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Uncertainties in Mean River Discharge Estimates Associated With Satellite Altimeter Temporal Sampling Intervals: A Case Study for the Annual Peak Flow in the Context of the Future SWOT Hydrology Mission

F. Papa, S. Biancamaria, C. Lion, and W. B. Rossow

***Abstract*—In the context of the Surface Water and Ocean Topography (SWOT) mission, investigations are needed to refine the error budget for discharge estimations. This letter proposes to evaluate the uncertainties in the estimation of mean river discharge around the seasonal peak flow due to the satellite temporal sampling intervals. The daily time series of *in situ* river discharge measurements for 11 large rivers are used to analyze the uncertainties associated with the sampling of four altimeter repeat cycles: the 35-, 22-, and 10-day repeat cycles in the nadir-looking configuration of current altimeters and the 22-day repeat cycle in the SWOT wide-swath configuration, where a given location is observed every cycle twice at the equator and six times in higher latitudes. Results show that, for boreal rivers, a sampling of 35 or 22 days from current nadir altimeters is too coarse to give an accurate estimate of the average discharge around the seasonal peak flow, whereas for all watersheds, the uncertainties associated with a 10-day repeat cycle or the 22-day repeat cycle in the SWOT wide-swath configuration are within the range of acceptable uncertainties (15%–20%). In addition, the absolute maximum mean discharge uncertainties associated with the SWOT time sampling have a strong relationship with the variance of the river discharge. This suggests that, rather than the commonly used basin area, the magnitude of the short-time-scale variance of the discharge could be used as a predictor of the uncertainties associated with temporal sampling intervals when estimating average discharge around the seasonal peak flow.**

***Index Terms*—Error budget, hydrology, river discharge, surface water, Surface Water and Ocean Topography (SWOT).**

I. INTRODUCTION

CONTINENTAL freshwater runoff or discharge, as well as the spatial distribution and storage of fresh water on land, is a key parameter of the global water cycle and plays an important role in driving the climate system [1]. Moreover, natural disasters of hydrological origin dramatically affect human societies, with large economic losses during water-related extreme events such as floods or droughts.

Despite a widespread recognition of the need for better observations at global scale, surface freshwater measurements are still limited mostly to sparse *in situ* networks of gauges, the number of which has dramatically decreased during the last two decades, particularly in remote areas [1]. In addition, public access to recent observations is generally restricted.

Over the last 20 years, satellite remote sensing techniques have become more useful for hydrologic investigations [1]–[3]. In particular, satellite altimetry (TOPEX–Poseidon (T–P), Jason-2, ERS-1/2, GFO, and ENVISAT missions) has been used for systematic monitoring of water levels in large rivers, lakes, and floodplains [4], and several studies have demonstrated the capability of using these sensors locally for estimating river discharge in large rivers (still limited to rivers with a width of few kilometers), including the Ganges–Brahmaputra [5] or the Ob River [6]. Indeed, the construction of empirical regression curves between altimetry-derived river water heights in large river basins and *in situ* measurements of river discharge can provide altimetry-based discharge estimates for times when *in situ* discharge observations are missing or can even extend the time series of river discharge forward/backward. This technique has several limitations [1], [5], [7], such as the quality of the current altimetry data themselves over continental water bodies, the current altimeter sampling frequency along track, and the spatial coverage of current satellite altimetry missions which is not adequate for global-scale investigations due to their orbit track separation at the equator (few tens to hundreds of kilometers). In addition, a major drawback in the use of current altimetric measurements to monitor river stage and discharge is the temporal sampling rate at a given location, which is 10 days for T-P/Jason-2 and 35 days for ERS-1/2 and ENVISAT. With such space/time sampling intervals, current satellite altimeters cannot compete with observations made daily or twice daily by *in situ* gauges, a frequency required to study local hydrological processes, to evaluate flood risk or for the management of water resources. Nevertheless, for studies related to climate, the use of current radar altimetry is

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F. Papa, S. Biancamaria, and C. Lion are with the Laboratoire d'Etudes en Géophysique et Océanographie Spatiales, Centre National de la Recherche Scientifique–Centre National d'Etudes Spatiales–Institut de Recherche pour le Développement–Université Paul Sabatier, 31400 Toulouse, France (e-mail: fabrice.papa@ird.fr).

W. B. Rossow is with the National Oceanic and Atmospheric Administration Cooperative Remote Sensing Science and Technology Center, The City College of New York, New York, NY 10031 USA.

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still extremely valuable as a complement to ground-based observations [5].

The future wide-swath altimetry measurements made by the Surface Water and Ocean Topography (SWOT) satellite mission (to be launched in 2020) will provide high-resolution characterization of water surface elevations with 2-D global maps of terrestrial surface water extent and storage changes and discharge estimates [1]. Previous studies [1], [7]–[9] have reviewed the expected accuracy of the variables that will be measured and investigated the different errors which will affect SWOT data and the derived discharge. Instantaneous discharge estimated globally from SWOT is expected to have errors below 25%, even if, locally, these errors might be higher for ungauged basins. These errors are primarily due to errors on SWOT measurements (error on water elevation will be equal to or below 10 cm, error on the water mask will be around 20% of the true area, and error on the river slope will be equal to or below 1 cm/1 km). Other anticipated sources of error come from ancillary data needed to compute the discharge (bathymetry and friction coefficient). When estimating monthly or average river discharge from instantaneous discharge estimates, the temporal resolution of the satellite observations will also be a source of uncertainties.

In this letter, we focus on the evaluation of the uncertainties due to the temporal sampling on the estimation of mean river discharge around the annual peak flow. Even though it is important to accurately monitor low-flow and high-flow discharges, the hydrologic events around the yearly peak flow are of particular importance as they are generally associated with the flood waves.

The *in situ* measurement and observation of river discharge are, in general, well established, and ideally, the goal for *in situ* discharge data accuracy is within ±5% of the true value. However, given the difficulties to measure the depth and velocities (and, consequently, the true discharge), particularly in large and strong-flowing rivers, the community agrees that a 15%–20% accuracy is generally acceptable. When using radar altimetry, the accuracy of river discharge estimates depends, among other factors, on the satellite temporal sampling: For instance, mean discharge estimates will likely be more accurate for a river with several views per orbit than for a river with one revisit. Former and current radar altimeters (T/P, Jason-2, ERS-1/2, and ENVISAT) view nadir along the orbit track, so a particular point is observed only once every repeat cycle except at overpasses (ascending and descending views) where two measurements are made. Given the intertrack interval ($\sim$300 and $\sim$80 km at the equator for T-P/Jason-2 and for ERS-1/2 and ENVISAT, respectively), most of continental water bodies that are monitored are sampled only once and not always at an adequate location to measure river discharges. Unlike a nadir-viewing instrument, wide-swath instrument might see the same location from adjacent orbits, so a particular point might be observed several times every repeat cycle. With its wide-swath altimetry measurements, the SWOT mission will offer a global spatial coverage with the number of views of a given location per cycle varying as function of latitude and ranging from twice at the equator to more than six times at high latitudes. At the time of writing, SWOT nominal orbit will have a 22-day repeat period and a global coverage of the Earth up to the latitudes of 78° north and 78° south.

Using T-P (10-day repeat cycle) and ERS-2 and ENVISAT (35-day repeat cycle) altimeters, Papa *et al.* [5] and Kouraev *et al.* [6] showed that the errors of the discharge estimated indirectly from altimetric measurements (at 10 days, monthly, or annual time scales) are, on average, well within the range of acceptable errors (5%–20%). However, the impact of the temporal sampling on the accuracy of the river discharge estimates during the annual peak flow is still not well known. For instance, if all overpasses occurred during flood stage, it leads to an overestimation of the average discharge based on these observations, whereas in other cases, the sensor may completely miss the peak flow event. Over the Ganges–Brahmaputra river system, Papa *et al.* [5] showed that, even with a coarse 35-day sampling interval (ERS-2/ENVISAT), the underestimation or overestimation of the *in situ* mean discharge, in general, never exceeds 20%. Using a similar methodology, the goal of this study is to assess the effects that different altimeter repeat cycles (10-, 22-, and 35-day temporal samplings and with a "real" SWOT repeat cycle in the wide-swath configuration) will have in estimating mean discharge around the yearly peak flow. For this, we will use daily *in situ* gauge measurements from 11 large rivers around the world. Section II presents and discusses the data sets and the methodology. Section III presents and discusses the results. The conclusions are given in Section IV.

II. DATA SET AND METHODOLOGY

We analyze the daily time series of *in situ* river discharge measurements for 11 large rivers (Table I), which represent a fair sample of different environments, from the tropics to boreal regions. These time series are provided by the following: 1) the HYBAM project (www.ore-hybam.org) for the Amazon and Congo Rivers and 2) the Global Runoff Data Center[1] for the other rivers. These 11 rivers were selected because of the availability of fairly long (more than a decade), accurate (evaluated), and continuous measurements.

Using these data sets, we performed the following analysis for each of the 11 rivers, with T representing the repeat cycle of the satellite (10, 22, or 35 days).

The date of the peak flow is identified for each year in the *in situ* record. A sliding window of T days is applied to the record, starting T days before the peak flow and going to the peak flow date in each year. The window moves with one-day steps; at each step, the average discharge is calculated using all T days in the window (the true mean) and using only the two endpoints. The same calculation is done for all the years for which *in situ* discharge is available (Table I). The difference (in percent of true mean) between the two means at each step is averaged over the years. The analysis is done for each of the 11 stations.

In parallel, "true" SWOT observation times were determined for each of the 11 gauge locations by calculating the number of times that each gauge location is viewed from the satellite

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[1] Global Runoff Data Centre (2009), Long Term Mean Monthly Discharges and Annual Characteristics of GRDC Station/Global Runoff Data Centre, Koblenz, Federal Institute of Hydrology (BfG).

TABLE I

INFORMATION ON THE DAILY *IN SITU* RIVER DISCHARGE TIME SERIES USED IN THIS STUDY: RIVER NAME, GAUGE STATION NAME AND LOCATION, FIRST AND LAST YEARS OF THE AVAILABLE TIME SERIES, CATCHMENT'S AREA, MEAN VALUE AND STANDARD DEVIATION (STD) FOR THE ENTIRE DAILY DISCHARGE TIME SERIES, AND THE NUMBER OF VIEWS OF THE GIVEN GAUGE STATION PER SWOT CYCLE

River Name	Station Name and locations	Time series	Catchment area (km^2)	Mean Discharge/ STD (m^3/s)	Number of samples per SWOT cycle
Amazon	Obidos (1.92°S; 55.67°W)	1968-2008	4618000	172700 / 49840	2
Congo	Brazzaville (4.25°S; 15.28°E)	1968-2008	3500000	40500 / 9300	2
Danube	Ceatal Izmail (45.21°N; 28.72°E)	1954-2008	807000	6580 / 2550	2
Irrawaddy	Sagaing (21.98°N;96.10°E)	1978-1988	117900	8170 / 6820	2
Lena	Kusur (70.70°N; 127.65°E)	1954-2003	2430000	16950 / 23860	6
Mekong	Phnom Penh (11.58°N; 104.96°E)	1960-1973	663000	13305 / 13300	2
Mississippi	Vicksburg, MS (32.31°N; 90.95°W)	1954-1999	2964000	17370 / 9620	2
Niger	Lokoja (7.80°N; 6.77°E)	1970-1993	2077000	4830 / 4890	2
Ob	Shalekard (66.57°N;66.53°E)	1954-1999	2949000	12800 / 11190	6
Orinoco	Puente Angosta (8.15°N; 63.60°W)	1950-1989	836000	31650 / 21690	2
Yenisey	Igarka (67.48°N; 86.50°E)	1980-2003	2440000	19170 / 23180	3

during a cycle using the relationship between the number of revisits and latitude [7]. The same analysis is done as previously, but instead of considering only the two endpoints of the 22-day repeat cycle, we consider all observations of the target within the 22-day repeat cycle. The numbers of revisits per cycle for each station are given in Table I, but note that the SWOT sampling is not uniformly distributed in time during one repeat cycle. Depending on the location, a target may be observed twice on two consecutive days and, then, not be sampled again for the next ten days. In our case, for the Amazon at Obidos, two observations are made on the 16th and 17th days of the cycle, whereas there are up to six observations for the Lena River in Siberia, with irregular sampling on the 2nd 5th, 8th, 11th, 18th, and 21st days of the cycle. Globally, the maximum time between two observations for a target is 13 days [7]. Note also that, in this study, we have only considered the SWOT measurements that observe the gauge location directly. However, because of its wide swath, SWOT will also measure water elevations upstream and downstream of the gauge location, which could then be used to infer water elevation at the gauge location using hydrodynamic models or statistical relationships and, therefore, increase the number of samples on the mean discharge estimate [10]. Thus, the SWOT temporal sampling uncertainty computed in this study corresponds to the maximum expected error.

Finally, in the present study, we are interested in the effect of temporal sampling only. It is important to remind here that these uncertainties represent only a source of error among many other uncertainties associated with the estimates of instantaneous and mean river discharges from altimeter data. Indeed, as discussed in the introduction, the river water height needs to be first converted into discharge, and such retrieval errors [7], [9] will also largely impact the results. These effects will not be discussed here.

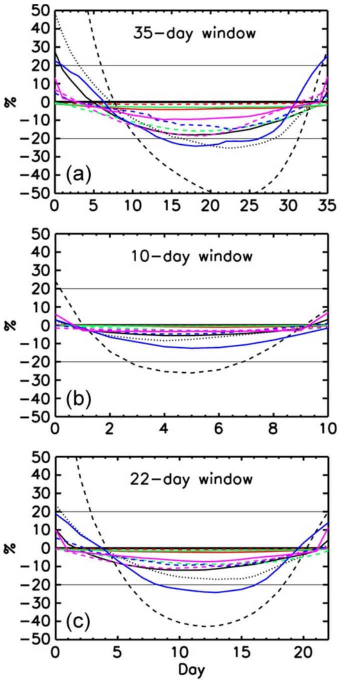

Fig. 1. Uncertainty of the (a) 35-, (b) 10-, and (c) 22-day sampling intervals in the estimation of mean river discharge around the yearly peak flow for 11 large rivers (see text for details and the method): (Black solid line) The Ob, (black doted line) the Yenisey, (black dashed line) the Lena, (red solid line) the Orinoco, (red dashed line) the Amazon, (green solid line) the Congo, (green dashed line) the Niger, (blue solid line) the Irrawaddy, (blue dashed line) the Mekong, (purple solid line) the Danube, and (purple dashed line) the Mississippi.

III. RESULTS AND DISCUSSION

The results for the 35-, 22-, and 10-day temporal samplings are plotted in Fig. 1 for the 11 stations. The x-axis values represent the lower endpoint of a T-day sliding window. For zero, the lower endpoint of the time window is at peak minus T days, and the upper endpoint is on the day of the peak discharge. At five, the lower end is at peak minus T plus five days, and the upper end is at peak plus five days and so on. The y-axis represents for each step the average difference over the years between the average discharge calculated using only the two endpoints and the true mean discharge calculated using all days in the time window. The y-axis values are expressed in percent of the true mean.

As expected, with the 35-day window (Fig. 1(a); the case of ERS/ENVISAT altimeters), the uncertainties are the largest, with big differences from river to river. The largest differences are found for the three basins in Siberia, the Ob, the Yenisey, and the Lena, for which river discharge is characterized by a sharp and rapid increase at the end of the snowmelt season when the river ice breaks up. High river discharge values last only few weeks before a sharp decrease. For instance, for the Lena River, when one of the endpoints is within ±5 days of the date of the peak flow, the average overestimation can be more than 200%

of the true mean. When the two samples bracket the peak flow date (around day 14 to 25), the underestimation is between 30% and more than 50%. The Yenisey and Ob Rivers show the same patterns but with smaller over-/underestimation, particularly for the Ob River for which the flood season and high peak flow last longer [11], [12]. For midlatitude and tropical watersheds, the results show differences within the acceptable range of uncertainties for river discharges, i.e., around ±20%. In most tropical watersheds (Amazon, Niger, Orinoco, etc.), when one of the endpoints is on the date of the peak flow ($day = 0$, for instance), the mean discharge using the two endpoints overestimates the true 35-day mean river discharge by about 10%. Then, the differences show almost permanent underestimations of the 35-day mean discharge as soon as the peak flow is missed by three to four days. Moving the window forward shows that the differences (underestimates) are less than 5%, even with a 35-day sampling interval, and reach a maximum when the two samples bracket the peak flow date. The differences are larger for midlatitude watersheds, but the differences are generally less than 15% with a maximum underestimation of ~20% for the Mississippi. Note that, among the tropical watersheds, the Irrawaddy shows the largest uncertainties (maximum and minimum underestimations above 20%) which might be explained by sharp increases and variability of the river discharge value during the monsoon season. This behavior is similar to the one found in [5] for two other large rivers of the region, the Ganges and the Brahmaputra.

As also expected, a ten-day sampling [Fig. 1(b)], which is the repeat cycle of T-P and Jason-2 radar altimeters, leads to much smaller errors when estimating the discharge around the peak flow. Tropical basins, such as the Amazon, the Orinoco, or the Congo, show almost no difference between the ten-day bracket and the true mean discharge (uncertainties below 2%). With a ten-day sampling interval, all rivers except the Lena are within ±20%. The maximum error for the Lena is an underestimation (25%) when the two samples bracket the peak flow date (day 5). Nevertheless, uncertainties for around day 0 for the Lena are reduced from more than 200% with a 35-day repeat cycle to ~20%. For the Yenisey and Irrawaddy Rivers, the large uncertainties noticed with the 35-day sample are reduced to less than 10% with a ten-day repeat cycle.

Fig. 1(c) shows the results for a 22-day repeat cycle for the SWOT mission with only nadir view, i.e., when the targets are visited only once every 22 days. As an intermediate case between the 35- and 10-day sampling intervals, the results still show fairly good estimates of mean discharge around the peak flow for most tropical basins (Amazon, Congo, and Orinoco) and uncertainties in midlatitude basins on the order of 10%. The Irrawaddy and Yenisey have the largest errors but with maximum over-/underestimations around 20%. For the Lena River, a sampling of 22 days is still too coarse to give an accurate estimate of the peak flow mean discharge with uncertainties ranging from ~100% to −40%.

However, as mentioned earlier, "true" SWOT observation times are more frequent per orbit repeat cycle with each gauge location sampled at least twice within a 22-day repeat cycle. Using the real SWOT orbit sampling (Table I), Fig. 2 shows that the errors on estimated discharge around the peak flow are greatly reduced and well within the range of acceptable uncertainties for all 11 rivers. For the boreal and midlatitude basins [Fig. 2(a)], the over-/underestimation of mean discharges is always under 20%. The Lena, which is now sampled up to six times in a cycle, also shows uncertainties within this range. The Ob River, which already showed acceptable errors with a 22-day cycle [Fig. 1(c)], is now sampled six times in a true SWOT configuration, reducing uncertainties to less than 5%.

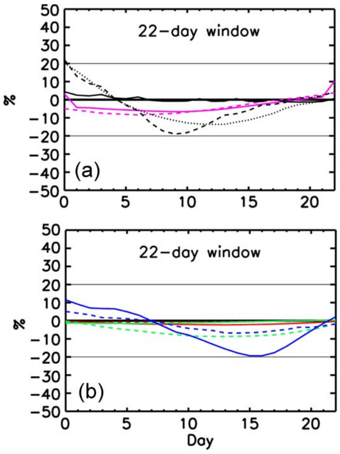

Fig. 2. Same as Fig. 1 with the SWOT 22-day repeat cycle but taking into account the number of SWOT views per cycle. For clarity, we separate (a) the rivers in boreal/midlatitude environments and (b) the ones located in the tropics.

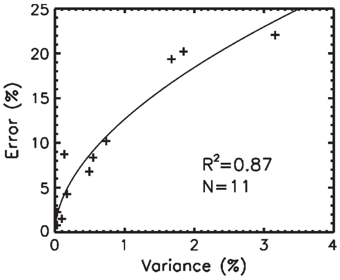

Fig. 3. Relationship between the uncertainties on the monthly discharge estimates around the yearly peak flow in the context of SWOT 22-day repeat cycle and the percentage of total discharge variance for frequencies above 1/(20 days) estimated for the 11 stations.

For the tropical watersheds (Fig. 2(b); two revisits minimum as in Table I), all associated uncertainties are below 10%, except for the Irrawaddy, which still shows larger errors (overestimation of ~10% and underestimation of ~20%) even when it is sampled twice. For the Amazon, the Congo, the Mekong, and the Orinoco, the uncertainties are on the order of a few percent. Thus, these results show that, for the 11 rivers considered here, the uncertainties associated with SWOT temporal sampling when estimating mean discharge around the annual peak flow are well within the range of acceptable errors.

Absolute maximum mean discharge errors for each river [as in Fig. 2(a) and (b)] have been plotted as a function of the percentage of river discharge variance for frequencies above 1/(20 days) (Fig. 3). This percentage is computed as follows. For each daily discharge time series for the 11 rivers, a Fourier transform is calculated, and the integral of its variance (which is the square of the Fourier transform amplitude) over all time scales less than 20 days is computed as a percentage of the total variance. This percentage gives the relative contribution of frequencies above 1/(20 days) to the discharge variance and is expected to be larger for rivers with significant variability at shorter time scale. Fig. 3 shows that the temporal sampling error is associated with the short-time-scale variability of the river discharge time series. A regression analysis gives a quantitative estimate of the relationship between discharge variance and SWOT temporal sampling errors in a form of a power law, statistically significant at 99% confidence level ($R^2 = 0.87$ with 11 points and p-values < 0.01 with $|R| > 0.735$). Quite logically, for rivers with large short-time-scale variance, typically the boreal rivers with freeze/thaw cycles and the monsoon-affected Irrawaddy, the SWOT sampling error is larger. Usually, temporal sampling errors on mean river discharge are parameterized as a function of the river catchment area [7]. However, we show that, in the case of estimates of the mean discharge around the seasonal peak flow, the uncertainty has a strong relationship with the variance of the river discharge. In the case of these 11 large rivers, the correlation between the absolute discharge errors and the catchment's area is only $R^2 = 0.18$. Thus, the magnitude of the short-time-scale variance is a stronger predictor of the peak discharge error than the basin area. Although this analysis only had 11 samples, we suggest that the relationship with the variance could then be a new tool to infer the quality of future SWOT measurements at other gauge locations, if some past discharge time series is available to calibrate the relationship.

IV. CONCLUSION

This letter has reported the first effort to evaluate the uncertainties in the estimation of mean river discharge around the seasonal peak flow due to satellite altimeter temporal sampling intervals. Analyzing the daily time series of *in situ* river discharge measurements for 11 large rivers in different environments, the results show that, for high-latitude rivers, a sampling of 35 or 22 days in the nadir-looking configuration of current altimeter mission is too coarse to give an accurate estimate of the average discharge around the seasonal peak flow. For tropical watersheds, however, such time sampling intervals lead to uncertainties that generally never exceed 20% and, thus, are in the range of uncertainties acceptable for river discharge estimations. On the other hand, the uncertainties associated with a ten-day repeat cycle are well within the range of acceptable errors from tropical to Siberian rivers. Owing to its wide-swath altimetry technique, which will enable to observe a given location at least twice at the equator and up to six times in high latitudes every repeat cycle, the uncertainty due to SWOT time sampling on the average discharge around the seasonal peak flow is greatly reduced when compared to a 22-day repeat cycle instrument with a nadir-looking angle. We found that these uncertainties are generally well within the range of acceptable errors for boreal watersheds (absolute maximum mean discharge uncertainties from 5% to 20%), midlatitude watersheds (absolute maximum mean discharge uncertainties ~10%), and tropical watersheds (absolute maximum mean discharge uncertainties from 2% to ~20%). Moreover, we find that absolute maximum mean discharge uncertainties around the seasonal peak flow have a strong relationship with the variance of the river discharge. Thus, around the peak flow, we suggest that the magnitude of the short-time-scale variance of the discharge could be used as a predictor of the uncertainties rather than the commonly used basin area.

The future launch of the SWOT mission in 2020 will represent a step increase for continental hydrology, and further studies are needed to refine the SWOT error budget for discharge estimates. For instance, the uncertainties for smaller rivers (~100-m to ~1-km width) have not been addressed here and require further investigations. Moreover, we have addressed in this letter the source of errors due to the temporal sampling of the satellite only, but in reality, it will combine with other sources of uncertainty. These issues need to be addressed in future works.

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REFERENCES

[1] D. E. Alsdorf, E. Rodriguez, and D. P. Lettenmaier, "Measuring surface water from space," *Rev. Geophys.*, vol. 45, no. 2, p. RG2 002, May 2007. doi: 10.1029/2006RG000197.

[2] J. F. Crétaux, A. V. Kouraev, F. Papa, M. Bergé-Nguyen, A. Cazenave, N. Aladin, and I. S. Plotnikov, "Evolution of sea level of the big Aral Sea from satellite altimetry and its implications for water balance," *J. Great Lakes Res.*, vol. 31, no. 4, pp. 520–534, 2005.

[3] F. Papa, C. Prigent, F. Aires, C. Jimenez, W. B. Rossow, and E. Matthews, "Interannual variability of surface water extent at global scale, 1993–2004," *J. Geophys. Res.*, vol. 115, p. D12 111, Jun. 2010. doi: 10.1029/2009JD012674.

[4] F. Frappart, F. Papa, J. S. Famiglietti, C. Prigent, W. B. Rossow, and F. Seyler, "Interannual variations of river water storage from a multiple satellite approach: A case study for the Rio Negro River basin," *J. Geophys. Res.*, vol. 113, p. D21 104, Nov. 2008. doi: 10.1029/2007JD009438.

[5] F. Papa, F. Durand, W. B. Rossow, A. Rahman, and S. Bala, "Satellite altimeter-derived monthly discharge of the Ganga–Brahmaputra River and its seasonal to interannual variations from 1993 to 2008," *J. Geophys. Res.*, vol. 115, p. C12 013, Dec. 2010. doi: 10.1029/2009JC006075.

[6] A. V. Kouraev, E. A. Zakharova, O. Samain, N. M. Mognard, and A. Cazennave, "Ob' river discharge from Topex–Poseidon satellite altimetry (1992–2002)," *Remote Sens. Environ.*, vol. 93, no. 1/2, pp. 238–245, Oct. 2004.

[7] S. Biancamaria, K. M. Andreadis, M. Durand, E. A. Clark, E. Rodriguez, N. M. Mognard, D. E. Alsdorf, D. P. Lettenmaier, and Y. Oudin, "Preliminary characterization of SWOT hydrology error budget and global capabilities," *IEEE J. Sel. Topics Appl. Earth Obs. Remote Sens.*, vol. 3, no. 1, pp. 6–19, Mar. 2010.

[8] K. M. Andreadis, E. A. Clark, D. P. Lettenmaier, and D. E. Alsdorf, "Prospects for river discharge and depth estimation through assimilation of swath-altimetry into a raster-based hydrodynamics model," *Geophys. Res. Lett.*, vol. 34, p. L10 403, May 2007. doi: 10.1029/2007GL029721.

[9] M. Durand, E. Rodriguez, D. E. Alsdorf, and M. Trigg, "Estimating river depth from remote sensing swath interferometry measurements of river height, slope, and width," *IEEE J. Sel. Topics Appl. Earth Obs. Remote Sens.*, vol. 3, no. 1, pp. 20–31, Mar. 2010.

[10] S. Biancamaria, M. Durand, K. M. Andreadis, P. D. Bates, A. Boone, N. M. Mognard, E. Rodríguez, D. E. Alsdorf, D. P. Lettenmaier, and E. A. Clark, "Assimilation of virtual wide swath altimetry to improve Arctic river modeling," *Remote Sens. Environ.*, vol. 115, no. 2, pp. 373–381, Feb. 2011.

[11] F. Papa, C. Prigent, and W. B. Rossow, "Ob' river flood inundations from satellite observations: A relationship with winter snow parameters and river runoff," *J. Geophys. Res.*, vol. 112, p. D18 103, 2007. doi: 10.1029/2007JD008451.

[12] F. Papa, C. Prigent, and W. B. Rossow, "Monitoring flood and discharge variations in the large Siberian rivers from a multi-satellite technique," *Surv. Geophys.*, vol. 29, no. 4/5, pp. 297–317, Oct. 2008.