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# A Comparative Hydrometeorological Analysis of the 2009, 2010, and 2011 Red River of the North Basin Spring Floods

Peter Rogers, James Kaiser, David Kellenbenz, and Mark Ewens
National Weather Service - Grand Forks, North Dakota

## 1. OVERVIEW

The Red River of the North (Red River hereafter) basin encompasses approximately 45,000 square miles across portions of eastern North Dakota, extreme northeastern South Dakota, northwestern and west-central Minnesota, as well as southern Manitoba. Being one of the longest rivers in the continental United States that flows north, the Red River begins in Wahpeton, North Dakota, where the Bois de Sioux and Otter Tail Rivers converge. It then flows north through the larger cities of Fargo and Grand Forks, North Dakota, and Winnipeg, Manitoba before emptying into Lake Winnipeg. The river sits at the bottom of a flat, glacial lake bed, known as Lake Agassiz. The slope of the river is very shallow, decreasing from south to north (Figure 1). In some locations across the northern valley, the river decreases only one to two feet per mile. By comparison, there are several tributaries that feed the Red River, some of which descend 950 feet within 80 to 90 miles. Flow across the basin is regulated by several dams and reservoirs operated by the United States Corps of Engineers, including Lake Ashtabula, Lake Traverse, Orwell Dam, Homme Dam, and Red Lake Dam.

Frequent springtime flooding is a consequence of the basin's topography and climatology, and has been documented in other studies highlighting previous events (Haley 1965, Andrews 1969, Nelson 1951, NWS 1997, IRRBTF 2000). After a long winter, temperatures typically first rise above freezing across the southern basin, resulting in snowmelt and eventual runoff into the river system. As the swollen river flows north, it encounters less slope, greater amounts of snow and ice due to a colder air mass, and delayed seasonal melting. Ice jams commonly result from these factors and in turn, impede the flow and hold back excessive water. Since the river channel itself is shallow and no more than a few hundred yards at its widest point, water quickly spreads out across the surrounding landscape. Known as overland flooding, this water can extend beyond the river channel for several miles on either side due to the wide, flat primary flood plain.

The severity of a spring flood also depends on several hydrometeorological factors (Bluemle 2001), including: a) autumn precipitation, b) soil moisture content at freeze-up, c) river streamflow at freeze-up, d) river ice thickness, e) frost depth, f) amount of snow, g) water equivalency of snow pack, h) speed of the melt cycle, and i) late winter snow storms and/or early spring rains. No two floods are the same. Thus, it is difficult to quantify the degree to which each of these interdependent factors impacts the overall magnitude of the resulting crest.

The 2009, 2010, and 2011 Red River basin spring floods were epic events, producing record to near-record flows at many locations. The floods required significant preparation and mitigation from a diverse collective of governmental and non-governmental federal, state, and local organizations. This report will highlight the similarities and differences between these three consecutive annual floods and attempt to identify those specific factors that were most important during each event. It will be divided into three comparative parts, discussing factors related to the autumn (Section 2), winter (Section 3), and spring (Section 4) seasons. A discussion and summary section will be provided at the end to discuss findings and highlight comparisons.

## 2. AUTUMN SEASON COMPARISON

Meteorological autumn is defined by the three months of September, October, and November. Precipitation accumulation throughout the previous calendar year can contribute to springtime flooding. However, autumn provides a focal point for the amount of liquid water in the river system prior to freeze-up, or the time when rivers, lakes, and soils freeze. This liquid water can be determined by analyzing rainfall, soil moisture, and river baseflows. It is important to note that a wet autumn, defined by above average precipitation, does not always result in a flood the following spring. For example, of the ten highest recorded crests along the Red River at Fargo, only six of these floods were preceded by precipitation above the 1981-2010 autumn normal of 5.72 inches (Table 1). However, when no other factors are considered, the probability of a spring flood increases with increasing autumn precipitation. From a climatological perspective, the basin has become increasingly wet since the mid-1990s (Figure 2).

a) Rainfall

In autumn 2008, portions of the Red River basin received four to six inches of precipitation above the 1971 to 2000 average (Figure 3). From September to November 2008, the Grand Forks University climate station (FGF) received 11.97 inches of precipitation - rain and snow water equivalent (i.e., melted snow) - breaking the old record of 10.41 inches set in 1957. Fargo Hector International Airport (FAR) received 10.67 inches of precipitation, breaking the old record of 10.25 inches set in 1977. Some areas in the southern Red River basin received over one foot of precipitation from September through November, priming the headwaters area of the Red River with excessive soil moisture. These record precipitation totals also resulted in atypical autumn rises on rivers throughout the region in October, with record levels at many locations for the time of year (not shown).

Conversely, autumn of 2009 was not as wet when compared to 2008 and markedly skewed towards higher values across the southern basin. Portions of southeastern North Dakota, northeastern South Dakota, and west-central Minnesota were approximately 4 inches above the 1971 to 2000 average (Figure 3), whereas precipitation anomalies in the northern basin were much lower with near normal to slightly below normal precipitation. FGF received only 3.98 inches of precipitation from September through November, and this was 0.42 inches below normal, while FAR received 7.91 inches of precipitation, or 2.19 inches above normal.

Above-normal precipitation was more widespread in autumn 2010, similar to that in 2008, but to a lesser magnitude. Much of the basin received 1.5 inches to 4.5 inches above the 1971 to 2000 average (Figure 3). FGF received 7.98 inches, which was 3.58 inches above normal, and FAR received 8.46 inches, which was 3.25 inches above normal. The majority of this precipitation fell in September and was spread out between three different rainfall events, each resulting in over an inch of accumulation at FGF and FAR. An additional 2 inches of liquid precipitation fell across much of the basin from a strong Colorado low pressure system in late October. Interestingly, very little snow fell during the 2008 and 2009 autumn seasons, whereas most of the basin was snow covered by Thanksgiving 2010 due to a series of November snow events.

b) Soil Moisture at Freeze-up

The amount of moisture in the soil prior to freeze-up is important since it impacts the available storage for additional liquid water after the spring thaw and the speed of the frost onset (i.e. more moisture tends to delay freeze-up). High (low) soil moisture will provide less (more) springtime storage and higher (lower) surface runoff rates once the ground thaws sufficiently to allow infiltration of surface water.

Direct soil moisture measurements are not performed within the Red River basin, so proxy information is used in an attempt to quantify the amount of soil saturation. These include the Palmer drought severity index (PDSI), the standard precipitation index (SPI), the Climate Prediction Center "Leaky Bucket" and the National Centers for Environmental Prediction (NCEP) Land Data Assimilation System (NLDAS). To the extent these processes agree, guidance from the Sacramento Soil Accounting (SAC) model is used to further refine the estimates of soil moisture.

Complicating the issue is the wide range of soil types and vegetative cover across the basin. Although technically just outside of the Prairie Pothole Region, the topography contains numerous sloughs and small lakes which act as depression storage. Some of these bodies of water also support native plant species, which due to their deeper root systems allow moisture to penetrate to a greater soil depth compared to much of the surrounding agricultural land. In fact, agricultural practices across the basin over the past century have led to a semi-permanent impenetrable soil layer 6-12 inches below the surface (L. Atkinson and K. Larson 2013, personal communication). This layer has been observed in field studies across much of the basin and can be as much as a foot thick, yet its effects on flooding are unknown and provide an area of research that should be aggressively pursued. For these reasons, soil moisture content, percolation rates, and the depth to which surface water is able to penetrate the soil are not consistent from one area to the next, and the current National Weather Service Hydrologic Forecast System (NWSHFS) schema cannot fully resolve the detail necessary to capture these variances. In atypical melt pattern years this may lead to incorrect soil infiltration rates and routing of surface water.

Leading into the winter months of December, January, and February, soil moisture was anomalously high across the entire Red River basin in 2008, 2009, and 2010. The PDSI (which depicts long-term moisture conditions) at the end of November in 2008, 2009, and 2010 was +2.0 or greater (Figure 4, left panel). November 2009 was the least moist, but still above average, whereas November 2010 was the wettest with the entire basin labeled "Extremely Moist." Although liquid precipitation was above normal for each individual calendar year (not shown), the cumulative effect of three consecutive wet years most likely contributed to very wet soil conditions in 2010.

The spatial distribution of soil moisture is better visualized using the NCEP North American Regional Reanalysis (NARR; Figure 4, right panel). For all three years, soil moisture was very high across the basin's headwaters. The anomalies were not as strong across the central and northern basin, but still positive. Soil moisture was generally near or above normal across much of North Dakota, but it was much below normal across central and northeastern Minnesota, continuing into northwestern Wisconsin.

c) River Streamflow at Freeze-up

With little water movement in the river system during winter, the Red River's streamflow entering freeze-up serves as a starting point for the following spring. The river does not have to rise as much to reach a certain level when streamflows are high. Autumnal seven-day average streamflows at Wahpeton, Fargo, Grand Forks, and Drayton ranged from the high side of normal (> 50%) to much above normal (≥ 90%) from 2008 through 2010 (Figure 5). Because of ongoing precipitation events each autumn, it is difficult to quantitatively separate baseflow from runoff. However, the cumulative effect of three wet years resulted in near-record or record streamflows in late 2010 prior to the 2011 flood.

## 3. WINTER SEASON COMPARISON

Meteorological winter is defined by the three months of December, January, and February. Climatologically, temperatures are well below freezing in winter across the Red River basin. The progression and timing of sub-freezing air, combined with snow cover or lack thereof and the amount of soil moisture, determines the frost depth, or the depth to which the soil is frozen solid. It is difficult to determine the full impact of frost depth on the extent and magnitude of the flood the following spring independent of all other factors. However, it plays a critical role in determining the magnitude of surface runoff into the river system. A deeper frost depth reduces moisture penetration into the soil, thus allowing prolonged ponding and runoff into the river system. A more shallow frost depth can thaw more quickly, allowing snowmelt water to saturate the soil to deeper levels first before running off into the river system.

Snow depth varies significantly throughout the winter as it compacts, drifts, and changes density. However, additional liquid water from snowfall (snow water equivalent, SWE) accumulates and does not runoff into the river system. Snow depth is less important than SWE as it relates to spring flooding. In 2009, many basin residents did not fully comprehend the flood threat because there was not as much snow compared to the winter preceding the 1997 flood (NWS 1998). It is important to note that surface-based observations can be deceiving in determining flood threat, since many flood factors are unseen. As with autumn rains, above average SWE in winter does not in itself guarantee spring flooding. Conversely, below average SWE does not mean spring flooding cannot occur.

a) Temperature, Initial Snowpack, and Soil Frost Depth

Observations of soil temperature and frost depth across the Red River basin are sparse due to a limited number of sites with the proper equipment. In addition, it has been shown that measured frost depths from National Weather Service (NWS) liquid-in frost depth probes are deeper than those interpolated from deep soil temperature data collected by the automated North Dakota Agricultural Weather Network (NDAWN; Akyuz et al. 2008). Trends between these datasets, however, were nearly identical.

There are a variety of factors that impact the exactitude of these observed data. These include the frequency of calibration of NDAWN soil temperature systems, the known instrument drift of the temperature equipment employed, and the aforementioned variances of soils. As there are no known in-situ data to actually observe the behavior of sub-surface frost, much of what is understood is conceptually derived.

For example, we know that “dry soils” will not freeze as readily as “wet soils.” Therefore, temperatures below 0 degrees Celsius (°C) may not connote significant frost, or frost with the tensile strength necessary to prevent infiltration. For this reason, frost depth as indicated by the NWS liquid-in frost depth probes may not equate to the depth of the 0 °C isotherm. Quantifying this difference between wet and dry is based on information from the United States Department of Agriculture (USDA) and other agricultural sources.

From this, year-to-year comparative generalizations about frost depth can be made based on air temperature, soil temperature, and snow depth data. Assuming the Fargo NDAWN data are representative of the region; the average daily temperature first dropped below freezing on 8 November 2008, and remained consistently below that mark after 15 November (Figure 6). Meanwhile, the 1200 UTC snow depths did not exceed one inch until 6 December 2008, meaning sub-freezing air was in contact with bare ground for nearly three weeks. The rate at which soil temperatures from 20 to 50 cm decreased slowed significantly once snow started to accumulate. This would suggest the snow provides an insulating layer between the sub-freezing air and warmer soil at greater depths. However, the prolonged period of snow-free ground allowed the 50-cm soil depth to drop below freezing by early March.

In contrast, the average daily temperature at Fargo did not consistently drop below freezing in 2009 until 2 December (Figure 6), and was followed by three 1- to 2-inch snowfalls over the following two weeks. While not much snow, the insulating effect kept the 40-cm soil depth above freezing until mid-February, and the 50-cm depth remained above 0 °C the entire winter. 2010 was similar to 2009, in that the time elapsed between sub-freezing temperatures and significant snowfall was minimal (Figure 6). The daily average temperature at Fargo consistently dropped below freezing beginning on 17 November 2010 and was followed by a substantial snowpack five days later. Interestingly, only the near-surface-to-20-cmsoil depths dropped below freezing. Since greater soil moisture tends to delay freeze-up, this shallower sub-freezing soil layer compared to 2008 and 2009 may have been the result of the extremely moist conditions region-wide prior to freeze-up as shown in Figure 4.

b) Snow and Snow Water Equivalent (SWE)

As mentioned in Section 2a), snowfall prior to the meteorological winter season was minimal in two of the three years, with 2010 being the exception. Above-average snowfall, sometimes by as much as 20 inches, was observed for each winter season at the three climate stations (Figure 7) maintained by the National Weather Service office in Grand Forks, North Dakota. The lesser amounts and anomalies at the Grand Forks International Airport (GFK) are likely due to its more open site location, being more prone to blowing and drifting snow. Snow measurements for FAR were made by an observer located in Moorhead, Minnesota.

SWE is a better predictor for the possible magnitude and extent of a spring snowmelt flood. Interestingly, there was significantly more liquid water in the snowpack at FAR compared to

FGF and GFK each winter season (Figure 8). In fact, below-average SWE values were observed at FGF and GFK in 2010-2011. For 2008-2009 and 2009-2010, FGF and GFK SWE values were slightly above or below average.

Since point observations may not be representative of a region, it is important to investigate the spatial distribution of snow depth and liquid water across the basin. At 0600 UTC 1 March 2009, the axis of greatest snow depth bisected North Dakota from northwest to southeast (Figure 9, left panel). The spatial distribution of snow depth one year later was similar, but the highest values extended a bit farther south into northeastern South Dakota and southwestern Minnesota. In 2011, the distribution was very different with the snow depth maxima across northeastern South Dakota into west-central Minnesota. Snow depth and snowfall are not synonymous due to melting and compaction, which can result in lower depths compared to cumulative snowfall. However, it is clear that in each year, the lower Sheyenne River Basin and Red River headwaters received more snow than the northern Red River Valley and most of northwestern Minnesota. In general, greater snow depth equates to greater SWE values. In this case, the areas of greatest snow depth do indeed match well with the areas of highest SWE (Figure 9, right panel).

## 4. SPRING SEASON COMPARISON

Meteorological spring is defined by the three months of March, April, and May. The primary factors to consider during this period include the melt cycle and any additional precipitation as the snowpack is ripening, or changing phase from solid to liquid. SWE with respect to snow depth is a measure of the density of the snowpack. Snow density is one of the precursors used to monitor the snowpack as it warms and ripens before melting initiates. Operational experience suggests that once the density is around 20 percent (i.e., one inch of water equivalent per five inches of snow depth), the snowpack is nearing the liquid phase. When this occurs, the snowpack temperature is near the freezing/melting point of 0 °C, or 32 degrees Fahrenheit (°F). The time required for ripening will vary as diurnal surface temperature fluctuations, latent heat release due to condensation of atmospheric water vapor, and thermal input associated with warm rainfall interact with the snowpack. However, the latent heat of condensation is nearly seven times larger than the latent heat of melting, so that a saturated air mass in contact with the ground (i.e., fog) will accelerate the melt with or without additional rainfall. All these processes occurred at least once in these major flood events.

Historically, major springtime floods across the basin tend to occur in April, but can be as late as early May (Nelson 1951). Meteorological conditions for these events typically unfold with a cold and active March period, which prolongs the snow season and allows additional snowpack to accumulate. Furthermore, as melting of the snowpack is delayed later into the spring, there is an increased threat for convectively enhanced heavy rains. Rainfall on the existing snowpack adds to the SWE and quickens the snowpack ripening and eventual runoff into the river system.

Additional rainfall coinciding with the onset of runoff, or falling on frozen ground can worsen the flood's severity.

The state of the soil (i.e., frozen or thawed and wet or dry) is also an important consideration during the melt cycle. As has been previously stated, much of what is known is parameterized and not actually observed. That does not prevent us from making scientifically based suppositions. The ratio of surface runoff to soil infiltration from water in the system is determined by the amount of frost and moisture in the soil.  If the ground is frozen during the melt, it acts as a slab of concrete and there is near 100 percent surface runoff.  If the ground has thawed after the snow depth drops to zero and air temperatures rise above freezing (Figure 6), some amount of infiltration is expected if the soil is not already saturated.  Preliminary in-house research at the NWS North Central River Forecast Center (NCRFC) suggests this ratio varies widely from year-to-year and location-to-location depending on a number of different factors that are not yet fully understood.  However, for the 2009, 2010, and 2011 floods, surface runoff was high compared to infiltration (50 to 80 percent), since the soil was either frozen or saturated for most of the melt cycle (S. Buan 2013, personal communication).

a) 2009 Melt Cycle and Precipitation

In 2009, FAR received a record amount of precipitation (rain and snow water equivalent) for the month of March.  Between 2.5 and 3 inches of liquid precipitation fell across the southern basin on 22-24 March (Figure 10), coinciding with the latter half of a prolonged period of above freezing temperatures (14-17 March and 20-24 March). The daily average temperatures of 18-19 March were in the middle 20s, but hourly values climbed above freezing during the day.  The heavy precipitation that fell helped melt the remaining snowpack and triggered extremely efficient runoff (greater than 90%).  This high rate of runoff can be visualized by examining the rates of change in river stage at the Fargo river gauge (FGON8) for all three years (Figure 11).

The widespread, heavy rainfall over the water-laden snowpack and frozen soil (i.e., no soil infiltration) caused all the Red River's southern tributaries to discharge high volumes of runoff nearly simultaneously.  Record flow was observed upstream of FGON8 along the Wild Rice River at Abercrombie (crested 26 March 2009) and along the Red River at Wahpeton (crested 24 March 2009), which included contributions from the Bois de Sioux and Otter Tail Rivers.  Flow at Wahpeton was approximately 20% greater than that observed in 1997 (not shown). Undoubtedly, the crest at Wahpeton would have been much higher had the diversion (completed in 2005) not been in place.  The Red River at FGON8 crested on 28 March at 40.84 ft., over a foot and a half higher than the previous record set in 1997.  The middle and upper Sheyenne River basin did not contribute to this initial crest since this area received little rainfall and its deeper snowpack remained frozen.   Rather, once its snowmelt reached the main-stem Red River, it prolonged the flooding during the recession phase (not shown).  Rainfall enhanced the snowmelt runoff and caused a peak along the Sheyenne River at Kindred at the end of March.

However, the snowmelt flood was delayed and arrived approximately two weeks later at Valley City and Lisbon (Figure 12).

b) 2010 Melt Cycle and Precipitation

In contrast, the springtime hydrometeorological conditions leading to the 2010 flood were vastly different. A large, central Plains storm system transported low-level moisture across much of the basin beginning the second week of March. As the low center slowed and stalled over Iowa, cloud cover and fog persisted for 7-10 days and light rain bands wrapped north and west over the Red River basin on 9-12 March. Three rounds of light rain resulted in widespread amounts of 1.5 to 2.0 inches. Interestingly, the prolonged fog hindered on-the-ground observations of the ripening and melting of the snowpack and progress of the thaw.

Record warm daily minimum temperatures were observed at FAR and GFK on 8-15 March (Table 2) and surface dew point temperatures during this period ranged from 30 to 40 °F. The snowpack ripened extremely efficiently due to a large release of latent heat. Melting due to light rain increased snowpack temperatures and condensation associated with advection fog warmed the surface layer. These two processes acted on an extremely pristine snowpack, one with few ice layers which would have slowed the melting process. The mid-winter snowpack temperatures of 15 to 20 °F at the beginning of the month increased relatively quickly and the spring melt-runoff cycle started in an extraordinarily early and unanticipated way. During this time, the ground also remained frozen, meaning little soil infiltration occurred and the melt water increased surface runoff.

The melt cycle also produced a gradual release of runoff into the river system spatially across the Red River basin. The tributaries in west-central Minnesota, including the Rabbit, Otter Tail and Buffalo River basins, were the first to experience this unusual melt initiation sequence of advection fog, rainfall and the prolonged period of melting temperatures. With a lesser snowpack and SWE in comparison to other parts of the Red River basin, the crest wave moved into the main-stem river sooner than the crest wave from the Bois de Sioux River, which had a deeper snowpack in its basin and was slower to ripen. This gradual melt initialization process took longer where the snow was deeper, especially across the Wild Rice River basin in North Dakota, and was delayed even longer to the northwest. This overall progression from east to west in runoff initialization allowed the peak flows on the tributaries to offset each other along the main-stem Red River, which minimized the potential for a higher overall crest.

This overall pattern was highly anomalous and differed from a typical south-to-north melt cycle, as in 2009 when very heavy rainfall also resulted in a nearly simultaneous release of water from the tributaries across the southern basin. The majority of flood crests observed in 2010 were also anomalous in that they occurred in March, whereas most of the larger Red River basin floods peak in mid to late April.

c) 2011 Melt Cycle and Precipitation

The 2011 spring melt-runoff was climatologically more typical of historical Red River floods. A cold March resulted in a more prolonged period of residual snowpack and SWE to accumulate across the watershed. This sub-freezing period ultimately gave way to warmer temperatures by the beginning of April. These above-freezing temperatures occurred first in the southern basin where the runoff initiated by 1 April. The ground completely thawed during the melt cycle (Figure 6), but saturated soil limited the amount of infiltration and increased surface runoff. The crest along the Red River at Wahpeton occurred on 7 April, while the Wild Rice River at Abercrombie crested on 6 April. These flows combined to result in a crest of 38.81 ft. on 9 April at FGON8.

In 2011, it took 11 days for the Red River at FGON8 to rise from its defined flood stage of 18 ft. to its crest. However, in 2009, it took only 8 days to rise from flood stage to its crest of 40.84 ft., about two feet higher. This difference is highlighted in Figure 11. This suggests that the temperature-induced runoff into the river system was much slower than the rainfall-enhanced runoff. This was supported by the range of crest dates along the main-stem river (Figure 13). The crest dates in 2011 ranged from 7 April at Wahpeton to 14 April at East Grand Forks, a period of 7 days. The 2010 range for these same locations was 5 days. The 2009 range of dates was also 7 days, but is suspect in this analysis due to the melt-runoff being interrupted by a winter storm and sub-freezing temperatures at the end of March, which slowed runoff across the northern basin. During the 2011 melt-runoff there were no significant liquid precipitation events which impacted the flows in the river system.

## 5. DISCUSSION

The 2009, 2010, and 2011 Red River basin floods, taken together, were historically unprecedented. The economic impacts to the basin were staggering and the disruptions to livelihoods and business were widespread and long-lasting. As of this writing, there are no known reports that summarize the actual or estimated monetary loss due to the floods. On all accounts, the 2009 flood was the most severe of the three events. Of the thirty-two locations that the National Weather Service in Grand Forks issues river flood forecasts for, six observed all-time record crests, and another fourteen were ranked second or third highest crest in the observational record (Table 3). The Red River at FGON8 increased from flood stage at 18.0 ft to its record crest of 40.84 ft. in approximately one week in late March 2009. Overland flooding was extensive, especially across portions of southeastern North Dakota along the lower Sheyenne and Wild Rice Rivers downstream to the Red River around the Fargo-Moorhead area. In addition, the Red River spread out several miles from its channel north of Grand Forks, so that the ring-diked town of Oslo, Minnesota became a virtual island for several weeks.

The 2010 flood was still a major event, but more manageable when compared to 2009. Only five river forecast point crests ranked in the top three (Table 3). The rate at which rivers rose to their crests was similar to 2009, but their magnitude was generally lower. Overland flooding was still problematic, but not as widespread or severe. No record crests were observed in 2011 at the river forecast points, but eleven crests ranked in the top three, four of which were along the main-stem Red River (Table 3). The rivers rose much more gradually in 2011 compared to 2009 and 2010, but interestingly, overland flooding was worse in some areas. This was particularly true near the confluence of the Sheyenne, Maple, and Rush Rivers where the timing of individual crests coincided west of the Fargo-Moorhead area. Interstate 29 was closed across a span of 31 miles north of Fargo for several days due to water over the roadway. More common overland flooding occurred again north of Grand Forks surrounding the city of Oslo, Minnesota.

Of the hydrometeorological factors monitored to predict Red River floods and discussed in the preceding sections, the 2009 flood was a summation of above-average autumn rainfall (5 inches or more), high soil moisture at freeze-up (PDSI greater than 2.5), high winter river baseflow (75$^{th}$ percentile or higher), deep frost depth (4 feet or more; based on National Weather Service liquid-in frost depth probes), above-average SWE (3 inches or more), a rapid melt cycle (at least 5 consecutive days with average temperature greater than 32 °F), and heavy precipitation during the melt (1 inch or more; Figure 14 and Table 4). Quantitative descriptors for each factor are based on operational experience and local unpublished research conducted at the National Weather Service forecast office in Grand Forks, North Dakota. The first five of these factors set the stage for significant springtime flooding. However, the combination of a rapid snowmelt basin-wide, made worse by additional rainfall, guaranteed a significant, and in some places record-setting flood event. In addition, saturated, frozen soils did not allow the snowmelt and additional rainfall to infiltrate the topsoil and only increased the rate of runoff into the river system. The cumulative and unfortunate timing of crests from individual tributaries contributed to record flow on the main-stem Red River.

Factors that differed in 2010 included less autumn rainfall and frost depths that were not as deep compared to 2009 (Table 4). Autumn rainfall was well above average across the southern basin, but near or slightly below normal across much of the northern basin. In addition, the ground thawed more quickly in the spring, allowing for greater infiltration of snowmelt and additional rainfall into the soil, reducing overall runoff. Even with a rapid melt cycle quickened by advection fog and additional rainfall, the lesser magnitude of the 2010 flood may be best explained by the unequal spatial distribution of the runoff. In general, the crests along the Minnesota tributaries moved into the main-stem Red River before those of the North Dakota tributaries. This east-to-west initialization of the runoff likely played a key role in the overall lower crests during the 2010 flood. Interestingly, the evolution of the snowmelt and additional springtime rains likely resulted in the late March crests during the 2009 and 2010 floods (Figure 14).

The 2011 flood was more synonymous with how a typical Red River flood evolves. The majority of river crests occurred in April and the rate of rise was much slower than in 2009 and 2010. However, the cumulative effect of the two previous wet years played an instrumental role in 2011. The major differences for the 2011 flood compared to 2009 and 2010 were the lack of a rapid snowmelt cycle and minimal additional rainfall during the melt (Table 4). Had these factors occurred in 2011, the flood's magnitude could have surpassed that of 2009. Instead, a gradual south-to-north snow melt resulted in more manageable crests.

Due to the number of hydrometeorological factors involved in Red River Basin floods and their complex interdependency, it is difficult to state with certainty that one or two factors outweigh all others. However, from the above analysis, the snowmelt cycle and rainfall during the melt appear to be critical factors to a flood's overall extent and magnitude (Figure 14). In 2010, less favorable conditions for flooding prior to the spring were made worse by a rapid melt, advection fog, and additional rainfall. Conversely, in 2011, favorable conditions for flooding prior to the spring were eased by a slow melt and little additional precipitation. Since the melt cycle and springtime precipitation are not well known until several days before the rivers crest, it is imperative that decision makers prepare for a variety of possible outcomes based on the known factors prior to the melt onset.

## 6. SUMMARY

The 2009, 2010 and 2011 spring floods across the Red River basin will be recorded as three of the most significant and high-impact flood events in modern history for the northern Plains. How these individual, yet consecutive events relate to the overall wet cycle that has been in place across the basin since the mid-1990s is yet to be seen and is a topic for further study. Numerous river level records were broken during this three-year period, with several river forecast points in the top three for all-time highest crests. These high river levels over this period can be attributed to many hydro-meteorological factors including above average rainfall in autumn, extremely wet soil conditions leading into freeze-up, thick river ice and deep frost, multi-seasonal above normal precipitation, and a rapid melt combined with additional precipitation at the onset of the melt. While no two floods are the same, it is apparent that the 2009-2011 spring floods in the Red River basin will be remembered for their severity and long-lasting impacts throughout the region. Lastly, it is worth mentioning there was no spring snowmelt flood in 2012 due to much drier conditions the preceding year. However, the return to above-normal snowfall for the 2012-2013 winter season, combined with an unseasonably cold March and April led to a manageable, yet historically late spring snowmelt flood in 2013.

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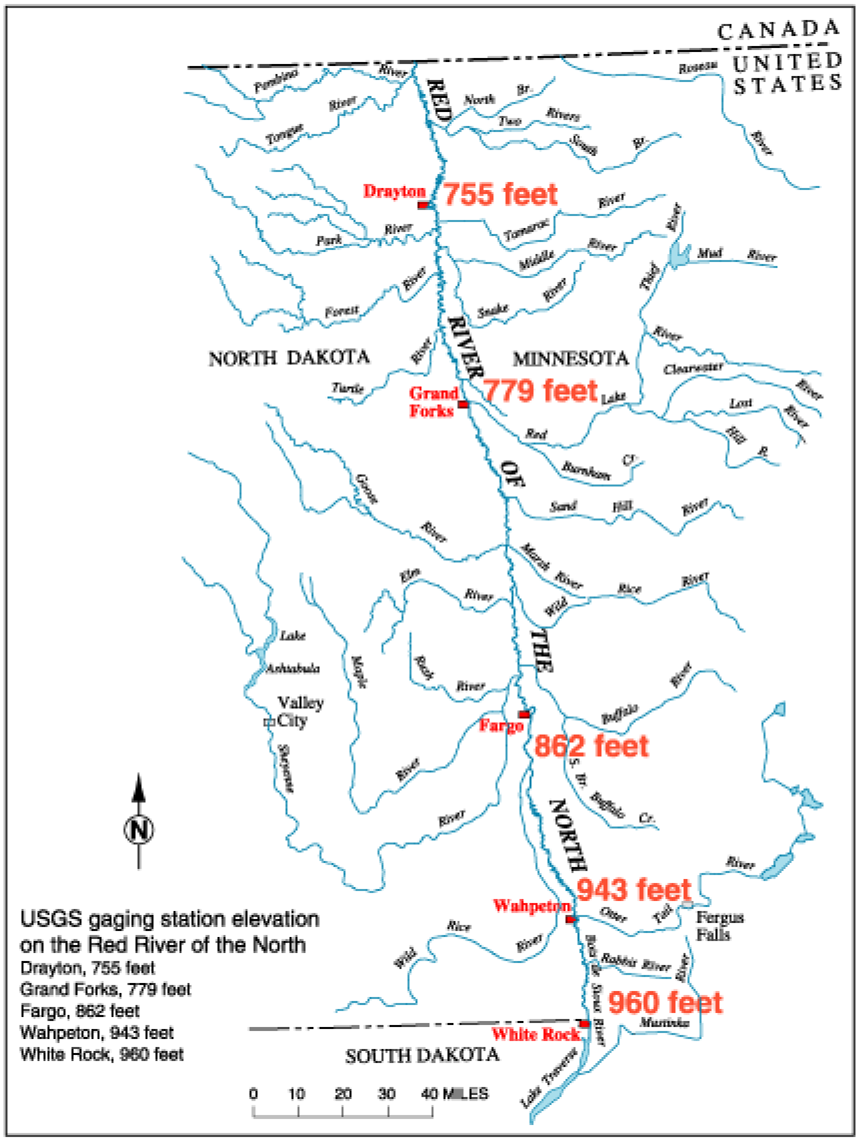


Figure 1: Red River of the North and its tributaries, highlighting the elevations at major cities and the gradual slope of the river channel. Image courtesy of the U.S. Geological Survey (USGS).

| FGON8 Top Ten Crests | Sept | Oct | Nov | Total | | Diff |
|---|---|---|---|---|---|---|
| | | | | | | |
| (1) 40.84 ft on 03/28/2009 | 5.08 | 4.46 | 1.13 | 10.67 | | **4.95** |
| (2) 39.72 ft on 04/18/1997 | 3.18 | 2.41 | 2.38 | 7.97 | | **2.25** |
| (3) 39.10 ft on 04/07/1897 | 1.31 | 2.21 | 2.42 | 5.94 | | **0.22** |
| (4) 38.81 ft on 04/09/2011 | 5.82 | 1.91 | 0.73 | 8.46 | | **2.74** |
| (5) 37.34 ft on 04/15/1969 | 2.23 | 1.75 | 0.37 | 4.35 | | **-1.37** |
| (6) 37.13 ft on 04/05/2006 | 3.91 | 0.96 | 0.12 | 4.99 | | **-0.73** |
| (7) 36.99 ft on 03/21/2010 | 2.06 | 5.44 | 0.41 | 7.91 | | **2.19** |
| (8) 36.69 ft on 04/14/2001 | 3.64 | 1.96 | 4.13 | 9.73 | | **4.01** |
| (9) 35.39 ft on 04/09/1989 | 3.22 | 0.49 | 1.18 | 4.89 | | **-0.83** |
| (10) 34.93 ft on 04/19/1979 | 0.92 | 0.13 | 1.11 | 2.16 | | **-3.56** |

Table 1: Top ten flood crests (ft) along the Red River at Fargo, ND (FGON8); September, October, and November precipitation totals from the preceding year; and the total difference from the 1981 to 2010 autumnal normal.

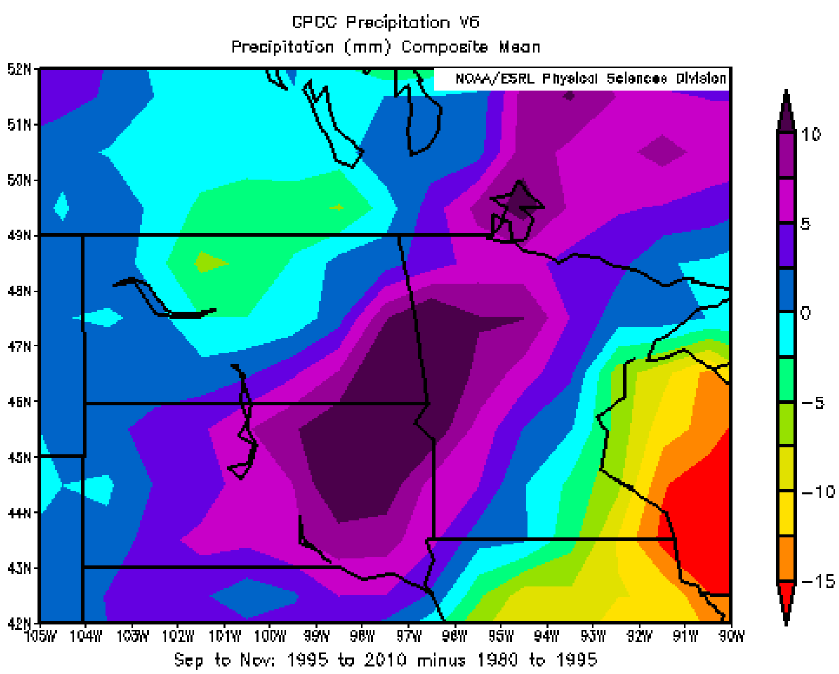


Figure 2: September through November 1995 to 2010 precipitation composite mean anomaly (mm). Anomaly was calculated using the 30-year (1980-2010) September through November precipitation composite mean (mm). Image created by NOAA ESRL.

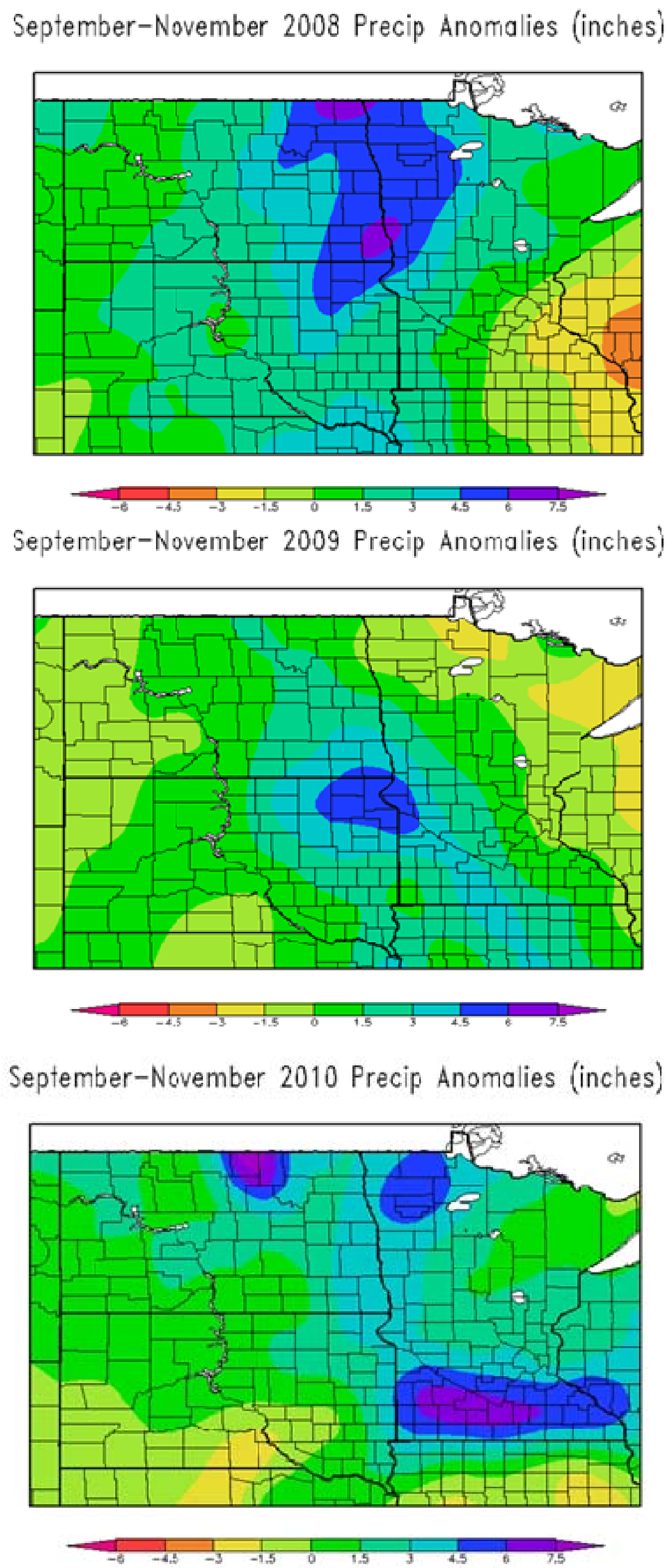


Figure 3: Departure from normal (1971-2000) precipitation (inches) from September through November 2008 (top), 2009 (middle), and 2010 (bottom) across the Dakotas and Minnesota. Image created by High Plains Regional Climate Center.

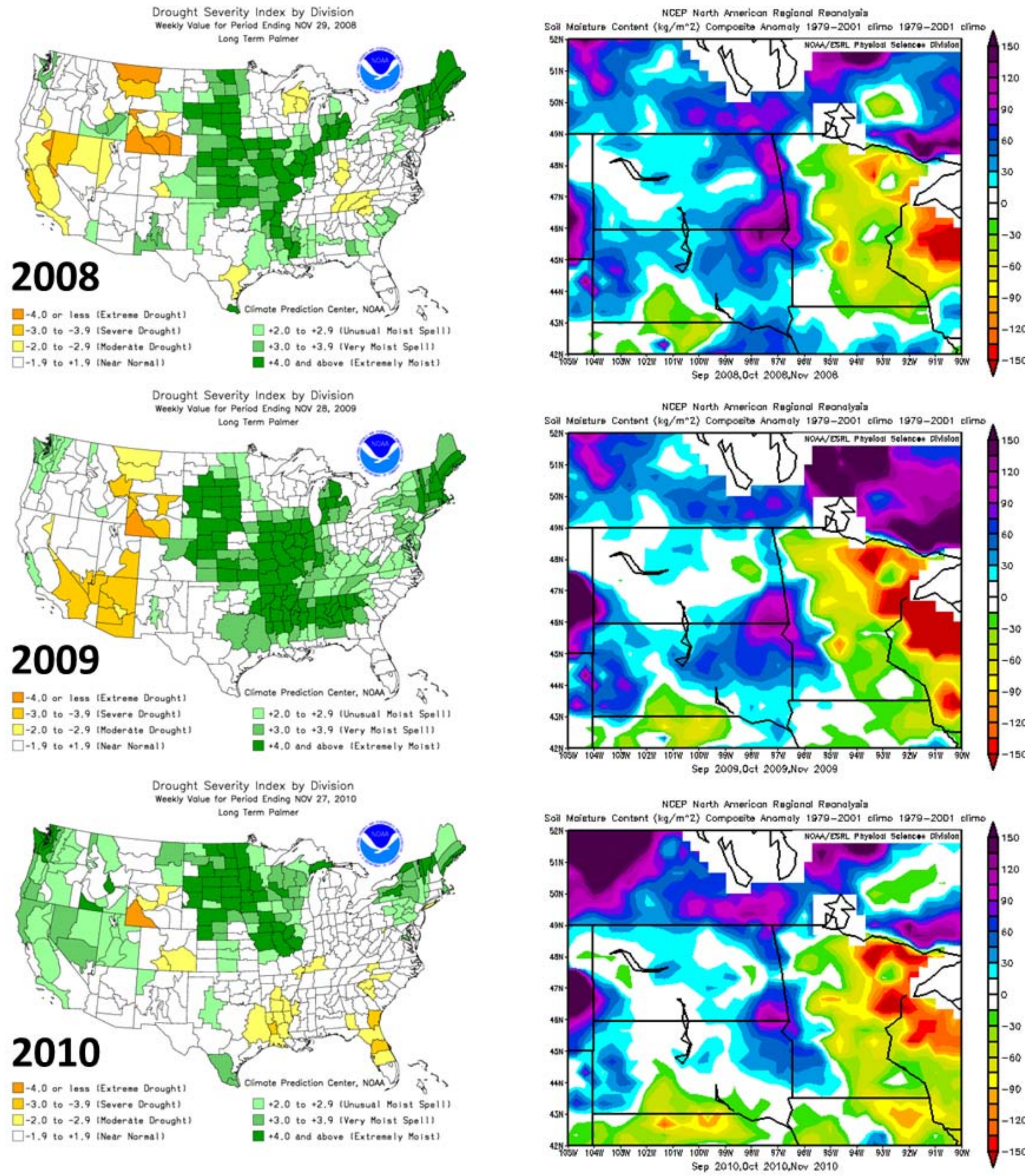


Figure 4: Palmer drought severity index (PDSI) ending the last week of November in 2008, 2009, and 2010 (left panel) and NCEP North American regional reanalysis (NARR) September, October, and November soil moisture content (kg $m^{-2}$) anomalies (1979-2001) in 2008, 2009, and 2010 (right panel).

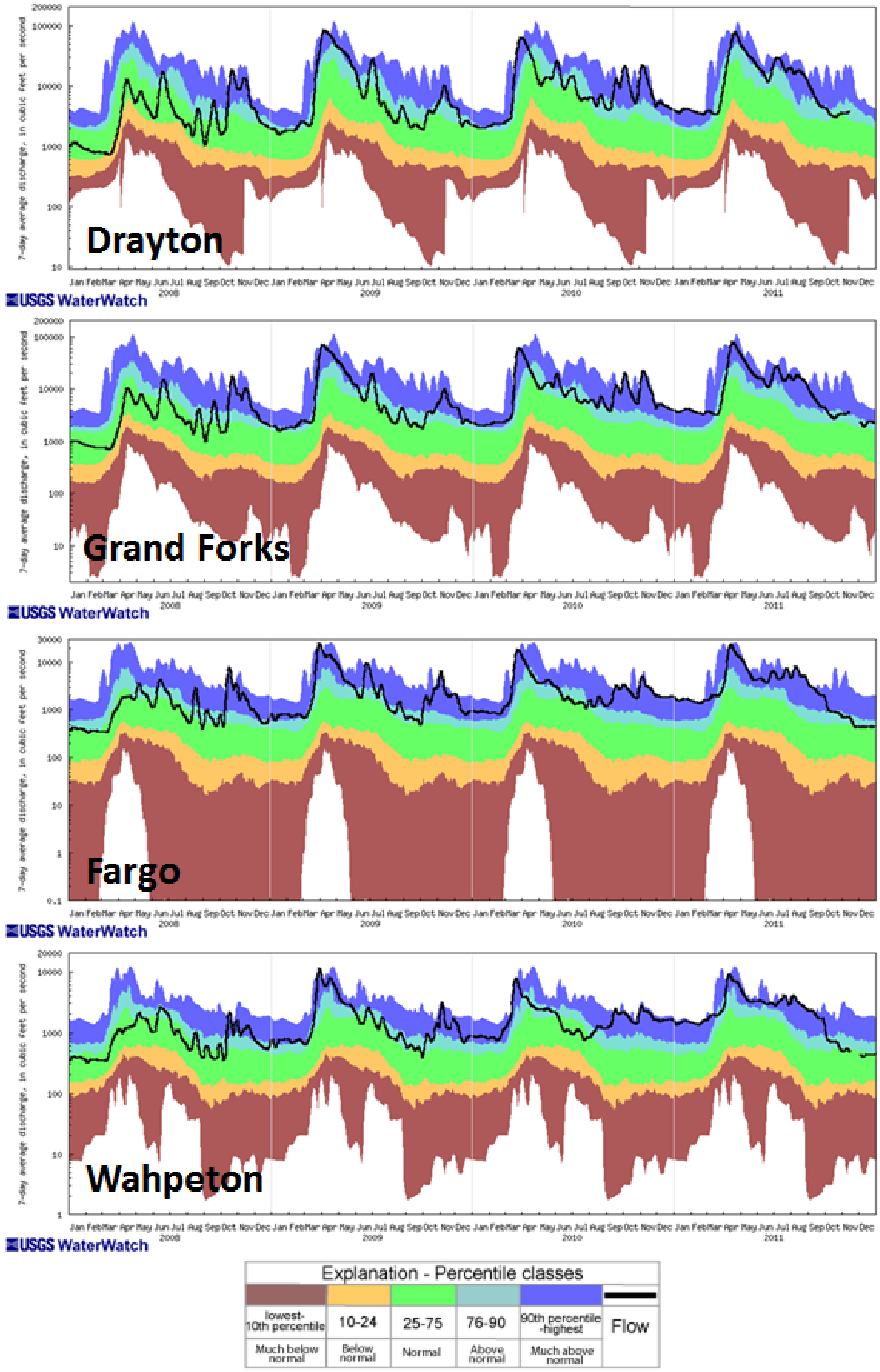


Figure 5: Duration hydrograph of 7-day average streamflow from 2008 to 2011 for Wahpeton, Fargo, Grand Forks, and Drayton. Graphic is a compilation of individual images courtesy of the U.S. Geological Survey (USGS).

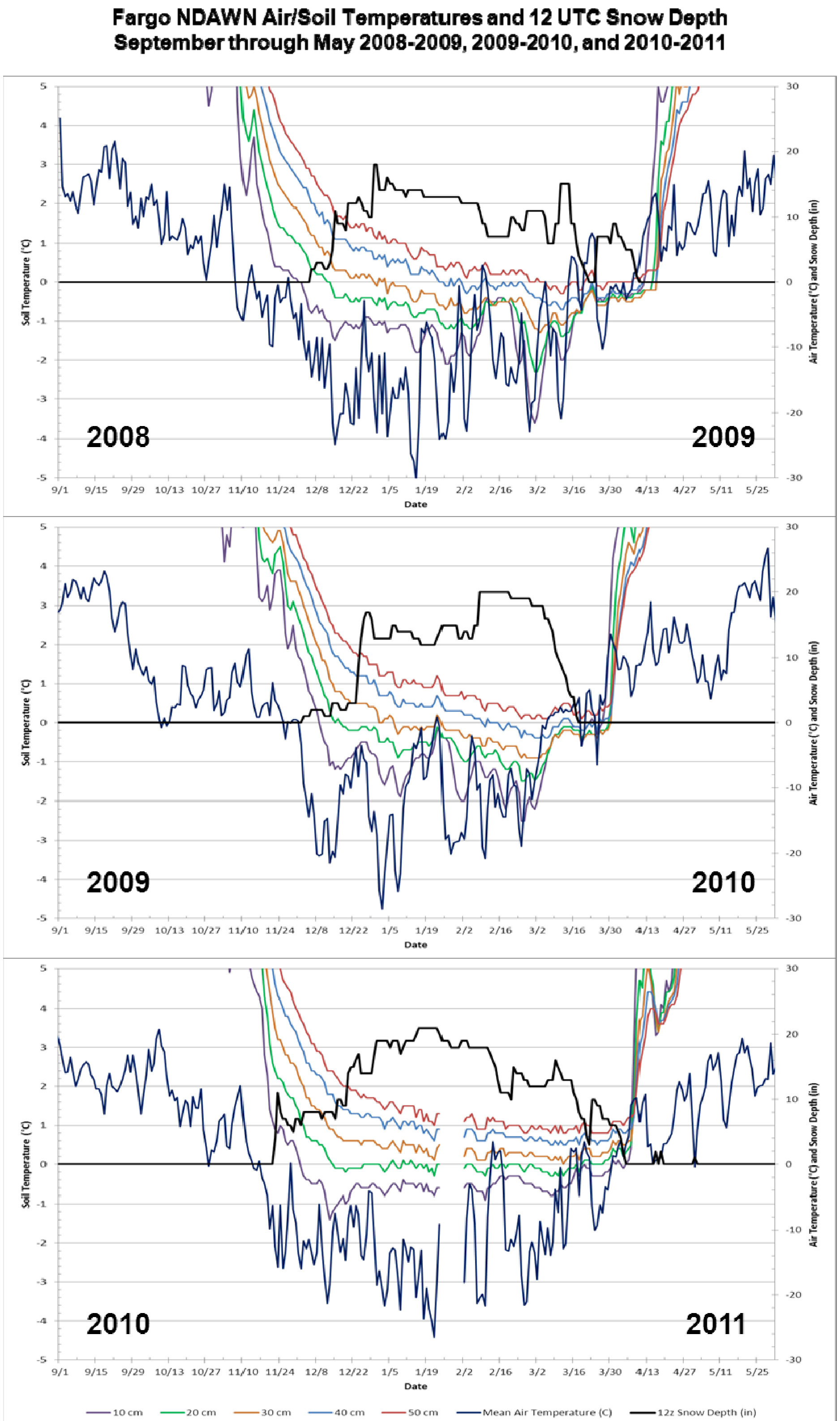


Figure 6: Fargo NDAWN air/soil temperatures and 1200 UTC snow depth September through May 2008-2009, 2009-2010, and 2010-2011.

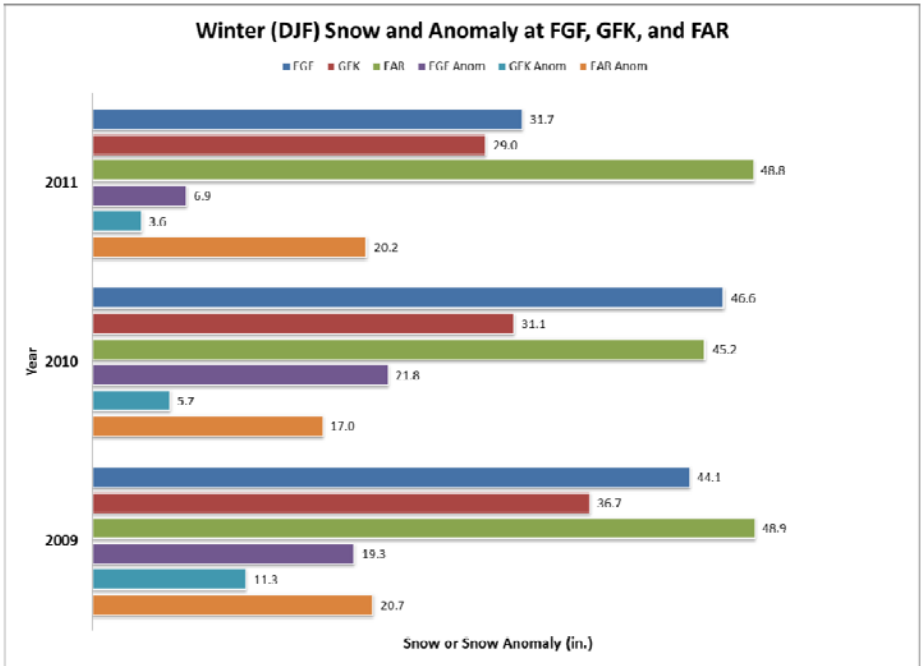


Figure 7: Winter (December, January, February) snowfall and snowfall anomaly at Grand Forks University climate station (FGF), Fargo Hector International Airport (FAR), and Grand Forks International Airport (GFK).

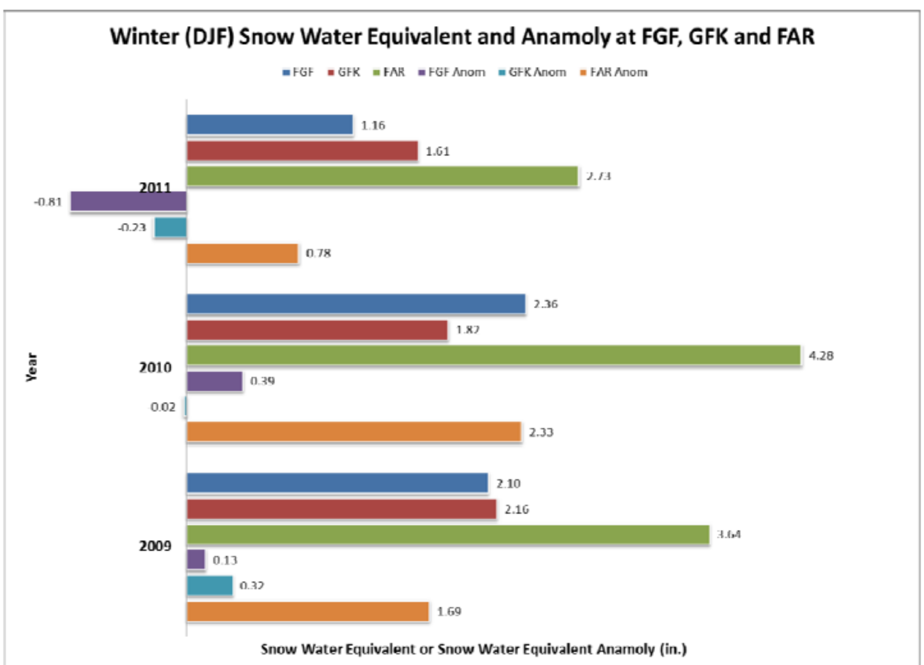


Figure 8: Winter (December, January, February) snow water equivalent and snow water equivalent anomaly at Grand Forks University climate station (FGF), Fargo Hector International Airport (FAR), and Grand Forks International Airport (GFK).

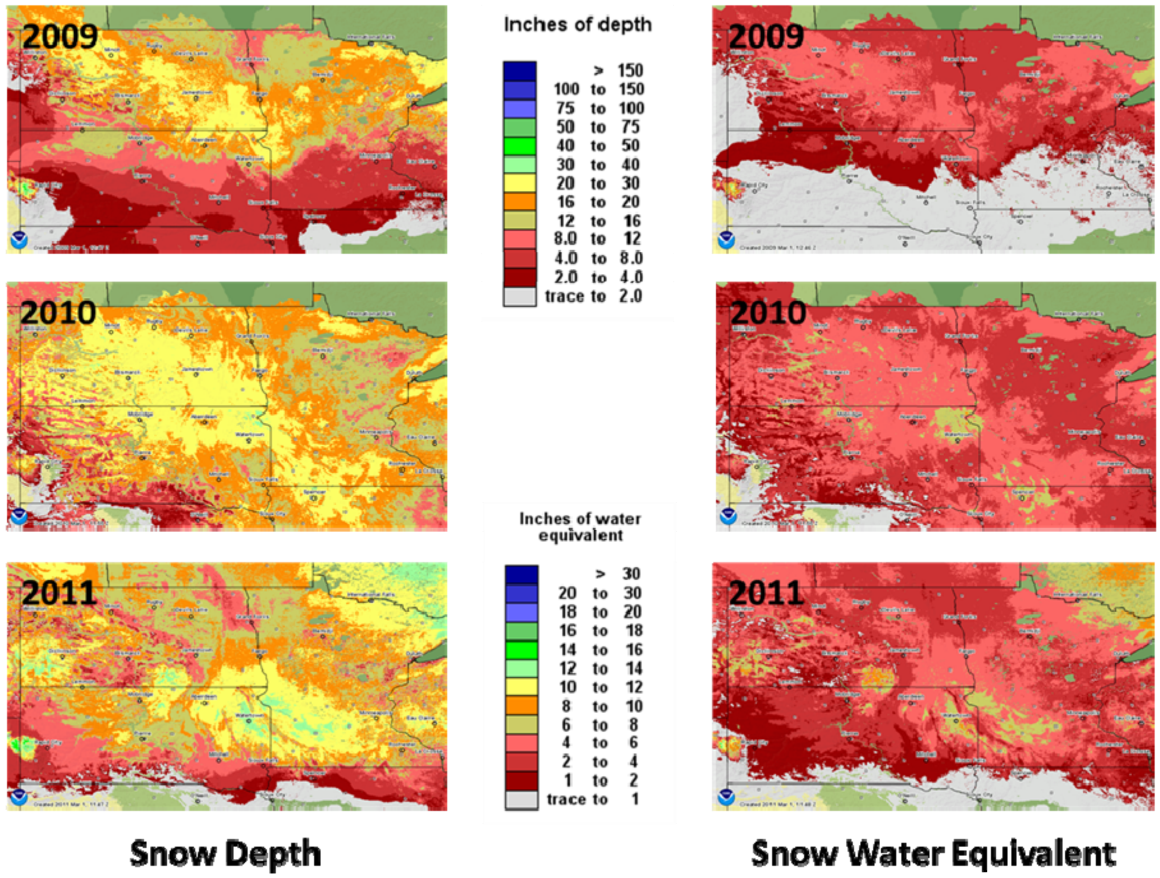


Figure 9: National Operational Hydrologic Remote Sensing Center (NOHRSC) modeled snow depth and snow water equivalent at 0600 UTC 1 March 2009, 2010, and 2011.

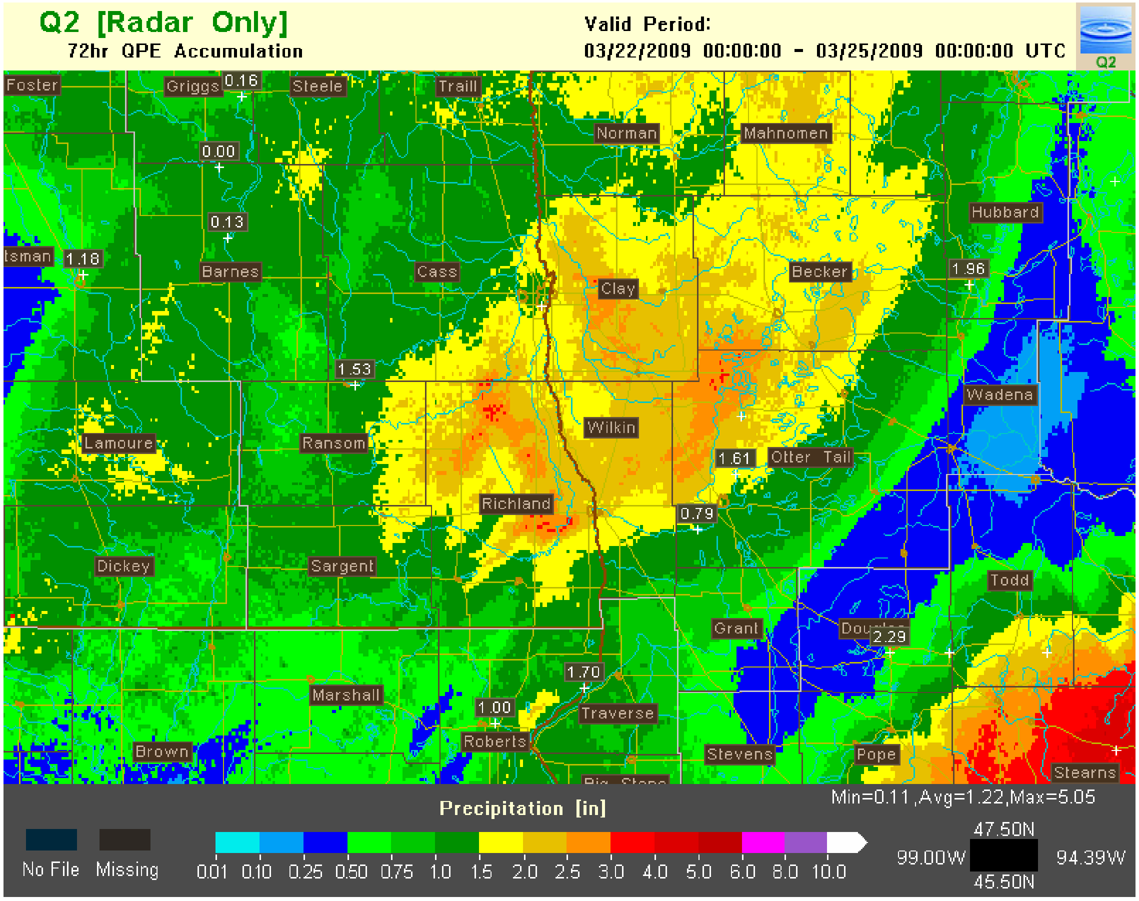


Figure 10: Total 72-hour precipitation in the southern Red River valley from 0000 UTC 22 March to 0000 UTC 25 March 2009. Notice the heavy rainfall in the 1.5- to 3-inch range across Sargent and Richland Counties in North Dakota extending northeastward into Clay, Wilkin, Becker and Otter Tail Counties in Minnesota.

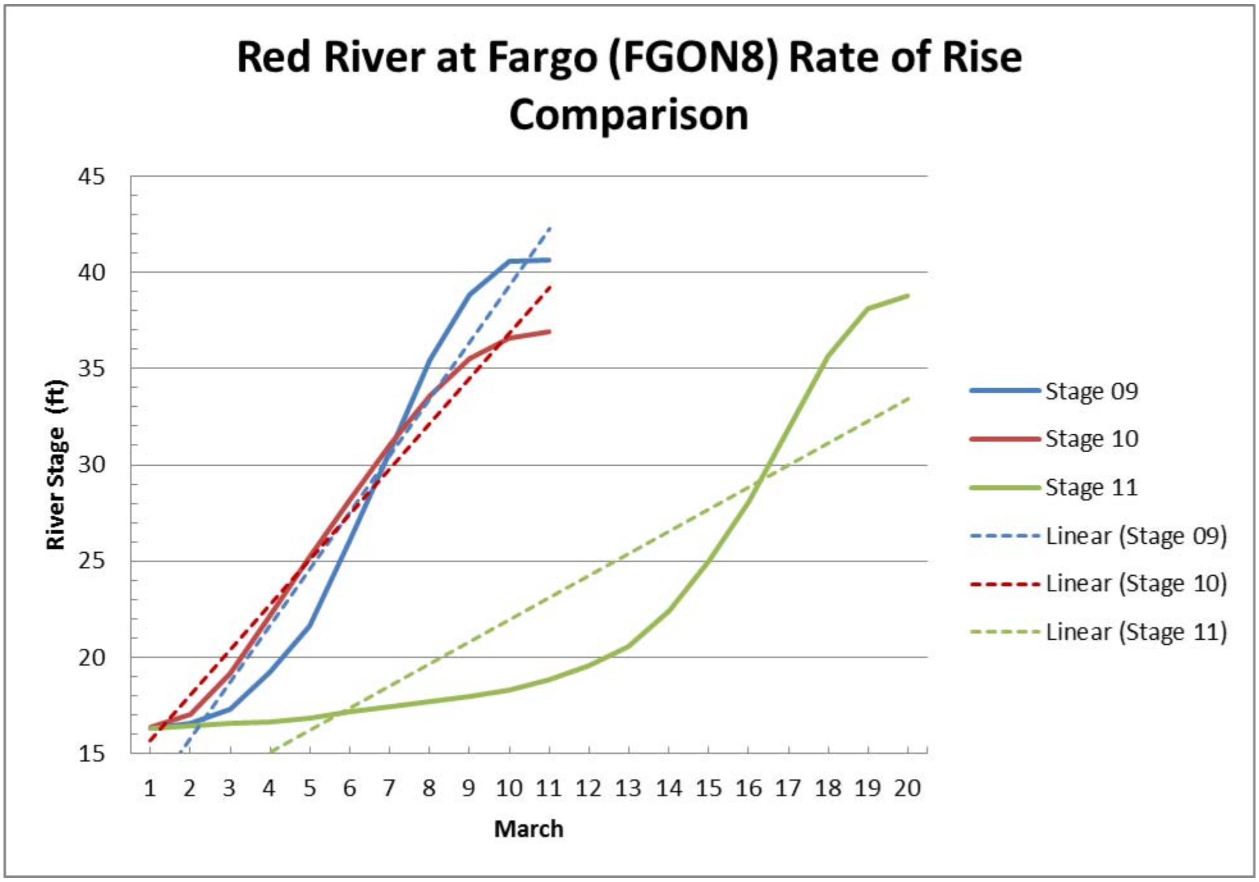


Figure 11: Red River at Fargo (FGON8) rate of rise for each of the spring floods beginning on 1 March. Linear regression curves are included to show the relative rate of rise. The river rose more rapidly in 2009 and 2010 due to additional rain on top of the snow pack compared to the more gradual snow melt induced rise in 2011. Advection fog also played a critical role in 2010.

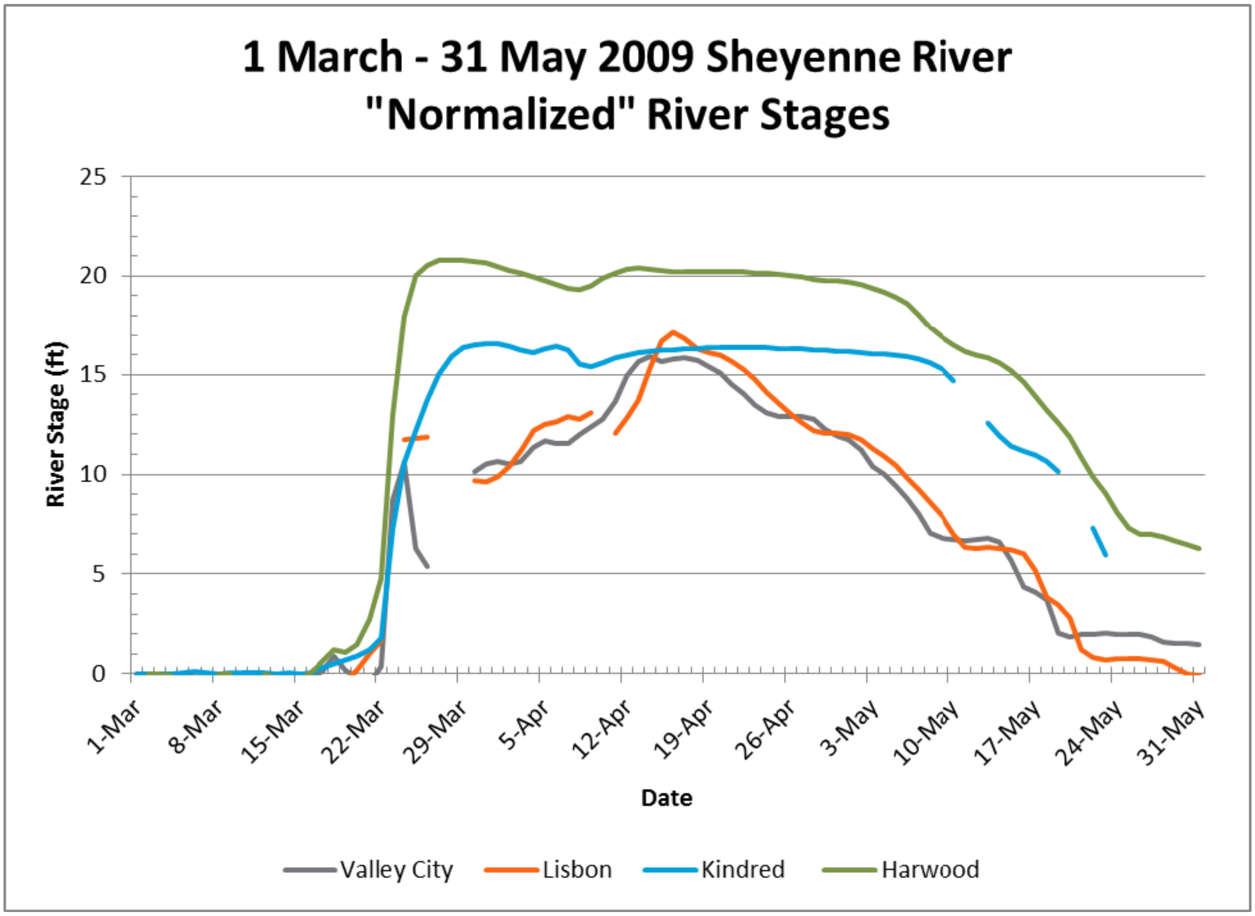


Figure 12: 2009 Sheyenne River normalized river stages from 1 March to 31 May. Curves were normalized by subtracting the river stage value at 0000 UTC 1 March from the entire time series at each location. Notice the latter peak flows at Lisbon and Valley City where snow melt was delayed compared to the Kindred and Harwood peaks where heavy rainfall induced dramatic rises in stage.

| FAR Rank | Value (°F) | Ending Date | | GFK Rank | Value (°F) | Ending Date |
|---|---|---|---|---|---|---|
| 1 | 34.0 | 3/15/2010 | | 1 | 33.8 | 3/15/1977 |
| 2 | 31.6 | 3/15/1977 | | 2 | 33.0 | 3/15/2010 |
| 3 | 31.1 | 3/15/1990 | | 3 | 31.6 | 3/15/1990 |
| 4 | 30.3 | 3/15/1973 | | 4 | 30.9 | 3/15/1985 |
| 5 | 30.2 | 3/15/1927 | | 5 | 30.1 | 3/15/1973 |

Table 2: 2010 March 7th to 15th average low temperatures. Fargo (FAR) is left-hand column, Grand Forks (GFK) is right-hand column. All eight nights were above freezing (previously unprecedented in the period of record) allowing the snowpack to continue to ripen/melt.

| FORECAST POINT | 2009 CREST (FT) | 2009 DATE | 2010 CREST (FT) | 2010 DATE | 2011 CREST (FT) | 2011 DATE |
|---|---|---|---|---|---|---|
| Wahpeton | 17.50 (3) | 24-Mar | 16.49 | 16-Mar | 15.69 | 7-Apr |
| Fargo | **40.84 (1)** | 28-Mar | 36.99 | 21-Mar | 38.81 (4) | 9-Apr |
| Halstad | 40.63 (2) | 30-Mar | 39.28 (5) | 22-Mar | 40.51 (3) | 12-Apr |
| East Grand Forks | 49.33 (4) | 1-Apr | 46.09 | 20-Mar | 49.86 (3) | 14-Apr |
| Oslo | **38.37 (1)** | 1-Apr | 37.87 (5) | 21-Mar | 38.09 (2) | 15-Apr |
| Drayton | 43.82 (2) | 6-Apr | 42.18 | 28-Mar | 43.17 (4) | 19-Apr |
| Pembina | 52.71 (2) | 15-Apr | 49.73 | 1-Apr | 51.92 (3) | 24-Apr |
| Abercrombie | **27.78 (1)** | 25-Mar | 24.61 | 19-Mar | 25.99 (4) | 6-Apr |
| Valley City | **20.69 (1)** | 13-Apr | 14.13 | 23-Mar | 20.66 (2) | 18-Apr |
| Lisbon | **22.86 (1)** | 16-Apr | 19.46 (3) | 22-Mar | 21.70 (2) | 20-Apr |
| Kindred | 21.55 (4) | 31-Mar | 21.44 | 21-Mar | 21.29 | 27-Apr |
| W Fargo Diversion | 22.88 (5) | 27-Mar | 21.82 | 25-Mar | 22.66 | 29-Apr |
| Harwood | 891.72 (3) | 29-Mar | 891.56 (4) | 20-Mar | 891.82 (2) | 10-Apr |
| Enderlin | 14.14 (2) | 24-Mar | 13.71 (3) | 18-Mar | 13.31 (5) | 11-Apr |
| Mapleton | 909.73 (3) | 25-Mar | 909.44 (5) | 17-Mar | 909.77 (2) | 7-Apr |
| Sabin | 19.08 (3) | 25-Mar | 17.58 | 15-Mar | 16.20 | 4-Apr |
| Hawley | 10.60 (5) | 25-Mar | 9.60 | 15-Mar | 9.16 | 12-Apr |
| Dilworth | 25.86 (3) | 25-Mar | 24.29 (5) | 17-Mar | 22.89 | 6-Apr |
| Twin Valley | 13.53 | 25-Mar | 14.71 (4) | 14-Mar | 9.78 | 11-Apr |
| Hendrum | 33.56 (2) | 29-Mar | 31.76 | 17-Mar | 33.06 (3) | 12-Apr |
| Shelly | 24.95 (3) | 25-Mar | 22.52 | 17-Mar | 22.43 | 12-Apr |
| Climax | 33.43 (3) | 1-Apr | 29.85 | 23-Mar | 34.56 (2) | 13-Apr |
| High Landing | **13.61 (1)** | 25-Mar | 12.21 | 14-Mar | 11.27 | 11-Apr |
| Crookston | 25.63 | 24-Mar | 23.97 | 15-Mar | 20.77 | 7-Apr |
| Minto | 8.35 | 24-Mar | 8.62 | 18-Mar | 4.23 | 5-Apr |
| Alvarado | 109.63 (3) | 26-Mar | 109.66 (2) | 18-Mar | 105.46 | 12-Apr |
| Hallock | 808.40 | 28-Mar | 810.26 (2) | 15-Mar | 808.47 (5) | 11-Apr |
| Grafton | 15.71 | 16-Apr | 12.29 | 22-Mar | 12.56 | 13-Apr |
| Walhalla | 16.63 (2) | 19-Apr | 8.94 | 18-Mar | 16.55 (3) | 18-Apr |
| Neche | 21.61 | 20-Apr | 15.97 | 20-Mar | 21.78 | 11-Apr |
| Roseau | NA | NA | 16.06 | 16-Mar | NA | NA |
| Hillsboro | 16.67 (2) | 25-Mar | 15.64 (3) | 20-Mar | 15.50 (5) | 9-Apr |

Table 3: 2009, 2010, and 2011 crest statistics for the thirty-two National Weather Service Grand Forks Forecast Office river forecast points. Crest rank is provided in parentheses if in the top five and all-time record crests are bold-faced. Data highlighted in light blue were affected by ice and/or backwater and the date of maximum gauge height is not the same as the date of maximum observed flow. Data for the Roseau River at Roseau are not available (NA) for 2009 and 2011.

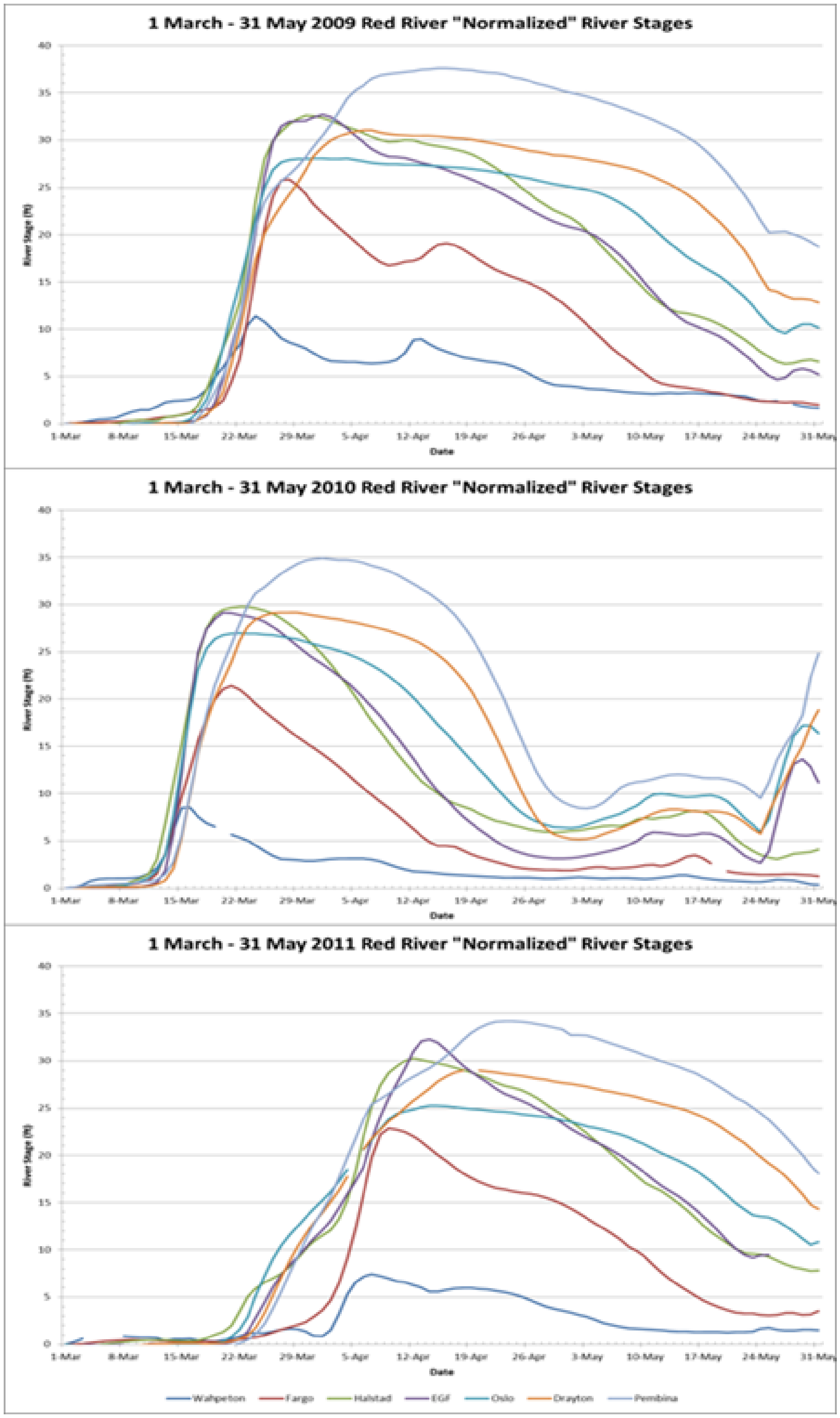


Figure 13: 2009, 2010, and 2011 Red River normalized river stages from 1 March to 31 May. Curves were normalized by subtracting the river stage value at 0000 UTC 1 March from the entire time series.

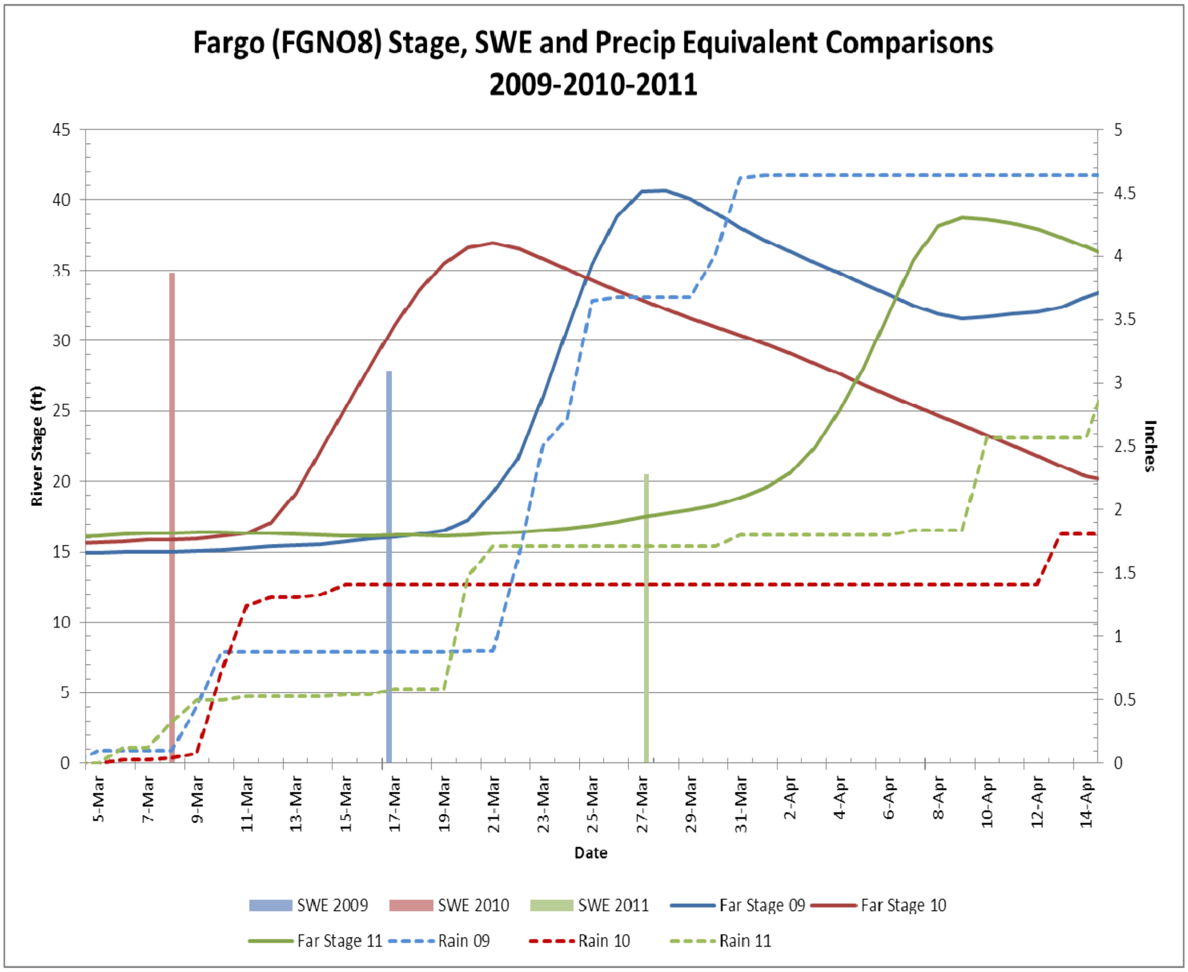


Figure 14: 2009, 2010, and 2011 FGNO8 river stage, SWE, and liquid equivalent precipitation at Fargo (FAR) at the start of the melt/runoff and during the rising limb of the hydrograph.

| Red River Spring Flood Factor | 2008-2009 | 2009-2010 | 2010-2011 |
|---|---|---|---|
| | | | |
| Above Average Autumn Rainfall (5 inches or more) | X | - | X |
| High Soil Moisture (PDSI > 2.5) | X | X | X |
| High River Streamflow (75th percentile or higher) | X | X | X |
| Deep Frost Depth (4 feet or more) | X | - | - |
| Above Average SWE (3 inches or more) | X | X | X |
| Rapid Melt Cycle (at least 5 days in a row avg. T > 32F) | X | X | - |
| Heavy Precipitation during Melt (1 inch or more) | X | X | - |

Table 4: Basin-wide average major flood factors that influenced the 2009, 2010, and 2011 floods. A (-) indicates little to no influence for the indicated flood season.