Estimation of River Discharge using Multi-Mission Satellite Altimetry and Optical Remote Sensing Imagery

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Motivation

- Despite the need to pay more attention to the global water cycle and resources, the number of in-situ river discharge measurements is decreasing.
- Because of the increasing lack of in-situ measurements, there is a strong motivation to derive river discharge from remote sensing data.
- Our goal is to estimate discharge using only remote sensing data without the need of in-situ data for calibration.
- On the basis of existing data and methods at DGFI-TUM we want to use as much remote sensing data as possible.

Background

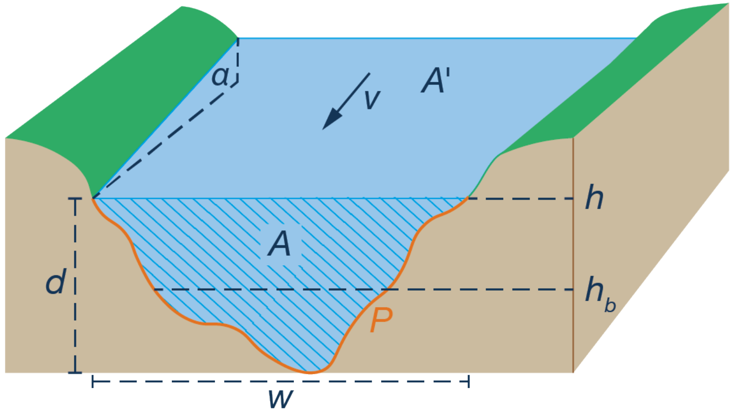
Estimating Discharge requires the cross-sectional Area A and velocity v:

$$Q = v \cdot A$$

v is estimated using the Manning Formula, requiring the hydraulic radius R, flow gradient I, and a roughness coeficcient k_{st}:

$$v = k_{st} \cdot R^{\frac{2}{3}} \cdot I^{\frac{1}{2}}$$

$$R = \frac{A}{P} \qquad I = \frac{\Delta h}{\Delta x}$$



A	*Cross-Sectional Area*
A'	*Surface Area*
P	*Wetted Perimeter*
h	*Water-Level*
h_b	*Baseflow*
w	*Surface Width*
d	*Depth*
v	*Velocity*
tan(α)	*Slope*

Data

- DGFI-TUM's "Database of Hydrological Time series of Inland Waters" (DAHITI, https://dahiti.dgfi.tum.de) provides **water level** time series of lakes, reservoirs, rivers, and wetlands derived from multi-mission satellite altimetry for hydrological applications [Schwatke et al. 2015].

- Recently, two products were added to DAHITI:
  1. **Surface area** time series of lakes and reservoirs derived with the Automated Water Area Extraction Tool (**AWAX**) [Schwatke et al. 2019]
  2. Estimated **volume variations** of lakes and reservoirs using a bathymetry derived with a **hypsometric function** [Schwatke et al. 2020, in review]

- Now, we use **AWAX** to extract land-water masks and surface area time series of river reaches and the **hypsometric function** fitted to long-term satellite altimetry in order to derive the **river bathymetry**.

- Using the Manning formula, we estimate **discharge** time series for up to 18 years solely based on remote sensing data. [Scherer et al. 2020, in preparation]

Study Areas and Data

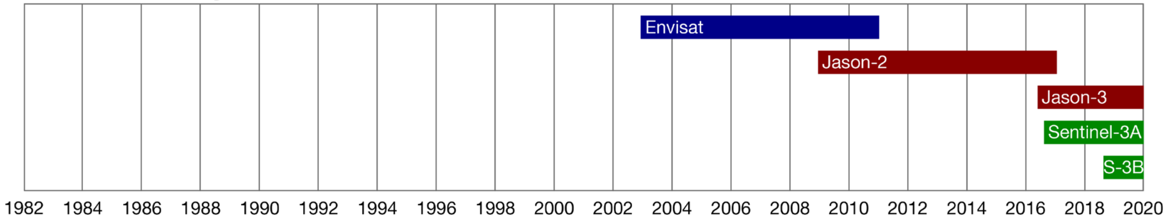
We focus on the Lower Mississippi River, because of the large amount of in-situ data available for validation:

- Water level and discharge time series
- Bathymetric survey data

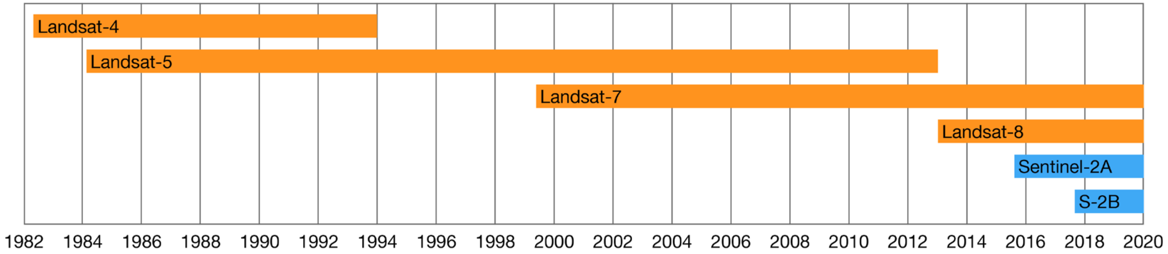
In this display, we focus on the study area enclosing the Vicksburg and the surrounding reaches.

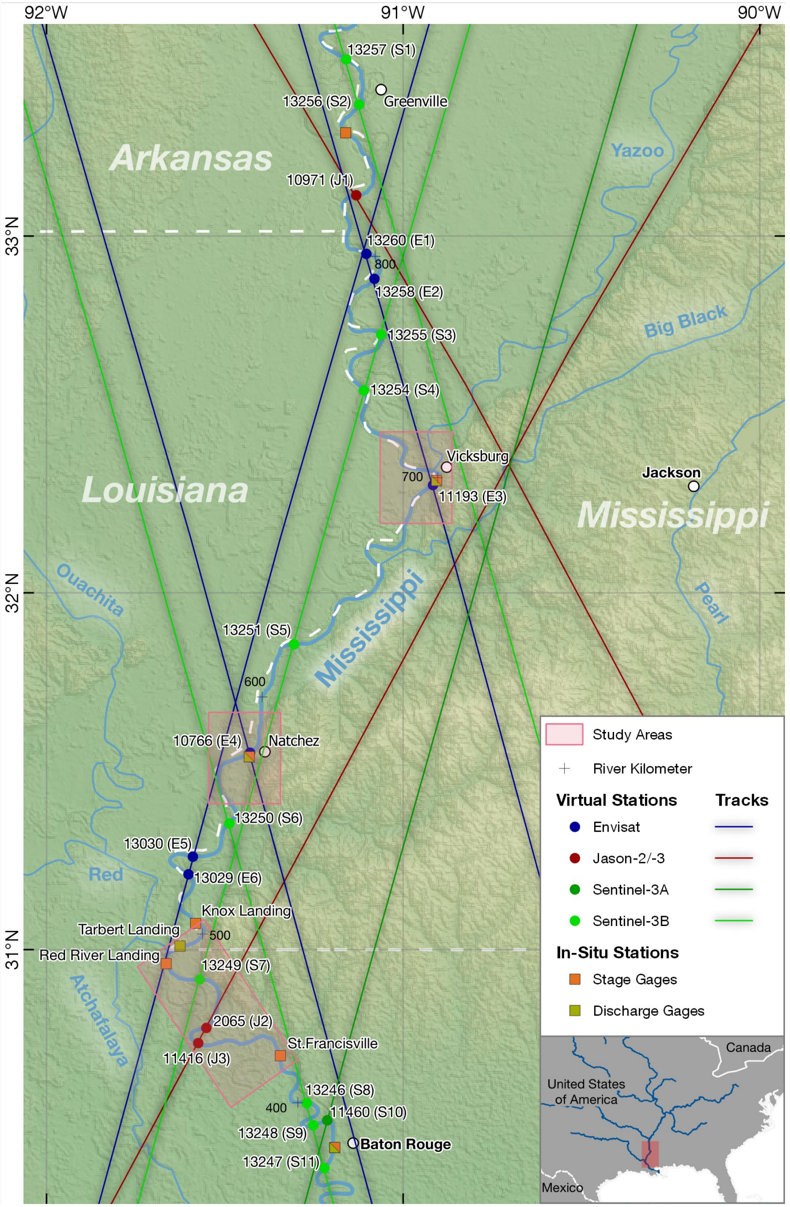
We use remote sensing data acquired by the following missions:

Satellite Altimetry Missions



Multispectral Missions





Methodology Overview

1. **Determination of Virtual Station Elevation**
   We determine the virtual station elevations to combine the data to a **long-term time series** and calculate the **flow gradient**.

2. **Bathymetry**
   The river bathymetry is constructed by stacking AWAX land-water masks ordered by the respective water level.

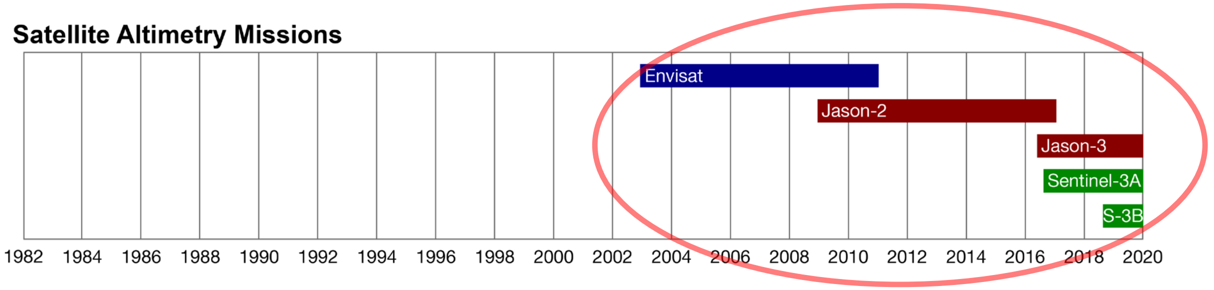
3. **Hypsometry**
   In order to use as much data as possible a hypsometric function is estimated to predict missing water levels.

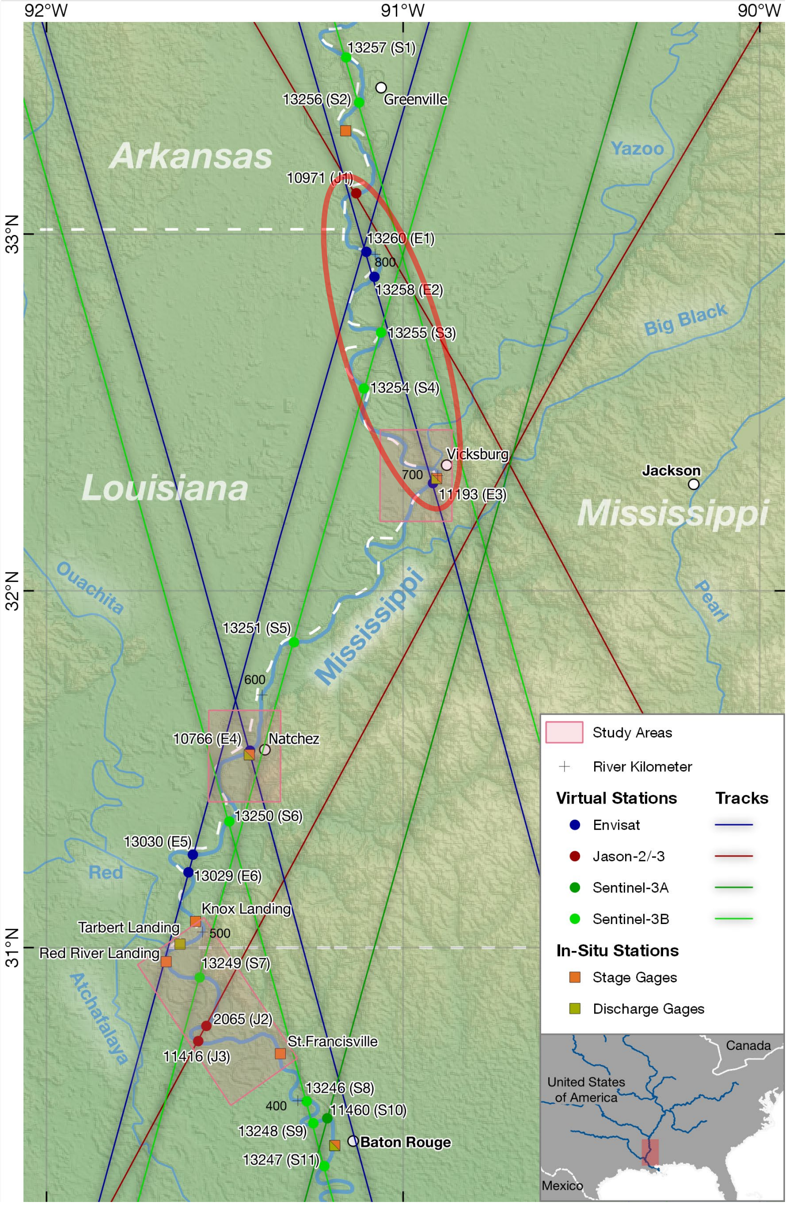
4. **Parameters for the Manning Equation**
   The **geometric parameters** are extracted from the estimated bathymetry and the **roughness coefficient** is set using a literature decision guide.

Methodology

1. Determination of Virtual Station Elevation

- The figures show the spatial and temporal distribution of the altimetry missions.
- We estimate the virtual station elevations using a linear adjustment of water level differences between contemporaneous measurements.
- Thus, we can combine the data to a single long-term time series by subtracting the station elevation from the altimeter measurements.
- Additionally, the flow gradient is calculated using the adjusted virtual station elevations and the along river distance.

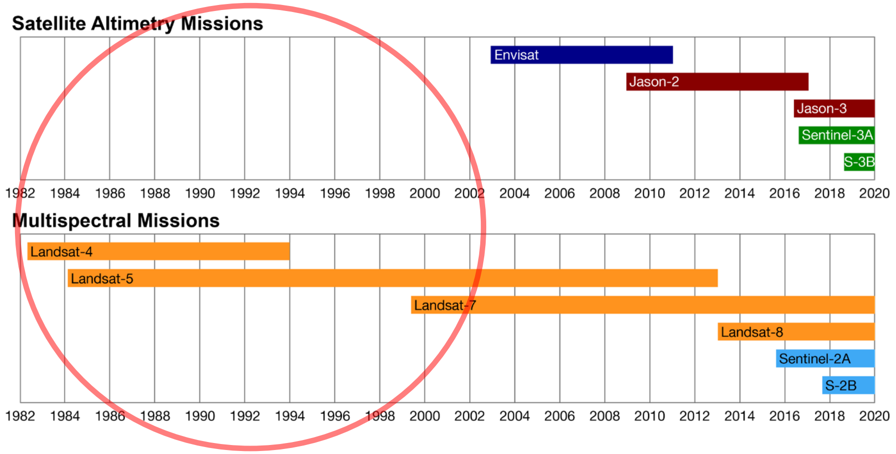




Methodology

2. Bathymetry

- The bathymetry is constructed by stacking AWAX land-water masks for the river reach of interest ordered by the respective water level.
- The goal is to use as much data as possible to observe water level extremes and thus a large part of the bathymetry.
- However, for about 20 years (1982-2003) there is only multispectral data available:



- Therefore, a hypsometric function is fitted to the available data pairs and used to predict the missing water levels.

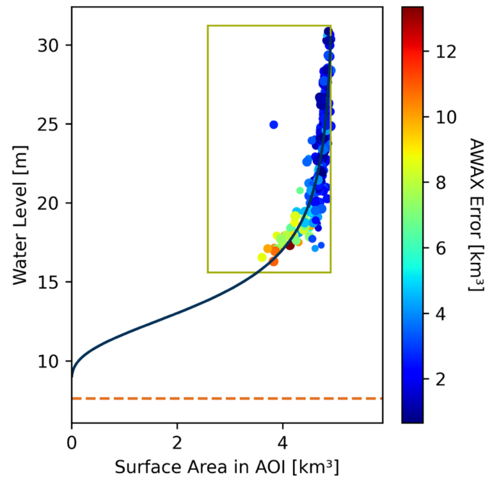
Methodology

3. Hypsometry

- A modified version [Schwatke et al. 2020, in review] of the hypsometric relation by Strahler [1952] is fitted to the synchronous observations of water level y and surface area x at the river reach of interest:

$$y = \left[\frac{x_{min} - x}{x_{min} - x_{ip}} \cdot \frac{x_{max} - x_{ip}}{x_{max} - x}\right]^{z} \cdot y_{scale} + y_{min}$$

where z, the lower (x_{min}) and upper (x_{max}) surface area limits, the x-value of the inflection point x_{ip}, the scale factor y_{scale} and the minimum water level y_{min} are fitted to the data.



Reach hypsometry (blue line) and h_0 (dashed orange) at river kilometer 721.1. The green rectangle shows the bounds of the entire available water level and surface area observations. The area error refers to the entire scene.

- The river bed elevation h_0 is used as a boundary condition for y_{min}. It is estimated using an empirical width (w) to depth (d) relationship [Moody and Troutman 2002] for each synchronous observation:

$$h_0 = y - d\;;\; d = 0.27\left(\frac{w^2}{7.2^2}\right)^{0.39}$$

Methodology

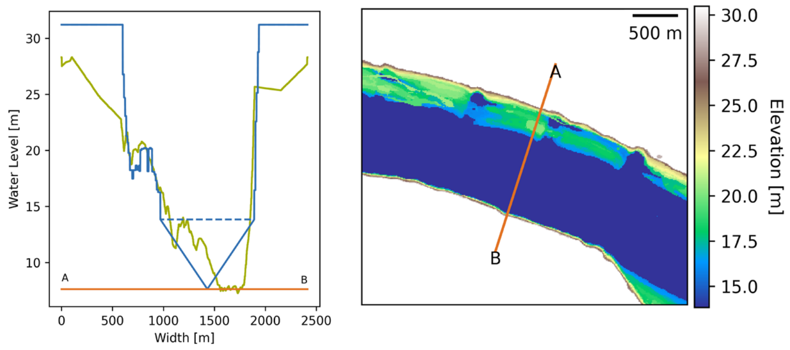
3. Parameter for the Manning Equation

- In order to determine the **geometric parameters** (cross-sectional area $\boldsymbol{A}$ and wetted perimeter $\boldsymbol{P}$), the cross-sectional geometry (left) is extracted from the constructed bathymetric layer (right).

- Below the minimum hypsometric water level (dashed blue line), the geometry is continued to the estimated bed elevation h_0 (orange line) using a triangular shape.

- The **roughness coefficient $\boldsymbol{k_{st}}$** is set based on geomorphological features quantified by adjustment factors. These are chosen using the AWAX water occurrence mask and a decision guide by Arcement and Schneider [1989].

- The **flow gradient $\boldsymbol{I}$** is calculated using the adjusted station elevations and the along river distance.



Estimated (blue) and in-situ (green) cross-sectional geometry (left) and constructed reach bathymetry (right) at river kilometer 721.1.

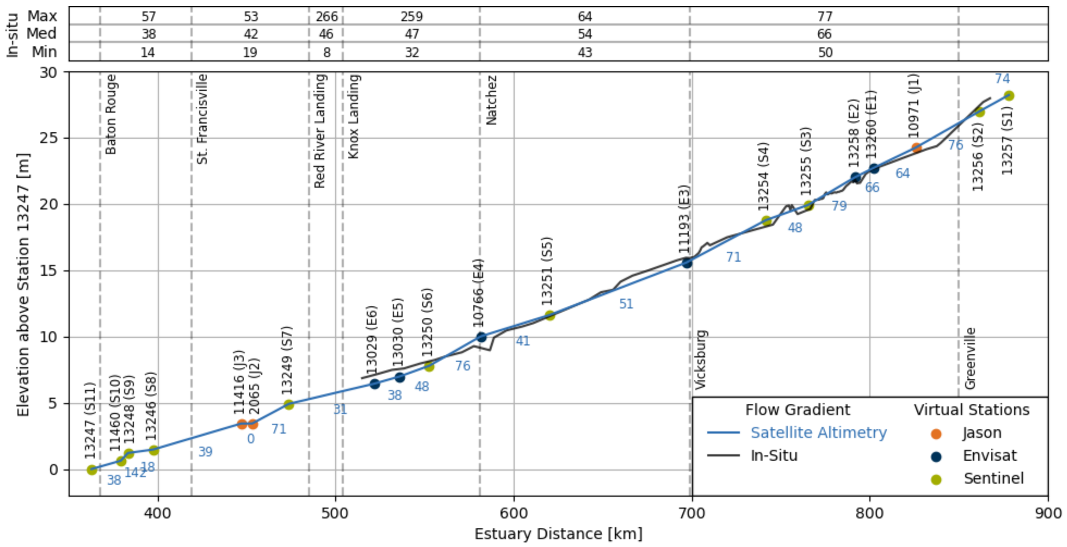
Results and Validation

Flow Gradient

- The figure shows the calculated flow gradient ([10^{-6}], blue) derived from the adjusted virtual station elevations.

- The black line shows the longitudinal profile derived from bathymetric survey data.

- The table at the top shows the minimum, median, and maximum observed flow gradient [10^{-6}] derived from water level measurements at gauges (dashed gray lines).



- The in-situ data shows the high variability of the flow gradient. The estimated constant flow gradient is mostly within the boundaries and close to the median value. The largest deviations occur between adjacent stations.

- In contrast to a gradient extracted from DEM data, which is based on a short observational period, the result of this method using adjusted elevations from long-term data is probably closer to the average flow gradient.

Results and Validation

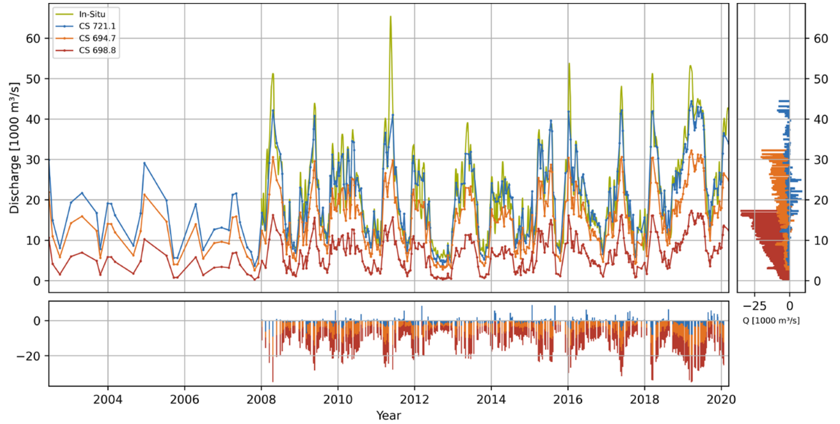
Discharge Time Series

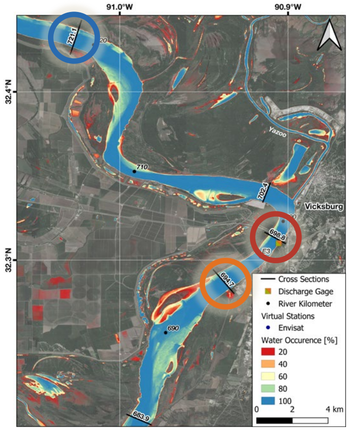
- The left figure shows the in-situ (green) and estimated discharge time series for three cross-sections (CS) at Vicksburg. The map shows the CS locations. While **CS 698.8** is located at the gauge, **CS 721.1** and **CS 694.7** were selected to be situated in straight, wide, and regular reaches which we identified using the AWAX water occurrence mask.

- The table shows the normalized root mean squared error (NRMSE), Nash–Sutcliffe efficiency (NSE), squared Pearson correlation coefficient R^2, estimated *I* and k_{st}, and the percentage of the actual cross-sectional area *A* covered by the estimated geometry.

- The errors at CS 698.8 are high because the cross-sectional area was underestimated. This was caused by the under average width visible in the map, as the empirical with-to-depth relationship underestimated the increased depth caused by dredging.

- The results are significantly better for the selected CS in straight, wide, and regular reaches.





CS	NRMSE [%]	NSE	R^2	k_{st}	*I* $[10^{-6}]$	*A* [%]
721.1	11.18	0.947	0.972	50.0	71	92.73
698.8	74.72	-1.360	0.954	38.5	71	58.87
694.7	34.56	0.495	0.974	43.5	51	93.08

Summary

- We estimate long-term (up to 18 years) discharge time series using satellite altimetry and remote sensing data.

- For all 3 study areas in our paper [Scherer et al. 2020, in preparation], the validation at the selected cross-sections in straight, wide, and uniform river segments against the closest in-situ measurements yields a median NRMSE of 16.56% with a minimum of 7.46% and a maximum of 35.23%.

- The linear adjustment of the virtual station elevations enables us to combine satellite altimetry data from multiple virtual stations and missions to one single long-term water level time series.

- The flow gradient derived from the virtual station elevations shows a high agreement with the average actual flow gradient.

- The hypsometric function previously used for lakes and reservoirs is sufficient to predict water levels for river reaches.

Outlook

- Data from long repeat orbit missions (e.g. Cryosat-2) would improve the spatial resolution of the flow gradient.
- Using average parameters from multiple CS per reach should make the method more robust.
- Using hypsometric water levels to estimate discharge would extend the resulting discharge time series over the period of the Landsat mission starting with the launch of Landsat 4 in 1982.
- In future, the synchronous observations of water level, surface area, and time variable flow gradient by the SWOT mission could be used to improve our methodology.
- We will test more complex shallow water equations to estimate the flow velocity.

References

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