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An open-book watershed model for prototyping space-borne flood monitoring systems in International River Basins

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Abstract

A new era involving both simple and complex hydrologic modeling of un-gauged river basins may now emerge with the anticipated global availability of high resolution satellite rainfall data from the proposed Global Precipitation Measurement (*GPM*) mission. This era of application pertains to rapid prototyping of *GPM*-based flood monitoring systems for downstream nations in International River Basins (IRBs) where basin-wide in-situ rainfall data is unavailable due to lack of either an infrastructure or a treaty for real-time data sharing with upstream riparian nations. In this paper, we develop, verify and apply an open-book watershed model for demonstrating the value of a parsimonious modeling scheme in quick prototyping of satellite rainfall-based flood monitoring systems for lowermost nations in flood-prone IRBs. The open-book watershed modeling concept was first formulated by Yen and Chow [1969. A laboratory study of surface runoff due to moving rainstorms. Water Resources Research 5(5), 989−1006] more than 30 years ago as a convenient and pragmatic framework to understand the underlying physics behind surface hydrologic phenomena. Our developed model is based on first principles of conservation of mass and momentum that parsimoniously represents the static geophysical features of a basin with minimum calibration. Such a generic and parsimonious representation has the added potential to supplement complex hydrologic models for stakeholder involvement and conflict management in transboundary river basins, among many additional applications. We first demonstrate the physical consistency of our model through sensitivity analysis of some geophysical basin parameters pertinent to the rainfall-runoff transformation. Next, we simulate the stream-flow hydrograph for a 4-month long period using basin-wide radar (WSR-88D) rainfall data over Oklahoma assuming an open-book river basin configuration. Finally, using the radar-simulated hydrograph as the benchmark, and assuming a two-nation hypothetical IRB over Oklahoma, we explored the impact of assimilating NASA's real-time satellite rainfall data (IR-3B41RT) over the upstream nation on the flow monitoring accuracy for the downstream nation. We developed a relationship defining the improvement in flow monitoring that can be expected from assimilating IR-3B41RT over transboundary regions as a function of the relative area occupied by the downstream nation for a semi-arid region. The relative improvement in flow monitoring accuracy for the downstream nation was found to be clearly high (over 100% reduction in root mean squared error) when more than 90% of the basin is transboundary. However, flow monitoring accuracy reduces considerably when 10% or less of the basin area is transboundary to the downstream nation. Our findings, although hypothetical and very regime-specific, illustrate very clearly the feasibility of utilizing anticipated GPM data to alleviate the current flood monitoring limitations experienced by many nations in IRBs through the application of a generic and parsimonious model.

Keywords: Flood forecasting; Satellite rainfall; Global Precipitation Measurement mission; International River Basins; Open-book watershed; Hydrologic modeling

1. Introduction

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. This concept models

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the geometric shape of a basin as two leaves of a book that are actually "open" or exposed in order to represent the hillslope as two planar surfaces bisected by a river in between (Fig. 2). The overland flow generated at the hillslope is then routed to the main channel as sheet flow to derive the streamflow hydrograph at the watershed outlet. Such an open-book configuration is a powerful yet simple concept to represent the physics of surface runoff generation at the fundamental scale of runoff contributing areas of a basin.

Over the last 30 years, many studies have emerged based on the open-book modeling concept, which have continued to establish its value as a scientific tool in advancing the science of hydrology. For example, the Kinematic Routing and Erosion (KINEROS) model (Woolhiser et al., 1990) used essentially an open-book concept to simulate surface flow over planar regions. Gutowski et al. (2002) have coupled an open-book type hydrologic model with an atmospheric component to study the coupled land-atmosphere hydrologic cycle. More recently, Niedzialek and Ogden (2004) applied the open-book modeling approach to assess hypotheses behind surface runoff generation and the effect of hysteretical behavior of soils during wetting and drying cycles. The most compelling justification for using an open-book modeling concept is generally the fact that results from field 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 simple schemes, such as the open-book watershed modeling framework discussed above, in conjunction with more complex schemes, may now emerge with the anticipated global availability of high resolution satellite rainfall data from the proposed Global Precipitation Measurement (*GPM*) mission (Hossain and Katiyar, 2006; Smith et al., in press). This era of application pertains to rapid prototyping of *GPM*-based flood monitoring systems for downstream nations in International River Basins (IRBs) where basin-wide in-situ rainfall is unavailable due to lack of either an infrastructure or a treaty for real-time data sharing among riparian nations.

Terrestrial water flow recognizes no 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 basins, known as International River Basins (IRB), have transboundary rivers flowing through many nations within the basin before draining out to oceans or lakes. IRBs are ubiquitous in all 5 continents and a total of 145 countries are geographically associated in their drainage area. These basins account for more than 40% of earth's inhabitable land mass and 50% of total surface flow (Wolf et al., 1999). *GPM* on the other hand is currently being developed as an international collaboration of space agencies to provide high resolution and accurate space-borne rainfall data from passive microwave platforms (Smith et al., in press). The scales at which *GPM* rainfall data is planned for delivery (3–6 h and 10 km × 10 km) are considered most relevant for flood monitoring in medium to large river basins where in-situ rainfall data is usually not available (Hossain and Lettenmaier, in press).

Table 1 provides 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 have more than 95% of their territory "locked" within IRBs (Giordano and Wolf, 2003). According to our estimates, there are at least 20 such locked and flood-prone nations at the downstream end that, 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 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 nations (taken from Hossain and Katiyar, 2006). As an example, Bangladesh, situated at the downstream most region of the Ganges–Brahmaputra–Meghna (GBM; Fig. 1) basin, 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 data, it is possible to monitor flood levels in the interior and the south of Bangladesh with only two to three days lead time (Flood Forecasting and Warning Center—FFWC—of Bangladesh: www.ffwc.net). Hydrologically, this current lead time of forecasting could be increased as, the mean time of concentration of the GBM basin ranges anywhere between 7–14 days or higher (Paudyal, 2002).

Although a satellite can sense rainfall across political borders, its estimates are associated with a complex-natured uncertainty that requires assessment in order to understand the associated trade-off between the intuitive benefits and the anticipated flood prediction uncertainty (Hossain, 2006; Hossain and Anagnostou, 2006). Considering that floods account for about 15% of the annual global death toll by natural hazards, the critical challenge now is to identify the specific downstream nations within IRBs that could actually benefit from a pre-programmed satellite-based flood monitoring system in anticipation of *GPM*. Tables 1 and 2 collectively indicate that a large number of areal composition is possible of a downstream nation in IRBs (ranging from 1% to 99% of total basin area). This naturally leads us to the question: *what is the minimum areal extent of an IRB that needs to be transboundary (and hence un-gauged) to a flood-prone downstream nation for the benefits of satellite rainfall to outweigh the flood monitoring uncertainty?* Another question is: *what role is played by a watershed's geophysical and geo-morphological parameters (e.g. valley slopes, soil type, vegetation, river bed slope etc.) and flow regime in dictating the utility of satellite rainfall for downstream nations in IRBs for flood monitoring?*

As the number of flood-prone IRBs is large (>40), conventional data-intensive implementation of existing complex (i.e., physically-based distributed) hydrologic models on case-by-case IRBs is considered time-consuming for completing a global assessment of the utility of *GPM* (Hossain and Katiyar, 2006;

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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 forecasting in Bangladesh.

Hossain et al., in press). The assessment of the impact of assimilating satellite rainfall over upstream nations in improving flood monitoring of lowermost ''locked'' riparian nations has an additional complexity that existing hydrologic-cum-error modeling paradigms are not usually tailored to address. This complexity involves the hydro-political aspect of flood monitoring in IRBs wherein the delineation of the political boundaries of riparian nations in the rainfall-runoff modeling-cum-monitoring framework is not explicitly accommodated for. While many existing modeling frameworks can adequately assess the basin response time to rainfall for an IRB as a whole (e.g., Nijssen and Lettenmaier, 2004; Coe, 2000; Nijssen et al., 1997; Wood et al., 1997; among others), a parsimonious hydro-political component is essential towards making a preliminary (and proxy) understanding of the impact of *GPM* rainfall data on overcoming the transboundary limitations of flood monitoring. This preliminary understanding can consequently optimize our efforts towards more detailed and expensive analyses involving physically-based hydrologic models that have complex data needs on specific basins that are identified as in need of satellite rainfall data by the rapidly executable parsimonious framework.

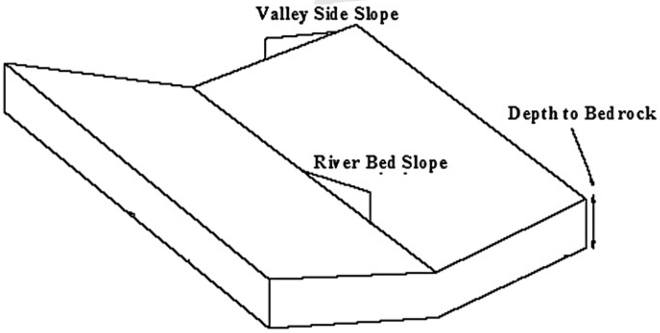

Fig. 2. Geometric representation of the open-book watershed topography. The depth to bedrock is essentially the effective soil column.

In this paper, we develop, verify and apply a generic approach, based on the open-book watershed model, for assessment and prototyping of satellite rainfall-based flood monitoring systems in lowermost nations for IRBs. The flood we aim to model is essentially the river flooding of the plains caused by widespread and systematic rainfall (such as the Monsoon). Our choice for an open-book is governed by the powerful simplicity it offers in modeling the political boundaries of an IRB (discussed in detail in Section 4). While the idea of using the open-book model as a generic concept appears pragmatic and appealing, there appears little precedence, to the best of our knowledge, on its application for assessing satellite-based flood modeling in large river basins. Hence, an assessment of the appropriateness of the open-book approach is equally necessary before the concept can be considered any further for prototyping *GPM*-based flood forecasting systems. Herein, we demonstrate the physical consistency of our proposed model through sensitivity analysis of pertinent geophysical basin parameters. Using simulated runoff from radar rainfall data as reference, we then explore in detail the impact of assimilating satellite rainfall data over upstream nations on the flood

Table 1
Global distribution of nations and their contributing area in International River Basins (IRBs)

Percentage within IRBs	No. 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

Source: Wolf et al., 1999.

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Table 2
A non-exhaustive list of lowermost riparian nations situated in flood-prone International River Basins

Name of downstream country	International River Basin	% 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	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. [Acknowledgement: Dr. Aaron Wolf of the Freshwater Disputes Database at Oregon State University; http://www.transboundarywaters.orst.edu].

monitoring accuracy of the downstream country. The developed model and the subsequent model application in our study are expected to build an objective framework to seek answers to the open question: *Can a parsimonious open-book watershed modeling framework be a pragmatic and proxy alternative for rapid and global identification of IRBs in greater need of a GPM-based flood monitoring system?* Our generic model developed herein should not be construed as an effort to uniliaterally promote simple approaches over the complex hydrologic modeling schemes that have the capability to represent the fine-scale hydrologic variability of a watershed given adequate data (Silberstein, 2006). Rather, we would like to stress that a parsimonious representation of the watershed has the added potential to supplement complex hydrologic models for a number of applications in light of emerging space missions for rainfall measurement. These applications are stakeholder involvement and conflict management in transboundary river basins (Wolf et al., 1999), model identification (Wagener and Kollat, in press), assessing impact of land use (Koivusalo et al., 2006) and assessing the impact of input data quality (Boughton, 2006).

In what follows next in the paper, we first provide a detailed description of the theory behind our open-book watershed model (Section 2: Model development). This is followed by physical consistency checks to demonstrate the correctness of the code-based implementation of the hydrologic theory (Section 3: Model verification). In Section 4 (Model application) we describe briefly the region, datasets and the satellite rainfall data that were used to demonstrate an application of the open-book model for prototyping flood monitoring systems for IRBs. Finally, the main conclusions and long-term implications of our study are provided in Section 5.

2. Model development

Our open-book watershed model comprises two primary components: (1) a hydro-political module that models the territorial representation of member nations within an IRB; and (2) a hydrologic modeling module that models the rainfall-runoff transformation based on first principles of conservation of mass and momentum. As noted earlier in Section 1, the hydro-political module is necessary to gauge the worth of having space-borne rainfall information over upstream nations that have political boundaries dissimilar from basin delineating boundaries. The hydrologic modeling module functions essentially within the hydro-political module. A simple regression type forecast module embedded with the hydrologic module's streamflow simulation component can provide the necessary river flow monitoring capability (for examples see Pingel et al., 2005; Webster and Hoyos, 2004). In the following section we describe these two modules in further detail drawing from a real-world example of an IRB to elaborate.

2.1. Hydrologic module

The hydrologic module 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 is 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 explicitly to simulate the response of the unsaturated zone to precipitation (Fig. 2). The infiltration and subsurface flow are computed using a water balance approach where depth to bedrock and soil porosity are used to define the soil's moisture storage capacity for each grid volume. Herein, the depth to bedrock signifies essentially the effective soil column and not the geologic depth to rock strata. 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 streamflow is modeled as a 1-D kinematic flow.

2.1.1. Infiltration (excess rainfall calculation)

The following water balance equation is used for each grid volume,

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

where $s(t)$ is the soil moisture storage, $p(t)$ is the precipitation, $q_{se}(t)$ is the overland saturation-excess flow and $q_{ss}(t)$ is the sub-surface flow at time t. Evaporation and saturated flow are ignored in the mass balance equation because the open-book model is primarily intended for flood events. The $q_{ss}(t)$ and $q_{se}(t)$ are computed as follows:

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$$q_{ss} = \frac{s(t) - S_f}{t_c} \quad \text{if } s(t) > S_f \tag{2a}$$

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

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 subsurface flow. t_c is approximated from Darcy's law assuming a triangular groundwater aquifer and hydraulic gradient approximated by ground slope.

$$t_c = \frac{L\phi}{2K_s \tan\beta} \tag{2c}$$

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 is depth to bedrock/effective soil column; and φ is porosity).

2.1.2. Overland flow routing

The excess rainfall i over the saturated grids (when $s(t) > S_b$ or $q_{se} > 0$) is represented as $q_{se}\Delta t$. This is routed using Manning's or Darcy-Weisbach's equation along the steepest gradient using the schematic shown in Fig. 3. The overland flow (or, lateral discharge) per unit width, q_o, is given as

$$q_0 = iL_0 \cos\theta \tag{4a}$$

where i is excess rainfall (computed from q_{se}), L_0 is inter-pixel distance along the steepest gradient, θ is $\tan^{-1}$ (slope).

A cutoff Reynolds number (Re) of 3000 is used to determine the regime of the overland flow as being laminar (<3000) or turbulent (>3000). This regime classification is important in defining the surface roughness for overland flow velocity calculation.

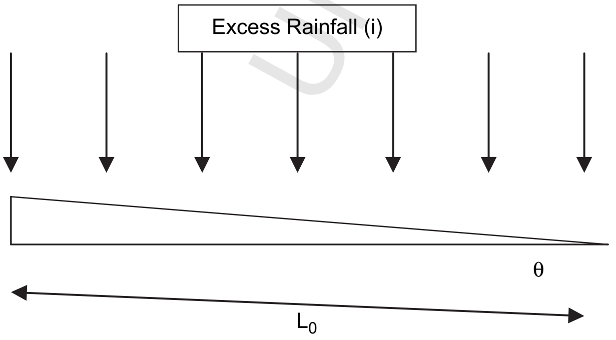

Fig. 3. Overland flow routing from excess rainfall over saturated pixels/zones.

$$\mathrm{Re} = \frac{4q_0}{\nu} \tag{4b}$$

where ν is kinematic viscosity.

For laminar overland (sheet) flow regime, the friction factor is a function of excess rainfall intensity. Chow and Yen (1976) provided the following relationship to compute the resistance coefficient for such laminar regimes,

$$C_L = 96 + 108i^{0.4} \tag{4c}$$

where, i is in inches/hour.

The friction factor, f, for overland flow is then calculated as follows:

$$f = C_L/\mathrm{Re} \tag{4d}$$

Finally, the depth of overland flow, y, and flow velocity, V, are calculated using Darcy-Weisbach equations (4e) and (4f), respectively.

$$y = \left(\frac{fq_0}{8gS_0}\right)^{1/3} \tag{4e}$$

$$V = q_0/y \tag{4f}$$

where S_0 is the slope.

For a turbulent overland flow regime ($\mathrm{Re} > 3000$), the Manning's equation is used directly to compute y and V (in English units) as follows,

$$y = \left(\frac{nq_0}{1.49S_0}\right)^{3/5} \tag{4g}$$

$$V = q_0/y \tag{4h}$$

2.1.3. River flow routing

Channel flow basically follows Manning's equation. Solution to this equation is calculated iteratively as outlined in Chow et al. (1988) using the Newton method.

$$Q = \frac{1.49}{n} S_0^{1/2} A R^{2/3} \tag{5a}$$

$$f(y_j) = Q_j - Q \tag{5b}$$

$$y_{j+1} = y_j - \frac{f(y_j)}{(\mathrm{d}f/\mathrm{d}y)_j} \tag{5c}$$

where j is iteration index, y is flow depth, Q is discharge in the channel, A is area, R is hydraulic radius, n is Manning's roughness coefficient.

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2.2. The hydro-political module

For a given IRB, the hydro-political module 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 parameters are required as inputs: (1) average river bed slope; (2) average valley side slope; (3) soil type; (4) effective soil column depth. These parameters can be distributed if necessary. The IRB is then idealized as one 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. 4, 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 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. 2, right panel).

It is appropriate to mention, at this stage, that the manner in which each riparian nation is seamed into the primary open-book representing the IRB as one hydrologic unit is considerably idealized in our hydro-political module. In the real-world, topographic divides and political boundaries rarely follow the rigid Euclidean geometric pattern. However, we would like to stress that our model is a necessary first attempt to focus development on a non-unique (i.e., generic) and parsimonious way of globally assessing satellite rainfall data anticipated from *GPM* for a large number of IRBs. Our open-book representation allows easy modeling of the certain hydro-political features of an IRB that existing modeling frameworks do not address without requiring additional data or calibration. These are: (1) consideration of all the upstream nations as one lumped region lacking surface rainfall data due to un-gauged terrain or absence of cooperative rainfall data sharing agreements (discussed in Section 4); (2) consideration of a given combination of upstream nations lacking surface rainfall data due to newly emerging geo-political events (such as civil war or annulment of a cooperative agreement on water sharing). Hence, while the idealization of riparian nations as open-books may raise concerns, which are understandable, we would also like to emphasize that that such a potential limitation alone should not hamper our ability to investigate the usefulness of the proposed model paradigm, and particularly so when our intention is to primarily conduct an approximate and hydrologically relevant assessment of the numerous IRBs in the vast un-gauged regions of the world. We believe that the weaknesses of our model if any, may be revealed in our results upon validation with a real-world system and as a result, we may also modify it with a more appropriate method in the future. In addition, we would also like to highlight that the level of idealization can indeed be systematically reduced by: (1) adopting the in-situ Digital Elevation Model data; (2) higher ordered open-book watershed representations (i.e., with higher number of discretizations) for tributaries and distributaries; and (3) actual political boundaries of riparian nations within the open-book framework. Fig. 5 provides a schematic on how the two modules (hydro-political and hydrologic) are integrated algorithmically in our final model code.

3. Verification of the open-book model

Coding implementation of hydrologic theory was rigorously assessed before the model was applied any further for our investigation. In this study, we conducted physical consistency

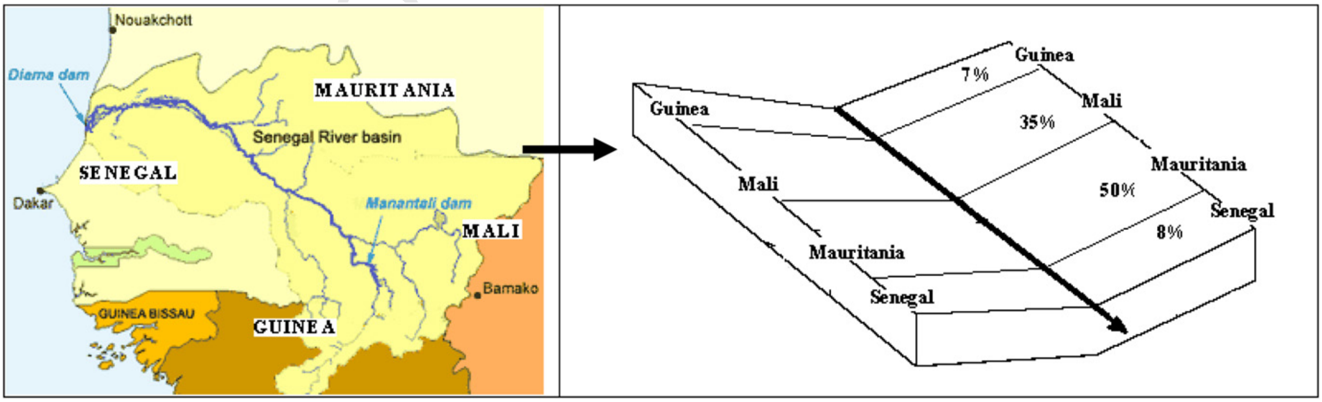

Fig. 4. An open-book watershed idealization of the Senegal IRB. (Left panel) Actual basin with boundary shown in orange dotted line; arrows mark the downstream direction of the main stem of the Senegal river. (Right panel) An open-book watershed of total drainage area of the entire Senegal IRB; each 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.

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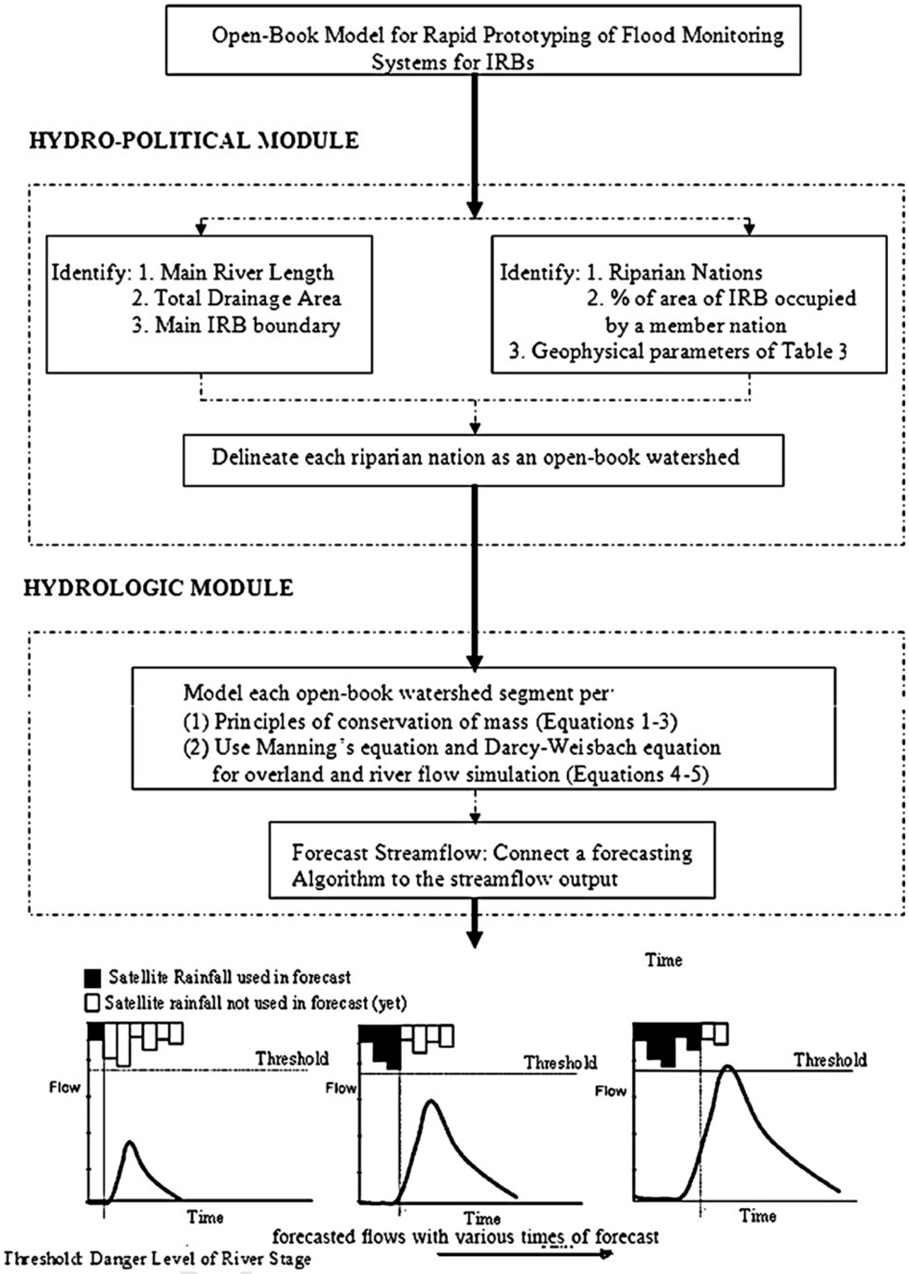

Fig. 5. Algorithmic flowchart summarizing the blueprint for assessment of satellite-based flood forecasting in IRBs. The two major modules are (1) Hydro-political module and (2) Hydrologic Modeling Module. The Hydrologic Modeling Module is applied on the fundamental open-book watersheds for simulating the rainfall-runoff process.

analyses of our model of the following geophysical parameters to the rainfall-runoff transformation process using a hypothetical open-book and a storm event: (1) Impact of initial saturation of soil; (2) Effective soil depth (i.e., soil's total water storage capacity until saturation). The dimensions of the open-book watershed considered was a 9 × 6 grid network at a 200 m grid resolution (9 grids long, 6 grids wide with the river halving the basin into two longitudinal halves). Other pertinent geomorphological parameter values and the rainfall storm used for the sensitivity analyses are shown in Table 3. Rainfall intensity was assumed spatially constant while changing only in time. In addition to these consistency checks, we also conducted numerical stability analyses of our code for various space-time resolutions and identified the stable regions of operation which yielded an accurate closure in mass balance. This was important as the explicit nature of solving the grid-based process equation warranted the proper selection of spatial and temporal steps. An advantage of having an explicit scheme was to use the model in computationally intensive Monte Carlo experiments for assessing error propagation of satellite rainfall error and parameter uncertainty (Hossain and Katiyar, 2006; Wagener and Kollat, in press).

Fig. 6 demonstrates that the model mimics in a manner intuitively expected from hydrologic theory. We observe that the

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Table 3
Open-book geophysical parameters used for verification of the code

Dimension	6 (width) × 9 (length)	Hypothetical rain event	
Grid resolution	100 m	Time (h)	Rainfall (mm/h)
River bed slope	0.001	1	50.0
Valley side slope	0.01	2	100.0
Kinematic viscosity	9.83×10^{-7} m^2/s	3	50.0
Manning's "n"	0.015	4	0.0
Channel width	100 m	5	0.0
Depth to bedrock, D	0.50 m	6	0.0
Saturated hydraulic conductivity, K_s	0.65 cm/h	7	50.0
Porosity, φ	0.50	8	150.0
Field capacity, S_f	0.25	9	50.0

hydrograph peaks are consistent in time with the two rainfall hyetograph peaks (in Table 3). We also observe that the model is noticeably sensitive to initial saturation level of the soil. The overland flow manifests faster for the 100% saturated as well as for the shallower soil (i.e., effective soil depth being 50% shallower than the other cases). The second streamflow peaks however are all similar mainly due to the high rainfall rates which caused the soil to become saturated after the first storm peak. In Fig. 7, we demonstrate the code's ability to honor the mass balance for a few combination of space-time resolutions and open-book watershed sizes. Stable numerical calculations are achieved with the code when the ratio of the spatial resolution (Δx) to temporal resolution (Δt) is greater than 2 m/min.

4. Application of the open-book model

In an application of the open-book model for demonstrating its potential value for prototyping flood forecasting systems in IRBs, we make three major assumptions: (1) dams in regulated rivers do not act as a control structure during the flooding season (e.g. *Farakkha* Barage in the Indian Ganges upstream of Bangladesh); (2) downstream nations in flood-prone IRBs have "adequate" in-situ networks for rainfall measurement; (3) downstream nations in flood-prone IRBs lack access to real-time rainfall data from upstream nations. We chose the region of Oklahoma bounded by −100° W—95° W and 37° N—34° N (Fig. 8) to demonstrate an application of our model using an in-situ and satellite rainfall datasets. This region is under the Oklahoma Mesonet (Brock et al., 1995) comprising a dense network of 114 hydro-meteorological stations and soil moisture probes (Brock et al., 1995; shown in yellow circles in Fig. 8). Rainfall data was derived from radar rainfall fields of WSR-88D observations using the National Weather Service multi-component precipitation estimation algorithm with real-time adjustments based on mean-field radar-rain gauge hourly accumulation comparisons (Fulton et al., 1998). Hereafter, we shall refer to this rainfall as "*reference rainfall*" on account of its high level of accuracy. A hypothetical open-book configuration was implemented over the study region at a 25 km grid resolution (20 grids long and 12 grids wide, Fig. 8) with a longitudinal channel dividing it symmetrically into two halves (of 10 × 6 grids). This configuration accommodated a two-nation IRB with a "movable" political boundary (red line in Fig. 8) to study the impact of integrating satellite rainfall data over upstream nation (discussed next). We selected a period of 4 months (May 1, 2002 to August 31, 2002; daily time steps) for hydrologic simulation. The downstream end of the open-book and the basin outlet was chosen at the eastern side (the region of lowest elevation in Oklahoma). Table 4 summarizes the pertinent geophysical parameters of the open-book model fitted over the region. These parameters were derived using available in-situ data from Mesonet databases. The soil moisture field on May 1, 2002, 00:00 h for initialization of the model was approximated from Mesonet soil moisture measurements and a 6-month spin-up of the NOAH land surface model from a previous study by Hossain and Anagnostou (2005).

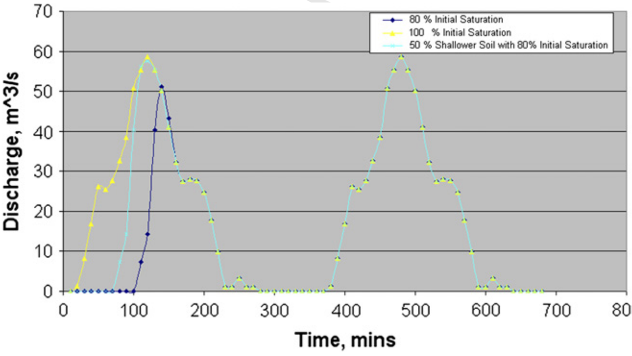

Fig. 6. Physical consistency of the open-book model code.

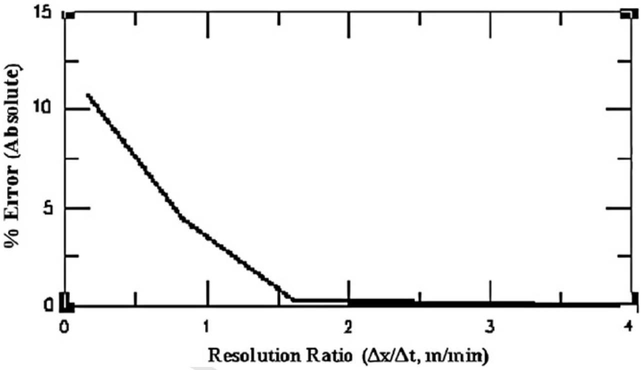

Fig. 7. Numerical accuracy of the open-book model code. Regions of stable space-time scales (x-axis) are shown against the absolute error in the code's ability to honor the mass balance (y-axis).

For assimilation of satellite rainfall data we chose the real-time satellite rainfall data-product produced by NASA—3B41RT. This is a global rainfall data product produced from Infra-red (IR) geostationary platforms at hourly time-steps on a best effort basis. More details on the data product may be obtained by referring to Huffman et al. (2003, in press). We first preprocessed the satellite data to remove the high level of systematic bias (positive) that was observed in the data. Fig. 9 shows the streamflow that is simulated using basin-wide radar rainfall data, which can also be compared with the hydrograph generated with basin-wide IR-3B41RT

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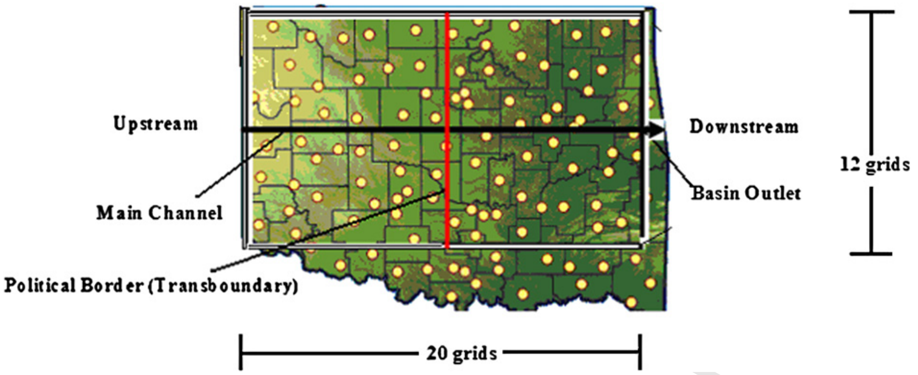

Fig. 8. The Oklahoma study region for application of the open-book model. The yellow circles indicate the location of the Mesonet stations. Red line is the "movable" political border between two nations for the assessment framework. An "international river" is assumed to partition the region into two equal longitudinal halves.

data. [*Note: High discharge values are explained by our choice of a uniform and shallow effective soil depth of 0.5 m throughout the region. For more realistic representation of the effective soil column, findings reported by* Nijssen et al. (2001) *could be used as a starting point in future works*]. For further details on the level of uncertainty of the satellite rainfall data and the reference rainfall data (WSR-88D), the reader is referred to the detailed error analysis presented in the work of Hossain and Anagnostou (2006). For the implication of rainfall data uncertainty on hydrologic simulation by an open-book model, the reader is referred to the work of Hossain and Katiyar (in press).

Next, assuming a 30–70% two nation configuration (downstream and upstream nations occupy 30% and 70% of the total basin area, respectively), we derived the impact of assimilating satellite rainfall data in the upstream nation on the downstream nation's flow monitoring capability (Fig. 10). It is observed that significant improvement can be achieved for a downstream country limited by 70% in acquisition of basin-wide rainfall data.

Finally, in Fig. 11 we derive the relationship between the improvement in flow monitoring accuracy achieved with satellite rainfall data assimilation over the upstream nation versus percentage of basin area occupied by downstream nation. Herein improvement is defined in relative terms as the percentage reduction in streamflow prediction uncertainty for the downstream nation. Prediction uncertainty is quantified on the basis of the relative root mean squared error (RRMSE). While parameter uncertainty will no doubt have an effect in the hydrologic simulation of streamflow per se, we observed that, for a few non-unique parameter sets, the overall relationship between flow monitoring improvement and percentage of basin area occupied by downstream nation remained essentially similar. A more detailed investigation of parameter uncertainty would however be necessary this explore in detail the role of model's parametric uncertainty on assessment of the hydro-political implications of satellite-based flood modeling. In general, relative improvement in flow monitoring accuracy for the downstream nation can be as high as over 100% (when greater than 90% of the basin is transboundary to the downstream nation). However, when 20% or less of the basin area is transboundary to the downstream nation, there is very little to be gained in terms of improvement in flow monitoring accuracy (Fig. 11). It appears that for IR-3B41RT to have non-negligible improvement (>60% reduction in Relative RMSE in streamflow prediction), the downstream nation should not occupy more than 80% of the total IRB area.

As a disclaimer, a few issues need to be articulated herein. Firstly, the assessment derived above is very specific to the hydrologic and flow regime for the semi-arid region of the Southern plains of the United States. Furthermore, the relationship derived above is for a hypothetical case assuming the

Table 4
Open-book model's geophysical parameters for the Oklahoma study region

Dimension	12 (width) × 20 (length)
Grid resolution	25 km
River bed slope	0.005
Valley side slope	0.001
Kinematic viscosity	9.83×10^{-7} m^2/s
Manning's "n"	0.015
Channel width	100 m
Effective soil depth, D	0.50 m
Field capacity, S_f	0.25
Saturated hydraulic conductivity, K_s	0.65 cm/h (silty loam soil)
Porosity, φ	0.50

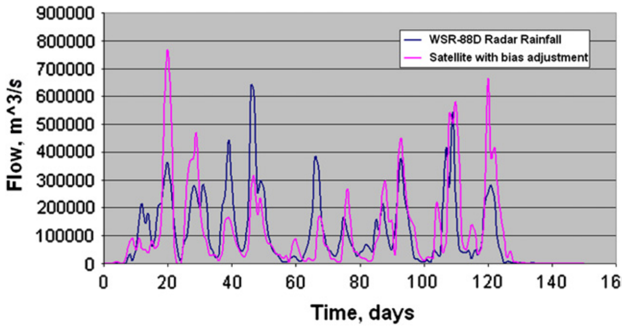

Fig. 9. Simulation of streamflow using basin-wide radar (WSR-88D) rainfall and satellite (IR-3B41RT) rainfall over the Oklahoma Mesonet region.

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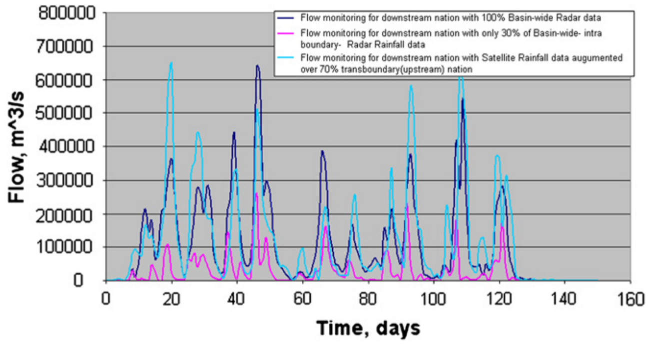

Fig. 10. Impact on flow monitoring for the downstream nation with/without assimilating IR-3B41RT rainfall over upstream nation. The downstream nation is assumed to have access to intra-boundary WSR-88D rainfall data comprising 30% of total basin area.

Oklahoma region as a two nation IRB. The average flows simulated in this case (in the range of ∼100,000–600,000 m^3/s), are very different in magnitude from flows observed in many IRBs, such as the Ganges (∼5000–50,000 m^3/s) or the Brahmaputra basins (∼10,000–100,000 m^3/s). Caution naturally needs to applied in how the relationship derived in Fig. 11 can be interpreted for a global assessment. While interpreting the global implications of Fig. 11, one needs to factor in the variability in flow regime, hydrologic response to rainfall, season, vegetation, topography, climate etc. Nevertheless, our work illustrates very clearly the feasibility of utilizing the anticipated GPM rainfall data in improving the current hydro-political scenario of flood monitoring in IRBs. This illustration should be the primary motivation for initiation of more complex analysis involving a combination of generic approaches, such as the open book model, and complex approaches, such as the fully distributed physically-based models (Hossain et al., in press).

5. Conclusion

A new era of application of simple lumped and complex models may now emerge with the anticipated global availability of high resolution satellite rainfall data from the proposed Global Precipitation Measurement (*GPM*) mission. This era of application pertains to rapid prototyping of *GPM*-based flood monitoring systems for downstream nations in International River Basins (IRBs) where basin-wide in-situ rainfall is unavailable due to lack of either an infrastructure or a treaty for real-time data sharing between riparian nations. In this paper, we have developed, verified and applied an open-book watershed model, as a generic and parsimonious approach, for illustrating the feasibility of utilizing satellite rainfall data in prototyping flood monitoring systems for lowermost nations in IRBs. Preliminary results on the Oklahoma region assuming a hypothetical two-nation IRB have indicated that our proposed open-book watershed modeling framework has potential to qualify as a valuable tool for rapid prototyping of satellite-based flood monitoring systems for lowermost riparian nations in anticipation of the *GPM*. As a general rule of thumb, subject to certain assumptions, our work has identified that, for the specific satellite rainfall data of NASA (IR-3B41RT), that is currently available in real-time, to be effective in improving a downstream nation's flow monitoring capability, the transboundary upstream area should be greater than 20%.

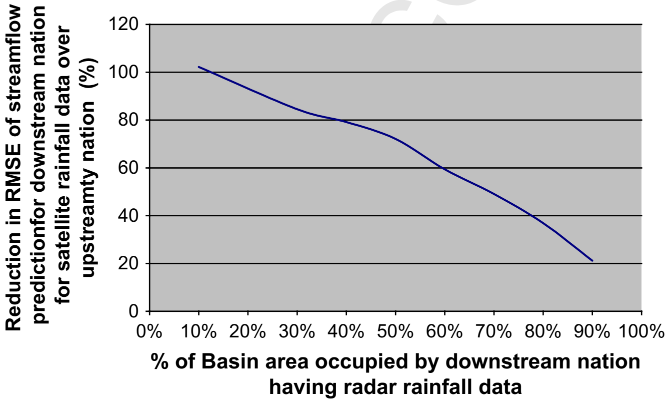

Fig. 11. Impact of assimilating IR-3B41RT rainfall data over upstream nation on the flow monitoring accuracy of the downstream nation. Relationship shown as % reduction in relative root mean squared error in streamflow prediction versus % of basin area occupied by the downstream nation.

There are no doubt, limitations to our approach, with the most notable one being the idealization of riparian nations across political borders in the form of rigid Euclidean geometric configurations. However, we do believe that, at this early juncture of the assessment of anticipated GPM data to overcome hydro-political limitations of flood monitoring in IRBs, especially when there is no preceding work, such a potential limitation alone should not hamper our ability to investigate the usefulness of the proposed framework. While there exists a possibility of mapping the rule of thumb (Fig. 11) globally based on a climate classification scheme, Nijssen et al. (2001) have previously summarized the pitfalls of over-interpreting the Koppen classification approach to transfer inference from one basin to another purely based on climate similarity. For the comprehensive assessment, there is no alternative to repeating the work on the basis of in-situ data sets characterizing the landscape and the dynamic hydrometeorological input for the IRBs.

While testing more rigorously the accuracy of our proposed framework, a wide range of critical questions may also emerge. Such as: *what is the role played by the uncertainty associated with initial soil moisture conditions? How significant is the contribution of stream-flow measurement error on the assessments derived from the open-book framework versus a conventional DEM-based distributed model? What is the relationship between the complexities of topography, vegetation, climate and area of un-gauged drainage region on the accuracy of satellite-based flood forecasting in IRBs?* We believe these questions are important and demand a resolution in a step-by-step manner as we continue to make progress in understanding the utility of satellite rainfall data in overcoming the transboundary limitations of real-time data sharing in flood-prone nations of IRBs. However, we would like to articulate that no amount of effort in trying to resolve these questions can be considered useful until the very model itself has

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been assessed in terms of its consistency to mimic the physical reality to an acceptable level of accuracy. Hence, as natural extension to this work, we intend to perform a more rigorous assessment of our open-book model using a wide range of real-world scenarios involving major IRBs, actual DEM and landscape data. Some of the work of this nature has already begun, and we hope to report them at some point in the future.

Uncited reference

Huffman et al., 2003

Acknowledgments

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