



Ice-Run Destruction of Spencer Dam on Nebraska's Niobrara River

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The breakup of an ice cover triggered a major ice run that destroyed Spencer Dam, a run-of-river hydropower dam on the Niobrara River in northern Nebraska, USA. The dam's destruction led to an investigation (under the auspices of the Association of State Dam Safety Officials) that yielded useful insights for the design and operation of similar dams located on rivers subject to dynamic ice-cover breakup and subsequent ice runs. The insights range from how rivers in the Northern Great Plains (NGP) form ice, how NGP weather patterns affect ice formation and ice-cover break-up, how morphologies of NGP rivers affect ice runs, and how infrastructure (dams, bridges, levees) need to be designed and operated with the mindset that ice runs can instigate catastrophic failures. The March 2019 destruction of Spencer Dam was not the first time that the dam had suffered a major failure owing to river ice, though records of the earlier failures had been inadequately maintained and lessons not learnt. This paper reviews the weather and ice-formation processes that led to the destruction of Spencer Dam and severely damaged several bridges spanning the river. More research needs to be done on ice in NGP rivers, including on the thermal responsiveness of NGP river channels. The Niobrara River's location and morphology played substantial roles affecting the destruction of Spencer Dam.

1. Introduction

Early one morning in March 2019, an ice run destroyed Spencer Dam, a run-of-river hydropower dam on the Niobrara River in northern Nebraska, USA. Figure 1 shows the location of Spencer Dam and the Niobrara River, a tributary of the Missouri River. After the dam's destruction, Nebraska Dam Safety Program (NDSP) contacted the dam's owner, Nebraska Public Power District (NPPD), who agreed with NDSP that the destruction be investigated by the Association of State Dam Safety Officials (ASDSO) using ASDSO's previously developed guidelines (ASDSO, 2016). ASDSO convened an oversight group and chose an independent investigation panel (the writers of this paper). The panel's investigation focused on determining what happened (the physical causes), why it happened (the human and organizational causes) and the lessons to be learned from the dam's destruction. The panel's report to ASDSO can be found on ASDSO's website (Baker et al., 2020a). The report's general conclusions also were published in several, dam-industry journals (Baker et al. 2020b, Baker et al. 2021).

This paper draws from the panel's report and focuses on the dam's destruction owing to river-ice processes. Many of those processes prompt needs for further research regarding river ice formation and movement in rivers like the Niobrara River, and the design of infrastructure (dams, bridges, levees) in or adjoining or them.

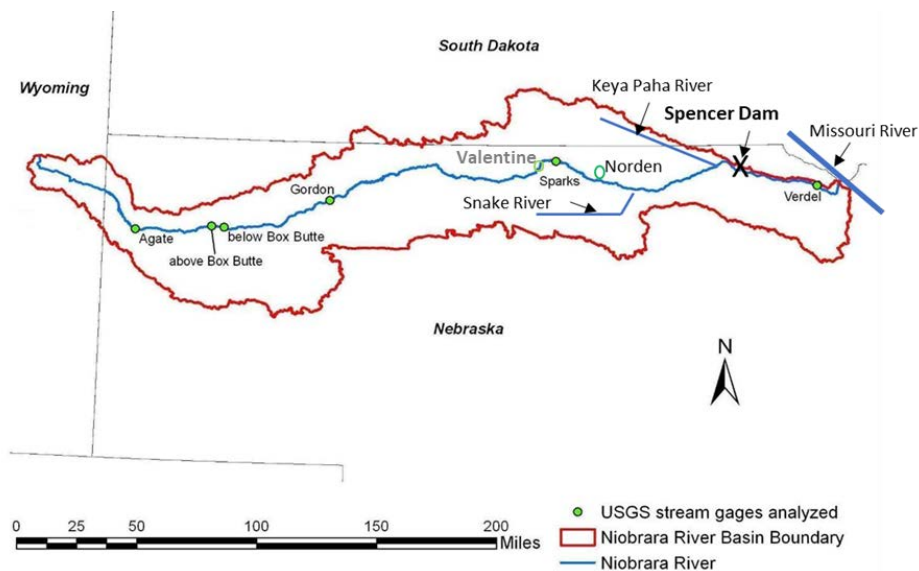


Figure 1. The course and watershed of the Niobrara River (Source: WEST Consultants)

Presently, few people understand the ice-related power of rivers in North America's Northern Great Plains (NGP). When ice moved on the Niobrara River early that morning, not only Spencer Dam failed but so did three bridges on the river: the deck of one bridge was completely lifted off its support piers and abutment columns and dumped about a kilometer downstream; the upstream beam of another bridge was severely bent; and an approach to yet another bridge washed out. This lack of understanding can lead to difficulties facing the design and operation of civil infrastructure, such as dams, bridges, and levees in the NGP. An irony regarding the destruction of Spencer Dam is that the dam drew power from the river's flow, yet the dam's

design and owners did not fully grasp the immense power that the river's flow could muster when the river formed and moved ice.

2. Spencer Hydropower Dam

Spencer Dam was the only active hydropower facility on the Niobrara River, which flows from west to east across most of northern Nebraska before entering the Missouri River (Figure 1). The facility produced electricity as a run-of-river hydropower dam that formed a small reservoir (pool) on the river. Figure 2 is an aerial view of the dam's layout, and Figure 3 shows the powerhouse and adjacent spillway operating in late 2013.

The dam had three main structural elements, as Figure 2 illustrates: an arced, 976-metre-long, earthen embankment dam with a maximum height of 7.95 m; a multi-bay, buttress-type concrete spillway (Figures 3 and 4) fitted with four 10.2-metre-wide Tainter (radial) gates (Figure 4a) and five 10.2-metre-wide needle-beam stoplog bays (Figure 4b); and a powerhouse on the north end (Figure 3). Each needle-beam stoplog bay contained five needle beams and six stacks of wood stoplogs. The needle beams were operated by the positioning of a pneumatic jack between a welded bracket on the side of the needle beam and the operator walkway. The needle beams then are lifted to free the bottom of the beams from a pocket in the concrete crest, letting the bottom of the beam swing downstream. A 3.1-metre-wide, ice sluice-bay with a lift gate separated the spillway from the powerhouse (Figure 4a). The powerhouse accommodated two Westinghouse generators, which together had a maximum capacity of 3,000 MW. River discharge through the powerhouse varied throughout the year, with summer flows averaging 48 m³/s and the maximum discharge used for hydropower operation being about 566 m³/s.

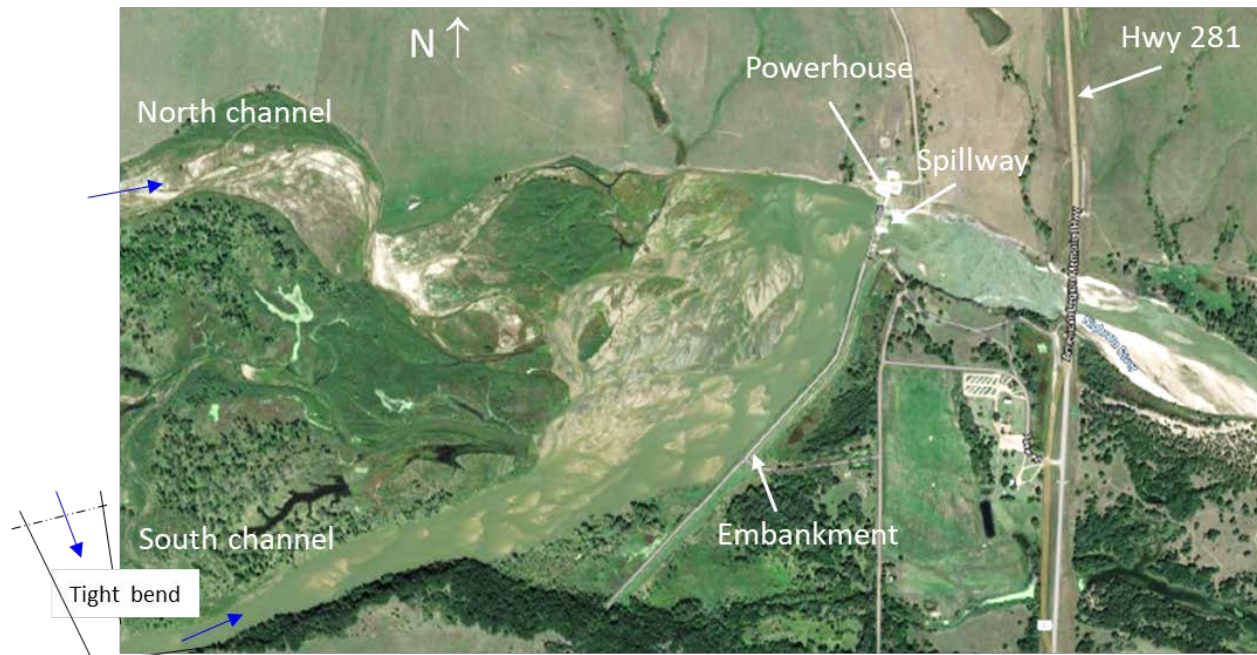


Figure 2. Layout of Spencer Dam and approach channels of the Niobrara River. The south channel included a tight bend bordered by a rock bank (Source: Google Earth)

The dam's destruction was not the only ice-related difficulty experienced by the dam (ASDSO 2020). The dam was built in the late 1920s and had a storied history regarding ice. Several of the dam's past incidents and failures could have been warning signs to the dam owner and regulator. An ice-run in March 1935 caused the dam's embankment to breach. In 1936, the dam's spillway detached and slid from its shale-rock base; the spillway was rebuilt in the 1940s. In March 1960, a major ice run severely damaged the spillway and the embankment, and again in March 1966, a further major ice run damaged the spillway and punched a hole in the upstream face of the powerhouse (Omaha World Herald 1966).



Figure 3. Photo of Spencer Dam powerhouse and spillway operating in November 2013 (Source: NPPD)



(a)



(b)

Figure 4. Views of the dam's spillway during flushing of sediment from the pool: (a) the four Tainter (radial) gates; and, (b) the five stoplog bays with needle beams and timber planks. Note the antidunes angled to the radial gates (Source: NPPD)

The pool formed by Spencer Dam was a relatively small, typical of a run-of-river facility. Storage curves from 1999 indicate that the pool's capacity at normal pool was about 1.0×10^7

m³. At the theoretical top of the embankment, the storage was about 2.0×10^7 m³. Whereas the storage below normal pool likely fluctuated significantly between the twice-yearly flushing (Spring and Fall) of sediment the pool accumulated, the surcharge storage above normal pool remained relatively constant since the reservoir level was only above normal pool during flooding. The pool had two main approach channels (north and south) that entered on either side of an upstream island (Figure 2). The north channel flowed directly towards the spillway. The south channel flow was diverted north along the embankment towards the spillway. The island upstream of the pool is large and occasionally is overtopped by flows that created minor secondary channels.

Over the years leading up to March 2019, Spencer Dam had been well maintained, and prior ice-related failures repaired, or parts of the dam modified. Baker et al. (2020a) summarizes the repairs and modifications completed after 1994, gives a history of dam-safety inspections, and elaborates the most recent features of the dam and their condition prior to March 2019.

3. The Niobrara River Upstream of Spencer Dam

The location and morphology of the Niobrara River were major factors in the Spencer Dam's destruction. They influenced the volume of ice formed and the manner and directions whereby the river's ice moved toward the dam.

3.2 Location

A noteworthy, but little appreciated, feature of the NGP location of Spencer Dam is that the location may experience dynamic, fluctuating weather patterns, which create challenges for the design and operation of the dam and other infrastructure. Nebraska's mid-latitude and mid-continent location (Figure 5) causes Nebraska to experience frigid winters and rapid warming periods (especially in spring) that can lead to major ice runs and jams along the state's rivers.

The influence of frigid weather is amplified by the elevation variation of the Niobrara River, whose headwaters are in the high plains of northeastern Wyoming. The river's highest elevation is about 1,678 m, and its elevation at Spencer Dam is approximately 427 m. The topography of the NGP contributes to the region's fluctuating weather patterns. The Rocky Mountains (or continental divide) act like an atmospheric dam, forcing hot air from the south and cold air from the north to pool up over the NGP, initiating energetic fluctuations in weather. The fluctuations may produce low-pressure systems that can generate storms. Such storms occur most frequently during winter and spring, when the atmospheric jet stream dips southward, and actively influences weather over the NGP. During such periods, the atmospheric expressway often formed by the NGP may create fast-moving weather systems. If the fast-moving cyclones generate substantial rates of atmospheric-pressure decrease (bombogenesis), the cyclones become "bomb cyclones", which cause Nebraska and surrounding states to experience large fluctuations of warmer and colder weather, especially as winter merges into spring. This was the case in March 2019, when the river grew large volumes of ice and then the weather and the river's watershed substantially relatively abruptly increased water runoff and river flow.

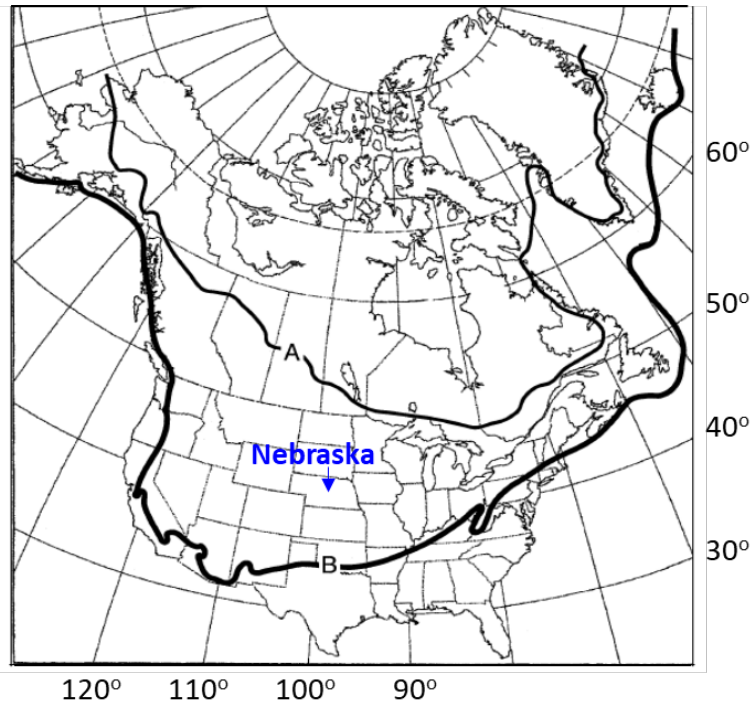


Figure 5. Map indicating the location of Nebraska and regions of frigid winters. The A-line is the southern boundary of area where the average air temperature of the coldest winter month is $\leq -18^{\circ}\text{C}$; and, the B-line is the southern boundary where the average air temperature of the coldest month is $\leq 0^{\circ}\text{C}$. (Source: adapted from USACE 2002)

3.2 Morphology

The morphology of the Niobrara River in the reach containing Spencer Dam reflects the interactions of water-flow hydrodynamics, sediment transport, the terrain through which the river flows, and the presence of bridges. Most reaches of Niobrara River, from about the small town of Norden to the river's confluence with the Missouri River, have a braided channel with a bed largely comprising medium to fine sand. Figure 6 shows a reach upstream of Spencer Dam.

Alexander et al. (2009) describe the hydraulic characteristics of the Niobrara River. They document extensive data measured at USGS streamflow gage sites along the river and provide a useful reference for obtaining a sense of how the river behaves hydrologically and hydraulically. The data include characteristics of the river reach in the vicinity of Spencer Dam and discharge data obtained from USGS gages. Upstream of Spencer Dam, extending as far as Norden, the Niobrara River flows along a braided channel, about 300-450 m wide, marked by the frequent shifting of the river's main channel and the consequent wide, ill-defined floodplain formed by the river. The river's natural channel is irregular in width, in accordance with the river's braided morphology. Flow depths along the reach are shallow, ranging from about 0.1-1 m during conditions of mean flow. Immediately downstream of the dam, the river flows for about 8 km along a single channel that meanders from bank to bank. From this section down to the confluence with the Missouri River, the river once more becomes braided. Both the braided and the single-channel reaches are marked by sand bars, which become vegetated islands in the braided reaches.

A feature of the river's morphology upstream of Spencer Dam is the presence of bridges. Each bridge typically confines the river to a single channel through the bridge waterway. Upstream of Spencer Dam, bridge waterways are about 100 to 150-metre-wide, nominally about a third of the overall width of the braided channel. This narrowing of the river at bridge crossings confines the river to a single channel and increases sediment transport through the bridge waterway. Channel narrowing makes bridges potential locations for accumulations of drifting ice to develop. The reach shown in Figure 6 includes the Highway 11 bridge where much ice rubble accumulated before running into Spencer Dam. The river at this location narrows significantly, then turns about 90-degrees and widens as it flows downstream toward the dam.



Figure 6. The Niobrara River at a reach including the Highway 11 Bridge, 8.5 km upstream of Spencer Dam. The river width here is about 153 m (Source: adapted from Google Earth)

3.3 Ice Formation and Ice Runs

The influence of ice on the Niobrara River's morphology is unclear and not described in leading references about the Niobrara River (e.g., the U.S. Geological Survey's report by Alexander et al. 2009), though evidence of river-ice presence and movement is readily apparent from the type of vegetation found along the banks of the river's main channel and the scarring of tree trunks. The river's shallow banks along active channels typically are vegetated by low vegetation, such as grasses and small bushes.

The braided morphology and readily erodible sand bed and bars of the Niobrara River downstream of Norden, and the dynamic nature of the weather patterns over the NGP, substantially influence ice formation, ice movement and ice accumulation along the Niobrara River upstream of Spencer Dam (e.g., Kempema et al. 2020). The influences are multiple and include the entire gamut of ice formation, break-up and jamming processes, and need to be further researched. For example, no descriptions exist of ice-formation processes in the Niobrara River that lead to occurrence of ice runs on the Niobrara River. The present lack of knowledge about ice formation and movement in braided channels complicates the design and operation of Spencer Dam and other run-of-river dams. Additional incidents related to ice-jams have

occurred for run-of-river dams, but those incidents are infrequent, usually buried in legal suits, and never thoroughly investigated and documented; e.g., the 1978 Markland Dam Incident on the Ohio River (Tuthill 1999). This lack also compromises the functioning of bridges over rivers like the Niobrara River.

A point to emphasize is that the period (or time scale) associated with each of the multiple influences is important when considering ice-induced failure of Spencer Dam. To begin with, the river's shallowness causes the water to cool relatively fast and enables ice to form comparatively quickly. The channel's relatively steep slope, swift currents and undular bed (the bed is marked by a variety of alluvial bedforms such as ripples, dunes and antidunes) mix water and affect the nature of ice formed. The currents rapidly move ice, peeling anchor ice from the channel's bed, and conveying it downstream as slush that may freeze as a new ice cover. However, the river's braided morphology complicates the downstream movement of ice. There are many locations (e.g., bends and bars) that can impede ice drift, causing ice to accumulate and jams to form. Relatedly, the swift currents impose substantial hydrodynamic forces on ice accumulations and the river's channel boundaries, such as at bridges.

For the same weather conditions, shallower and wider channels, like those of the braided Niobrara River characterize the NGP and produce more ice than do deep channels, because their comparatively large water-surfaces and shallowness (Kempema et al. 2020). Consequently, the river upstream of Spencer Dam can produce large volumes of ice. The amount of heat entering a river also depends on the heat flux associated with groundwater seepage into the river flow. The Niobrara River receives a substantial amount of its baseflow from groundwater flow. Though the rate of inflow likely still is low such that it does not significantly affect the rapid cooling of the river during frigid weather, the inflow likely is warmer than is the river water. This inflow of warmer water is important when considering anchor-ice formation and release, and the eventual weakening of an ice cover. Frequent cycles of formation and release of anchor ice may increase the overall volume of ice formed per unit area of the riverbed.

The channel characteristics of the Niobrara River influence how ice covers form then break-up. Ice covers form on the river through the combined action of accumulation of drifting ice slush and pans, and ice growth over regions of quiescent flow or no flow (e.g., over low bars and in back waters). The cover then thickens thermally, as ice crystals grow downward and fill cavities between accumulated slush and pans. Snow deposited on the cover's surface thickens the cover. Figure 7 depicts ice along the Niobrara River upstream from Spencer Dam. Some open-water leads may remain in the cover, doing so at locations where groundwater flow enters the river at a pronounced rate or where turbulence is substantial and persistent.

Most years, the onset of warmer weather causes the river's ice cover to warm, weaken and disintegrate, largely in place. During this process of thermal break-up, gaps between ice crystals enlarge, though the cover's thickness usually does not diminish notably. However, fluctuations in weather patterns cause the ice cover to break-up dynamically (a mechanical break-up of the cover) and produces pieces of broken ice usually termed ice rubble.

Once an ice cover breaks up along the Niobrara River, the river's channel characteristics affect the movement of the resulting broken ice (ice rubble) along the river, and the occurrence of ice

congestion, jam formation, and the manner of subsequent failure of a jam. The river's many bends and bars would hamper ice movement, as would the bridges across the river. At these locations the channel narrows, making it easier for drifting ice floes and ice rubble (and clusters of ice rubble) to lodge across the channel, or between the piers of a bridge. Studies show that ice movement along a river is affected especially by the ratio of ice-rubble length compared to channel width (e.g., Osada et al. 2020, Lucie et al, 2017); for rivers the size and characteristics of the Niobrara River the largest length dimension of the rubble is nominally about 6 m, though the rubble can be highly variable in plan size. Though ice strength and shape play roles, congestion and jamming occur at locations where channel width is less than about eight times ice rubble length (Lucie et al. 2017).

The relative shallowness of the Niobrara River and the presence of bars in the wider regions of the river, as well as sharp turns in flow paths, created locations where jams initiated. Moreover, larger pieces of ice rubble and clusters of ice are less likely to negotiate turns and bifurcations around bars. Once a jam forms it retards flow, backs up water and may then produce an untidy series of accumulation steps that involve ice rubble being shoved and compacted at a downstream location of greater constriction. Figure 7 shows ice rubble jammed in a reach of the Niobrara River.



Figure 7. Ice rubble jammed in a reach of the Niobrara River during March 2019 (Source: A resident living near the river)

Upstream of Spencer Dam, the Niobrara River's braided bed of erodible sand is susceptible to bed scour, notably when local velocities increase. Therefore, scour may occur at the toe of ice jams formed along the Niobrara River and cause more flow to pass beneath the jam. The development of scour consequently may cause a jam to collapse. Flow-induced erosion and collapse of the Niobrara's sand banks adjoining the jam also act to weaken jams along the river. In the latter case, a jam may form at an upstream location then release only to re-form at a location downstream; this process may occur for several cycles. The release of an ice jam may produce a surge of water and ice rubble, especially if the release is relatively sudden. Channel characteristics play a pronounced role influencing the suddenness of a release. If the channel's bed scoured quite quickly, jam collapse could be swift. Channel steepness increases flow velocity and, thereby, affects bed scour and the hydrodynamic loading of the jam. Also, channel steepness affects the hydraulics of the surge resulting from the sudden failure of an ice jam.

4. Ice-Run Destruction of Spencer Dam

An adverse convergence of factors related to the physical setting of Spencer Dam led to an ice run that overwhelmed and destroyed Spencer Dam early in the morning of March 14, 2019. Though such an event could be deemed infrequent, the ice problems were foreseeable, especially as a similar incident had occurred in 1966.

4.1 Conditions Leading up to the Ice Run

From February through early March 2019, frigid winter temperatures prevailed over the Niobrara River watershed. The air temperatures at the town of Spencer were below average (NOAA 2019). This weather prevailed across much of Nebraska. For example, in Lincoln Nebraska, the air temperatures reached near-record lows (notably on February 21 and 25, and March 3 and 4). The lowest recorded values of air temperature there were about -21°C to -23°C . These weather conditions enabled an ice cover of substantial thicknesses to form on the Niobrara River. Estimates of ice-cover thickness upstream of Spencer Dam (based on observed thicknesses of ice rubble at Spencer Dam) indicate that the average thickness of ice cover was up to about 0.6 m.

The likelihood of a dynamic break-up of the ice cover was heightened by the relatively thick and wet snowpack that lay on frigid ground in the watershed of the Niobrara River. The snowpack was estimated to have a liquid water content of about 0.05 to 0.1 m (USACE 2019). During the days preceding March 14, the air temperatures in the watershed of the Niobrara River were warming, indicating the onset of spring. The maximum air temperatures during March 11-13 were 4 to 10°C , though the minimums were -13 to -1°C . The warming weather led to increased snowmelt runoff to the river and thereby to increased water flow in the river. For example, though the USGS gage at Verdel was ice-cover affected, the gage indicated that the river's discharge had increased continuously during March 11-13, particularly during March 13; the gage indicated the discharge went from $85\text{ m}^3/\text{s}$ on March 12 to $255\text{ m}^3/\text{s}$ on March 13; the maximum peak flow for the gage's 80-year record was $1,104\text{ m}^3/\text{s}$, on March 27, 1960.

A fast-moving large storm called Winter Storm Ulmer tracked northeastward during March 12-14. The storm underwent bombogenesis and became a bomb cyclone early on March 13. The bomb cyclone (Figure 8), pushed mild air and moisture northward, hastening snowmelt and adding about two inches of rainfall on melting snow in the river's watershed upstream of Spencer Dam. As evening developed on March 13, the rain became freezing rain, wind speeds became exceeded 100 km/hr and blizzard-like conditions prevailed as the bomb cyclone passed over the watershed of the Niobrara River.

4.2 The Ice Run Conditions Experienced at Spencer Dam

On the evening of March 13, 2019, preceding the dam's failure early on March 14, two dam operators were on site. At 8:00 PM on the evening of March 13, the operators logged that they had opened all four of the radial gates in Bays 1-4 to their maximum opening of 1.82 m. This was necessary to maintain the pool's normal operating level. However, by midnight the pool was rising, so the operators started to release the stoplogs by jacking the needle beams. By 3:00 AM on March 14 the operators had managed to release all but one needle beam in Bay 5 (the

first stoplog bay) and two beams in Bay 6, and the three remaining stoplog bays still had stoplogs in place.

However, all the needle beams and stoplogs in Bays 8 and 9 remained in place throughout the event, because they were frozen in place. The wall that contains the embankment extends further upstream and downstream than the piers between bays. This orientation shaded the stoplogs, resulting in ice buildup. Had it just been the freezing rain, all the stoplog bays would have been frozen. Rain fell most of the night, but at some point, after 3:00 AM, the rain had become freezing rain. At 2:58 AM one of the operators shot a video of a piece of ice passing under one of the open gates. This video showed how the gate was bouncing and the operating deck was shaking as the ice passed under the gate. According to the operators there was significant vibration on the operating deck due to the released needle beams dangling in the flow. At some point before the video was shot, the vibrations were so violent that they caused the hoist chains on Gate 3 to break and the gate closed as a result. The combination of freezing-rain ice on the walkway surface, wind, and vibration made the deck unsafe for the operators to walk across to access the spillway's south end to attempt to lift the remaining needle beams.

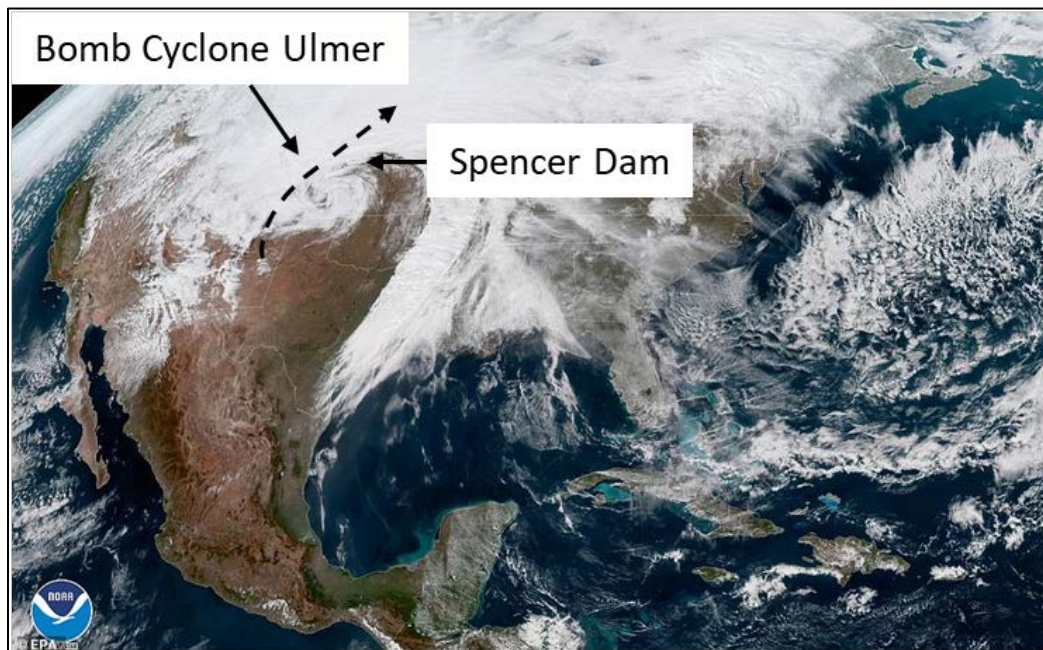


Figure 8. Winter Storm Ulmer becoming a bomb cyclone on Wednesday, March 13 (Source: National Oceanic and Atmospheric Administration [NOAA]).

At about 4:38 AM, one of the operators shot videos and took pictures of the trash-rake room in the powerhouse. The room's floor was beginning to flood. At this time, their access to the operating deck through the powerhouse was beginning to be cut off by the flooded floor. At about this time, the operators decided to drive to the embankment access road across the river and on to the embankment where they could access the remaining stoplog bays from the south end of the spillway. Unfavorable weather and road conditions slowed the drive, and upon arriving at the gated fence to the embankment access road, the operators noticed water on and around the access ramp and surmised that the embankment was overtopping. Although it was unclear how much overtopping was occurring, they realized the overtopping was unsafe. The

operators said that they did not see any ice in this overtopping flow at that time. They then turned around and headed back to the powerhouse, stopping to warn a resident living downstream of the dam along the access road. When returning to the powerhouse, the operators saw three fireballs at the substation, indicating to them that the powerhouse may have been flooded. By the time they arrived at the powerhouse, they observed a hole in the upstream wall of the powerhouse, but the reservoir had already dropped. They were unaware that the dam had failed and, seeing that there was nothing they could do there, they became concerned about Highway 281 washing out and phoned 911. Then, they headed to the highway bridge (immediately downstream of the dam) to warn people not to cross in the event it had been damaged by the flood.

Post-failure investigations showed a gage in the generator room that was 2.3 m above the floor that was half filled with water. A clock on the wall of the powerhouse office had stopped at 5:15 AM. Ice was piled on the embankment and pool's rim, where ice was piled about 1.4 m above the top of the embankment during the flood event, though it is unclear if the ice on the embankment was even higher, because no measurements were available.

The embankment had breached in two locations: the north breach just south of the spillway was about 200 m wide; the south breach, near the embankment-access road was about 245 m wide. Most dam engineers and dam-safety professionals would probably picture an overtopping breach (with water only) much differently than one caused by mostly ice. In a normal situation, the embankment could not be expected to survive about 0.3 m (a foot) of overtopping considering the embankment shell material is sand. The sand on the downstream face would quickly erode leaving the steep clay core to either erode or collapse. It is believed that the overtopping initially was mostly by ice rubble. The rubble could have gouged the embankment, weakening it for water erosion, although gouging was not identified elsewhere on the intact crest. Erosion of the downstream face elsewhere along the embankment was observed. An indication of the level of pressures exerted through the ice mass accumulated at the dam, which may have failed the weakened embankment, was evident from the deformations of the steel beams of the Highway 11 Bridge and the steel beams and gates of the dam's spillway.

4.3 Ice-Run Aftermath

Once the ice run had passed the extent of Spencer Dam's destruction could be assessed. Figure 9 indicates where the two breaches formed through the dam's embankment. The series of photos in Figures 10a-e show the destroyed dam and the altered adjacent areas. The photos attest to the power that an ice run can muster.

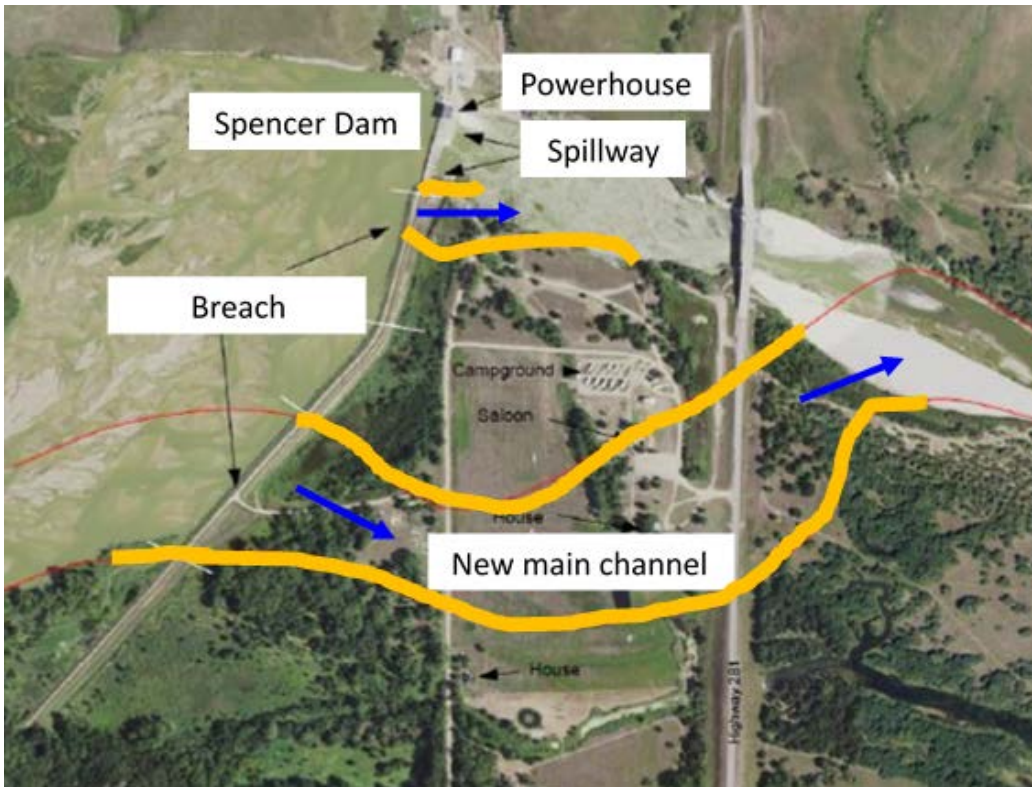


Figure 9. Details of dam site and adjacent area showing breach locations and the new main channel after the event (Source: adapted from Google Earth)



(a) of Figure 10



(b)



(c)



(d)



(e)

Figure 10. Views of the dam site and areas adjacent to the site (after the ice run), March 15, 2019 (Sources: NPPD, NEMA, Omaha World Herald): (a) view of the powerhouse at 8:00 AM (ice impact had largely demolished the upstream wall); (b) devastated Spencer Dam; (c) view along the spillway now with its radial gates and a concrete pier missing (note here how the wall containing the embankment is wider (upstream to downstream) than the piers. This configuration caused the two south bays to be shaded, enabling ice build-up over the winter); (d) view looking upstream at the Highway 281 bridge with breached south-approach embankment; and, (e) view, looking upstream, of ice rubble on the remnant embankment (note the headcutting on the embankment's downslope)

5. Complicating Factors

The layout of the bridges upstream of the Spencer Dam, the layout of Spencer Dam itself, and the braided morphology of the Niobrara River, presented complicating factors that may have reduced the capacity of Spencer Dam to pass ice rubble and led to the dam's destruction:

- Tight bends in the river's braided reaches (e.g., Figure 2) were locations where the flow substantially narrowed such that ice rubble could congest, back-up flow, then burst as a surge of water and rubble.
- Also, bridge crossings were locations where the river narrowed (Figure 6) and ice rubble accumulated and backed-up flow, eventually creating a surge of water and ice when the bridge failed and (or) the river's bed scoured. Evidence, by way of ice rubble accumulations on bridge decks and the river's banks point to these locations as potential locations releasing surges.
- To reach the spillway section a major portion of the flow had to pass along the dam's arced embankment (Figure 2), which functioned as a guidebank, directing flow obliquely to the dam's spillway.
- The oblique angle at which the flow from the south approached the spillway, and the relative shallowness of the flow affect the spillway's capacity to pass flow and ice rubble (Figure 2).
- The operation of the gates, especially the stoplog gates, prompts a question about the duration needed to fully open all the gates relative to the flow-travel times associated with surges of flow, particularly a surge resulting from the collapse of an upstream ice jam (Figure 3).
- The operation of the gates at night and during frigid weather conditions (including freezing rain) also raises questions.

The dam's layout posed problems for the movement of ice rubble conveyed to the dam from the reach upstream of the dam. When the rubble was weak and comprised smaller pieces, typically after a thermal break-up of the cover (or during freeze-up), the rubble would disintegrate when impacting the dam and its spillway. Evidently (according to the dam's operators), such ice rubble was not particularly problematic during a typical year. However, when the rubble was relatively hard and large in block size (as would result from the dynamic break-up of the upstream ice cover), the spillway experienced major difficulties passing the ice. For gate-opening widths of 10.2 m and taking ice congestion to become problematic when the maximum length of an ice piece was about $10.2 \text{ m}/8 = 1.3 \text{ m}$ suggests that congestion and blockage could occur at gates when they attempted to pass ice pieces larger than this plan length. This estimate is made worse for large pieces of ice rubble obliquely approaching a gate opening; the opening's capacity to pass ice decreases as the angle increases relative to a line perpendicular to the spillway crest.

As the ice overtopped the embankment, liquid water contained within the accumulated ice likely dropped out on the downstream side of the dike as ice tumbled down the slope. Because water was likely a small percentage of the overtopping volume of water and ice, initially there may have only been several centimeters of water overtopping the embankment with ice. This water

flowing out from under the ice likely initiated a headcut erosion on the downstream toe of the embankment that worked its way through the crest at the breach location(s); evidence for such a headcut exists in the remnant embankment. Portions of the embankment that remained standing after the embankment breached show signs of this headcutting (Figure 10e).

With a small amount of water in the initial overtopping flow, it would take longer to fail the dike compared to being overtopped by several feet of water. It is also possible that the surge of inflow pushed ice rubble up and over the dike all at once in a wall of ice and water without the gradual increase in reservoir depth. It is believed that eventually at least 0.6 m of water overtopped the embankment, as water was found in the housing of a gage in the powerhouse that was about 0.6 m higher than the embankment crest. Long, uniform deposits of ice and local channels in the ice downstream from the south end of the embankment that were observed after the failure could be signs the embankment was overtopped by a thick layer of ice rubble for several minutes or more (Figures 10c&e). With ice being deposited downstream from the south end of the embankment the breach may not have fully developed until the ice deposited downstream either was forced out of the way by flow through the breach, or water and ice that was backed up at the downstream highway embankment was suddenly released as the embankment failed.

6. Conclusions

This paper describes and illustrates the ice-run destruction of Spencer Dam on the Niobrara River, Nebraska. Baker et al. (2020a) include the following conclusions regarding the ice run's destruction of the dam and the importance of improved understanding of river-ice formation and movement:

- There are thousands of dams in cold-weather regions in 31 states of the U.S. (Figure 3). Run-of-river dams or dams forming small reservoirs in cold-weather regions can be vulnerable to large ice run events. Until the destruction of Spencer Dam, the dam safety industry did not consider that ice runs could fail dams. Ice runs are not included in well-used guidelines, such as those prepared by the U.S. Army Corps of Engineers or the U.S. Bureau of Reclamation. Decades can pass between major ice runs, requiring research into river history to understand the true risk. There are few available data, that at this moment it would be difficult to tie these events to realistic recurrence periods, but major ice runs may be less frequent than the floods that cause them because floods also occur when there is little or no ice present, or when the ice is much weaker (during a thermal breakup of the cover). However, damaging ice runs are most certainly more likely on rivers like the Niobrara than other loadings such as the extreme floods for which the dam safety industry designs and routinely checks.
- As ice jams and major runs of river ice can severely affect river-related infrastructure (notably dams and bridges) more research is needed to determine how the design and operation of these structures can mitigate or avert the adverse effects of river ice. Insights, such as those reported by Gebre et al. (2013), Stolze (2013) and this paper, should be extended in this regard.

- The design and operation of river-related infrastructure should account for sequences of winter and spring weather patterns that may cause ice jams and major ice runs to occur at the rivers where such infrastructure is located. Research is needed to define such sequences. The research should involve an international effort because weather patterns may encompass several countries. Several countries having river-related infrastructure subject to adverse effects posed by weather sequences and river ice would benefit from the research. For example, communication and warning systems should be established for rivers that can produce major ice runs.
- To date there has been no attempt to determine return periods for damaging ice runs (or the dynamic break-up of ice covers). On rivers where ice runs are possible, a method for determining the return period for damaging ice runs is needed to better assess the risk to infrastructure, as Beltaos (1995) infers.
- Ice formation and movement in channels of relatively complex geometry or containing low dams or bridges require further investigation.

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