Greater Mississippi River Basin

Precipitation Trends

March 2025

Anna Wolverton
MVD Meteorologist & NWS Liaison

Cover image: Vibrant river image using high-resolution elevation data

Credit: Dan Coe/meanderandflow.com

Table of Contents

Introduction

The hydrologic conditions are shifting within the Mississippi River Basin, and the impacts are diverse and extensive. Temperatures are rising, snowpack is decreasing, and record rainfall events seem to be happening more and more often. The Mississippi River Basin is the largest watershed in North America, covers 1.25 million square miles, and drains 41% of the contiguous United States. How are the trends in hydrometeorology impacting this immense basin? When analyzing any trends within this watershed, it is prudent to look at the trends within each sub-basin, as topography and microclimates vary widely. The Mississippi River Basin is generally divided up into six sub-basins: 1) Upper Mississippi, 2) Missouri, 3) Ohio, 4) Tennessee-Cumberland, 5) Arkansas-Red, and 6) Lower Mississippi.

Trends in temperature and precipitation are generally calculated in 30-year periods. This is based on the statistical guideline that a minimum of 30 data points is required to reliably determine a mean trend. This helps remove any annual variations that may occur and ultimately reveals common trends over time. Thirty-year averages provide a baseline for comparing current weather to the "average" weather. For example, the Mississippi Valley experienced one of its wettest periods during the five-year period between January 2015 and December 2019. This falls in line with the data that reveals that the annual precipitation is increasing throughout much of the Mississippi Valley. However, the years since 2020 have been relatively drier and the Mississippi River has been plagued with low water several times. Nonetheless, it is imprudent to not make assumptions that the climate is shifting back towards a drier pattern, as the annual precipitation totals for the basin during those dry years did not necessarily correlate with the record-low river stages (i.e., the precipitation was not record low). This goes to show that there are other nuances at play within the greater hydrometeorological shifts that influence the Mississippi Valley other than total annual precipitation.

This document will cover the various shifts in hydrometeorology affecting the Mississippi Valley and highlight the changes that have been found.

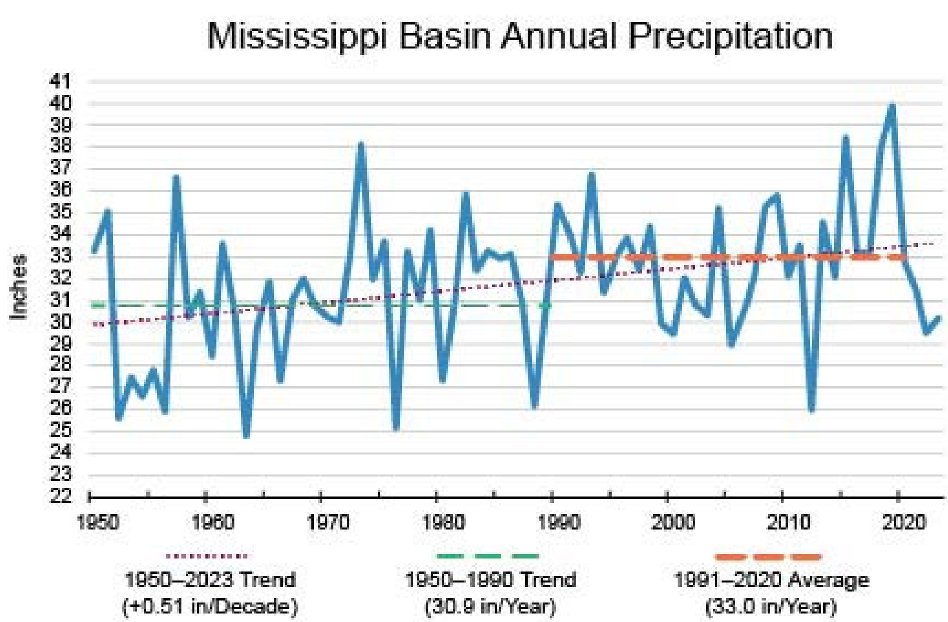

FIGURE 1. Annual precipitation totals within the Greater Mississippi River Basin between 1950–2023. Orange line indicates the trend. Green dashed line indicates the average annual precipitation between 1950–1990. Yellow dashed line indicates average annual precipitation between 1991–2020.

Annual Precipitation is Increasing

Annual precipitation is on the rise throughout most of the Greater Mississippi River Basin. The average annual precipitation within the basin has increased by +0.51 inches per decade since 1950. Within the last 30 years (1994–2023), the average precipitation has increased by +0.62 inches per decade, indicating a more significant increase within the most recent years.

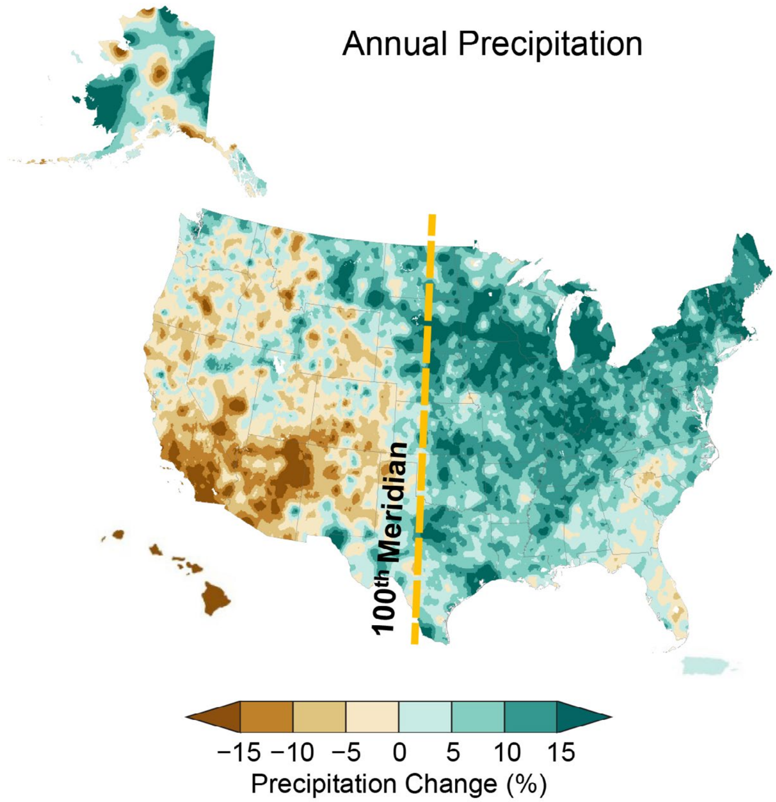

FIGURE 2. The difference between the annual average precipitation for the present day (2002–2021) compared to the average for the first half of the last century (1901–1960) (Figure credit: NOAA NCEI and CISESS NC).

Of the six sub-basins, the Ohio Basin has seen the greatest increases where, between 1994–2023, the average annual precipitation increased by +1.52 inches per decade. This is a significant increase from the +0.81 inches per decade through the preceding half century (1950–1993). The only areas that are seeing a decrease in precipitation are the far western portions of the Missouri, Arkansas, and Red Basins, generally west of the 100th meridian line. East of the 100th meridian, these sub-basins and the rest of the Greater Mississippi Basin are seeing an increase in yearly precipitation.

Annual Precipitation Trends per Basin

The following graphs present the annual precipitation between 1950–2023 within each sub-basin of the Greater Mississippi River Basin. The blue line depicts the trend in annual precipitation per decade since 1950, which is also quantified in the upper-right corner of each graph.

Every sub-basin has seen an increase since 1950. While not plotted on these graphs, an increasing trend in annual precipitation in each sub-basin can also be found since the beginning of reliable records in 1895 (listed below). However, the increase since 1950 has been significantly higher than the increase since 1895. The difference in these trends illustrates how precipitation is increasing at a greater rate now than in the early 20th century.

Trends per basin since 1895:

Missouri (+0.09 in/decade)

Ohio (+0.38 in/decade)

Arkansas-White-Red (+0.21 in/decade)

Upper Mississippi (+0.35 in/decade)

Tennessee (+0.51 in/decade)

Lower Mississippi (+0.50 in/decade)

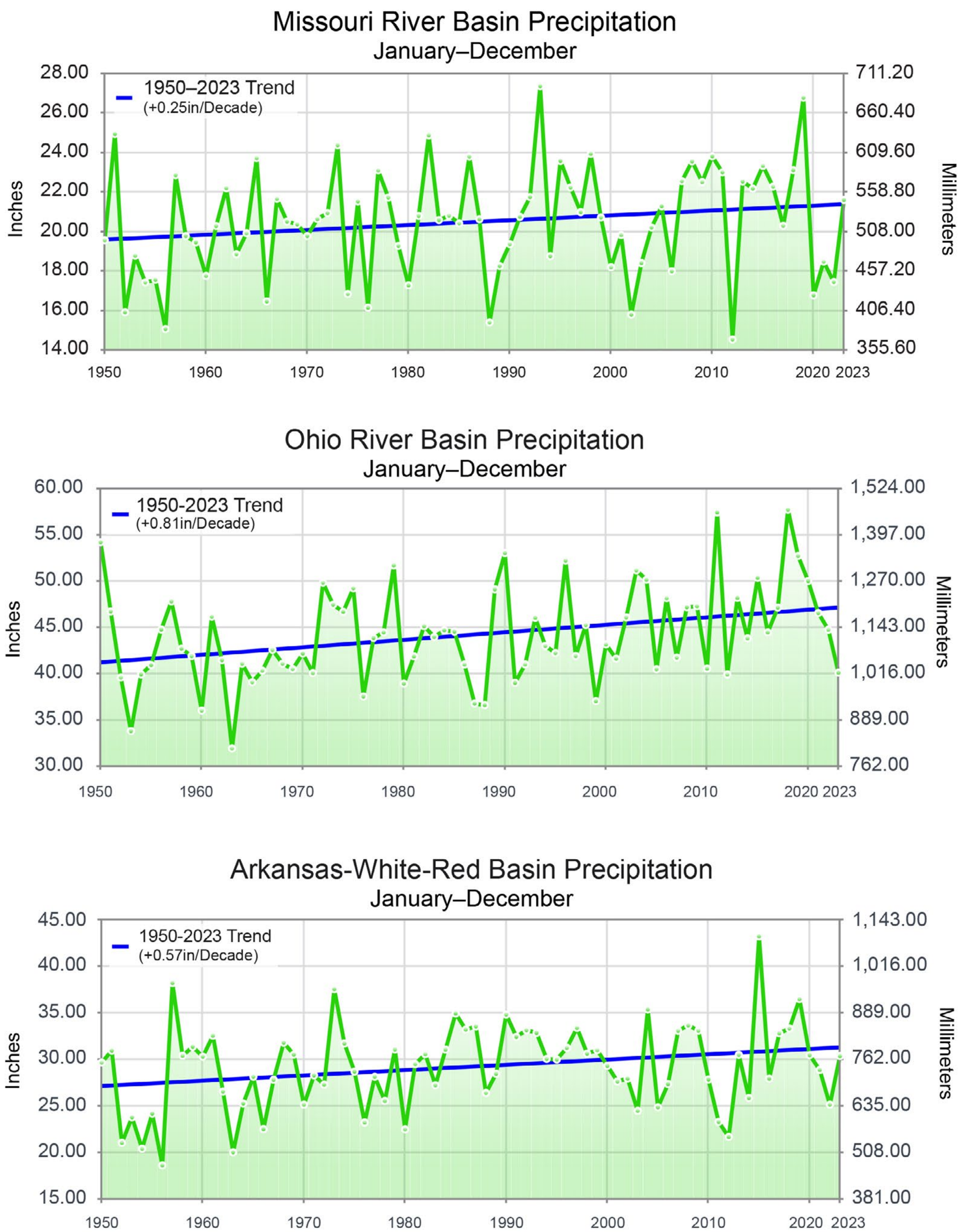

FIGURE 3.1: Annual precipitation for the three sub-basins of the Mississippi River Basin with a 1950-2023 blue trendline. (Figure credit: NOAA NCEI Climate at a Glance).

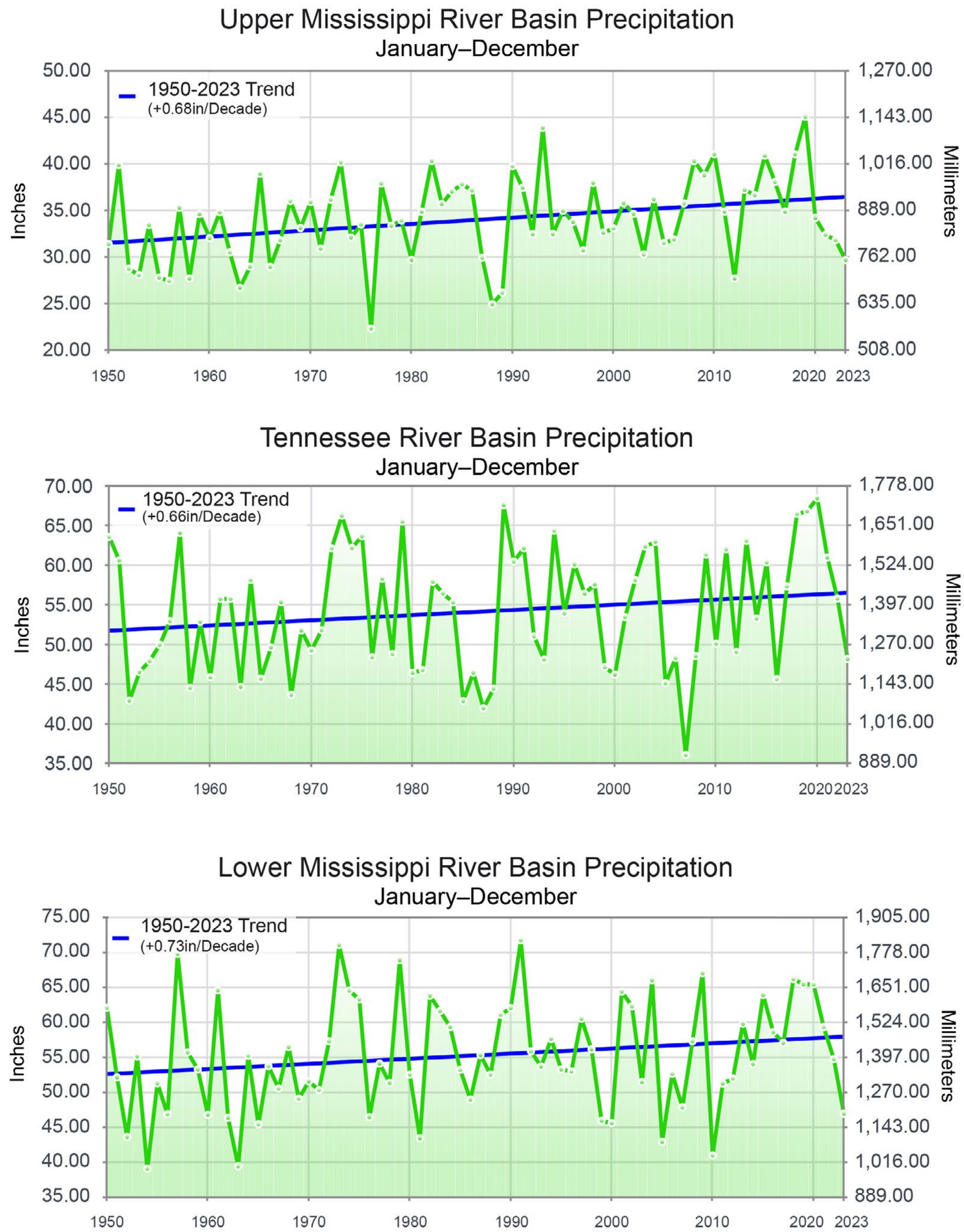

FIGURE 3.2: Annual precipitation for the three sub-basins of the Mississippi River Basin with a 1950-2023 blue trendline. (Figure credit: NOAA NCEI Climate at a Glance).

Seasonal Precipitation Trends

Meteorological Seasons:

Winter: December–February

Spring: March–May

Summer: June–August

Fall: September–November

Since 1950, the Mississippi River Basin has generally seen an increase in precipitation year-round. The only sub-basin which has seen a decreasing trend in a particular season is the Missouri Basin in the summer with a trend of −0.02 in/decade. This trend is more pronounced when looking at the 30-year period of 1994–2023, which shows −0.16 in/decade. Over the southern and eastern portions of the basin, there have been significant increases in summer precipitation with the Ohio, Tennessee, and Lower Mississippi Basins all seeing trends equal or greater to +0.3 in/decade. This is notable, as summer is typically the driest season of the year for parts of the Lower Mississippi and Tennessee Basins. Of greater note is the trend for the period 1994–2023, which shows a significant increase of +1.06 in/decade within the Lower Mississippi Basin and +0.78 in/decade within the Tennessee Basin.

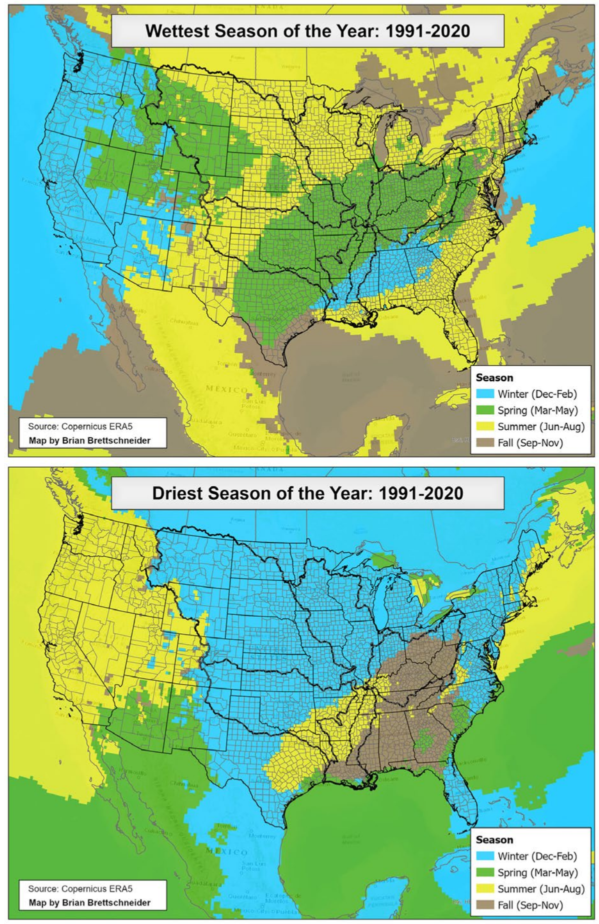

FIGURE 4. Created by Climatologist Brian Brettschneider using NCEI climate normal data for 1981–2010.

While this would lead one to believe that the dry season is getting wetter and that the chances for drought would be decreasing, the following sections will elaborate upon how this is not necessarily the case.

1950-2023 Seasonal Precipitation Trends per Decade

Season	Upper Miss	Missouri	Ohio	Tennessee	Arkansas-White-Red	Lower Miss
Winter	0.14	0.03	0.12	0.10	0.17	0.07
Spring	0.20↑	0.13	0.18	0.03	0.22↑	0.15
Summer	0.11	−0.02↓	0.30↑↑	0.37↑↑	0.09	0.30↑↑
Fall	0.22↑	0.10	0.21↑	0.17	0.08	0.22↑

TABLE 1. Created via the Climate at a Glance: Regional Time Series page with a three-month seasonal scale using data going back to 1950. The light green shading with a single up arrow indicates trends greater than +0.20 in/decade, and the dark green shading with two up arrows indicates trends greater than +0.30 in/decade. The red shading with a down arrow indicates a negative trend.

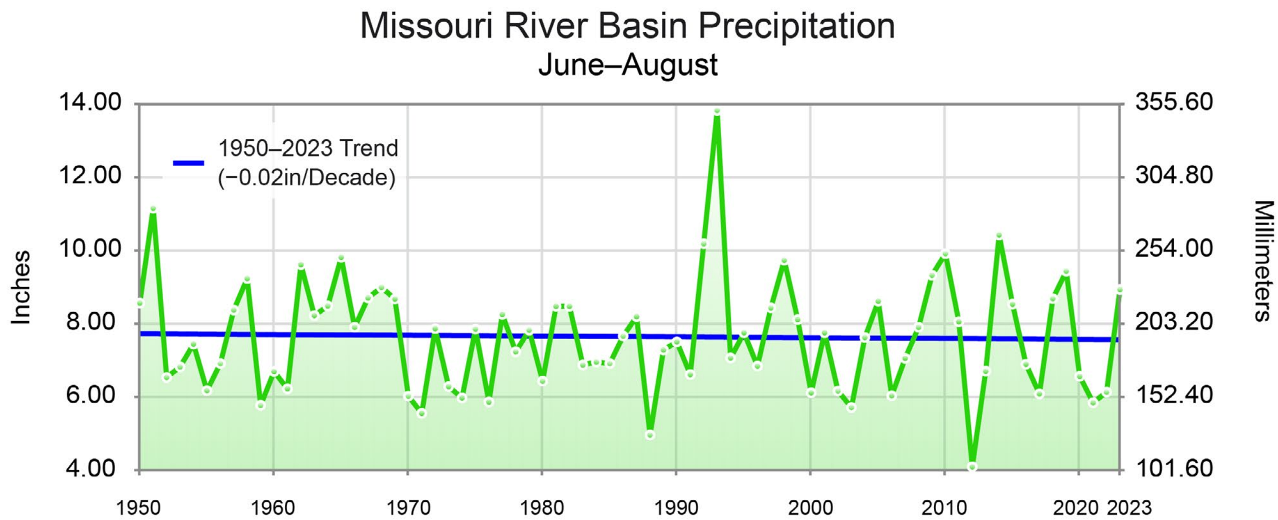

FIGURE 5. The seasonal summer precipitation in the Missouri River Basin since 1950 showing a slight negative trend (Figure credit: NOAA NCEI).

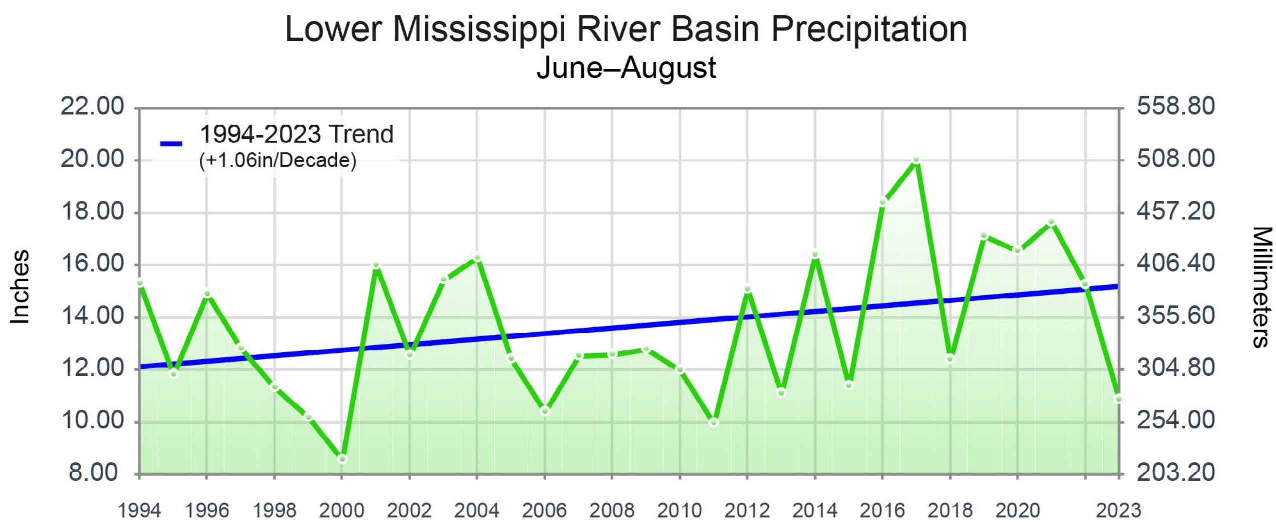

FIGURE 6. The seasonal summer precipitation in the Lower Mississippi Basin for the period 1994–2023 showing a significant increasing trend (Figure credit: NOAA NCEI).

Rains are Gaining Intensity

Not only is annual precipitation increasing, but the characteristics of the precipitation are changing. Specifically, heavy precipitation events have been occurring more frequently since the 1950s. Heavy or extreme precipitation events happen when the air is completely saturated. For each degree Celsius the temperature rises, the atmosphere can hold between 6–7% more moisture (Clausius–Clapeyron equation). This means that with increased temperatures, there is an increased risk for extreme precipitation, as warmer air can inherently hold more moisture. Extreme precipitation events can be defined in several ways and with various thresholds. In general, extreme precipitation events are defined as days with precipitation totals in the top 1% of all days with precipitation.

Heavy precipitation events are resulting in more precipitation with greater intensity than in the past. The Midwest, which includes portions of the Upper Mississippi and Ohio Basins, has seen a 45% increase in total precipitation from extreme precipitation events since 1958. Put simply, this means more rain is falling during extreme precipitation events, is occurring in shorter amounts of time, and is then increasing the risk of flash flooding and impacts (NCA5 and NCA4).

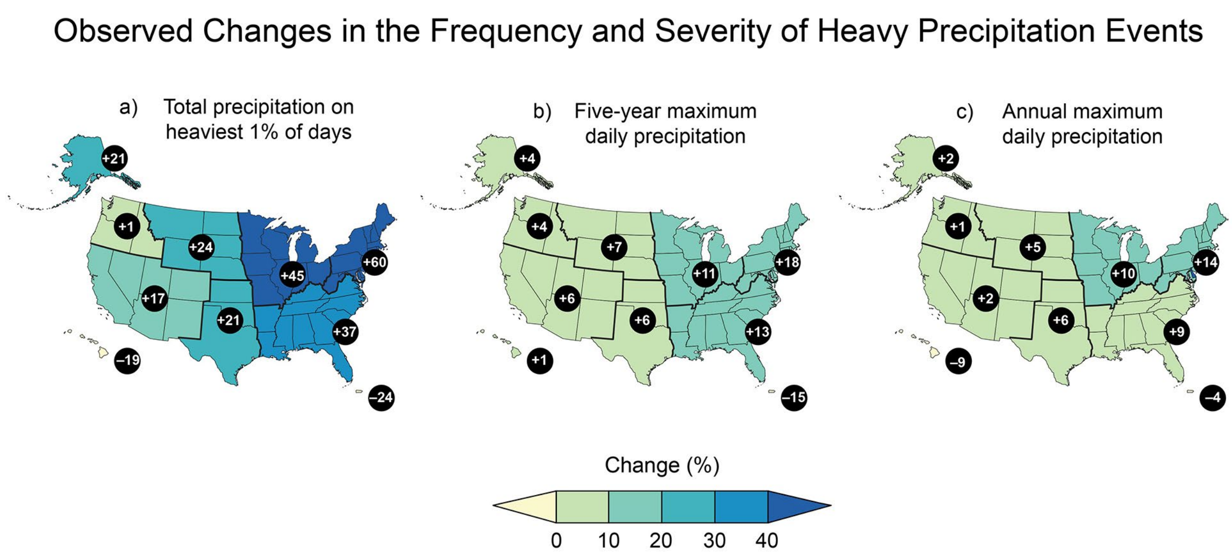

FIGURE 7. These maps show changes in three measures of extreme precipitation: a) total precipitation on the heaviest 1% of days, b) daily maximum precipitation in a five-year period, and c) the annual heaviest precipitation amount over 1958–2021. Numbers in black circles depict percent changes at the regional level (Figure credit: a) adapted from Easterling et al. 2017, b) and c) NOAA NCEI and CISESS NC).

Transitions Between Precipitation Extremes

Precipitation has increased in all aspects in recent decades, as well as the extreme variability of it. Studies have found that the frequency of transitions between wet periods to dry periods and vice versa are increasing. In parts of the Ohio and Upper Mississippi sub-basins, the time between these transitions is decreasing (Ford et al. 2021; Loecke et al. 2017). This aligns with model projections, which indicate that the number of days with precipitation amounts greater than the 90th percentile of all precipitation days, as well as the number of no-precipitation days, will increase under a warmer climate. Conversely, the number of days with precipitation in the 10th to 80th percentile is projected to decrease (CSSR). These findings suggest that there will be less time with near-normal conditions and more time with oscillations between wet and dry extremes.

There is also a seasonal aspect to precipitation transitions Dai et al. 2016 found that the seasonal variability is changing as spring precipitation is increasing and late summer precipitation is decreasing within the Upper Mississippi sub-basin. This undoubtedly has an effect on seasonal streamflow within the Greater Mississippi Basin. If this transition continues, the Upper Mississippi could see more flooding in the spring and more drought in the late summer timeframe.

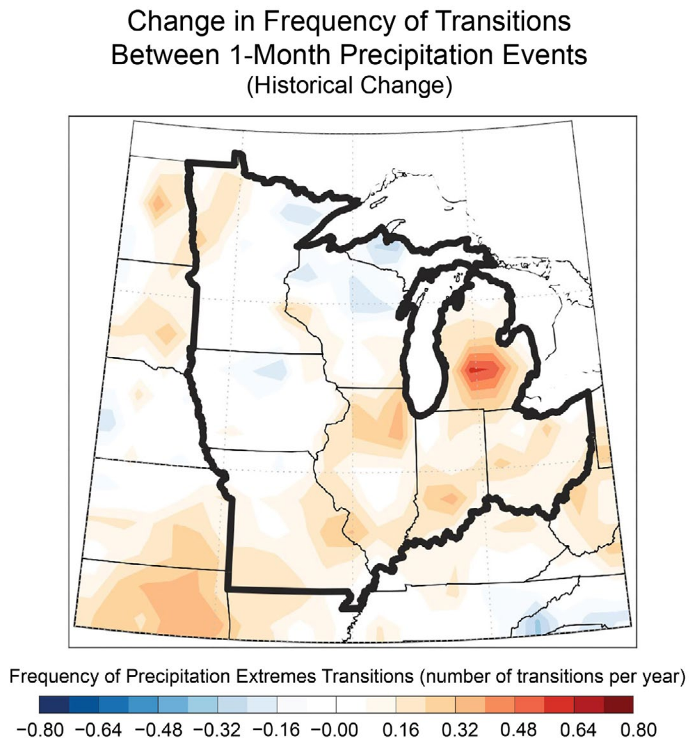

FIGURE 8. Plotted is observed changes in transition frequency (from wet to dry or dry to wet). This is based on the Standardized Precipitation Index difference between the periods 1951–1980 and 1981–2010 (Figure credit: NCA5 Midwest Chapter).

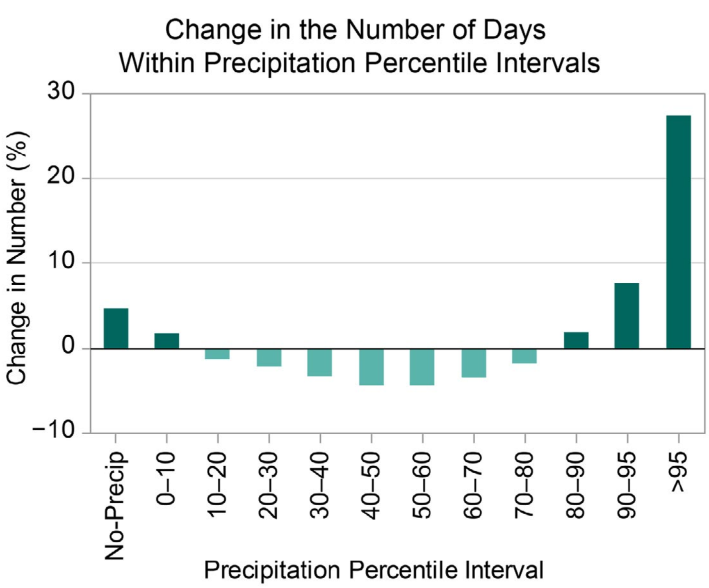

FIGURE 9. The projected change in the number of days with daily zero and non-zero precipitation days. The precipitation percentile intervals are based on daily non-zero precipitation amounts from the 1976–2005 reference period (Figure credit: CSSR 2017).

Drought: Occurring More Rapidly

Rapid-onset droughts, also known as flash droughts, are droughts that develop and intensify more rapidly than those developing from the lack of precipitation alone. Flash droughts are set in motion by a lack of rainfall along with abnormally high temperatures, wind, and radiation. They can materialize in a matter of days or weeks and are a threat to much of the U.S. Studies have shown that droughts are not necessarily occurring more frequently, but are developing more rapidly (Qing et al. 2022). As temperatures increase, evapotranspiration increases. This means plants are pulling more water out of the soils and leaving soils depleted more quickly than in the past. The occurrence of flash droughts could increase if heatwaves are accompanied by periods of little to no rainfall (NCA5).

Even though annual precipitation is increasing throughout much of the Mississippi Basin, an increase in soil moisture is not expected as higher temps lead to increased evapotranspiration. When rain falls after a flash drought occurs, there is more runoff as the soils can become impervious like concrete and do not allow for the absorption of rainfall. If the occurrence of extreme heatwaves and flash droughts increases (not just in summer but also in spring and fall), this could alter the normal Mississippi River streamflow. The relationship is a complex one indeed, as well as interconnected, as drought does not depend solely on a lack of precipitation, but also high temperatures, evapotranspiration, and soil moisture (NCA4).

Droughts affect the Mississippi River by drying up the soil moisture and ultimately leading to low streamflow within the upstream tributaries of the river. This becomes a significant issue when it occurs over a large area. The Mississippi River has six major sub-basins. When drought impacts one basin, the big river can usually rely on the streamflow from the other sub-basins to supplement the loss. If the drought is large enough and occurs across two sub-basins or more, it can lead to low water issues on the mainstem river.

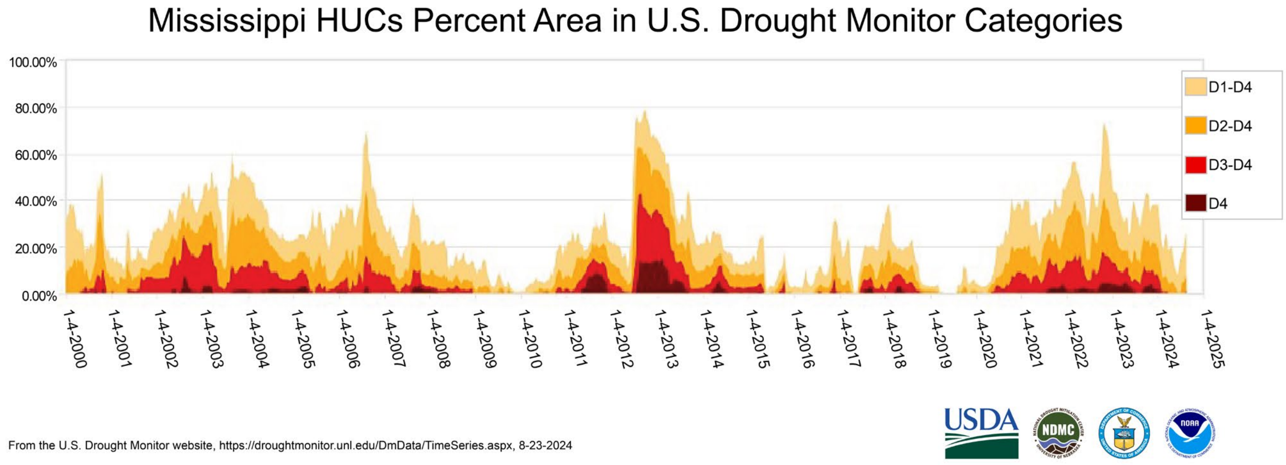

FIGURE 10. This time series shows the percent area of the Mississippi Basin in drought back to January 2000. The U.S. Drought Monitor (USDM) is the entity responsible for identifying drought. The USDM uses four categories of drought: D1, which is the least intense, to D4, which is the most intense.

Temperature Trends

While precipitation is the most direct influence on streamflow on the Mississippi River, temperatures can also lead to impacts on it. Within the CONUS, temperatures have risen by 2.5°F since 1950, with the winter months warming much more quickly than summer months in the northern states (NCA5). As mentioned before, warmer temperatures allow the atmosphere to hold more moisture and are the main reason annual precipitation is increasing. Temperature can also increase evaporation and evapotranspiration. When heatwaves occur (whether in the summer or winter months), more water escapes the rivers and streams and can incrementally decrease the streamflow. Depending on the length of the heatwave, this can have impacts on overall streamflow.

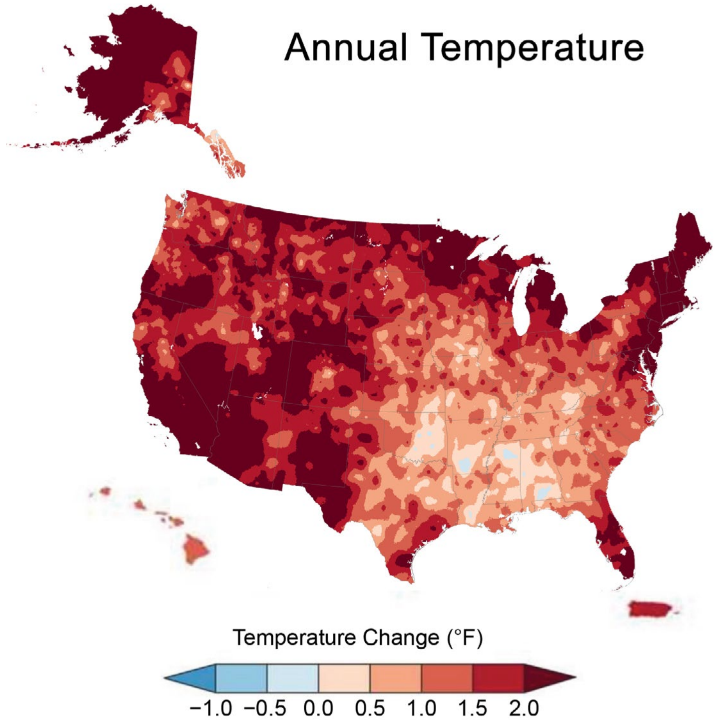

FIGURE 11. The change in annual temperature between the period of 2002–2021 and 1901–1960 (Figure credit: NOAA NCEI).

Less Snowpack, More Winter Rains

With temperatures increasing throughout the globe, winter snowpack is declining and more winter precipitation is falling as rain (NCA4). There has been observed decreases in the length of winter across portions of the Upper Mississippi and Ohio sub-basins, along with reduced snowfall (NCA5). This means that the water cycle is shifting in areas that are accustomed to maintaining a snowpack every winter. Historically, precipitation would fall as snow in these areas and accumulate throughout the winter. Instead, higher temperatures are causing it to fall as rain and immediately soak into the soil or run off into the rivers. With decreased or even nonexistent snowpack to melt and slowly moisten the soils and rivers in the spring, they tend to dry up quicker during the summer when temperatures soar.

Model projections indicate that a smaller snowpack could shift the daily maximum streamflow over the Upper Mississippi sub-basin and cause the spring peak flow to occur up to a month earlier than normal (Byun et al. 2019). A smaller snowpack could also “alter surface water availability for irrigation and may increase pressure on groundwater resources.” “Increases in evaporative demand…have decreased runoff efficiencies, meaning that less rain and melted snow end up reaching streams” (NCA5). While this research and these findings have been found across portions of North America, this is the case for only scattered locations in the Upper Mississippi Basin.

Tropical Cyclone Changes

Since 1900, no significant trends have been found in the number of tropical cyclones (TCs) making landfall in the U.S. However, the characteristics of TCs have been changing. Studies have shown that TCs have been intensifying more rapidly since the early 1980s. The average forward speed of TCs has decreased since 1900. The rate of decay of landfalling TCs has been found to be slowing, which allows storms and their impacts to extend farther inland. Much of this can be attributed to either increasing temperatures or increasing sea surface temperatures, which both allow for higher moisture content within a TC. Tropical Depression Cristobal exemplified this trend when it travelled all the way to the Iowa–Wisconsin border in June 2020 before being declared extratropical. This system brought strong winds, heavy rainfall, and even mudslides to the Upper Mississippi region.

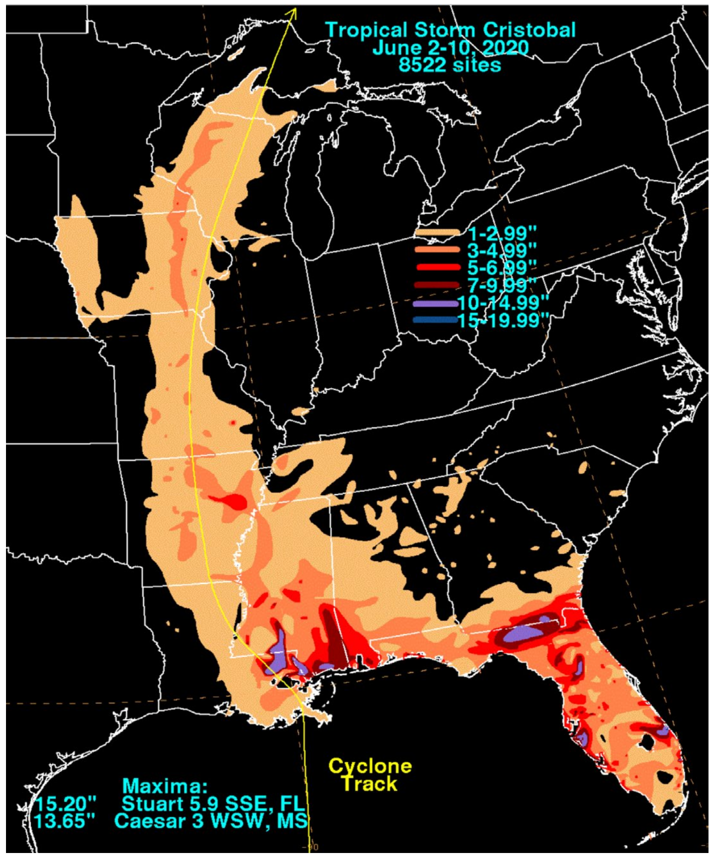

FIGURE 12. Tropical Storm Cristobal made landfall in Louisiana on June 7, 2020. It moved slowly up the Mississippi River Valley and brought heavy rainfall to much of the mainstem basin (Figure credit: WPC).

Other studies have found that TCs have become increasingly likely to stall near the North American coast. Stalling systems like Harvey in 2017 and Florence in 2018 have resulted in increased rainfall across coastal regions. Given the slower-moving and stalling TCs in conjunction with warmer air and sea surface temperature, rainfall rates within TCs are projected to increase by about 15% (NCA5 & NOAA State of the Science).

Mississippi Basin Streamflow Changes

Precipitation extremes are increasing within the Mississippi River Basin, both on the wet side and the dry side. The big question is: How will these precipitation changes affect streamflow? There is not a one-to-one relationship between precipitation and streamflow, thus the answer is multidimensional. While precipitation may be the biggest factor when determining streamflow, it also depends on soil moisture, runoff, groundwater, land usage, soil characteristics, and evapotranspiration.

While annual precipitation has increased across most of the basin, soil moisture has not increased significantly. This can partly be attributed to higher temperatures leading to increased evapotranspiration. Again, evapotranspiration leads to quicker depletion of soil moisture, especially in the summer and fall months. Along the same lines, it has been found that runoff has increased in recent decades over portions of the Upper Mississippi and Ohio sub-basins ([NCA5 Midwest Chapter]). In simple terms, more rain is falling, but the soils are not soaking it up and it is therefore running off into the rivers more. This may be attributed to the increase in extreme precipitation. When heavy rain falls on hard, dry soils, the ground can act like concrete and be impervious. Some of the rain will soak in to the dry soils but most of it will run off. There are other factors, such as land use changes and dwindling groundwater, that also impact the amount of water moving into streams and rivers.

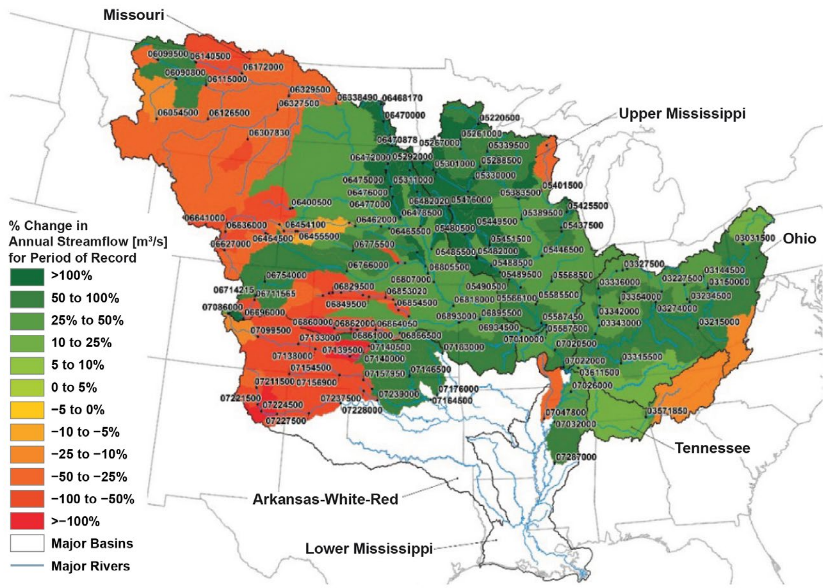

FIGURE 13. The percent change in annual streamflow from 1900 to 2020. Significant trends are colored with increasing trends in green and decreasing trends in orange (Figure credit: MRG&P 34).

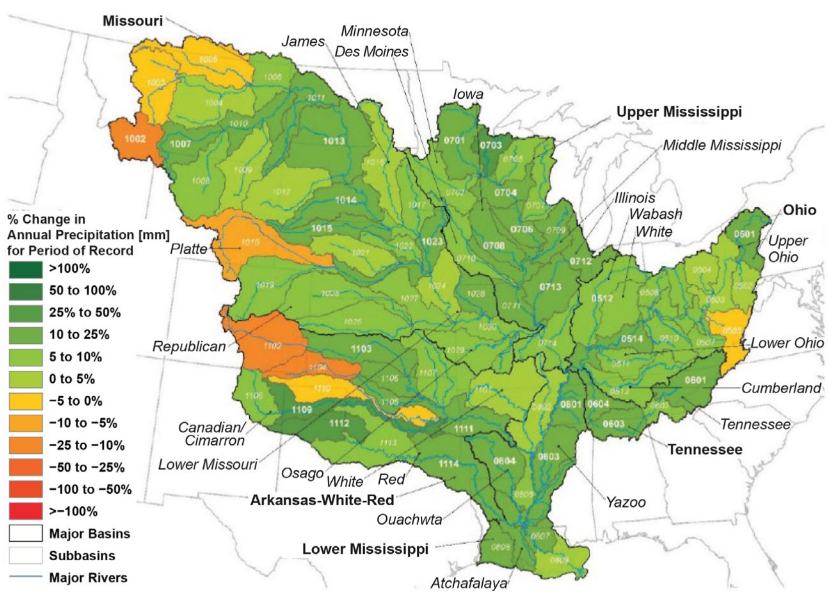

FIGURE 14. The percent change in annual precipitation from 1900 to 2020. (Figure credit: MRG&P 34).

Several studies have shown that annual streamflow has increased across much of the Mississippi Basin (MRG&P 34, NCA5). However, the far-upper Missouri and Arkansas sub-basins have shown decreasing trends in streamflow in a manner similar to the trends of annual precipitation in those same areas. Nonetheless, looking at the basin as a whole, the rate at which the streamflow is increasing is significantly higher than the observed increase in annual precipitation (Figure 14 vs 15). The MRG&P 34 study states that the majority of the Mississippi River Basin is receiving between 10–25% more rainfall now than it did 100 years ago, while more than 25–100% increases have occurred in streamflow. This demonstrates the multidimensional relationship between precipitation and streamflow.

One aspect which may provide a better explanation for this disparity is anthropogenic activity. In the western Plains (the upper Missouri and Arkansas basins), groundwater pumping for irrigation is prevalent and may be leading to reduced streamflows and increased evapotranspiration as crops are cultivated there in a naturally drier microclimate. The drastic increases in streamflow over the interior basin are likely the result of more engineered and efficient river channels (MRG&P No. 34). While the combination of a more efficient hydraulic system and a moderate increase in precipitation may explain the disproportionate increases in streamflow, there are likely lesser factors that contribute as well, such as land use changes, tile drainage, urbanization, etc.

Major Sub-Basin Streamflow Trends

When analyzing the changes in streamflow within the three major sub-basins that contribute to the Lower Mississippi River, there was a subtle shift in the contributions between 1930–2014 (the fixed interval the MRG&P No. 34 study settled on). At the beginning of the period of record, the relative annual contributions from the Ohio, Upper Mississippi, and Missouri Rivers were 61%, 23%, and 16%, respectively. By 2014, these contributions had shifted to 55%, 28%, and 18%. While total streamflow has increased in all basins, the increases in the Upper Mississippi and Missouri outpaced the increase out of the Ohio. While it has not been proven, these disproportionate increases may be a result of the large-scale channel improvement programs that occurred during this timeframe.

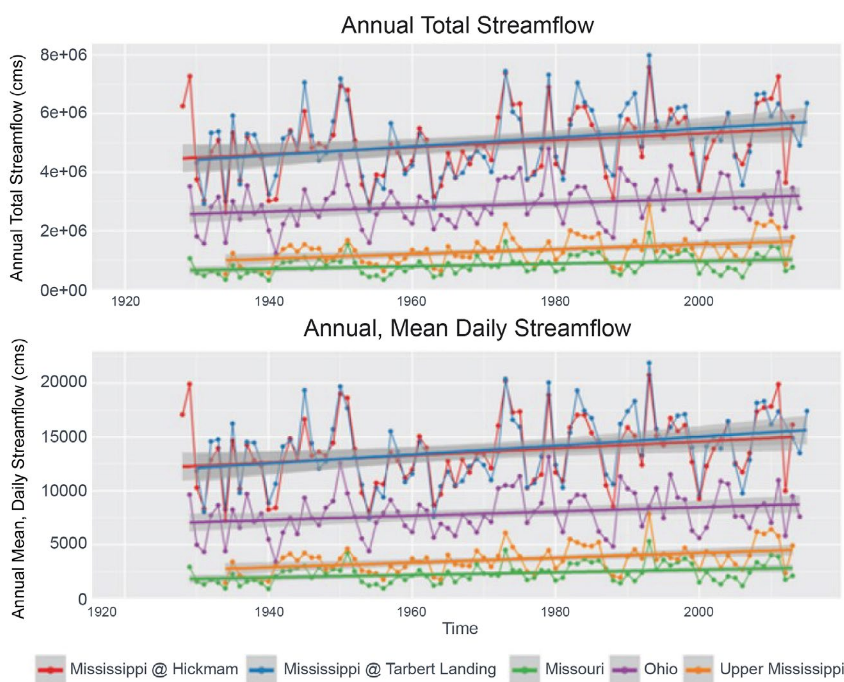

FIGURE 15. Change in annual total and annual average streamflow. Streamflows from the Ohio River were measured at Metropolis, IL; from the Missouri River at Hermann, MO; and from the Upper Mississippi River as the difference between flows at Thebes, IL and Hermann, MO (Figure credit: MRG&P 34).

Mississippi River Flood Trends

Water is moving more efficiently into rivers now, but does this mean there is more flooding? Again, there are a few things to keep in mind when analyzing the flood trends on the Mississippi River specifically. First off, there was a cutoff program in the 1930s and 1940s that shortened the river by 25% between Memphis and Baton Rouge. This helped to considerably reduce flood heights. Secondly, the reservoirs that assist with flood control within the basin were mostly completed by 1960. These two programs have benefitted river stages and the amount of flooding that occurs. However, now that precipitation is increasing across most of the basin, how does flooding in the present day compare to that of the mid–20th century or even the beginning of the 20th century?

In-house analysis completed at the Mississippi Valley Division evaluated three aspects of flooding along the mainstem Mississippi River: magnitude, frequency, and duration. The magnitude of flooding can be assessed by looking at peak (or maximum) annual river stages. According to the data, peak stages have increased at St. Louis and Cairo since 1900, while peak stages fell on the Lower Mississippi River below Cairo after the completion of the cutoff program. Since the mid-1960s, peak stages have gradually increased on the Lower Mississippi River as well.

When looking at flood frequency, a similar trend can be seen, with minor to major flood stages generally occurring more often since the 1960s. The one stretch of the river that contradicts this is the Ohio–Mississippi confluence region around Cairo. Here, the occurrence of minor and moderate flooding has not increased, while major flooding has. The reason for a lack of minor to moderate flooding increase is likely attributed to the two large flood control reservoirs upstream, Kentucky Lake and Barkley Lake, which both help to hold back water when the Mississippi River is running high. The major flooding increase may be attributed to extreme precipitation events occurring more frequently.

To consider flood duration, the number of days spent annually above flood stage was calculated. The trendlines here were similar to the other parameters at each particular location on the river. In conclusion, flood magnitude, frequency, and duration increased since the mid–1960s on the mainstem Mississippi River. Keep in mind though, flood stages (minor/moderate/major) have remained static since the early 20th century, while the amount of flood protection has increased significantly. Given the presence of engineered levees, floodways, and backwater areas, major flooding on the Mississippi River is mostly contained and is not nearly as damaging as it was in the early 20th century.

Flood Stages:

- St. Louis: minor = 30 ft; moderate = 35 ft; major = 40 ft
- Cairo: minor = 40 ft; moderate = 45 ft; major = 53 ft
- Arkansas City: minor = 37 ft; moderate = 40 ft; major = 44 ft
- Vicksburg: minor = 43 ft; moderate = 46 ft; major = 50 ft
- Red River Landing: minor = 48 ft; moderate = 55 ft; major* = 64 ft (*this stage should never be reached as the trigger to operate the Morganza Floodway is below this stage)
- Baton Rouge: minor = 35 ft; moderate = 38 ft; major = 40 ft

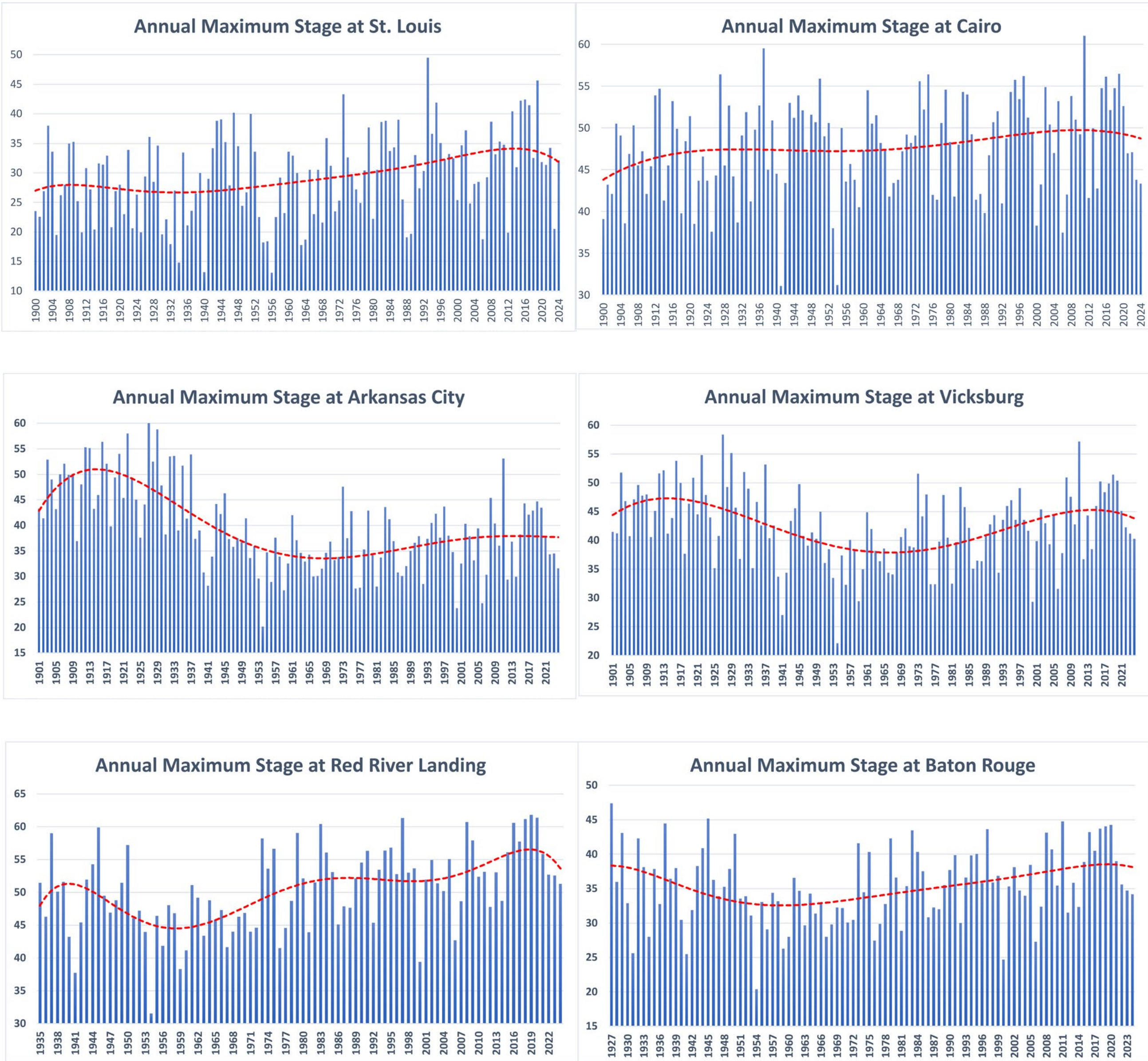

FIGURE 16. Annual maximum river stage observed at various points along the mainstem Mississippi River with a dashed red trendline.

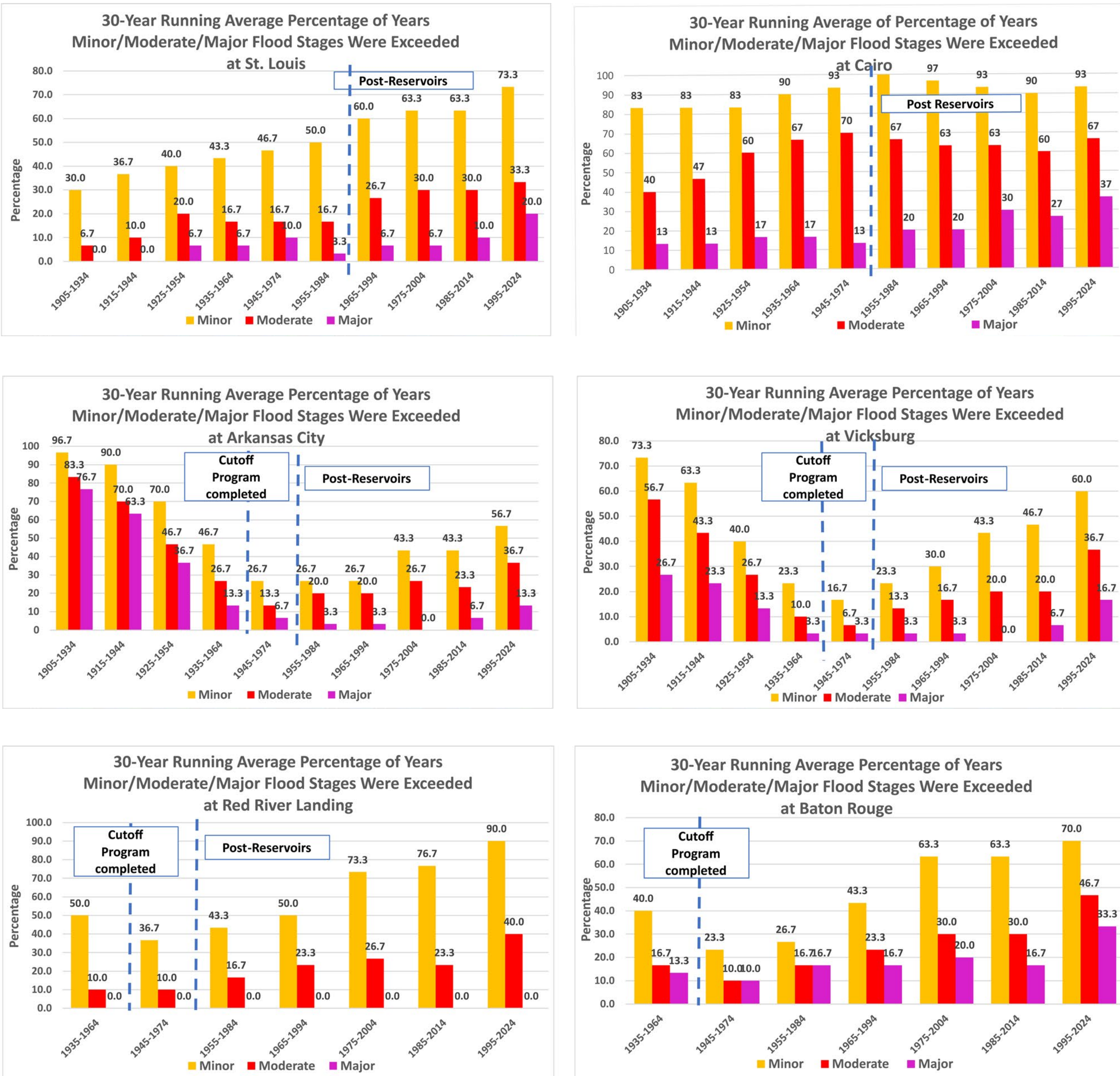

FIGURE 17. Running 30-year average percentage of years that exceed minor, moderate, and major flood stages at various points along the mainstem Mississippi River.

FIGURE 18. Annual number of days spent above flood stage at various points along the mainstem Mississippi River.

Mississippi River Low Water Trends

It is imperative to look at low water trends as well, given that the current climate is leaning more towards frequent extremes, including both flood events and drought periods. When analyzing the trends of low water and annual minimum stages, the trends are similar to flooding trends in that the cutoff program, reservoirs, and overall channel improvement programs have aided in improving river levels. The annual minimum stages have generally increased since the 1960s despite the last few drought years (2021–2024) causing a downward trend towards the end of the timeline. However, the minimum stages are still not as low as those that occurred in the early- to mid-20th century.

As for the frequency of low water, the average percentage of years reaching low water has decreased since the large-scale channelization changes in the first half of the 20th century. There is some indication that low stages may be on the rise on the Middle Mississippi River between St. Louis and Cairo. However, low stages there are still not occurring as often as they were before the channel improvement program.

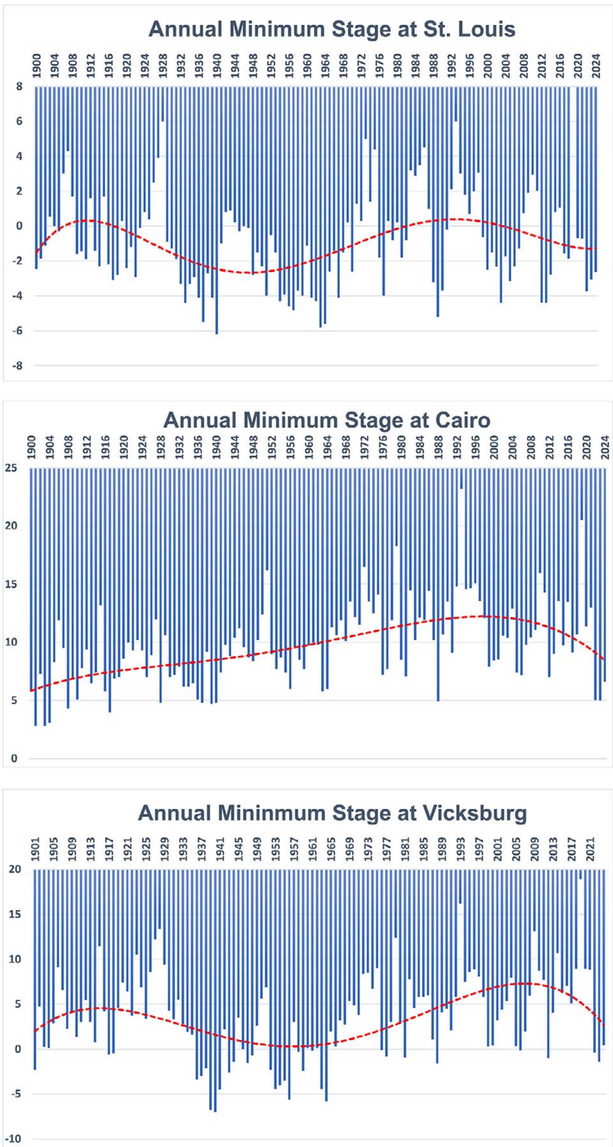

FIGURE 19. Annual minimum river stage observed at various points along the mainstem Mississippi River with a dashed red trendline.

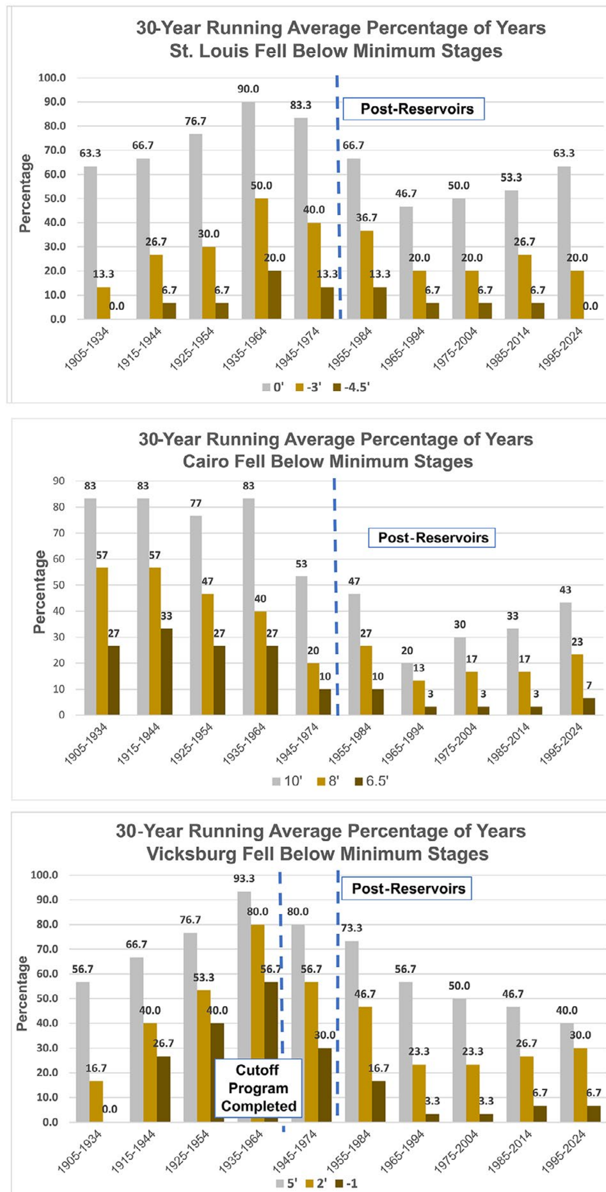

FIGURE 20. Running 30-year average percentage of years which fell below critical low water stages at various points along the mainstem Mississippi River.

Summary

Precipitation is increasing across most of the basin. Streamflow is increasing. Drought is occurring more rapidly. Extreme transitions from low to high water or from dry to wet periods are occurring more frequently and with less time in between. Despite all that, the Mississippi River continues to serve as an important commercial highway. The engineering of levees, cutoffs, reservoirs, floodways, and backwater areas have improved the reliability of conditions along the mainstem river. However, due to increases in precipitation and precipitation extremes, both flooding and low water are occurring more often on the river. That said, when flooding does occur, it is contained within those levees, floodways, and backwater areas and does not (typically) flood areas outside of this. This goes for low water as well, as navigation on the river is still maintained at low water levels, and dredges maintain an operational channel throughout the length of the river. The impacts have been mitigated thanks to the engineering of the river. As they have been engineered with extremes in mind, the Mississippi River and its valley remain resilient, and improvements continue to increase their strength.

Bibliography:

USGCRP, 2023: *Fifth National Climate Assessment.* Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023

Communicating Climate Change in the Upper Mississippi River Basin: https://www.noaa.gov/sites/default/files/2022-03/Technical_Version_Upper_MS_River_Communicating_CC.pdf.

Chen, L. and T.W. Ford, 2023: Future changes in the transitions of monthly-to-seasonal precipitation extremes over the Midwest in Coupled Model Intercomparison Project Phase 6 models. *International Journal of Climatology*, 43 (1), 255-274. https://doi.org/10.1002/joc.7756

Wehner, M.F., J.R. Arnold, T. Knutson, K.E. Kunkel, and A.N. LeGrande, 2017: Droughts, floods, and wildfires. In: *Climate Science Special Report: Fourth National Climate Assessment, Volume I* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 231-256, doi: 10.7930/J0CJ8BNN.

Qing, Y., Wang, S., Ancell, B.C. et al. Accelerating flash droughts induced by the joint influence of soil moisture depletion and atmospheric aridity. *Nat Commun* **13**, 1139 (2022). https://doi.org/10.1038/s41467-022-28752-4

Otkin, J. A., M. Svoboda, E. D. Hunt, T. W. Ford, M. C. Anderson, C. Hain, and J. B. Basara, 2018: Flash Droughts: A Review and Assessment of the Challenges Imposed by Rapid-Onset Droughts in the United States. *Bull. Amer. Meteor. Soc.*, **99**, 911–919, https://doi.org/10.1175/BAMS-D-17-0149.1.

Bhatia, K.T., Vecchi, G.A., Knutson, T.R. et al. Recent increases in tropical cyclone intensification rates. *Nat Commun* **10**, 635 (2019). https://doi.org/10.1038/s41467-019-08471-z

Li, L., Chakraborty, P. Slower decay of landfalling hurricanes in a warming world. *Nature* **587**, 230–234 (2020). https://doi.org/10.1038/s41586-020-2867-7

Hall, T.M., Kossin, J.P. Hurricane stalling along the North American coast and implications for rainfall. *npj Clim Atmos Sci* **2**, 17 (2019). https://doi.org/10.1038/s41612-019-0074-8

NOAA State of the Science Fact Sheet: Atlantic Hurricanes and Climate Change. May 2023. https://sciencecouncil.noaa.gov/wp-content/uploads/2023/05/1.1_SOS_Atlantic_Hurricanes_Climate.pdf

Knapp, C.N., D.R. Kluck, G. Guntenspergen, M.A. Ahlering, N.M. Aimone, A. Bamzai-Dodson, A. Basche, R.G. Byron, O. Conroy-Ben, M.N. Haggerty, T.R. Haigh, C. Johnson, B. Mayes Boustead, N.D. Mueller, J.P. Ott, G.B. Paige, K.R. Ryberg, G.W. Schuurman, and S.G. Tangen, 2023: Ch. 25. Northern Great Plains. In: *Fifth National Climate Assessment*. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.CH25

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 change in the United States. In: *Climate Science Special Report*: Fourth National Climate Assessment, Volume I [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 207-230, doi: 10.7930/J0H993CC.

Wehner, M.F., J.R. Arnold, T. Knutson, K.E. Kunkel, and A.N. LeGrande, 2017: Droughts, floods, and wildfires. In: *Climate Science Special Report: Fourth National Climate Assessment, Volume I* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 231-256, doi: 10.7930/J0CJ8BNN.

Kossin, J.P., T. Hall, T. Knutson, K.E. Kunkel, R.J. Trapp, D.E. Waliser, and M.F. Wehner, 2017: Extreme storms. In: *Climate Science Special Report: Fourth National Climate Assessment, Volume I* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 257-276, doi: 10.7930/J07S7KXX.

Hydraulics Hydrology & Coastal CoP

Mississippi Valley Division