Estimation of River Discharge Using Satellite Altimetry and Optical Remote Sensing Images

DANIEL SCHERER[1,2], CHRISTIAN SCHWATKE[2] & PETER KRZYSTEK[1]

Abstract: In this paper, a new approach for estimating the discharge of large rivers based on long-term remote sensing data and using the Manning equation is presented. The key idea is to observe the river's cross-sectional geometry from the combination of satellite altimetry and water masks extracted from optical remote sensing imagery. The water surface heights measured by the satellite altimeter missions (Envisat, Jason-2/-3) are combined with monthly water surface masks from Landsat and Sentinel-2 satellite imagery. By fusing both observations, the river bathymetry is estimated based on an adapted hypsometric function and a predicted river bed height. A linear adjustment of altimetry data measured at various virtual stations provides the required flow gradient. Finally, the roughness coefficient is calculated from substantiated compensation factors for geomorphologic features observable with satellite imagery. Note that all mandatory parameters are estimated based on remote sensing data. The validation of the method at the Lower Mississippi River shows that uniform and straight river sections are the most suitable for this new methodology. At six of seven suitable river sections, the Normalized Root Mean Square Error (NRMSE) varied between 12.59% and 26.16%. The Nash-Sutcliffe Efficiency (NSE) was in a range from 0.710 to 0.923. The NRSME deteriorates at nine non-uniform river sections between 38.17% and 108.25%.

1 Motivation

Water is an essential element on Earth. The global water cycle influences the climate decisively. Aside from its use for drinking and hygiene, most of the total surface freshwater withdrawals are used for thermoelectric power, agricultural irrigation, mining and other industries (MAUPIN ET AL 2014). However, freshwater is only 2.5% of the Earth´s water reserve and only 0.3% is stored in lakes or flows in rivers, while the rest is bound in permanent ice or groundwater (GLEICK 2012). While the water cycle is affected by global warming, it also influences the climate. As water cycles between the land, oceans, and atmosphere, it changes the dynamics of the climate system (CHAHINE 1992). Hence, changes in the water cycle result in climate change. River discharge measurements are essential for water management purposes, such as watershed protection and computing storm runoff volumes, runoff predictions, or reservoir storage and using them as an input for hydrological models (HUNGER & DÖLL 2008; NRCS 2015). Despite the need for increased attention to the global water cycle and resources, continuous in-situ river discharge measurements declined from around 6000 stations in 1979 to 1000 stations in 2009 (HANNAH et al. 2011). Because of the increasing lack of in-situ measurements, there is a strong motivation to derive river discharge from remote sensing data. Based on previously sampled in-situ discharge

[1] Hochschule für angewandte Wissenschaften München, Fakultät für Geoinformation, Karlstr. 6, 80333 München, E-Mail: [dscherer, peter.krzystek]@hm.edu
[2] Technische Universität München, Deutsches Geodätisches Forschungsinstitut DGFI-TUM, Arcisstr. 21, 80333 München, E-Mail: [daniel.scherer, christian.schwatke]@tum.de

measurements, TOURIAN et al. (2017) predicted the discharge using satellite altimetry water level measurements. However, it is a challenge to estimate discharge purely from remote sensing data, as in-situ data for calibration is not available everywhere and long-term changes of the river morphology are not represented by the rating curve. BJERKLIE et al. (2003) demonstrated the main problems of measuring discharge from remote sensing data, which is the estimation of the river´s flow velocity and depth. From satellite altimetry, only water level variations above the baseflow, the lowest occurred water level, are observable. However, the flow velocity depends on the whole geometry of the river cross-section and thus, the depth is required for the discharge estimation.

2 Study Area and Data

Sixteen locations along the Lower Mississippi River between river mile 276 and 340 were chosen as the study area. Figure 1 shows a map of the gage locations and satellite altimetry.

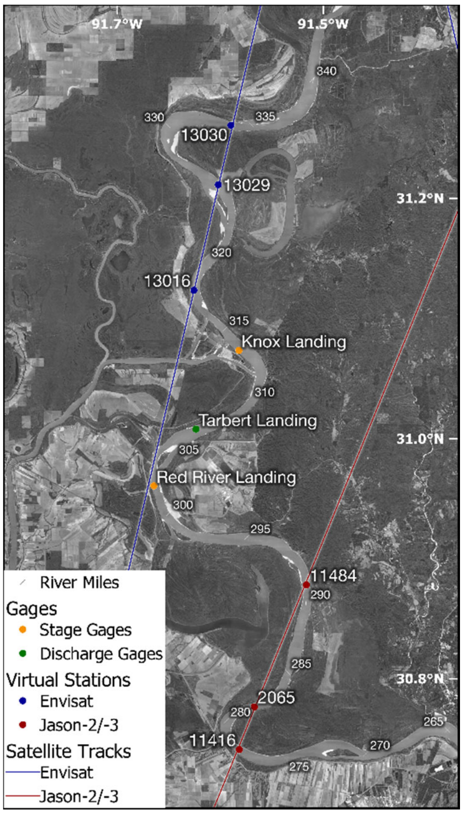

Fig. 1: Overview of gage locations and satellite altimetry

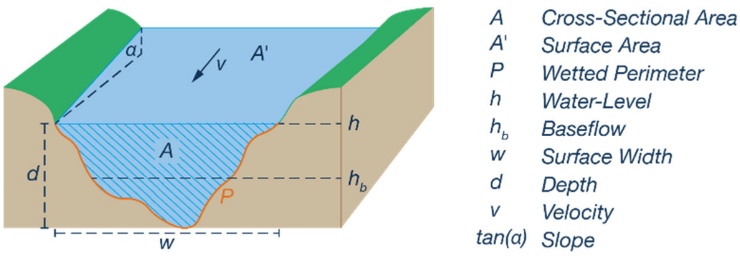

Fig. 2: At-a-station hydrographic parameters

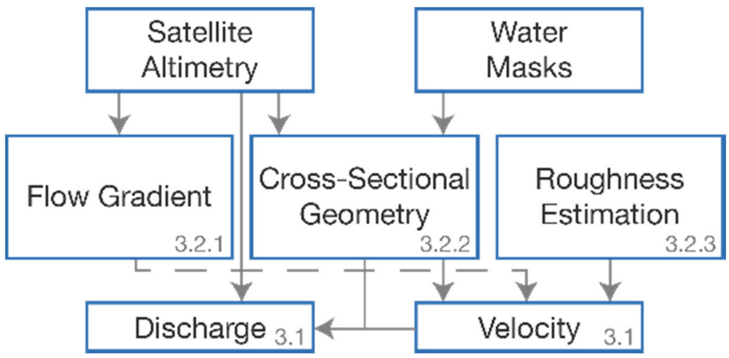

Fig 3: Methodology flowchart

2.1 Remote Sensing Data

Satellite altimetry data from the Jason-2/-3 and Envisat missions were downloaded from the Database for Hydrological Time Series of Inland Waters (DAHITI) for six virtual stations in the study area where the satellite tracks cross the Mississippi River (SCHWATKE et al. 2015). Two additional upstream stations were used for the estimation of the flow gradient. Jason-2/-3 data was available from 2008 to 2019 with a repeat cycle of 10 days and Envisat data was available from 2002 to 2010 with a repeat cycle of 35 days.

Monthly water masks and surface area time series from the Automated Water Area Extraction Tool (AWAX) were used to determine the river widths and surface area. AWAX uses satellite imagery from Landsat and Sentinel-2 missions to measure the time-variable water surface of a given stretch of water. The spatial resolution of AWAX depends on the image availability. Landsat data is available since 1984 and has a resolution of 30 m. The Sentinel-2 mission launched in 2015 and provides imagery with a spatial resolution of 10 m. Cloud obscured pixels are reconstructed using a derived long-term water probability mask (SCHWATKE et al. 2019).

2.2 In-Situ Data

Within the study area, river discharge is measured at the Tarbert Landing discharge range and the water level is measured at Red River Landing and Knox Landing. The time series data of those gages were used for validation. The main reason for selecting this study area is that important bathymetric data is available in order to validate the estimated cross-sectional geometry. To evaluate the estimated flow gradient, the Low Water Reference Plane (LWRP) was used, which establishes a common hydraulic based datum along the river for civil engineering projects. Additionally, measured river velocities were utilized for validation. All the in-situ data were available on the U.S. ARMY CORPS OF ENGINEERS (2019) Mississippi Valley Division website.

3 Methodology

Discharge cannot be measured directly but depends on several hydrographic parameters, which are shown in Figure 2. All cross-sectional parameters that are functions of stage are elements of the at-a-station hydraulic geometry (JULIEN 2018). For discharge estimation, it is key to know the water velocity v and the cross-sectional area A of the river at the study site. Some hydrographic variables like river width w and surface area A' can be measured from satellite imagery, and the water level h can be derived from satellite altimetry. The flow velocity cannot be measured by these instruments. Therefore, it must be calculated from hydrologically established formulas like the Gauckler-Manning-Strickler formula. This requires a roughness parameter, the slope of the river $tan(\alpha)$ and the cross-sectional geometry expressed as the relationship of the wetted perimeter P and A. Yet, the cross-sectional geometry cannot be observed below the minimum water level, which is the baseflow h_b and has to be predicted by a hypsometric relation.

Figure 3 shows a flowchart of the processing steps, the input data and the describing sections.

3.1 Fundamental Equations

As described by AIGNER & BOLLRICH (2015), the fundamental equation for calculating the discharge Q at a river cross-section is:

$$Q = \bar{v} \cdot A \tag{1}$$

where $\bar{v}$ is the depth-averaged flow velocity [m/s], and A is the cross-sectional area [m²]. Both parameters cannot be measured from remote sensing data directly. In order to estimate parameter A, the cross-sectional geometry is constructed from numerous combinations of water level measurements from satellite altimetry and river widths extracted from remote sensing imagery (Section 3.2.2). Parameter $\bar{v}$ is estimated using the Gauckler-Manning-Strickler formula:

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

where k_{st} is the roughness coefficient [$m^{1/3}/s$], I is the flow gradient and R is the hydraulic radius [m] which is expressed as $R = A/P$, with P as the wetted perimeter [m].

3.2 Parameter Estimation

3.2.1 Flow Gradient

The flow gradient I is determined from multiple satellite altimetry measurements at eight virtual stations along the river by a linear adjustment. The time differences between the measurements are used for the weighting function.

3.2.2 Cross-Sectional Geometry

Cross-sectional geometry is required for estimating the parameters A, P and R. Void-free monthly water masks from the AWAX algorithm are combined with monthly averaged water level measurements from satellite altimetry. For every water pixel, the lowest water level is used to set up a bathymetric raster for the extent of the water masks, representing the bathymetry down to the lowest observed water level, the observed baseflow. Because the acquisition time of Landsat imagery is backwards the satellite altimetry missions numerous water masks lack synchronized water level measurements. Therefore, a hypsometric curve is fitted to the available data to use this additional data as well. This requires the estimation of the river depths using an empirical width w to depth d relationship based on a study by MOODY & TROUTMAN (2002). By reshaping their obtained relations:

$$\begin{gathered} \overline{w} = 7.2Q^{0.50\pm0.02} \Leftrightarrow Q = w^2/7.2^2 \\ \overline{d} = 0.27Q^{0.39\pm0.01} \end{gathered} \tag{3}$$

The depth can be estimated with:

$$\overline{d} = 0.27(w^2/7.2^2)^{0.39} \tag{4}$$

To estimate the river bed elevation h_0, synchronized data from satellite altimetry and water masks are used to get the monthly width w_m and water level h_m and calculate the monthly depth d_m. Finally, the river bed elevation is averaged from all observed differences between h_m and d_m and subtracted from all the water level measurements. The following logistic function is fitted to the observed synchronized water level and surface area a data:

$$h(a) = \frac{y_1 - y_0}{1 + e^{-m\cdot(a-b)}} + y_0 \tag{5}$$

where y_1 is the maximum and y_0 is the minimum of the curve, e is the Euler's number, m is the slope and b represents the position of the curves' midpoint. The data is weighted by the errors estimated from the AWAX algorithm to improve the fitting. Using the predicted water levels, the bathymetric raster can be expanded below the observed baseflow down to the lowest predicted water level, the predicted baseflow. The remaining gap between the predicted baseflow and the estimated bed elevation is filled with a triangular shape.

3.2.3 Roughness Coefficient

It turned out that the estimation of the roughness coefficient k_{st} is the most challenging part of the method. In this study, a constant value is used, which is actually changing with the water level. ARCEMENT & SCHNEIDER (1989) described a method to determine the roughness coefficient based on different adjustment factors:

$$k_{st} = \left((n_b + n_1 + n_2 + n_3 + n_4)m\right)^{-1} \tag{6}$$

where n_1 is a correction factor for surface irregularities, n_2 is a value for variations in shape and size of the channel cross-section, n_3 is a value for obstructions, n_4 is a value for vegetation and flow conditions, and m is a correction factor for the channel meandering. The base value n_b depends on the channel type, its bed material and the grain size. It is too ambitious to determine the grain size from remote sensing, but the channel material can be estimated from high-resolution satellite imagery. Quantitative geomorphologic methods, as described by SCHUMM (1977) and a decision guide by ARCEMENT & SCHNEIDER (1989), help to determine the adjustment factors. The discharge estimation can be calibrated by adjusting the roughness coefficient.

4 Case Study

4.1 Closed Loop Test

A closed loop test was performed at Tarbet Landing to validate the methodology and the significance of the parameters, thereby showing that they can be substituted by remote sensing data. As different water-level data products were used at shifted locations along the river, all heights were adjusted along the LWRP.

4.1.1 Fundamental Equation

First, Equation 1 was used to calculate the discharge based on the in-situ water level. The multibeam bathymetric data was used to determine the cross-sectional area A. The in-situ velocity to water level relationship was used as mean velocity $\bar{v}$. Compared to the in-situ discharge time series, the NRMSE was 9.72%, and the NSE was 0.963.

4.1.2 Satellite Altimetry

The in-situ water level time series were substituted by satellite altimetry data to evaluate the usability of inland satellite altimetry. Depending on the virtual station used as input time series, the NRMSE increased up to 23.87%.

4.1.3 Gauckler-Manning-Strickler Formula

Next, $\bar{v}$ was estimated using Equation 2. A constant k_{st} of 36.23 was calculated using the adjustment factors n_b=0.02, n_1=0.001, n_2=0.001, n_3=0, n_4=0.002 and m=1.15. The NRMSE was 8.94% with in-situ water levels as input and the flow gradient I from adjusted altimetry measurements, which was $50 \cdot 10^{-6}$ at Tarbert Landing and steeper than the gradient from the LWRP ($22 \cdot 10^{-6}$) and the gradient from adjusted in-situ water level measurements ($39 \cdot 10^{-6}$).

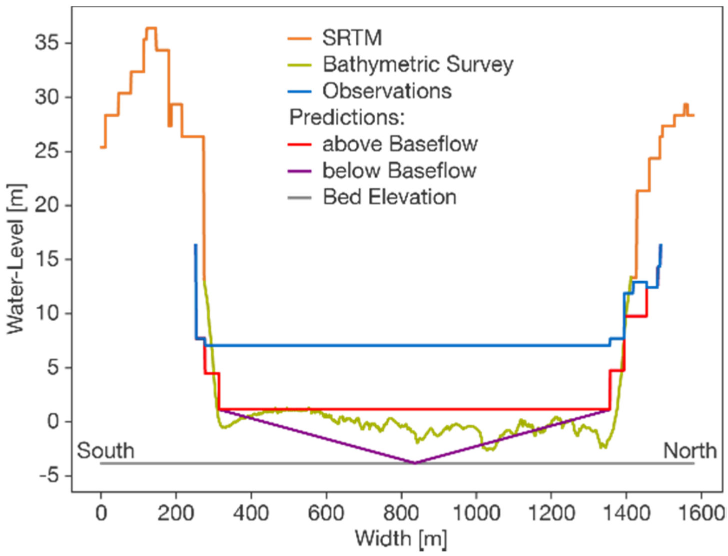

Fig. 4: Observed, predicted and surveyed cross-sectional geometry at Tarbert Landing

4.1.4 Cross-Sectional Geometry

Using cross-sectional geometry derived from in-situ water level data and AWAX water masks to estimate A, the NRMSE was 10.08%. With a geometry based on altimetry water level data, the NRMSE was between 9.18% and 34.31% depending on the used virtual station. Figure 4 shows the geometry constructed from water masks combined with Jason-2/-3 altimetry observations and predictions and the in-situ bathymetry from multi-beam bathymetric data.

4.2 Full Remote Sensing Results

Finally, discharge was estimated for 16 cross-sections solely using remote sensing data. The cross-sections were chosen by the location of in-situ gages, virtual stations or geomorphologic features, such as straight or widening river sections. The cross-sectional geometry was estimated as described in Section 3.2.2, and the flow velocity was calculated with the Gauckler-Manning-Strickler formula based on the flow gradient from adjusted altimetry measurements and the constant k_{st} of 36.23. In total, the NRMSE ranged from 12.59% to 108.25%. However, it was possible to classify the cross-sections by channel form based on the bathymetric survey data. For cross-sections that were heavily dredged by the river, the NRMSE was 38.17% or greater. These sections were all located in curved river sections, which can be avoided in future studies. The best results were achieved in straight and widened river segments, where the cross-sectional form was uniform or the river sections had multiple channels. For seven of eight such river segments, the NRMSE was 26.16% or less. Figure 5 shows an exemplary discharge time series for Tarbert Landing.

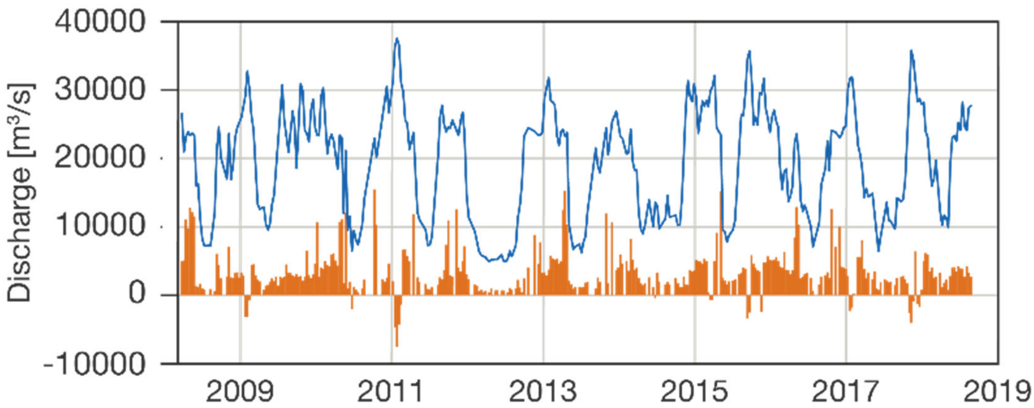

Fig. 5: Resulting discharge (blue) and errors (orange) based on remote sensing data for Tarbert Landing

5 Conclusion and Outlook

The study showed that estimation of river discharge solely using satellite data is possible. The best results could be achieved at straight and widened river segments, which can be identified using satellite imagery. At six of seven suitable river sections, the NRMSE varied between 12.59% and 26.16%. The NSE ranged from 0.710 to 0.923. The roughness coefficient was the weakest parameter. In further studies, the Gauckler-Manning-Strickler equation should be exchanged for other methods with dimensionless roughness coefficients. Calibration would improve the resulting discharge time series, e.g. adjusting the roughness parameter to minimze the RMSE.

6 References

AIGNER, D. & BOLLRICH, G., 2015: Handbuch der Hydraulik. Für Wasserbau und Wasserwirtschaft. 1. Aufl. Beuth Wissen. s.l.: Beuth Verlag GmbH.

ARCEMENT, G.J. & SCHNEIDER, V. R., 1989: Guide for selecting Manning's roughness coefficients for natural channels and flood plains. USGS.

BJERKLIE, D.M., DINGMANN, S.L., VOROSMARTY, C.J., BOLSTER. C.H. & CONGALTON, R., 1989: Evaluating the potential for measuring river discharge from space. Journal of Hydrology **278**(1-4), 17-38.

CHAHINE, M.T., 1992: The hydrological cycle and its influence on climate. Nature **359**(6394), 373-380.

GLEICK, P.H., 2012: Water Resources. Encyclopedia of climate and weather. 2. ed. Vol. 2. S.H. Schneider (Editor), New York: Oxford Univ. Press, 817-823.

HUNGER, M. & DÖLL, P., 2008: Value of river discharge data for global-scale hydrological modeling. Hydrology and Earth System Sciences **12**(3), 841-861.

HANNAH, D.M., DEMUTH, S., VAN LANEN, H.A.J., LOOSER, U., PRUDHOMME, C., REES, G., STAHL, K. & TALLAKSEN, L.M., 2011: Large-scale river flow archives: importance, current status and future needs. Hydrological Processes **25**(7), 1191-1200.

JULIEN, P.Y., 2018: River Mechanics. Second Edition. New York: Cambridge University Press.

MAUPIN, M.A., KENNY, J.F., HUTSON S.S., LOVELANCE, J.K., BARBER, N.L. & LINSEY, K.S. 2014: Estimated use of water in the United States in 2010, **1405**. Circular. Reston Virginia: U.S. Geological Survey.

MOODY, J.A. & TROUTMAN, B.M., 2002: Characterization of the spatial variability of channel morphology. Earth Surface Processes and Landforms **27**(12), 1251-1266.

NRCS (NATURAL RESOURCES CONSERVATION SERVICE), 2015: National Engineering Handbook Part 630 Hydrology. Chapter 5: Streamflow Data. Fort Worth, Texas: U.S. Department of Agriculture.

SCHWATKE, C., DETTMERING, D., BOSCH, W. & SEITZ, F. 2015: DAHITI - an innovative approach for estimating water level time series over inland waters using multi-mission satellite altimetry. Hydrology and Earth System Sciences **19**(10), 4345-4364.

SCHWATKE, C., SCHERER, D. & DETTMERING, D., 2019: Automated Extraction of Consistent Time-Variable Water Surfaces of Lakes and Reservoirs Based on Landsat and Sentinel-2. Remote Sensing **11**(9), 1010.

SCHUMM, S.A., 1977: The fluvial system. A Wiley-Interscience publication. New York: Wiley.

TOURIAN, M.J., SCHWATKE, C. & SNEEUW, N., 2017: River discharge estimation at daily resolution from satellite altimetry over an entire river basin. Journal of Hydrology **546**, 230-247.

US ARMY CORPS OF ENGINEERS, 2019: Mississippi Valley Division url: www.mvd.usace.army.mil