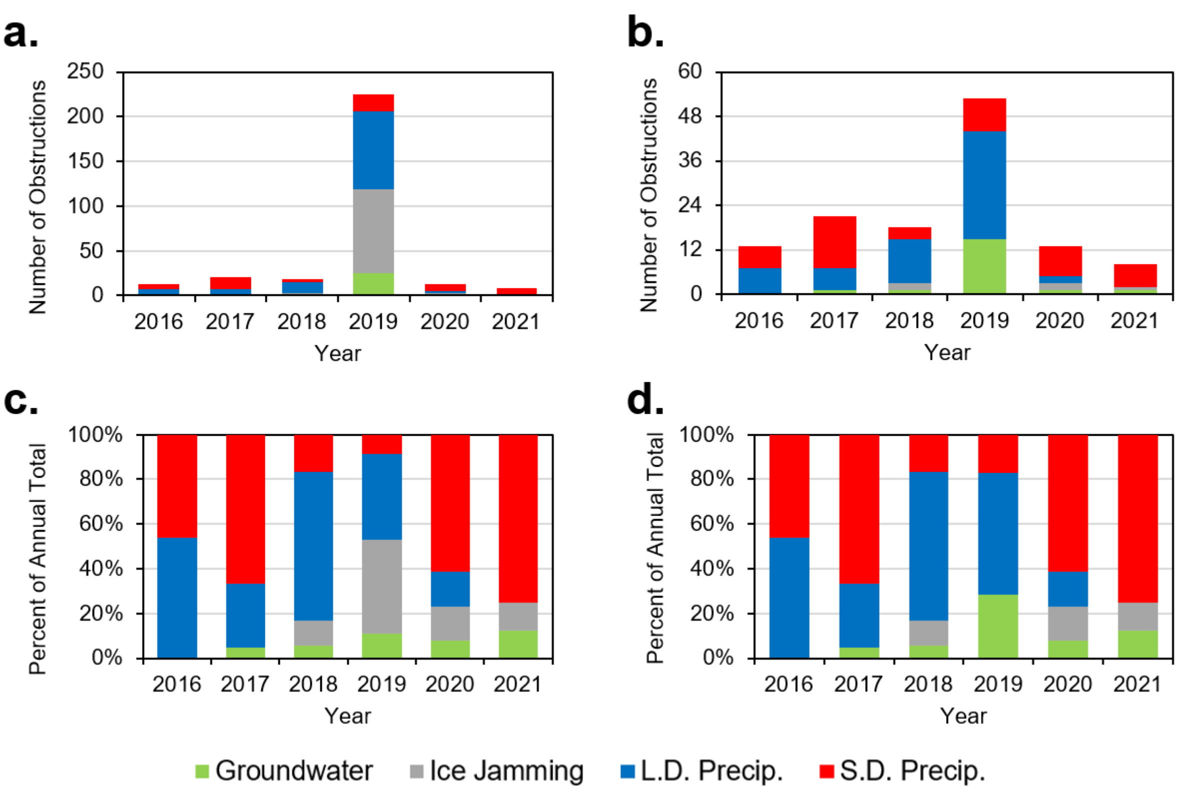

Figure 4.4. *Number of obstructions by root weather-related cause on an annual basis (a) with March 2019 and (b) without March 2019. In addition, the annual distribution of obstructions by cause are represented out of 100% (c) with March 2019 and (d) without March 2019 from 2016-2021.*

Excluding March 2019, the average number of water obstructions annually is 21; while the median number of water obstructions per year, which is likely a better representation of the actual number of water obstructions per year given the skew 2019 brings to the results, is 16 obstructions per year. This places the year 2016 (only 6 months included in the study period), 2020, and 2021 (8 months included in the study) below normal in terms of total number of water obstructions. For the root weather-related causes of water obstructions, the annual median number per year (excluding March 2019) is as follows: groundwater, one; ice jamming, one; long-duration precipitation, seven; short-duration precipitation, seven. On a median basis, this places the annual distribution for groundwater and ice jamming at 6% each and 44% each for long-duration and short-duration precipitation (Figure 4.4d). Therefore, water obstructions in Nebraska are more likely to occur via long- and short-duration precipitation as they account for 88% of the water obstructions in Nebraska annually.

Throughout the year, water obstructions tend to peak during late spring through late summer and are at an annual low during the fall, winter, and early spring due to the occurrence of long- and short-duration precipitation water obstructions (Figure 4.5a and b). While the study period does have an extra summer represented in the data as reflected in Figure 4.5, this does not change the frequency of water obstruction occurrences within these months. When removing summer of 2016 for the dataset, June had a total of 22 (4 less), July had 28 (same number if July 2016 was included), and August had 15 (only 2 less). If the summer of 2021 is removed, June and July have the same amount if the data were included at 26 and 28, respectively, while August would only have 7 (10 less). The frequency of the weather-related causes for water obstructions are highly dependent on the time of year for their peak occurrence (Figure 4.5c and d). Groundwater induced water obstructions can occur at any time of the year, though typically peak in occurrence during late summer. During late fall through early spring

(November through March), groundwater and ice jamming are the top occurring causes to water obstructions accounting for 100% of the total water obstruction causes when excluding March 2019. This is attributed to the climatology of long- and short-duration precipitation, as the frequency of these events are lower during this time frame. Except for ice jamming, it needs to be stated that the other three weather-related causes can happen at any time of the year with a varying level of frequency. This will be further investigated in Section 4.2 with the climate data.

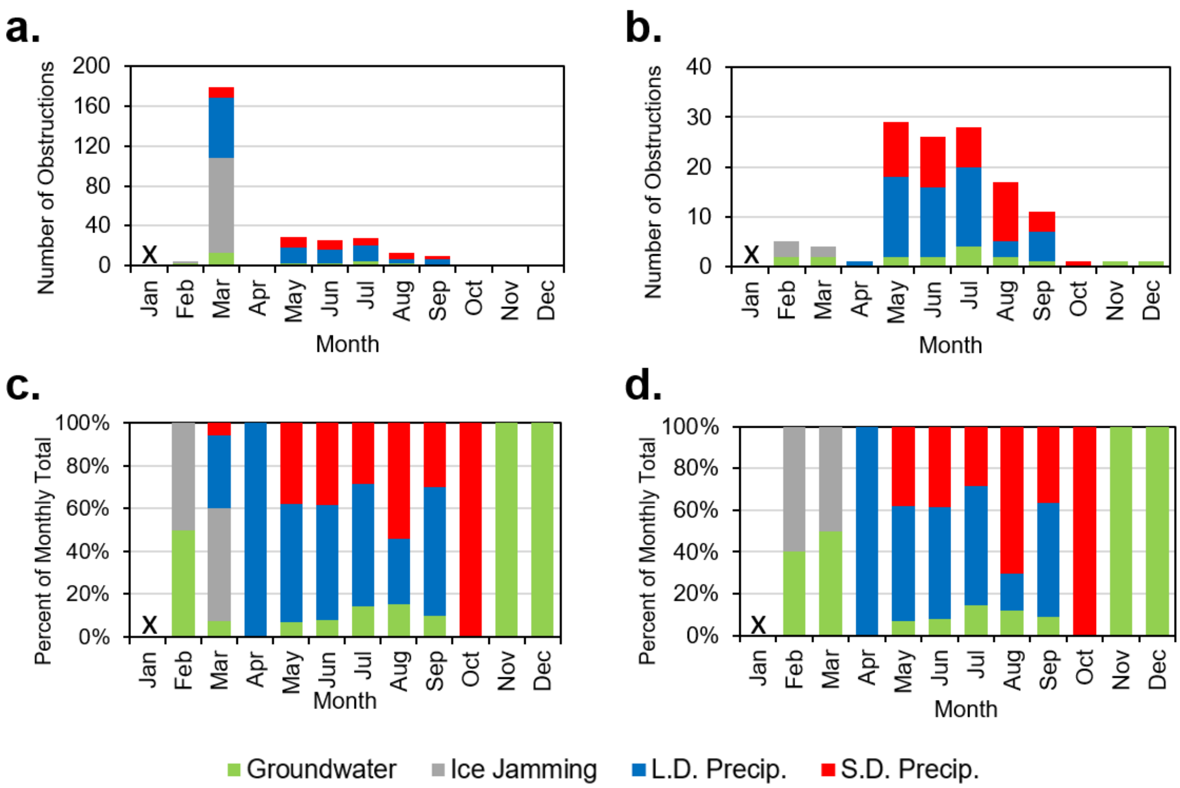

Figure 4.5. *Number of obstructions by root weather-related cause summarized by month (a) with March 2019 and (b) without March 2019. In addition, the monthly distribution of obstructions by cause are represented out of 100% (c) with March 2019 and (d) without March 2019 from 2016-2021. The X's represent months when no water obstruction occurred.*

The study period can be further examined by month and by year (Figure 4.6). With the study period starting in June 2016, only three months in 2016 (June, August, September), had water obstructions that consisted of long- and short-duration precipitation. Two multi-obstruction events occur during 2016, which account for nine of the 13 obstructions. These events were caused by a June 2016 MCS across eastern Nebraska (District 1, 2, 3) and a September 2016 convective training in northeast Nebraska (District 3). The year 2017 is like 2016, with most of the obstructions being induced from long- and short-duration precipitation events in the late spring and summer season. However, 2017 has six total multi-obstruction events, albeit four of these events only cause two water obstructions per event. The year 2018 only has one multi-obstruction event (June 2018 northeastern Nebraska stratiform rainfall), though it is responsible for 12 of the 18 total water obstructions. The year 2019 has the most water obstructions of any year. The water obstructions mainly occur in five of the 12 months, including March, May, July, November, and December. This is in large part due to the year having the highest number of groundwater water obstructions accumulated throughout the year as at least one new event occurred in eight of the 12 months. March 2019 is the only month in the study period when all weather-related causes of roadway water obstructions are observed. The majority of the water obstructions are ice jamming and long-duration precipitation events. The years 2020 and 2021 were similar in nature as both had the least number of obstructions, with most being short-duration precipitation events. While 2019 is of course an extreme year for ice jamming and groundwater obstructions, each year, except for 2016, has at least one ice jamming and one groundwater water obstruction. The year 2016 may have ice jamming and groundwater induced flooding prior to June, which would not be included in the analysis since the dataset begins in June.

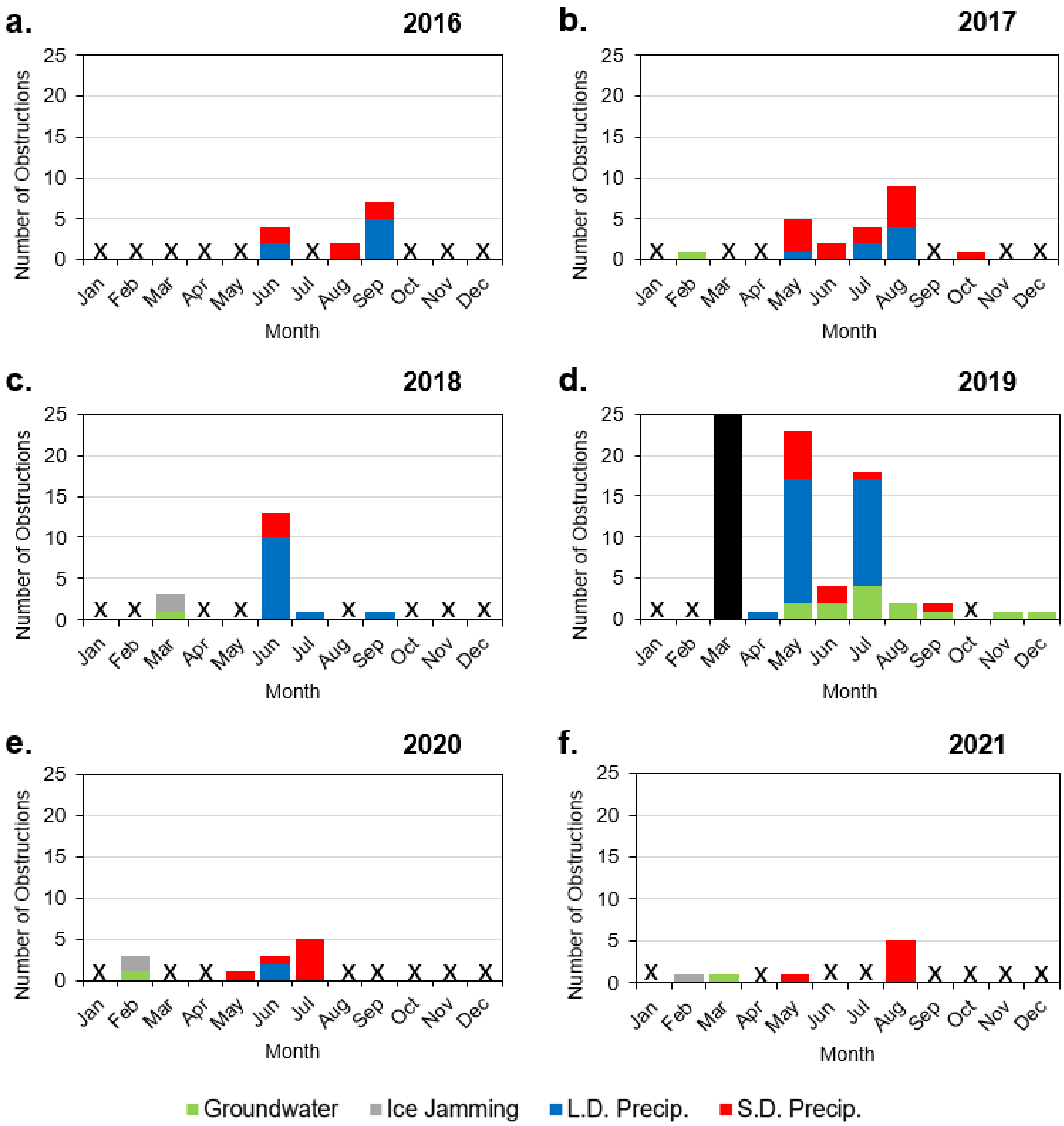

Figure 4.6. *Monthly water obstruction totals by each year in the study period by weather-related cause (a-f; 2016-2021). Black bar represents March 2019, which goes off this scale in the subplot. The numbers for this month were Groundwater with 12, Ice Jamming with 94, L.D. Precipitation with 58, and S.D. Precipitation with 10 to total up to 174 water obstructions. Months with X's denote 0, or no water obstructions occurred.*

4.1.3 Spatial Distribution of Obstructions

The spatial distribution examines where water obstructions are occurring on a seasonal interval (Figure 4.7; Table 4.2). Water obstructions during the winter season, which have only been induced by groundwater and ice jamming, are focused in the northern and eastern portion of the state in Districts 2, 3, and 8. When excluding March 2019, a much different outlook is presented for the spring as the spatial relationship is quite similar to the fall season, with the only difference being there are not any ice jamming water obstructions in the fall season, as would be expected. In the spring, the number of obstructions start to spread more throughout Nebraska. During the summer, obstructions occur in each district throughout the state. District 3, which is located in the northeastern domain of the state, has the most ice jamming, and long and short-duration precipitation water obstructions in the spring (Table 4.2). Not far behind is District 8 (located in north-central Nebraska), with groundwater induced water obstructions and short-duration precipitation (excluding March 2019) occurring most frequently. For the summer season, long- and short-duration water obstructions occur the most frequently in District 4, which is located on the periphery of south-central and south-eastern Nebraska. While all locations are prone to having water obstructions at any time of the year, the five-year water obstruction climatology reveals there are areas more favorable for water obstructions and closely related to the climate of Nebraska.

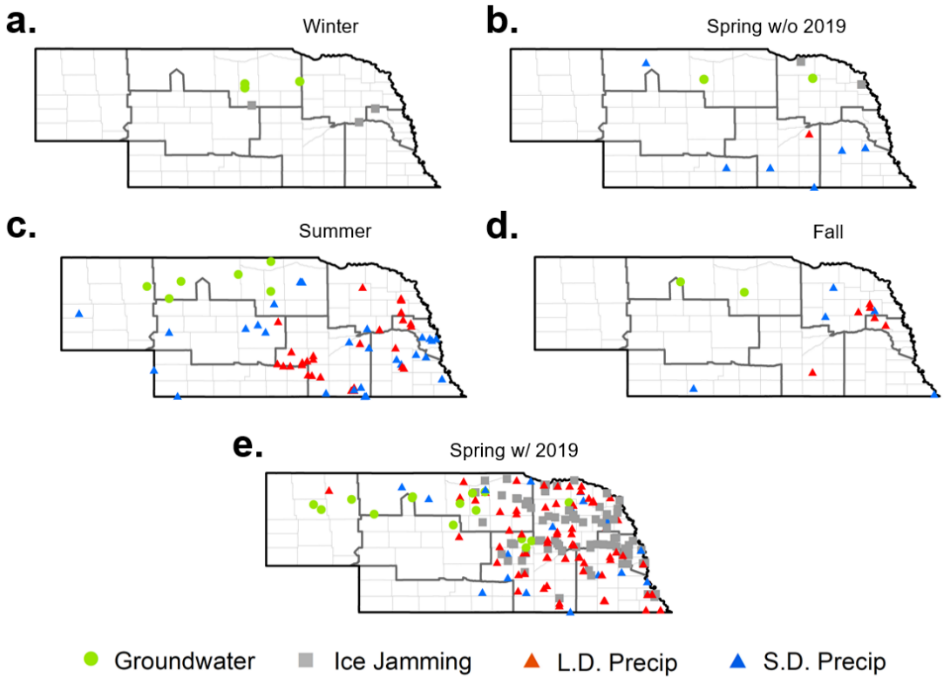

Figure 4.7. *Locations of water obstructions summarized by meteorological season (2016-2021).*

Table 4.2. *NDOT District water obstruction totals summarized by season and by root weather-related cause (2016-2021). Bolded values represent district with the most obstructions by cause. Values in brackets represent number of obstructions excluding March 2019. Cells without brackets signify there were no obstructions in March 2019.*

Winter					**Spring [Spring w/o March 2019]**				
District	Groundwater	Ice Jamming	LD Precip	SD Precip	District	Groundwater	Ice Jamming	LD Precip	SD Precip
1					1		8 [0]	17 [6]	3 [0]
2		**1**			2		19 [0]	3 [0]	1
3		**1**			3	1	**41 [2]**	**24 [2]**	**7 [0]**
4					4	3 [0]	15 [0]	**19 [8]**	4 [3]
5					5	3 [1]		1 [0]	
6					6	3 [1]		1 [0]	
7					7				1
8	**3**	**1**			8	**6 [3]**	13 [0]	10 [1]	**5 [3]**
Total	3	3	0	0	Total	16 [6]	96 [2]	75 [17]	21 [8]
Summer					**Fall**				
District	Groundwater	Ice Jamming	LD Precip	SD Precip	District	Groundwater	Ice Jamming	LD Precip	SD Precip
1			4	5	1				1
2			3	5	2			2	
3			9	1	3			**3**	**3**
4			**16**	**8**	4			1	
5	1			1	5				
6			1	4	6	**1**			
7				2	7				1
8	**7**			4	8	**1**			
Total	8	0	33	30	Total	2	0	6	5

The spatial distribution of the water obstructions was also examined by the study year (Figure 4.8). In 2016, water obstructions are generally confined along the Elkhorn River impacting US 275 in Districts 2 and 3 throughout eastern Nebraska, primarily from long-duration precipitation. In 2017, six different weather events which have both long- and short-duration precipitation obstructions are scattered across Nebraska, as all districts except for Districts 1 and 5 have at least one water obstruction during the year. The year 2018 is like 2016, where a lot of the water obstructions are confined along the Elkhorn River, as well as the Logan Creek Dredge in eastern Nebraska where these obstructions primarily consist of long-duration precipitation obstructions. The year 2018 also has ice jamming events with one of them being along the Logan

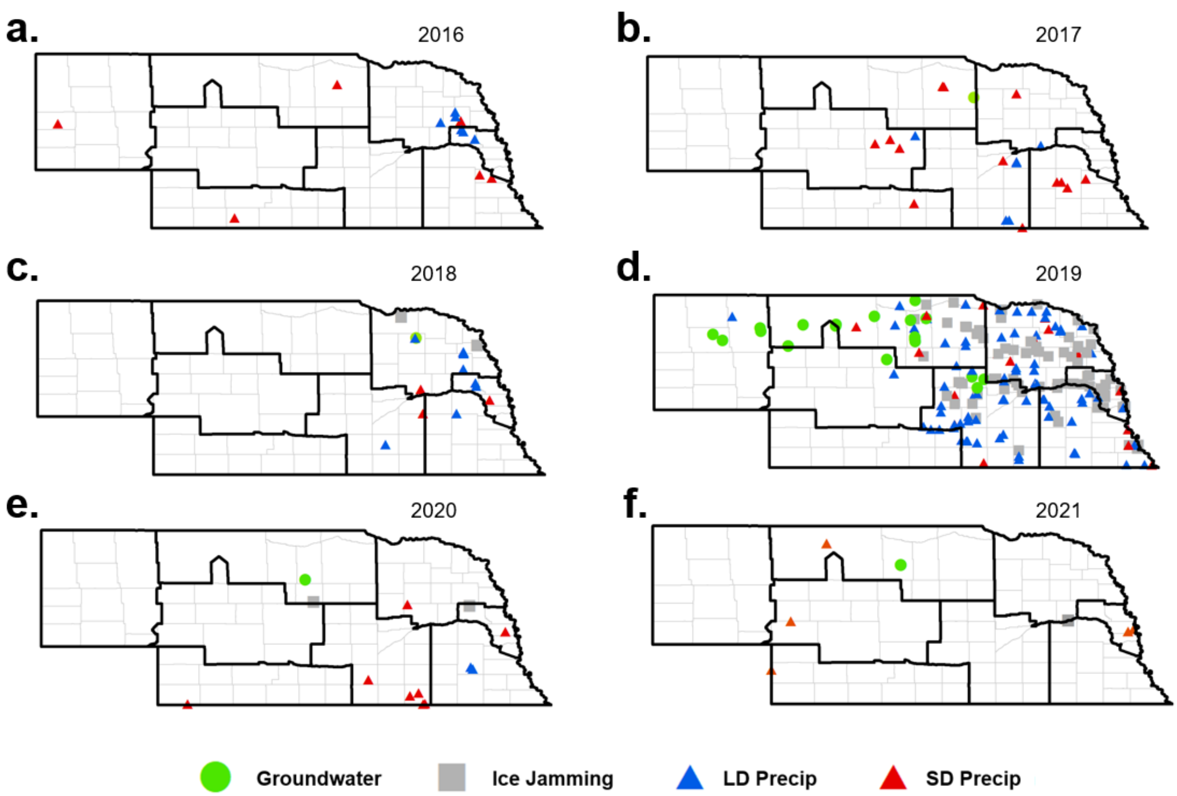

Figure 4.8. *Locations of water obstructions by year and by root weather-related cause (2016-2021).*

Creek Dredge and the other along the Niobrara River in far northeast Nebraska (District 3). Most water obstructions during the outlier year of 2019, which has the most total water obstructions by far, occur in Districts 1, 2, 3, 4, and 8. District 5 also has multiple obstructions in 2019, which is the only year along with 2016 to have at least 1 obstruction in the district. Since 2019, ice jams are clearly confined to the northeastern domain of Nebraska, where the Platte River, Loup River, Elkhorn River, and Logan Creek Dredge in north-central and north-eastern Nebraska are the primary rivers to have ice jamming obstructions. There is also a high number of long-duration precipitation obstructions occurring along these rivers due to other events excluding March 2019 (e.g., September 2016, June 2018). In addition, groundwater obstructions occur the most frequently in 2019, and are generally confined to District 8 in the Sandhills region. The bulk of the water obstructions in 2019 are in March, when most of the long-duration precipitation and ice jamming water obstructions occur, and are confined to northern and eastern Nebraska (Figure 4.9). The years 2020 and 2021 are quite similar, as there is not any clustering of obstructions confined to one specific area in Nebraska except for short-duration precipitation obstructions in Thayer County, which is in southeastern Nebraska (Figure 4.8). Otherwise, these two years primarily consisted of single obstruction cases scattered throughout all of Nebraska.

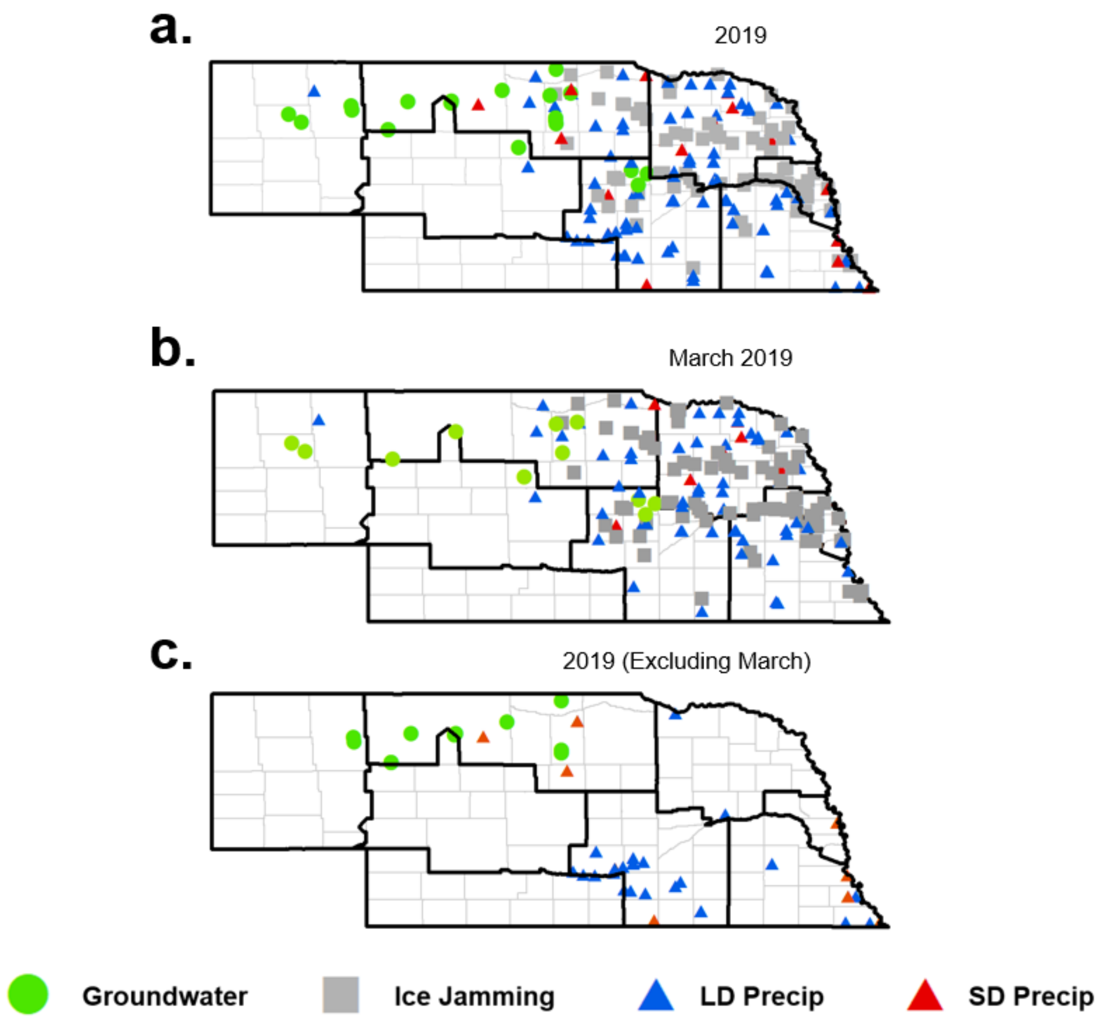

Figure 4.9. *Water obstructions by root weather-related cause in (a) 2019, (b) March 2019, and (c) 2019 without March.*

When all years and all obstructions are compiled, it is evident that all NDOT districts experience at least two of the four different weather-related causes over the five-year period, even without March 2019 (Figure 4.10). Much of these obstructions occur where there is a greater density of roadways (bias more toward eastern Nebraska; Figure 3.3), and thus, a greater exposure to the hazards that may cause water obstructions. Furthermore, there are districts and general areas where certain causes to water obstructions are occurring more frequently than

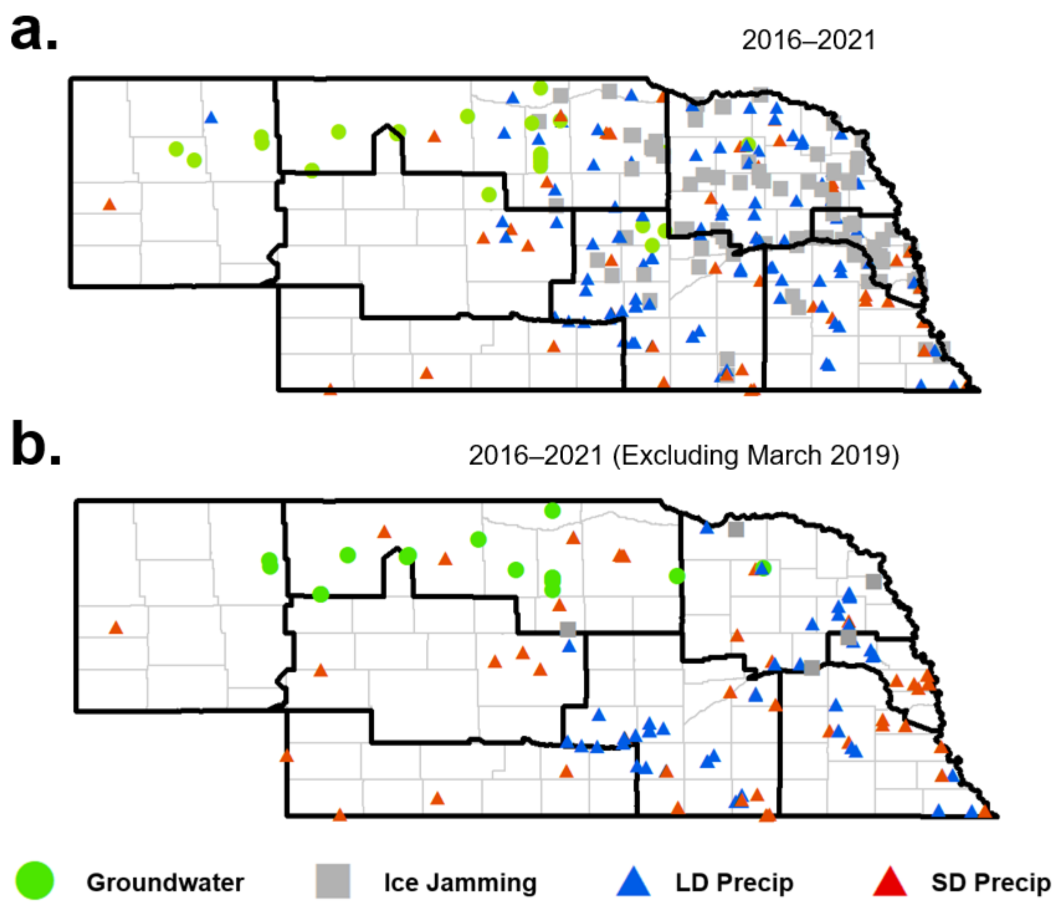

Figure 4.10. *All water obstruction locations over the study period by root weather-related cause (a) with March 2019 and (b) without March 2019.*

Others, which is also in large part closely correlated with Nebraska's weather, climate, and river network. Generally, groundwater obstructions are confined to the northern domain of Nebraska (Figure 4.11), with District 8 having the most at 17 total since June 2016 (Table 4.3). Water obstructions caused by ice jamming are generally confined to the northeastern domain of Nebraska, with the majority of these obstructions occurring north of the Platte River in District 3. Long-duration precipitation water obstructions are generally confined to the eastern half of Nebraska, with District 4 having the most at 36 water obstructions over the five-year period with and without March 2019. Even though long-duration precipitation obstructions occur more in the eastern part of the state, long-duration precipitation events causing water obstructions can still occur anywhere within the state. It is more favored for these events to occur in the central and eastern portion of the state given the climatology of long-duration precipitation and what kinds of weather systems generally produce these events. The same cannot be said with short-duration precipitation obstructions, as these events occur more widespread throughout the state, though it is still District 4 that has the most obstructions with and without March 2019 for this study period.

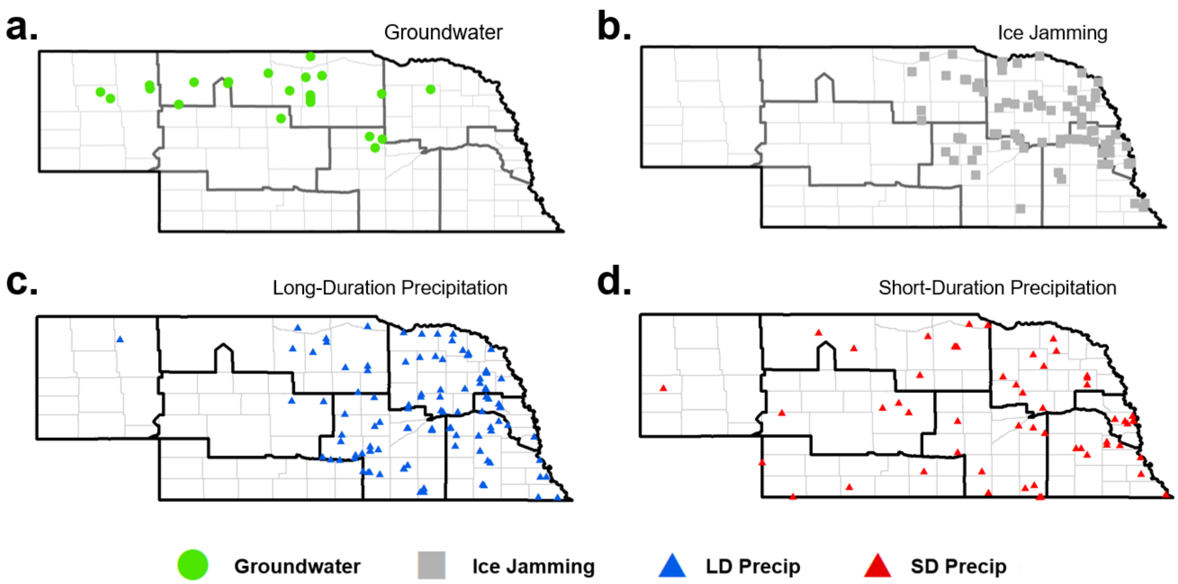

Figure 4.11. *All water obstruction locations over the study period (2016-2021) paneled by their respective root weather-related cause.*

Table 4.3. *NDOT District water obstruction totals by root weather-related cause (2016-2021). Bolded values represent district with the most obstructions by cause. Values in brackets represent number of obstructions excluding March 2019. Cells without brackets signify there were no obstructions in March 2019.*

District	Groundwater	Ice Jamming	LD Precip.	SD Precip.
1		8 [0]	21 [10]	9 [6]
2		20 [1]	8	6
3	1	**42 [3]**	36 [12]	11 [4]
4	3 [0]	15 [0]	**36 [23]**	**12 [11]**
5	4 [2]		1	1
6	4 [2]		2	4
7				4
8	**17 [14]**	14 [1]	10 [1]	9 [7]
Total	29 [19]	99 [5]	114 [57]	56 [43]

4.1.4 Frequency Analysis

The computation of the density analysis with and without March 2019 reveals general clustering of water obstructions which can then warrant further investigation (Figure 4.12 and 4.13). For the entire study period (March 2019 included and excluded), the area of interest for groundwater obstructions are generally across District 8 (northern Nebraska) as previously discussed (Figure 4.12a and 4.13a). The one area that displays the highest density of obstructions is in Rock County (northern Nebraska) where significant clustering of events is identified and will be further examined.

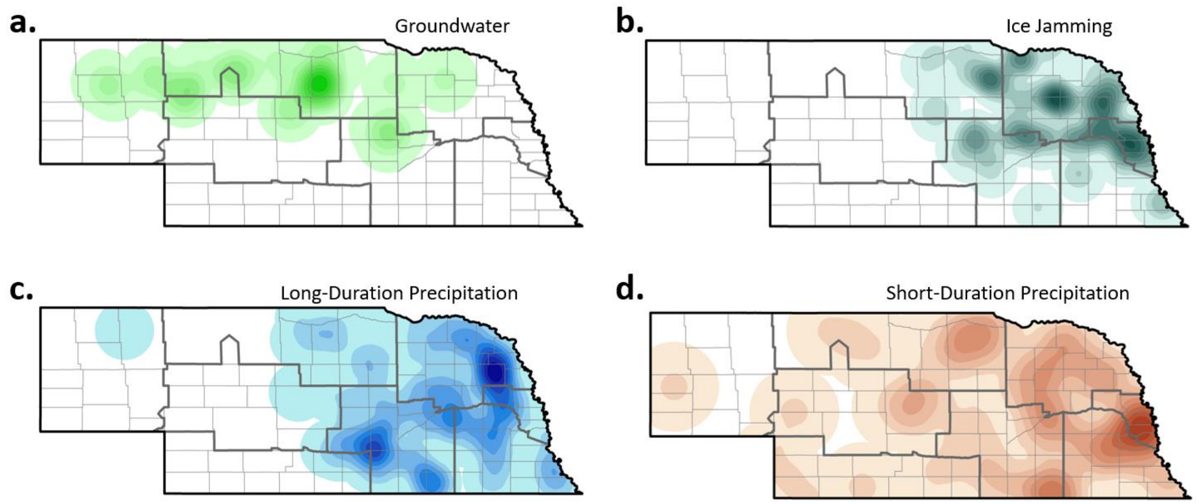

Figure 4.12. *Kernel density results for all water obstructions over the study period (2016-2021) by root weather-related cause. The darker colors represent a higher density or clustering of water obstructions.*

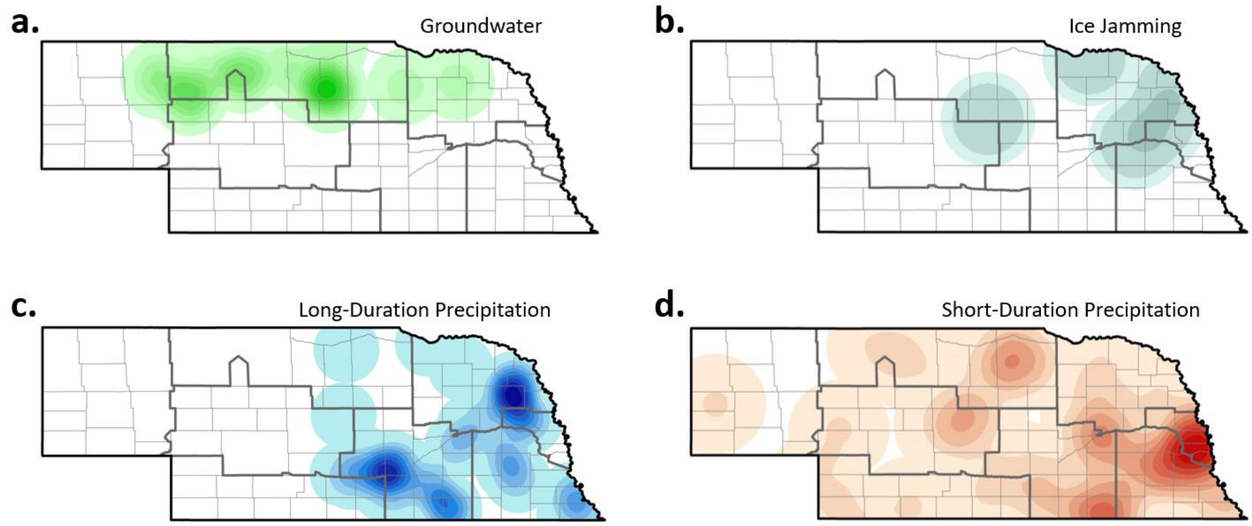

Figure 4.13. *Kernel density results for all water obstructions over the study period (2016-2021; excluding March 2019) by root weather-related cause. The darker colors represent a higher density or clustering of water obstructions.*

For ice jamming water obstructions, there are several high-density areas when March 2019 is taken into account, considering this event alone has 94 ice jamming induced water obstructions. These are primarily along the Platte River in District 2 and 3, along the Elkhorn River in Districts 3 and 8, and along the Logan Creek Dredge in District 3 in northern and northeastern Nebraska (Figure 4.12b). However, when March 2019 is removed, there is only a broad area identified for ice jam water obstructions since there are only five other ice jamming obstructions outside of March 2019 (Figure 4.13b). These general areas include; Middle Loup River, North Loup River, and Calamus River in Districts 4, 5, and 8; the Niobrara River in District 3; and the Platte River, Elkhorn River, and Logan Creek Dredge in District 1, southeastern District 3, and northern parts of District 1; all of which are generally located north of the Platte River in northern and eastern Nebraska. Given these areas are broader and more generalized, there is not any significant clustering displayed where ice jamming water obstructions are a major issue. This may suggest that any roadway along or near a river could be prone to ice jamming water obstructions; however, the frequency in which these obstructions occur due to ice jamming are small. In addition, exploring the historical ice jamming data before this study period could aid in locating ice jam obstructions in the past.

When March 2019 is included or excluded from the dataset, there are three general high-density areas of note for long-duration precipitation water obstructions (Figure 4.12c and 4.13c). One of these areas is along the Elkhorn River, which exhibits the highest density factor in Nebraska. Another area, which is highly recognized as the July 2019 precipitation event, is along the Platte River near the corner of Districts 4, 6, and 7 primarily in Buffalo, Hall, and Adams County in south-central Nebraska. The next most significant long-duration precipitation water obstruction clustering is in Thayer County in District 4 with and without March 2019. Overall, all long-duration precipitation water obstruction hotspots are in the eastern half of Nebraska. As emphasized previously, this does not mean the western domain of Nebraska cannot have long-duration precipitation water obstructions. Historically speaking, they are more likely to occur in central/eastern Nebraska, specifically in the three areas discussed above.

Short-duration precipitation obstructions exhibit a much more general and widespread area where the frequency of these events is non-zero in almost all of Nebraska (Figure 4.12d and 4.13d). While there are multiple high frequency areas identified, even without March 2019, the one area that stands out is in District 2, mainly in Douglas and Sarpy County. In addition, Thayer County in District 4 (south-central Nebraska) exhibits a high frequency of short-duration precipitation water obstructions as well. Short-duration precipitation obstructions have a more western extent than any other weather-related cause, confirming the most common way a roadway will have a water obstruction in Districts 6 and 7 (central and southwest Nebraska) is by short-duration precipitation.

During the study period, 68% of water obstructions are associated with a river, i.e., occur along a river between June 2016 and August 2021. Whether including or excluding March 2019, the Elkhorn River has the most water obstructions associated with it (Table 4.4). This is also evident in the density analysis with and without March 2019, where obstructions along this river occur the most in Cuming and Dodge County in eastern Nebraska (Figure 4.14b and c). There are 40 obstructions along the Elkhorn River within the five-year period, with the majority of these being in the form of ice jamming in Cuming and Dodge County in large-part due to March 2019. When excluding March 2019, long-duration and short-duration precipitation water obstructions are the dominant causes along the Elkhorn River although there is still one ice jam water obstruction along the river. The Platte River, Wood River, and Logan Creek Dredge in central and eastern Nebraska also experience a higher number of water obstructions, with most of them being in the form of ice jamming when including March 2019 and long-duration

Table 4.4. *Total number of water obstructions over the study period along with obstruction totals by root weather-related cause associated with rivers in Nebraska.*

2016-2021						2016-2021 w/o March 2019					
River	Total	Groundwater	Ice Jamming	LD Precip.	SD Precip.	River	Total	Groundwater	Ice Jamming	LD Precip.	SD Precip.
Elkhorn River	40		26	9	5	Elkhorn River	14		1	8	5
Platte River	21		13	7	1	Wood River	6			6	
Logan Creek Dredge	12		4	8		Platte River	5		1	3	1
Missouri River	11		7	1	3	Logan Creek Dredge	4			4	
North Fork Elkhorn River	8		7		1	Davis Creek	3			2	1
Niobrara River	7		4	2	1	Little Blue River	3			3	
North Loup River	7		6	1		Middle Branch Middle Loup	3	3			
Wood River	7		1	6		Missouri River	3				3
Loup River	6		3	2	1	Rose Creek	3				3
Big Blue River	5		2	3		Little Nemaha River	2			1	1
Beaver Creek	4		4			Loup River	2			1	1
Cedar River	4		3	1		Middle Creek	2			1	1
Davis Creek	4			3	1	Niobrara River	2			2	
Little Nemaha River	4		2	1	1	North Oak Creek	2			2	
Cuming Creek	3			1	2	Republican River	2				2
Little Blue River	3			3		Salt Creek	2			1	1
Middle Branch Middle Loup	3	3				Scott Creek	2			1	1
Middle Creek	3			2	1	Big Nemaha River	1			1	
Middle Loup River	3		3			Big Papillion Creek	1				1
Rose Creek	3				3	Brazil Creek	1		1		

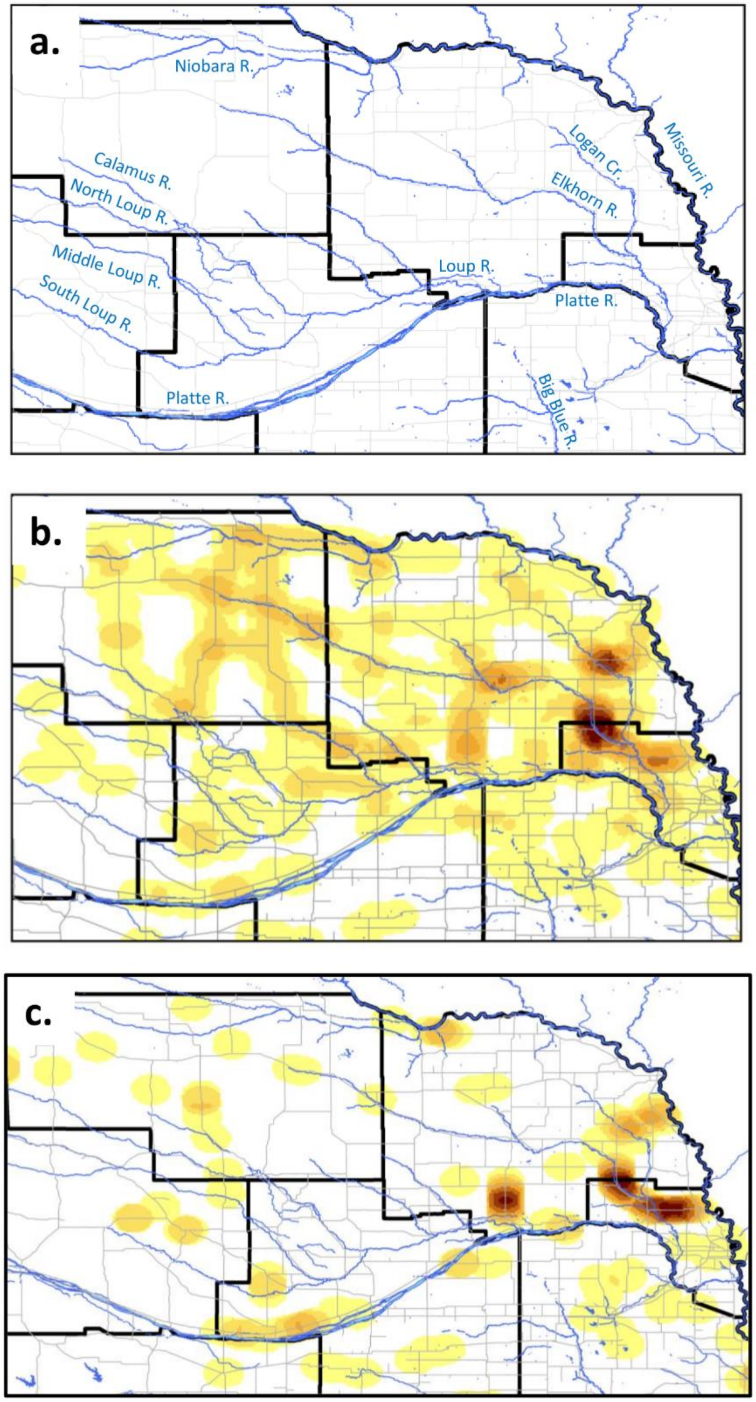

Figure 4.14. *a) Reference map with state and federal roadways along with labeled rivers in Nebraska, b) line density analysis results of water obstructions (2016-2021), c) same as (b), without March 2019 in the data.*

precipitation when excluding March 2019. It should be noted that most of these river-associated obstructions are in Districts 2, 3, and 4, suggesting that the greater exposure of roadways along rivers and general higher density of roadways in central and eastern Nebraska creates a higher vulnerability to being obstructed (Figure 3.3, Figure 3.4).

Along with the top rivers prone to water obstructions over the past five years, the number of obstructions for each state and federal roadway is also important to quantify (Table 4.5). When including and excluding March 2019, US 275 has the most water obstructions, and most are in the form of either ice jamming (including March 2019 data) or from long-duration precipitation (excluding March 2019 data). In addition, US 183 in northern Nebraska also has the same number of water obstructions as US 275 when excluding March 2019 (eight), with most of these being in the form of groundwater obstructions. US 183 is the only roadway to have all weather-related causes occur on it outside of March 2019, which is a significant finding and one

Table 4.5. *Total number of water obstructions over the study period along with obstruction totals by root weather-related cause associated with state and federal highways in Nebraska.*

2016-2021						2016-2021 w/o March 2019					
Route	Total	Groundwater	Ice Jamming	LD Precip.	SD Precip.	Route	Total	Groundwater	Ice Jamming	LD Precip.	SD Precip.
US 275	20	0	13	6	1	US 183	8	5	1	1	1
US 81	14	0	2	8	4	US 275	8	0	1	6	1
US 20	13	4	2	3	4	US 20	7	2	0	1	4
NE 12	12	1	3	6	2	US 6	7	0	0	2	5
US 183	10	6	1	2	1	US 81	6	0	0	3	3
NE 14	9	0	5	4	0	NE 5	5	0	0	4	1
US 30	9	0	4	4	1	US 136	5	0	0	3	2
US 6	9	0	1	3	5	US 30	5	0	0	4	1
NE 91	8	2	2	4	0	NE 61	4	3	0	0	1
NE 92	8	0	1	4	3	NE 74	4	0	0	3	1
US 136	8	0	2	4	2	NE 8	4	0	0	1	3
NE 5	7	0	1	5	1	I-80	3	0	0	2	1
US 281	7	1	3	3	0	NE 12	3	1	1	1	0
US 34	7	0	4	2	1	NE 2	3	0	0	0	3
NE 2	6	0	0	3	3	NE 97	3	3	0	0	0

worth discussing further. When including March 2019, US 20 and NE 12 in northeast Nebraska are the only other two roadways to have all four weather-related causes creating water obstructions. When analyzing these roadways down to the county level and when considering the impacts of March 2019 on water obstructions along with the occurrence of extreme precipitation events, NE 5 in Thayer County (District 4), US 183 in Rock County (District 8), US 275 in Cuming and Dodge Counties (District 3), and US 136 in Nemaha County are most prone to obstructions (Table 4.6). In other words, these are the five locations for water obstructions over the study period that will be discussed further along with the top ten locations in Section 4.5.

4.2 Nebraska Climate

4.2.1 Temperature and Precipitation

From a seasonal perspective, the spatial distribution for average temperatures is spatially consistent throughout a given year through Nebraska with temperatures increasing further southeastward (Figure 4.15). Furthermore, temperatures tend to increase on average for the spring, summer, and fall periods towards the southeastern region of the state (Districts 1 and 2). During winter, temperatures are slightly colder along the northeastern periphery of the state (Districts 8 and 3). Overall, Nebraska displays a wide temperature contrast during a given year, as winter average temperatures range from 20–36°F while summer average temperatures range from 66–78°F over the past 30 years (Figure 4.15). Average temperatures have generally trended upward since 1991 in each season (except for winter) ranging from 0.25–1.25°F per decade, although these trends are not statistically significant (Figure 4.16). Overall, the concerning factors with these seasonal trends are the decreasing temperatures in winter and generally increasing trends in spring. Colder than normal temperatures followed by warmer than normal temperatures can perhaps promote river ice break-up and ice jamming situations. In addition, this can also promote more flooding by long- or short-duration precipitation if the ground is still

Table 4.6. *Total number of water obstructions over the study period along with obstruction totals by root weather-related cause associated with state and federal highways in their respective counties in*

2016-2021								2016-2021 w/o March 2019							
Route	County	District	Total	Groundwater	Ice Jamming	Prolonged	Short Term	Route	County	District	Total	Groundwater	Ice Jamming	Prolonged	Short Term
NE 5	Thayer	4	7	0	1	5	1	NE 5	Thayer	4	5	0	0	4	1
US 183	Rock	8	7	6	0	1	0	US 183	Rock	8	5	5	0	0	0
US 275	Cuming	3	7	0	3	3	1	NE 74	Adams	4	4	0	0	3	1
NE 12	Knox	3	6	0	3	3	0	US 275	Cuming	3	4	0	0	3	1
NE 74	Adams	4	5	0	0	4	1	US 275	Dodge	2	4	0	1	3	0
US 136	Nemaha	1	5	0	2	2	1	US 30	Buffalo	4	4	0	0	3	1
US 20	Holt	8	5	0	2	0	3	NE 61	Cherry	8	3	3	0	0	0
US 275	Dodge	2	5	0	2	3	0	NE 8	Thayer	4	3	0	0	0	3
US 81	Platte	3	5	0	1	3	1	US 136	Nemaha	1	3	0	0	2	1
NE 94	Thurston	3	4	0	2	2	0	US 20	Holt	8	3	0	0	0	3
US 20	Pierce	3	4	1	0	2	1	US 20	Pierce	3	3	1	0	1	1
US 275	Madison	3	4	0	4	0	0	US 6	Lancaster	1	3	0	0	1	2
US 30	Buffalo	4	4	0	0	3	1	US 81	Polk	4	3	0	0	2	1
US 6	Lancaster	1	4	0	0	2	2	I-480	Douglas	2	2	0	0	0	2
US 81	Polk	4	4	0	0	3	1	I-80	Buffalo	4	2	0	0	2	0

frozen or if there are rain-on-snow events. This may be something to consider when examining which roadways need to be examined for possible mitigation due to high frequencies of water obstructions by ice jamming.

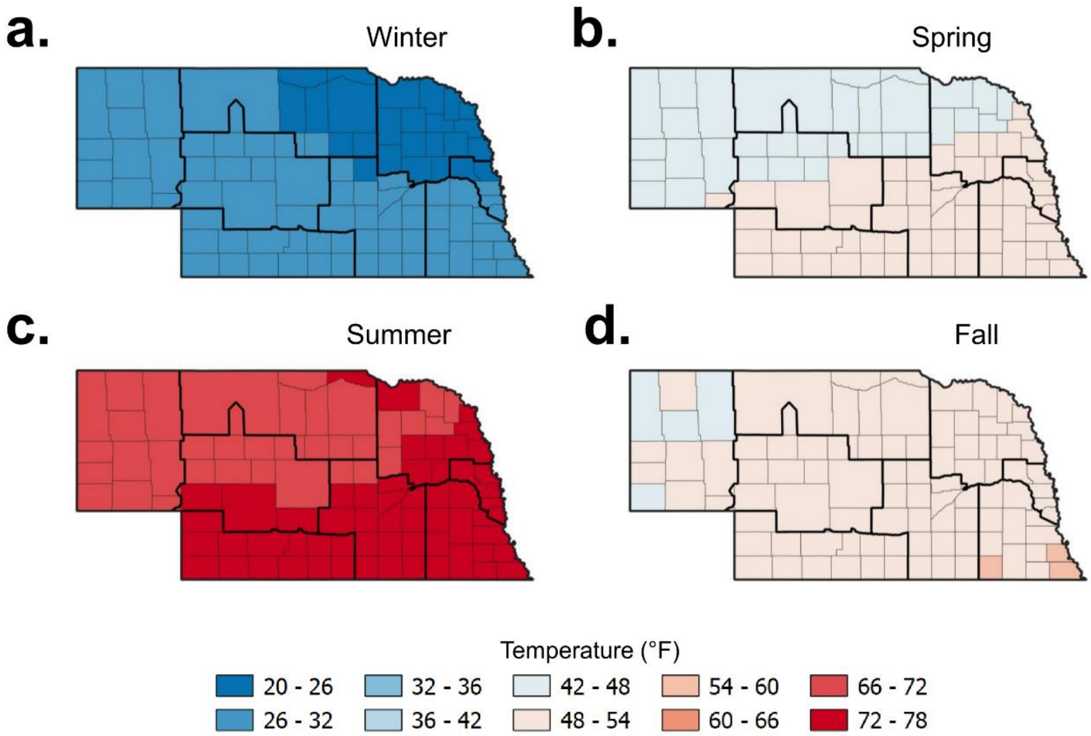

Figure 4.15 *Average seasonal temperature (°F) averages by county (1991-2020). Data for this figure from NCEI.*

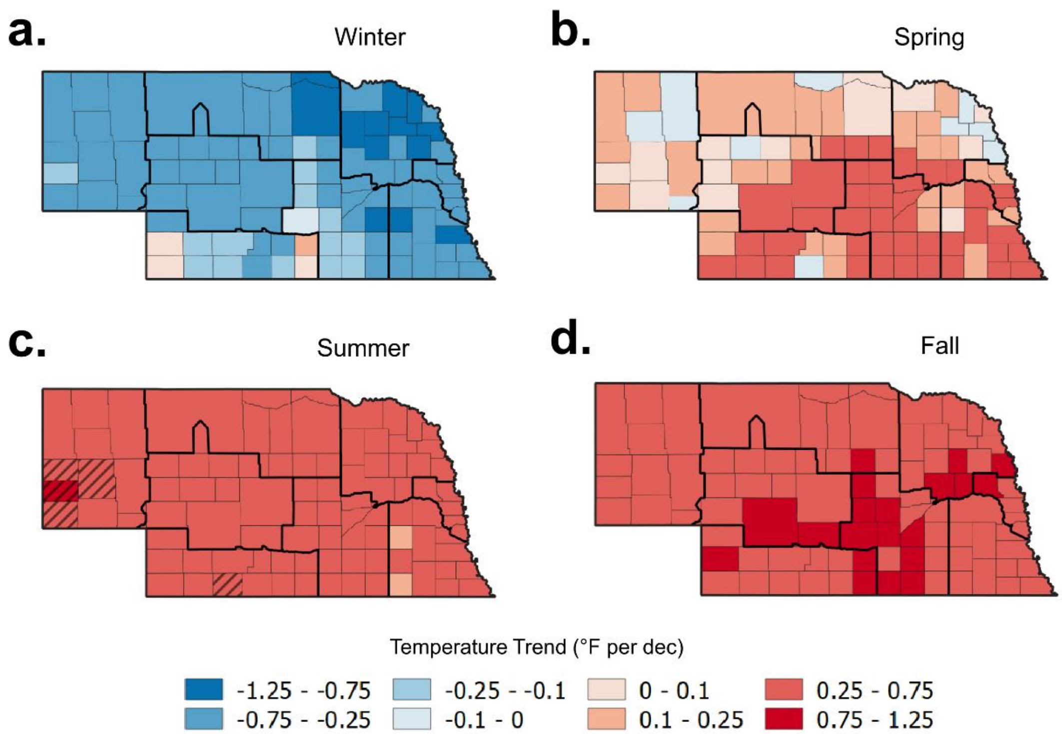

Figure 4.16 *Seasonal temperature trends (°F per decade) by county (1991-2020). Hatching represents statistical significance to the 95% confidence level. Data for this figure from NCEI.*

The wide range of temperatures in Nebraska throughout a given year allows for all forms of precipitation (rain, freezing rain, sleet, snow) to be a potential contributor when it comes to surface transportation disruptions. Where temperatures are greater, liquid precipitation totals will generally be greater as well, and this holds true in Nebraska as seasonal precipitation totals tend to follow the same spatial pattern as average seasonal temperatures (Figure 4.17). Specifically, for each season, precipitation increases on average toward the southeastern portion of the state due to being closer to the primary source of moisture, the Gulf of Mexico. For example, summer precipitation in Districts 1, 2, and 3 (eastern Nebraska) has the highest yearly totals on average, as well as the highest number of flash-flood warnings. Precipitation in this area averages between 11.0-13.0 inches versus precipitation in District 5 (western Nebraska) at 5.0-7.0 inches.

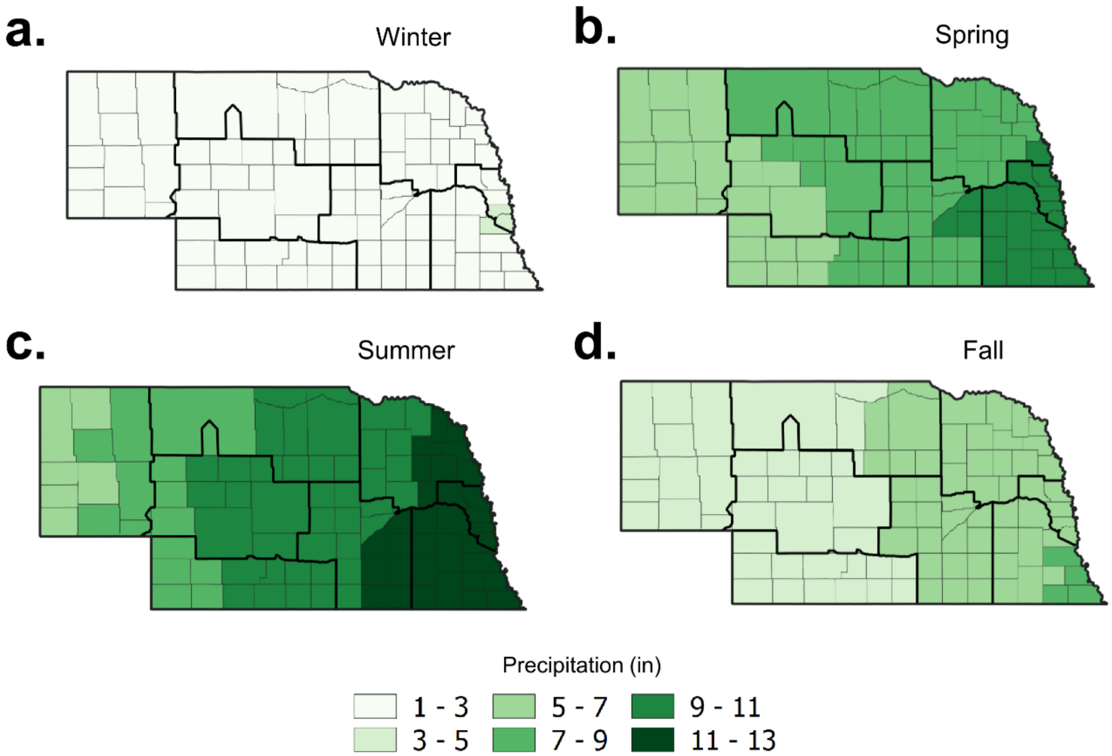

Figure 4.17. *Seasonal precipitation averages (inches) and by county (1991-2020). Data for this figure from NCEI.*

In south-central and southeastern Nebraska, Districts 1, 2, and 4 also exhibit the highest number of thunderstorm days and severe thunderstorm reports per year on average (Doswell et al. 2005; SPC 2022). Therefore, based on spatiotemporal risk, the south-central and eastern domains of Nebraska, comprising of Districts 1, 2, 3, and 4, has a greater risk for purely precipitation roadway water obstructions based on a 30-year precipitation climatology, and aligns well with actual water obstruction data. In terms of storm type, mesoscale convective systems (MCSs), or simply damaging lines of thunderstorms, all have a greater frequency of occurrence in the south-central and eastern domains of Nebraska (Guastini and Bosart 2016; Ashley et al. 2019; Cheeks et al. 2020). In addition, extratropical cyclones in the form of Colorado Low type systems have mean storm tracks that tend to favor precipitation in the south-central and eastern domains of

Nebraska (Fritzen et al. 2021). Therefore, these storm modes all contribute to the seasonal and interannual averages of precipitation (Figure 4.17) and tend to be more numerous further eastwards in the state.

Precipitation trends more variable for each season. In general, winter and spring precipitation totals have increased ranging from 0.001–0.050 inches per decade and 0.001-0.150 inches per decade for most counties, respectively (Figure 4.18a and b). The most robust, and

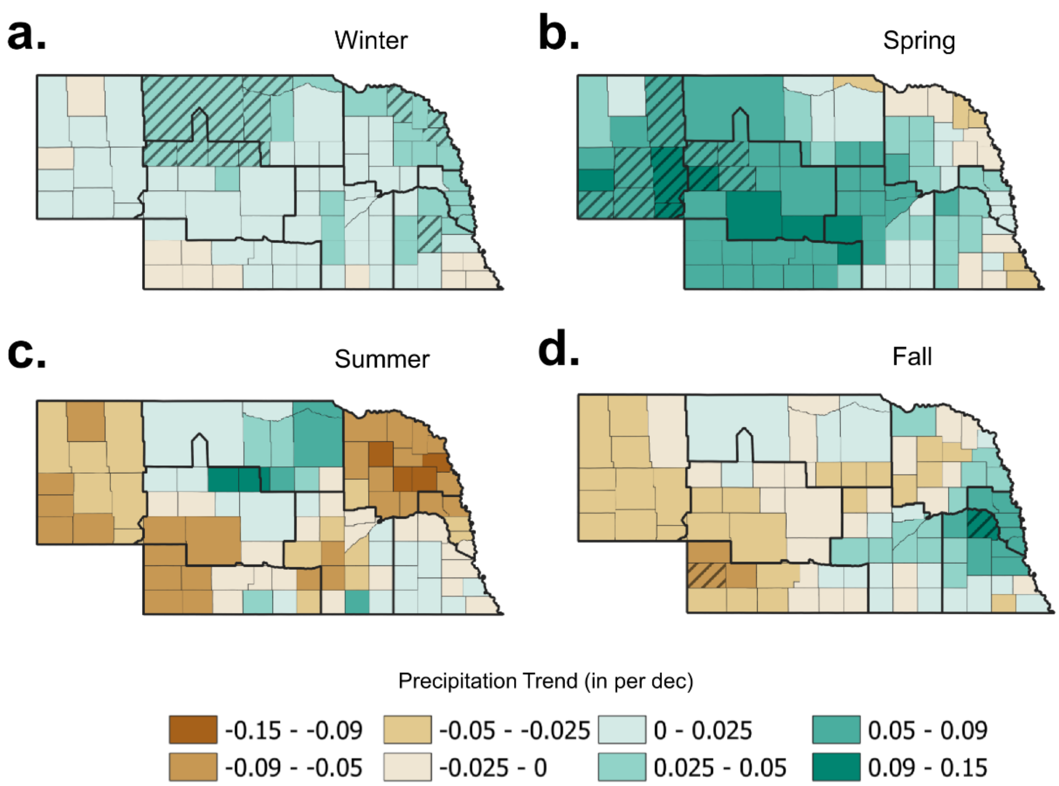

Figure 4.18. *Seasonal precipitation trends (inches per decade) by county (1991-2020). Hatching represents statistical significance to the 95% confidence level. Data for this figure from NCEI.*

statistically significant, of these increasing trends have occurred in Districts 3, 4, 8 in the winter, and in Districts 4 and 5 for the spring. On the other hand, summer and fall precipitation trends observed have more counties with decreasing trends than increasing trends, with most of these decreases being insignificant ranging from -0.150– -0.025 inches per decade (Figure 4.18c and 4.18d). The most robust of these trends occurred in Districts 3, 5, 6, and 7. The current trends in extreme precipitation (see Section 2) makes increasing water obstructions on roadways a possibility. This could be especially true in Districts 1, 2, 3, 4, and 8 that experienced more water obstructions than any other part of the state during the study period.

4.2.2 Palmer Indices

In addition to temperatures and precipitation, precursor soil moisture anomalies can play a critical role in flooding and water obstructions. Examining the PDSI, all seasons generally present the same spatial display of anomalies on average (Figure 4.19). All districts, with the exception of Districts 8 and 3, had PDSI values that averaged near normal over the past 30 years. Areas with PDSI values ranging from 2.0–2.9 are categorized as being unusually moist over a 30-year period (Palmer 1965). Areas located in Districts 8 and 3 would be considered unusually moist for the study period. The PHDI, which is a proxy used for groundwater anomalies also follows the same spatial pattern as the PDSI (Figure 4.20). In terms of groundwater saturated thickness, PHDI and actual groundwater levels are very similar in spatial distribution in that the Sandhills region of Nebraska displays the highest levels (greatest thickness) on average over the past 30 years (UNL 2022), further confirming the use of PHDI as a proxy for groundwater anomalies. The thickness for the majority of the Sandhills region exceeded 500 feet, which is the thickest area of the Ogallala Aquifer throughout the High Plains region (McGuire et al. 2012). For specific annual risk, data reveals that late summer, fall, and early winter are periods when PDSI and PHDI values are the highest (average near 1.5) across all

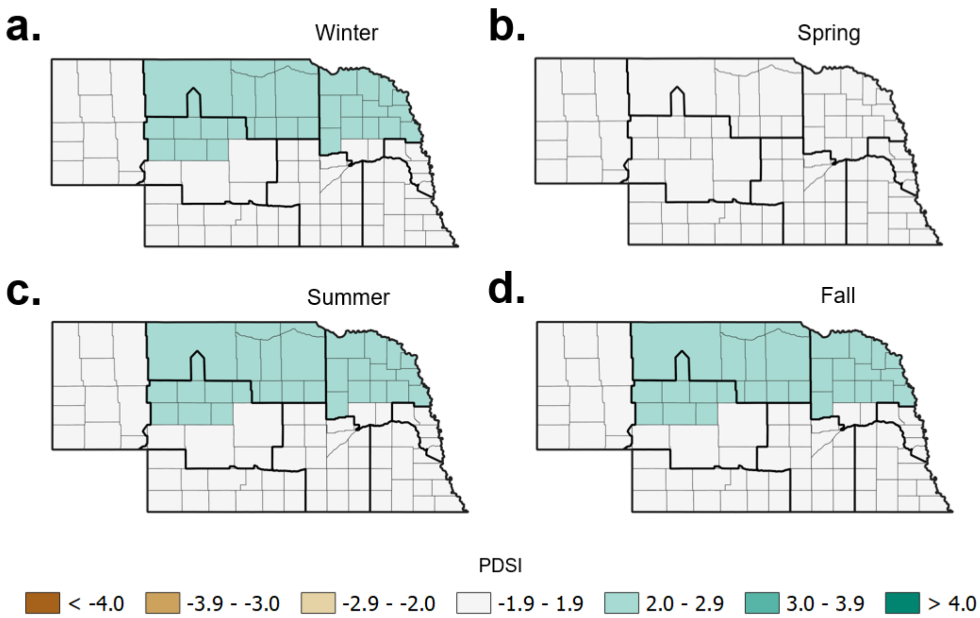

Figure 4.19. *Seasonal Palmer Drought Severity Index (PDSI) averages by climate division (1991-2020). Data for this figure from NCEI.*

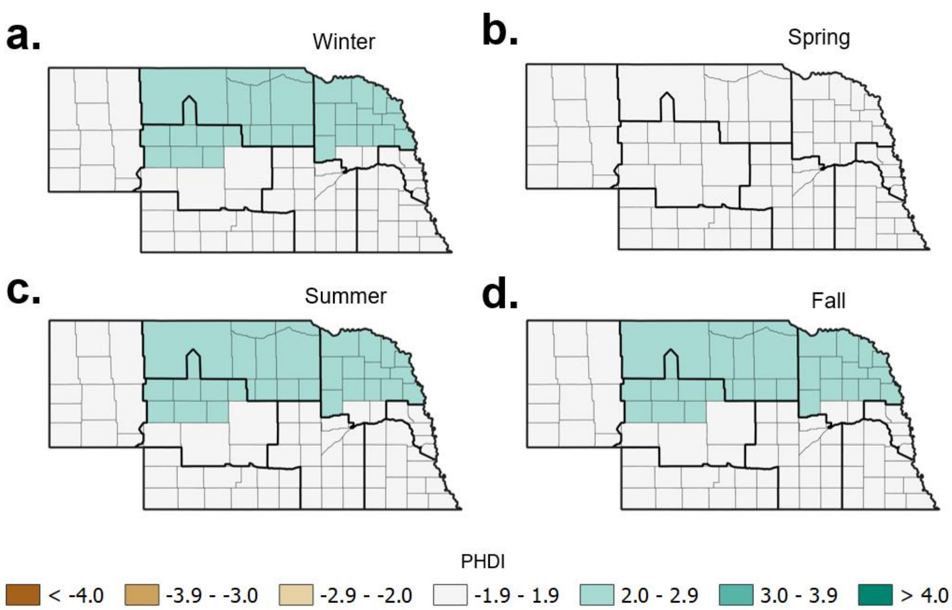

Figure 4.20 *Seasonal Palmer Hydrological Drought Index (PHDI) averages by climate division (1991-2020). Data for this figure from NCEI.*

of Nebraska. For specific spatial risk, the combination of PDSI and PHDI suggests the northern and northeastern domains of the state (Districts 8 and 3) have a higher likelihood of experiencing a greater number of roadway water obstructions caused by groundwater flooding. The spatial and temporal risks align well with what the actual water obstruction data indicates, confirming the characteristics of groundwater water obstructions generally follow the same average annual pattern. Both indices have widespread (albeit statistically insignificant) increases throughout Nebraska ranging from 0.01–1.5 PDSI/PHDI per decade (Figure 4.21 and 4.22).

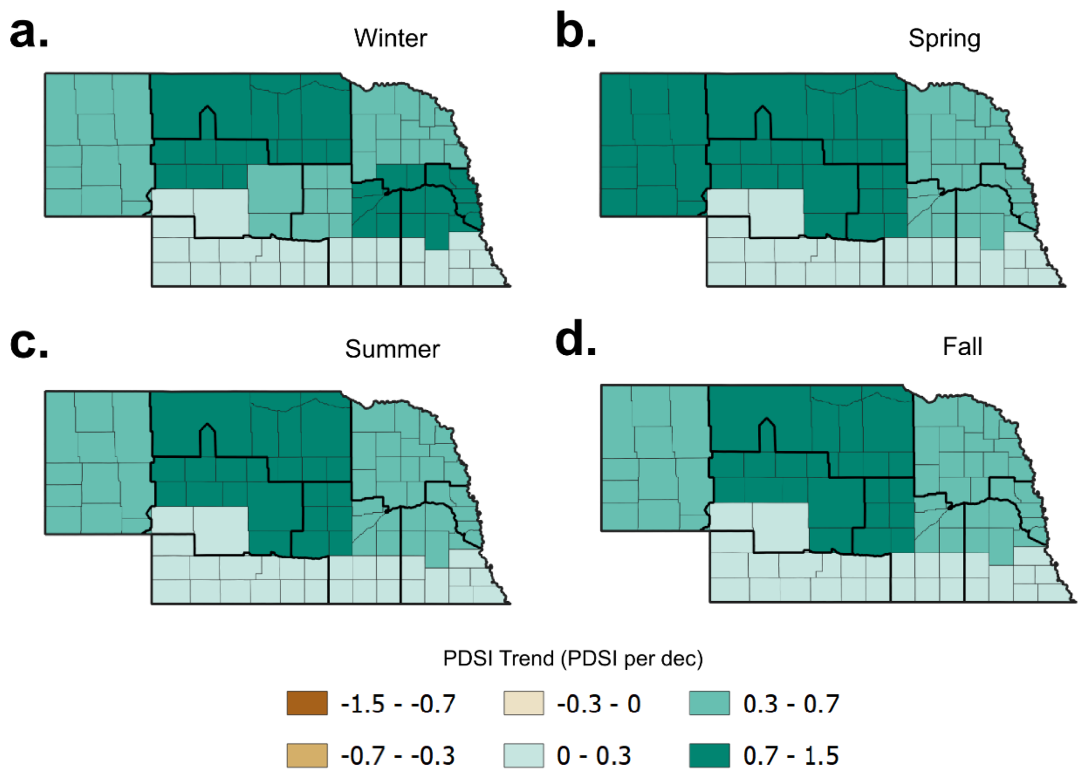

Figure 4.21. *Seasonal PDSI trends (PDSI per decade) by climate division (1991-2020). Hatching represents statistical significance to the 95% confidence level. Data for this figure from NCEI.*

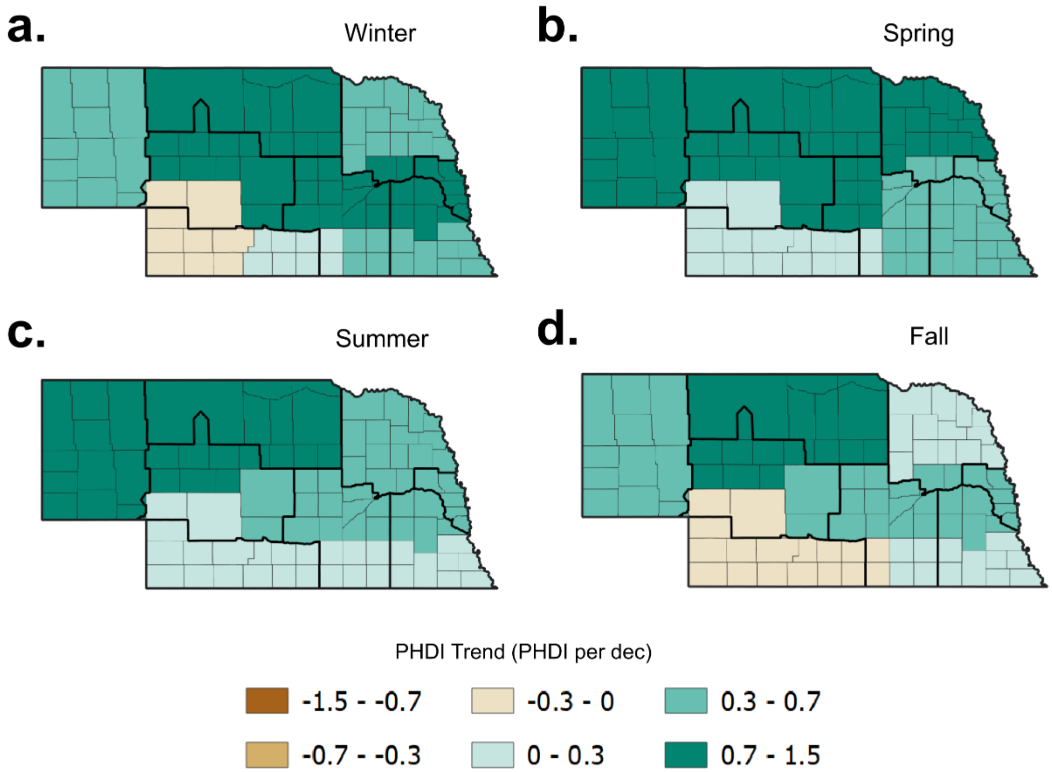

Figure 4.22. *Seasonal PHDI trends (PHDI per decade) by climate division (1991-2020). Hatching represents statistical significance to the 95% confidence level. Data for this figure from NCEI.*

The most robust of these increases coincide with the highest averages of PDSI and PHDI, which are in District 8. Other robust annual increases, from 0.7–1.5 PDSI/PHDI per decade, are observed over the past 30 years throughout much of Districts 4 and 6 in central Nebraska.

4.2.3 Ice Jamming

Temperatures are generally the coldest on average in the northeastern portion of Nebraska during the winter season (Figure 4.15a). However, because all of Nebraska can experience freezing temperatures for long enough periods of time to allow all rivers to freeze-up, the state is prone to freeze-up and break-up ice jams (Figure 4.23). Climatologically, over 80%

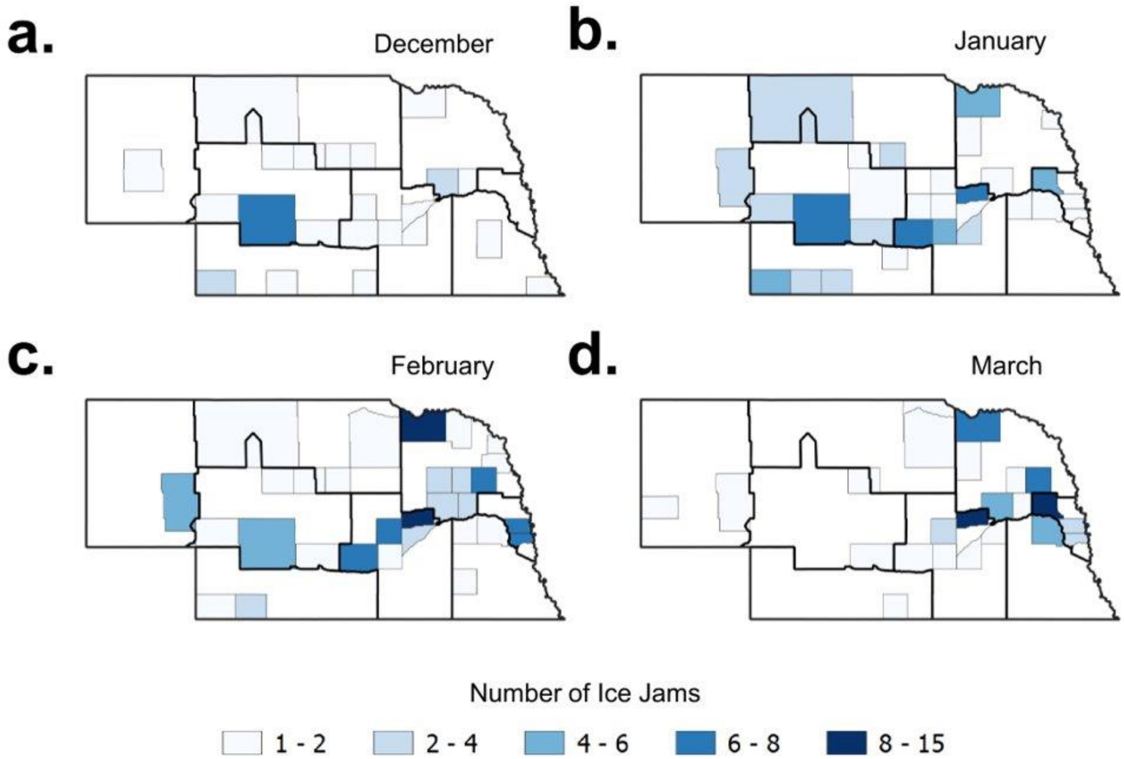

Figure 4.23 *Monthly sum of observed river ice jams by county (1991-2020). Data used for this from the CRREL Ice Jam Database.*

of the ice jams observed in December and January are freeze-up ice jams. Seventy percent of the ice jams in February and 96% of the ice jams in March are break-up ice jams across Nebraska. In order: the Platte River, North Platte River, Loup River, Elkhorn River, Middle Loup River, Niobrara River, and Logan Creek Dredge are at the top in terms of where ice jams have occurred the most over the past 30 years. Particularly, Districts 2, 3, and 4 along these rivers are where ice jams have been the biggest problem historically and where they have induced the most ice jamming related water obstructions. The Lower Platte River Basin is a location with historically one of the highest numbers of ice jams and has been studied extensively for specific problem areas and potential mitigation efforts (White 1996). In general, ice jams occur north of the Platte

River in Nebraska and are prone to occur along bottleneck areas of the Platte River, Loup River, and Elkhorn River (e.g., Nance County, Dodge County, Lincoln County, Sherman County). Therefore, it can be inferred that counties with the highest number of ice jams have been at a higher risk of roadway water obstructions by ice jamming. Given the state and federal highway road networks are much denser in the eastern portion of the state, especially in Districts 1, 2, and 3, ice jam water obstructions are more likely to occur in these areas given the greater exposure of roadways near or along rivers.

4.2.4 Summary of Nebraska Climate

This climatological analysis provides insight into when and where water obstructions in Nebraska could occur on an average basis, further giving insight into water obstructions prior to the study period. From the climatological analysis, the following can be inferred about the occurrence of roadway water obstructions in Nebraska:

- Precipitation totals are greater on an annual basis toward south-central and eastern Nebraska on average. Districts 1, 2, 3, and 4 are districts with the greatest density of state and federal highways and at a higher climatological risk for roadway water obstructions caused specifically by long- and short-duration precipitation events.
- Ice jamming can occur anywhere in Nebraska, the greatest risk for water obstructions caused by ice jamming, climatologically and based on previous literature, is focused more generally in central and eastern Nebraska north of the Platte River and in the Platte River Basin (Districts 2, 3, 4).
- The highest average values of the PDSI and PHDI are in the Sandhills region and where the greatest saturated thicknesses of actual groundwater levels are located, placing Districts 3, 6, and 8 at the greatest climatological risk for groundwater water obstructions.

4.3 Study Period Conditions

Before analyzing the relationships between the meteorological conditions associated with each water obstruction, it is necessary to have a fundamental understanding of what weather and climate conditions are over the study period, and how these conditions compare to years prior to June 2016. This analysis may also provide further insight into how frequently water obstructions may have occurred in the past given how they occur in this study period.

4.3.1 Temperatures and Precipitation

Over the past 30 years, temperature and precipitation rankings for all seasons in Nebraska experience both ends of the climatological extremes (Figure 4.24). More specifically, several

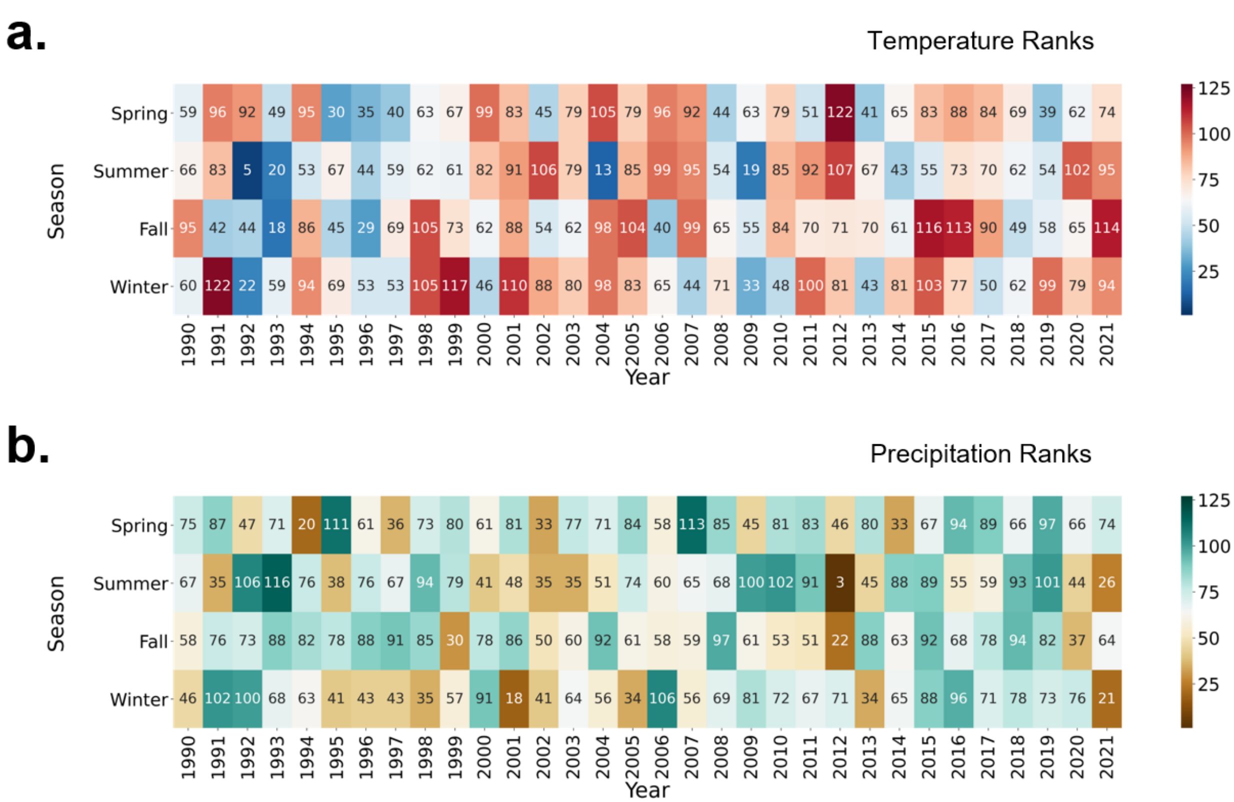

Figure 4.24. *Seasonal 127-year period, or the climatological record (1895-2021), for temperature and precipitation rankings by year over the 1990-2021 period. Data for this figure from NCEI.*

seasons, e.g., winter 1991, summer 1992, winter 1999, summer 2004, spring 2012, are amongst the hottest or coldest seasons in the climatological record (1895 to present). This is also the case for precipitation, as many seasons, e.g., summer 1993, winter 2001, summer 2012, are amongst the top wettest or driest seasons on record. When examining summer 2016 through summer 2021 for both temperatures and precipitation, conditions are near-normal to slightly warmer than normal and generally wetter than normal. Of course, there are some exceptions to this, such as the summers of 2016, 2020, 2021 and fall of 2020 where rankings are on the drier side. Out of the 20 total seasons within the study period for roadway water obstructions, 15 of them have precipitation rankings in the wetter half of the 127-year climate record and six seasons are in the top 75th percentile of wettest seasons. For temperatures, 11 of the 20 seasons are on the warmer half, with four of these seasons being in the top 75th percentile of warmest seasons.

From an annual and spatial perspective, 2018 and 2019 are the only years to have more counties with temperature anomalies near-normal or below normal (Figure 4.25). Otherwise, temperature anomalies for the other years in Nebraska are 1.0–4.0°F above normal. For annual precipitation anomalies, 2018 and 2019 (coolest years in the study period) have the most widespread and highest precipitation anomalies throughout Nebraska (Figure 4.26). Districts 1, 2, 3, 4, 6, and 8 all have majority of counties with precipitation anomalies 9.0–13.0 inches above normal. The year 2017 was another year where many counties have precipitation anomalies at least an inch above normal; however, in 2020, 86 of the 93 counties in Nebraska have precipitation anomalies below normal. Despite how wet 2019 is, this still has implications on the number of water obstructions 2020 experienced, even if precipitation totals are below normal.

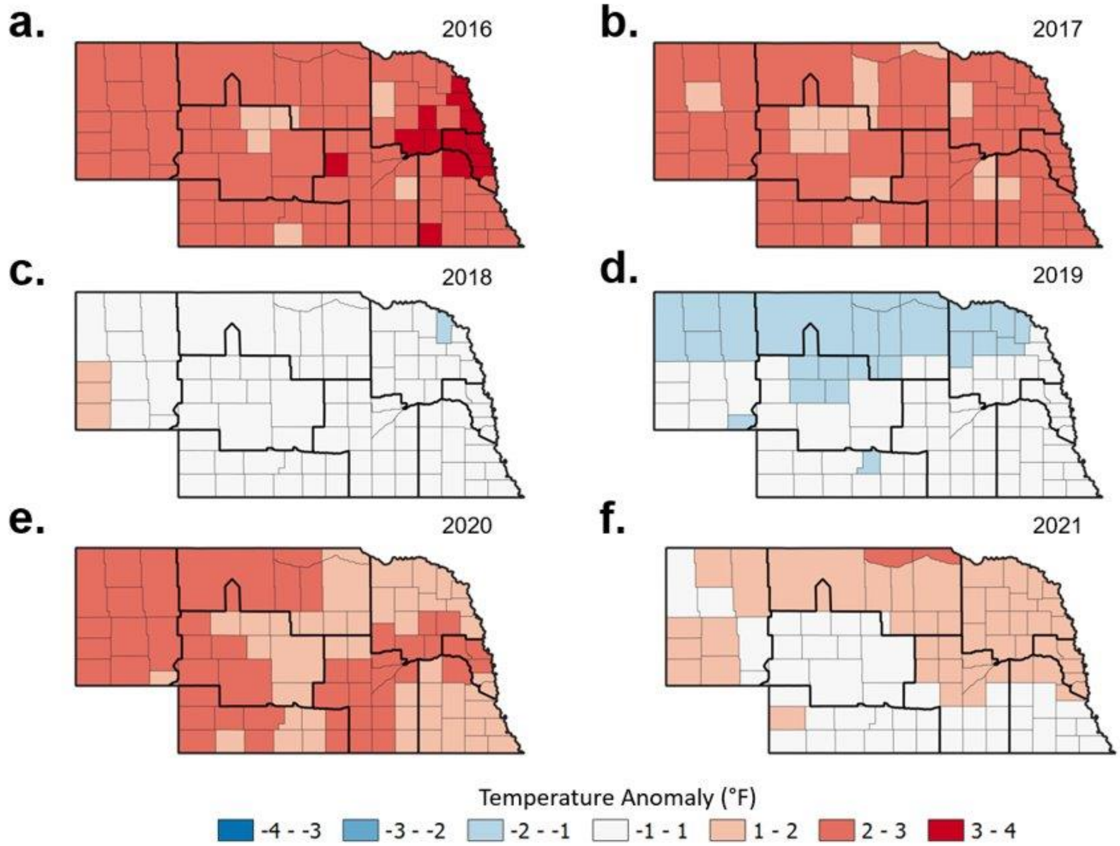

Figure 4.25. *Annual averaged daily temperature anomalies (1900-2000 base period) for each study period year for each county (2016-2021). Data for this figure from NCEI.*

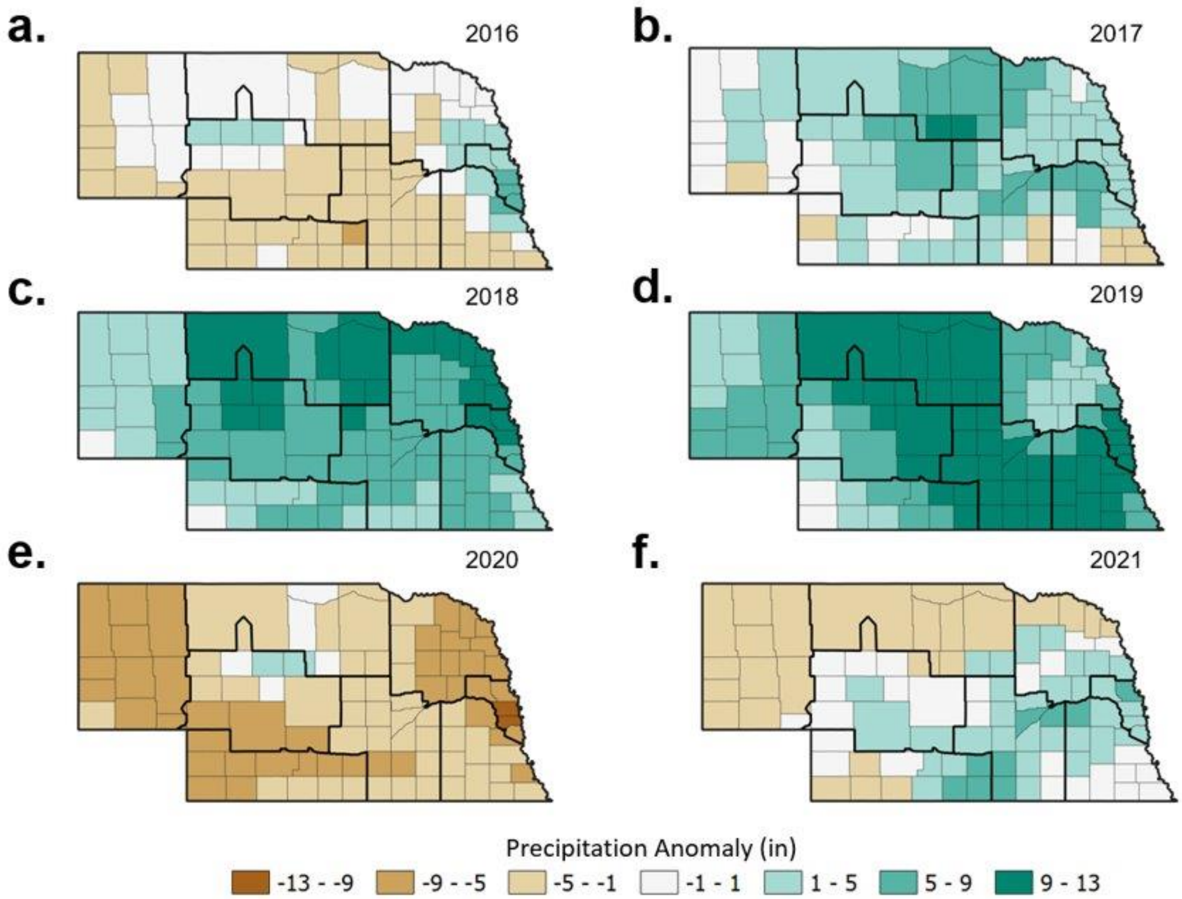

Figure 4.26. *Annual averaged precipitation anomalies (1900-2000 base period) for each study period year for each county (2016-2021). Data for this figure from NCEI.*

<u>4.3.2 Palmer Indices</u>

While temperature and precipitation rankings over the past 30 years show interannual variability and a lack of a noticeable pattern, the PDSI and PHDI indicate wet and dry cycles. Furthermore, the PDSI and PHDI indicate 5–7 year long dry and wet cycles over the 32-year period, with rankings on both end of the extremes across Nebraska (Figure 4.27). Wet cycles occur from 1992 to 1999, 2007 to 2011, and 2014 to 2020; while dry cycles occur between 2000 to 2006 and between 2012 to 2013. During this study period, PDSI and PHDI rankings are in a wet cycle as some seasons in late 2018, all of 2019, and early 2020 are in the top three wettest on

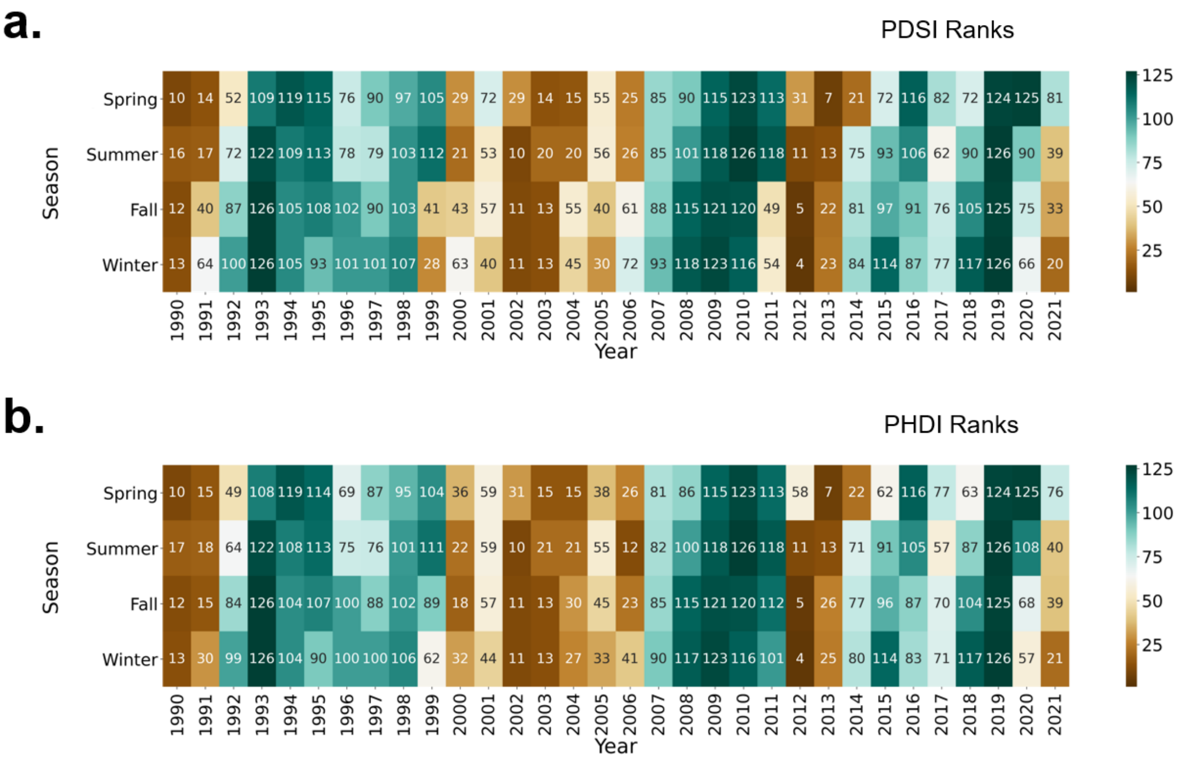

Figure 4.27. *Monthly PDSI and PHDI rankings by year (1990-2021) over the 127-year period (1895-2021), or the climatological record. Data for this figure from NCEI.*

Record. This is evident from an annual average perspective for both the PDSI and PHDI as values exceed 4.0 (extremely moist) in District 8 and much of Districts 4 and 6 from 2018 to 2020 (Figure 4.28 and 4.29). District 8 in northern Nebraska for each year in the study has average PDSI/PHDI values at a minimum of 2.0 (unusually moist). Overall, the study period for Nebraska is an extremely moist period and one of the highest ranked moisture periods in the climatological record, which has major implications on the frequencies of water obstructions even if precipitation totals are below normal. An example of this is the year 2020, while 2019 is very wet for a large portion of Nebraska, 2020 is on the drier side. Though because Palmer indices are still on the moist side in 2020, water obstruction numbers in 2020 are still near the 5-year median.

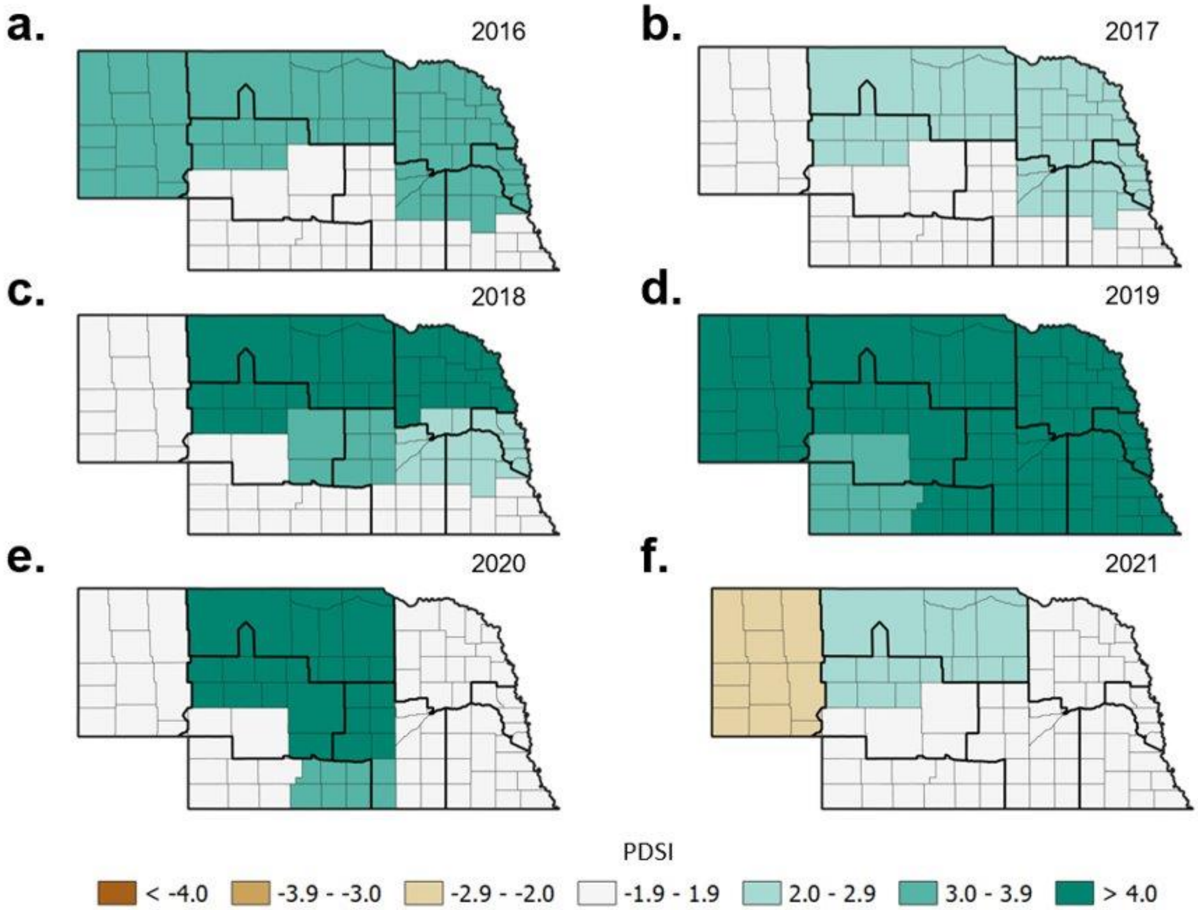

Figure 4.28. *Annual averaged PDSI values for each study period year for each climate division (2016-2021). Data for this figure from NCEI.*

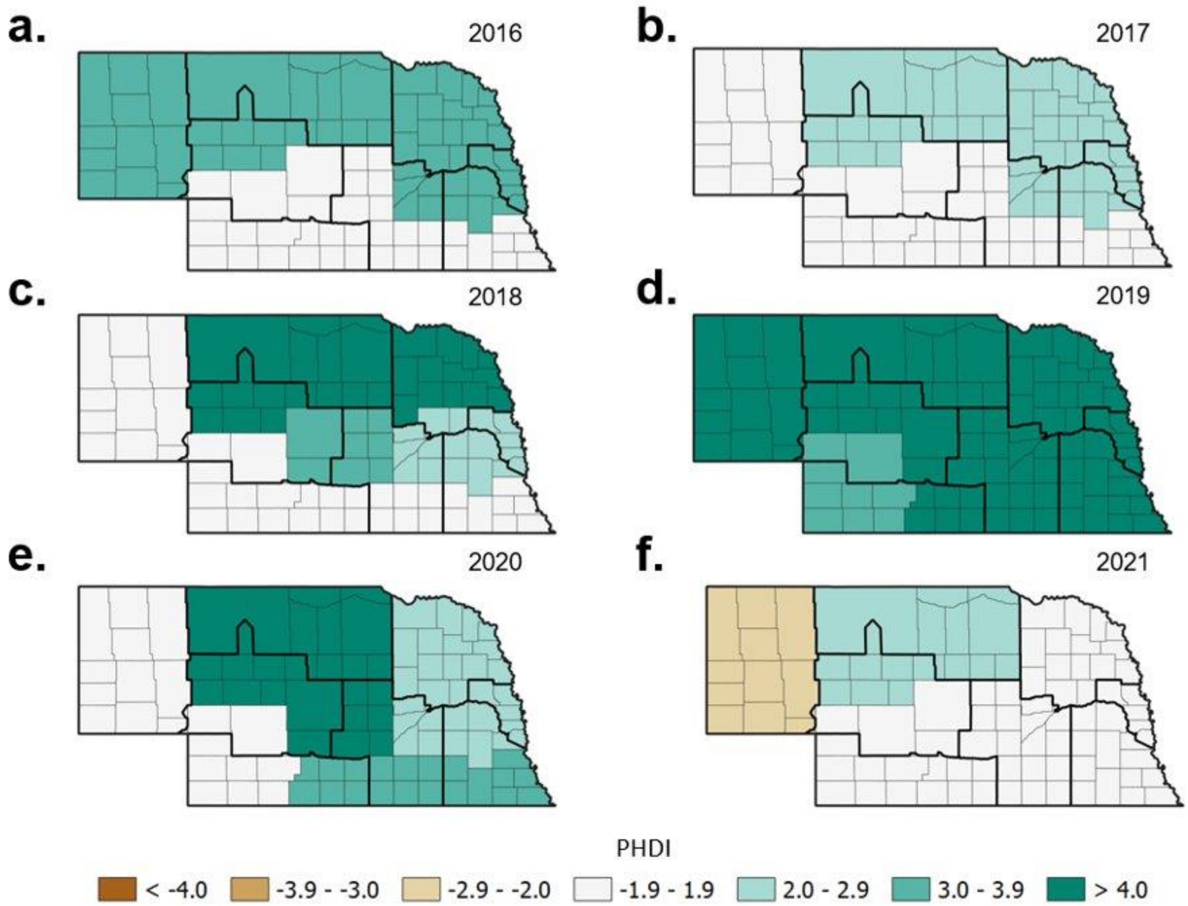

Figure 4.29. *Annual averaged PHDI values for each study period year for each climate division (2016-2021). Data for this figure from NCEI.*

4.3.3 Ice Jamming

With winter temperatures for the study period averaging above normal for many counties across Nebraska, river ice jams during the period are likely below normal when compared to other years during the 32-year climatological period. There are periods prior to 2016 where ice jams occur more frequently, such as 1993, 1997, 2004, 2010, and 2011 (Figure 4.30). Thus, these years could very well have more ice jam water obstructions than what is experienced during the 2016-2021 study period. The most active time when ice jams are occurring during the study period is in February and March. The lower number of ice jams overall during this period does

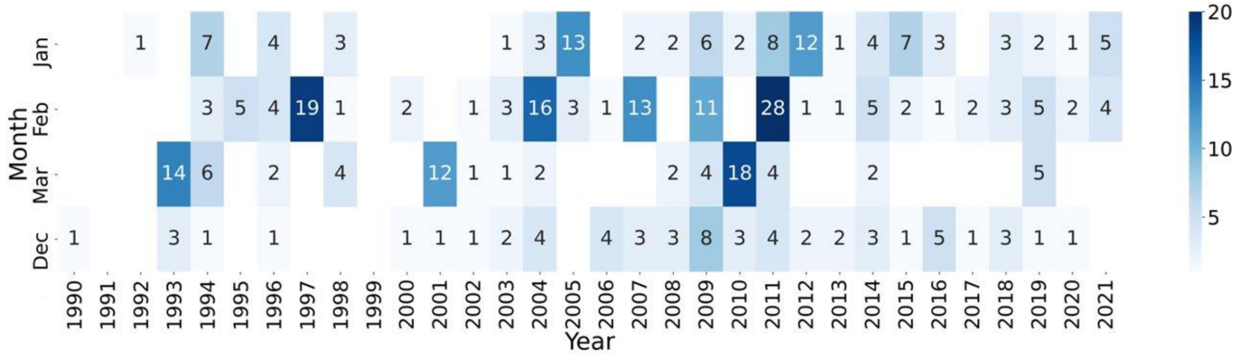

Figure 4.30. *River ice jam totals by month (Jan, Feb, Mar, Dec) in Nebraska (1990-2021). Data from CRREL Ice Jam Database.*

not highlight the severity of the March 2019 historic floods. Thus, even though the number of ice jams during a month/year may be low, the severity of each situation may vary completely. Therefore, if there is at least one ice jam occurring within a given month/year, then the likelihood of this ice jam leading to a water obstruction on the roadway increases. In other words, outside of March 2019, the likelihood ice jam water obstructions occur in other months/years in the study period is high. As noted earlier, temperatures across Nebraska allow for ice to form on rivers in all parts of the state, and this holds true for the smaller study period window of 2016 to 2021 as ice jams are quite widespread throughout the state (Figure 4.31). Though, the number of ice jams within the study period are relatively lower than the number of ice jams in other 5-year periods as indicated in Figure 4.30. Ice jams occur along the Platte River every year in the study period, with most of them clustering along the boundary of Districts 1, 2, and 3. Though it is District 4 that has the most ice jams throughout the study period with the majority of these coming in 2018 and 2019. An important note is there are no observed ice jamming reports south of the Platte River, though this does not mean ice jam water obstructions did not occur south of the Platte River. The caveat with the ice jamming database is there may be some spatial bias with where

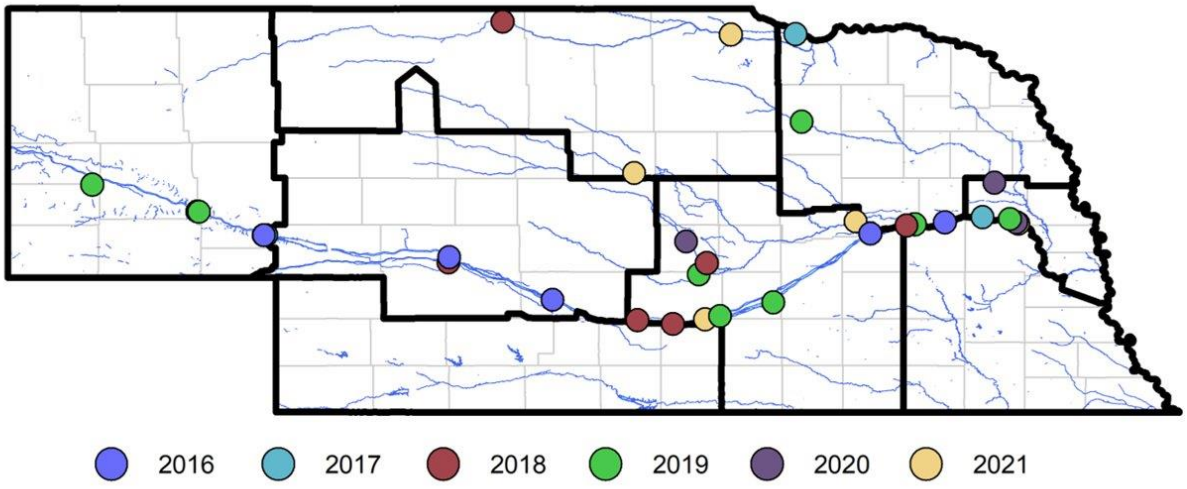

Figure 4.31. *Observed locations of river ice jams (2016-2021). Data from CRREL Ice Jam Database.*

USGS stream gages are located, and ice jams in some locations may go undocumented. Therefore, the methods highlighted in Section 3 is a better approach than strictly using the ice jamming database in determining if a water obstruction is caused by ice jamming. However, the density of ice jam water obstructions is likely higher north of the Platte River and where there is a greater exposure to roadways and a colder winter climatologically (e.g., Districts 2 and 3 in northeastern Nebraska).

4.4 Associated Meteorological Conditions

4.4.1 Precipitation

In addition to examining the water obstruction climatology, the final portion of this research aims to gather the meteorological conditions to develop a better understanding towards water obstruction occurrences. This study period, overall, is characterized by wetter than normal conditions as discussed in Section 4.3. NOAA Atlas 14 precipitation reoccurrence intervals revealed 95 of the 298 water obstructions (32%) in the study period have precipitation amounts high enough to be flagged as having a 1-year or higher reoccurrence interval (Figure 4.32). Eight of the 95 obstructions with reoccurrence intervals are flagged as being 25-year precipitation events. Two of these occurred in 2016, and the remaining 25-year precipitation events occurred in July of 2019 along the border of Districts 4 and 7 in south-central Nebraska. This is an area with a notable clustering of heavy precipitation reoccurrence, as 10-year, 5-year, and 2-year floods have occurred in and around Buffalo, Hall, and Adams County. All these are due to the 9-11 July 2019 long-duration precipitation event. Dodge and Cuming County (along US 275) is another area to note where clustering of these high reoccurrence intervals occur and is considered a top water obstruction location in the state. The largest long-duration precipitation event that caused a water obstruction is in Dodge County during June 2016 along US 275 when 4.96 inches of rain was recorded in just seven hours in eastern Nebraska. The other high reoccurrence

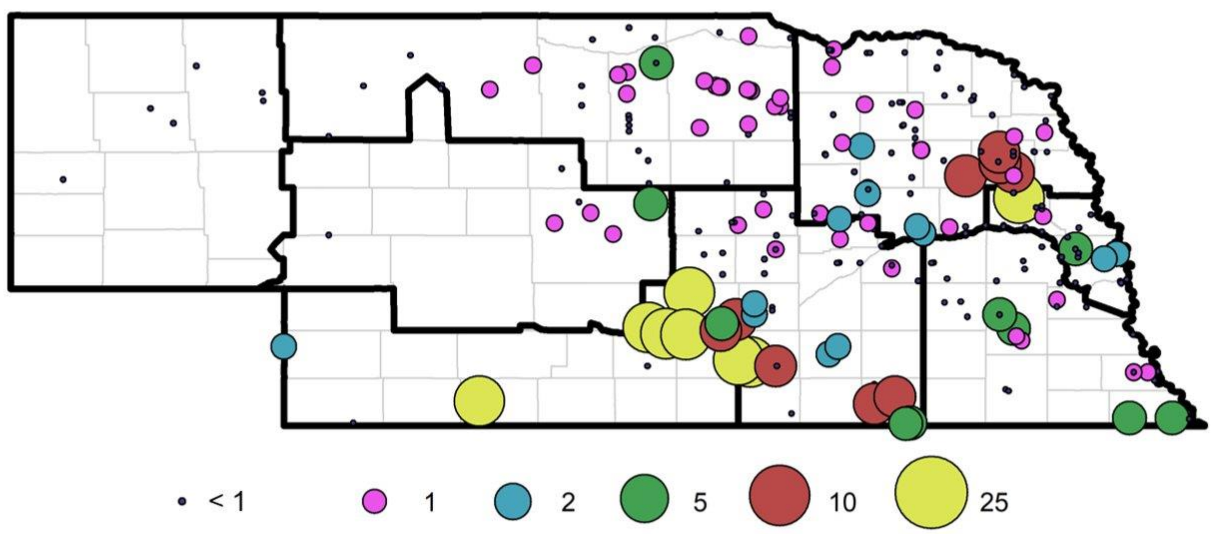

Figure 4.32. *NOAA Atlas 14 average reoccurrence intervals in year(s) for each water obstruction (2016-2021).*

Intervals occurred in September 2016 in this general area. The March 2019 historical flooding event had many water obstructions associated with 1- and 2-year precipitation reoccurrence intervals. It is important to note that the NOAA Atlas 14 is based on precipitation and not on total localized flooding (NOAA 2008). In other words, for the March 2019 event, given there are 41 breaches to levees across the state because 30 stream gages in eastern Nebraska had reached all-time record levels, this event is regarded as a 1000-year flood (NDNR 2021). In summary, while precipitation from this event only reaches 1- and 2-year reoccurrence interval totals, the widespread nature to it, the rapid snowmelt, and the ice jamming all contribute to the flooding scenario across the state as being much more substantial for a 1000-year flood. All in all, District 4 in southern Nebraska has the highest number of reoccurrence intervals longer than 2-years, which attributes to why District 4 is the high-frequency water obstruction location for long- and short-duration precipitation water obstructions. Therefore, a relationship may be established between the amount of precipitation causing water obstructions and the root weather-related cause. It is established that areas with more precipitation tend to have more water obstructions, though the number of water obstructions caused by specific precipitation totals has yet to be discovered.

With and without March 2019 included in the dataset, water obstructions associated with long-duration precipitation have the highest amount of precipitation associated with the obstruction followed by short-duration precipitation (Figure 4.33a and b). On average, without March 2019 included, long-duration precipitation amounts that result in a water obstruction are near 2.40 inches prior to obstruction occurring, while short-duration precipitation is 1.50 inches. Precipitation in association with groundwater and ice jamming water obstructions are inflated when March 2019 is included in the dataset as the average amount to induce these types of obstructions are 0.60 and 1.40 inches, respectively. Without March 2019, the averages drop to

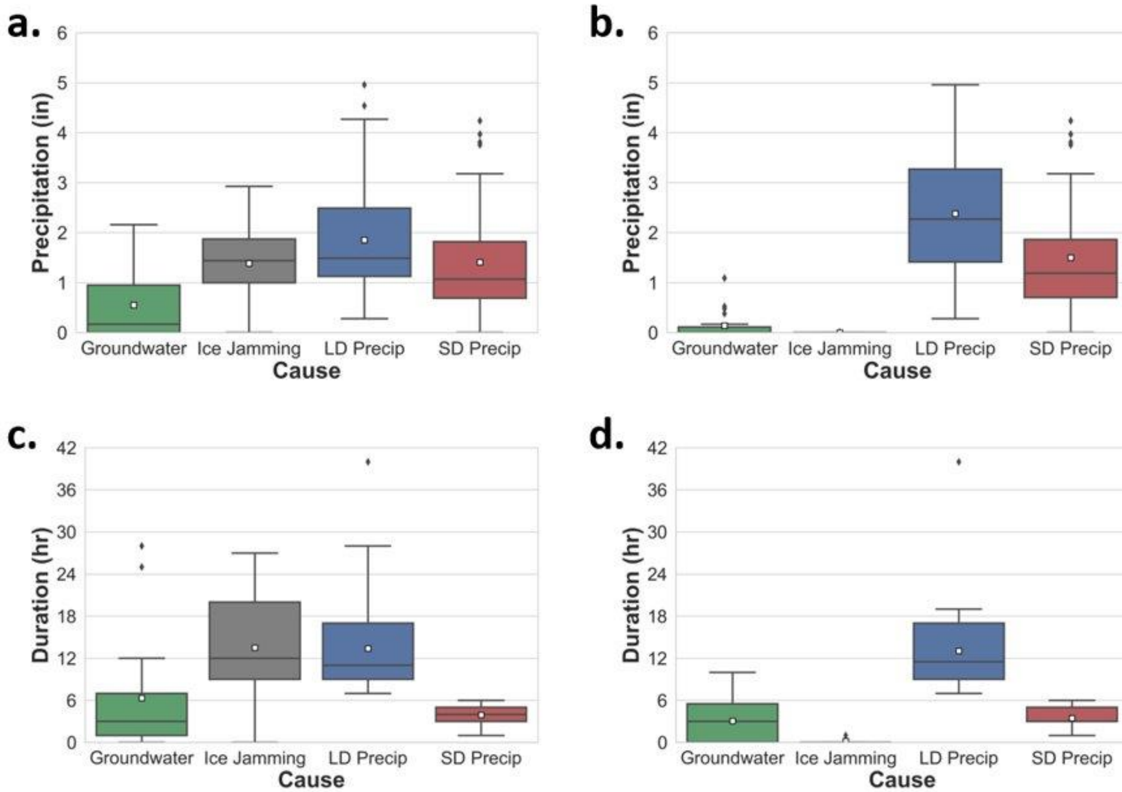

Figure 4.33. *Box and whisker plots of precipitation (inches) per water obstruction event by each obstruction's root weather-related cause (a) with March 2019 and (b) without March 2019, as well as the weather-related cause precipitation duration (hours) (c) with March 2019 and (d) without March 2019 from 2016-2021.*

0.10 inches for groundwater and less than 0.10 inches for ice jamming water obstructions. Precipitation amounts associated with each weather-related cause do have a statistically significant (95% confidence level) correlation with the precipitation duration prior to the water obstruction. In other words, the longer the duration of the precipitation event, in general, the higher the precipitation totals are. With March 2019, the correlation between precipitation amounts and duration is 0.32, while this correlation increases to 0.40 without March 2019. Therefore, with long-duration precipitation having the highest amount of precipitation associated with water obstructions on average, the number of hours of precipitation prior to the water obstruction is also typically the highest (Figure 4.33c and d). This is in large-part due to the criteria for a water obstruction to be caused by long-duration precipitation, as it is dependent on the duration. Even so, this still varies tremendously from the duration of precipitation associated with groundwater and ice jamming water obstructions. On average, without March 2019 in the dataset, the duration of precipitation inducing groundwater-related water obstructions are 4 hours while ice jamming was less than 1 hour. This suggests more important factors than simply precipitation causing these types of obstructions to occur, such as precursor PHDI conditions for groundwater water obstructions and precursor river conditions and temperatures for ice jamming water obstructions. These precursor conditions for ice jamming are especially noteworthy, because not all ice jamming obstructions have precipitation associated with them. In fact, two of the five ice jamming events outside of March 2019 did not have any precipitation to induce the ice jamming and result in an obstruction. Thus, the rapid melting of ice and increased discharge and water levels were the main causes for these obstructions.

When considering the amount of time prior to a water obstruction, short-duration precipitation in the 1-hour, 1 to 3-hour, and 1 to 6-hour periods prior to the obstruction occurring has the highest precipitation amount prior to a water obstruction than any other weather-related cause with and without March 2019 (Figure 4.34 and 4.35). From the 1 to 12-hour period onward, long-duration precipitation totals surpass the short-duration precipitation amounts. With March 2019 included in the dataset, the means between long- and short-duration precipitation are not statistically significant different beyond the 1 to 12-hour period. When March 2019 is excluded from the dataset, there are significant differences. Therefore, precipitation totals tend to be higher in the six hours leading up to the water obstruction for short-duration precipitation events. Thus, it is likely that short-duration precipitation is either occurring closer to when the

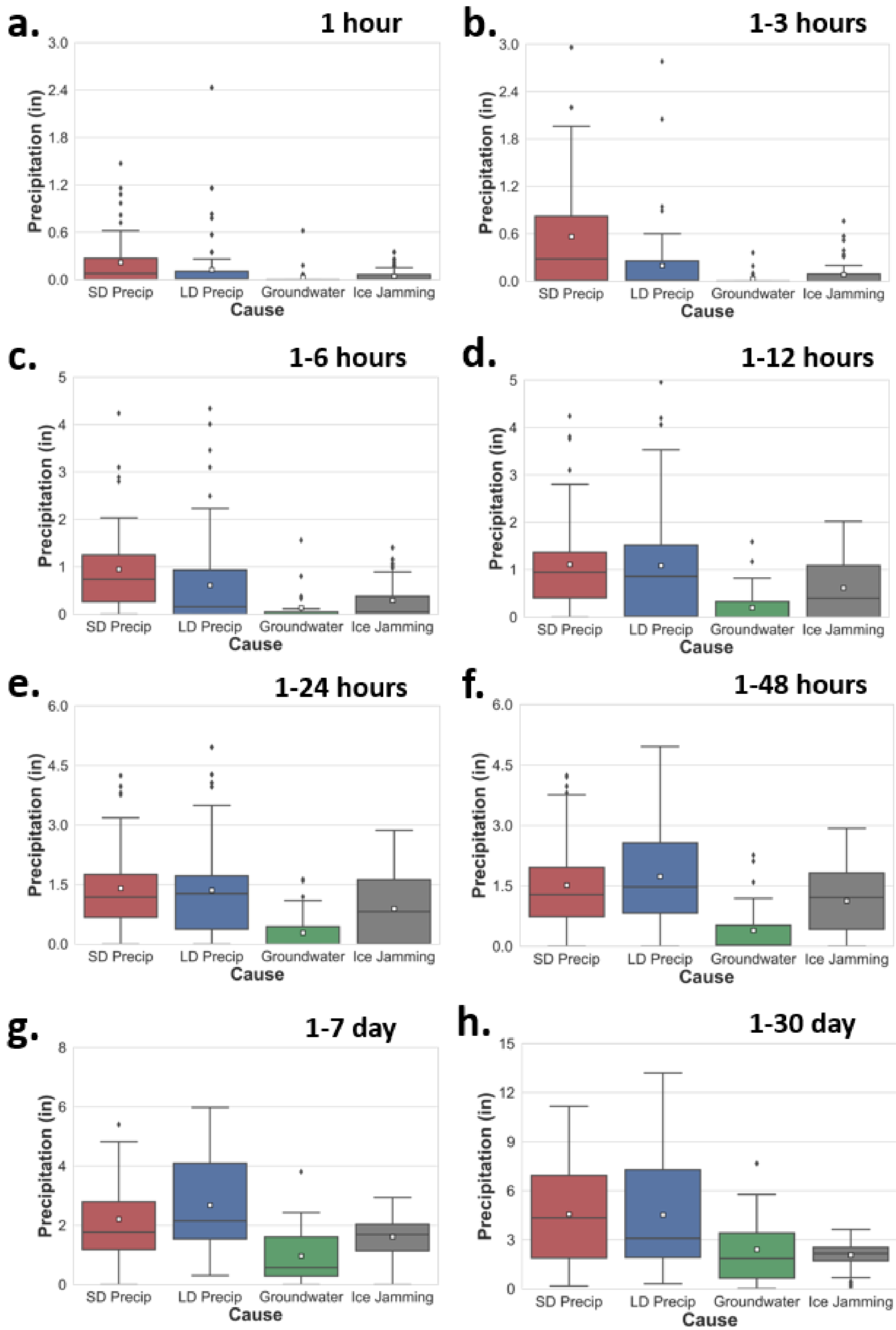

Figure 4.34. *Box and whiskers of precipitation accumulation (inches) prior to the water obstruction occurring by root weather-related cause (2016-2021).*

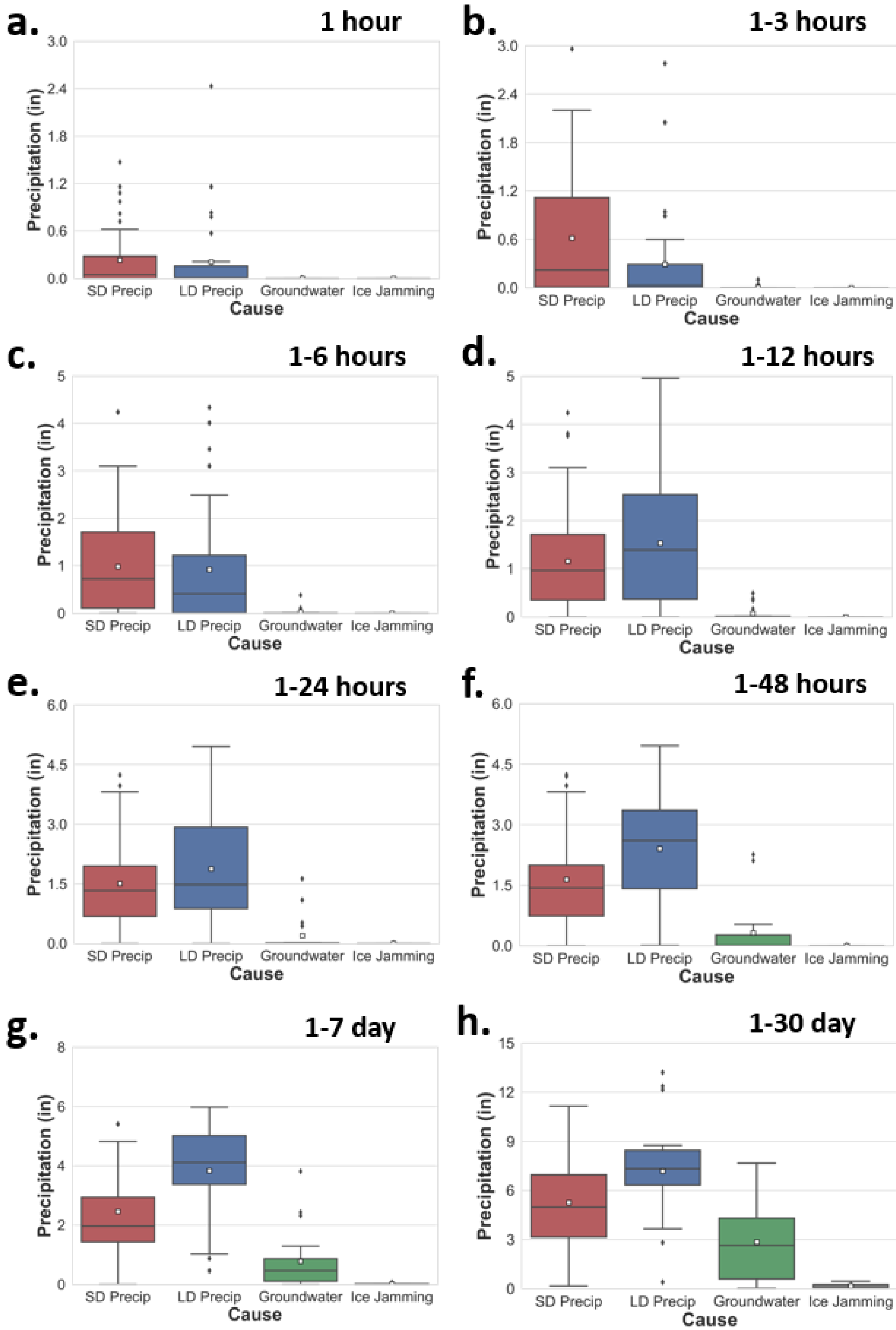

Figure 4.35. *Box and whiskers of precipitation accumulation (inches) prior to the water obstruction occurring by root weather-related cause (2016-2021; excluding March 2019).*

Water obstruction begins than other causes or are ongoing when the water obstruction has already occurred. However, long-duration precipitation, due to its longer period, typically ends up having more precipitation. These intervals do not necessarily overlap with the duration of the precipitation prior to the water obstruction. In other words, short-duration precipitation events that lasts four hours may occur between six to 12 hours prior to the water obstruction, and the same can be true with the other weather-related causes and their respective durations. As a reminder, long-duration precipitation and short-duration precipitation events are the total precipitation durations prior to the obstruction. When excluding March 2019, groundwater and ice jamming obstructions do not tend to produce much precipitation prior to the obstruction within the two days leading up to the obstruction. However, this changes for groundwater obstructions beyond the 2-day period, as the average amount of precipitation in the three to seven days and three to 30 days prior notably increases. This suggests the precipitation for groundwater water obstructions do not tend to occur the day of or even two days prior to the water obstruction and precipitation is more likely to occur at some point within the same week as the water obstruction or before. In other words, this delay is needed for the groundwater levels to rise and result in a groundwater water obstruction.

As for when the water obstruction occurs with respect to when precipitation is occurring, with and without March 2019, each obstruction cause exhibits a similar story except short-duration precipitation events. These events a majority of the time will not have a water obstruction occurring until after the precipitation is finished (Figure 4.36). In other words, during a short-duration precipitation water obstruction, precipitation is still typically ongoing more often than not. The caveat to this, however, is the exact timing of the water obstruction is likely highly dependent on when it is entered into the CARS511 system by NDOT. Thus, any water obstruction may have been ongoing for a period of time before NDOT reports the obstruction

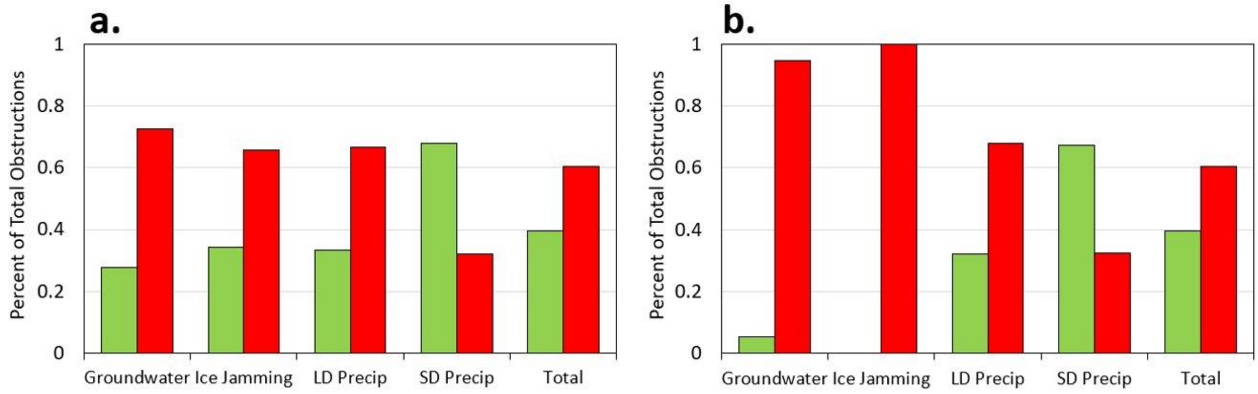

Figure 4.36. *Precipitation timing with respect to the water obstruction occurring a) 2016-2021 and b) 2016-2021 without March 2019. Green bars represent percentage of cases when precipitation is ongoing during the obstruction. Red bars represent percentage of cases when the water obstruction occurs after the precipitation is finished.*

Into the system. Without March 2019, 95% of groundwater cases and 100% of ice jamming cases do not have precipitation occurring when the obstruction is reported.

When examining precipitation totals further, the greatest number of water obstructions occur (29% of the dataset) when precipitation totals are in the 1.0–1.5-inch range, which is highly attributed to the March 2019 event (Figure 4.37a). When excluding March 2019, there is a wider range of outcomes in terms of precipitation totals (Figure 4.37b), suggesting a definitive threshold of precipitation in order for a water obstruction is not possible without understanding precursor conditions, geographical influences, and land use influences as discussed in Section 2. While the precipitation amounts associated with each water obstruction are still highly dependent on the root weather-related cause, the number of obstructions is typically around the same range (~15–30 obstructions). In terms of how these precipitation events compare to the monthly mean total is dependent on if March 2019 is included in the dataset. With March 2019 included, 63% of water obstructions have precipitation that surpasses the monthly mean amount of precipitation

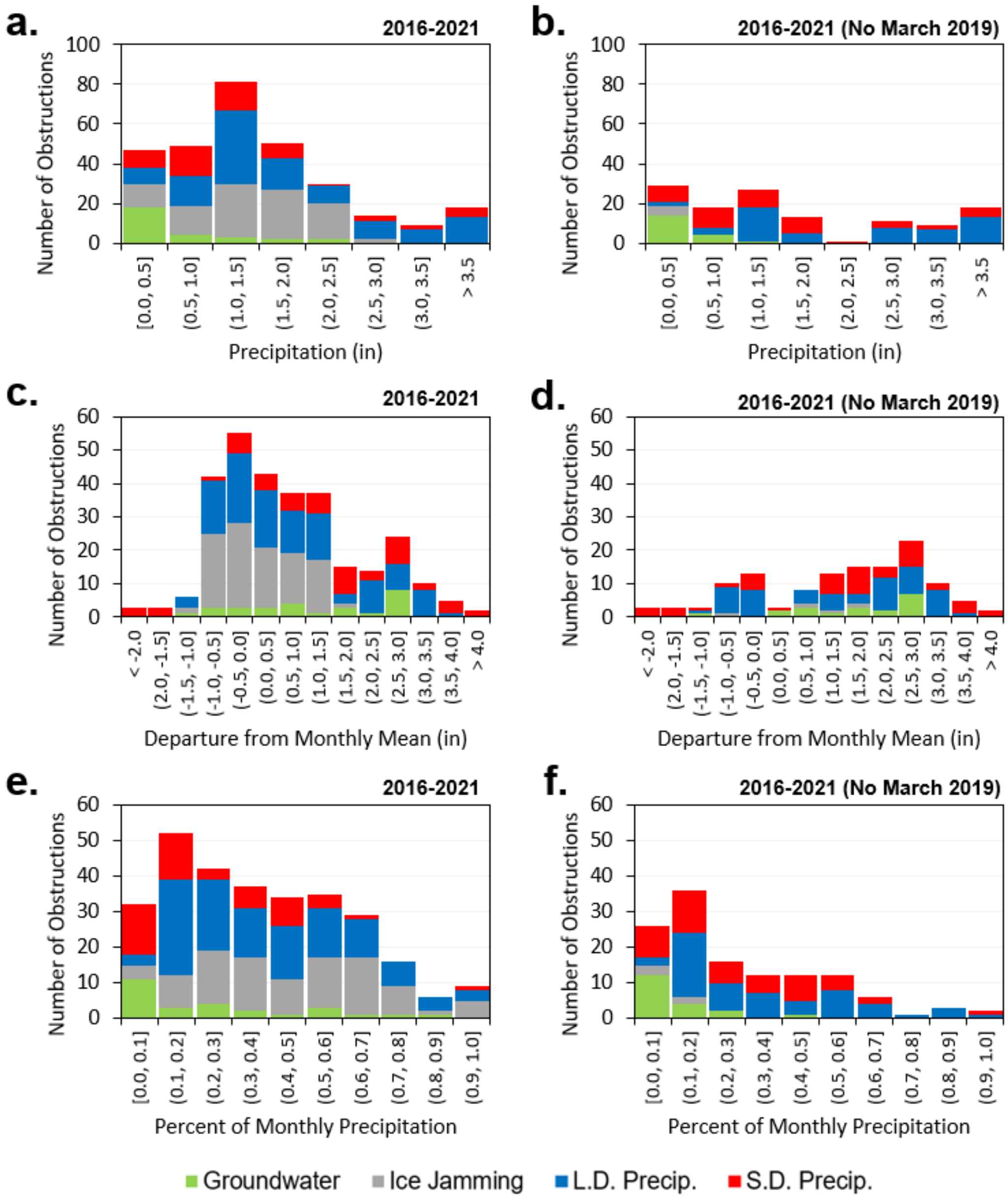

Figure 4.37. *Precipitation data for each water obstruction event by root weather-related cause as shown by (a) and (b) precipitation totals, (c) and (d) precipitation total subtracted from monthly mean total, (e) and (f) how much the precipitation accounted for the monthly precipitation total. (a) (c) and (e) are for the entire study period (2016-2021) while (b), (d), and (f) excludes March 2019.*

For that respective location (Figure 4.37c). However, this does not hold true when excluding March 2019 as there is a larger number of obstructions that have precipitation lower than the monthly mean (Figure 4.37d). Further, most of the precipitation associated with these water obstructions have amounts in the range of 1.0–3.0 inches below the monthly mean. In terms of how much the precipitation associated with the water obstruction accounts for in terms of the monthly total amount of precipitation at the respective location, this is again highly dependent on if March 2019 is included. With March 2019, there are a greater number of water obstructions in which the associated precipitation account for more than 50% of the monthly total than without March 2019 (Figure 4.37e and f). Without March 2019, a higher percentage of water obstructions have precipitation totals responsible for only 1% to 30% of the monthly total. Overall, these lower amounts with respect to the mean and overall lower percentages attributes to the overall anomalous precipitation totals and precursor conditions in the month prior and month of the water obstructions during the study period.

With March 2019 included, over 200 water obstructions have associated precipitation totals of less than 2.0 inches in the previous month with respect to the month when the water obstruction occurs, and nearly 170 water obstructions had 2.0–4.0 inches total during the month when the obstruction occurs (Figure 4.38a and b). Without March 2019, it is evident there are still a higher number of water obstructions that have much higher precipitation totals prior to the water obstruction in the 2.0–6.0-inch range, and totals in the 4.0–8.0-inch in the month of the obstruction (Figure 4.39a and b). To put this into a more meaningful perspective, precipitation departures for a large number of water obstructions are within one inch below or above normal in the month prior to the water obstruction (Figure 4.38c and 4.39c); however, over 78% of water obstructions are within months when precipitation departures are greater than one inch above normal (Figure 4.38d and 4.39d), consequently, causing nearly three fourths of water

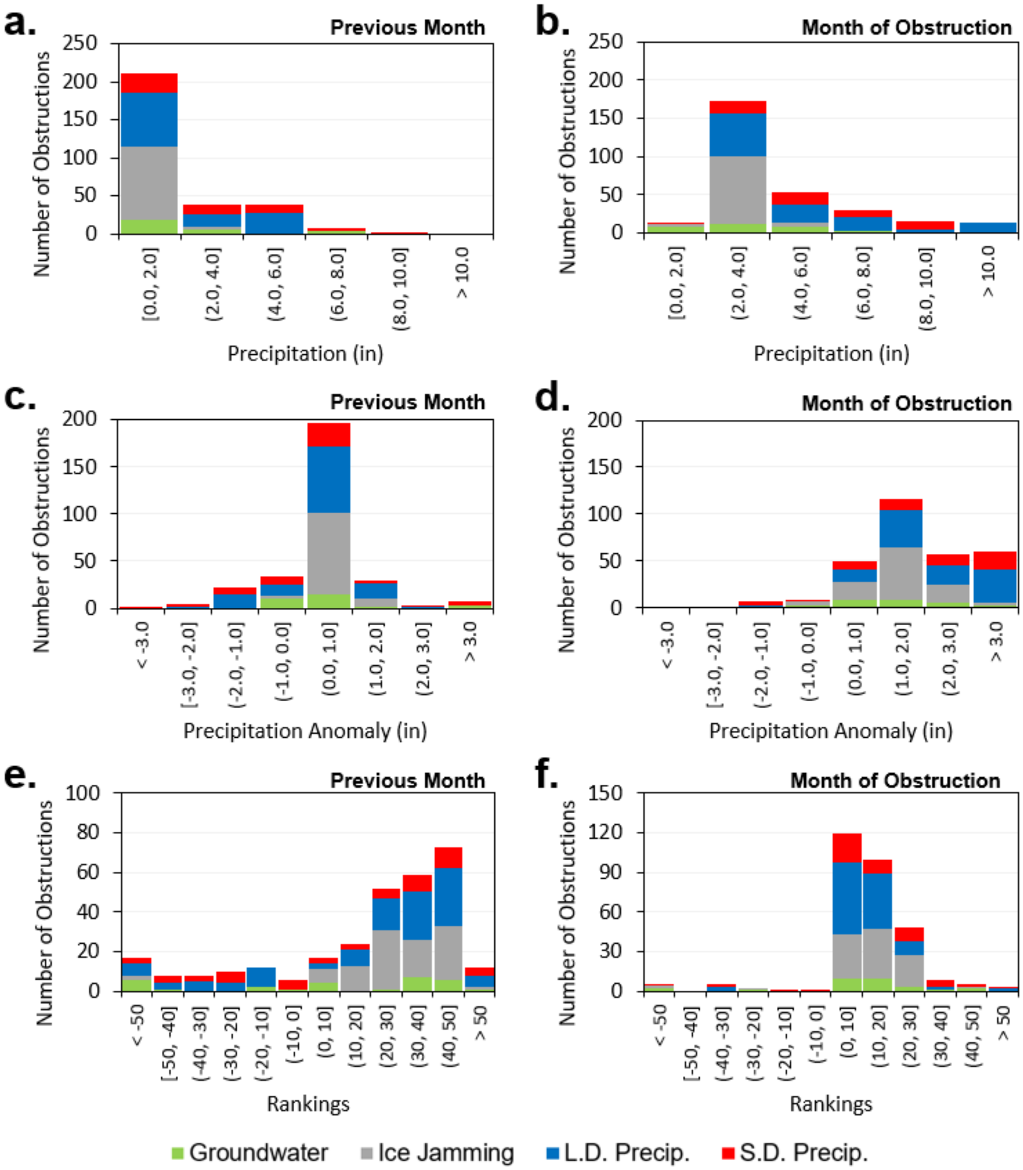

Figure 4.38. *Precipitation data for the previous month with respect to the month when the water obstruction occurred by root weather-related cause as shown by (a) and (b) precipitation totals, (c) and (d) precipitation anomalies (1900-2000 base period), (e) and (f) precipitation rankings where the negative values signify dry years (-1 being the driest) and positive values being the wet years (1 being the wettest). Water obstruction data from 2016-2021.*

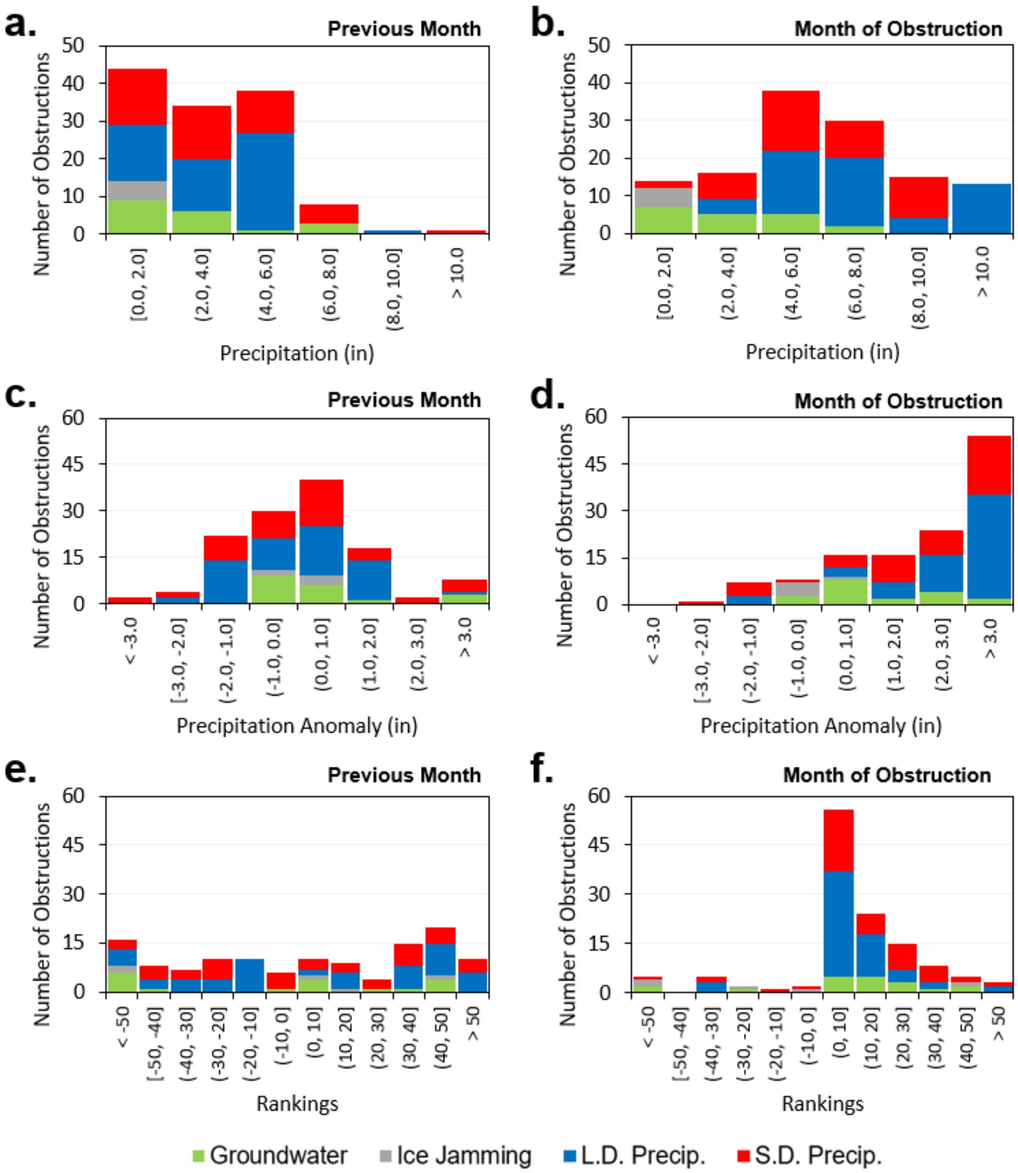

Figure 4.39. *Precipitation data for the previous month with respect to the month when the water obstruction occurred by root weather-related cause as shown by (a) and (b) precipitation totals, (c) and (d) precipitation anomalies (1900-2000 base period), (e) and (f) precipitation rankings where the negative values signify dry years (-1 being the driest) and positive values being the wet years (1 being the wettest). Water obstruction data are from 2016-2021 without March 2019.*

Obstructions to occur within months with precipitation rankings in the top 20 wettest of all time (Figure 4.38f). In fact, even when excluding March 2019, the greatest number of water obstructions occur in months when precipitation totals rank in the top 10 wettest of all time (Figure 4.39f). An important caveat is this may depend on when in the month the water obstruction occurs. In other words, a majority of a month can be below normal in precipitation, then experience the precipitation associated with a water obstruction and become well-above normal in terms of the monthly total.

4.4.2 Precipitation Characteristics

In addition to precipitation totals with respect to the root weather-related causes, the precipitation mode and system-type responsible for the precipitation is also important to examine to further understand and increase the predictability of water obstructions. While short-duration precipitation events have a much more widespread nature to them in terms of where they occur in Nebraska, stratiform precipitation has generally been confined to the eastern and northern domain of the state. This same pattern is evident when comparing the precipitation mode of stratiform or convective tied with each water obstruction across Nebraska (Figure 4.40). Though, 83% of the water obstructions associated with stratiform precipitation occur in March 2019, without March 2019 only 13% of water obstructions in the study period were associated with purely stratiform precipitation. Thus, convective precipitation tends to cause a higher number of water obstructions given that precipitation rates are typically larger and consequently lead to more precipitation accumulation. Furthermore, the precipitation mode may also be tied with root weather-related causes to water obstructions (Figure 4.41). One hundred percent of ice jamming events are associated with long-duration precipitation during the time of the year when long-duration precipitation is the dominant mode of precipitation and when ice jamming occurs climatologically. When removing March 2019, convective precipitation causes more

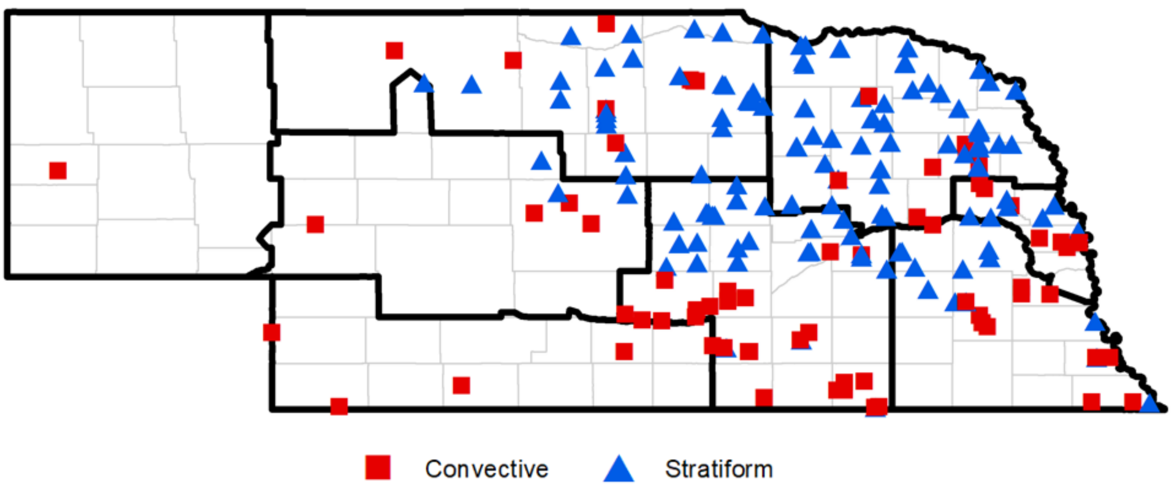

Figure 4.40. *Convective and stratiform precipitation induced water obstruction locations for the study period (2016-2021).*

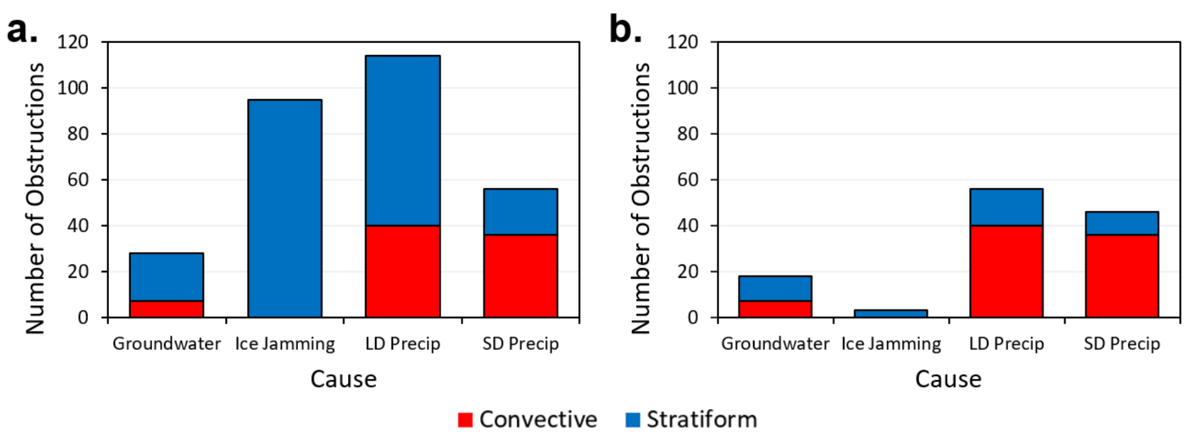

Figure 4.41. *Water obstruction totals by root weather-related cause and classified by convective or stratiform precipitation mode (a) with March 2019 and (b) without March 2019 from 2016-2021.*

Obstructions than stratiform precipitation. The same is true for short-duration precipitation obstructions, as a higher percentage of obstructions are in the form of convective precipitation as well.

For groundwater water obstructions, convective and stratiform precipitation both contribute to the cause. When examining precipitation totals with respect to precipitation mode, convective precipitation averages about 0.5 inches more and about 3 hours less in duration than stratiform precipitation on average (Figure 4.42). However, averages from these are skewed by the extremes during the study period, thus, the medians show precipitation totals for both are

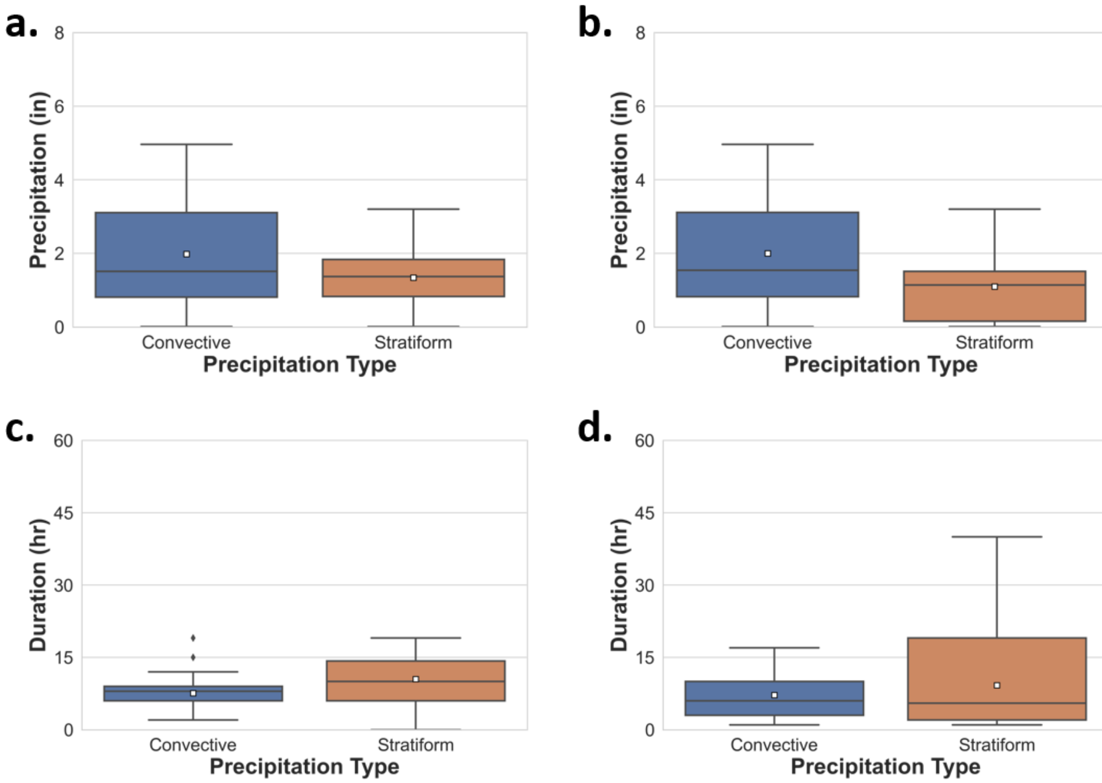

Figure 4.42. *Box and whisker plots of precipitation (in) per water obstruction event by each obstruction's precipitation type (a) with March 2019 and (b) without March 2019 as well as the precipitation type's duration (hours) (c) with March 2019 and (d) without March 2019 from 2016-2021.*

Near 1.8 inches while the duration is around 6 hours. Statistically, there are no significant differences between the population means of convective and stratiform precipitation for duration; however, there are statistically significant differences between the totals for each mode. In summary, while convective and stratiform precipitation events tend to have similar durations on average, water obstructions are more likely to occur when the precipitation mode is convective.

The system type is also examined and related to the root weather-related causes. March 2019 is predominately due to an extratropical cyclone that creates a wide swath of precipitation lasting for a long time in the eastern and northern domains of Nebraska (Figure 4.43a).

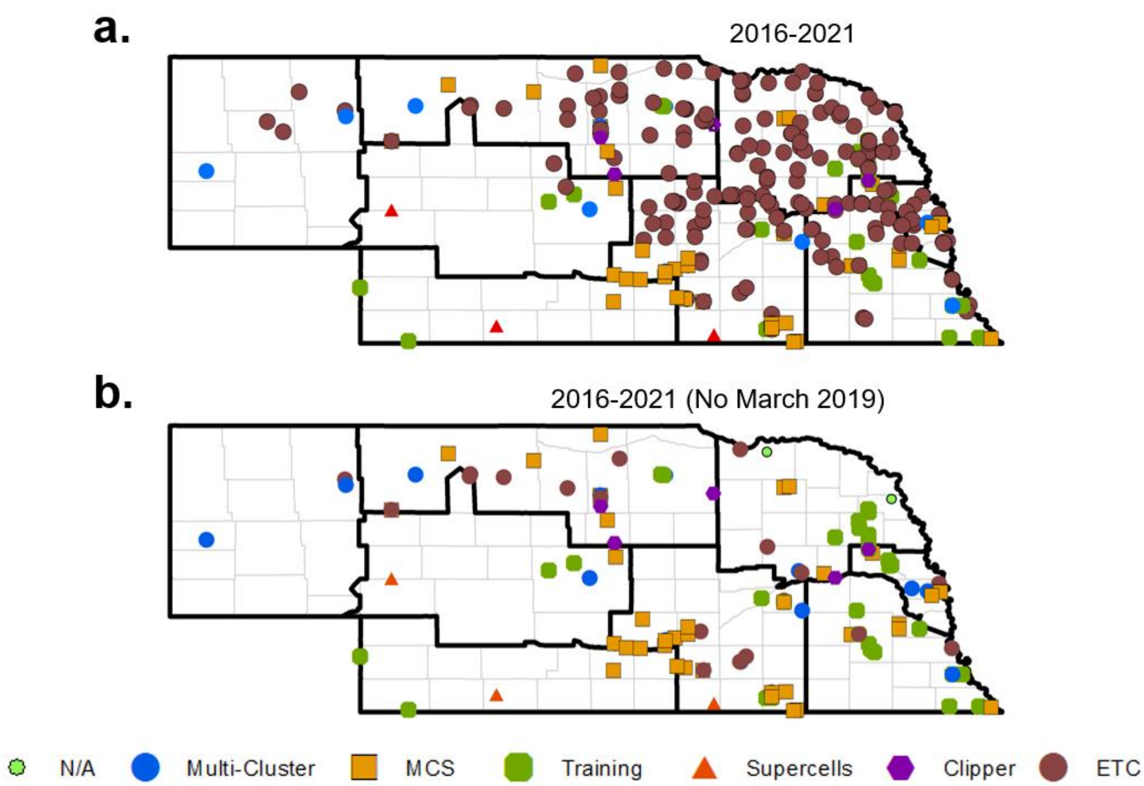

Figure 4.43. *Water obstruction locations displayed by their respective system type including multi-cluster thunderstorms, mesoscale convective systems (MCS), convective training, supercells, Alberta-Clipper systems, and extratropical cyclones (ETC) over the study period (2016-2021).*

Multi-cell clusters, convective training, and supercells display the most widespread occurrences over MCS’s and extratropical cyclones when excluding March 2019 (Figure 4.43b). Though any one of these storm types can occur in any part of the state, the occurrence of these storms favors different portions of the state on average. Groundwater events, which generally occur in the northern tier of Nebraska in District 8, have all storm types except for convective training and supercells to cause a water obstruction. The only storm type to cause ice jamming is in the form of an Alberta-Clipper system or no system type at all when excluding March 2019 (Table 4.7). For long- and short-duration precipitation, MCS’s and convective training are the most common system types causing water obstructions in Nebraska. MCS’s and convective training are the two most common system types when excluding March 2019 at 33% and 28%, respectively. In terms of precipitation totals for each of these storm types, water obstructions associated with MCS’s have the most precipitation on average with 2.30 inches (Figure 4.44a and b). Following MCS’s are convective training and supercells producing 1.90 inches of precipitation on average to induce water obstructions. In terms of duration, convective training scenarios last the longest, just over 10 hours on average, followed by MCS’s and extratropical cyclones. Supercells are some of the quickest events (less than three hours on average) yet are some of the top precipitation producers resulting in water obstructions. In summary, all these different system

Table 4.7. *Water obstructions event totals by system type and by root-weather related cause with and without March 2019 (2016-2021).*

Type	Groundwater	Ice Jamming	LD Precip.	SD Precip.	Type	Groundwater	Ice Jamming	LD Precip.	SD Precip.
Clipper	3	3			Clipper	3	3		
ETC	16	93	70	16	ETC	6		12	6
MCS	5		20	16	MCS	5		20	16
Multi-Cluster	4			3	Multi-Cluster	4		1	9
Supercells				3	Supercells				3
Training			23	12	Training			23	12
N/A	1	3			N/A	1	2		

types can occur anywhere in Nebraska just like how any weather-related cause can occur. However, over the past five years, there is evidence to support that some system types may be favored to occur more often in some districts than in others. Overall, MCS's and convective training will tend to produce the most precipitation out of all system types, making these types more likely to result in a water obstruction than others, all of which are in the form of convective precipitation.

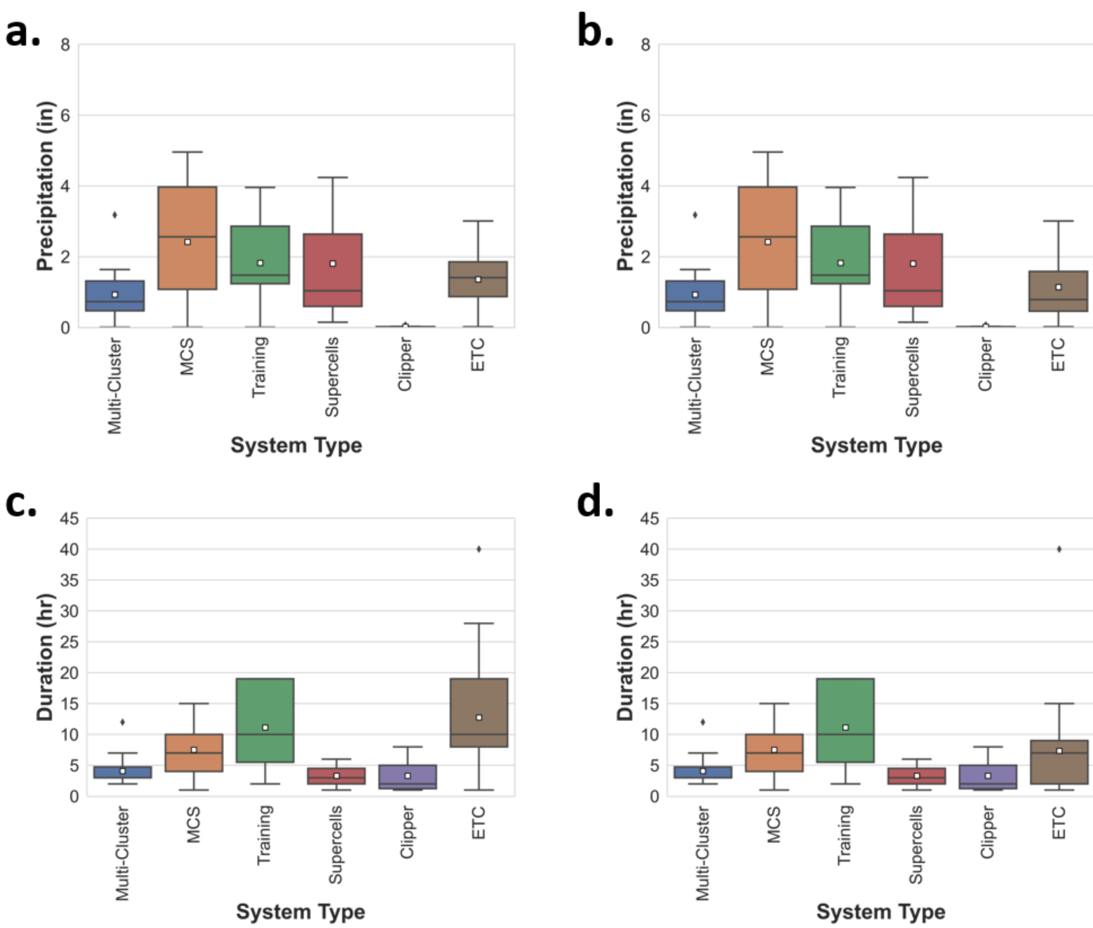

Figure 4.44. *Box and whisker plots of precipitation totals (inches) per water obstruction event by each obstruction's respective system type (a) with March 2019 and (b) without March 2019, along with system type duration (hours) (c) with March 2019 and (d) without March 2019 from 2016-2021.*

4.4.3 Palmer Indices

It has been mentioned previously there are likely precursor conditions, especially for groundwater water obstruction scenarios, that attribute to water obstructions occurring when precipitation totals are perceived to be on the lower end of the spectrum. PHDI anomalies were investigated for this portion of the analysis due to its correlation with groundwater levels and its 0.96 positive statistically significant correlation with the PDSI. Whether including or excluding March 2019, PHDI anomalies in the previous month and during the month of the water obstruction for most water obstructions show that approximately three-quarters of water obstructions in the study period are above 4.0 PHDI, which is considered an extremely moist condition (Figures 4.45a and b, 4.46a and b). There are only two water obstructions that have a PHDI value in the previous month below -1.0, both of which occur in 2021. One of these water obstructions is due to ice jamming, and the other is due to short-duration precipitation, which results in almost 2.0 inches of rain in 4 hours. There are no PHDI values below -2.0 associated with a water obstruction in the study period, a value below -2.0 would be considered some degree of drought. With a high number of obstructions associated with high PHDI precursor conditions and within months when PHDI values are extremely wet, the PHDI anomalies are well above normal for the majority of these water obstructions. A high percentage of water obstructions having precursor and current month PHDI rankings are in the top 20 and even top 10 wettest in the climatological record (Figures 4.45d, c, e, and f, 4.46d, c, e, and f). This is especially true for groundwater scenarios, as 69% of water obstructions induced by groundwater had precursor PHDI values above 4.0 and rankings in the top 10 wettest. In all groundwater water obstruction scenarios, groundwater level percentiles have at least been in the top 70th percentile. In 20 of the groundwater water obstructions, groundwater levels are in the top 98th percentile. Therefore, when considering these precursor PHDI, PDSI, and groundwater levels in

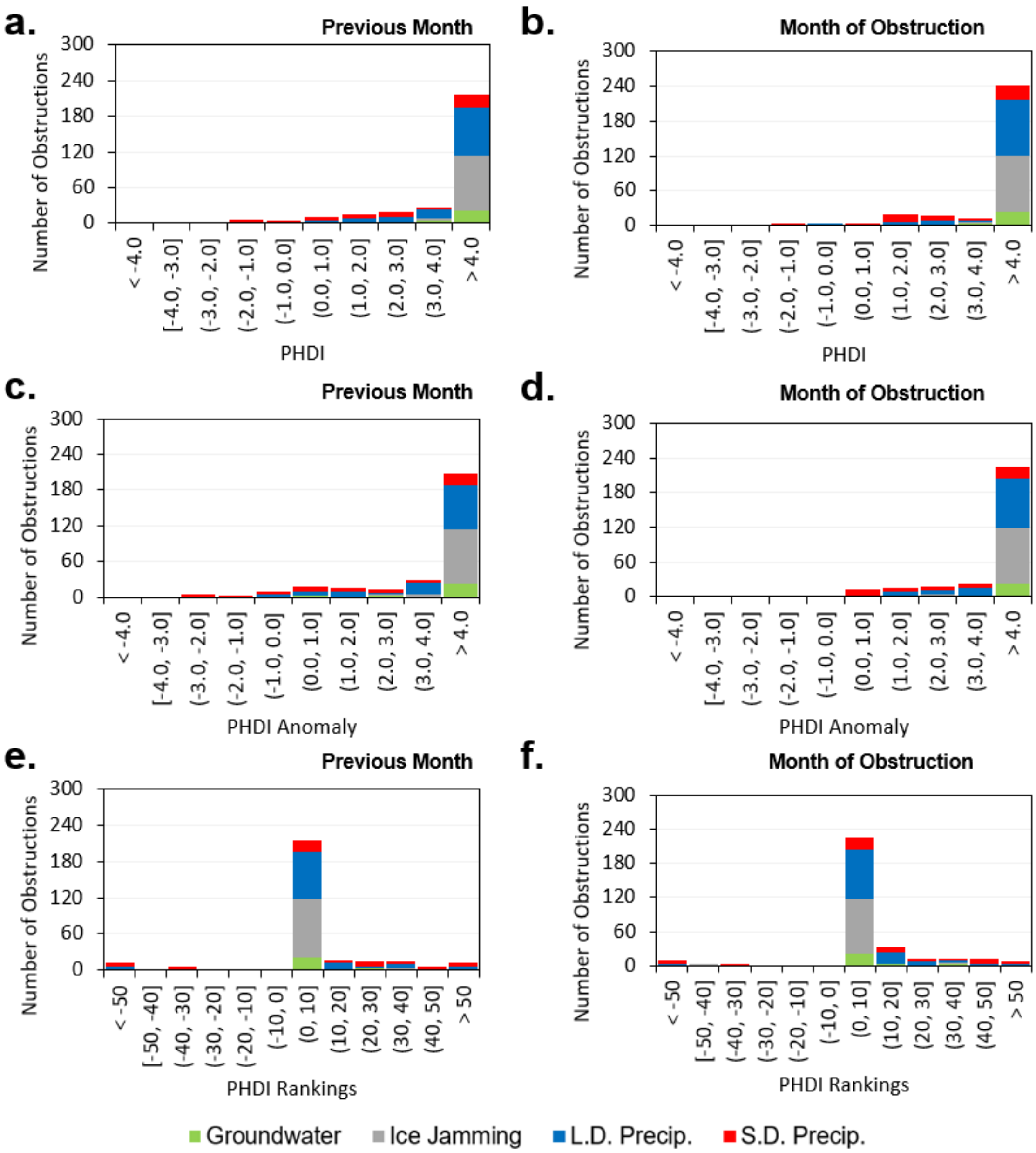

Figure 4.45. *PHDI data for the previous month with respect to the month when the water obstruction occurred by root weather-related cause as shown by (a) and (b) precipitation totals, (c) and (d) precipitation anomalies (1900-2000 base period), (e) and (f) precipitation rankings where the negative values signify dry years (-1 being the driest) and positive values being the wet years (1 being the wettest). Water obstruction data from 2016-2021.*

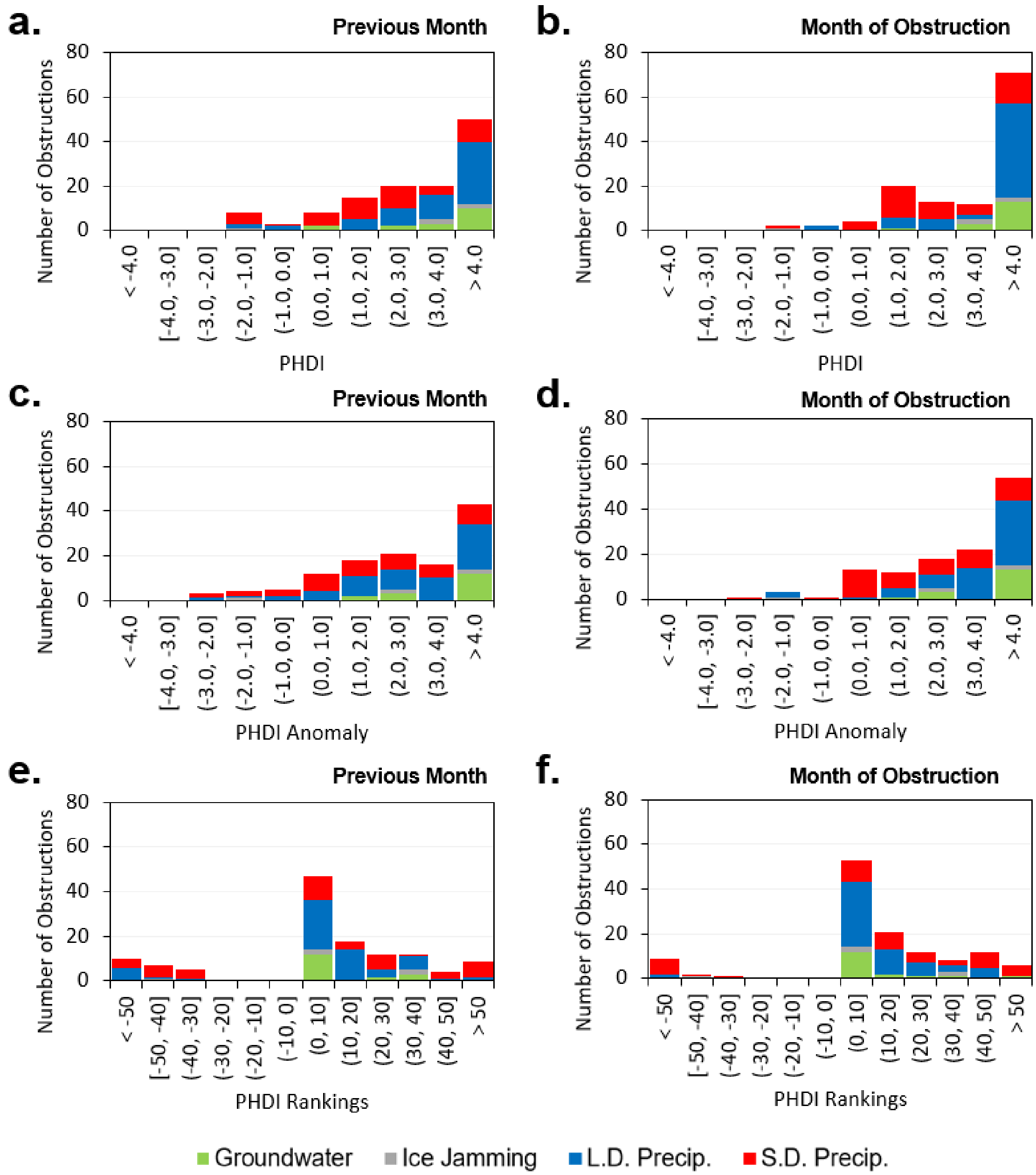

Figure 4.46. *PHDI data for the previous month with respect to the month when the water obstruction occurred by root weather-related cause as shown by (a) and (b) precipitation totals, (c) and (d) precipitation anomalies (1900-2000 base period), (e) and (f) precipitation rankings where the negative values signify dry years (-1 being the driest) and positive values being the wet years (1 being the wettest). Water obstruction data from 2016-2021 excluding March 2019.*

association with groundwater and other water obstructions, precipitation totals do not necessarily need to have a reoccurrence interval flagged by the NOAA Atlas 14 be greater than 1-year to induce a water obstruction. For example, in the 91 cases when the precipitation associated with the water obstruction is less than one inch, 85% of these cases have precursor PHDI/PDSI values above 2.0, which signifies some degree of moisture surplus. In the 203 cases with reoccurrence intervals less than 1-year by the NOAA Atlas 14, 91% have precursor PDSI/PHDI values above 2.0.

4.4.4 Water Gage Data

In addition to evaluating precipitation totals and Palmer Indices prior to the occurrence of a water obstruction, available water gage data needs to be investigated to understand water level and discharge characteristics in the onset of a water obstruction. Though, it needs to be stated that discharge characteristics, and thus discharge departures, are highly dependent on the stream size, which then may impact the results herein. It has been noted previously that 68% of water obstructions for June 2016 to August 2021 occur along or near a river and are potentially impacted by river flooding. The monthly average departures from the daily median water gage heights and discharge values follow a similar pattern to the monthly occurrence of water obstructions (Figure 4.47a and b). In other words, at the time when a water obstruction is occurring, the water gage height and water discharge levels are above normal the most during the early spring and summer, coinciding with peak water obstruction occurrence and peak rainfall totals climatologically. When excluding March 2019, water gage levels tend to have the greatest departures from the daily median in May, June, and July when the average departures are at least 6 feet above normal. In the same pattern, average water gage discharge departure peaks during these same months when averages are above 5000 feet^3 per second (Figure 4.47c and d). When examining these water gage levels and discharge departures by root weather-related cause, water

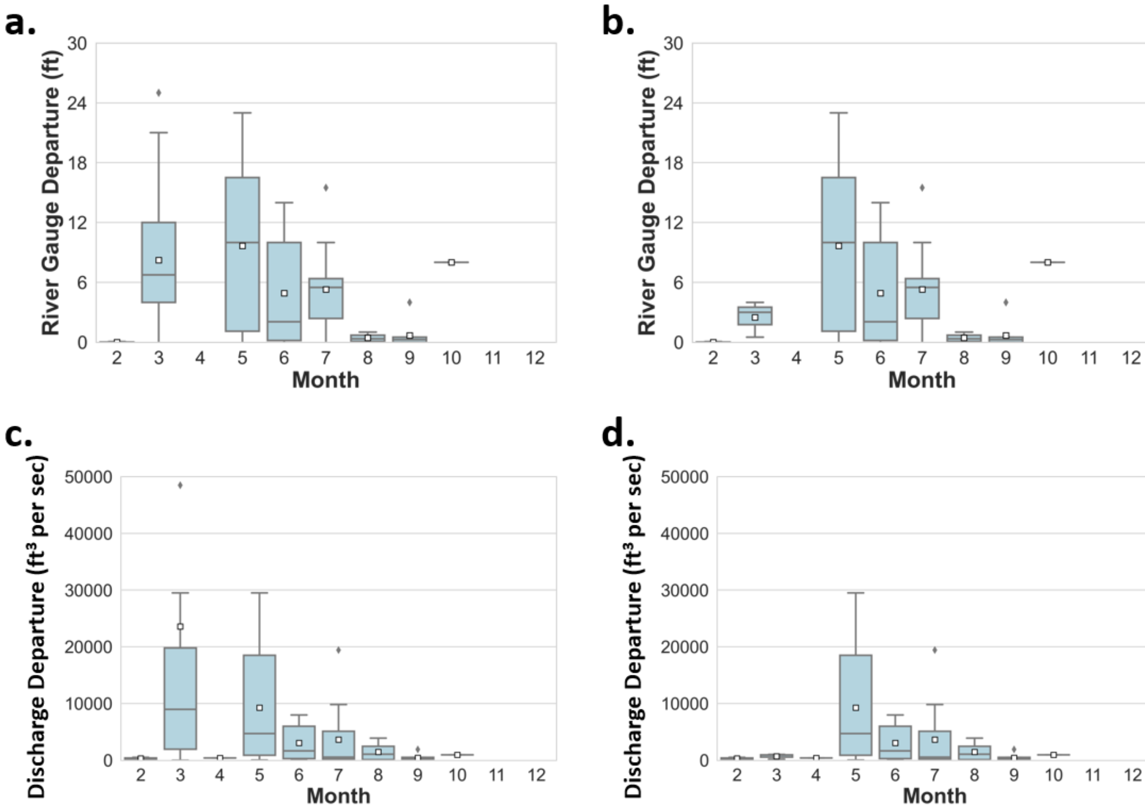

Figure 4.47. *Box and whisker plots of water gage departures from the 40-year respective daily medians by month a) water height departure (ft) (2016-2021); b) same as (a) excluding March 2019; c) water discharge departure (ft3 per sec) (2016-2021); d) same as (c) without March 2019. January not included in this plot due to no water obstructions occurring.*

obstructions associated with long-duration precipitation have the highest averages with seven feet above normal and 6000 $feet^3$ per second above normal without March 2019 (Figure 4.48). This is likely attributed to long-duration precipitation producing more rainfall on average in conjunction with snowmelt acting to increase runoff, consequently, creating higher water levels and water discharge than other weather-related causes. When March 2019 is included in the dataset, the skew is evident in that ice jamming water level average departures exceeded

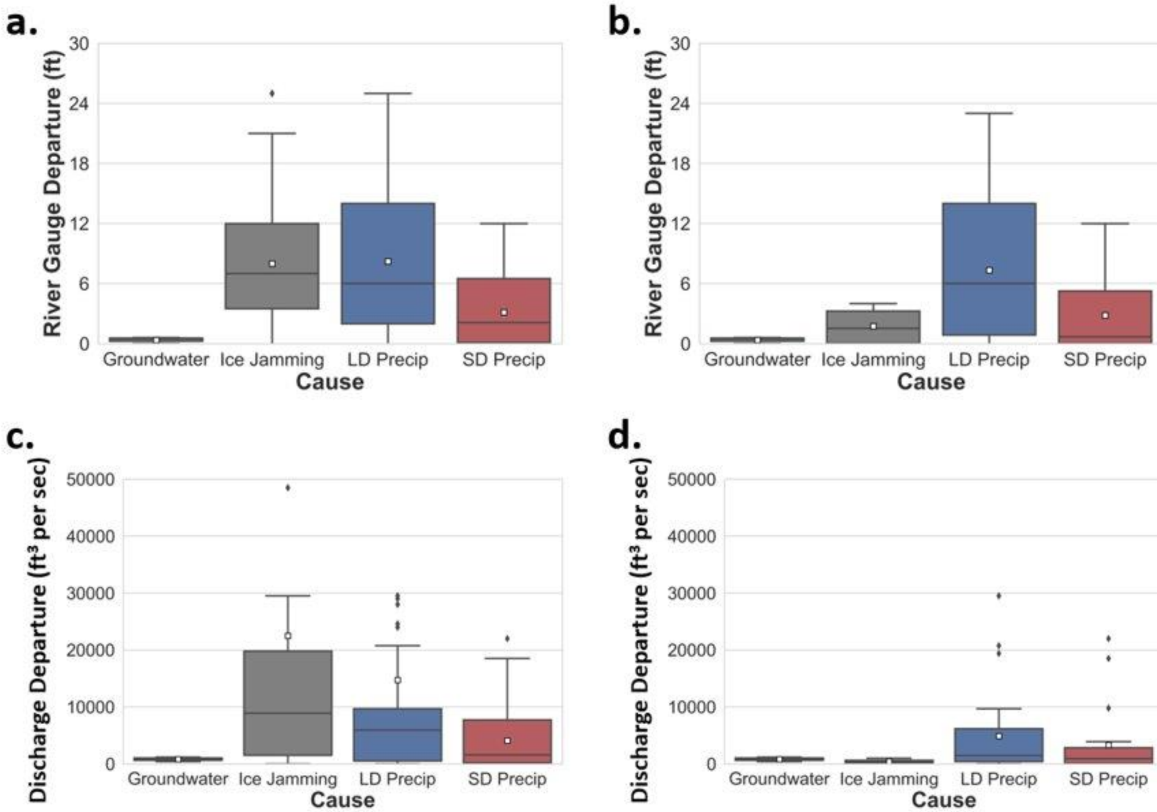

Figure 4.48. *Box and whisker plots of water gage departures from the 40-year respective daily medians by root weather-related cause a) water height departure (ft) (2016-2021); b) same as (a) but without March 2019; c) water discharge departure (ft^3 per sec) (2016-2021); d) same as (c) without March 2019.*

long-duration precipitation for average discharge departure. When March 2019 is removed, the averages for ice jamming decrease to a water level of three feet above normal.

The caveat with using these data is that in a large portion of the water obstructions associated with a river, the stream gage data are not within five miles of the water obstruction. Therefore, averages presented in this analysis may be underestimated. From a forecasting perspective, water levels and discharge generally display the same characteristics in terms of how they increase in values with time prior to the water obstruction occurring. In two cases, one being from ice jamming (Figure 4.49a and b) and the another being from long-duration precipitation (Figure 4.49c and d), water gage levels gradually rose along with water discharge hours prior to the water obstruction, and the water obstructions occurs just after the peak of the water height and discharge. Therefore, this kind of analysis can be utilized by NDOT in the potential onset of a water obstruction in order to increase the predictability of these obstructions, especially in locations along rivers that flood frequently.

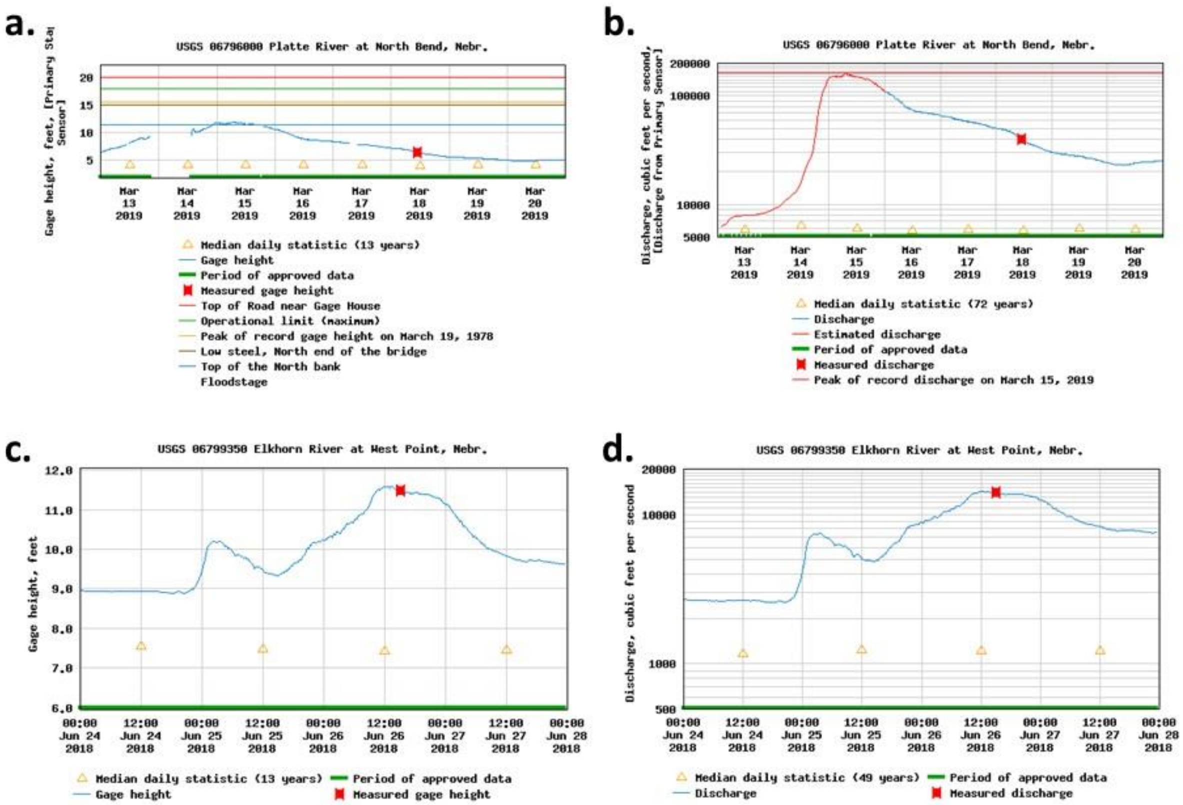

Figure 4.49. *Water gage information through time with respect to the water obstruction occurrence for 2 cases: a) gage height and b) discharge for ice jamming along the Platte River on March 14, 2019; and c) gage height and d) discharge for long-duration precipitation along the Elkhorn River on June 26, 2018 (Source: USGS 2022).*

4.4.5 National Weather Service Information

The final component to this research, and what can potentially be another form of mitigation action, is the communication with the National Weather Service (NWS) in order to proactively prepare for the onset of potential water obstructions. Therefore, analysis is completed to also understand NWS information available during these obstruction events. In other words, are there weather advisories ongoing prior to water obstruction occurring? In total, 77% of all water obstructions during the period either have a Flood or Flash Flood Watch/Advisory issued before the obstruction occurs, while 5% of the water obstructions do not have a Watch/Advisory issued until after the obstruction and 18% do not have any Watch/Advisory associated with the obstruction (Table 4.8). Without March 2019 in the dataset, these numbers shift to 50% of water obstructions having a Watch/Advisory issued beforehand while 50% do not. In 42% of the cases, without March 2019, there is no Watch/Advisory issued at all, thus only 8% have something in effect after the water obstruction took place.

Table 4.8 *National Weather Service Flood and Flash Flood Watch, Advisory, and Warning count per weather-related cause (2016-2021). Bracketed values are of the study period excluding March 2019.*

	NWS Advisories/Watches				NWS Warnings	
	Before obstruction	During obstruction	After obstruction	None issued	Warnings issued	No warnings
Groundwater	7 [4]	5 [0]	0 [0]	17 [15]	5 [0]	24 [19]
Ice Jamming	36 [1]	58 [1]	1 [0]	4 [4]	89 [1]	10 [4]
LD Precipitation	39 [17]	56 [20]	6 [6]	13 [13]	96 [45]	18 [11]
SD Precipitation	10 [10]	18 [8]	8 [8]	20 [20]	38 [30]	18 [16]
Total	92 [33]	137 [29]	15 [14]	54 [52]	228 [76]	70 [50]

Groundwater and ice jam water obstructions have the highest percentage of obstructions without a Watch/Advisory issued by the NWS. For groundwater, four of the 23 water obstructions (excluding March 2019) have an NWS Watch/Advisory issued beforehand; however, it expires prior to the water obstruction occurring. Thus, there are no NWS Watches/Advisories before a groundwater water obstruction, which again, occur generally in District 8 where the responsible office is the NWS North Platte CWA. In addition, there are no Flood or Flash Flood Warnings during any of the groundwater water obstructions. This is likely due to the complexity of groundwater water obstructions, in that these events do not need noteworthy amounts of precipitation to cause an obstruction and the precipitation does not need to occur in close time with the obstruction. In addition, the precipitation to initiate these events do not typically occur within the same day as the water obstruction. The same is true for ice jamming water obstructions, excluding March 2019, where three of the five obstructions did not have any Watch/Advisory or Warning issued with the ice jamming, all of which occurred in the NWS Omaha/Valley CWA.

Long-duration precipitation water obstructions are the best forecasted out of all obstruction causes, where only 34% of the water obstructions do not have any association to a Watch/Advisory, and only 20% do not have a current Warning. However, the opposite is true for short-duration precipitation water obstructions, as 61% of these obstructions do not have a Watch/Advisory, and only 35% do not have a Warning tagged along with the obstruction.

Watches/Advisories and Warnings can also be examined by system type (Table 4.9). Overall, multi-cell clusters and supercells have the highest percentage of obstructions where a Flood or Flash Flood Watch/Advisory and Warning is not issued. This may be attributed to these systems having other Watches and Warnings tagged along with them including a Severe Thunderstorm Watch/Warning or Tornado Watch/Warning. Just over 50% of MCS cases also do

Table 4.9. *National Weather Service Flood and Flash Flood Watch, Advisory, and Warning count per storm type (2016-2021).*

	NWS Advisories/Watches				NWS Warnings	
	Before obstruction	During obstruction	After obstruction	None issued	Warnings issued	No warnings
Multi-Cluster	2	2	2	8	7	7
MCS	14	6	4	17	28	13
Training	4	18	3	10	29	6
Supercells	0	1	1	1	2	1
Clipper	0	0	0	6	1	5
ETC	69	108	5	13	161	34
Total	89	135	15	55	228	66

not have a Watch/Warning, likely due to the same reasonings. Climatologically, MCSs, multi-cell clusters, supercells, and convective training events all typically occur in summer, which attributes to these months having the highest rainfall totals on an annual basis and are known to cause water obstruction issues. During the winter season, ETCs, Colorado Lows, and Alberta-Clipper systems tend to be the systems that occur most in the winter months. The Alberta-Clipper systems also have a large percentage of obstructions when there is no Watch/Advisory or Warning, likely due to these storms producing snowfall, and the small liquid equivalent does not typically cause flooding.

Over the study period, the percentage of water obstructions that do not have an NWS Watch/Advisory and Warning until after the water obstruction takes place or no watch or warning is issued at all tends to vary throughout the year (Figure 4.50). The late-fall through mid-spring tends to have the highest percentage of water obstructions that do not have any Watch/Advisory or Warning, except for March 2019. From April through August, the number of

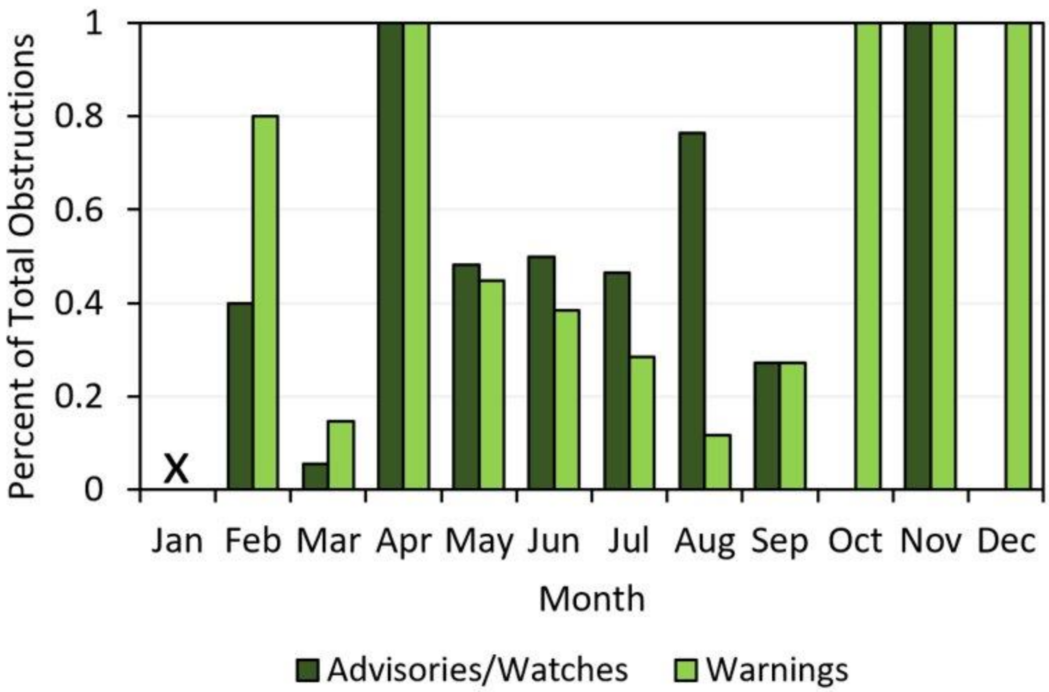

Figure 4.50. *Percent of total obstructions by month that did not have a National Weather Service Watch/Advisory or Warning until after the water obstruction occurred or none issued at all (2016-2021). Months with X's denote 0 obstructions occurred.*

Water obstructions unwarned by the NWS decreases, while the number of water obstructions that do not have any Watch/Advisory increases. This is likely attributed to when the system types have occurred over the past five years. It is still worth noting there are several water obstructions occurring certain times of the year that may not have an NWS Watch/Advisory or Warning tagged along with it. Therefore, it is important to recognize there may not always be an NWS Watch/Advisory tagged with every onset of a potential water obstruction. Public information regarding the potential for water over a roadway may not always be available and is especially true for groundwater water obstructions. This can create a hazardous situation for drivers if it is unknown to them when water is over a payment until they approach the situation and consequently having to make the decision to turnaround or proceed. Therefore, to improve the issuance of this information, the use of additional data including the water obstruction spatiotemporal climatology to understand when and where water obstructions have occurred historically, knowing the precursor soil moisture and groundwater conditions, knowing the quantitative precipitation forecasts (QPFs) along with the system type and precipitation mode, and knowing the river water gage levels may all act to further the predictability of water obstructions. Having all this information at hand will help to proactively prepare for potential water obstructions in all NDOT districts.

4.5 Top Water Obstructions Locations

The top water obstruction locations are derived by examining several factors, including high-density clustering of water obstructions confirmed by the actual number of obstructions over the past five years, how these water obstructions differ when March 2019 is removed from the dataset, and meteorological and climatological factors that may increase the vulnerability and likelihood of a water obstruction occurring.

4.5.1 NE 5 in Thayer County, Nebraska

Obstructions in Thayer County (District 4) are caused by ice jamming, long-duration precipitation, and short-duration precipitation obstructions (Figure 4.51). Of the seven water obstructions that occur along N 5 in Thayer County, five of them occur in 2019 with only two associated with the historical March 2019 flooding event. Obstructions along this roadway occur in three of the six calendar years examined in this study period, though the only ice jamming event along this roadway is associated with March 2019. Otherwise, this roadway has been prone to both long- and short-duration precipitation obstructions over the past five years. All obstructions, except for the one that occurred in 2017, has an NWS Flood or Flash Flood Watch in place prior to the obstruction occurring. Following guidance from the line density analysis, the primary hotspot where water obstruction segments overlap is on the Little Blue River. In six of

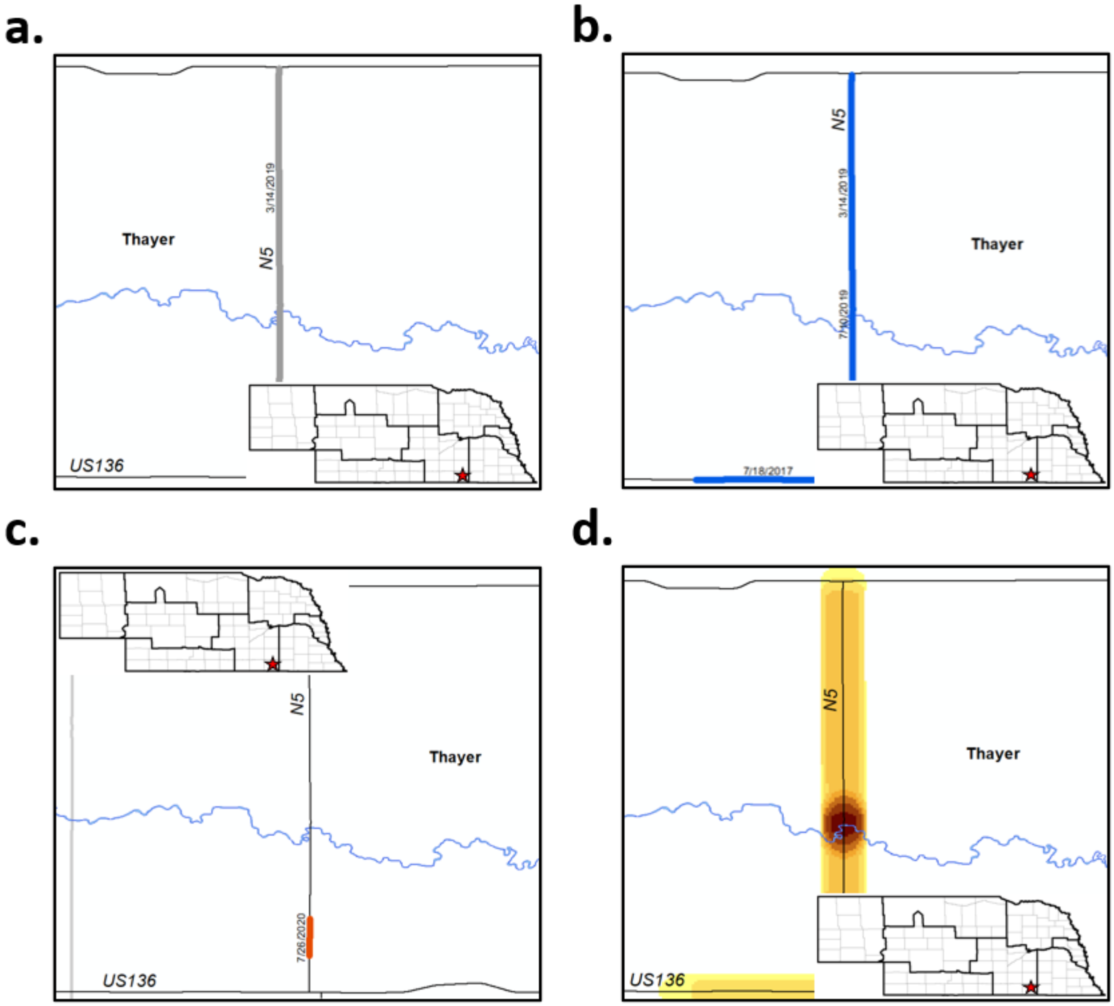

Figure 4.51. *Roadway water obstruction segments caused by (a) ice jamming, (b) long-duration precipitation, (c) short-duration precipitation, and (d) line density analysis results where the darker color represents a higher clustering of obstructions (2016-2021).*

The seven water obstruction cases, Little Blue River water gage levels are above the daily median water height number by 6.0 feet on average, and discharge numbers were 6600 feet^3 per second. The reference postings for five of the seven obstructions on this roadway have the Little Blue River as the flooded area (between mile marker 4 and 5, and from 1 to 11). Precursor soil moisture conditions are also on the wetter side with PDSI anomalies 3.0 units above normal. With these precursor soil moisture conditions, it likely will not take high amounts of rainfall to cause flooding. In fact, only two of the seven obstructions along NE 5 are noted in the NOAA Atlas 14 (NOAA 2008) as having a significant reoccurrence interval. July 2017 had a 1-year flood with the event accumulation being 1.54 inches of rain in 8 hours, and July 2020 had a 10-year flood with 3.76 inches of rain in five hours. Neither of these events resulted in a roadway closure. Roadway closures are associated with the March 2019 historical precipitation event, and an MCS is associated with May and July 2019 long-duration precipitation events.

4.5.2 US 183 in Rock County, Nebraska

Except for one long-duration precipitation water obstruction located more northward of the hotspot, US 183 in Rock County has experienced groundwater flooding between mile markers 153 and 163 on six separate occasions (Figure 4.52). Five of the six groundwater events are in 2019, with only one of them being associated with the March 2019 flooding event. Only one of these obstructions caused the segment of the roadway to be closed (February 2020), otherwise it was just lane closures. Water obstructions on this roadway are typically caused by precipitation that happens 1–3 days in advance with precipitation totals of less than 0.5 inches, perhaps providing an explanation as to why only two of the obstructions along this roadway have NWS Flash Flood or Flood Watch in place. Both obstructions are due to the March 2019 precipitation event. The key with water obstructions caused by groundwater is the precursor PHDI anomalies, as in for all groundwater water obstruction cases on this roadway, precursor PHDI rankings are in the top five wettest of all time with anomalies averaging near 8.0 units above normal. In terms of the timing, late summer, winter, and early spring all have groundwater obstructions along US 183. While the likelihood of water obstructions closing this roadway have been low over the past five years, if precursor soil moisture or groundwater anomalies are above normal, even low amounts of precipitation (e.g, < 0.5 inches) can continue to cause obstructions on this road in the future.

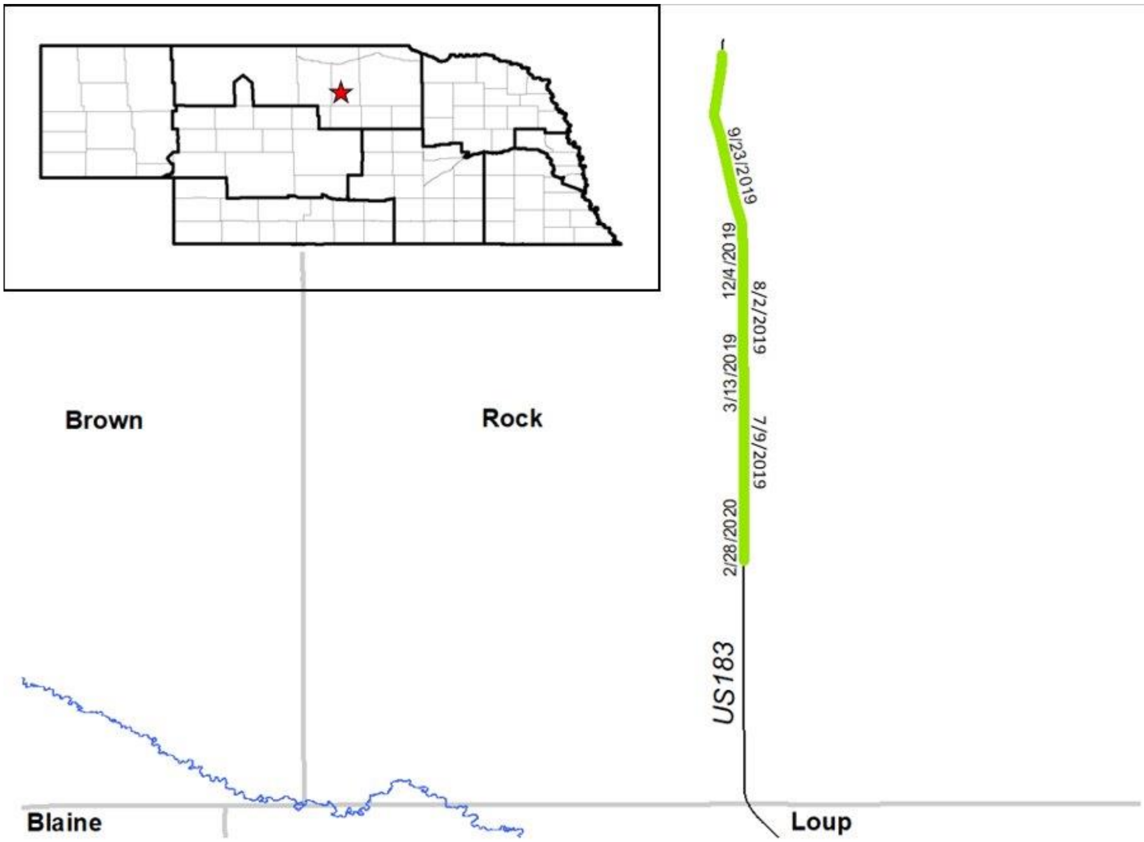

Figure 4.52. *Groundwater water obstruction road segments with date of the obstruction (2016-2021).*

4.5.3 US 275 in Cuming and Dodge County, Nebraska

US 275 in Cuming County along the Elkhorn River is another location where water obstructions have occurred more frequently during the study period (Figure 4.53). Obstructions occur in three of the six calendar years in this study as they did not occur in 2017, 2020, or 2021 at this location. They occur in June and September 2016, June 2018, and the rest are in March 2019. March 2019 is the only period when ice jamming along the Elkhorn River in Cuming County causes water to obstruct the roadway. More frequently, long-duration and short-duration precipitation causes obstructions at this location. Specifically, the area with the highest clustering of water obstructions is south of the intersection of US 275 and NE 32 located in

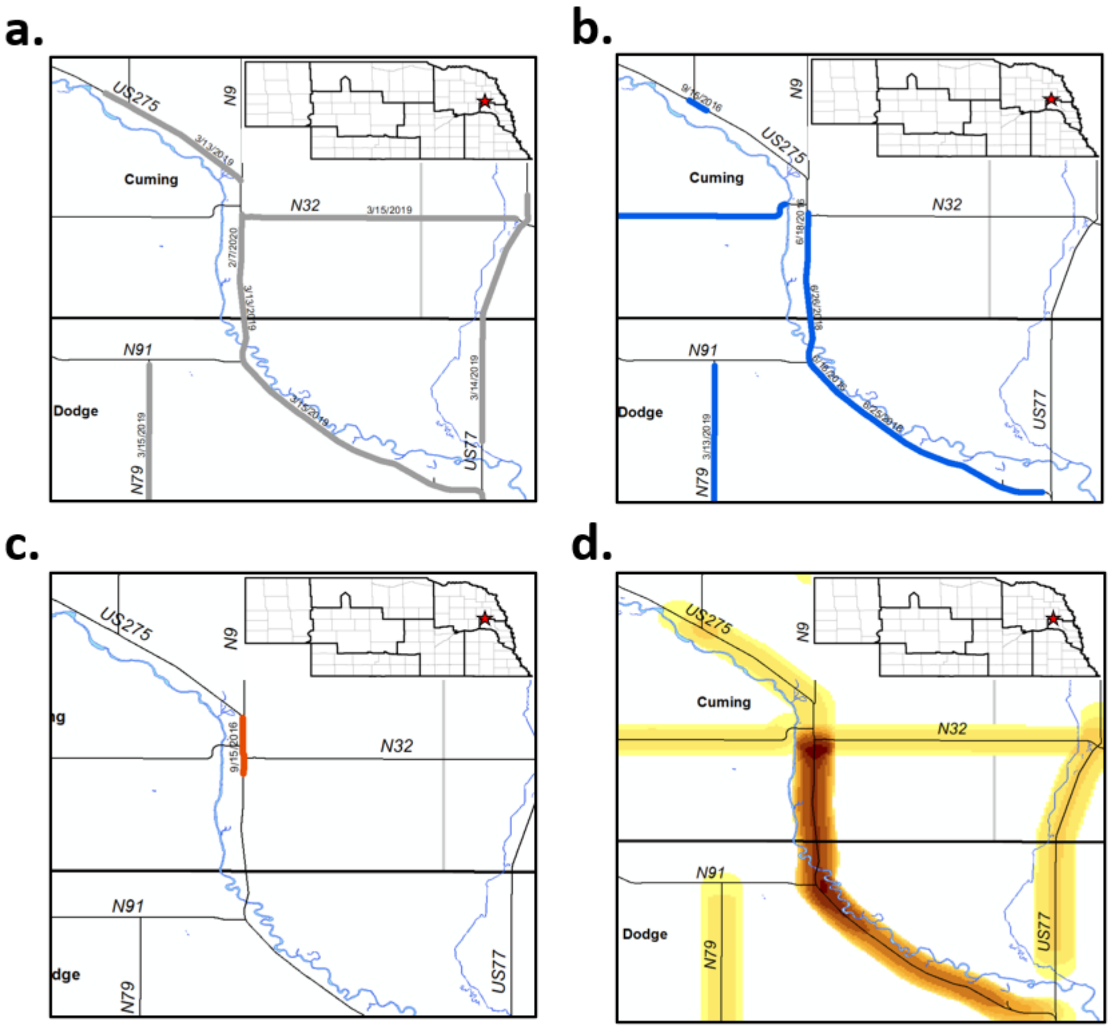

Figure 4.53. *Roadway water obstruction segments caused by (a) ice jamming, (b) long-duration precipitation, (c) short-duration precipitation, and (d) line density analysis results where the darker color represents a higher clustering of obstructions (2016-2021).*

West Point, Nebraska. Every event, except for the June 2016 obstruction, has a Flash Flood or Flood Watch along with a Flash Flood Warning in place prior to the water obstruction taking place along US 275 in Cuming County. The only time when river levels are above the USGS flood stage when an obstruction is taking place is in March 2019. Otherwise, river levels are not quite at flood stage, though they are at least one foot above the median water level and are well above the median discharge. Outside of March 2019, soil moisture anomalies prior to each of the other five obstructions along this roadway are also well above normal as PDSI rankings were in the top 25 wettest of all time. Two of the obstructions were associated with 10-year floods (3.1 inches of rain in 6 hours), while the other events do not have significant enough precipitation to be considered for a reoccurrence interval in the NOAA Atlas 14. Given this is a location where, climatologically, ice jams have occurred over the past 30 years and where some of the highest precipitation totals annually are located, this might be an area to investigate for mitigation efforts. The obstruction issue continues further south, along US 275 into Dodge County, where the roadway is even closer to the Elkhorn River in some areas (Figure 4.53). Only one obstruction along this roadway in Dodge County is attributed to March 2019, otherwise each year except 2017 and 2021 has at least one obstruction. All five obstructions along this roadway result in a segment closure of the roadway. These segments include mile markers 127 to 130 (occurred twice), 118 to 140 (occurred twice), and 118 to 127 (ice jamming in February 2020). The February 2020 ice jamming is the only obstruction to not have an NWS Watch/Advisory/Warning ongoing or occurring before the obstruction along US 275 in Dodge County.

4.5.4 US 136 in Nemaha County, Nebraska

The final area to be examined as a high-frequent water obstruction location is along US 136 in Nemaha County between mile markers 230 and 241 (Figure 4.54). Over the five study period years, obstructions have only occurred in one year, and that was 2019. However, it was on three separate events including the March 2019 historical flooding event, May 2019 extreme precipitation, and in June of 2019. Notably, all these obstructions did result in a full road closure. Ice jamming, short-duration precipitation, and long-duration precipitation obstructions have all occurred over the Little Nemaha River. Discharge and water level departures from the daily medians were much above normal on all obstruction occasions. In terms of NWS

Watches/Advisories/Warnings, four of the five obstructions did have a Flood or Flash Flood Watch and Flash Flood Warning before or during the obstruction. Since these obstructions are over the Little Nemaha River, there is high confidence this is the source for these obstructions. When combined with the climatology of precipitation in southeast Nebraska, this area is at a greater risk for water obstructions and should be further examined.

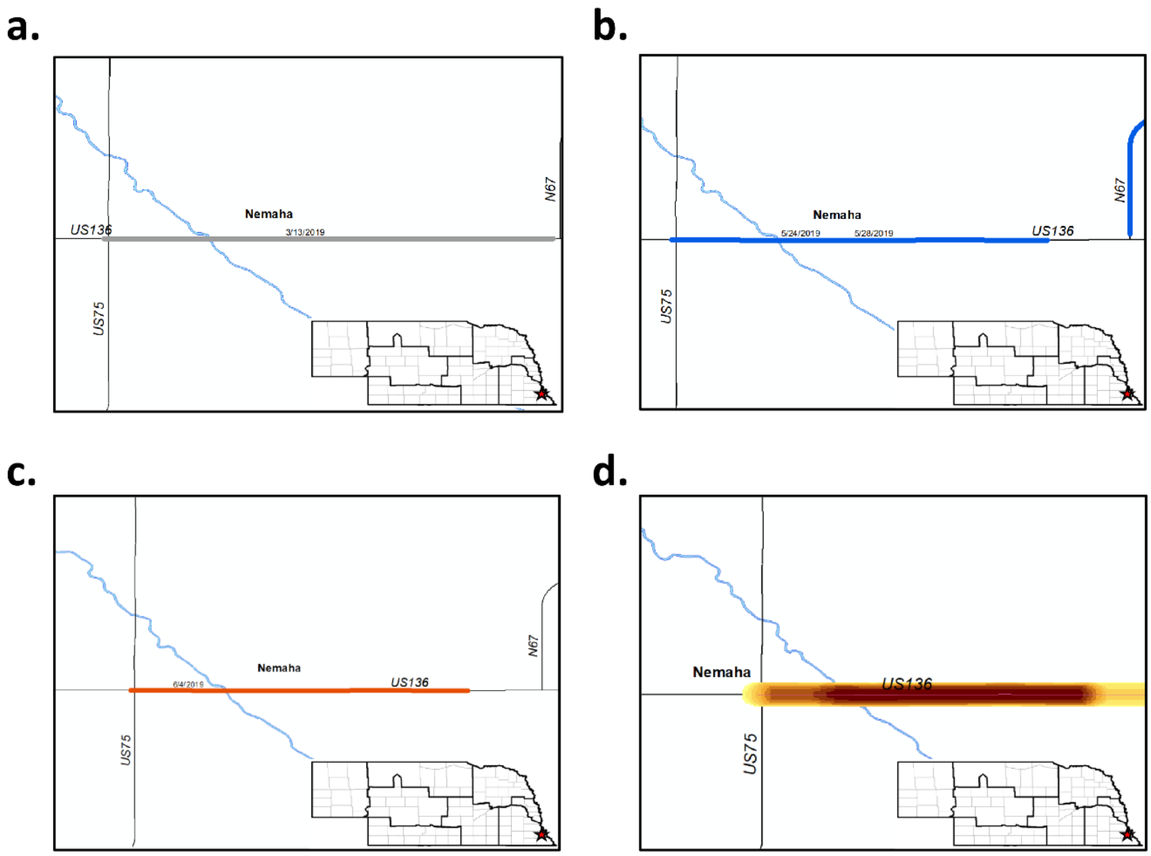

Figure 4.54. *Roadway water obstruction segments caused by (a) ice jamming, (b) long-duration precipitation, (c) short-duration precipitation, and (d) line density analysis results where the darker color represents a higher clustering of obstructions (2016-2021).*

4.5.5 Other High-Frequent Water Obstruction Locations

In addition to the five high-frequent water obstruction locations already examined, there are more locations (albeit a lower obstruction frequency) to be noted. While the details regarding these locations will not be discussed in depth, they will certainly be noted and could be also further explored along with the first five locations (Table 4.10). The following are the next five locations and brief summaries:

- NE 74 in Adams County between mile markers 13-14, 18-20, 29-31 in southern Nebraska. The primary source or nearest waterbody that may be impacting the water obstructions between mile markers 13 and 14 is the Scott Creek, while between markers 18 and 20 is uncertain, and between markers 29 and 31 is the Little Blue River. Obstructions at these locations were from three different events including March 2019 historical flooding, July 2019 extreme precipitation, and May 2020 single obstruction event. Four of the five obstructions at these locations resulted in at least a single lane closure and all obstructions were caused by long- or short-duration precipitation events.
- US 20 in Pierce County between mile markers 361 and 368 in northern Nebraska. On this roadway between these mile markers, all causes except for ice jamming have occurred on four separate occasions in three different years. Two of the four obstructions at this location resulted in a full road closure.
- US 6 in Lancaster County between mile markers 303 and 308 in southeastern Nebraska. Middle Creek is the primary source for these obstructions. Long- and short-duration precipitation events have occurred in total on four separate occasions, though, none of those obstructions resulted in a lane or full road closure.
- NE 9 in Thurston County between mile markers 15 and 21. The Logan Creek Dredge in northeastern Nebraska. The March 2019 historical flooding event and the June 2016

Table 4.10. *Top ten water obstruction locations within the study period (2016-2021) in Nebraska.*

High-Frequent Water Obstruction Location	River Association	Total Obstructions	Total Obstructions (w/o March 2019)	Groundwater	Ice Jamming	L.D. Precip	S.D. Precip	Number of Years Obstructed
NE 5 in Thayer County between mile markers 4 and 5	Little Blue	7	5		1	5	1	3
US 183 in Rock County between miles markers 154 and 164	N/A	7	5	6		1		2
US 275 in Cuming County between mile markers 118 and 124	Elkhorn	7	4		3	3	1	3
US 275 in Dodge County between mile markers 125 and 128	Elkhorn	5	4		2	3		4
US 136 in Nemaha County between mile markers 230 and 241	Little Nemaha	5	3		2	2	1	1
NE 74 in Adams County between mile markers 13-14, 18-20, 29-31	Scott Creek, Little Blue	5	4			4	1	2
US 20 in Pierce County between mile markers 361 and 368	N/A	4	3	1		1	1	3
US 6 in Lancaster County between mile markers 303 and 308	Middle Creek	4	3			2	2	2
NE 9 in Thurston County between mile markers 18 and 21	Logan Creek Dredge	3	2			3		2
NE 61 in Cherry County between miles markers 171 and 172	N/A	3	3	3				2

excess precipitation event were the only events to cause three total obstructions at this location, though, all obstructions resulted in a closure. Long-duration precipitation has been the primary cause for these obstructions, though, ice jamming and short-duration precipitation events have occurred on multiple occasions at nearby locations, especially further south on NE 9 and on NE 94.

- NE 61 in Cherry County between mile markers 171 and 172 in northern Nebraska. At this location, three groundwater flooding obstructions occurred on three separate occasions in two of the five years studied. This location, alongside the aforementioned US 183 location are at the top in terms of groundwater water obstructions.

5 Summary and Conclusions

Impacts to the transportation sector by weather-related hazards can be substantial, especially within the context of a changing climate which may result in more extreme precipitation events. Precipitation, ice jamming, and groundwater are the primary weather-related causes for water obstructions on state and federal highways in Nebraska. For Nebraska specifically, the surface transportation is the backbone of the state's economy. Thus, with an increasing interest in analyzing water obstructions due to the significant direct and indirect impacts to society, the main goals for this study were to use the CARS511 dataset to further the understanding of where water obstructions occur, when they occur, and why (meteorologically) they occur. In addition, this research sought to understand how closely related water obstructions are to climate patterns in Nebraska. With that, this research highlights five main findings:

- Temporally, water obstructions occur during each year of the dataset (2016–2021), while summer has the greatest number of water obstructions in a given year. Long- and short-duration precipitation are the most common causes of water obstructions in the spring, summer, and fall, while ice jamming and groundwater are the most common causes of water obstructions in the winter.
- Spatially, long- and short-duration precipitation obstructions occur the most in District 4, ice jamming obstructions in District 3, and groundwater obstructions in District 8. When excluding March 2019 from the dataset, Districts 3 and 8 are the only districts to experience all four weather-related causes for water obstructions, while District 7 tends to only experience short-duration precipitation obstructions. An important note is that all districts can experience any type of weather-related cause for water obstructions if the necessary meteorological and/or precursor conditions are present.

- Meteorologically, long-duration precipitation tends to produce the most water obstructions with 2.40 inches on average of rainfall, while short-duration precipitation produces 1.50 inches on average. The dominant precipitation mode for precipitation obstructions is convective and in the form of an MCS or convective training followed by the duration of the event. Groundwater and ice jamming obstructions do not need these precipitation totals to occur in order for obstructions to occur, as precursor PHDI anomalies for groundwater and precursor river ice conditions and temperature swings for ice jamming are more important factors.
- In terms of precipitation timing, the long- or short-duration obstructions tends to have precipitation occurring very near to the time of the obstruction while precipitation that induces groundwater obstructions tends to occur within the three to seven days prior to a water obstruction, which makes the predictability of these events difficult.
- Climatologically, water obstructions during the study period tend to follow the spatial ranking patterns of the 30-year average precipitation and Palmer Indices values in terms of where groundwater obstructions occur. This also holds true for the monthly/seasonal climatological variables and respective water obstructions and the root weather-related cause.

These findings were then used to aid in the process of determining the top-five water obstruction locations in Nebraska based on the 5-year study period. These locations generally displayed a high kernel density of water obstructions occurring when compared to other locations, these locations also have obstructions in almost all the years examined in this study, and these locations climatologically have an increased susceptibility to being obstructed given meteorological averages and trends. These locations are as follows (in no particular order):

- NE 5 in Thayer County between mile markers 4 and 5 over the Little Blue River.

- US 183 in Rock County between mile markers 154 and 164.
- US 275 in Cuming County between mile markers 118 and 124 along the Elkhorn River south of West Point, Nebraska.
- US 275 in Dodge County between mile markers 125 and 128 along the Elkhorn River.
- US 136 in Nemaha County between mile markers 230 and 241 along the Little Nemaha River.
- Other locations in the top ten high-frequent water obstruction list including locations on NE 74, US 20, US 6, NE 9, and NE 61.

As noted, there are areas where it is possible to mitigate traffic disruptions by implementing structural or non-structural mitigation strategies, including deeper ditches, installation or maintenance of culverts, increased signage, raising the roadway, etc. In addition, there is also a proactive and empirical forecasting approach to better understand the probability of potential water obstruction situations based on this research. When precipitation is imminent for a given area, it is important to examine what the water obstruction climatology is for the area. In other words, assessing what kind of water obstructions have occurred in this area, what time of year do they occur, which specific roadways are involved, and the specific location of where historical obstructions is essential to understand potential locations that may be at a higher risk. Next, informing what current NWS Watches/Advisories are active and how this compares to when they have been active or not in place in previous water obstruction scenarios. In addition, assessing the kind of system producing the precipitation mode amount issued by the NWS is critical in getting a sense of what the probability of a water obstruction might be, and where that water obstruction may occur. Furthermore, real-time monitoring of water gage levels at locations where impacts are higher in probability will also aid in informing the probability of a water obstruction occurring. Finally, an assessment of precursor soil moisture and groundwater levels using Palmer Indices or other tools is necessary given water obstructions have occurred in the past even when precipitation totals did not surmount to what may be perceived as substantial. The combination of these assessments enacts for a more proactive approach when forecasting the probability of a potential water obstruction occurring at any given location.

While the research provided in-depth analyses on water obstructions, meteorological, and climatological data, there are limitations that need further discussion. One of these being the limited water obstruction dataset provided by NDOT, as historical water obstructions only go back to June 2016. While some conclusions were able to be drawn from the data provided, it emphasizes the need for a longer archive of obstructions. In addition, the closest weather station information may not have been totally representative of the conditions at some water obstruction locations, thus, precipitation totals and averages may be not representative of the conditions. The same can be said with the stream gage analyses. Therefore, water height and discharge averages could also be incorrect for some water obstruction events. It is also possible there have been a number of short-duration precipitation events causing water obstructions, especially water on pavement that have not been documented in the CARS511 system. This could be due short-duration precipitation typically impacting a small number of miles on average and more likely do not produce enough substantial precipitation to induce a lane closure. These are all speculations that emphasize the importance of documenting all water obstruction events in the CARS511 historical archive for future work. A repeat of this analysis will only strengthen the results and increase the confidence where, when, and why different types of water obstructions occur.

References

Ashley, W. S., Haberlie, A. M., & Strohm, J. (2019). A climatology of quasi-linear convective systems and their hazards in the United States. *Weather and Forecasting*, *34*(6), 1605-1631.

Boselly, S. E. (2001). *Roadway flash flooding warning devices feasibility study* (No. ITS-IDEA Project 79).

Brown, R., Curley, J., & Smith, B. (2014). Transport Resilience Review: A review of the resilience of the transport network to extreme weather events. *Department for Transport: London (UK)*.

Brown, S., & Dawson, R. (2016). Building network-level resilience to resource disruption from flooding: Case studies from the Shetland Islands and Hurricane Sandy. In *E3S Web of Conferences* (Vol. 7, p. 04008). EDP Sciences.

Chang, H., Lafrenz, M., Jung, I. W., Figliozzi, M. A., Melgoza, R., Ruelas, D., & Pederson, C. (2011). Future flooding impacts on transportation infrastructure and traffic patterns resulting from climate change.

Cheeks, S. M., Fueglistaler, S., & Garner, S. T. (2020). A satellite-based climatology of central and southeastern US mesoscale convective systems. *Monthly Weather Review*, *148*(6), 2607-2621.

Cold Regions Research Laboratory (CRREL). (2021). Ice Jam Database. Retrieved from https://icejam.sec.usace.army.mil/ords/

Das, S., Sun, X., Goel, S., Sun, M., Rahman, A., & Dutta, A. (2020). Flooding related traffic crashes: findings from association rules. *Journal of Transportation Safety & Security*, 1-19.

Davis, R. S. (2001). Flash flood forecast and detection methods. In *Severe convective storms* (pp. 481-525). American Meteorological Society, Boston, MA.

Dawson, R.J., Gosling, S., Chapman, L., Darch, G., Watson, G., Powrie, W., Bell, S., Paulson, K., Hughes, P., Wood, R., Thompson, D., Johns, D., 2016. Chapter 4: Infrastructure in UK Climate Change Risk Assessment 2017 (CCRA 2017). In: Adaptation Sub-Committee (ASC) of the Committee on Climate Change, London (UK).

Doswell, C. A., Brooks, H. E., & Maddox, R. A. (1996). Flash flood forecasting: An ingredients-based methodology. *Weather and forecasting*, *11*(4), 560-581.

Doswell III, C. A., Brooks, H. E., & Kay, M. P. (2005). Climatological estimates of daily local non-tornadic severe thunderstorm probability for the United States. *Weather and Forecasting*, *20*(4), 577-595.

Drobot, S. D., Benight, C., & Gruntfest, E. C. (2007). Risk factors for driving into flooded roads. *Environmental Hazards*, *7*(3), 227-234.

Easterling, D. R., K.E. Kunkel, J.R. Arnold, T. Knutson, A.N. LeGrande, L.R. Leung, R.S. Vose, D.E. Waliser, and M.F. Wehner. (2017). *Precipitation changes in the United States. Climate Science Special Report: Fourth National Climate Assessment*, D. J. Wuebbles et al., Eds., Vol. I, U.S. Global Change Research Program, 207–230, https://doi.org/10.7930/J0H993CC

ESRI. (2019a). ArcMapVersion (10.7.1). Redlands, CA; ESRI.

ESRI. (2019b). *Kernel density (spatial analyst)*. Kernel Density (Spatial Analyst)-ArcGIS Pro | Documentation. Retrieved from https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/kernel-density.htm

ESRI. (2019c). *Line density (spatial analyst)*. Line Density (Spatial Analyst)-ArcGIS Pro | Documentation. Retrieved February 22, 2022, from https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/line-density.htm

Faturechi, R., & Miller-Hooks, E. (2015). Measuring the performance of transportation infrastructure systems in disasters: A comprehensive review. *Journal of infrastructure systems*, *21*(1), 04014025.

Federal Highway Administration (FHWA). (2020, October 22). *Status of the nation's highways, bridges, and transit*. U.S. Department of Transportation/Federal Highway Administration. Retrieved from https://www.fhwa.dot.gov/policy/23cpr/

Flanagan, P. and Mahmood, R. 2021. Spatio-temporal analysis of extreme precipitation climatology in the Missouri River Basin from 1950 – 2019. *Journal of Applied Meteorology and Climatology*. 60, 811-827.

Flanagan, P. X., Mahmood, R., Umphlett, N. A., Haacker, E., Ray, C., Sorensen, W. & Fajman, P. (2020). A hydrometeorological assessment of the historic 2019 flood of Nebraska, Iowa, and South Dakota. *Bulletin of the American Meteorological Society*, *101*(6), E817-E829.

Fritzen, R., Lang, V., & Gensini, V. A. (2021). Trends and Variability of North American Cool-Season Extratropical Cyclones: 1979–2019. *Journal of Applied Meteorology and Climatology*, *60*(9), 1319-1331.

Guastini, C. T., & Bosart, L. F. (2016). Analysis of a progressive derecho climatology and associated formation environments. *Monthly Weather Review*, *144*(4), 1363-1382.

Hammond, M. J., Chen, A. S., Djordjević, S., Butler, D., & Mark, O. (2015). Urban flood impact assessment: A state-of-the-art review. *Urban Water Journal*, *12*(1), 14-29.

Hydrometeorological Design Studies Center (HDSC). (2005, November 7). *Precipitation Frequency Data Server*. PF Map: Contiguous US. Retrieved from https://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html?bkmrk=pa

Healy, D., & Hicks, F. E. (2006). Experimental study of ice jam formation dynamics. *Journal of Cold Regions Engineering*, *20*(4), 117-139.

Huntington, T. G. (2006). Evidence for intensification of the global water cycle: review and synthesis. *Journal of Hydrology*, *319*(1-4), 83-95.

Iowa State University (ISU). (2022). *Iowa Environmental Mesonet*. Iowa State University Iowa Environmental Mesonet. Retrieved from https://mesonet.agron.iastate.edu/

Jamshidi, M. (2021). *Nebraska Surface Transportation*. Retrieved from https://dot.nebraska.gov/media/114376/fy2021-program-book.pdf

Jaroszweski, D., Hooper, E., & Chapman, L. (2014). The impact of climate change on urban transport resilience in a changing world. *Progress in Physical Geography*, *38*(4), 448-463.

Jenelius, E., Petersen, T., & Mattsson, L. G. (2006). Importance and exposure in road network vulnerability analysis. *Transportation Research Part A: Policy and Practice*, *40*(7), 537-560.

Kalantari, Z., & Folkeson, L. (2013). Road drainage in Sweden: current practice and suggestions for adaptation to climate change. *Journal of Infrastructure Systems*, *19*(2), 147-156.

Kalantari, Z., Briel, A., Lyon, S. W., Olofsson, B., & Folkeson, L. (2014). On the utilization of hydrological modelling for road drainage design under climate and land use change. *Science of the Total Environment*, *475*, 97-103.

Koetse, M. J., & Rietveld, P. (2009). The impact of climate change and weather on transport: An overview of empirical findings. *Transportation Research Part D: Transport and Environment*, *14*(3), 205-221.
Kramer, M., Terheiden, K., & Wieprecht, S. (2016). Safety criteria for the trafficability of inundated roads in urban floodings. *International journal of disaster risk reduction*, *17*, 77-84.
Kundzewicz, Z. W., Kanae, S., Seneviratne, S. I., Handmer, J., Nicholls, N., Peduzzi, P., ... & Sherstyukov, B. (2014). Flood risk and climate change: global and regional perspectives. *Hydrological Sciences Journal*, *59*(1), 1-28.
Lwin, M. M., Yen, W. P., & Shen, J. J. (2014). Effects of Hurricane Katrina on the performance of US highway bridges. *Journal of Performance of Constructed Facilities*, *28*(1), 40-48.
Macdonald, D. M. J., Bloomfield, J. P., Hughes, A. G., MacDonald, A. M., Adams, B., & McKenzie, A. A. (2008). Improving the understanding of the risk from groundwater flooding in the UK.
Martínez-Gomariz, E., Gómez, M., Russo, B., & Djordjevic, S. (2016). Stability criteria for flooded vehicles: a state-of-the-art review. J. Flood Risk Manage.
McGuire, V. L., Lund, K. D., & Densmore, B. K. (2012). Saturated thickness and water in storage in the High Plains aquifer, 2009, and water-level changes and changes in water in storage in the High Plains aquifer, 1980 to 1995, 1995 to 2000, 2000 to 2005, and 2005 to 2009. *US Geological Survey Scientific Investigations Report*, *5177*, 28.
Moore, J. T., Glass, F. H., Graves, C. E., Rochette, S. M., & Singer, M. J. (2003). The environment of warm-season elevated thunderstorms associated with heavy rainfall over the central United States. *Weather and Forecasting*, *18*(5), 861-878.
National Center for Environmental Information (NCEI). (2021). Climate at a Glance. Retrieved from https://www.ncdc.noaa.gov/cag/
National Drought Mitigation Center (NDMC). (2022). *Map Archive*. NASA Grace. Retrieved from https://nasagrace.unl.edu/Archive.aspx
Nebraska Department of Natural Resources (NDNR). (2021, September 17). *Nebraska flooding: March 2019*. ArcGIS StoryMaps. Retrieved from https://storymaps.arcgis.com/stories/9ce70c78f5a44813a326d20035cab95a
Nebraska Department of Natural Resources (NDNR). (2022). *Nebraska Ice Report Summaries*. Nebraska Department of Natural Resources (NeDNR). Retrieved from https://dnr.nebraska.gov/floodplain/nebraska-ice-report-summaries
Nebraska Department of Transportation (NDOT). (2021). CARS511 Historical Archive. Retrieved from the Nebraska Department of Transportation.
National Oceanic and Atmospheric Administration (NOAA). (2008). *Precipitation-frequency atlas of the United States*. NOAA Atlas 14. Retrieved from https://www.weather.gov/media/owp/oh/hdsc/docs/Atlas14_Volume3.pdf
National Research Council, Committee on Climate Change, US Transportation, Transportation Research Board, Division on Earth, & Life Studies. (2008). *Potential impacts of climate change on US transportation: Special report 290* (Vol. 290). Transportation Research Board.
National Weather Service (NWS). (2017, March 8). *NWS Products and Criteria*. National Weather Service. Retrieved from https://www.weather.gov/otx/NWS_Products_and_Criteria
Ott, R. L., & Longnecker, M. T. (2015). *An introduction to statistical methods and data analysis*. Cengage Learning.

Ou-Yang, B., Chu, C. C., Da, Y. B., Liu, X. F., & Zhang, H. Y. (2015). Highway flood disaster risk evaluation and management in China. *Natural Hazards*, *75*(2), 381-397.

Palmer, W. C. (1965). *Meteorological drought* (Vol. 30). US Department of Commerce, Weather Bureau.

Pedrozo-Acuña, A., Moreno, G., Mejía-Estrada, P., Paredes-Victoria, P., Breña-Naranjo, J. A., & Meza, C. (2017). Integrated approach to determine highway flooding and critical points of drainage. *Transportation research part D: transport and environment*, *50*, 182-191.

Peters, J. M., & Roebber, P. J. (2014). Synoptic control of heavy-rain-producing convective training episodes. *Monthly Weather Review*, *142*(7), 2464-2482.

Pielke Jr., R. A., & Downton, M. W. (2000). Precipitation and damaging floods: Trends in the United States, 1932–97. *Journal of climate*, *13*(20), 3625-3637.

Pisano, P., Goodwin, L., & Stern, A. (2002, October). Surface transportation safety and operations: the impacts of weather within the context of climate change. In *Proceedings from The Potential Impacts of Climate Change on Transportation Workshop, US Department of Transportation: Centre for Climate Change and Environmental Forecasting. http://climate. volpe. dot. gov/workshop1002/pisano. doc*.

Polemio, M., & Lollino, P. (2011). Failure of infrastructure embankments induced by flooding and seepage: a neglected source of hazard. *Natural Hazards and Earth System Sciences*, *11*(12), 3383-3396.

Pregnolato, M., Ford, A., Robson, C., Glenis, V., Barr, S., & Dawson, R. (2016). Assessing urban strategies for reducing the impacts of extreme weather on infrastructure networks. *Royal Society open science*, *3*(5), 160023.

Pregnolato, M., Ford, A., Wilkinson, S. M., & Dawson, R. J. (2017). The impact of flooding on road transport: A depth-disruption function. *Transportation research part D: transport and environment*, *55*, 67-81.

Qi, Y., Zhang, J., & Zhang, P. (2013). A real-time automated convective and stratiform precipitation segregation algorithm in native radar coordinates. *Quarterly Journal of the Royal Meteorological Society*, *139*(677), 2233-2240.

Rodrigue, J. P., & Notteboom, T. (2013). 3.1–Transportation and Economic Development. *The Geography of transport systems*.

Schumacher, R. S., & Johnson, R. H. (2005). Organization and environmental properties of extreme-rain-producing mesoscale convective systems. *Monthly weather review*, *133*(4), 961-976.

Schumacher, R. S., & Johnson, R. H. (2006). Characteristics of US extreme rain events during 1999–2003. *Weather and Forecasting*, *21*(1), 69-85.

Shattuck, R. F. (1988). Ice jams at highways and bridges—Causes and remedial measures. *Transportation Research Record*, *995*, 29-34.

Storm Prediction Center (SPC). (2022). *Storm prediction center WCM page*. Storm Prediction Center. Retrieved from https://www.spc.noaa.gov/wcm/

Steward, D. R., & Allen, A. J. (2016). Peak groundwater depletion in the High Plains Aquifer, projections from 1930 to 2110. *Agricultural Water Management*, *170*, 36-48.

TRIP. (2022). *Key facts about the U.S. surface transportation system - trip*. National Transportation Research Nonprofit. Retrieved from https://tripnet.org/wp-content/uploads/2020/04/TRIP_Fact_Sheet_NATL.pdf

UNL. School of Natural Resources. (2022). Retrieved from https://snr.unl.edu/data/water/groundwater/

United States Geological Survey (USGS). (2022). *National Water Information System: Web Interface*. USGS current water data for Nebraska. Retrieved from https://waterdata.usgs.gov/ne/nwis/rt

Walsh, C. L., Ford, A., Barr, S., & Dawson, R. J. (2012). A spatio-temporal modelling framework for the integrate assessment of cities in Earth Systems Engineering 2012. In *A technical symposium on systems engineering for sustainable adaptation to global change. Centre for Earth Systems Engineering Research, Newcastle University, Newcastle upon Tyne (UK)*.

White, K. D. (1996). *Ice jam flooding and mitigation: Lower Platte River Basin, Nebraska* (Vol. 96, No. 1). US Army Cold Regions Research and Engineering Laboratory.

White, K. D., & Eames, H. J. (1999). CRREL ice jam database.

White, K. D., Tuthill, A. M., Vuyovich, C. M., & Weyrick, P. B. (2007, June). Observed climate variability impacts and river ice in the United States. In *Proc. 14th Workshop on the Hydraulics of Ice Covered Rivers* (pp. 20-22).

Wilcox, R. R. (2010). *Fundamentals of modern statistical methods: Substantially improving power and accuracy*. Springer.