Lower Mississippi Slope and Stream Power

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Abstract

For decades scientists and engineers have sought to better understand the short and long-term geomorphology of the Mississippi River. A critical component of river morphology and river response is a river's adjustment of slope throughout a system. Utilizing 20 historical gaging stations across 600 miles of the Lower Mississippi River between the Ohio River Confluence and the Old River Control Complex (ORCC), reach averaged slopes through time were computed for consecutive reaches and are presented. Combining this slope data with historical discharge data allows the computation of stream power which is also presented. The importance of stream power is its direct relationship to a stream or river's ability to transport sediment, especially bed material which controls the channel bed and morphology. Analysis of the slope and stream power data reveals a complex river response as the river reacted and continues to respond to major adjustments in length and slope.

Slope and Stream Power Analysis: Definitions, Methods, and Limitations

For this study, slope is defined as a reach averaged water surface slope between two gaging stations computed as the difference in water surface elevations at the two gages divided by the length of river between the two gages.

Mackin (1948) relates the importance of slope to a graded stream or stream in equilibrium. According to Mackin, "a graded stream is one in which, over a period of years, slope is delicately adjusted to provide, with available discharge and the prevailing channel characteristics, just the velocity required for transportation of all of the load supplied from above." The science and understanding of channel response has continued to progress through time resulting in various qualitative relationships. One of the most common conceptual models developed and often utilized is Lane's balance, which determines expected channel response with the relationship of a stream's discharge and slope to the stream's bed material sediment load and size. Lane (1955) proposed the relationship:

$$\text{Eq. 1.}\quad Q_w S \sim Q_s D_{50}$$

where

Q_w = water discharge

S = slope of the stream

Q_s = bed material load, defined as sediment in transport of sizes readily available in considerable quantities in the stream bed.

D_{50} = bed material particle diameter or size of sediment

Lane's balance ties in with the second component of this study, stream power, which is basically the left side of Lane's relation. The concept of stream power is often attributed to Ralph Bagnold. While he acknowledges that prior attempts at using the general power equation (Power=Work/time) in channel hydraulics occurred, he is the first to compare experimental transport results with stream power. Bagnold writes in his 1966 paper, "The available power supply, or time rate of energy supply, to unit length of a stream is clearly the time rate of liberation in kinetic form of the liquid's potential energy as it descends the gravity slope," and mathematically defined stream power with Equation 2:

$$\text{Eq. 2.} \quad \Omega = pgQS$$

where

Ω = Stream power, Watts/m

p = density of water, kg/m^3

g = acceleration due to gravity, m/s^2

Q = water discharge, m^3/s

S = water surface slope, m/m

For this investigation, stream power refers to the values computed from equation 2 and is considered the amount of energy or power that the river has to move sediment. The importance of stream power is that it is often related to a stream or river's ability to transport bed material which is the material that is impacting and changing the channel bed and morphology of the channel.

Methodology

This section discusses the data and methods used to compute the slope and stream power results.

Base Data: A database of daily stages and discharges throughout the river was first developed. Daily stage data was compiled for 20 stations in the study reach (Figure 1). The stations, their locations in river mile, and the period of record used in the study are included in Table 1. Daily discharges are also available at Hickman, Memphis, Helena, Arkansas City, Vicksburg, and Natchez which are labeled in red in Figure 1.

Figure 1. Gage Locations

Table 1. Stage Gaging Stations

Station	River Mile (1962)	Period of Record
Wickliffe	951.5	1933-2019
Columbus	937.2	1933-2019
Hickman	922	1933-2019
New Madrid	889	1930-2019
Tiptonville	872.4	1960-2019
Caruthersville	846.4	1933-2019
Osceola	783.5	1933-2019
Memphis	734.4	1933-2019
Star Landing	707.2	1933-1991
Mhoon Landing	687.5	1933-1978, 2017-2019
Helena	663.1	1930-2019
Friar Point	652.5	1946-2002, 2014-2019
Fair Landing	632.5	1946-1994
Rosedale	592.2	1931-2019
Arkansas City	554.3	1929-2019
Greenville	531.5	1929-2019
Lake Providence	487.2	1925-2019
Vicksburg	437.6	1925-2019
St Joseph	396.4	1927-1996
Natchez	363.3	1927-2019

Slope Computations: Water surface slope was computed on a daily bases for all reaches with available data. First, stages were converted to elevations using the appropriate gage datum, and then slope was computed by dividing the difference in the upstream and downstream water surface elevations by the distance between the stations. Both the gage datums and distances can change through time and must be considered. Reach distances can vary from relocation of the gages or from changing lengths of the river and were determined for different time periods through historical documentation and distance measurements using aerial maps and surveys. The most drastic changes in lengths occurred as a result of the cutoff period that consisted of 14 man-made cutoffs and two natural cutoffs, all occurring between 1929 and 1942 (Winkley, 1977). Since the extensive construction of revetments, the lengths have remained relatively consistent since about the mid-1960s.

Computed daily water surface slopes are shown through time for the reach from Vicksburg to Natchez as an example (Figure 2). While broader trends can be observed, the graph highlights the variability associated with the daily slopes. This variability is likely driven by the natural unsteady flow nature of the system as the slope can have relation to the magnitude of the discharge and can also be impacted by changes throughout a hydrograph such as rising and falling limbs of the hydrograph. Once the daily slopes are computed, they can then be averaged over each water year to produce a simplified time series to better display the general long term trends. An example for the same Vicksburg to Natchez reach is shown in Figure 3, and similar figures are presented in the results section for each reach. For these annually averaged results, a value is only included for each year where data is available for at least 350 days within the respective year.

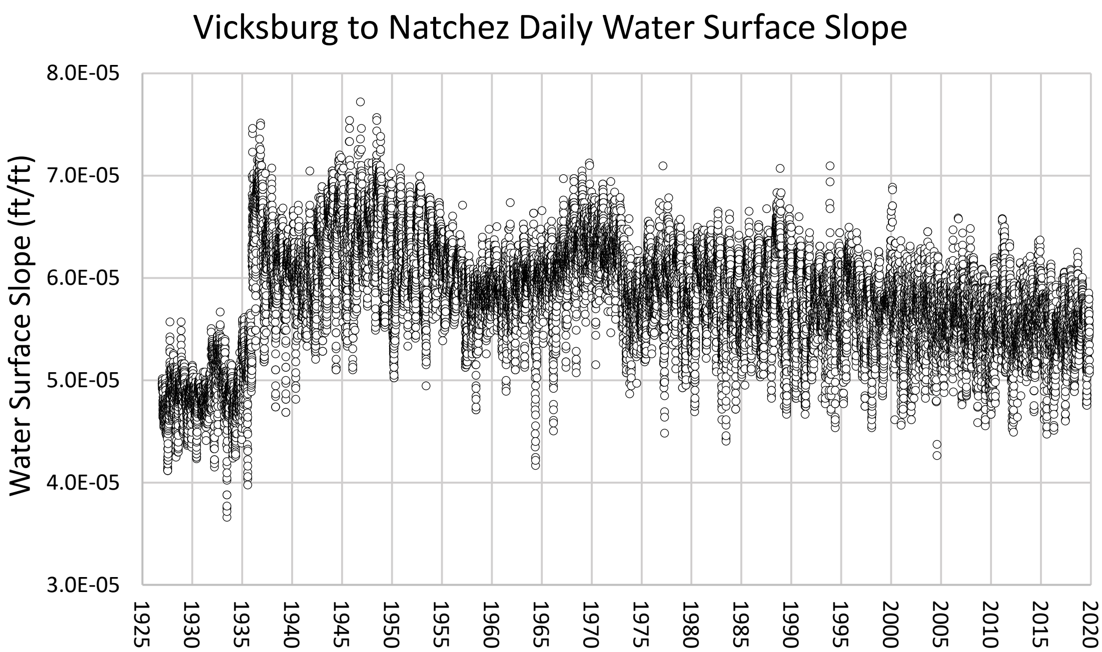

Figure 2. Daily water surface slope example

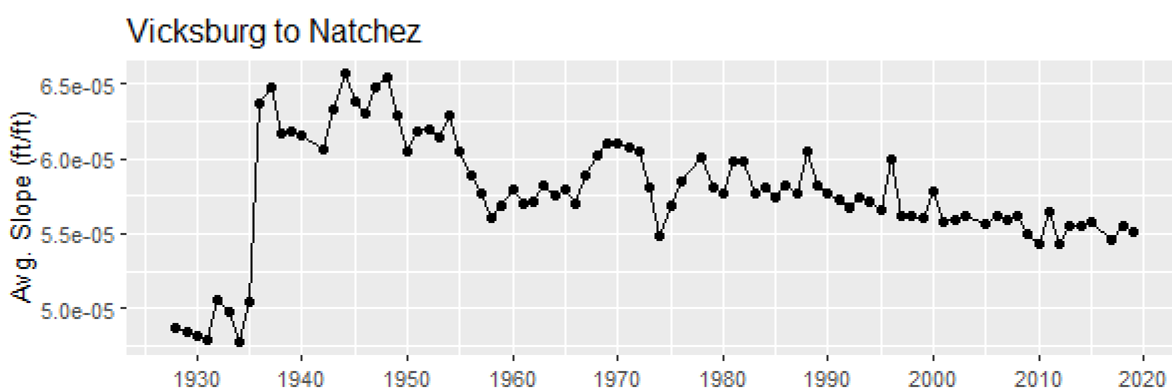

Figure 3. Average annual water surface slope example

Stream Power Computations: Daily stream power values for each reach were computed using equation 2. The previously computed daily slopes for each reach were combined with a daily discharge from one of the eight discharge stations. A lag time for the discharge was accounted for where determined to be appropriate. Constant values of $p = 1000\ kg/m^3$ and $g = 9.81\ m/s^2$ were used for all computations. Using this information, daily stream power values for each reach were computed. Using the same approach as the results for slope, stream power values were averaged by water year to produce time series of average stream power and are presented in the results section.

Interpretation

While a time series plot of average slopes can easily display changes and trends in slope adjustments, the reason behind these changes is not necessarily captured within the charts. The changes in slope can be a result of the adjustments of two variables, reach length and the water surface elevation difference between gages. The most drastic impact on slope is a result of the shortening of a reach associated with cutoffs which immediately increases the average slope of a reach. If a river has the freedom to meander, lengthening of the river can also occur reducing the slope, but at a much slower rate. As for variations in slope due to changes in the difference in water surface elevations or head difference between gages, the slope can also trend the same direction for multiple reasons. For example, the slope can steepen as a result of upstream water levels increasing, the downstream water levels decreasing, or both occurring simultaneously. Because different combinations of aggradation and degradation can occur as the system's slope adjusts, combining slope information with specific gage trends is extremely helpful in understanding the morphologic response. In the case of the LMR, Biedenharn et al., (2017) developed specific gage trends based on the same gages and time periods as the data used for this slope and stream power assessment which can provide valuable insight into the morphology of the river when combined with the slope and stream power results presented in this report.

Similar to slope, stream power can also be analyzed as a time series to show temporal trends. A second approach of comparing stream power spatially throughout the river provides the opportunity to identify stream power discontinuities, which can be related to imbalances in sediment transport capacity. For example, utilizing Lane's balance (Eq. 1), a stream in dynamic equilibrium will have balanced its stream power with the sediment supply such that the stream is neither aggrading nor degrading. However, if the stream power in a reach is significantly altered, while the sediment supply (right side of Eq. 2) remains unchanged, then dramatic morphologic changes could be expected. Taking this relation one step further and using stream power from an upstream reach to be representative of sediment supply allows the opportunity to hypothesize an expected response due to changes in the relation of upstream and downstream stream power. For example, a decrease in downstream stream power, such as the backwater effect from a dam, with no change of stream power upstream would typically cause channel aggradation in the lower stream power reach.

Limitations

As with most river engineering or geomorphic analyses, uncertainty or limitations exist for the slope and stream power analysis. A few specific examples are presented below.

- Computations of slope and stream power within this report are considered broad scale reach averages as the method is limited by the locations of historic gage data, which can range from 20 to close to 100 miles apart in some reaches

- Reach length between gages is a critical variable in computing slope and stream power, and the lengths are ever changing to some degree. The lengths and dates used in this study are limited by the availability of historic documentation and mapping. However, the most drastic changes in lengths are a result of cutoffs which are well documented and should be well represented in this analysis.

- Tributary flow inputs or diversions within a reach can complicate computations and understanding of slope and stream power.

Results

Graphs of average annual slope through time were created for 12 consecutive reaches. The reaches were determined by stations with a complete period of record from 1930's to present and are presented in order of upstream to downstream (Figure 4). Figure 5 shows 12 reaches side by side and is a good visualization of the reach slopes relative to each other through time. In Figure 5 reaches upstream to downstream are presented left to right and the abbreviations of each reach are the first 2 letters of the upstream gage and first 2 letters of the downstream gage (e.g., WI-CO = Wickliffe to Columbus). Similar to the slope trends, annual average stream power plots were created for each consecutive reach. Only the summary stream power plot displaying the average annual stream power for each reach is presented as the bottom plot in Figure 5.

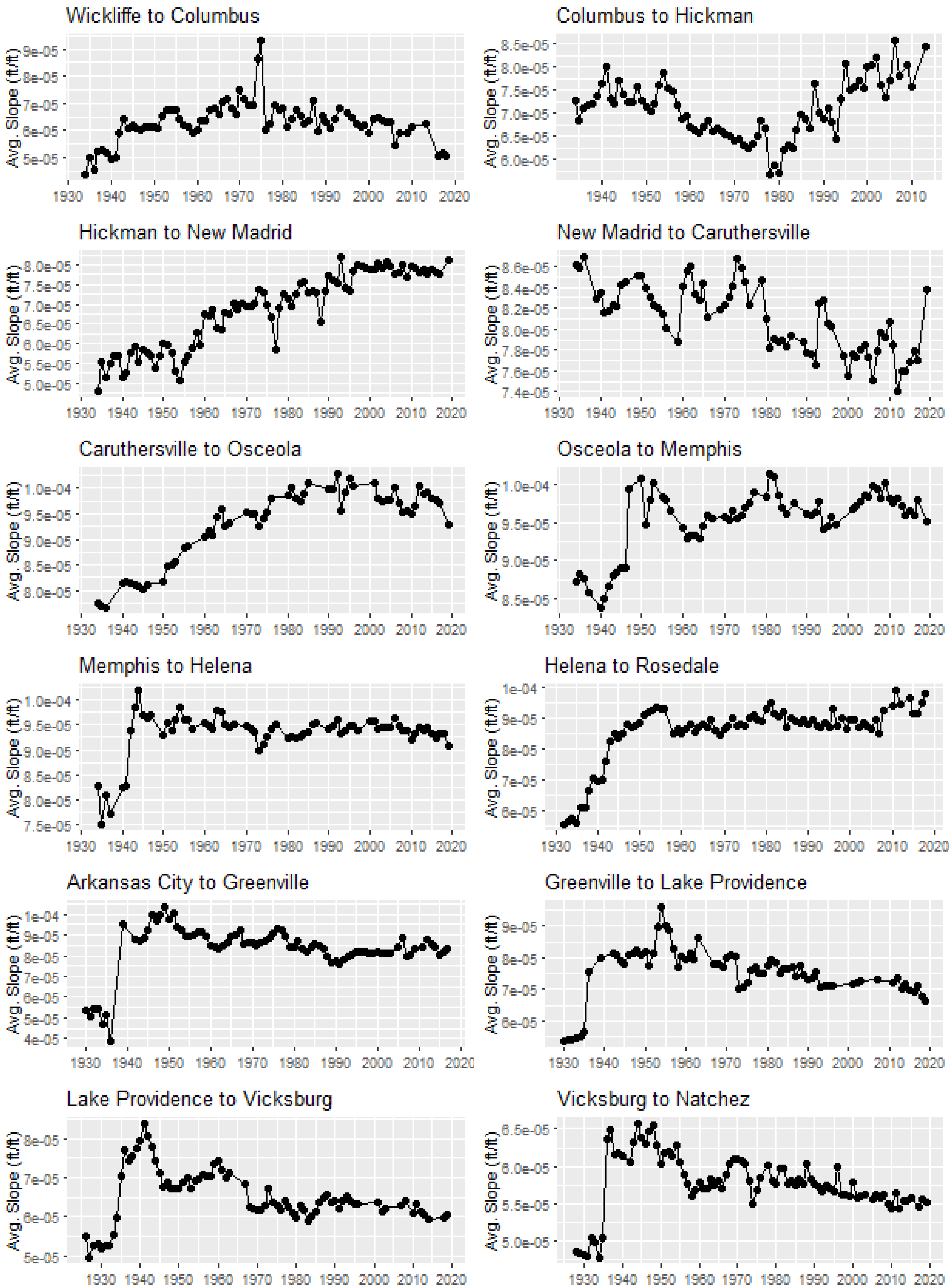

Figure 4. *Annual averaged slope for consecutive reaches*

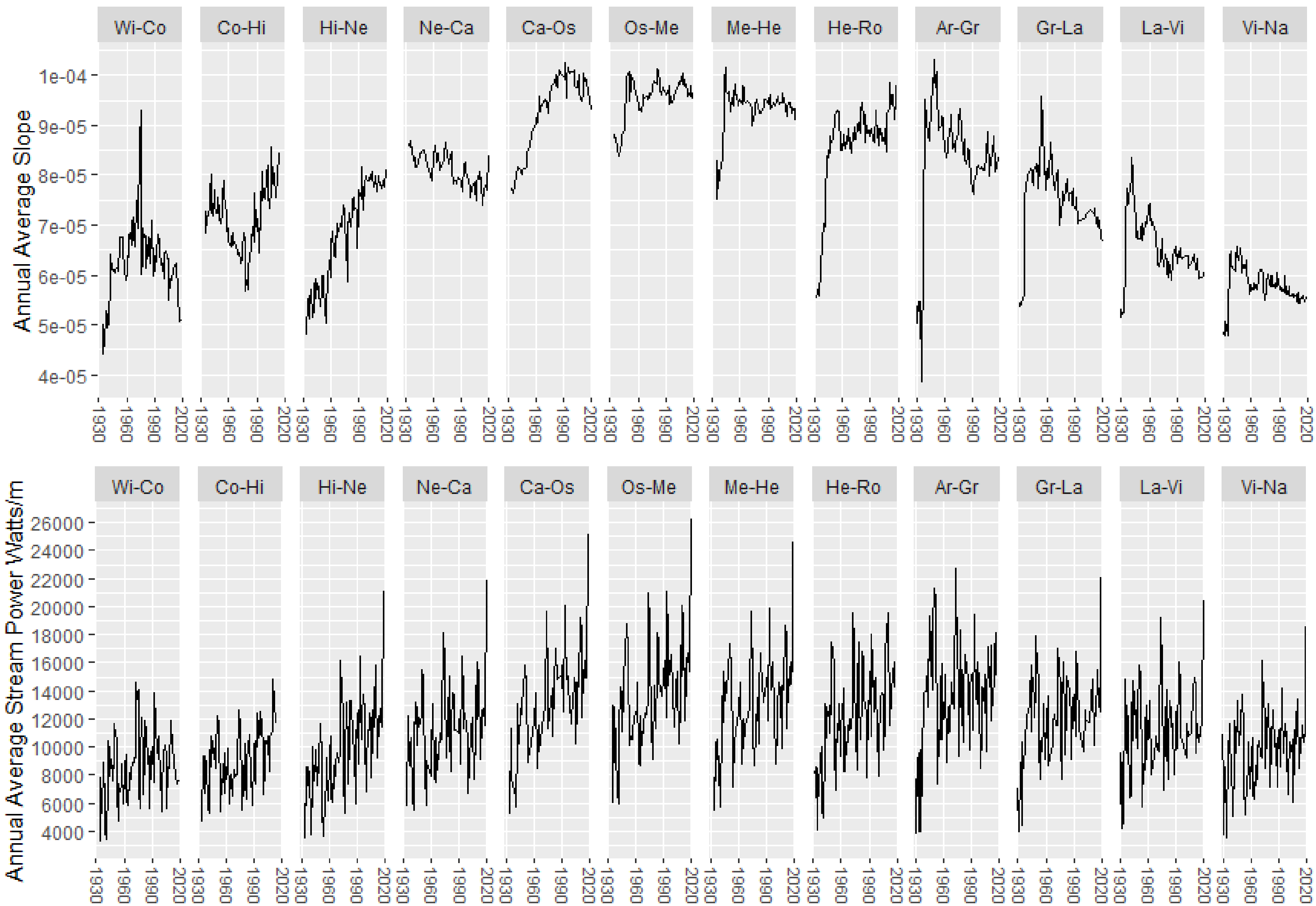

Figure 5. Summary plot of LMR slope (top) and stream power (bottom)

Discussion

Examining the individual slope trends throughout the LMR and the summary plot highlights key temporal and spatial trends. Some of the most noticeable changes to the slopes across the system are the increases in the 1930's and 1940's, especially in the reaches downstream of Memphis. This is a time period when cutoffs were being constructed on the LMR, resulting in a much shorter river. Winkley (1977) lists the major cutoffs constructed on the river along with location and length each one shortened the river. In total 14 man-made neck cutoffs were constructed between Memphis and Natchez from 1929 to 1942, and two additional cutoffs occurred naturally resulting in a shortening of the river by nearly 150 miles. These cutoffs drastically influenced the river slope throughout the LMR. Figure 6 compares the slopes pre and post cutoffs with pre-cutoff values being an average of all years for each reach prior to the cutoffs and post cutoffs representing current conditions, computed as an average of all years after 2010. Currently, all but one reach has increased slopes compared to the pre-cutoffs with the largest difference being the slopes from Helena to Rosedale and Arkansas City to Greenville being nearly 70% and 60% steeper, respectively. Downstream of the Arkansas River, the largest tributary input within the LMR, there is a similar pattern through time as the slope across all reaches follow a similar trend. There is the immediate steepening when the cutoffs were constructed and then a long term flattening which continues to present day. Even with the continued adjustments for nearly a century, the slopes are still higher than the pre-cutoffs time period.

The stream power results presented above have significate variability in the annual average stream power from year to year as it is highly dependent on the discharge hydrograph making it much more difficult to visually compare spatially. One interesting aspect of this chart is the extremely high annual stream power for 2019 relative to other flood years such as 2011 and 1973 when peak flows were much higher, indicating that the river had much more energy and potential to transport sediment due to the long duration of 2019 high water. Although difficult to compare when presented the same as the slope data, there is tremendous value as the stream power is more closely related to sediment transport and the changing geomorphology. These values are still being used in the development of a stream power budget similar to a sediment budget with the hopes of highlighting any discontinuities through the system which may help to infer future morphologic response of the LMR.

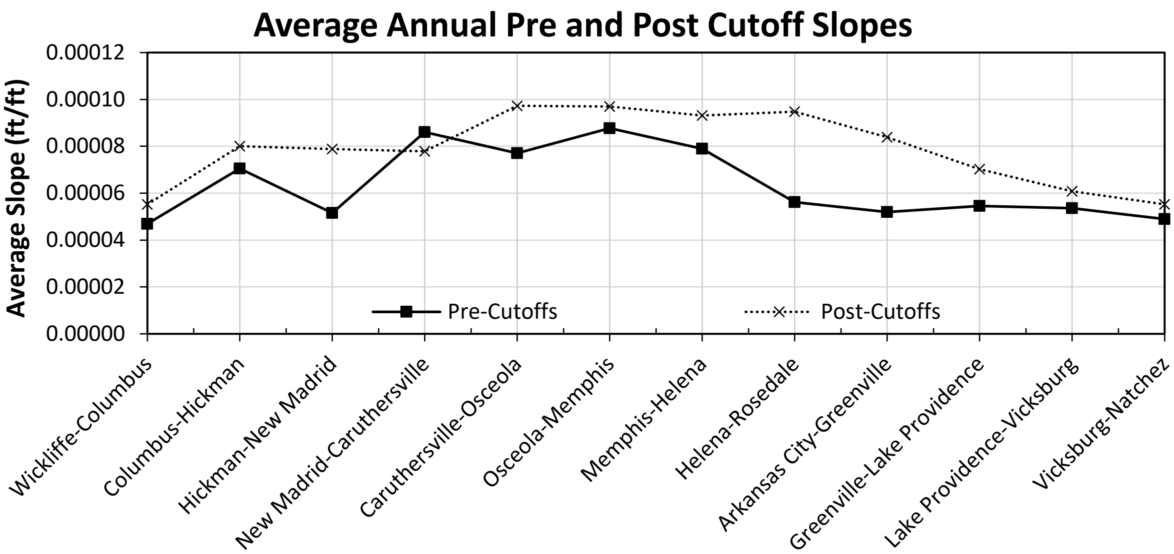

Figure 6. Pre and post-cutoff slope changes

Conclusions

Reach averaged slope and stream power values were computed for multiple reaches on the LMR upstream of the ORCC. Analyzing the slope and stream power throughout the system highlights the river's complex response, with the most dramatic changes occurring after the cutoffs in the 1930s and early 1940s. First, there was an immediate impact as the shortening of the river greatly increased the slope and stream power in the river. This resulted in disruptions to the energy and sediment continuity, and since that time, there has been continued morphologic adjustment, which is expected to continue into the future. Though predicting a final long-term quasi-equilibrium state of the LMR has a high level of difficulty and tremendous uncertainty due to complexities and ever-changing driving factors, an improved understanding of the adjustments of slope and energy throughout the system are a critical component of understanding the long-term geomorphology of the LMR. This is a major goal of the US Army Corps of Engineers, Mississippi Valley Division's Mississippi River Geomorphology and Potomology Program that funded this effort, which is just one small piece of a broad scale research program focused on developing an improved understanding of the Mississippi River.

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