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ORIGINAL PAPER

The emerging role of satellite rainfall data in improving the hydro-political situation of flood monitoring in the under-developed regions of the world

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Abstract The systematic decline of in situ networks for hydrologic measurements has been recognized as a crucial limitation to advancing hydrologic monitoring in medium to large basins, especially those that are already sparsely instrumented. As a collective response, sections of the hydrologic community have recently forged partnerships for the development of space-borne missions for cost-effective, yet global, hydrologic measurements by building upon the technological advancements since the last two decades. In this article, we review the state-of-the-art on flood monitoring in medium and large ungauged basins where satellite remote sensing can facilitate development of a cost-effective mechanism. We present our review in the context of the current hydro-political situation of flood monitoring in flood-prone developing nations situated in international river basins (IRBs). Given the large number of such basins and the difficulty in acquisition of multi-faceted geophysical data, we argue that the conventional data-intensive implementation of physically based hydrologic models that are complex and distributed is time-consuming for global assessment of the utility of proposed global satellite hydrologic missions. A more parsimonious approach is justified at the tolerable expense of accuracy before such missions begin operation. Such a parsimonious approach can subsequently motivate the identified international basins to invest greater effort in conventional

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and detailed hydrologic studies to design a prototype flood forecasting system in an effort to overcome the hydro-political hurdles to flood monitoring. Through a modeling exercise involving an open-book watershed concept, we demonstrate the value of a parsimonious approach in understanding the utility of NASA-derived satellite rainfall products. It is critical now that real-world operational flood forecasting agencies in the under-developed world come forward to collaborate with the research community in order to leverage satellite rainfall data for greater societal benefit for inhabitants in IRBs.

Keywords Flood monitoring · Satellite remote sensing · Precipitation · International river basins · Forecasting · Hydrologic modeling · Decision support tools

1 Introduction

Operational flood monitoring systems in medium and large river basins require the input of data that can describe: (1) the evolving hydrologic state of the basin; and (2) landform (comprising vegetation, topography, and channel network) that dictate the response of the basin to hydrologic forcing. Of these two types, data on the hydrologic state requires higher spatio-temporal resolution measurement because of the dynamic nature of the hydrologic cycle leading to the generation of surface runoff during a flood event. Data characterizing the landform may be considered relatively static at the timescales of a typical flooding phenomenon and hence, less frequent measurements usually suffice. Among the components that describe the hydrologic state, the most important ones for a flood monitoring system are—(i) precipitation; (ii) soil moisture, and (iii) river discharge.

However, the systematic decline of in situ networks for hydrologic measurements of these dynamic components has lately been recognized as an impediment to advancing hydrologic monitoring in medium and large river basins, especially those that are ungauged or already sparsely instrumented (Stokstad 1999; Shiklomanov et al. 2002). As a collective response, sections of the hydrologic community have recently forged partnerships for the development of space-borne missions for cost-effective, yet global, hydrologic measurements. Examples are the Hydrospheric State (HYDROS) mission for global mapping of soil moisture conditions (Entekhabi et al. 2004), the Water Elevation Recovery (WatER) mission for surface flow measurement (Alsdorf et al. 2003, 2005), and the global precipitation measurement (GPM) mission for global monitoring of rainfall (Smith et al. 2006). There is no doubt that the hydrologic community as a whole will gradually become dependent on these space-borne missions for most of its data needs for hydrologic research and operational monitoring.

In particular, we should note that consideration of the law of conservation of mass at the land–atmosphere interface of the hydrologic cycle makes rainfall the primary determinant of floods. Rainfall's intimate interaction with the landform magnified by highly wet antecedent conditions leads to large-scale flooding in river basins. Furthermore, due to the climatologic abundance of rainfall, floods are more catastrophic over tropical river basins that lack adequate surface stations necessary for real-time rainfall monitoring (Hossain 2006). Hence, for the case of flood monitoring, our success in leveraging the satellite missions (such as GPM) will depend largely on the feedback provided by hydrologists on the assessment of satellite rainfall data to the data producing community (Hossain and Lettenmaier 2006).

In this article, we therefore find it timely to review the state-of-the-art on flood monitoring in medium and large ungauged river basins where satellite rainfall remote sensing can provide a cost-effective alternative to expensive and declining in situ rainfall measurement networks. Our review is presented in the context of the current hydro-political situation of flood monitoring in developing nations situated in international river basins (IRBs). We believe that the hydro-political aspect of flood monitoring is often overlooked by hydrologists engaged in developing satellite-based prediction schemes for IRBs (Hossain and Katiyar 2006). Conversely, the research community on the hydro-politics of international rivers should be made cognizant of the potential opportunities possessed by emerging satellite remote sensing data to tackle the persistent problems on transboundary flood management. The overall aim of this article is to promote greater interaction between the two diverse research communities for more effective feedback to the remote sensing data producing community. Such interaction can play a positive role in demonstrating greater societal benefits and consequently strengthen the scientific community's argument for proposed global hydrologic missions against the backdrop of dwindling financial support from federal agencies (Zielinski 2005).

The article is organized as follows. Section 2 provides an overview of the hydro-political situation of flood monitoring in flood-prone nations in IRBs with special emphasis on decision-making. This is followed by a brief introduction to GPM (Sect. 3). In Sect. 4, a parsimonious hydrologic modeling scheme for assessing the utility of satellite rainfall data for flood monitoring in IRBs is described. Section 5 presents an assessment of the value of the modeling scheme. Finally, Sect. 6 (Conclusion) summarizes the salient points of our review.

2 Overview of global hydro-political situation of flood monitoring in IRBs

Terrestrial water flow does not recognize political boundaries, only the topographic limits of the catchments. Yet more than 260 river systems of the world are subject to international political boundaries (Wolf et al. 1999). These river systems flow through multiple nations within the basin before draining out. An IRB is such a basin within the jurisdiction of many nations. IRBs are ubiquitous in all five continents and a total of 145 countries are geographically associated in their drainage area. These basins account for more than 40% of the Earth's inhabitable land mass and more than 50% of global surface flow (Wolf et al. 1999).

Table 1 presents a global distribution of the percentage of a nation's area lying within an IRB (after Wolf et al. 1999). Survey indicates that about 33 countries are 'locked' within IRBs (Giordano and Wolf 2003). According to our estimates, there are at least 20 such locked and flood-prone nations in under-developed regions that are located specifically at the downstream end. These nations, while comprising only a small portion of total drainage area, are forced to cope with a non-negligible share of the flood mass that is generated beyond their borders. This fact makes these locked countries heavily dependent on rainfall and discharge information from not just within their borders but also beyond from the upstream nations. In Table 2, we provide a non-exhaustive list of examples of such downstream under-developed nations (taken from Hossain and Katiyar 2006).

Table 1 Global distribution of nations and their contributing area in international river basins (IRBs) [Source: Wolf et al. (1999)]

Percentage within IRBs (%)	Number of countries
90–100	39
80–90	11
70–80	14
60–70	11
50–60	17
40–50	10
30–40	10
20–30	13
10–20	9
0–10	11

Table 2 A non-exhaustive list of lowermost riparian (under-developed) nations situated in flood-prone international river basins (IRBs)

Name of down stream country	IRB	% Of total basin area
Cameroon	Akpa/Benito/Ntem	41.8
Senegal	Senegal	8.08
Ivory Coast	Cavally	54.1
Benin	Oueme	82.9
Botswana	Okovango	50.6
Nigeria	Niger	26.6
Bangladesh	Ganges–Brahmaputra–Meghna (GBM)	7.0
Brunei	Bangau	46.0
Laos	Ca/Song Koi	35.1
Myanmar	Irrawaddy	91.2
Cambodia	Mekong	20.1

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. (Acknowledgment: Dr. Aaron Wolf of the Freshwater Disputes Database at Oregon State University; http://www.transboundarywaters.orst.edu)

As an example, consider the case of Bangladesh. It is situated at the most downstream region of the Ganges–Brahmaputra–Meghna (GBM; Fig. 1) basin, and yet it does not receive any upstream river flow and rainfall information in real time from India (for lack of an adequate water treaty) during the critical monsoon rainy season spanning June–September. Bangladeshi authorities, therefore, measure river flow at staging points where the three major rivers enter Bangladesh (Ganges, Brahmaputra, and Meghna; shown in red circles in Fig. 1) and at other points downstream. On the basis of these limited data, it is possible to monitor flood levels in the interior and the south of Bangladesh with only two to three days forecast lead time [Flood Forecasting and Warning Center (FFWC) of Bangladesh: www.ffwc.net; Paudyal 2002]. Hydrologically, this current lead time of forecasting could be increased, as the mean time of concentration of the GBM basin ranges anywhere between 7 and 14 days. A longer monitoring range in flood-prone IRBs would have a consequentially beneficial impact of enhancing the utility of a decision-support tool that ingests these forecasts. For example, 7–10-day forecasts are currently considered much more useful than daily forecasts in the monsoon-affected Asian countries for agricultural decision-support as they inform farmers of the potential benefits of

Fig. 1 The Ganges–Brahmaputra–Meghna (GBM) basin. Bangladesh represents the lowermost riparian nation comprising 7% of total basin area. Circles in red indicate the major boundary conditions for current river flow monitoring

delayed sowing or early reaping of crops, while a 21-day forecast is considered most ideal [Asian Disaster Preparedness Center (ADPC), 2002]. Extended forecasts also assist in economic decision-making for developing countries through early disbursement of rehabilitative loans to regions anticipated to be affected by floods (Ninno et al. 2001).

One particular example of international cooperation among riparian nations to overcome transboundary hurdles to IRB flood monitoring is the Mekong River Commission (http://www.mrcmekong.org). This Commission's river monitoring network has demonstrated a capability for 7-day river flow forecasting in downstream Cambodia on the basis of real-time sharing of hydrologic data from ground-based and space-borne platforms across political boundaries (USAID/OFDA 2004). Such transboundary cooperation clearly demonstrates the potential benefits a flood-prone nation can enjoy from the ingestion of satellite rainfall over upstream regions in its forecasting system. However, for most cases, such transboundary cooperation for the sharing real-time data is usually not possible (Hossain and Katiyar 2006). Hence, most flood-prone riparian nations in IRBs are either limited in their options or forced to employ proxy approaches. For example, very recently, climate-based approaches using model forecast rainfall products from the European Center for Medium Range Forecasting (ECMWF) have been initiated for addressing the limitations of flood forecast over monsoon-affected nations (Webster and Hoyos 2004). Although based on physically sound principles of early detection of weather patterns and intra-seasonal variability, these approaches do not leverage the hydrologic time-lag that exists between rainfall and runoff as a function of landform characteristics and thus can often suffer from inaccurate spatio-temporal modeling of flood inundated regions (Hossain and Katiyar 2006). In the current state of the art, it therefore seems that satellite (discussed next), with its vantage of space, is perhaps the only pragmatic way to overcome the transboundary limitations of real-time basin-wide rainfall measurement for a nation locked in an IRB.

3 The global precipitation measurement (GPM) mission

The heritage of GPM originated two decades ago when infrared (IR) radiometers on geostationary satellites were launched to provide high-resolution measurement (Griffith et al. 1978). While geostationary IR sensors have substantial advantages in that they provide essentially time-continuous observations, a major deficiency is that the quantity being sensed is only indirectly related to precipitation (Huffman et al. 2001). Subsequently, space-borne passive microwave (PMW) radiometers evolved as a more credible alternative (in terms of accuracy) a decade later. PMW sensors work on the principle that naturally emitted radiation in the microwave wavelengths is affected by the composition of atmospheric hydrometeors. PMW sensors are considered more accurate under most conditions for precipitation estimation over land than their IR counterparts.

In 1997, the Tropical Rainfall Measuring Mission (TRMM), the first space-borne active microwave (AMW) precipitation radar (TRMM-PR), was launched. Although radar generally is the most accurate remote sensing technique for precipitation estimation, radar technology is expensive, and TRMM-PR has limited spatial coverage (at latitudes between about 35′ S and 35′ N) with a sampling frequency about once per day. Therefore, the constellation of PMW sensors, and a fourth, AMSR-E, flying on board the NASA Aqua research satellite, continue to represent a middle ground between IR sensors and TRMM-PR in terms of sampling frequency, accuracy, and global coverage.

Global precipitation measurement is therefore being planned now as a global constellation of low earth orbiting satellites (some of them existing) carrying various PMW sensors (Smith et al. 2004). It will essentially be an expansion of the TRMM mission in space and time, which would provide near-global coverage of land areas, and would formally incorporate a means of combining precipitation radar with PMW sensors to optimize sampling and retrieval accuracy. The GPM Core satellite will be similar in concept to the TRMM satellite, and will house a precipitation radar of improved accuracy as well as a PMW sensor. Through this configuration, GPM aims to provide consistent global precipitation products with temporal resolution ranging from 3 h to 6 h and spatial resolution in the range 25–100 km^2 (Smith et al. 2006; see also http://gpm.gsfc.nasa.gov).

4 The need for parsimonious hydrologic modeling schemes to assess satellite rainfall data

Since there exists a time lag between rainfall and the transformed stream-flow, and because this lag increases according to the size of the basin, floods can be forecasted at a point downstream of a large basin, knowing the river flow at some point upstream in conjunction with a hydrologic model (Webster and Hoyos 2004; Lettenmaier and Wood 1993). However, as the number of flood-prone IRBs is large (Table 1), we consider the conventional data-intensive implementation of physically based hydrologic models that are complex and distributed on case-by-case IRBs time-consuming and very challenging for completing a global assessment of the utility of GPM. A logical alternative is to employ a more parsimonious approach in order to realize the timely completion of the global assessment at the expense of a tolerable loss of detail and accuracy. Such a framework 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 (hydro-political) limitations of flood forecasting in IRBs; (2) satellite rainfall estimates are not perfect and, hence, the uncertainty associated with these estimates has a consequential nonlinear and deteriorating impact on the accuracy of flood forecasts.

One such parsimonious hydrologic modeling approach is the open-book watershed concept. The open-book watershed modeling concept was first formulated by Yen and Chow (1969) as a convenient and pragmatic framework to understand the underlying physics behind surface hydrologic phenomena. Over the last 30 years, many studies have emerged based on the open-book modeling concept, which have established its value as a scientific tool in advancing hydrologic prediction (see for example, Woolhiser et al. 1990; Gutowski et al. 2002; Niedzialek and Ogden 2004). The most compelling justification for using an open-book modeling concept is generally the fact that field results are difficult to obtain, are often site-dependent, have uncertain boundary conditions, are time-consuming, and expensive to conduct.

A new era of application of the open-book watershed modeling framework may now emerge with the anticipated global availability of high-resolution satellite rainfall data from the proposed GPM mission (Smith et al. 2004; Hossain and Katiyar 2006). This era of application pertains to rapid prototyping of GPM-based flood monitoring systems for downstream nations in IRBs. We therefore promote an open-book watershed model concept to demonstrate the value of parsimonious approaches in inferring the utility of satellite rainfall data for transboundary flood management. Our model comprises two primary components: (1) a hydro-political component that models the territorial representation of member nations within an IRB; and (2) a hydrologic modeling component that models the rainfall-runoff transformation based on first principles of conservation of mass. The hydro-political component gauges the worth of having space-borne rainfall information over upstream nations that have political boundaries dissimilar from basin delineating boundaries, while the hydrologic modeling module functions essentially within the hydro-political component. We summarize these two components below. The interested reader may refer to the recent work of Katiyar and Hossain (2006) for more details.

4.1 Hydrologic component

The hydrologic component employed in the open-book model is a quasi-three dimensional physics-based distributed parameter hydrologic model developed for first-order watersheds where runoff is produced by saturation, excess mechanism (as may be the case for most flood-prone IRBs in Africa, Asia, and South America that are usually humid with moderate to dense vegetation). The hydrologic module models the basin's drainage in an open-book configuration (Fig. 2) as a square-grid volume domain, where the individual processes of overland flow and infiltration to the subsurface are linked to simulate the response of the unsaturated zone to precipitation. The infiltration and sub-surface flow are computed using a water balance approach, where depth to bedrock and soil porosity are used to define the soil's

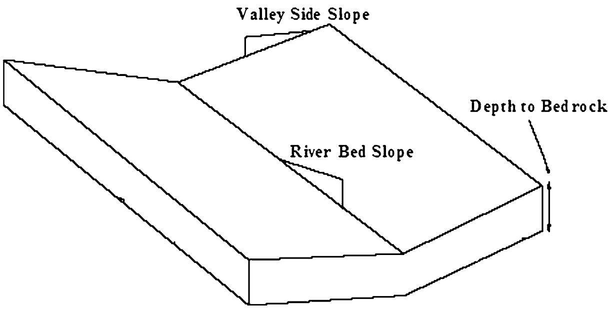

Fig. 2 Geometric representation of the open-book watershed topography. The depth to bedrock essentially represents the effective soil column in the vadose zone. Valley slope is the average hillslope for overland flow

moisture storage capacity for each grid volume. Excess rainfall is then calculated from knowledge of this time-varying infiltration, saturation-excess runoff, by keeping track of the soil moisture conditions for each grid volume at each successive time-step. The overland flow is then routed on the basis of this excess rainfall along the direction of steepest gradient for each grid surface until it laterally drains into the main channel. The stream-flow is then modeled as a 1-D kinematic flow. Herein, we describe the process equations for the infiltration module that dictates the partitioning of rainfall. Since the rest of the model components (related to overland and river routing) are trivial, their elaboration is avoided here.

For infiltration calculation, the following water balance equation is used for each grid volume,

$$\frac{\mathrm{d}s(t)}{\mathrm{d}t} = p(t) - q_{\mathrm{se}}(t) - q_{\mathrm{ss}}(t) \tag{1}$$

where, $s(t)$ is the soil moisture storage, $p(t)$ is the precipitation, $q_{\mathrm{se}}(t)$ is the overland saturation-excess flow and $q_{\mathrm{ss}}(t)$ is the sub-surface flow at time t. The $q_{\mathrm{ss}}(t)$ and $q_{\mathrm{se}}(t)$ are computed as follows,

$$q_{\mathrm{ss}} = \frac{s(t) - S_{\mathrm{f}}}{t_{\mathrm{c}}} \quad \text{if } s(t) > S_{\mathrm{f}} \tag{2a}$$

$$q_{\mathrm{ss}} = 0 \quad \text{if } s(t) < S_{\mathrm{f}} \tag{2b}$$

where, S_{f} is the soil moisture storage at field capacity (defined by the soil type) and t_{c} is the grid response time to sub-surface flow. t_{c} is approximated from Darcy's law assuming a triangular groundwater aquifer and hydraulic gradient approximated by ground slope.

$$t_{\mathrm{c}} = \frac{L\phi}{2K_{\mathrm{s}} \tan\beta} \tag{2c}$$

Herein, L is the grid size, K_{s} the saturated hydraulic conductivity and β is the grid slope. The sub-surface flow draining out from a grid volume is not routed in the soil medium as it would comprise an insignificant component during the duration of the flood event (an assumption).

The overland saturation-excess flow $q_{se}(t)$ is computed as follows,

$$q_{se} = \frac{s(t) - S_b}{\Delta t} \quad \text{if } s(t) > S_b \tag{3a}$$

$$q_{se} = 0 \quad \text{if } s(t) < S_b \tag{3b}$$

where S_b is the soil's storage capacity computed as $D\varphi$ (D = depth to bedrock/effective soil column; and φ is porosity).

4.2 The hydro-political component

For a given IRB, the hydro-political component identifies the main river(s) and the length(s) of the main stem of the river(s) in the IRB along with the drainage area contributed by each riparian nation. For each riparian nation, four additional static geophysical parameters are required as inputs: (1) average riverbed slope; (2) average valley side slope; (3) average soil type; (4) average depth to bedrock. The IRB is then idealized as an open-book watershed with an area equivalent to the total drainage area (see Fig. 2). The length and width are so chosen in a manner to represent the overall geometric shape of the basin to a reasonable degree of qualitative consistency. The member riparian nations comprising the IRB are identified along the downstream direction of main river(s) reach. These riparian nations are then represented through smaller open-book watersheds organized within the main open-book watershed, each possessing the nation-specific geophysical properties of river slope, valley side slope, an area equivalent to their relative areas and depth to bedrock.

As an example, consider the case of Senegal in the Senegal IRB (Fig. 3, left panel). The IRB comprises (along the downstream direction of the main stem of the Senegal river) the following four nations: Guinea, Mali, Mauritania, and Senegal. The relative areas (i.e., % of total IRB drainage area) occupied by these riparian nations are 7, 35, 50, and 8%, respectively (from Wolf et al. 1999). The Senegal IRB can therefore be idealized as an approximate open-book watershed of a total area equivalent to the total drainage area of the IRB and then further discretized into

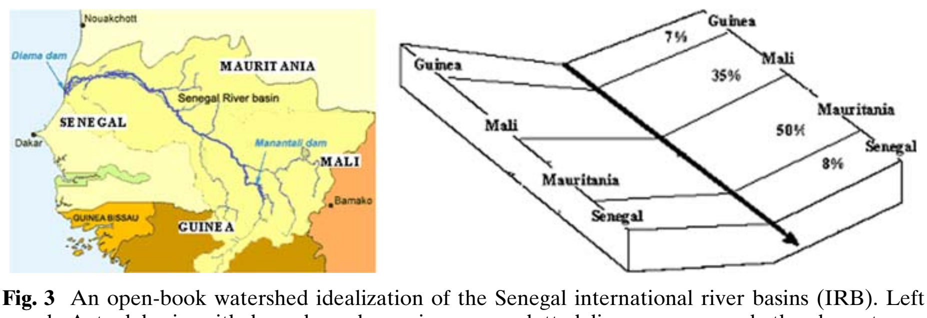

Fig. 3 An open-book watershed idealization of the Senegal international river basins (IRB). Left panel: Actual basin with boundary shown in orange dotted line; arrows mark the downstream direction of the main stem of the Senegal River. Right panel: An open book watershed of total drainage area of the entire Senegal IRB; each riparian nation is represented by additional sub-open book watersheds; the area of each sub-watershed is equivalent to the % of total IRB drainage area occupied by each member nation. (Taken from Katiyar and Hossain 2006)

four smaller open-book sub-watersheds. The riparian nations are then represented within the main open-book watershed by the four sub-watersheds, each having area proportional to their relative areas (Fig. 3, right panel).

5 The value of a parsimonious hydrologic model approach

Recently, Katiyar and Hossain (2006) have demonstrated the physical consistency of the open-book hydrologic model concept through sensitivity analysis of pertinent geophysical basin parameters to the rainfall-runoff transformation. In a hypothetical exercise, they simulated the stream-flow hydrograph for a 4-month long distributed radar rainfall (WSR-8D) record over Oklahoma assuming an open-book configuration. Using the radar-simulated hydrograph as the benchmark, and assuming a two-nation hypothetical IRB over Oklahoma, the impact of integrating NASA's real-time satellite rainfall data (IR-3B41RT; Huffman et al. 2003) over the upstream nation on the flow monitoring accuracy of the downstream nation was evaluated. A definitive relationship defining the improvement in flow monitoring emerged as a function of the relative area occupied by the downstream nation. It was observed that the relative improvement in flow monitoring accuracy for the downstream nation can be high (over 100%) when more than 90% of the basin is transboundary (Figure 4). However, flow monitoring accuracy reduces considerably when 10% or less of the basin area is transboundary to the downstream nation. Finally, Katiyar and Hossain (2006) mapped this relationship globally on the basis of climateregime similarity using the Koppen classification. The mapping scheme identified 5 specific downstream nations (North Korea, Bangladesh, Senegal, Mozambique and Uruguay) that could potentially benefit significantly from the assimilation of NASA's IR-3B41RT data in their flood monitoring systems.

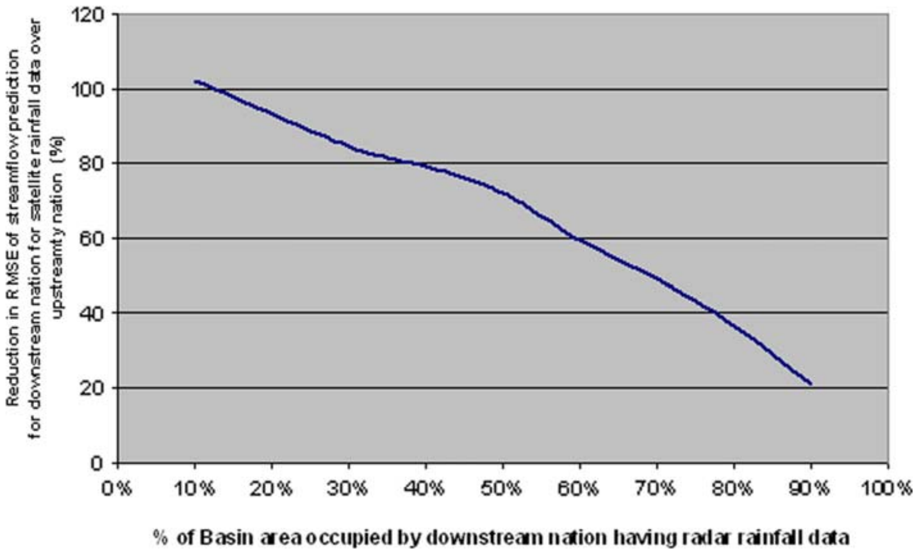

Fig. 4 Impact of assimilating NASA's IR-3B41RT rainfall data over upstream nation on the flow monitoring accuracy of the downstream nation. Relationship shown as % reduction in relative root mean squared error in stream-flow prediction versus % of basin area occupied by the downstream nation. (Taken from Katiyar and Hossain 2006)

6 Conclusion

The systematic decline of in situ networks for hydrologic measurements has been recognized as a crucial limitation to advancing hydrologic monitoring in medium to large basins, especially those that are already sparsely instrumented. As a collective response, sections of the hydrologic community have recently forged partnerships for the development of space-borne missions for cost-effective, yet global, hydrologic measurements by building upon the technological advancements since the last two decades. In this article, we have reviewed the state-of-the-art on flood monitoring in medium and large ungauged basins where satellite remote sensing can provide a cost-effective alternative to the dwindling in situ network of gauges. Our review was cast in the context of the current hydro-political situation of flood monitoring in flood-prone developing nations situated in IRBs. Given the large number of such basins, the conventional data-intensive implementation of existing distributed physically based hydrologic models on a case-by-case basis may be time-consuming for deriving a global assessment of the utility of proposed global satellite hydrologic missions. Our review indicates that a more parsimonious approach would be justified at the tolerable expense of accuracy. Such a parsimonious approach can subsequently motivate the identified international basins to invest greater effort in conventional and detailed hydrologic studies to design a prototype forecasting system in an effort to surmount the hydro-political hurdles to transboundary flood management. Through a modeling exercise involving an open-book watershed concept and a hypothetical basin, we have highlighted the value of parsimonious approaches in gauging the utility of NASA-derived satellite rainfall products.

As the path ahead, it is important that we now encourage real-world operational flood forecasting agencies in the under-developed world to come forward and collaborate with the research community on hydrology, hydro-politics, and satellite rainfall remote sensing. The objective of such an effort should be the extension of tangible societal benefits to inhabitants of flood-prone IRBS through leveraging the upcoming global satellite missions. As an example, the Flood Forecasting and Warning Center of Bangladesh, with a network of 114 rainfall stations, 30 river discharge stations and continually updated landform data, can offer an ideal platform for the design and testing of prototype space-borne monitoring systems in tropical IRBs based on GPM, HYDROS, and WatER missions. The conceptual framework outlining the design of a prototype system has already been described by Hossain (2006). With the research work that is on-going with the operational flood agency in Bangladesh, we hope to report some of our findings on the potential of satellite data in improving decision support during flood-related hazards in IRBs in a forthcoming article.

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