Changes in Hydrology and Suspended-Sediment Transport in the Mississippi River Basin over the Past Century

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Abstract

Altered hydrological conditions in the Lower Mississippi River are a result of changes in precipitation, rainfall-runoff relations and anthropogenic factors that play a role in the magnitude and frequency of hydrologic events. Numerous studies have shown the significance of climate change and extreme weather events on peak flows, low-flows, and flooding, etc. Contributing to shifting hydrologic patterns such as precipitation, are human-induced changes to the natural environment such as agriculture, urbanization, channelization, dam construction, etc., that often vary in spatially-systematic ways according to regional demands for water. Changing flow regimes also affect sediment-transport rates and channel stability, challenging on-going efforts in flood protection, stream restoration and water-quality management.

Results of this study show that in general, although most of the Mississippi River Basin is receiving more rainfall than it did 100 years ago, there are vast areas where water yields have decreased significantly, particularly in the western part of the basin and particularly in spring. Precipitation has also shifted temporally such that winter precipitation has significantly decreased in many areas while spring and autumn precipitation has generally increased. Parts of the western basin are experiencing 25 to more than 50% less discharge per unit area than they did 100 years ago. In contrast, the mid-continent is generating considerably more water than it did 100 years ago. In part this can be attributed to increases in precipitation and a greater influence of hurricane-related rainfall, but anthropogenic effects cannot not be minimized. The result is that the lower Mississippi River is receiving more flow from its major HUC-2 tributaries (Ohio, Missouri and Upper Mississippi Rivers) than at the turn of the 20th century. Integrated over an average year and excluding inputs from other smaller tributaries, brings average-annual increase in flows to the Lower Mississippi River to about 1.62 million m³/s (57.2 million ft³/s). Average, mean-daily flow contributions from the Ohio, Upper Mississippi and Missouri Rivers have changed from 61%, 23% and 16% in 1930, to 55%, 28% and 18% in 2014, respectively.

Although the direction of the changes (positive or negative) varies across the basin, these effects are widespread and sizeable in magnitude, indicating that anthropogenic influences have been a major determining factor on changes in streamflow regimes over the past century. The direction and magnitude of these influences can clearly be sorted by region. While anthropogenic activities have resulted in increases in water yield in the central part of the basin (increases of
50-100% decreasing eastward to 0-10%), activities at the basin margins have caused decreases in flow. In the west, decreases of 25-100% are typical.

The average-annual delivery of suspended sediment to the Lower Mississippi River has declined by about 300%, from about 600 Mt/y in 1940 to about 100 Mt/y, currently. The largest actual decline is from the Missouri River (about 250 Mt/y) largely due to the trapping of sediment behind impoundments. Decreases in sediment delivery to these reservoirs are also noted. Other researchers have similarly reported on a large decline in suspended-sediment loads discharged by the Mississippi River to the Gulf of Mexico. These reductions in loads have consequences for river stability, protection of hydraulic structures, nutrient transport, and replenishment of coastal wetland areas.

**Introduction**

Recent years has seen significant hydrologic events affecting the Mississippi River Basin. Flood protection on the lower Mississippi River (below Cairo, IL) is a major focus of the Mississippi Valley Division, U.S. Army Corps of Engineers (CoE). Altered hydrological conditions as a result of changes in precipitation and rainfall-runoff relations must play a role in the magnitude and frequency of flow events from tributary basins (e.g., Yang et al. 2015). Numerous studies have shown the significance of climate change and extreme weather events on peak flows, low-flows, and flooding, etc. Contributing to shifting hydrologic patterns are human-induced changes to the natural environment such as agriculture, urbanization, channelization, dam construction, etc. Changing flow regimes also affect suspended-sediment transport rates and channel stability, challenging on-going efforts in flood protection, stream restoration and water-quality management. To assess and quantify spatial and temporal trends, and anthropogenic effects on hydrologic conditions within the Mississippi River Basin, daily precipitation and streamflow over the past 100 years were analyzed on an annual and seasonal basis. Peak-flow rates over one through 7 days were also investigated. All data was set in the framework of the four-digit hydrologic-unit code basins (HUC4) developed by the USGS to differentiate spatial variability across the major sub-basins. Temporal variability was evaluated over the entire period as the difference between conditions at the beginning and end of the recorded period (i.e., 1900-present). This paper represents an abridged version of a much larger report including data appendences and scores of maps produced for the CoE (Simon et al., in press).

**Available Historic Data and Methods**

**Daily-Precipitation and Hurricane-Related Data**

The fundamental data unit for precipitation that was available for this study was daily climate data, some dating back to the mid- to late-1800s, and available through the Global Historical Climatology Network-Daily (GHCND). These were accessed online through NOAA’s National Climatic Data Center. The entire GHCND database was downloaded and data for all stations within the study area were extracted for the parameter PRCP (precipitation). Figure 1 (Left) shows the location of all 6,815 GHCND precipitation gages with at least one complete calendar year of data that was used in this study. Additional information on the GHCND database and its contents are available online at (http://www1.ncdc.noaa.gov/pub/data/ghcn/daily/ghcnd-stations.txt).
Hurricane-related rainfalls were estimated following the methodology outlined in Darby et al. (2013; 2016) using NOAA’s International Best Track Archive for Climate Stewardship (IBTrACS) database (version v03r02) (Knapp et al., 2010; available online: https://www.ncdc.noaa.gov/ibtracs/). IBTrACS was used to locate the paths of all recorded hurricanes (at daily time steps), intersecting or passing near the Mississippi Basin for the available period of record, 1950–2014 (Figure 2). The IBTrACS data comprise six hourly best-track positions and intensity estimates. Only storms designated as being in a tropical phase with one-minute maximum, sustained surface-wind speeds exceeding 34-knots (17.5 m/s) are included in the analysis.

**Mean-Daily and Peak-Annual Streamflow**

Mean-daily discharge data were obtained through batch downloads using the USGS Water Services Tool (https://waterservices.usgs.gov/rest/DV-Test-Tool.html). There are 6,186 flow stations with at least one complete calendar year of data within the study area (Figure 1, Right). For the majority of these gages, the drainage or contributing area to the gage is published. Where drainage areas were not defined, areas were estimated using either the USGS online tool, StreamStats version 4 Beta Application (https://streamstatsags.cr.usgs.gov/streamstats/), or for smaller basins, delineating the basin area using GIS. Additional mean-daily discharge data at gages along the Mississippi River main stem were obtained through the CoE River Gages website (http://rivergages.mvr.usace.army.mil/ WaterControl/new/layout.cfm).
Instantaneous, peak-annual discharge data were available at 8,210 USGS gages. However, only 7,118 gages have at least 10 annual observations, which was considered the minimum number required for flood frequency analysis.

**Sediment Data: Suspended-Sediment Concentrations**

To analyze the spatial distribution of suspended-sediment loads and to investigate how these have changed with time, it was decided to use the raw, concentration and associated discharge data from the time of sampling. Discrete suspended-sediment concentration with corresponding instantaneous flow data were obtained using USGS’ Sediment Data Portal (https://cida.usgs.gov/sediment/). Within the study area there are 1,638 gages with at least 10 samples (Figure 3), which was considered the absolute minimum number required for generating sediment transport-rating relations.

![Figure 3. Locations of USGS suspended-sediment stations (Left) and GHCND pan-evaporation gages (Right) used in this study.](image)

**Ancillary Data: Dams, Pan-Evaporation and Geospatial**

Information on the location, characteristics and construction date of dams is important to the investigation both in terms of understanding changes in flow regimes at particular gages and in determining their role in trends in evaporation and water-yield. These data were obtained from CoE’s National Inventory of Dams (NID). Within the study area there are 13,629 impoundments listed in the NID database with published completion dates and data on the surface area of impounded water. This excludes privately-owned dams, and only considers dams owned by Federal, State, or Local Governments, as well as those owned by public utilities or whose ownership type is not listed.

To achieve a better understanding of the role of impoundments in altering hydrology and water availability, evaporation data were required across the basin. In addition to precipitation data, the GHCND database contains Class A pan-evaporation observations stored under the parameter EVAP. Pan evaporation is an empirical measurement of evaporation, which is a function of temperature, wind, humidity, and solar radiation. This parameter can be used to estimate evaporation from open bodies of water (WMO, 1966; Farnsworth and Thompson, 1982). Unlike GHCND precipitation data, pan-evaporation data from the entire continental U.S. were used, with 830 gages having sufficient data for this study (Figure 6).
Additional sources of geospatial data were obtained from the USDA NRCS’ Geospatial Data Gateway (https://datagateway.nrcs.usda.gov/). This included delineations of HUC-2s and HUC-4s from the USGS Watershed Boundary Dataset as well as 1:24,000 hydrography networks. All spatial data presented in this study is projected using the Albers equal-area conic projection, USGS version.

**General Methodology**

All data were sorted by HUC4. Using this database, annual and seasonal values of precipitation and streamflow were computed from mean-daily values for each GHCN and USGS station, respectively. Three gages were established as the minimum within a given HUC4 for a given year (or season) to generate median values of total precipitation, water yield, and normalized water yield (median water yield per median total precipitation) for each of the 84 four-digit hydrologic unit code (HUC4) basins developed by the USGS. If there were greater than 15 years of data, that particular HUC4 was included in the analysis of annual and seasonal trends.

**Water Yield and Precipitation Weighted Water Yield:** Water yield, the amount of runoff per unit drainage area, is a convenient metric to compare stations of different sizes, providing a measure of runoff production for a given area. Temporal trends in water yield reflect hydrologic changes resulting from the combined effects of changing precipitation regimes as well as landscape changes imposed by humans. For example, if annual water yield is normalized (divided) by total-annual precipitation, any changes in flow due to altered precipitation regimes are removed, revealing the effects of anthropogenic changes on runoff and potentially, sediment yields.

**Index Stations:** To evaluate changes in absolute values of water discharge (not water yield) provided at the outlets of each HUC-4 and particularly the HUC-2’s, trends in streamflow (in m$^3$/s) were examined at select “index” stations. These stations were chosen based on their location along the major rivers or tributaries, period of record, and approximate drainage area. Where drainage area was approximately equal to the drainage area of its encompassing HUC-4 or if smaller, the first upstream gage with an adequate record was selected. Approximately 400 gages where chosen to represent regional (HUC-2) and sub-regional (HUC-4) changes in streamflow. The majority of the streamflow to the Lower Mississippi (~60%) originates in the Ohio River Basin. Contributions from the Upper Mississippi (including the Illinois River) were computed as the difference between flows at Thebes, IL and Hermann, MO. The CoE gage at Hickman, KY (MS113D) was chosen to represent the flows at the upstream boundary of the Lower Mississippi just below the confluence with the Ohio River. Flows at the CoE gage at Tarbert Landing, LA (01100Q) were used to represent flows along the Lower Mississippi,

**Analysis of Median-Annual Values:** Trends of annual data were analyzed using calendar years and were determined using multiple methods: simple linear regression, annual Kendall tau (Hirsch et al. 1982), and seasonal Kendall tau (Hirsch and Slack 1984) trend tests. The Kendall tau trend test is a non-parametric test for monotonic trends based on Kendall’s tau statistic with a continuity correction, and was implemented using the statistical package R and the library EnvStats (Millard 2013). It is a common metric utilized by the USGS to assess trends in water quality (Hirsch et al. 1982). In the test, the null hypothesis is tau and is equal to 0 while the alternative hypothesis is that the true tau is not equal to 0, where positive values of tau indicate an increasing monotonic trend and negative values indicate a decreasing trend. The test
statistic itself is \( z \) and the \( p \)-value of \( z \) allows the user to accept or reject the null hypothesis. Although the Kendall tau statistic was used to determine the statistical significance of the trend, the magnitude and rate of change was computed using a linear regression and determining the difference between the calculated values for the first and last years of record for that HUC4.

**Annual Trend Analysis with Seasonality:** A more complex form of the Kendall-\( \tau \) trend test accounts for monotonic trends within individual seasons: winter (Dec-Feb), spring (Mar-May), summer (Jun-Aug), and fall (Sept-Nov). The seasonal Kendall-tau trend test is appropriate for testing annual trends when all seasonal trends are in the same direction. When the seasonal Kendall test is not appropriate (e.g., increasing trends in summer and fall seasons but decreasing trends in spring and winter), the determination of the trend defaults to the first Kendall trend test using annual values. As with the analysis of the annual data, total change over the period was determined using linear regression and solving for the difference between the first and last year of record within that season and HUC4.

**Determining Annual Suspended-Sediment Yields:** Annual suspended-sediment yields at the sub-regional (HUC-4) level were determined using two separate methods. The first method involved calculating the suspended-sediment yield at a discharge that could be used to compare with other sites and that represented a meaningful geomorphic condition. The discharge selected for this purpose was the \( Q_{1.5} \), a flow rate that is commonly used to represent the “effective discharge” (Leopold et al., 1964; Dunne and Leopold, 1978; Williams 1978; Castro and Jackson, 2001; Simon et al., 2004). Of course, there can be substantial variability around this average value (Williams, 1978), but it has been shown to be a good measure of this parameter for Level III ecoregions across the United States (Simon et al., 2004). To calculate representative sediment yields at the \( Q_{1.5} \) for each sub region (HUC-4) the following procedure was used:

- Select an “index” station for each of the HUC-4 sub-regions representing the most downstream site with an extensive data set;
- Develop a first-approximation sediment-transport rating using a single power function from instantaneous discharge and concentration data;
- Solve the resulting sediment-transport relation using the \( Q_{1.5} \) for that station; and
- Divide by drainage area to obtain a suspended-sediment yield in t/y/km².

Using a constant value of flow frequency allowed for direct comparison between sites and sub-regions as well as investigating how suspended-sediment yield varied at a single site (sub-region) over time. The earliest sampled decade for HUC-4 index stations is the 1930s. Many regions do not have sufficient sampling to determine temporal trends until the 1970s.

The sediment station in each HUC-4 with the greatest drainage area, greatest number of suspended-sediment samples, and longest period of record was selected at the representative “index” station. Transport ratings were developed for each decade of available data to determine whether the transport ratings were shifting with time. Examples from the Arkansas and the Missouri River are shown in Figure 4. The change in sediment load can be easily visualized by noting where the black vertical line (representing the \( Q_{1.5} \)) crosses each regression line. Using results from only the first and last decades of suspended-sediment observation, load (and yield) at the \( Q_{1.5} \) was computed to quantify net change over the period. If a sediment station did not have a calculated \( Q_{1.5} \)-value from the peak-flow analysis at the same gage, the \( Q_{1.5} \) was estimated based on a relation between drainage area and \( Q_{1.5} \) for gages within the corresponding HUC-4.
The second method was aimed at providing mean-annual suspended-sediment loads and yields for each sub-region to obtain a spatial distribution of sediment contributions across the basin. In this case, suspended-sediment transport ratings were developed for every sediment station in the database. Instead of automatically accepting the first-approximation rating relation based on a single power function, every relation was visually inspected to determine if in fact, a more accurate representation of the general relation between flow and concentration could be attained using several linear segments (in log-log space). Where necessary, the rating relations were adjusted using one or more additional segments. For sediment stations with associated mean-daily flows (minimum of one complete year), daily sediment loads were calculated. These values were then summed for each year to obtain annual loads, divided by the number of years to obtain an average, and then divided by drainage area to obtain average, annual sediment yield for each station. To then characterize suspended-sediment yields at the HUC-4 level, the median value from all of the stations in the sub region was reported. The data set of sampled suspended-sediment concentrations at each station was considered sufficient if there were a minimum of 10 observations and if the maximum sampled flow was at least 75% of the calculated Q₁.₅.

Figure 4. Examples of decadal shifts in sediment-transport ratings from index stations along the Arkansas (Top) and Missouri Rivers (Bottom). Note: the vertical black line represents the Q₁.₅.
Precipitation, Hydrology and Suspended-Sediment Results

Geospatial presentation of results in the form of maps provides a succinct way of visualizing and interpreting spatial and temporal trends in the data. Due to space limitations, however, we can only provide examples of these in the sub-sections to follow.

Summary of Precipitation Results

On an average-annual basis, most of the Mississippi River Basin receives more rainfall than it did 100 years ago (Figure 5). Typical increases are in the range of 10-25%. The largest increases have occurred in the Upper and Lower Mississippi and the Tennessee River Basins, and may exceed 150 mm (about 6 inches). Large percent increases in the Missouri River Basin represent increases of less than 100 mm (about 4 inches) per year. A few of the far-western HUC-4s show decreases in annual precipitation. Peak annual-rainfall totals over 1-, 3-, 5- and 7-days also show increases over most of the basin indicating that inputs of precipitation have become more intense.

On a seasonal basis there were:
- Dramatic and significant increases in seasonal precipitation during the fall, with up to 150 mm (about 6 inches) more rainfall in some HUC-4s. Statistically-significant increases are recorded for HUC-4s south and east of a line extending from south-central Oklahoma to southwestern New York (Figure 6). This spatial pattern is similar to the changes (increases) identified in hurricane-related precipitation.
- Moderate increases during spring across the entire basin with decreases in the Red River and upstream areas of the Arkansas;
- Moderate increases during winter in the upper Mississippi and Tennessee, decreases in the Ohio, and little change in the Missouri;

Figure 5. Percent change in annual rainfall for all HUC-4s (Top Left) and for HUC-4s with statistically significant trends only (Top Right). Change for all HUC-4s (Bottom), with significant trends shown in blue.
During summer, small decreases throughout the Missouri and Tennessee, small increases in the Ohio, and moderate increases in the Upper Mississippi, Arkansas and Red River Basins.

Seasonal-peak precipitation mirrors the changes in total precipitation with the exception of important declines in peak-winter precipitation in the Rockies and much of the Missouri Basin. The dramatic increases in fall precipitation along the Appalachians is reinforced by increases in peak values with 3-day totals increasing by hundreds of mm. These results point to an increasing influence of hurricanes in the southeast and the Ohio River Basin. Hurricanes that are making landfall and impacting the Mississippi River Basin are, on average, producing more rainfall on both an annual basis and over one to seven day periods than they did in 1950 (Figure 7). The spatial distribution of these changes seem to indicate a combination of effects related to general circulation patterns and a potential orographic effect from the Appalachian Mountains.
Summary of Water-Yield Results

Changes in water yield reflect how discharge regimes have changed over the past century and represent a combination of changes in precipitation and anthropogenic influences. Average-annual changes in water yield show stark spatial differences between the central part of the basin where important increases have occurred (particularly in the upper Mississippi) and the contributing western basins (upper Missouri, Arkansas and Red River Basins, as well as the western floodplains of the lower Mississippi) which show large percentage decreases in flow (Figure 8). Increases and decreases in these respective regions can be substantial, in the range of 25-50% or even 50-100%. Similar spatial trends and magnitudes are apparent for the 1-day and 7-day peak water yields, reflecting vast changes in runoff generation and transmission through the river systems. The importance of water withdrawals and flow regulation in causing decreasing water yields is supported by the knowledge that this has occurred in some HUC4s that have experienced increases in precipitation.

![Figure 8. Percent change in annual water yield for all HUC-4s (Top Left) and for HUC-4s with statistically significant trends only (Top Right). Change for all HUC-4s (Bottom), with significant trends shown in blue.](image)

The spatial distribution of changes in seasonal water yields again shows the increase in discharges throughout the mid-continent and the decreases in the western-most parts of the basin. Winter and fall tend to show the greatest areal extent of increases while irrigation withdrawals that peak during the summer months in large parts of the upper Missouri and upper Arkansas and Tennessee Basins, have resulted in important decreases in summer water yields and the amount of water available for ecological processes.

With regard to peak-seasonal water yields, there again are stark spatial differences between the western regions showing decreases across the 1- to 7-day durations, and the central and eastern regions that generally showing increasing peak yields. This clear geographic difference is probably mostly related to differences in how human requirements for water vary spatially across the basin relative to the availability of water while recalling that precipitation increases are larger in the mid-continent and southeastern parts of the basin, particularly in the fall. The fact remains though that peak-annual and peak-seasonal flows have dramatically increased in
the central and eastern parts of the basin. This has implications for channel erosion and flood control.

**Summary of Precipitation-Weighted Water-Yield Results: Anthropogenic Influences**

Although the direction of the changes varies across the basin, these effects are widespread and sizeable in magnitude, indicating that anthropogenic influences have been a major determining factor on changes in streamflow regimes over the past century. While anthropogenic activities have resulted in increases in water yield in the central part of the basin, activities at the basin margins have caused decreases in flow. The direction and magnitude of these influences can be sorted by region (Figure 9):

- **Western-most part of the basin - Decreases:** Widespread reductions in water yield due to anthropogenic activities characterize most of these HUC-4s. Decreases in the range of -25% to -100% are typical. This includes most of the upper Missouri (e.g., main stem Missouri down to Oahe, the Yellowstone, Platte, Republican and Smoky Hill Rivers), upper and middle Arkansas and upper Red Rivers (e.g., Canadian and Cimarron Rivers).
- **Central part of the basin - Increases:** Anthropogenic activities have resulted in significant increases in water yield throughout this region, with the magnitude of the increase generally decreasing from west to east. The largest effects (50-100%) are seen in the middle and lower sections of the Missouri River, the lower Arkansas and parts of the upper Mississippi (e.g., Minnesota and Des Moines), transitioning to moderate increases (10-50%) in the mid-continent and tailing off to 0-10% in the middle Ohio River basin.
- **Eastern-most part of the basin - Decreases:** Human activities have resulted in mild decreases (generally 0-10%) in water yield in the upper basins of the Ohio and moderate decreases (-10 to -25%) in the upper and middle Tennessee River basins.
- **Southern-most part of the basin - Decreases:** The lower-most sub-basins of the lower Mississippi and Red River have had moderate reductions in water yield as a result of human activities. The greatest decrease has been in the Boeuf-Tensas (0805).

Seasonally, the spatial distribution of anthropogenic influences on water yield look much like those on an annual basis as described in the bulleted points above. Striking differences during the winter in the middle and lower Missouri basin and the Red and Washita Rivers, where winter flow releases are significantly greater now (>100%) than under the natural flow regimes before the dams.

Evaporation behind impoundments has increased drastically over the past century with the construction of thousands of dams which peaked in the 1960s and 1970s. Through the 1930s, evaporation relative to average-annual rainfall was about 0.1%. Starting in the 1960s and certainly by the 1980s, broad swaths of the Arkansas and Red River basins were losing more than 5% of their rainfall from evaporation behind impoundments (Figure 10).
Figure 9. Percent change in annual, precipitation-weighted water yield for all HUC-4s (Top Left) and for HUC-4s with statistically significant trends only (Top Right). Change for all HUC-4s (Bottom), with significant trends shown in blue.

Figure 10. Percentage of average-annual potential evaporation from impoundments in specific HUC-4s relative to decadal average-annual rainfall by decade.
Summary of Streamflow Trends from Index Stations

The most important result from the analysis of the HUC-4 index stations is that discharges from much of the interior part of the basin show important increases in annual streamflow over the past century (from 25% to > 100%). Still, some trends of decreasing streamflow for various sub-regions in the upper Missouri and Arkansas River Basins are identified. In the upper parts of the Missouri, Arkansas, Ohio, and Tennessee River Basins, maximum-daily and 7-day streamflows emanating from the HUC-4 index stations were observed to decrease significantly, probably as a result of effective flood-control efforts by dam operations (Figure 11).

![Figure 11. Change in annual (Left) and maximum-daily streamflow at index stations with significant trends over the past century.](image)

HUC-4 seasonal distributions are similar to the annual ones with the exception of during the winter, where increases in flow extend well up into the Missouri Basin, reflecting the release of water under ice-covered rivers. Also striking are the large (25% to > 100%), widespread increases in discharge during the fall throughout the Mississippi River basin with the exception of the upper parts of the Missouri, Arkansas and Red Rivers, which showed decreases during this season.

In 1930, the relative contributions to average- and total-annual flow from the Ohio, Upper Mississippi and Missouri Rivers were 61%, 23% and 16%, respectively. By 2014 contributions from these three major suppliers shifted slightly to 55% from the Ohio, 28% from the Upper Mississippi and 18% from the Missouri. In general, the amount of water being delivered to the Lower Mississippi River has increased over the past century. Total-annual and annual-average flows have increased at all index stations emanating from the major river basins (HUC-2s) over the period of record (Figure 12). The actual, average increases in mean-daily flows from the three main basins to the upstream boundary of the Lower Mississippi River are:

- Ohio River: 1,674 m$^3$/s (23.8%);
- Upper Mississippi River: 1,767 m$^3$/s (66.0%); and
- Missouri River: 986 m$^3$/s (54.8%).

This comes to an increase in average, mean-daily flows, of about 4,427 m$^3$/s (156,000 ft$^3$/s). Integrated over an average year and excluding inputs from other smaller tributaries, brings the
average, annual increase in flows to the Lower Mississippi to about 1.62 million m³/s (57.2 million ft³/s).

Peak-annual streamflows from the Upper Mississippi River, measured at Thebes, showed significant increases over the period of record, for all durations:

- 1-Day: 2,990 m³/s, (105,000 ft³/s);
- 3-Day: 10,300 m³/s, (364,000 ft³/s);
- 5-Day: 16,500 m³/s, (582,000 ft³/s); and
- 7-Day: 25,000 m³/s, (882,000 ft³/s).

![Figure 12. Change in total-annual and average-annual streamflow at the major index stations](image)

Increases in seasonal streamflows from the Ohio, Upper Mississippi, and Missouri were detected in all seasons, although flows in the Lower Mississippi were found to increase only during the winter, summer, and fall months.

**Summary of Sediment-Yield Results**

Suspended-sediment yields were calculated for all stations and all time periods at the Q₁₅ to represent conditions at the “effective discharge”. Maximum values occur in the Yazoo Basin (HUC 0803) with suspended-sediment yields of 154 t/d/km² and are 2.5 times greater than the next largest yielding region. Other areas of high yields include parts of the Upper Red (HUCs 1112 and 1113), the Kansas and Lower Missouri (HUC 1027 and 1030, respectively) and in two HUCS-4s in Upper Mississippi Rivers (704 and 706). In contrast, low-yielding regions (<0.25 t/d/km²) occur throughout the upper Missouri, the James River (HUC 1016) and the Mississippi Headwaters.

Index stations were used to establish transport relations by decade to evaluate the change in sediment transport over the period of sampling and to determine the spatial distribution of these changes. These are shown at the HUC-4 level in Figure 13. Results show that suspended-
sediment loads at the Q1.5 have declined from the outlets of all of the major (HUC-2) tributaries draining to the lower Mississippi River. About 5 million tons per day less sediment is reaching the lower Mississippi River (excluding the Atchafalaya) from its major tributaries at the Q1.5:

- Ohio River: -48.5% (286,000 t/d);
- Tennessee River: -46.4% (8,380 t/d);
- Upper Mississippi River: -47.3% (446,000 t/d);
- Lower Mississippi (Atchafalaya River): -30.0% (49,600 t/d);
- Missouri River: -86.1% (3,440,000 t/d);
- Arkansas River: -95.7% (768,000 t/d);
- Red River: -90.5% (775,000 t/d).

Still, there are some sub-regions that are providing greater sediment loads currently than at the beginning of the sampling periods. These are located in the Upper Mississippi basin where about 50% of the index sites (sub-regions) are showing increases in suspended-sediment yields.

![Figure 13. Change in suspended-sediment load at the Q1.5 at sediment index Stations, expressed in percent (Left) and in t/d (Right). Blank areas represent a lack of index stations.](image)

Using a data set of 970 gages, median, annual suspended-sediment yields from the sub-regions were found to vary over three orders of magnitude, ranging from 0.6 t/y/km² in HUC-1016 (James River) to 514 t/y/km² in HUC-1021 (Loup River) (Figure 14). The central 50% of the distribution of median values ranges from 20.1 to 95.1 t/y/km². Changes in median-annual suspended-sediment yields within each of the sub-regions reflect a broad range of hydrologic and anthropogenic changes over the past century. Marked decreases are observed across large parts of the Upper Missouri, throughout the Arkansas and Red River basins and in parts of the Upper Ohio and Lower Mississippi River Basins (Figure 15). These decreases are probably the result of land- and water-use practices that result in less water in the channels. In contrast, increases in median-annual yields have occurred throughout much of the mid-continent, including the Upper Mississippi and the lower Missouri Basins.
Figure 14. Average annual suspended-sediment yield by HUC-4 from station medians.

Figure 15. Changes in median-annual suspended-sediment yields over the period of record, by HUC-4.
To provide an evaluation of how sediment delivery to the lower Mississippi River has changed over time, sediment-load data from the outlet of the major contributing rivers was considered. To account not only for changes in hydrology, but also for changes in the relation between flow and sediment-transport rates, shifts in the rating relations were included in the analysis. Decadal sediment-transport curves were developed for the major (HUC-2) index stations and used to determine average-annual values for each decade (Table 1).

### Table 1. Decadal average-annual sediment delivery to the Lower Mississippi River.

<table>
<thead>
<tr>
<th>Decade</th>
<th>Average Annual Sediment Load [Mt]</th>
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<tbody>
<tr>
<td></td>
<td>Ohio</td>
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<tr>
<td>1940s</td>
<td>49.6</td>
</tr>
<tr>
<td>1950s</td>
<td>58.7(^\text{a})</td>
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<tr>
<td>1960s</td>
<td>48.4(^\text{a})</td>
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<td>1970s</td>
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<tr>
<td>1980s</td>
<td>30.4</td>
</tr>
<tr>
<td>1990s</td>
<td>29.8</td>
</tr>
<tr>
<td>2000s</td>
<td>31.4</td>
</tr>
<tr>
<td>2010s</td>
<td>20.8</td>
</tr>
</tbody>
</table>

\(^{\text{a}}\) Uses 1940s transport curve; \(^{\text{b}}\) Uses 1950s transport curve; \(^{\text{y}}\) Uses 1970s transport curve

* Estimated from extrapolation of trend from 1970s-2010s, back to 1940s

Sediment delivery to the lower Mississippi River from the HUC-2 basins show drastic, monotonic decreases over the period 1940 to present. The percent reduction in average-annual, suspended-sediment loads are: 61% for the Ohio River, 33% for the Upper Mississippi River, 84% from the Missouri River and 96% for the Arkansas River. About 251 Mt less suspended sediment are discharged per year to the Lower Mississippi River today from the Missouri River than in the 1940s. In total, this represents about a 300% reduction in average-annual, suspended-sediment delivery from the major tributaries to the Lower Mississippi River, from about 616 Mt/y in 1940 to about 98 Mt/y currently (Figure 15). Numerous other researchers have similarly reported on a large decline in suspended-sediment loads discharged by the Mississippi River to the Gulf of Mexico (Keown et al., 1986; Meade and Moody, 2010; Heimann et al., 2011). These reductions in loads have consequences for river stability, protection of hydraulic structures, nutrient transport, and replenishment of coastal wetland areas.

![Figure 15. Decline in average-annual delivery of suspended-sediment to the Lower Mississippi River.](image-url)
Summary

Altered hydrological conditions in the Lower Mississippi River are a result of changes in precipitation, rainfall-runoff relations and anthropogenic factors that play a role in the magnitude and frequency of hydrologic events. Numerous studies have shown the significance of climate change and extreme weather events on peak flows, low-flows, and flooding, etc. Contributing to shifting hydrologic patterns such as precipitation, are human-induced changes to the natural environment such as agriculture, urbanization, channelization, dam construction, etc., that often vary in a spatially systematic way according to regional demands for water. Changing flow regimes also affect suspended-sediment transport rates and channel stability, challenging on-going efforts in flood protection, stream restoration and water-quality management.

Results of this study show that in general, although most of the Mississippi River Basin is receiving more rainfall than it did 100 years ago, there are vast areas where water yields have decreased significantly, particularly in the western part of the basin and particularly in spring. Precipitation has also shifted temporally such that winter precipitation has significantly decreased in many areas while spring and autumn precipitation has generally increased. Parts of the western basin are experiencing 25 to more than 50% less discharge per unit area than they did 100 years ago. In contrast, the mid-continent is generating considerably more water than it did 100 years ago. In part this can be attributed to increases in precipitation and a greater influence of hurricane-related rainfall, but the anthropogenic effects cannot not be minimized. The result is that the lower Mississippi River is receiving more flow from its major HUC-2 tributaries (Ohio, Missouri and Upper Mississippi Rivers) than at the turn of the 20th century. Integrated over an average year and excluding inputs from other smaller tributaries, brings the average, annual increase in flows to the Lower Mississippi River to about 1.62 million m$^3$/s (57.2 million ft$^3$/s). Average, mean-daily flow contributions from the Ohio, Upper Mississippi and Missouri Rivers have changed from 61%, 23% and 16% in 1930, to 55%, 28% and 18% in 2014, respectively.

Although the direction of the changes (positive or negative) varies across the basin, these effects are widespread and sizeable in magnitude, indicating that anthropogenic influences have been a major determining factor on changes in streamflow regimes over the past century. The direction and magnitude of these influences can clearly be sorted by region. While anthropogenic activities have resulted in increases in water yield in the central part of the basin (increases of 50-100% decreasing eastward to 0-10%), activities at the basin margins have caused decreases in flow. In the west, decreases of 25-100% are typical.

Results of this study are in direct contrast with results of McCabe and Wolock (2011) over the same time period. Those authors concluded that precipitation variability accounts for nearly all the variability in observed runoff in the conterminous U.S. based on rainfall-runoff simulations. Similar to the findings of McCabe and Wolock (2014) who determined that streamflow was only weakly correlated to known climate indices, the results of this study show unpredictability of water yields based solely on climate – in this case, precipitation.

Sediment yields were calculated for all stations with available data at the channel-forming discharge (Q1.5) and on an annual basis. Results for both the downstream-most stations in each
sub-region and for average conditions within each sub-region elucidate current rates of suspended-sediment transport as well as changes over the period of record. Suspended-sediment loads at the outlets of most sub-regions have drastically declined. From the major tributaries at the Q1.5, by 30% in the Arkansas, 46-48% in the Tennessee, Upper Mississippi and Ohio Basins, and 86% in the Missouri. Similar results were obtained for annual values. Still, increases in sediment yields are found in some sub-regions impacted by increased precipitation and water yields such as the upper Mississippi, and regions bordering the lower and middle Mississippi and Missouri Valleys where channels are responding to the lowering of the trunk streams downstream from dams or because of channelization activities.

The average-annual delivery of suspended sediment to the Lower Mississippi River has declined by about 300%, from about 600 Mt/y in 1940 to about 100 Mt/y, currently. The largest actual decline is from the Missouri River (about 250 Mt/y) largely due to the trapping of sediment behind impoundments. Decreases in sediment delivery to these reservoirs are also noted. Other researchers have similarly reported on a large decline in suspended-sediment loads discharged by the Mississippi River to the Gulf of Mexico. These reductions in loads have consequences for river stability, protection of hydraulic structures, nutrient transport, and replenishment of coastal wetland areas.

References