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Improving Flood Forecasting in International River Basins

PAGES 49, 54

In flood-prone international river basins (IRBs), many riparian nations that are located close to a basin's outlet face a major problem in effectively forecasting flooding because they are unable to assimilate in situ rainfall data in real time across geopolitical boundaries. NASA's proposed Global Precipitation Measurement (GPM) mission, which is expected to begin in 2010, will comprise high-resolution passive microwave (PM) sensors (at resolution ~3–6 hours, 10 × 10 square kilometers) that may provide new opportunities to improve flood forecasting in these river basins.

By F. Hossain and N. Katiyar

Research is now needed to realize the potential of GPM. With adequate research in the coming years, it may be possible to identify the specific IRBs that would benefit cost-effectively from a preprogrammed satellite-based forecasting system in anticipation of GPM. Acceleration of such a research initiative is worthwhile because it could reduce the risk of the cancellation of GPM [see *Zielinski*, 2005].

Forecasting Floods

Because there is a time lag between rainfall and the transformed streamflow, and because this lag increases according to the size of the basin, floods can be forecast at a point downstream of a large basin if the river flow at some point upstream is known in conjunction with a hydrologic model. A comparison of the global distribution of large-scale flood events with a map of IRBs (see Figure 1, bottom right) reveals a commonality that is currently overlooked in mainstream flood forecasting research.

This commonality is that for flood-prone nations situated within IRBs, the challenge of issuing effective flood forecasts as a decision support tool can be particularly difficult to overcome under two conditions: (1) when surface measurements of rainfall and other land surface parameters are largely absent due to inadequate in situ infrastructure or complex terrain (Figure 1, compare top panels); and (2) when there is no political agreement between riparian nations downstream and upstream to share hydrologic information (rainfall in particular) in real time for proactive flood management (Figure 1, compare bottom panels).

The first condition is commonly observed in many tropical basins of Asia, Africa, and South America that lack the financial resources for adequate real-time monitoring

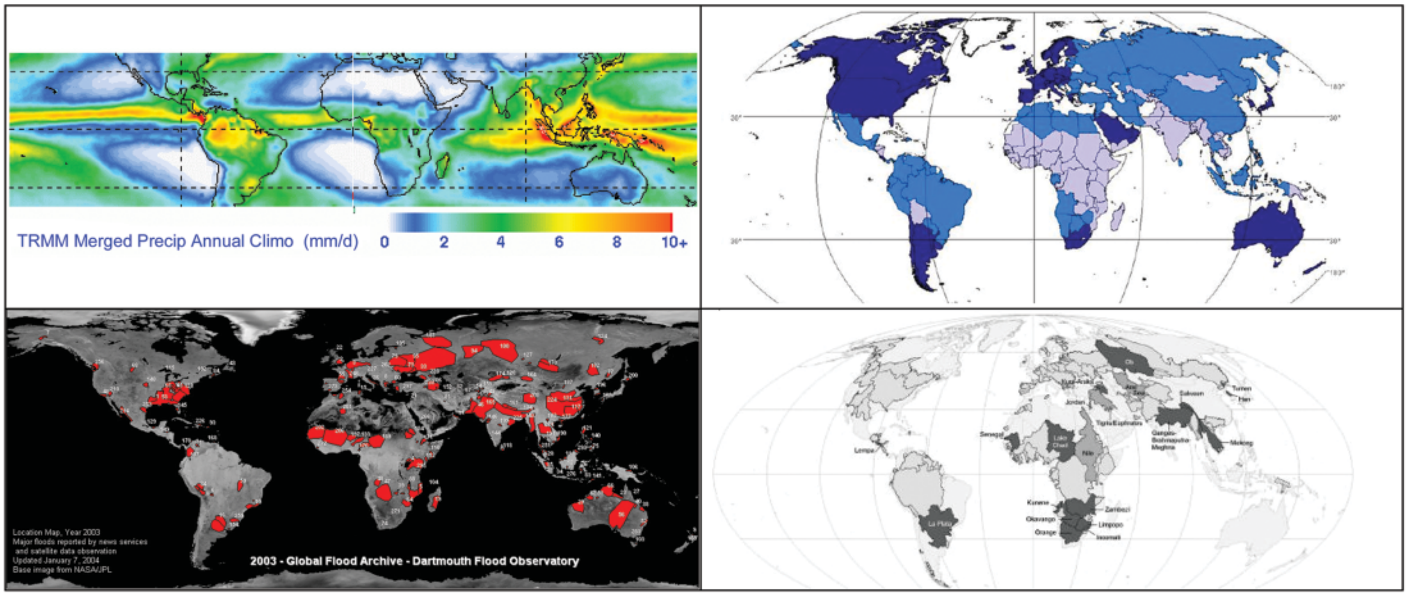

Fig. 1. Spatial dependency (qualitative) between the occurrence of large-scale floods and the geographical location of International River Basins (IRBs) (compare bottom panels) shown through two connecting themes: rainfall and lack of economic resources (top panels). (top left) A six-year climatologic rainfall map produced with data from the Tropical Rainfall Measuring Mission (TRMM; http://trmm.gsfc.nasa.gov). (bottom left) Global distribution of floods in 2003 (Source: Brakenridge, G.R., Anderson, E., Caquard, S., 2003, Flood Inundation Map DFO 2003-282, Dartmouth Flood Observatory, Hanover, N.H., digital media, http://www.dartmouth.edu/~floods/2003282.html). (top right) World Bank estimate of GDP per capita of nations in 1999 (lighter shaded countries are poorer). (bottom right): Map of IRBs with the darker shaded IRBs projected to be in a state of water stress due to lack of cooperative agreements for sharing water resources (© Transboundary Freshwater Dispute Database, Oregon State University, 2002).

of hydrological conditions (see Figure 1, top right). The second condition, barring a few exceptions (such as the Mekong River Commission in Southeast Asia), is common in many flood-prone developing nations and therefore limits flood forecasting lead times (see Figure 1, bottom right).

For example, Bangladesh, situated at the most downstream region of the Ganges-Brahmaputra-Meghna (GBM) basin (Figure 2), does not receive any upstream river flow and rainfall information in real time from India (due to lack of an adequate water treaty) during the critical monsoon season spanning June to September. Bangladeshi authorities, therefore, measure river flow at staging points where the three major rivers enter Bangladesh (Ganges, Brahmaputra, and Meghna; Figure 2, circles) 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 a lead time of only 2–3 days (Flood Forecasting and Warning Center of Bangladesh; http://www.ffwc.gov.bd [*Paudyal,* 2002]). This lead time could be increased because the mean basin response time to rainfall of the GBM basin ranges from 7–14 days.

At least 33 countries have more than 95% of their territory land-locked within IRBs, according to surveys available at the Transboundary Freshwater Dispute Database at Oregon State University (http://www.transboundarywaters.orst.edu). Many of these nations are thus forced to cope with floods that are mostly generated outside their borders. This fact makes these land-locked countries, such as Bangladesh, heavily dependent on rainfall information not only from within their own borders but also from upstream nations.

Table 1 provides a nonexhaustive list of such flood-prone nations in IRBs that would require rainfall information in real time from upstream nations to achieve the basin response-equivalent flood forecasting range. There could be at least 50 such nations that could benefit from real-time rainfall information from neighboring upstream countries, according to conservative estimates by the author and colleagues.

Satellites for Improving Flood Forecasting

Rainfall is the single most important determinant of the state of surface runoff leading to large-scale floods. Because of the time lag between rainfall and the transformed runoff, it is logical to expect that satellite remote sensing of rainfall along with stream gauges and other satellite-derived surface parameters—such as elevation, vegetation, soils, and drainage networks (for modeling the rainfall-runoff transformation)—can potentially increase the forecasting lead time for many nations constrained within IRBs.

A longer forecasting range would have the beneficial impact of enhancing the utility of a decision support tool that ingests these warnings. For example, 7- to 10-day forecasts are currently considered much more useful than daily forecasts in monsoon-affected Asian countries. These forecasts allow for better agricultural decision support by informing farmers of the potential benefits of delayed sowing or early reaping of crops. A 21-day forecast is considered most ideal [*Asian Disaster Preparedness Center,* 2002].

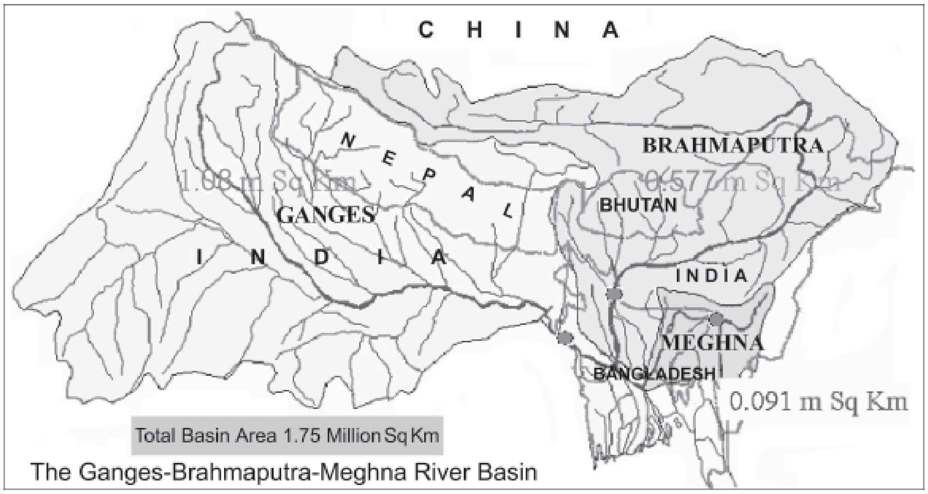

Fig. 2. The Ganges-Brahmaputra-Meghna (GBM) basin. Bangladesh represents the lowermost riparian nation, comprising 7% of the basin area. Red circles indicate the current boundary conditions for river flow forecasting by the flood forecasting agency.

However, the accuracy in predicting important flood parameters such as peak runoff and time-to-peak is dependent on the ability to monitor the spatiotemporal variability of rainfall. Although current satellite observations provide the means for estimating rainfall over large basins on both sides of the political border, these estimates are not perfect. The corresponding hydrologic predictive uncertainty can potentially outweigh the hydrologically intuitive benefits [*Hossain,* 2005].

Only a handful of studies in the current literature address streamflow prediction uncertainty due to satellite rainfall error [*Nijssen and Lettenmaier,* 2004; *Hossain and Anagnostou,* 2004]. Proper characterization of the nonlinear satellite rainfall error propagation in hydrologic models for flood forecasting is therefore a critical priority that should be resolved in the coming years in anticipation of GPM. Also, for the greater benefit of IRB inhabitants, research effort should place more emphasis on the utilization of existing streamflow measuring systems for validation and calibration of prototype spaceborne forecasting system, rather than on replacing the stream gauge networks.

Anticipating the GPM

Climate-based approaches using forecast products from the European Centre for Medium-Range Weather Forecasts recently have been initiated to address the limitations of flood forecast over monsoon-affected nations [*Webster and Hoyos,* 2004]. Although based on physically sound principles of the early detection of weather patterns and intraseasonal variability, these approaches do not leverage the hydrologic time lag that exists between rainfall and runoff. Thus, the approaches can suffer from inaccurate spatiotemporal modeling of flood inundated regions (Abu Saleh Khan, Flood Management Division, Institute of Water Modeling, Bangladesh, personal communication, 2005).

An assessment of the availability of satellite rainfall data across the geopolitical boundaries within an IRB has an additional complexity that existing hydrologic modeling efforts have usually not addressed. The study of the impact of the availability or unavailability of rainfall data via satellites over upstream nations on improving the forecasting range requires that political boundaries be physically modeled within the hydrologic modeling framework.

Given the large number of flood-prone IRBs that cover the vast ungauged regions of the world, a generic and parsimonious modeling blueprint for IRBs is timely in anticipation of GPM. Such a blueprint can be used for gauging the true potential of GPM for improving flood forecasting for IRBs.

This blueprint should physically model two competing hypotheses: (1) the vantage of satellites to view the Earth and the time lag between rainfall and downstream runoff make pseudo-real-time satellite rainfall ideal to address transboundary limitations of flood forecasting in IRBs; and (2) satellite rainfall estimates are not perfect, and hence the uncertainty associated with these estimates has a nonlinear and deteriorating impact on the accuracy of flood forecasts. Any research initiative that proposes to provide quantitative answers for a given IRB on the utility of GPM should seek to provide a clear understanding of the implications of using satellite rainfall on the forecast accuracy of river flows based on the above two hypotheses.

The hydrologic research community now needs to align its research direction toward developing such simple and robust blueprints tailored entirely for facilitating flood forecasting research for nations locked within flood-prone IRBs. One such effort is already under way by the authors of this article using the concepts of open-book watershed. (An open-book is a physicsbased mathematical analog to river basins.) There are plans by the author for validation of such an effort on the Ganges-Brahmaputra-Meghna (GBM) basin using the flood forecasting system of the Bangladeshi authorities.

Such blueprints could provide frugal means for conducting an approximate, yet global, assessment of the numerous IRBs without resorting to conventional distributed hydrologic models that are data intensive and usually require longer setup times. The blueprints should be amenable for rapid implementation over IRBs and as such, should be able to highlight the flood-prone nations that seem most likely to benefit cost-effectively from anticipated GPM rainfall data. This approach could subsequently motivate flood-prone nations to invest in a range of more detailed studies to design and test an enhanced GPM-based prototype forecasting system by 2010.

Table 1. A nonexhaustive list of lowermost riparian nations situated in flood-prone international river basins[a]

Name of Downstream Country	*International River Basin*	*Percent of Total Basin Area Occupied by the Country*
Cameroon	Akpa/Benito/Ntem	41.8
Senegal	Senegal	8.08
Ivory Coast	Cavally	54.11
Benin	Oueme	82.9
Botswana	Okovango	50.6
Nigeria	Niger	26.6
Bangladesh	Ganges-Brahmaputra-Meghna	7
Brunei	Bangau	46.03
Laos	Ca/Song Koi	35.1
Myanmar	Irrawaddy	91.2
Cambodia	Mekong	20.1

[a] These nations would typically depend on rainfall information from the upstream regions (nations) of the IRB in order to realize the hydrologically possible flood forecasting range of the basin response time. Source: Aaron Wolf, Transboundary Freshwater Disputes Database, at Oregon State University, Corvalis (http://www.transboundarywaters.orst.edu).

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True Color Earth Data Set Includes Seasonal Dynamics

PAGES 49, 55

Space exploration has changed our visual perception of planet Earth. In the 1950s, satellites revolutionized weather forecasting. Astronaut photography in the early 1970s showed us the Earth in color, the so-called 'Blue Marble' (Figure 1, left). Since 1972, satellite sensors have been acquiring atmosphere, land, ice, and ocean data with increasing spectral and spatial resolution. Satellite remote sensing systems such as the NASA Earth Observing System (EOS) help us to understand and monitor Earth's physical, chemical, and biological processes [*Running et al.,* 1999].

The false-color Earth image shown in the center of Figure 1, named Blue Marble, was created in 2000 with data from the Advanced Very High Resolution Radiometer (AVHRR), the Geostationary Operational Environmental Satellite (GOES 8), and the Sea-viewing Wide Field-of-view Sensor (SeaWiFS). New sensors such as the Moderate-Resolution Imaging Spectroradiometer (MODIS), aboard NASA Terra and Aqua satellites, allow the derivation of a wide range of geophysical parameters from measured radiances of a single sensor.

While false-color visualizations are artificially colorized from single- or multispectral data, true-color images are based on data which closely reflect the full spectral range of our visual perception: things in true-color images appear the way we would see them. In 2002, the authors of this article created the true-color Earth image on the right side of Figure 1. This image consists of separate layers created from the underlying MODIS land, ocean, sea ice, and atmosphere science products. Both (2000 and 2002) Blue Marble images have been widely used in museums, print media, and television documentaries, by mapping agencies, and in NASA's public communications about its missions and research initiatives.

The wide public use of the Blue Marble imagery motivated the authors to continue the project. The Blue Marble: Next Generation (BMNG) is a true-color and normalized difference vegetation index (NDVI) data set that displays land surface state at 500-meter spatial resolution and monthly temporal resolution. The BMNG was created using Terra MODIS science data collected in 2004; cloud disturbances were removed with a discrete Fourier technique.

Whereas cloud-free Earth imagery is commercially available, the BMNG aims to provide freely available imagery as a product complementary to the standard MODIS science datasets. Although the spatial resolution of the BMNG true color data is comparable to other data sets, seasonal variations have not been shown before in seamless true-color composites. Visualizations of snowfall, droughts, wet seasons, spring greening, and so forth, can be applied in formal and informal education. Visual perception of Earth system dynamics can foster interest to further explore the underlying science. Furthermore, the BMNG can help to increase public understanding (and therefore acceptance) of satellite missions and awareness of causes and effects of changes in Earth's climate system.

How to Create Cloud-Free Global Imagery

Seamless cloud-free spatial and temporal compositing of the Earth's surface is not a trivial task. It is dependent on sophisticated atmospheric corrections (e.g., water vapor, ozone, and aerosol absorption and scattering [*Vermote et al.,* 1997]) and cloud screening. Even then, cloudy pixels and remote sensing artifacts such as heavy dust and smoke, calibration errors, and illumination conditions [*Los et al.,* 2000] can disturb satellite data. Temporal compositing can be used to remove such irregularities.

For the BMNG data set, a temporal adjustment based on second- and third-order discrete Fourier series was used. This method is

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