

Measuring the Volumetric Storage Changes in the Mississippi  
River

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By

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Approved by

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## Abstract

Storage change in rivers is a fundamental indicator of hydraulic processes, providing a numerical link between fluxes in and out of the channel, both via tributaries and via exchange with hyporheic groundwater. The spatial nature of storage change makes its in situ characterization impossible over long distances. New applications of remote sensing allow for measurement of this fundamental quantity. River width and height measurements derived from satellite data can be used to compute change. Storage change for a 2000 km stretch of the Mississippi River was computed for 2008 to 2010 assuming no temporal change in river width. Rates of storage change varied from  $-0.3$  to  $0.25 \text{ km}^3$  per day. These values of change approximately followed seasonal cycles and were consistent with discharge data from the river as well. Temporal integration of storage change yields storage anomaly, which can be thought of as the difference between the actual river storage and storage at the initial time. Storage anomaly has a range of approximately  $10 \text{ km}^3$ , which is approximately 2% of the annual flow of the river.

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## Introduction

Vast quantities of water occupy our planet. Not only is 70% of Earth covered in ocean, but untold amounts lie frozen in polar regions or in brackish groundwater [Oki and Kanae, 2006]. Rivers connect oceans and land, providing a critical link in the hydrological cycle. Despite water's importance, precise estimates of water storage and fluxes are elusive on the global scale.

Stream gaging stations provide data on the height of river surface over time. Continuous flow estimates require periodic site visits and continuous stage elevation, resulting in the need for significant resources to maintain a viable monitoring network [Hannah et al., 2011]. Additionally, many countries do not willingly share stream gage data.

In 2004, the United States conducted an investigation into its available water resources [Science and technology to support fresh water availability in the United States, 2004]. After much deliberation, the researchers came to one conclusion: they simply did not know the amount of water the U.S had to work with. While the US has invested much effort in developing assessments of their freshwater resources, little or no information is available in many other parts of the world

With satellite measurements of river height and river width, the volumetric changes in river storage change can be measured remotely. This change could be paired with a set length and an estimated width to find a total volume change across the volume. For a river channel,  $\text{Flow in} - \text{Flow Out} = dS/dt$ , so the change in storage that is measured will directly provide the difference between inflows and outflows, which is of great value as a fixed point in rivers where inflows and outflows are unknown.

The Mississippi River has always been a focal point of American investigation. Many cities call its shores home, and it has long been an important shipping route. Its size and relevance have made it the topic of many scientific inquiries throughout the years. As such, there are many data available for use as to its qualities. With so much information available as to its traits, the Mississippi is a logical place to start in regards to determining water volume changes.

If successful, these methods could be applied elsewhere.

## Data

River width data were obtained from the work of Allen and Pavelsky [2005a], where width was measured at an average discharge from 1756 Landsat scenes covering North America. For each Landsat path and row combination, the time of year when the observable rivers were most likely to be at mean discharge was calculated by analyzing

mean monthly discharge records from the Global Runoff Data Center [Allen and Pavelsky, 2015b]. The Landsat river width measurements were validated using more than 1000 geographically distributed streamflow and river width records from the U.S. Geological Survey (USGS) and the Water Survey of Canada (WSC). Daily discharge measurements were used to calculate the in situ mean annual discharge for each location [Kimbrough et al., 2003].

River height is measured using altimetry obtained from Envisat and Jason-2 satellites [Jason, 2001]. All data points from the target river “virtual stations” are then pulled into three vectors, so that each surface elevation anomaly has a date and a flow distance (distance from the mouth of the river) associated with it [Amidror, 2002]. Each virtual station represents a location where an altimeter orbital ground track intersects a river, and has an associated timeseries of measured river heights.

Jason-2 was launched June 20, 2008 by NASA, and Envisat was launched in 2002 by the European Space Agency, with both satellites intending to track ocean heights. The Envisat mission ended in 2012; however, the Envisat orbit was changed in October 2010, such that the satellite no longer orbited over the same Virtual Stations. Thus, we consider only Envisat data through October 15 2010. Jason-2 continues to operate at time of writing. The two altimeters produce overlapping data for a period of 824 days, from July 14, 2008 to October 15, 2010. Envisat has better spatial coverage, and Jason-2 has better temporal resolution; the spatial coverage point can be seen in Figure 1. There are a total of 14 Envisat and 7 Jason-2 virtual stations on the Mississippi.

Most water flux estimation methods use regression-based relationships between remotely measured inundated area and in-situ measured discharge to predict fluxes. However, this approach does not work well in environments where small changes in water heights yield little change in surface area yet significant changes in flow [LeFavour and Alsdorf, 2005]. The Shuttle Radar Topography Mission (SRTM) is an international research effort that obtained digital elevation models on a near-global scale. SRTM has been used to estimate stream channel water elevations, slopes, and discharges [LeFavour and Alsdorf, 2005].



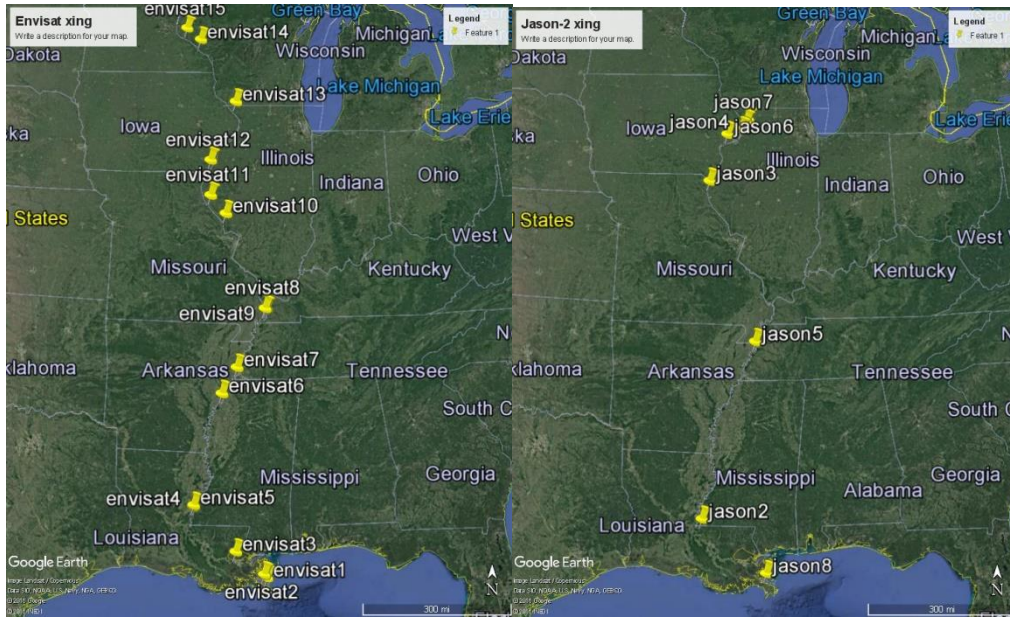


Figure 1: side by side comparison of the Envisat (left) and Jason-2 (right) satellites river crossings

## Methods

The portion of both altimeter records from July 14, 2008 to October 15, 2010 is extracted, representing the period when both Jason-2 and Envisat were operational. Each time block of height anomalies is then interpolated over a date, flow distance surface at a 1 day to 1 km resolution, using Delaunay triangulation, solved with bi-linear interpolation [Amidror 2002]. The three pieces are then concatenated into a single matrix covering the full timeframe and flow distance. A mean river surface height based on Shuttle Radar Topography Mission (SRTM) data is then added to data at each flow distance to convert it back to an elevation.

Landsat river widths are averaged to 1 km spatial resolution. Finding the change in storage required use of the equation

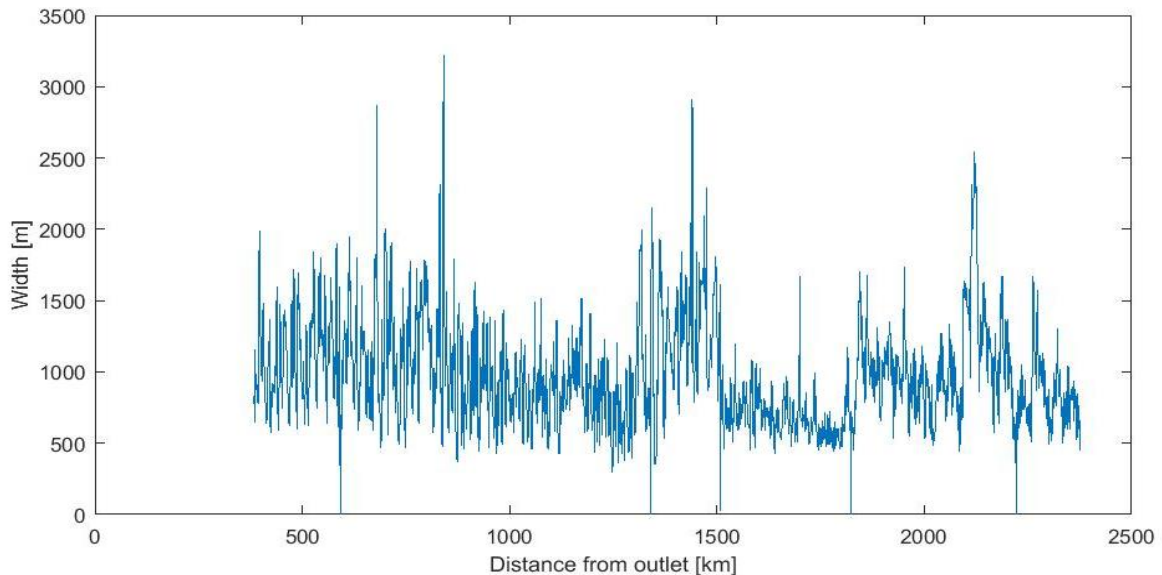
$$dS/dt(t,x) = (h(t_2,x) - h(t_1,x)) / \Delta t * W(x) * \Delta x$$

in which  $dS$  = change in storage,  $dt$  = change in time,  $h(t)$  = height at a given time,  $W(x)$  = width in meters, and  $\Delta x$  = the length of each river unit over which the interpolation was performed.  $dS/dt$  is in units of cubic meters per second. To find the total change along the river,  $dS/dt$  for each length must be summed, using the equation

$$dS_{river}(t) = \sum dS/dt(t,x) \Delta t.$$

That is, the total number of 1 km river cells must be added together to find the total change in meters cubed for the entire river, Matlab was used to calculate all equations, with  $h(t)$ ,  $W(x)$ , and  $\Delta t$  being given, and  $\Delta x$  always 1000 meters.

## Results



**Figure 2: River width, shown in distance from the outlet**

Figure 2 shows the width of the Mississippi River averaged to the 1 km intervals, from the original native widths at 30 m resolution derived from Landsat data. The wide variance in widths is clearly visible, and demonstrates the variable nature of the river, even between locations in relatively close proximity to each other. Values range from 500 meters to nearly 3.5 kilometers. Width generally increases in the downstream direction, but not always: between 1200 and 1500 m, widths are markedly higher, e.g., just downstream of the confluence with the Ohio River at Cairo, Illinois.

Figure 3 shows an arbitrary Virtual Station from the Envisat satellite, from a location 1399.1 km upstream from the outlet, downstream of the Ohio River confluence. River elevation varies by approximately 15 meters over the entire Envisat period; recall that only the data from July 14, 2008 to October 15 2010 are analyzed herein, as that is the period where Envisat overlaps with the Jason-2 altimeter.

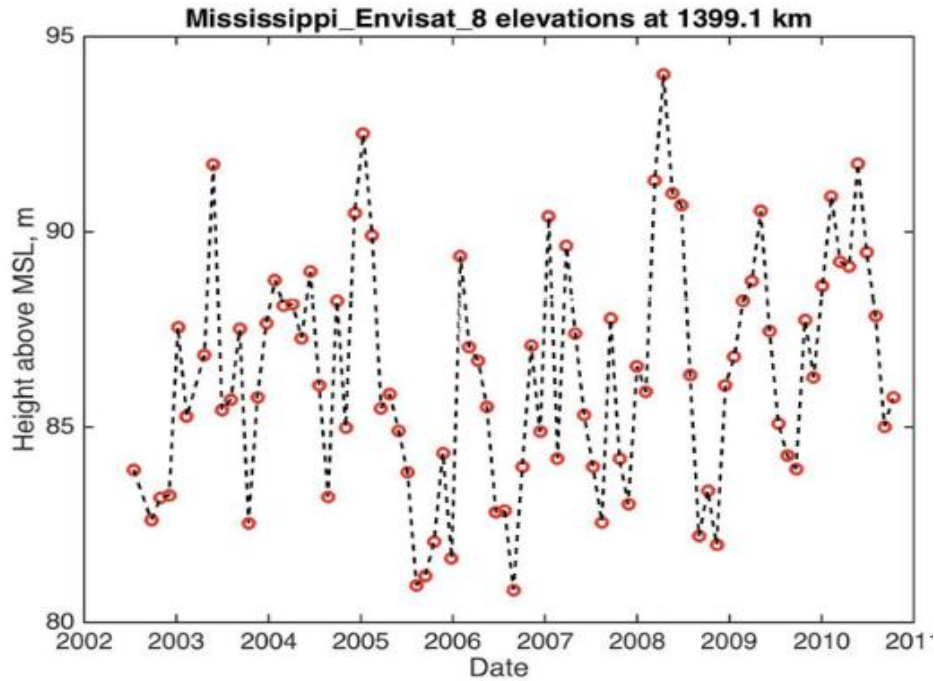


Figure 3: Altimetry measurements of Mississippi River height at Envisat Virtual Station 8 over time

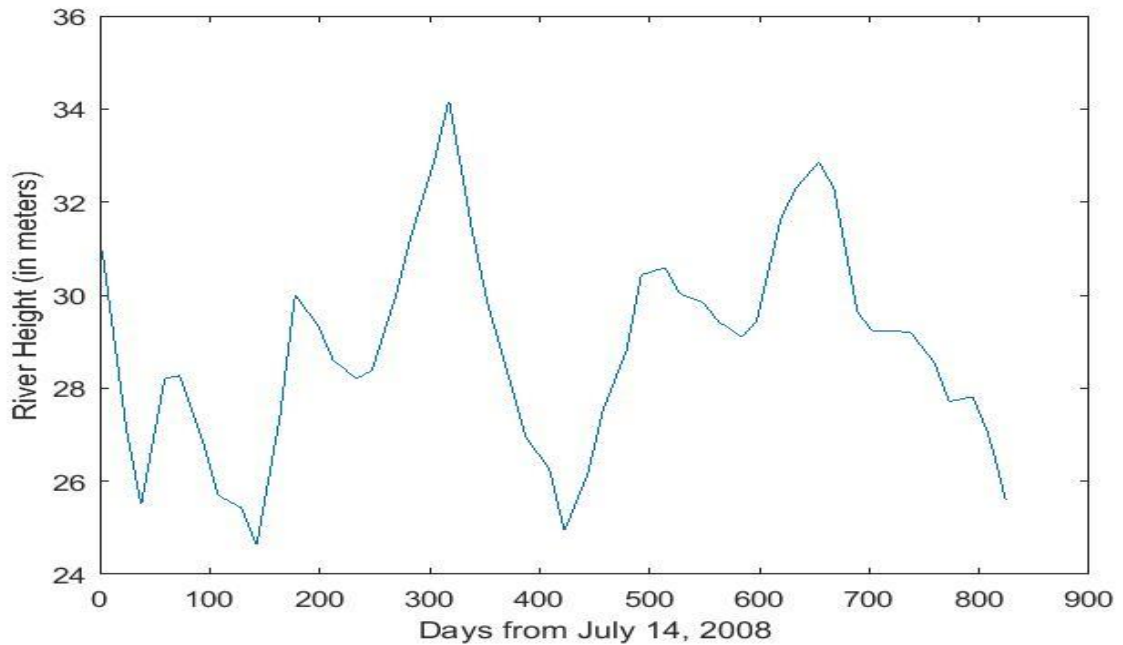
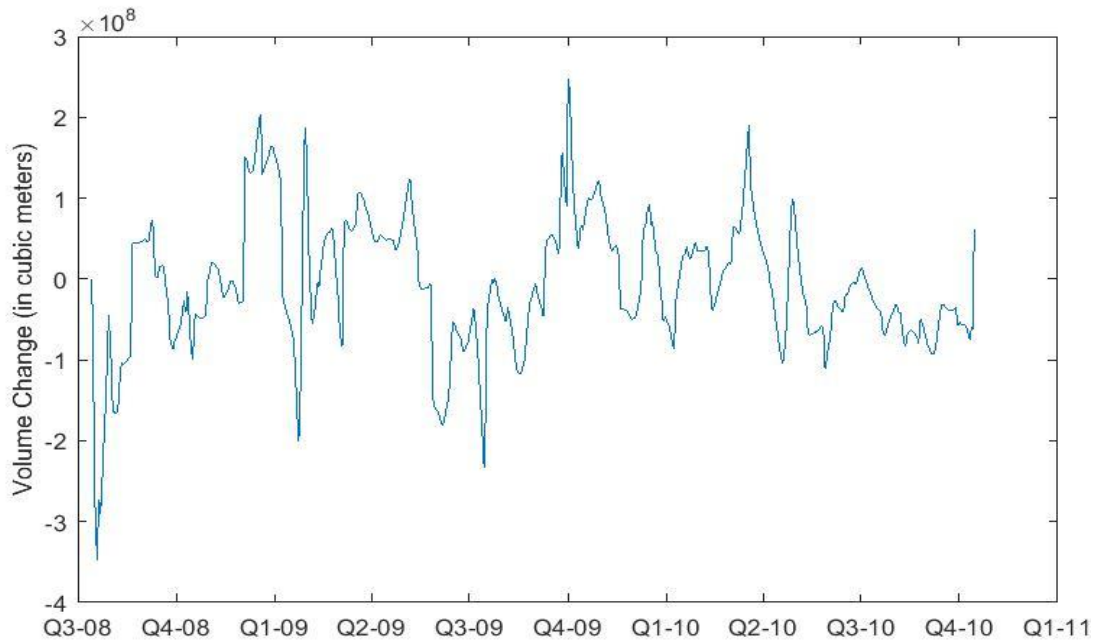


Figure 4: An interpolated timeseries of Mississippi River height for the 824 day study period

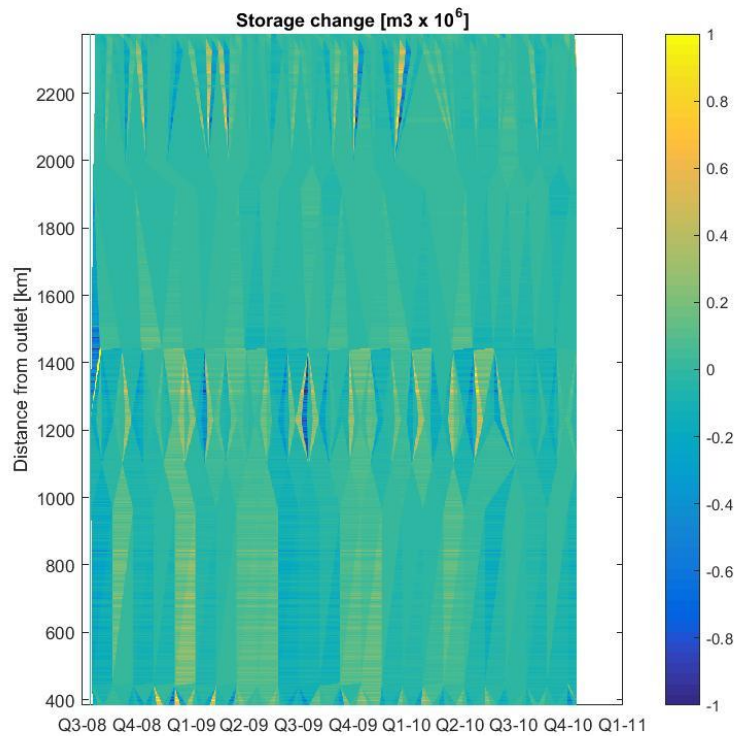
An interpolated time series for river height is shown for an arbitrary location in Figure 4; this location is near Vicksburg, Mississippi, and would thus represent Envisat virtual stations 4 and 5, and Jason-2 virtual station 2. In Figure 3 and Figure 4, the elevation of the surface of the river can be seen to rise and fall in accordance with the volume of the river seen in Figure 5 over time. Only the data in the study period are interpolated.



**Figure 5: storage change over an 824 day period**

$dS_{\text{river}}$  was calculated in MATLAB, and  $dS_{\text{river}}$  for July 2008 through October 2010 is shown in Figure 5. It is important to note that this is a representation of the change in storage, not storage itself; as such there are negative values representing loss of total volume. The values represent a volume change from one day to the next, and thus could also be written with units of  $\text{m}^3$  per day. Note that there are  $10^9 \text{ m}^3$  in a  $\text{km}^3$ . Thus, the rate of volume change in the Mississippi River varies from  $-0.3$  to  $0.25 \text{ km}^3$  per day. Change in storage is negative for Q3 for all three years in the dataset, when rainfall decreases and evapotranspiration increases over the Mississippi basin. Similarly, rates of change in storage are generally positive in Q4 for all three years.

The time and position series can be seen in a pcolor graphic in Figure 6. Brighter colors represent more positive values, while darker colors represent more negative values. Seasonal patterns are clearly visible, especially in the lower section of the river, e.g., for locations within 1100 km of the river outlet. There are several “bands” or ranges of locations where storage changes are larger, including from 2100 – 2300 km, and from 1100 to 1400 km.



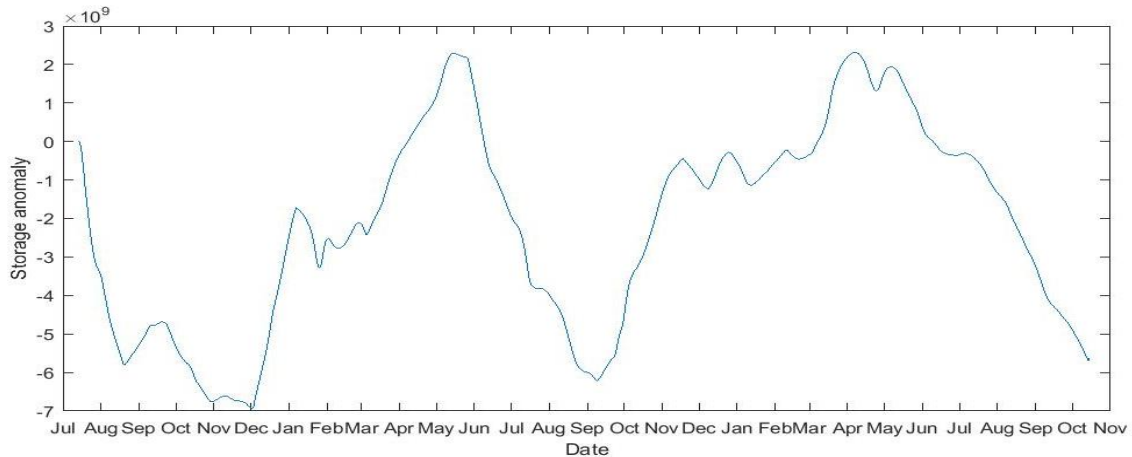
**Figure 6: Spatial and temporal variations in  $dS/dt$ . Color limits are limited to  $\pm 106 \text{ m}^3$  to emphasize more extreme values.**

## Discussion

Each data point represents a daily measurement; as such the values cover a range of 824 days, or approximately 2.25 years. Both years show a decrease in storage loss in the late summer, a sharp drop during the winter months, and a steady decline during the earlier stages of the summer. There is a peak in the fourth quarter of both years, likely due to high autumnal precipitation, followed by a sharp drop to winter low values. These values are consistent, and are logical given their respective time frames.

It is important to note that positive values in  $dS/dt$  mean that storage is increasing, not that storage is high. The same is true for negative values.

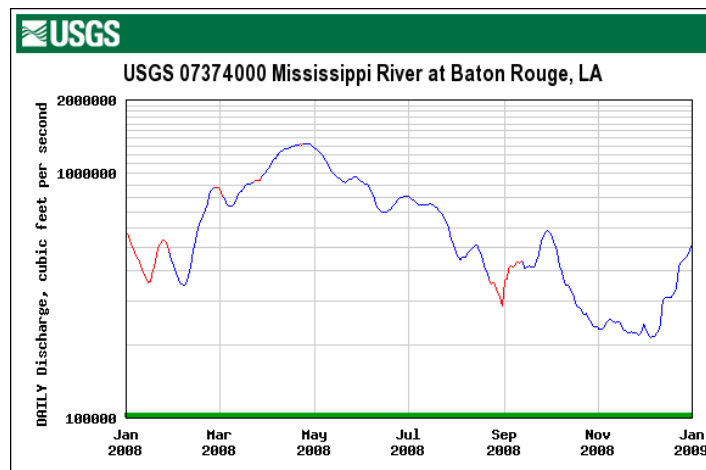
In order to determine seasonal variation more accurately, a look at storage anomaly would be more appropriate. The storage anomaly is found by summing the storage change over time. It represents not storage change, but rather a difference in storage from a given initial time (Figure 7).



**Figure 7: River's storage anomaly over time**

The minimum value is approximately  $-7 \text{ km}^3$ , and the maximum is approximately  $3 \text{ km}^3$ . Thus, the difference between storage between high flow and low flow on the Mississippi River is approximately  $10 \text{ km}^3$ . As a simple check on this figure, the river length we analyze is approximately 2000 km, and the average width is on the order of 1 km. Figures 3 and 4 show that the seasonal change in water height (equivalent to a height anomaly) is approximately 10 m. Using this “back-of-the-envelope” style calculation would lead to an expected storage anomaly would be  $20 \text{ km}^3$ , which is the same order-of-magnitude as the value of  $10 \text{ km}^3$  presented here. To our knowledge, this is the first time that the storage anomaly of the Mississippi River has been directly measured.

When compared to the average daily discharge over a year for the Mississippi River, more similarities can be seen. In Figure 8 a 2008 discharge chart from the United States Geological Survey, an early year rise and a mid-year drop are visible [USGS, 2008]. As volume in the river increases, naturally, the discharge would as well.



**Figure 8: 2008 discharge in the Mississippi River in cubic feet per second**

In situ gage height behaves in an identical manner (Figure 9).

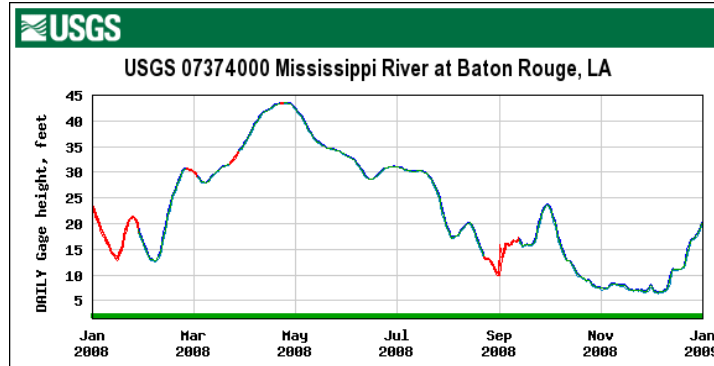


Figure 9: daily gage height for the river in 2008

There are some locations where storage change is larger than at others (Figure 6). This can be further explored by computing the temporal standard deviation of storage change at each location (Figure 10).

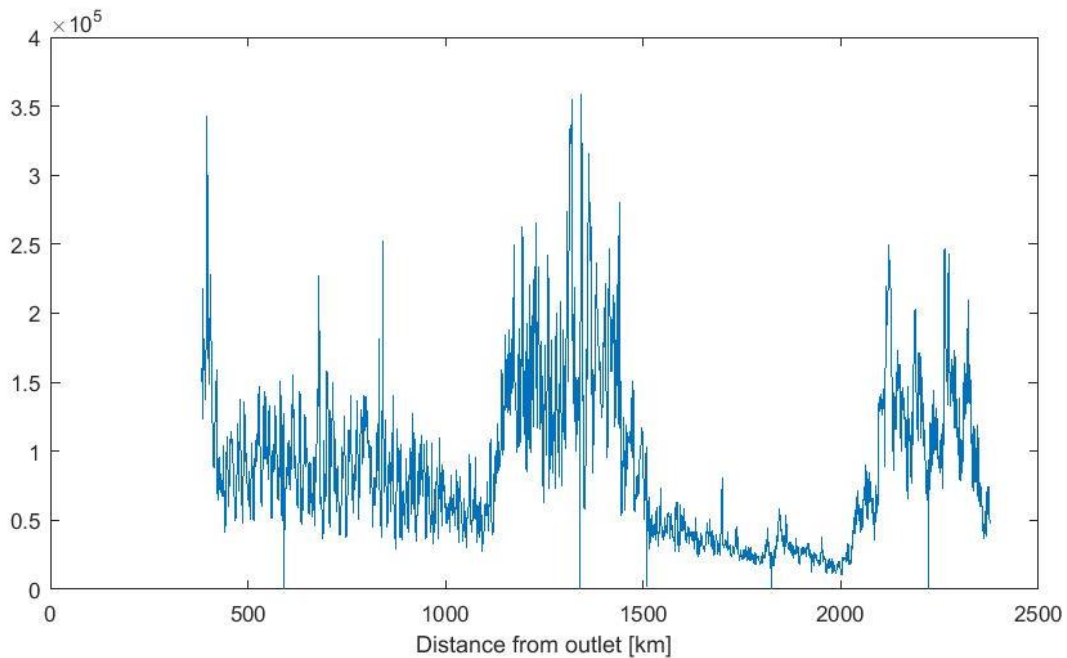


Figure 10: Standard deviation of the storage change by location. Units in  $\text{m}^3$  per day

Storage change standard deviation ranges from less than  $0.5 \text{ m}^3$  per day to greater than  $3.5 \times 10^5 \text{ m}^3$  per day, more than a factor of 7 difference. This large range highlights that some locations are far more important than others in storing water. There is an increase in deviation between distances 1000-1500, likely caused by the same variations affecting the storage change in Figure 6. This could be due to confluences with the Mississippi's tributaries. Note that there are two factors mathematically that control the variations in storage: height change variability and width variability. A 1 km grid point will have large variations in storage change if either it has a large width, or it has a large variability in river height; see equation (1). Comparison of Figure 10 with Figure 2 shows that many of the areas that are most important for channel storage change variations are characterized by high river widths. However, there are also locations where variations in river height

are apparently more important than width in determining where water storage occurs in the river, for example for locations greater than 2200 km from the outlet.

It should be mentioned that a series of 27 locks and several dams control both flow and height in the Mississippi River. With that in mind, all calculated values as to storage reflect both natural river variations, and human modification to the river system.

## **Conclusions**

The Mississippi River has long been an examined natural resource. This thesis presents a measurement of the storage changes along the Mississippi River. Daily storage change is computed for each 1 km grid cell along the river length; values are approximately  $\pm 10^6$  m<sup>3</sup> per day.

Summation along the approximately 2000 km of river length yields a storage change estimate for the entire Mississippi River channel. These values range from -0.3 to 0.25 km<sup>3</sup> per day. Integration of the storage change produces estimates of storage anomaly, which shows the total range in storage within the channel: this value is approximately 10 km<sup>3</sup> over the 2.25-year study period. The mean annual flow of the Mississippi is approximately 15,000 m<sup>3</sup>/s, which is equivalent to 473 km<sup>3</sup>/yr. Thus, the annual storage anomaly is approximately 2% of the annual flow of the river.

Storage change is spatially-variable; some locations along the river experience more storage change than others. These “hotspot” locations were identified, and it was found that they usually correspond to locations with large river widths. However, some of the hotspots are more controlled by large variations in river height.

## **Recommendations for Future Work**

As the data here represent the first step towards quantifying water resources, a logical continuation would be to apply similar methods to other bodies. Large lakes would be ideal, as they are not subject to the vast changes in width, depth, and general shape as rivers are. Additionally, working with smaller rivers that lack dams and locks would eliminate any question as to human interference.



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