CROSSING THE "VALLEY OF DEATH"

Lessons Learned from Implementing an Operational Satellite-Based Flood Forecasting System

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Making a research-grade satellite-based flood forecasting system operational in developing nations without long-term incubation involves challenging roadblocks.

If small is beautiful, then why do we still build large systems? A good example of this question is global climate models (GCMs). GCMs aim to model Earth's planetary-scale forcings from humans, atmosphere, hydrosphere, oceans, cryosphere, and landmasses, in a coupled manner, to predict the state of future world's climate. GCM climate projections have a big-picture institutional emphasis on policy and planning to prepare us against future possibilities, even if confidence is low (Brekke et al. 2008). However, when GCMs are applied to design a location-specific infrastructure (e.g., a dam) for adaptation against future climate change, the utility of the projections becomes inadequate (Salas et al. 2012).

We could probably argue the same about the utility of global-scale flood models that are considered as GCMs for water. Such platforms, which now exist in select institutions and agencies, can model synchronously the world's river basins (perform the rainfall–runoff transformation, soil storage dynamics, and evaporation calculations to solve the global water balance) and inform us on the streamflow dynamics at any river location. Using this GCM for water, we can pose and answer insightful questions for our world's terrestrial water balance in a changing climate, unlike a single basin model. We can use the answers in a similarly top-down manner as GCM climate projections on future possibilities. However, when such platforms are used to make decisions on adaptation based on the streamflow simulation/forecast at a specific river location, their utility, just like GCMs, is likely inadequate because they are not designed to handle complexity at such a local scale.

This argument about small versus large is very analogous to what the economists call the

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gross domestic product (GDP) per capita and the purchasing parity (PP) per capita (Abuaf and Jorion 1990). The former is a more global index that gives an idea on how the world's economies are faring relative to each other but cannot inform us on how much a dollar is really worth outside the United States, unless it is adjusted by the local purchasing power as in the PP per capita (World Bank 2011; Ong 1997).

TRANSBOUNDARY FLOOD FORECASTING AS A PERFECT CASE FOR "SMALL IS BEAUTIFUL." For those who believe that small is indeed beautiful (Schumacher 1973), then transboundary flood forecasting would be an appropriate case for building local solutions. This is the case for flood-prone downstream nations in international river basins (IRBs). A challenge faced by many such nations is the unavailability of in situ hydrologic data from upstream nations for issuing early flood warnings. As an example, anecdotally, we know that Namibia is currently struggling with cooperation from Angola and Zambia for the rivers draining from those nations. The challenges in the upstream countries are relatively minor, which fosters parochial interests and results in the lack of collaboration to solve holistic problems though systematic data collection and dissemination systems. The downstream countries bear the brunt of that lack of information, when rising water levels is the first and often the only sign of an impending flood.

It is estimated that about 33 downstream countries have more than 95% of their territory located within such basins and are therefore "blind" to what is happening to the water flowing in rivers from upstream nations (Hossain and Katiyar 2006). Many of these blind nations cannot prepare ahead for an impending flood because of the lack of timely data from conventional sources. Given the vantage point of space that is unique to satellites (unlike ground-based systems), hydrologic data from satellites, such as rainfall, water body extent, elevations, and streamflow, over the entire international river basin, can be a key solution to overcoming this transboundary hurdle. Although flooding in transboundary basins accounts for only 10% of all reported flood events, it is the cause for a disproportionate (33%) share of casualties (Bakker 2009). It is the lack of institutional capacity to handle transboundary flooding by riparian nations collectively, rather than a lack of resources, that has been the key reason for the disproportionate share of casualties.

Knowing the unique value of satellite data for transboundary flood forecasting, a wide range of research has been carried out over the last eight years on assessing the accuracy and utility of current and emerging satellite missions. One can find numerous research papers published in recent years on the topic of forecasting floods using satellite precipitation data, visible/microwave imagery of flood inundation data, radar altimetry data of river levels, and the proposed missions of Global Precipitation Measurement (precipitation) and Surface Water Ocean Topography (surface water).

Despite this obvious knowledge and the frequent assertions we often make championing the use of satellite data, what does it really take to ensure stakeholders in the developing world truly benefit from it? Do we know enough to "hit the ground running" and positively impact that stakeholder group desperately in need of guidance on current and future satellite water missions?

CROSSING THE VALLEY OF DEATH: A MAP FOR NEW TREKKERS. It is no surprise that a National Research Council (NRC) report popularized the term "valley of death" more than 10 years ago to describe the region where research on weather satellites had struggled to reach maturity for societal applications (National Research Council 2001). The term "valley of death" still survives among the satellite application community.

In this article, we would like to share with readers what we have learned trying to cross this valley of death for a flood-prone country and stakeholder nation: Bangladesh. This country is home to 160 million people, whose lives could be improved significantly with early information on the transboundary flooding from upstream nations (Fig. 1). The Bangladesh government currently does not receive any real-time upstream river flow and rainfall information from India (the country with the largest share of upstream drainage area) during the critical monsoon. Bangladeshi authorities, therefore, measure river flow at staging points where the Ganges and Brahmaputra enter Bangladesh and at other points downstream. On the basis of these data, it is possible to forecast flood levels in the interior and the south of Bangladesh with only 2–3 days of lead time (Flood Forecasting and Warning Center, Bangladesh: www.ffwc.gov.bd). The need to extend forecasting lead time beyond three days has a strong motivation from the standpoint of preventing loss of life and economic damage. Studies have shown that a 14–21-day forecast is ideal for Bangladesh, given that paddy-intensive agriculture requires a longer time for a decision on delayed sowing or an early harvest.

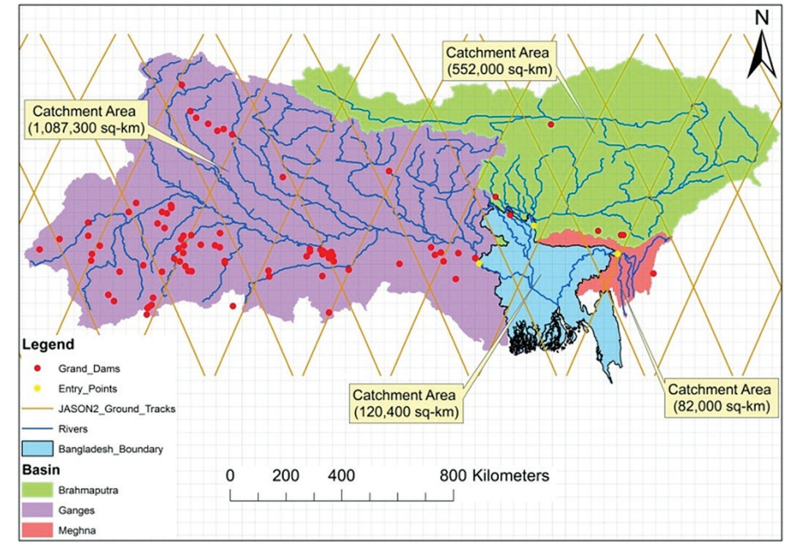


Fig. 1. Map of Ganges–Brahmaputra basin showing Bangladesh's location as the smallest, most downstream, and most flood-prone country in the basin. The locations in red are dams; cross tracks in brown represent *Jason-2* satellite paths.

We share our journey of crossing this valley of death as a set of sequential steps so that they serve as a roadmap for the research community wanting to implement similar applications for developing nations. We purposefully chose satellite radar altimetry (Alsdorf et al. 2007), which can measure the river-level dynamics (height), as a tool for transboundary flood forecasting as opposed to satellite remote sensing of precipitation or flood inundation estimation (width). A key reason for this was the long heritage of satellite radar altimetry (*Seasat* on Skylab in 1978) followed by a series of highly successful missions such as Ocean Topography Experiment (TOPEX)/Poseidon, the Jason series, and the *Environmental Satellite* (*Envisat*) that have proved the utility of space altimetry for monitoring of inland water bodies (Birkett et al. 2002).

Step 1: Do the research on theoretical feasibility on a popular and interdisciplinary research publication forum. Our altimetry-based forecasting application was spurred by the work of Biancamaria et al. (2011) in *Geophysical Research Letters* (which is a popular forum for quick new ideas published by the American Geophysical Union). Biancamaria et al. (2011) had shown the potential of satellite altimetry to forecast incoming transboundary flow for Bangladesh by detecting river levels at locations in India (Fig. 1). Using TOPEX/Poseidon satellite altimetry measurements of water levels in India, this work demonstrated in theory the feasibility of extending the forecasting lead time from 3 days to 8–10 days with no additional overhead costs (assuming the data were freely available). The TOPEX/Poseidon-based forecasting scheme reported an RMSE at the border points (where the river enters Bangladesh) of about 0.70 m and for lead times up to 10 days without having to rely on any upstream in situ (gauge) river-level data from India. This was a significant improvement considering that the traditional system that is currently in place is only able to forecast skillfully for up to three days of lead time.

Step 2: Disseminate widely the theoretical feasibility to potential stakeholder agencies through a two-way public education process and generate interest. Armed with this knowledge of theoretical feasibility, the past few years were spent on making the potential of satellite-based altimetry for river flow monitoring known to the Bangladesh stakeholder agencies. Our approach involved a two-way education process. We conducted frequent hands-on training workshops for the Institute of Water Modelling (IWM; Bangladesh) and the International Centre for Integrated Mountain Development (ICIMOD; Nepal) beginning in 2010. In these workshops, water resources staff members (managers, engineers, and scientists), who are conventionally trained in planning and disaster management, were taught to handle emerging hydrologic remote sensing technology. Each staff member was immersed in an intensive continuing education and hands-on programs to help them grasp inductively the fundamentals of remote sensing application for water resources monitoring. Once a general focus on hydrologic remote sensing was provided, we concentrated our efforts on the hands-on dissemination of satellite radar altimetry for flood forecasting.

Step 3: Respond to skepticism in an engaging way; do not lose stakeholder interest by talking more than listening. In our first such education effort in 2010, we opened the floor for honest and candid feedback from the end users, stakeholders, and engineering staff: many of whom could be responsible for modifying the existing decision-making tools for handling satellite data in the future. In our first iteration, we expected to receive a wholehearted endorsement of the great value satellites, particularly radar altimetry, would have for flood forecasting or other applications. Instead, we received very humbling feedback that made us realize that there is more work to be done on public education, engagement, and two-way learning. Some examples of the feedback we received are summarized below:

- "The remotely sensed discharge using satellite data has very high errors even during dry season. Why bother to use them?"
- "The method of satellite-based discharge estimation still requires in situ data, which means you still need to go to the field. So it's not as useful and cannot replace in situ measurements."
- "We have pressure transducers now that can measure water level every minute and relay the information real time. Why bother to use radar altimetry that will only cross a river section a few times a week or less?"
- "The scatter in elevation data across a river cross section is too much. What should be the 'standard' elevation of the water level at a given river cross section?"
- "Effective use of Landsat data to estimate the exact extent of a river will depend on the unlikely chance of the region being cloud free during the monsoon season."

Most of the skepticism expressed in the feedback from the stakeholder groups could have been robustly rebutted with more recent research that has been done to overcome many of the practical hurdles and skepticism. However, the unexpectedness of such humbling feedback made us realize that the "preaching to the choir" (i.e., to our community through research publications) needed to be complemented with more listening on the ground, where it matters more. This ground is the "trench" environment, where decision makers in the developing world have to work with the most limiting constraints and yet be able to produce tools that actually work. The incremental value of the latest scientific research is tremendous; therefore, there is a need to listen to the needs of such decision makers who stand to benefit more than our scientific community. In essence, this proverbial saying sums it up: "If you want someone to learn how to fish, don't just give them the fishing rod, teach them how to fish."

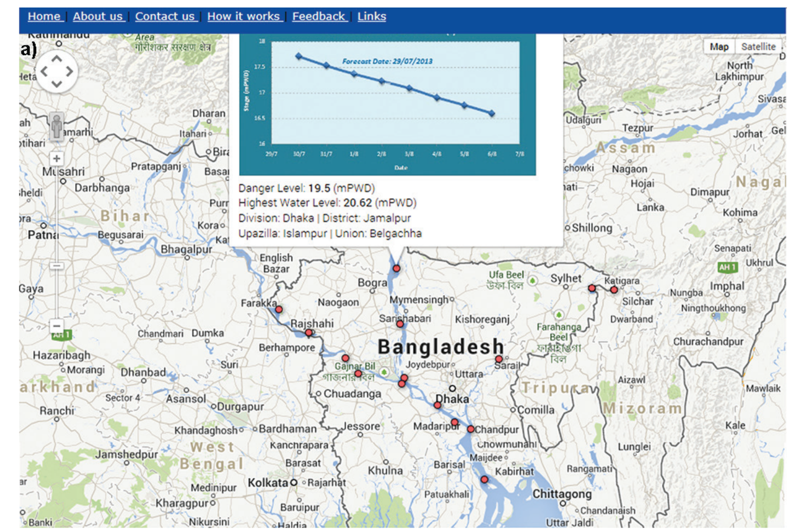
Step 4: Get commitment from stakeholder agencies to prototype and test the satellite forecasting system; start with the simplest of ideas when you teach them how to fish. Humbled by the feedback from stakeholders, we continued our two-way education/hands-on training workshops at IWM/ICIMOD for two more years to show that we were truly committed to making a satellite application that would benefit the stakeholder. This step also helped us to formulate the specifics of the satellite system that would work best in the operating conditions of the agency. For example, we quickly realized that we would need to work with the existing hydrologic–hydrodynamic models of the agencies and find ways to ingest the satellite altimetry data accordingly. Suggesting a new model, unless it was freely available, was not an option because of the increase in overhead costs. We also learned that keeping the operational overhead costs to a minimum was most important because of the business model followed by such agencies (IWM and ICIMOD). If a proposed new scheme is likely to add to further strain on time, effort, and computational resources of the agency, that scheme is less likely to be institutionally embraced without incubation. Thus, all new modeling schemes that we developed were based on free software tools that were highly popular, easily available, and user friendly [graphical user interface (GUI) driven] and with a demonstrated track record of operational use around the world. Once such system is based on the Hydrologic Engineering Center (HEC) suite of models built by the U.S. Army Corps of Engineers (USACE), which we have used in this case.

Step 5: Begin hands-on training of stakeholder staff for implementing the prototype system; patiently hand hold the staff and teach them from the ground up the basics of the system. Once the reciprocal commitment was obtained from the agency (IWM) to let us build the prototype system and train relevant staff on using it independently, we embarked on making *Jason-2* altimetry operational for extended flood forecasting in Bangladesh (up to eight days of lead time). A point to note is that our research publication had shown theoretical feasibility with the TOPEX/Poseidon altimeter, which stopped operating a few years ago. Thus, operational feasibility had to be shown using an altimetry mission that was actually operating at the time (i.e., *Jason-2*).

We engaged the stakeholders and staff from the Flood Forecasting Division of IWM over a period of four months to ensure the learning of theoretical feasibility happened. In the process, we listened carefully to the staff feedback and sought acceptable ways to overcome the constraints that they face day to day. What helped us in this regard was that the sustained capacity building training was supported by the U.S. Department of State Fulbright Program to the first author. We encourage interested trekkers of the valley of death to seek such similar opportunities because a sustained capacity building for ensuring learning can be the most critical step to building a successful satellite-based system. The goal of this capacity building was to achieve a sense of independence for staff of stakeholder agencies in managing and improving the *Jason-2* forecasting system with local resources and without overhead costs. Another goal was to help build the necessary intellectual base locally to handle emerging satellite water data and serve as a trainer institution for other agencies in the region.

Step 6: Allocate supporting resources to address unexpected hurdles during launch of the prototype system. Unexpectedly, various practical hurdles kept emerging during the last phases of the prototype launch that could not have been foreseen early enough. We soon realized the importance of keeping an open mind to persevere through such unexpected technical challenges in the developing world. We also realized the importance of having volunteer researchers who would be willing to tweak their research tools to the specified format for end users at short notice. One representative example of this was the realization that the streaming *Jason-2* data that are currently available with the shortest latency had the data structure format and content that only research experts on altimetry could handle (i.e., radar backscatter). Another example was that, while satellites typically use the ellipsoid as a datum reference, local agencies use the geoid (mean sea level) as the local datum and the relationship between the two is often not known. A solution to both of these hurdles was crafted by the volunteer researchers who developed a user-friendly GUI to process the radar backscatter data to river height information according to the local geoid datum.

Step 7: When launching the prototype, ensure complete ownership and independent operation; offer complimentary support as technical backstop. Once the *Jason-2* flood forecasting prototype was built with the necessary tailor-made training manuals, user documentation, and user-friendly computer models, we began the process of implementing the system. On 1 June 2013, *Jason-2* data began to be used routinely for generating 8-day forecasts of flooding inside Bangladesh. The data were routinely extracted, converted, and then processed for generating forecasts of river levels at entry points (i.e., border crossings) of Bangladesh rivers. These forecasts were then used to initialize the HEC hydrodynamic model that was tailor made for IWM staff. The entire process was independently managed and executed end to end by IWM staff. Interested readers may witness the culmination of this application at



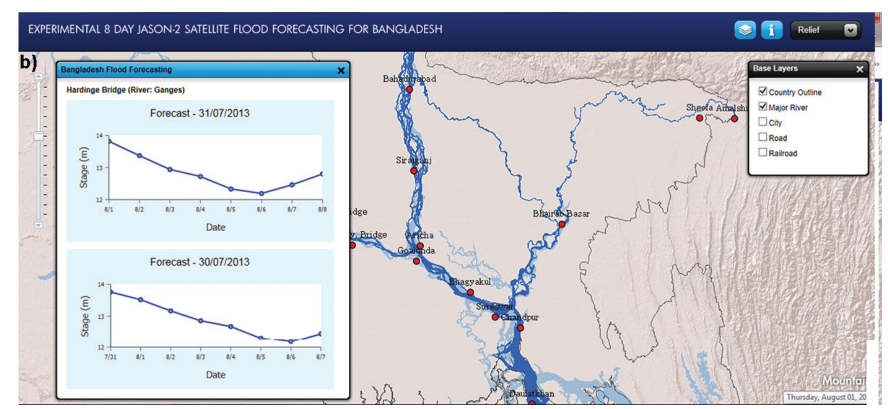


Fig. 2. (a) The web portal displaying the dynamic flood forecasting backup (mirror) services on a web–GIS interface at the ICIMOD website (from http://apps.geoportal.icimod.org/BDFloodforecasting). (b) The web portal displaying the dynamic flood forecasts on a web–GIS interface at the IWM website (from http://apps.iwmbd.com/satfor).

two dynamic web portals: i) the IWM web portal (at http://apps.iwmbd.com/satfor; shown in Fig. 2a and ii) the ICIMOD backup web portal (at http://apps.geoportal.icimod.org/BDFloodForecasting; shown in Fig. 2b).

A point to make here is that the initial launch was not entirely smooth during the month of June 2013. For example, during the initial days, the *Jason-2* data extraction for locations on transboundary rivers had to be retaught to one of the staff members who had not had much exposure to hands-on training earlier (they had attended lectures but not the laboratory assignments because of extensive travel commitments). Often times, a rapidly evolving flood event due to local rain events or opening of an upstream transboundary barrage between *Jason-2* overpasses would result in a rising flood height that the system could not foresee. Under such cases, the observational gauging network at the entry points of Bangladesh needed careful monitoring for adjustment of the forecasting procedure. Such adjustments needed to be devised and taught to the staff on a quick turnaround by us. This technical backstopping provides confidence to the staff members that they can lean on a broader group for the continued success of this endeavor. While all prototype tests require close support before a full-scale launch, our experience revealed that the relearning and teaching may need to be done as needed in the spirit outlined in step 3 (i.e., respond in an engaging way).

LESSONS LEARNED FOR THE FUTURE. The 2013 monsoon has served as our "test period" to provide verifiable evidence that the *Jason-2* forecasting system is able to generate skillful forecasts of flood levels up to eight days of lead time inside Bangladesh. The physical complexities of the *Jason-2* forecasting system are documented in a publication by Hossain et al. (2014) that interested readers may read in order to reproduce the system in another country. There is, however, another obstacle to overcome to experience complete buy-in by the government of Bangladesh and other stakeholder agencies in the region. This is an obstacle that all trekkers of the valley of death must not ignore if longevity of the system is a key goal. If the Bangladesh government can take responsibility for the system within the jurisdiction of the Flood Forecasting and Warning Center (www.ffwc.gov.bd) in a sustainable manner [i.e., without the need for donor agency support from the National Aeronautics and Space Administration (NASA), the U.S. Agency for International Development (USAID), or expert volunteers], then the altimetry system should survive as long as the satellite(s) continues to sample. We expect this step to be feasible, as IWM has been the lead designer and consultant for all flood forecasting-related services to FFWC and the Bangladesh government. We believe that we have gained sufficient wisdom to achieve longevity from the 2014 monsoon onward and use the experience as an example to encourage the other 32 downstream nations to step forward. If operational feasibility could be demonstrated, true ownership could be provided, and real technology transfer could be materialized, then why should the other stakeholder nations not want to invest in such a system of their own one day?

On behalf of numerous selfless colleagues, staff, and students spanning many universities, years, and agencies (particularly IWM, ICIMOD, NASA, and USAID), we express our pride in the operational launch of the 8-day transboundary flood forecasting system using satellite altimetry that is now being independently operated by a stakeholder agency. However, our article would not be complete for the readers if we did not share the key take-home messages for future travelers planning to cross the valley of death. We list these lessons below:

- Always aim for full ownership of a new idea, concept, or system for the stakeholders.
- Always seek two-way feedback and listen more than talk when promoting a satellite-based system.
- Keep the proposed system involving satellites as simple as possible in the beginning so that it appears independently manageable to stakeholder agencies.
- Train stakeholder agency staff members from the ground up through hands-on tasks in a thorough and patient way. True capacity is built from the ground up.
- Customize the satellite system solutions within the constraints of preexisting systems used by the stakeholder agency.
- Leverage free tools, models, and software that have widespread popularity.
- Utilize volunteer experts for rapid retailoring of research tools during the phase of prototype launching.

In closing, let us remember what Benjamin Franklin, Confucius, and many Chinese fortune cookies have repeated for centuries as the most important take-home message of all: "Tell me and I forget. Teach me and I remember. Involve me and I learn."

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Abstract

More than a decade ago, a National Research Council (NRC) report popularized the term "valley of death" to describe the region where research on weather satellites had struggled to reach maturity for societal applications. A similar analogy can be drawn for other satellite missions, since their vantage point in space can be highly useful for some of the world's otherwise fundamentally intractable operational problems. One such intractable problem is flood forecasting for downstream nations where the flooding is transboundary. Bangladesh fits in this category by virtue of its small size and location at the sink of the mighty Ganges and Brahmaputra. There has been the claim made that satellites can be a solution for Bangladesh in achieving forecasts with lead times beyond three days. This claim has been backed up by scientific research done by numerous researchers, who have shown proof of concept of using satellite data for extending flood forecasting range. This article aims to take the reader on a journey that had its humble beginnings with this promising research and ended with making the dream of an operational system that is independently owned by the stakeholders a reality. The idea behind this article is to shed light on some of the commonly experienced but less familiar (in the academic community) roadblocks to making an operational system based on recent research survive in developing nations without long-term incubation.