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# Water Resources Research

## TECHNICAL REPORTS: DATA

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### Key Points:

- A synthetic data set was created to evaluate the impact of altimetry satellites orbits on global discharge distribution estimation
- Under ideal retrieval conditions, most existing spatiotemporal sampling approaches could accurately capture global mean flow distributions
- Global distributions of extreme flows and peak duration rely on frequent temporal sampling rather than detailed spatial sampling

### Supporting Information:

- Figure S1
- Figure S2
- Figure S3
- Figure S4
- Supporting Information S1

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## A Synthetic Data Set Inspired by Satellite Altimetry and Impacts of Sampling on Global Spaceborne Discharge Characterization

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**Abstract** Despite being a critical component of Earth's water cycle, much remains unknown about freshwater fluxes in the world's rivers. Discharge can be estimated in situ by monitoring water surface elevation yet the declining worldwide coverage of gauges makes global discharge quantification challenging. Numerous studies have shown that satellite radar altimetry could provide global discharge estimates. In anticipation such groundbreaking datasets, one key question remains unanswered: how accurately could the various orbital configurations of altimetry missions capture global discharge distributions under optimal retrieval conditions? We here generate an idealized synthetic global discharge data set following mission orbits, and present the first evaluation of various spatiotemporal sampling strategies on global discharge distribution estimation. Our data are produced by superimposing six measurement footprints representing nine altimetry missions onto existing global discharge simulations. While this approach assumes accurate simulations and ignores uncertainties in spaceborne discharge estimation, it allows for an upper limit assessment of how satellite missions might capture global characteristics of hydrographs. We show that most orbits used could lead to accurate global mean flow distribution (<7%), which was expected but never demonstrated. We also find that accurate distributions of minimum flow (respectively, maximum flow and peak flow duration) require revisit times more frequent than 10 (respectively, 5 and 5) days, that is, finer than allowed by existing orbital strategies, and that global extreme discharge and peak flow distributions rely on temporal frequency rather than spatial coverage. Our analysis could inform future mission development and our data set be used to support potential global gap-filling experiments.

## 1. Introduction

River discharge has the unique capability to integrate the various components of the terrestrial water cycle over a large region (Fekete et al., 2012), and is a critical variable needed to understand the global water cycle (Negrel et al., 2011). Yet, little is known of surface water dynamics globally because the existing networks of in situ surface water monitoring gauges do not currently provide enough information (Alsdorf et al., 2007; Biancamaria et al., 2016). This knowledge gap is actually increasing as global stream gauging networks have been declining outside of developed nations over the last few decades (Enjolras & Rodriguez, 2009; Gleason et al., 2017; Hannah et al., 2010; Pavelsky et al., 2014; Shiklomanov et al., 2002), mainly due to operational expenses and to political instability (Fekete et al., 2015). Currently, only 60%–75% by volume of total surface water runoff flowing to the oceans is being monitored (Bjerklie et al., 2003; Dai et al., 2009; Pavelsky et al., 2014) and this overall lack of in situ hydrologic information ultimately leads to a poor understanding of river discharge globally.

Remote sensing techniques have become an increasingly popular tool to overcome the lack of in situ data and better understand the various components of the terrestrial water cycle (Alsdorf & Lettenmaier, 2003), including river discharge (e.g., Tourian et al., 2012). The primary river observations achievable by spaceborne platforms are water surface elevation, water surface slope, and inundated area; from which river discharge can be estimated (Alsdorf et al., 2007; Smith, 1997). This study specifically focuses on water surface elevation measuring radar altimetry satellites, given the extensive legacy of missions. Indeed, regular and

continuous observations of surface water elevation from space with radar altimeters started in 1992 with a nadir looking altimeter mission named TOPEX/Poseidon (1992–2005). Several other nadir altimeter missions such as the Jason series (2001–present), EnviSat (2002–2012), SARAL (2013–present), and Sentinel-3 (2016–present), later continued the legacy. These nadir altimeters observe water surface elevation in a single line along their orbital tracks, and although primarily designed to observe ocean surfaces, they have also been used relatively sporadically to generate water level timeseries for some rivers around the world. The upcoming Surface Water and Ocean Topography (SWOT) mission (Alsdorf et al., 2007), expected to launch in 2022, will measure water surface elevation in wide swaths instead of single lines, and will hence open new opportunities for satellite-based river observations.

While the measurement capabilities with nadir altimetry are a subject of active research, previous work (e.g., Baup et al., 2014; Biancamaria et al., 2018; Santos da Silva et al., 2010; Sulistioadi et al., 2015) has shown that observations for water bodies on the order of 50 m and larger are within reach. A wealth of the literature involves the development of methods and algorithms that estimate discharge from nadir altimetry, usually aided by localized knowledge (e.g., Hossain et al., 2014a, 2014b; Paris et al., 2016; Tarpanelli et al., 2013). Other discharge algorithm efforts have focused on SWOT specific discharge estimation (Bjerklie et al., 2003; Durand et al., 2014; Garambois & Monnier, 2015; Hagemann et al., 2017). A separate body of research has investigated potential means to fill the spatiotemporal gaps among river observations through statistical interpolation or data assimilation (e.g., Emery et al., 2020; Paiva, 2015; Yang et al., 2019; Yoon et al., 2013). Despite the maturity of altimetry-based discharge estimation research, relatively little attention has been given to the impact of sparse satellite sampling on large-scale discharge characterization.

Yet, the mere nature of Earth-observing satellite missions—including those using radar altimetry—imposes tight constraints on sampling capabilities. These constraints generate a trade space in orbit determination involving choices related to the number of ground tracks (spatial coverage) and the repeat cycle (temporal frequency) that are governed in part by orbital mechanics. As a result, designers for space missions generally have to choose between: (1) frequently revisiting a few places or (2) infrequently revisiting many places. In terms of understanding global discharge, the ramifications of this choice are as of yet, unclear. Allen et al. (2020) analyzed the difference in flow frequency distribution between daily gauge data and concurrent cloud-free Landsat observations and found no significant difference in the largest U.S. rivers except for hydrological extremes like maximum and minimum flow. Nickles et al. (2019) explored the impact of the upcoming SWOT mission's novel wide-swath sampling scheme in the Mississippi Basin and found that while SWOT will rarely observe peak flow, its observational frequency sufficient characterizes flow distributions. However, no research has to-date been produced to evaluate altimetry satellite sampling strategies—for any orbital configuration—from the perspective of global river discharge characterization. This knowledge is critically needed because rivers are dynamic systems with rapid variations across space and time that may not be accurately captured by the week-to-month revisits of individual satellites. Given the upcoming global-scale river observations that are expected from nadir (e.g., Sentinel 3) and wide-swath (i.e., SWOT) altimeters, such an analysis is timely.

The purpose of this study is therefore to: (1) Generate an idealized synthetic data set of river discharge for multiple orbits of radar altimetry satellites using an existing model simulated global discharge data set, and (2) Evaluate the impact of spatial and temporal sampling characteristics on global river discharge estimation. While observational and methodological uncertainties play a critical role in discharge remote sensing, they were not considered here because of their region-specific characteristics and in light of our stated focus on the sole impacts of spatiotemporal sampling. Thus, our ideally sampled discharge data set allows investigating the upper limit of observation-based discharge characterization that would be achieved if discharge estimation errors were minimized; and offers potential for further evaluation beyond the scope of this paper including merged multimission analysis and gap-filling efforts. Ultimately, determining the capabilities and limitations of satellite-based discharge estimation is critical for our understanding of the global hydrologic cycle, and lays a global-scale foundation for assessing the current and near-future state of space-based surface water observations.

## 2. Methodology

This study focuses on multiple nadir altimeters (i.e., Jason series & TOPEX-Poseidon, Sentinel-3, Envisat & SARAL) and on the upcoming wide-swath mission (SWOT). A hypothetical scenario based on three idealized conditions is used: (1) existing state-of-the-art global river flow simulations adequately represent natural discharge variability, (2) all studied altimetry missions operated during the same conjectural 10-year period (2000–2009), and (3) discharge can be estimated perfectly without instrument and algorithm uncertainty. Clearly, these conditions have strong limitations, though they are necessary to isolate the sole behavior of space/time sampling which is the stated goal of this study. The methodology consists of three main steps, each explained in greater detail below. First, an existing global data set of simulated daily river discharge was used, and river reaches likely observable by radar altimeters were identified. Second, this discharge data set was sampled with increasing complexity ultimately reaching the spatiotemporal characteristics of satellite altimeters. Finally, selected properties of the sampled discharge (flow magnitude and peak event duration) were determined and compared to those of the daily discharge reference.

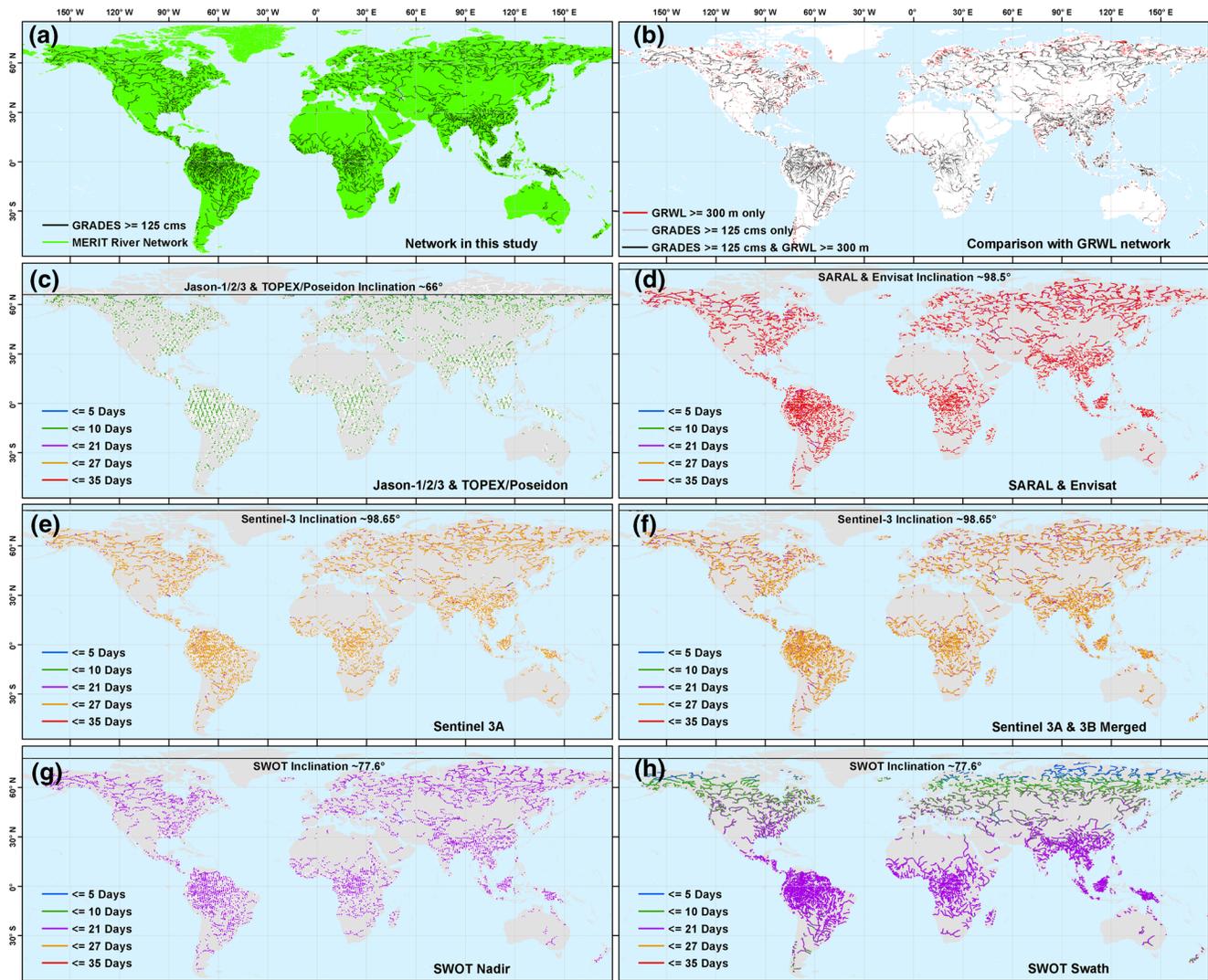
### 2.1. Reference Discharge

Continuous and uniformly distributed global in situ discharge data being unavailable, model simulated discharge was taken as an analog. This study uses the “Global Reach-Level A Priori Discharge Estimates for SWOT (GRADES)” (Lin et al., 2019) as its reference. GRADES is a 35 years (1979–2014) retrospective discharge simulation developed using high resolution precipitation (3 hourly at 0.1°) and other meteorological forcing in the combined VIC (Liang et al., 1994) and RAPID (David et al., 2011) models. The simulation was carried out for about 2.94 million river reaches and was globally calibrated and validated at daily and monthly scales using 14,000 in situ gauges. About 35% (64%) of the validation stations showed bias within  $\pm 20\%$  ( $\pm 50\%$ ), while 29% (62%) had a monthly Kling-Gupta Efficiency  $\geq 0.6$  ( $\geq 0.2$ ). A detailed description of the data, model setup, calibration, and validation of GRADES is available in Lin et al. (2019).

In this study, 10 years (2000–2009) daily river discharge from GRADES was used. Though the database contains simulated flow at 2.94 million river reaches, narrow river reaches are generally not observable by satellite sensors. Observational capabilities of satellite altimeters are commonly related to river width, hence a river width database called the Global River Width from Landsat (GRWL) (Allen & Pavelsky, 2018) was used to extract the widest reaches of the GRADES database. We only considered rivers with 300 m width or above—i.e., a conservative size compared to expected radar capabilities—in GRWL when selecting the largest reaches in GRADES. Note that the GRWL database is an independent river width data set derived from optical Landsat imagery, while the GRADES river network was derived from MERIT Hydro topography (Lin et al., 2019). Therefore, one cannot directly extract river reaches from GRADES using GRWL information. We instead crosschecked the agreement between GRWL rivers and selected large river reaches from GRADES using various mean flow values as threshold to find an optimal set of reaches. A optimal mean discharge of above 125 m<sup>3</sup>/s was found to be a suitable proxy for rivers with width greater than 300 m, and a set of the 124,540 largest GRADES river reaches satisfying this threshold was selected for analysis (Figures 1a and 1b). The details of the determination of the optimal threshold are further discussed in supporting information S1. Despite expected differences, the selected river reaches from the routing model simulation show acceptable agreement with GRWL, and adequately characterize the subset of global rivers that should be observable from space. The 10 years simulated discharge of these large river reaches at daily interval was then assumed as an accurate representation of global discharge and used as the reference data set as well as in the production of spatiotemporal samples.

### 2.2. Spatiotemporal Sampling

Nominal satellite orbit files, available from the AVISO + website and the Sentinel web portal, were used to determine the spatiotemporal coverage of selected altimetry missions. These orbits were overlaid on our altimetry observable river reaches to determine an average spatiotemporal revisit duration for individual missions (Figures 1c–1h) to illustrate the tradeoff between spatial coverage and temporal sampling frequency.



**Figure 1.** River network selection and revisit times. (a) Network derived by Lin et al. (2019) (green) along with our selected network (black) where the long-term (2000–2009) mean flow is  $125 \text{ m}^3/\text{s}$  or above, and (b) our selected river reaches compared with those of 300 m or greater width in GRWL. Spatiotemporal sampling features of selected river reaches by the orbits of all satellite missions considered in this study; (c) Jason-1/2/3 and TOPEX/Poseidon, (d) Envisat/SARAL, (e) Sentinel-3A, (f) Sentinel-3A-3 B merged, (g) SWOT nadir, and (h) SWOT swath. GRWL, Global River Width from Landsat. SWOT, Surface Water and Ocean Topography.

The spatiotemporal revisits of different satellite missions were then used to generate mission-specific sampled discharge data from the reference data set for our hypothetical 10 years time period (2000–2009) in two subsequent phases. First, an idealized conjectural regular temporal sampling of all rivers was explored, hence ignoring the footprints of various satellites and only considering sampling interval. In this analysis, discharge in all 124,540 selected river reaches was sampled at regular temporal intervals representative of the observation frequency of different satellite missions (10, 21, 27, and 35 days), though without applying any spatial sampling (SS) (i.e., orbit tracks). Note that the SWOT measurement strategy differs from other sensors in this study because of spatially variable and often temporally irregular sampling interval (Figure 1h) due to overlapping observation swaths (e.g., Biancamaria et al., 2016). For this regular sampling phase, finer intervals (3 and 5 days) were therefore also included to represent SWOT's more frequent observation frequency at high latitudes. In the second phase of our analysis, river discharge was sampled following the spatial and temporal sampling characteristics of each satellite mission. Here, only subsets of rivers observable by each satellite sensor were used. In this second phase, an initial SS experiment was first carried

out independently of temporal sampling (i.e., rivers observed by a given satellite were artificially sampled daily). In a subsequent experiment, discharge was sampled both spatially and temporally (SS + TS) following the actual sampling strategy of each sensor. Note that this final approach also includes SWOT's variable temporal sampling. It is important to state here again that no actual radar altimeter data were used to construct these synthetic discharge data sets and no considerations have been made for the uncertainty from satellite observations or associated discharge algorithms. Actual remote sensing estimates of discharge are subject to uncertainties and limitations (Durand et al., 2016; Yang et al., 2019), which have been excluded here so that this study could focus solely on the importance of different spatiotemporal sampling strategies.

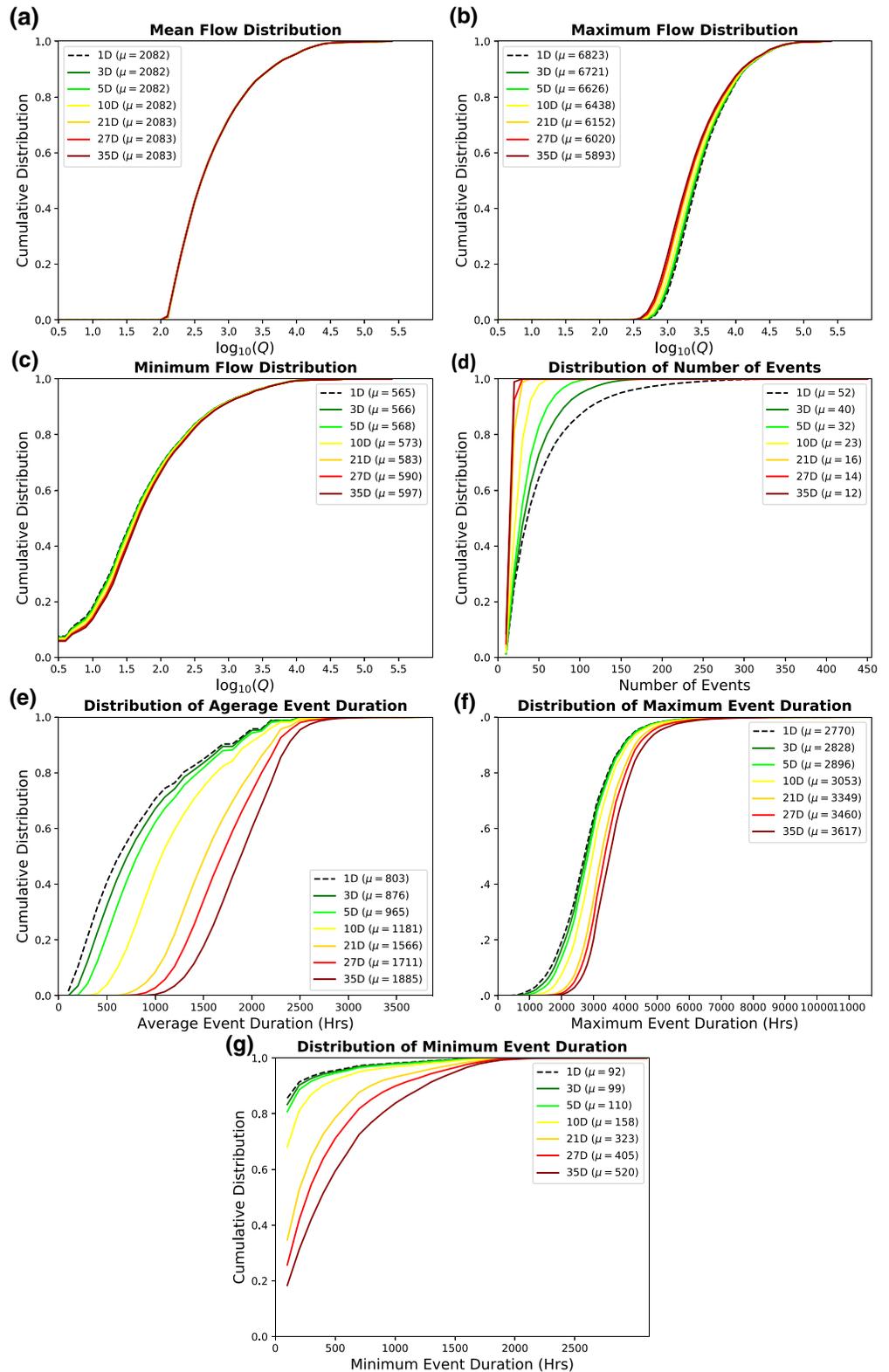
### 2.3. Discharge Characteristic Comparisons

The distributions of several properties of each set of sampled discharge and of the reference data set were then computed in order to quantify how well each sampling strategy could capture the characteristics of global discharge under our idealized conditions. These properties consist of simple flow magnitude statistics: long-term (i.e., 2000–2009) average, maximum, minimum flows, and their cumulative distributions. Additionally, hydrograph characteristics were further explored through the number of discharge events above normal flow and their average, maximum, minimum durations. Here, the 75th percentile of flow was used as an example threshold to define above normal conditions as those occurring only 25% of the time, although alternative quantiles in discharge frequency could equally be used (e.g., Leopold & Maddock, 1953).

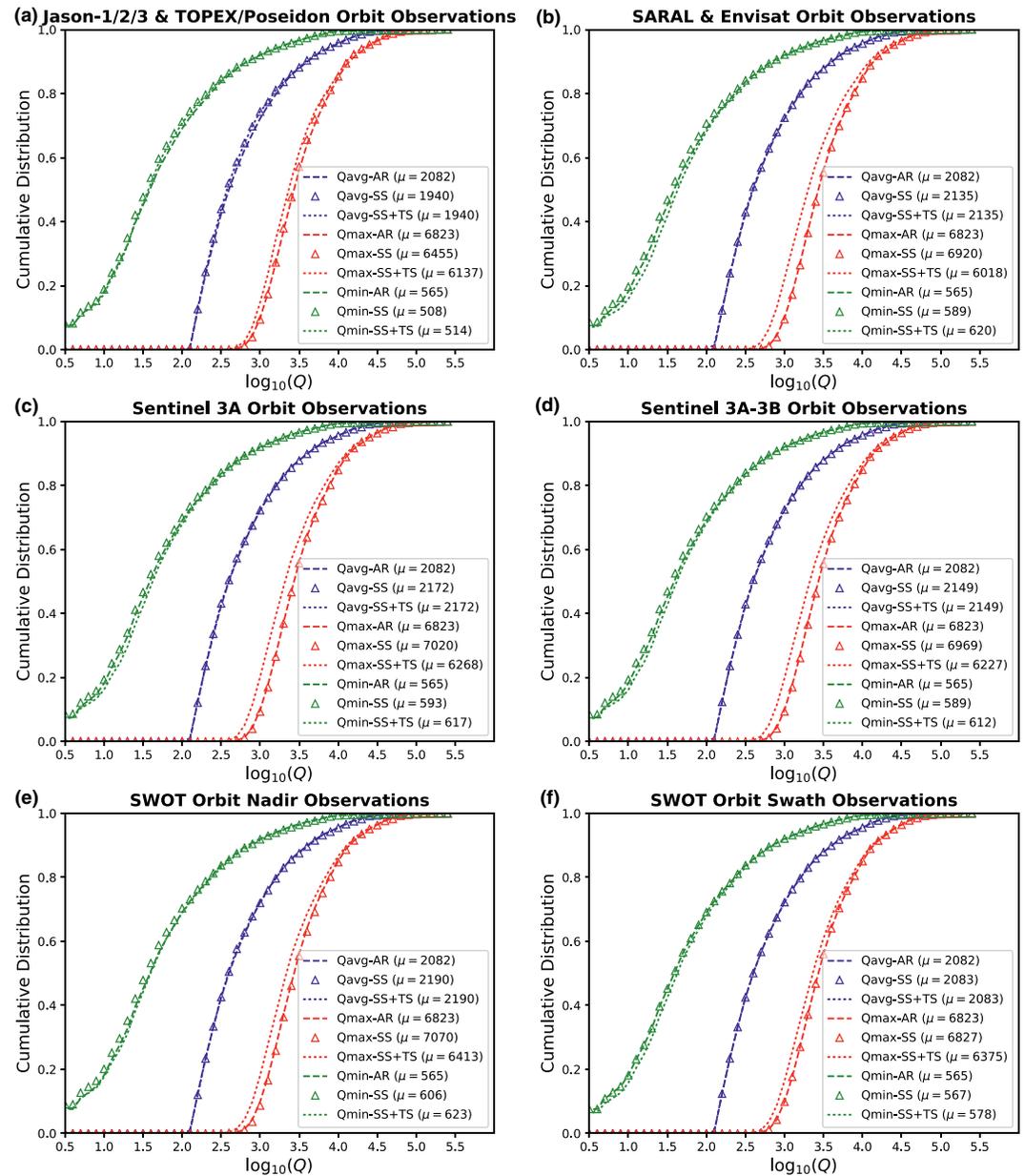
## 3. Results and Discussions

The first phase of analysis, that is, only temporal sampling applied to all observable reaches, is illustrated in Figure 2. The distribution of average flows at different time intervals appears very similar for all intervals used, indicating that the impact of temporal sampling on mean discharge distribution is minuscule (Figure 2a). Minimum discharge detection (Figure 2c) is also relatively well captured although the accuracy decreases with longer sampling intervals, with some deviations from the reference in the distribution noted for 10 days or longer intervals. A similar pattern is even more pronounced in the maximum flow distributions, where the detection performance degrades significantly after a 5 days sampling interval. The number of observed events exceeding the 75th percentile of flow, however, is significantly impacted when temporal sampling is applied (Figure 2d). Notable variation is similarly visible in the average, maximum, and minimum duration of events (Figures 2e–2g). In all flow duration cases, a major variation occurs in the distribution starting with 5 days sampling interval. These findings are further illustrated in global maps of differences in maximum and minimum discharge and of average event duration at various temporal sampling frequencies (see supporting information S2). Clearly, temporally sampled data will not be able to accurately capture event duration unless events are much longer than the sampling interval. More importantly, our simple regular sampling analysis suggests that revisit times characteristic of all altimetry orbit strategies evaluated here are likely insufficient to accurately capture natural peak flow duration in the Earth's largest rivers.

Mission-specific spatiotemporally sampled data sets were used in the second phase of the analysis. Figure 3 shows cumulative distributions of both SS and Spatiotemporal Sampling (SS + TS) on mean, minimum, and maximum discharge estimation over the largest river reaches. Figure 3 therefore allows comparing the properties of three different types of discharge data sets: the daily reference discharge of all 124,540 rivers (AR), the set of full daily discharge for spatially-subset Samples (SS), and the set of discharge sampled both temporally and spatially (TS + SS). Similarly to Figures 2a, 2c, Figure 3 suggests that all radar altimetry missions studied here could capture mean and to a lower extent minimum flow under our assumed ideal retrieval conditions. Like, Figures 2b and Figure 3 also show a significant variation in maximum flow distribution. However, an interesting outcome of this idealized sampling study is that the impact of SS in global maximum discharge distribution patterns is insignificant in contrast to that of the temporal sampling, as evidenced by the comparison of SS and SS + TS. For example, the Jason-1/2/3 and TOPEX/Poseidon orbit covers only 5,148 out of 124,540 selected river reaches. Yet, the cumulative distribution and the mean (values within parentheses in Figure 3) of maximum flows for SS nearly equal the reference (AR). Meanwhile,



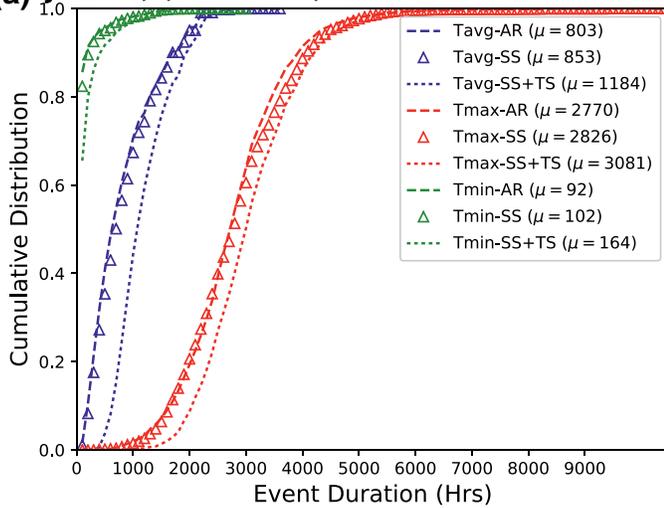
**Figure 2.** Impact of regular temporal sampling on global discharge estimation as evidenced in cumulative distributions of long-term (2000–2009) metrics. (a) Average, (b) maximum, and (c) minimum discharge. Mean discharge values ( $\mu$ ) of all reaches corresponding to each temporal sampling are reported here in  $m^3/s$ . Similarly, cumulative distributions of; (d) number of events exceeding 75th percentile of flow, (e) mean, (f) maximum, and (g) minimum event duration. Mean number of events and their mean durations ( $\mu$ ) are reported here in numbers and hours, respectively.



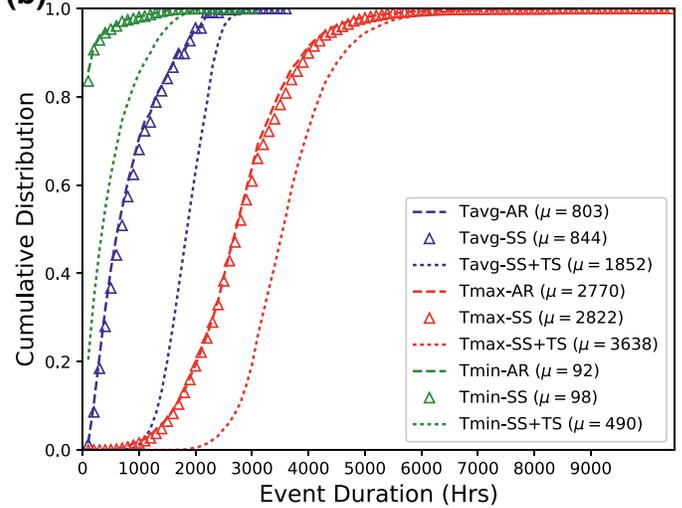
**Figure 3.** Impact of sampling of different radar altimeter satellite orbits on global-scale discharge estimation in terms of flow volume as evidenced in cumulative distributions of long-term (2000–2009) average, maximum, and minimum discharge. (a) Jason-1/2/3 and TOPEX/Poseidon, (b) Envisat/SARAL, (c) Sentinel-3A, (d) Sentinel-3A-3 B merged, (e) SWOT-nadir, and (f) SWOT-swath orbit observations. Cumulative distributions are shown for all reaches of the reference discharge (AR), SS, both Spatial and Temporal Sampling (SS + TS) by different orbit observations. Mean values are reported here in  $m^3/s$  within parentheses. SWOT, Surface Water and Ocean Topography.

a noticeable difference exists for Spatiotemporal Sampling (SS + TS) for the same orbit. Similar patterns are observed in the maximum flow distribution of the other satellite missions and their variation with respect to the reference (i.e., AR), and are more evident in case of less frequent revisit time. This indicates that temporal sampling is dictating the accuracy of global maximum discharge distribution estimation more so than spatial sampling. Mapped relative differences in maximum and minimum discharge show similar features where the maximum flow displays greater variation compared with minimum flow (see supporting information S2).

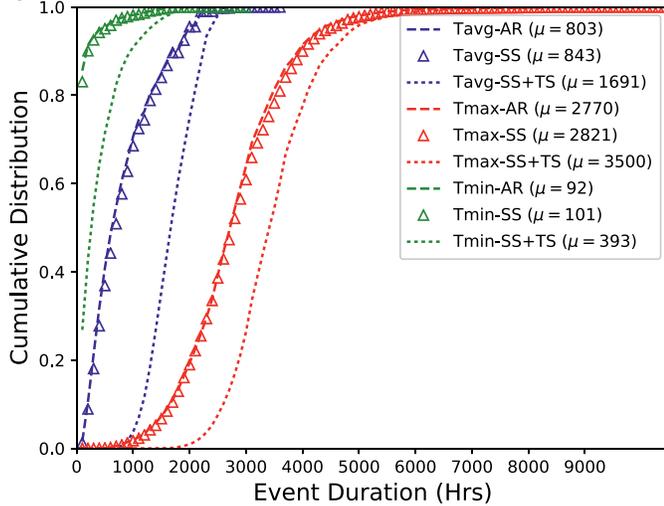
(a) Jason-1/2/3 & TOPEX/Poseidon Orbit Observations



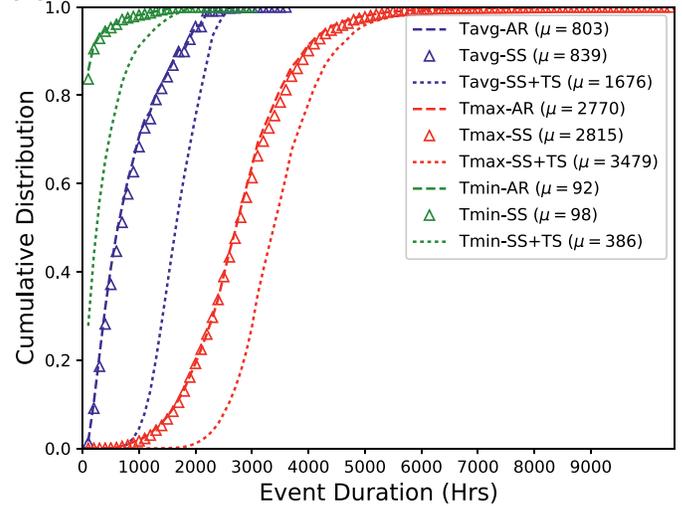
(b) SARAL & Envisat Orbit Observations



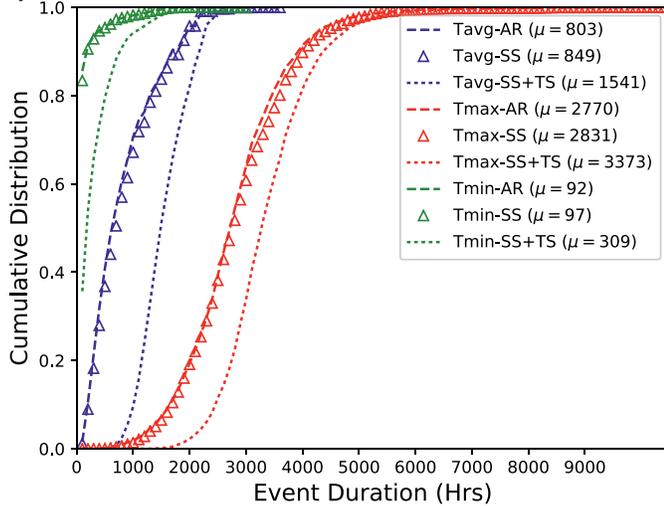
(c) Sentinel 3A Orbit Observations



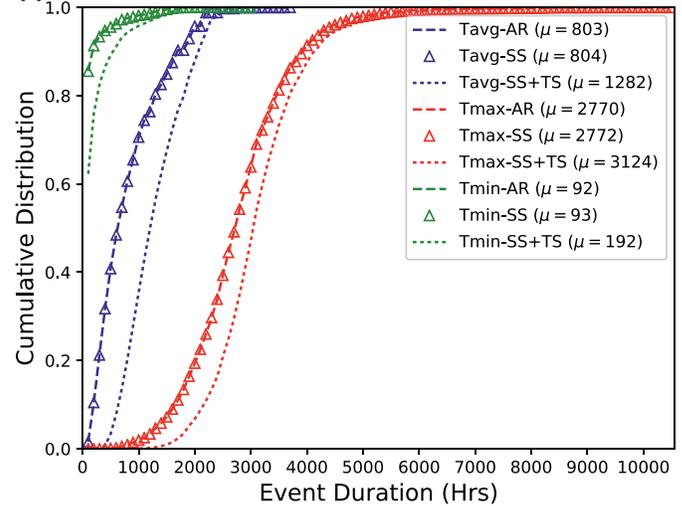
(d) Sentinel 3A-3B Orbit Observations



(e) SWOT Orbit Nadir Observations



(f) SWOT Orbit Swath Observations



The difference between the impact of spatial sampling while retaining daily timeseries (SS) and that of complete spatiotemporal sampling (SS + TS) is even more prominent in the distributions of mean, minimum, and maximum event duration (Figure 4) which is expected since observed event duration is tightly related to the frequency of observation as previously noted. All spatiotemporal samples following satellite orbits (SS + TS) show a significant variation in average, maximum, and minimum duration of peak events from the reference (AR) than seen from SS only. This is further strengthening the aforementioned finding that temporal sampling is more influential than spatial sampling for global-scale discharge distribution estimation. Consequently, the relatively more frequent temporal sampling of the Jason-1/2/3 and TOPEX/Poseidon orbit, and that of the SWOT-swath compared to other satellites, both show case enhanced yet limited capability of capturing peak events and their duration. Similar features are visible in mapped distributions of the average event duration (see supporting information S2). Overall, our results therefore suggest that the orbital characteristics of the radar altimetry missions studied here are insufficiently frequent and hence cannot adequately capture peak event duration even for our ideal retrieval conditions.

Table 1 provides global spatial averages of each temporal statistics (i.e., mean, maximum, and minimum) for discharge magnitude and peak event duration. Table 1 also includes an indicative temporal revisit for SWOT's swath that is computed here based on temporal means over one orbit cycle for each of our selected 124,540 river reaches and leads to a global spatial average of 11.49 days (other spatial statistics are median: 10.43 days, standard deviation: 5.41 days, minimum: 1.39 days, maximum: 20.86 days, unseen reaches: 3.13%). Table 1 quantitatively confirms our overall findings that global mean discharge is well captured (within 7%) for all orbits considered, but also notably suggests that finer spatial measurements generally lead to more accurate estimates. Global spatial averages of temporal minimum (maximum) values are observed within 10% (12%) and degrade with decreasing revisit times, as previously noted from cumulative distributions. Spatial averages of peak discharge duration statistics consistently show large relative errors (>50%) for mean and minimum duration although expectedly smaller errors for longer maximum event duration.

#### 4. Conclusions

This study presents a first-of-its-kind synthetic global river discharge data set sampled following the various observational footprints of radar altimetry missions along with a novel analysis of the impacts of spatiotemporal sampling on the potential estimation of global discharge distribution. Our results suggest—for the first time—that under ideal retrieval conditions, mean discharge distribution for the world's largest rivers could be accurately reconstructed on the global scale for all radar altimetry missions considered in this study. However, the extreme discharge values appear to require more frequent sampling for accurate detection, and sampled estimates of maximum (respectively, minimum) flow lose precision at 5 days (respectively, 10 days) intervals although their detection appears relatively independent of spatial resolution. The distributions of peak event duration—here defined as exceeding the 75th percentile—tell a bleaker story in that mean, minimum, and maximum event duration estimates are significantly affected by observation intervals longer than 5 days, although distributions are here again relatively independent of spatial resolution. This research hence indicates that potential future spaceborne missions concerned with the accurate determination of hydrograph amplitude and peak duration in the Earth's largest rivers may need to prioritize temporal over spatial resolution when negotiating the trade space of orbital configurations. Note that there is still value in high spatial coverage for accurate estimates of global mean discharge, which could have an impact on regional studies depending on basin size and orientation relative to satellite footprints.

Our results therefore offer an idealized first look at the capabilities of radar altimetry satellites to accurately capture global river discharge distribution. Even though important components of discharge estimation uncertainty were here excluded by design—e.g., simulation errors, spaceborne measurement errors, and discharge algorithm errors—the examination of the unique role of spatiotemporal sampling reveals valuable information about the potential and limitations of spaceborne river observation. Our preliminary assess-

**Figure 4.** Impact of sampling of different radar altimeter satellite orbits on global-scale discharge estimation in terms of flow duration as evidenced in cumulative distributions of average, maximum, and minimum duration of events exceeding the 75th percentile threshold. (a) Jason-1/2/3 and TOPEX/Poseidon, (b) Envisat/SARAL, (c) Sentinel-3A, (d) Sentinel-3A-3 B merged, (e) SWOT-nadir, and (f) SWOT-swath orbit observations. Cumulative distributions are shown here only for SS, both spatial and temporal sampling (SS + TS) by different orbit observations, and the reference discharge (AR). Mean values are reported here in hours within parentheses. SWOT, Surface Water and Ocean Topography.

**Table 1**  
Summary Statistics for Full Spatiotemporal Sampling

		Full spatiotemporal sampling (SS + TS)						
		Reference (AR)	J3J2J1TP	SWOT-nadir	Sentinel 3A	SARAL-Envisat	Sentinel 3A-3B	SWOT-swath
Sampling characteristics	Temporal revisit (in brackets if space/time varying)	1 day	9.92 days	20.86 days	27 days	35 days	27 days	[11.49 days]
	Number of rivers reach (percent covered)	124,540 (100%)	5,148 (4.1%)	9,551 (7.7%)	12,094 (9.7%)	15,558 (12.5%)	22,880 (18.4%)	120,645 (96.9%)
Discharge magnitude (m <sup>3</sup> /s)	Spatial average of temporal mean (percent error)	2,082 (0%)	1,940 (6.8%)	2,190 (5.2%)	2,172 (4.3%)	2,135 (2.5%)	2,149 (3.2%)	2,083 (0.0%)
	Spatial average of temporal maximum (percent error)	6,822 (0%)	6,137 (10.1%)	6,413 (6.0%)	6,268 (8.1%)	6,018 (11.8%)	6,227 (8.7%)	6,375 (6.6%)
	Spatial average of temporal minimum (percent error)	565 (0%)	514 (9.0%)	623 (10.3%)	617 (9.2%)	620 (9.7%)	612 (8.3%)	578 (2.3%)
Peak discharge duration (hours)	Spatial average of temporal mean (percent error)	803 (0%)	1,184 (47.4%)	1,541 (91.9%)	1,691 (110.6%)	1,852 (130.6%)	1,676 (108.7%)	1,282 (59.7%)
	Spatial average of temporal maximum (percent error)	2,770 (0%)	3,081 (11.2%)	3,373 (21.8%)	3,500 (26.4%)	3,638 (31.3%)	3,479 (25.6%)	3,124 (12.8%)
	Spatial average of temporal minimum (percent error)	92 (0%)	164 (78.3%)	309 (235.9%)	393 (327.2%)	490 (432.6%)	386 (319.6%)	192 (108.7%)

Note. The Temporal Revisit of SWOT-Swath is Spatially and Temporally Variable

ment is a necessary first step toward leveraging satellite altimetry observations for better understanding of global river discharge. To that end, our global-scale spatiotemporally sampled discharge data set—despite being idealized and with strong limitations—can facilitate future studies where other aspects and features of the global-scale spaceborne discharge estimation endeavor may be explored, including but not limited to region-specific observational error characteristics, synergistic multisensor approaches, and gap-filling efforts. Ultimately, this study shows satellite remote sensing as a potentially invaluable tool for understanding global distributions of river discharge magnitude and event duration, and provides the community with a global data set from which the limitations of space-based discharge can be better understood.

### Data Availability Statement

The discharge data set (GRADES) used in this study can be found at <http://hydrology.princeton.edu/data/mpan/GRADES/>; and the global river network at [http://hydrology.princeton.edu/data/mpan/MERIT\\_Basins/](http://hydrology.princeton.edu/data/mpan/MERIT_Basins/). The satellite altimeter orbit files used here are available at <https://www.aviso.altimetry.fr/en/data/tools/pass-locator.html> and <https://sentinels.copernicus.eu/web/sentinel/missions/sentinel-3/satellite-description/orbit>. All simulated discharge data sets, regular temporally sampled and orbital spatiotemporally sampled discharge data related to this study (Sikder et al., 2020) are made publicly available for research purposes at <https://doi.org/10.5281/zenodo.4064188>. The software used for the analysis is at <https://doi.org/10.5281/zenodo.3236649>.

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## References

- Allen, G. H., & Pavelsky, T. M. (2018). Global extent of rivers and streams. *Science*, 361(6402), 585–588. <https://doi.org/10.1126/science.aat0636>
- Allen, G. H., Yang, X., Gardner, J., Holliman, J., David, C. H., & Ross, M. (2020). Timing of Landsat overpasses effectively captures flow conditions of large rivers. *Remote Sensing*, 12(9). <https://doi.org/10.3390/rs12091510>.
- Alsdorf, D. E., & Lettenmaier, D. P. (2003). Tracking Fresh Water from Space. *Science*, 301(5639), 1491–1494. <https://doi.org/10.1126/science.1089802>
- Alsdorf, D. E., Rodriguez, E., & Lettenmaier, D. P. (2007). Measuring surface water from space. *Reviews of Geophysics*, 45, RG2002. <https://doi.org/10.1029/2006RG000197>
- Baup, F., Frappart, F., & Maubant, J. (2014). Combining high-resolution satellite images and altimetry to estimate the volume of small lakes. *Hydrology and Earth System Sciences*, 18(5), 2007–2020. <https://doi.org/10.5194/hess-18-2007-2014>
- Biancamaria, S., Lettenmaier, D. P., & Pavelsky, T. M. (2016). The SWOT mission and its capabilities for land hydrology. *Surveys in Geophysics*, 37, 307–337. <https://doi.org/10.1007/s10712-015-9346-y>
- Biancamaria, S., Schaefer, T., Blumstein, D., Frappart, F., Boy, F., Desjonquères, J.-D., et al. (2018). Validation of Jason-3 tracking modes over French rivers. *Remote Sensing of Environment*, 209, 77–89. <https://doi.org/10.1016/j.rse.2018.02.037>
- Bjerklie, D. M., Dingman, S. L., Vorosmarty, C. J., Bolster, C. H., & Congalton, R. G. (2003). Evaluating the potential for measuring river discharge from space. *Journal of Hydrology*, 278, 17–38. [https://doi.org/10.1016/S0022-1694\(03\)00129-X](https://doi.org/10.1016/S0022-1694(03)00129-X)
- Dai, A., Qian, T., Trenberth, K. E., & Milliman, J. D. (2009). Changes in continental freshwater discharge from 1948 to 2004. *Journal of Climate*, 22, 2773–2792. <https://doi.org/10.1175/2008JCLI2592.1>
- David, C. H., Maidment, D. R., Niu, G. Y., Yang, Z. L., Habets, F., & Eijkhout, V. (2011). River network routing on the NHDPlus dataset. *Journal of Hydrometeorology*, 12, 913–934. <https://doi.org/10.1175/2011JHM1345.1>
- Durand, M., Gleason, C. J., Garambois, P. A., Bjerklie, D., Smith, L. C., Roux, H., et al. (2016). An intercomparison of remote sensing river discharge estimation algorithms from measurements of river height, width, and slope. *Water Resources Research*, 52, 4527–4549. <https://doi.org/10.1002/2015WR018434>
- Durand, M., Neal, J., Rodriguez, E., Andreadis, K. M., Smith, L. C., & Yoon, Y. (2014). Estimating reach-averaged discharge for the river Severn from measurements of river water surface elevation and slope. *Journal of Hydrology*, 511, 92–104. <https://doi.org/10.1016/j.jhydrol.2013.12.050>
- Emery, C. M., Paris, A., Biancamaria, S., Boone, A., Calmant, S., Garambois, P.-A., et al. (2020). Discharge estimation via assimilation of multisatellite-based discharge products: Case study over the Amazon Basin. *IEEE Geoscience and Remote Sensing Letters*, 1–5. <https://doi.org/10.1109/LGRS.2020.3020285>.
- Enjollras, V. M., & Rodriguez, E. (2009). An assessment of a Ka-Band radar interferometer mission accuracy over Eurasian rivers. *IEEE Transactions on Geoscience and Remote Sensing*, 47(6), 1752–1765. <https://doi.org/10.1109/TGRS.2008.2006370>
- Fekete, B. M., Looser, U., Pietroniro, A., & Robarts, R. D. (2012). Rationale for monitoring discharge on the ground. *Journal of Hydrometeorology*, 13, 1977–1986. <https://doi.org/10.1175/JHM-D-11-0126.1>
- Fekete, B. M., Robarts, R. D., Kumagai, M., Nachtnebel, H. P., Odada, E., & Zhulidov, A. V. (2015). Time for in situ renaissance. *Science*, 349(6249), 685–686. <https://doi.org/10.1126/science.aac7358>
- Garambois, P.-A., & Monnier, J. (2015). Inference of effective river properties from remotely sensed observations of water surface. *Advances in Water Resources*, 79, 103–120. <https://doi.org/10.1016/j.advwatres.2015.02.007>
- Gleason, C. J., Wada, Y., & Wang, J. (2017). A hybrid of optical remote sensing and hydrological modeling improves water balance estimation. *Journal of Advances in Modeling Earth Systems*, 10, 2–17. <https://doi.org/10.1002/2017MS000986>
- Hagemann, M. W., Gleason, C. J., & Durand, M. T. (2017). BAM: Bayesian AMHG-Manning inference of discharge using remotely sensed stream width, slope, and height. *Water Resources Research*, 53, 9692–9707. <https://doi.org/10.1002/2017WR021626>
- Hannah, D. M., Demuth, S., van Lanen, H. A. J., Looser, U., Prudhomme, C., Rees, G., et al. (2010). Large-scale river flow archives: Importance, current status, and future needs. *Hydrological Processes*, 25(7), 1191–1200. <https://doi.org/10.1002/hyp.7794>
- Hossain, F., Maswood, M., Siddique-E-Akbor, A. H., Yigzaw, W., Mazumdar, L. C., Ahmed, T., et al. (2014b). A promising radar altimetry satellite system for operational flood forecasting in flood-prone Bangladesh. *IEEE Geoscience and Remote Sensing Magazine*, 2(3), 27–36. <https://doi.org/10.1109/MGRS.2014.2345414>
- Hossain, F., Siddique-E-Akbor, A. H., Mazumdar, L. C., ShahNewaz, S. M., Biancamaria, S., Lee, H., & Shum, C. K. (2014). Proof of concept of an altimeter-based river forecasting system for transboundary flow inside Bangladesh. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 7(2), 587–601. <https://doi.org/10.1109/JSTARS.2013.2283402>
- Leopold, L. B., & Maddock, T. Jr. (1953). *The hydraulic geometry of stream channels and some physiographic implications* (Geol. Surv. Prof. Pap. 252). Washington, DC: U.S. Government Printing Office. <https://doi.org/10.3133/pp252>
- Liang, X., Lettenmaier, D. P., Wood, E. F., & Burges, S. J. (1994). A simple hydrologically based model of land-surface water and energy fluxes for general-circulation models. *Journal of Geophysical Research*, 99(D7), 14415–14428.
- Lin, P., Pan, M., Beck, H. E., Yang, Y., Yamazaki, D., Frasson, R., et al. (2019). Global reconstruction of naturalized river flows at 2.94 million reaches. *Water Resources Research*, 55, 6499–6516. <https://doi.org/10.1029/2019WR025287>
- Negrel, J., Kosuth, P., & Bercher, N. (2011). Estimating river discharge from earth observation measurements of river surface hydraulic variables. *Hydrology and Earth System Sciences*, 15, 2049–2058. <https://doi.org/10.5194/hess-15-2049-2011>
- Nickles, C., Beighley, E., Zhao, Y., Durand, M., David, C., & Lee, H. (2019). How does the unique space-time sampling of the SWOT Mission influence river discharge series characteristics?. *Geophysical Research Letters*, 46, 8154–8161. <https://doi.org/10.1029/2019GL083886>
- Paiva, R. C. D., Durand, M. T., & Hossain, F. (2015). Spatiotemporal interpolation of discharge across a river network by using synthetic SWOT satellite data. *Water Resources Research*, 51, 430–449. <https://doi.org/10.1002/2014WR015618>
- Paris, A., de Paiva, R. D., da Silva, J. S., Moreira, D. M., Calmant, S., Garambois, P.-A., et al. (2016). Stage-discharge rating curves based on satellite altimetry and modeled discharge in the Amazon basin. *Water Resource Research*, 52, 3787–3814. <https://doi.org/10.1002/2014WR016618>.
- Pavelsky, T. M., Durand, M. T., Andreadis, K. M., Beighley, R. E., Paiva, R. C. D., Allen, G. H., & Miller, Z. F. (2014). Assessing the potential global extent of SWOT river discharge observations. *Journal of Hydrology*, 519, 1516–1525. <https://doi.org/10.1016/j.jhydrol.2014.08.044>
- Santos da Silva, J., Calmant, S., Seyler, F., Rotunno Filho, O. C., Cochonneau, G., & J Mansur, W. (2010). Water levels in the Amazon basin derived from the ERS 2 and ENVISAT radar altimetry missions. *Remote Sensing of Environment*, 114(10), 2160–2181. <https://doi.org/10.1016/j.rse.2010.04.020>

- Shiklomanov, A. I., Lammers, R. B., & Vörösmarty, C. J. (2002). Widespread decline in hydrological monitoring threatens PanArctic research. *Eos, Transactions American Geophysical Union*, 83(2), 13–17. <https://doi.org/10.1029/2002EO000007>
- Sikder, M. S., Bonnema, M., Emery, C., David, C., Lin, P., Pan, M., et al. (2020). *A synthetic global spatiotemporal sampled river discharge database for different satellite altimetry mission orbits*. Zenodo. <https://doi.org/10.5281/zenodo.4064188>
- Smith, L. C. (1997). Satellite remote sensing of river inundation area, stage, and discharge: A review. *Hydrological Processes*, 11(10), 1427–1439. [https://doi.org/10.1002/\(SICI\)1099-1085\(199708\)11:10<1427::AID-HYP473>3.0.CO;2-S](https://doi.org/10.1002/(SICI)1099-1085(199708)11:10<1427::AID-HYP473>3.0.CO;2-S)
- Sulistioadi, Y. B., Tseng, K.-H., Shum, C. K., Hidayat, H., Sumaryono, M., Suhardiman, A., et al. (2015). Satellite radar altimetry for monitoring small rivers and lakes in Indonesia. *Hydrology and Earth System Sciences*, 19(1), 341–359. <https://doi.org/10.5194/hess-19-341-2015>
- Tarpanelli, A., Barbetta, S., Brocca, L., & Moramarco, T. (2013). River discharge estimation by using altimetry data and simplified flood routing modeling. *Remote Sensing*, 5, 4145–4162. <https://doi.org/10.3390/rs5094145>
- Tourian, M. J., Sneeuw, N., Riegger, J., & Bárdossy, A. (2012). *A new method to derive river discharge from satellite altimetry (ENVISAT)*. In IEEE international geoscience and remote sensing symposium. Munich, Germany: IGARSS. <https://doi.org/10.1109/IGARSS.2012.6352425>
- Yang, Y., Lin, P., Fisher, C. K., Turmon, M., Hobbs, J., Emery, C. M., et al. (2019). Enhancing SWOT discharge assimilation through spatiotemporal correlations. *Remote Sensing of Environment*, 234(1), 111450–111513. <https://doi.org/10.1016/j.rse.2019.111450>
- Yoon, Y., Durand, M., Merry, C. J., & Rodríguez, E. (2013). Improving temporal coverage of the SWOT mission using spatiotemporal kriging. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 6(3), 1719–1729. <https://doi.org/10.1109/JSTARS.2013.2257697>