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Forecasting transboundary river water elevations from space

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[1] Over 90% of Bangladesh's surface water is generated upstream of its border, yet no real-time information is shared by India (the upstream country) with respect to two major transboundary rivers, the Ganges and Brahmaputra. This constraint limits operational forecasts of river states inside Bangladesh to lead times of no more than three days. Topex/Poseidon satellite altimetry measurements of water levels in India, combined with in-situ measurements inside Bangladesh allow extension of this lead time. We show that for both rivers, it is practically feasible to forecast water elevation anomalies during the critical monsoon season (June to September) near the Bangladesh border with an RMSE of about 0.40 m for lead times up to 5-days. Longer 10-day forecasts have higher errors (RMSE between 0.60 m and 0.80 m) but still provide useful information for operational applications. These results demonstrate the tremendous potential of satellite altimetry for transboundary river management. **Citation:** Biancamaria, S., F. Hossain, and D. P. Lettenmaier (2011), Forecasting transboundary river water elevations from space, *Geophys. Res. Lett.*, *38*, L11401, doi:10.1029/2011GL047290.

1. Introduction

[2] Two hundred and fifty-six major river basins, covering 45% of the global land area exclusive of Antarctica and Greenland, are split between two or more countries [*Wolf et al.*, 1999]. The absence of information sharing among some riparian nations has led to numerous tensions in the past [*Balthrop and Hossain*, 2010]. A classic case of uncoordinated management of transboundary flooding occurs in the Ganges-Brahmaputra River basins. More than 90% of surface water flowing through Bangladesh comes from the countries upstream - mostly India [*Nishat and Rahman*, 2009]. Hydrological measurements on the Ganges and Brahmaputra Rivers are viewed as sensitive by India, and no treaty provides for sharing of such data between the two nations at operational time scales [*Balthrop and Hossain*, 2010]. For this reason, water elevation (WE) forecasts in the interior and southern parts of Bangladesh are limited to lead times of two to three days [*Ahmad and Ahmed*, 2003]. Increasing this lead time would be very valuable both for disaster preparedness and agricultural water management.

[3] Previous studies have shown that combination of rainfall satellite measurements and modeling can successfully forecast streamflow in Bangladesh [*Nishat and Rahman*, 2009; *Hopson and Webster*, 2010; *Webster et al.*, 2010]. In particular, *Hopson and Webster* [2010] and *Webster et al.* [2010] developed a daily 1–15-day flood forecasting system for Bangladesh, based on statistically adjusted (with satellite observations) quantitative precipitation forecasts from the European Centre for Medium-Range Weather Forecasts (ECMWF). This system has successfully forecasted floods since 2004, with an accuracy of ±1 day in flood onset and retreat [*Webster et al.*, 2010]. However, *Hopson and Webster* [2010] highlight that "if river flow measurements higher up in the catchment were available and could be routed downriver to the forecast location, errors in rainfall-runoff modeling … could be reduced". Satellite altimetry observations have the potential to provide such information. *Birkinshaw et al.* [2010] have used both in-situ and altimetry WE time series on the Mekong basin, combined with hydrologic modeling to forecast discharge downstream. However, in their approach satellite altimetry is one of several data sources, and the impact of the lead time in the context of water management was not investigated. Here we show the potential for satellite altimetry to extend forecast lead time in a case where it is the only source of upstream river stage data.

2. The Brahmaputra and Ganges Rivers

[4] The locations of the Ganges and Brahmaputra rivers and the political boundaries of the riparian countries are shown in Figure 1. The drainage area of the Ganges basin is about 1,065,000 km^2. It is shared among China, India, Nepal and Bangladesh. The Brahmaputra has a drainage area of about 574,000 km^2 and is shared among China, India, Bhutan and Bangladesh [*Nishat and Rahman*, 2009].

[5] The upstream-most in-situ gauges in Bangladesh used in this study are located at Hardinge Bridge on the Ganges and at Bahadurabad on the Brahmaputra (Figure 1). WE (referenced to the Public Work Department, PWD datum of Bangladesh Government) have been collected by the Bangladesh Water Development Board (BWDB) and Institute of Water Modeling (IWM, Bangladesh). They are daily (some days missing) and are available from January 2000 to September 2005. Figure 2 shows in-situ WE time series measured at the Bahadurabad (Figure 2a) and Hardinge Bridge (Figure 2b) gauges for all years available in the period of record. The Brahmaputra can be considered unregulated with no major hydraulic structures, whereas the Ganges is highly regulated with at least 34 dams and diversion points in India and Nepal [*Hopson and Webster*, 2010]. The hydraulic structures are intended primarily for use during the dry season and do not act as a control structure to regulate flow during the monsoon season [*Jian et al.*, 2009]. At Bahadurabad and at Hardinge Bridge, the mean annual (monsoon season) discharges are around 16,800 m^3.s^{-1} (39,400 m^3.s^{-1}) and 7,100 m^3.s^{-1} (24,300 m^3.s^{-1}), respectively. The transboundary region of Meghna is relatively smaller than Ganges and Brahmaputra to have a significant

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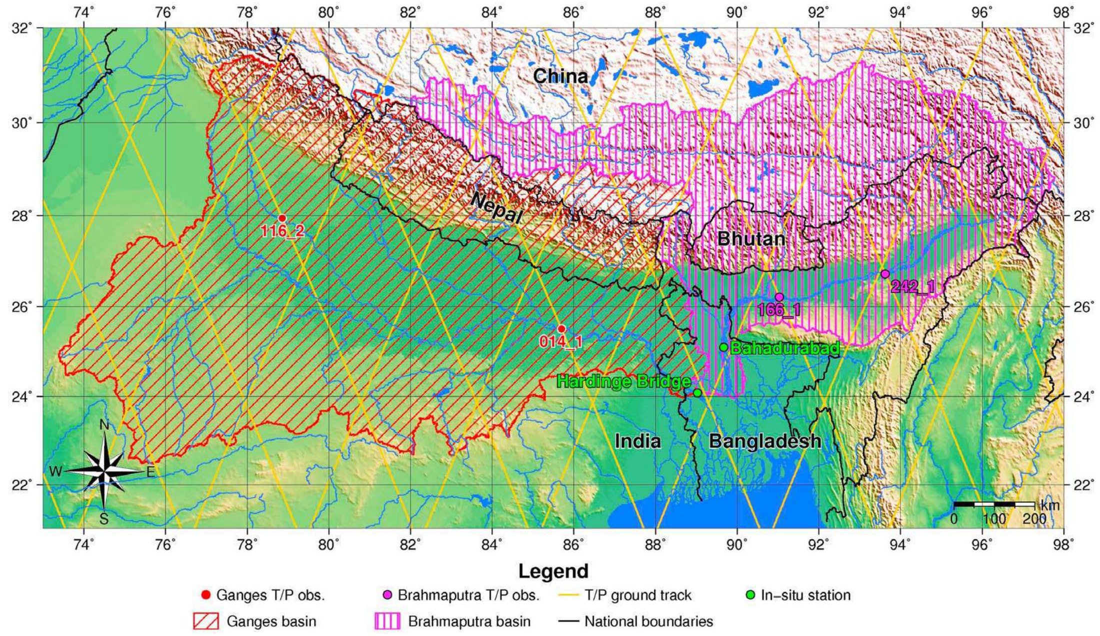

Figure 1. Map of the study domain. Ganges basin (red hatched area) and Brahmaputra basin (magenta hatched area) boundaries come from HYDRO1k. Locations of measurements from the satellite nadir altimeter Topex/Poseidon on the Ganges and the Brahmaputra rivers (available on HydroWeb) are represented, respectively, by red and purple dots (yellow lines correspond to the satellite ground tracks). Green dots correspond to the furthest upstream in-situ gauges in Bangladesh. The background topography used in this map is the ETOPO1 topography dataset. Lakes, rivers and political boundaries come from the CIA World Data Bank II.

impact on forecasting of WE inside Bangladesh and has not been considered in this study.

3. Methodology

[6] We used estimates of WE in India derived from the Topex/Poseidon (T/P) satellite nadir altimeter to forecast WE at Bahadurabad and Hardinge Bridge. T/P WE were computed by the Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (LEGOS) and were downloaded from the HydroWeb data base (http://www.legos.obs-mip.fr/en/soa/hydrologie/hydroweb/). T/P was a joint National Aeronautics and Space Administration (NASA) and Centre National d'Etudes Spatiales (CNES) satellite mission launched in August 1992, with a 10-day repeat period. In September 2002, the T/P orbit was changed due to the launch of a new satellite altimeter (JASON-1), which defines the T/P HydroWeb period of record from 1993 to mid-2002. Nadir

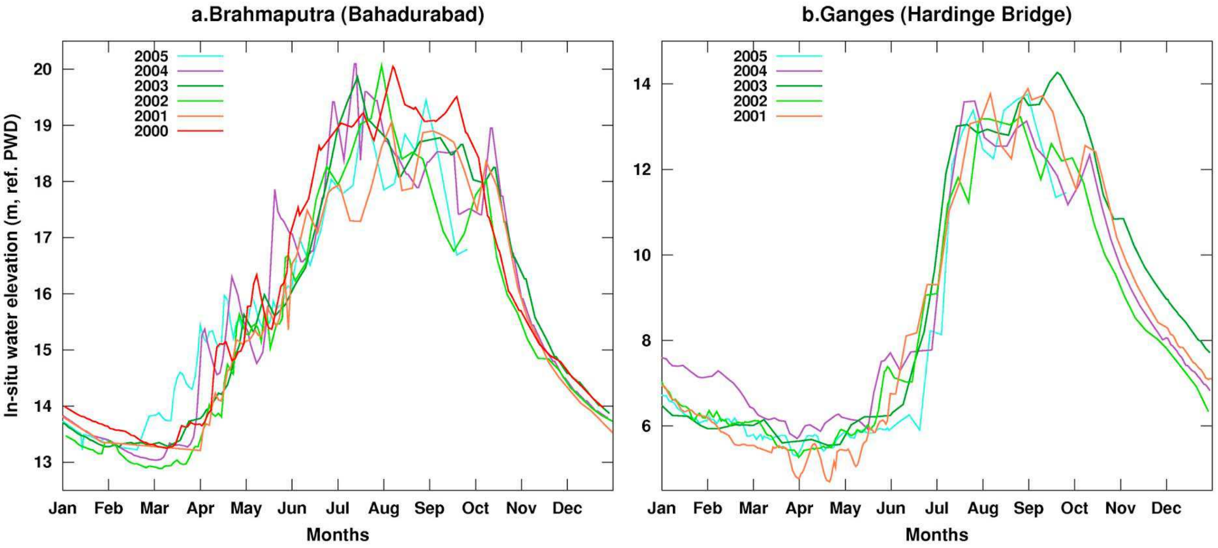

Figure 2. In-situ water elevation time series measured on the Brahmaputra at (a) Bahadurabad and (b) on the Ganges at Hardinge Bridge.

Table 1. Distance From the In-Situ Gauge, Number of Observations, Mean and Median Time Between Two Consecutive Observations and River Drainage Area, From HYDRO1k, for Each Topex/Poseidon Virtual Station, From HydroWeb, on the Ganges and Brahmaputra Rivers[a]

T/P Virtual Station	River	Distance to the Gauge (km)	Number of Observations	Mean/Median Time Between Observations (days)	Drainage Area (km^2)
166_1	**Brahmaputra**	**250**	**58**	**16/10**	**408,500**
242_1	Brahmaputra	550	71	14/10	345,100
014_1	**Ganges**	**530**	**25**	**22/20**	**756,900**
116_2	Ganges	1560	49	12/10	38,400

[a] Forecasts using time series from virtual stations in bold are shown in Figure 3.

altimeters like T/P measure WE only in a vertical plane, i.e. along the satellite's ground track (shown in Figure 1); therefore, relatively few locations on each river are observed. The locations (referred as "virtual stations") of the T/P measurements on the Ganges and the Brahmaputra in India are shown in Figure 1. The overlapping time period of T/P with in-situ WE measurements is January 2001 to August 2002 at Hardinge Bridge and January 2000 to August 2002 at Bahadurabad. Table 1 shows the distance between each T/P virtual station (VS) used in this study and the in-situ gauge on the river, along with the number of observations available in the T/P time series, the mean time between two consecutive observations, and the river drainage area at the VS. These four VS were selected to span a range of distances from the in-situ gauges and to have a maximum number of observations. Temporal gaps in T/P time series arise from instrument errors, inaccurate atmospheric corrections, and errors due to the re-tracking of the data and interaction with the surrounding land.

[7] Correlations between the in-situ WE anomalies (h_{insitu}) measured at the gauge locations and the upstream T/P WE anomalies in India (h_{alti}) k days earlier were computed as follows:

$$Corr_h(k) = \frac{\text{cov}[h_{insitu}(t), h_{alti}(t+k)]}{\text{stdev}[h_{insitu}(t)] \cdot \text{stdev}[h_{alti}(t+k)]} \qquad (1)$$

where k is the lead time, t corresponds to the date for which $h_{alti}(t + k)$ is available (for the few days when $h_{insitu}(t)$ is missing, it was linearly interpolated from the closest measurement in time), cov is the covariance, stdev is the standard deviation and $Corr_h$ is the correlation coefficient between the two time series. The lead time k was allowed to vary from 0 to 40 days. For each of these lead times, a linear fit was computed to relate the water surface elevation at the in-situ gauge and the water level at the VS k days earlier.

4. Forecasting Brahmaputra River WE Anomalies

[8] On the Brahmaputra River, correlations between in-situ and upstream T/P WE anomalies are quite high (>0.9) for lead time up to 25 days over the entire time period; however, this is somewhat misleading as much of the correlation is due to the high and almost concurrent seasonality of WE. For this reason, we computed correlations, for various lead times, only over the monsoon period (June to September) when floods occur. For this period, all correlations for lead times below 10 days are highly significant ($p < 0.05$). As expected, the highest correlations are for VS n°166_1, which is the closest to Bahadurabad. In-situ and upstream T/P WE anomalies remain significantly correlated (above 0.9 for VS n°166_1 and 0.8 for VS n°242_1 during the monsoon period) for a lead time around 5 days. Correlations for lead times less than 10 days, correlations remain above 0.8 for VS n°166_1, but decrease substantially for lead times greater than 5 days.

[9] For each VS and for lead times less than 5 days, the RMSE between the T/P forecasts and the in-situ measurements for the monsoon period is lower than or near 0.40 m with a minimum around 3 days (which corresponds to the maximum correlation). At lead times greater than 5 days, RMSE increases significantly and tends to stabilize for lead times above 10 days at around or slightly above 0.50 m for VS n°166_1 and 0.70 m for VS n°242_1.

[10] Figures 3a and 3b show the in-situ (blue curve) and forecasted WE anomalies at the gauge location from T/P VS n°166_1 (red triangles) for a 5-day and a 10-day lead time, respectively. Linear fits between time-lagged T/P and in-situ time series used to compute these forecasts are included in the auxiliary material.[1] These results are very encouraging as the forecast is quite close to the observation. On the other hand, it should be noted that some local maxima (like the one in August 2000) are slightly underestimated in the forecasted time series. This might be due to satellite measurement errors, errors in the T/P-in situ WE regression and the fact that the methodology used does not explicitly account for inflows between the location of the virtual and real gauges.

5. Forecasting Ganges River WE Anomalies

[11] During the monsoon, the correlation for VS n°014_1 (located 530 km upstream of the gauge, Table 1) is maximum for lead time around 5 days and then decreases (it is below 0.9 for lead times above 10 days). As VS n°116_2 is farther upstream from the gauge (1560 km, Table 1), the correlation is lower (still above 0.9 for lead times between 8 and 13 days) and is highest for a 10-day lead time. For lead times greater than 14 days, the correlation decreases and is similar to that for VS n°014_1. The different timing in the occurrence of the maximum correlation between the two VS is due to the large distance (above 1000 km) between them. As for the Brahmaputra River, RMSE during the monsoon period between in-situ and forecast WE anomalies from T/P data has a minimum around the same lead time that maximizes the correlation. For VS n°014_1 the RMSE is minimum at around 0.40 m for a 5-day lead time and remains between 0.40 m and 0.60 m for lead times below 10 days, beyond which, RMSE increases significantly. For VS n°116_2, the RMSE is higher, and its minimum value

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2011GL047290.

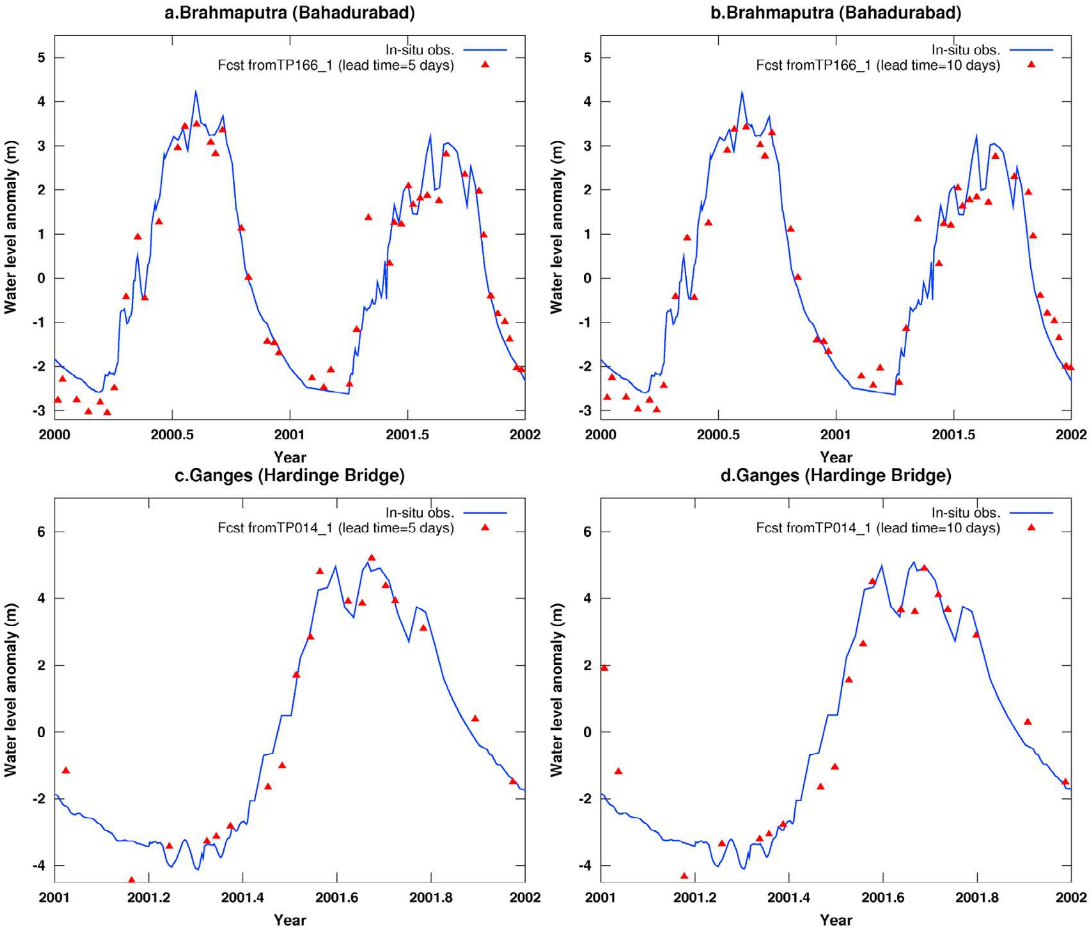

Figure 3. (a) Measured water elevation anomaly time series at Bahadurabad (blue) and the T/P virtual station n°166_1 forecasted water elevation anomalies at the gauge location for a 5-day lead time (red triangles). (b) Similar plot for 10-day lead time T/P virtual station n°166_1 forecasted water elevation anomalies. (c) Measured water elevation anomaly time series at Hardinge Bridge (blue) and the T/P virtual station n°014_1 forecasted water elevation anomalies at the gauge location for a 5-day lead time (red triangles). (d) Similar plot for 10-day lead time T/P virtual station n°014_1 forecasted water elevation anomalies. Plots of the linear fit between time-lagged T/P and in-situ time series used to compute these forecasts are included in the auxiliary materials.

is around 0.90 m for a 14-day lead time. This was expected due to the greater distance to the gauge.

[12] Figures 3c and 3d show the in-situ and forecasted WE anomalies at the gauge location from T/P VS n°014_1 for a 5-day and a 10-day lead time, respectively (see the auxiliary material Figure S1 for the linear fits between time-lagged T/P and in-situ time series used to compute these forecasts). As for the Brahmaputra River, the forecasts remain very close to the in-situ measurements.

6. Discussion

[13] Our results clearly show that T/P forecasts follow well the rising and receding trends in observed water surface elevation with modest bias. The persistence of high correlations between upstream and downstream WE anomalies for a range of practically useful lead times and the relatively low RMSE, compared to the differences in WE between low and high flows (around 6 m at Bahadurabad and 8 m at Hardinge Bridge, Figure 2), are encouraging. We believe that the relatively high forecast skill is due to the fact that even though the VS are far upstream (see Table 1), most of the runoff that reaches Bangladesh is generated far upstream, and the relationship between upstream and downstream water levels is affected primarily by channel processes. The Brahmaputra drainage area is around 506,000 km^2 at Bahadurabad and 345,000 km^2 at the 550 km upstream T/P VS n°242_1 (Table 1). On the Ganges, the drainage area is 944,000 km^2 at Hardinge Bridge and 756,900 km^2 at T/P VS n°014_1 530 km upstream (Table 1). Therefore, WE are less sensitive to local and short-term precipitation events and remain correlated over long distances. Combined with the higher impact of human activity, this could also explain higher RMSE on the Ganges: as its mean annual discharge is two times lower than that of the Brahmaputra, it is more affected by high frequency variations. For each VS, the ratio between the distance to the in-situ gage and the lead time which gives the maximum correlation is around 1 m.s^{-1}, the same order as the rivers' velocity [*Jian et al.*, 2009]. Because T/P data are not available after 2006, data from the new nadir altimeter Jason-2, launched in 2008 on the same orbit than T/P, would need to be used for real time forecast observations. The time latency of Jasonn-2 Interim Geophysical Data Record is around 2 days and the retracking

of this product can be done immediately, which means that near real time forecast is feasible.

[14] The current good quality of the forecast might even be improved using ancillary satellite data, such as precipitation or river width estimates. In addition, more accurate satellite-based WE measurements would help to better detect peaks in WE. This could be done by retracking altimeter measurements as suggested by *Lee et al.* [2009]. Moreover, the low time resolution in the T/P time series could be addressed by combining forecasts from different VS and using multiple satellite altimeters. Errors on these multi-source forecasts will vary in time depending on the altimeter and the VS used.

[15] The future Surface Water and Ocean Topography (SWOT) wide swath altimeter (a NASA/CNES mission, planned for 2019), will provide much improved forecast coverage (in both geographic extent, and the size of rivers for which coverage will be provided) and accuracy. SWOT will provide 2-D maps of WE along a 120 km wide swath with a 100 m horizontal resolution and a 10 cm minimum vertical accuracy (usually better) [*Rodríguez*, 2009], providing 2 to 4 observations on the study domain per repeat period (22 days), allowing a much more precise forecast of flooding or low flow events.

[16] Furthermore, the approach presented in this paper can augment alternative approaches, like that of *Webster et al.* [2010], that seek to improve forecast lead times by incorporating long lead probabilistic precipitation forecast information into streamflow forecasts. We also foresee a future pathway by which altimetric information from planned satellites like SWOT can be incorporated into hydrodynamic models.

7. Conclusions

[17] For both the Ganges and Brahmaputra rivers, it is possible to forecast WE anomalies during the monsoon season from upstream nadir altimeter measurements of WE anomalies with a lead time at least 5 days longer than is currently feasible, with RMSE around 0.40 m. 10-day forecasts during the monsoon season are also feasible, although with RMSE between 0.60 m and 0.80 m, depending on the river and the VS used. Our results demonstrate that satellite altimeter data have a huge potential to improve forecasting of WE anomalies at the Bangladesh borders and, therefore, could provide valuable information for flood forecast systems needed for downstream nations in large transboundary river basins more generally. Combining satellite altimetry measurements with weather, hydrological, and hydrodynamic forecast methods offers the potential to further extend forecast lead times. The use of multiple altimeter measurements, along with ancillary satellite observations can help to constrain forecast errors. We also emphasize the limitations of current generation satellite altimeters, which were primarily designed for oceanographic applications and are limited by their relatively infrequent repeat periods (10 days for Topex/Poseidon) and relatively inaccurate measurements of river heights. The proposed wide swath SWOT mission is expected to improve greatly both forecast accuracy and time sampling of rivers and may well represent a major breakthrough in the ability of downstream countries to manage riverine hazards.

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