

**Applications of TRMM-based Multi-satellite Precipitation Estimation for Global  
Runoff Simulation: Prototyping a Global Flood Monitoring System**

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**Capsule Summary:**

**A modular-structured framework that incorporates satellite-based near real-time rainfall  
flux into a cost-effective hydrological model for flood modeling quasi-globally**

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## **Abstract**

Advances in flood monitoring/forecasting have been constrained by the difficulty in estimating rainfall continuously over space (catchment-, national-, continental-, or even global-scale areas) and flood-relevant time scale. With the recent availability of satellite rainfall estimates at fine time and space resolution, this paper describes a prototype research framework for global flood monitoring by combining real-time satellite observations with a database of global terrestrial characteristics through a hydrologically relevant modeling scheme. Four major components included in the framework are (1) real-time precipitation input from NASA TRMM-based Multi-satellite Precipitation Analysis (TMPA); (2) a central geospatial database to preprocess the land surface characteristics: water divides, slopes, soils, land use, flow directions, flow accumulation, drainage network etc.; (3) a modified distributed hydrological model to convert rainfall to runoff and route the flow through the stream network in order to predict the timing and severity of the flood wave, and (4) an open-access web interface to quickly disseminate flood alerts for potential decision-making. Retrospective simulations for 1998-2006 demonstrate that the Global Flood Monitor (GFM) system performs consistently at both station and catchment levels. The GFM website (experimental version) has been running at near real-time in an effort to offer a cost-effective solution to the ultimate challenge of building natural disaster early warning systems for the data-sparse regions of the world. The interactive GFM website shows close-up maps of the flood risks overlaid on topography/population or integrated with the Google-Earth visualization tool. One additional capability, which extends forecast lead-time by assimilating QPF into the GFM, also will be implemented in the future.

**Keyword: Satellite Precipitation, Global Flood Modeling, TRMM**

## 1. INTRODUCTION

Floods impact more people globally than many other type of natural disaster (World Disasters Report, 2003) and they usually return every year in flood-prone regions. It has been established by experience that the most effective means to reduce the property damage and loss of life caused by floods is the development of flood warning systems (Negri et al., 2004). However, progress in large scale flood warning has been constrained by the difficulty of measuring the primary causative factor, i.e. rainfall fluxes, continuously over space (catchment-, national-, continental-, or even global-scale areas) and time (hourly to daily), due largely to insufficient ground monitoring networks, long delay in data transmission and absence of data sharing protocols among many geopolitically trans-boundary basins (Hossain, F. and D. P. Lettenmaier 2006). In addition, in-situ gauging stations are often washed away by the very floods they are designed to monitor, making reconstruction of gauges a common post-flood activity around the world (Asante et al. 2007), e.g., Hurricane Katrina in 2005 and Mozambique flood in 2000. In contrast, space-borne sensors inherently estimate precipitation across international basin boundaries and can not be destroyed by flooding. In reality, satellite-based precipitation estimates may be the only source of rainfall information available over much of the globe, particularly for developing countries in the tropics where abundant extreme rain storms and severe flooding events repeat every year. For instance, the Mekong River Commission, a partner in the Asia Flood Network, began downloading Tropical Rainfall Measuring Mission (TRMM) real-time data since 2003 to help calculate rainfall for the international Mekong River basins, located in China, Cambodia, Laos, Thailand, and Vietnam. These facts highlight the opportunity and need for researchers to develop alternative satellite-based flood warning systems that may supplement in-situ infrastructure for uninterrupted monitoring of extreme rainfall and

dissemination of flood alerts when conventional data sources are denied due to natural or administrative causes (Asante et al., 2007; Hong et al., 2007a).

Building on progress in remote sensing technology, researchers have improved the accuracy, coverage, and resolution of satellite-based rainfall estimates by combining imagery from infrared, passive microwave, and space-borne weather radar sensors (Adler et al., 2003). Today, multi-satellite imagery acquired and processed in real time can now provide near-real-time rainfall fluxes at relatively fine spatiotemporal scales (kilometers to tens of kilometers and 30-minute to 3-hour). These new suites of rainfall products have the potential for analyzing sub-daily variations and extreme flooding events. Shown in Fig. 1 is an example of quasi-global “heavy rain” event maps that are displayed at TRMM website. The map shows the areas (in red) over land that has accumulated rain totals from a flow of TRMM-based real-time precipitation estimation above a pre-selected threshold. Using such a simple rainfall threshold-based rain map, researchers and decision-makers alike can look at the evolution of regional to global scale events on a daily basis. For example, Fig. 1b identifies the spring flooding of the Southeast of United States, wherein data from TRMM and other satellites estimated more than 16 inches of rain in the regions of Tennessee, Alabama and Georgia during May 4-9, 2003. Figure 1c shows the corresponding rain accumulation that exceeded 35 mm per hour over the 5 day period (left panel); while the right panel shows that after 85 hours, rain totaled 472.7 mm within a 200 km radius surrounding Nashville, TN.

While these global heavy rain outlooks on emerging flooding events are potentially useful, this rainfall threshold-based approach has limited implications from a terrestrial hydrologic perspective. First, they are independent of terrain, soil type, soil moisture and vegetation. Furthermore, they do not take into consideration the local/regional hydrologic regimes that

determine the pertinent rainfall-runoff relationships. As a result, such a simple statistical approach of thresholds is inadequate in capturing the spatiotemporal variability of estimated runoff and consequently, does not optimally extract valuable hydrologic information contained in rainfall fluxes estimated by satellites. Improvement is particularly important in anticipating the planned Global Precipitation Measurement (GPM) mission that beckons hydrologists as an opportunity to improve flood prediction capability for medium to large river basins, especially in the underdeveloped world where ground instrumentation is absent. The GPM mission (<http://gpm.gsfc.nasa.gov>) is envisioned as a constellation of operational and dedicated research satellites to provide microwave-based precipitation estimates for the entire globe. Hossain and Lettenmaier (2006) have argued that before the potential of GPM can be realized, there are a number of hydrologic issues that must be addressed prior to the adoption of global satellite rainfall datasets in hydrologic models. Accuracy, in particular, will depend on the sensible use of the spatiotemporally varying rainfall fluxes as derived from satellites and not on the accumulated rainfall volumes that are currently adopted in thresholding techniques.

This paper describes a module-structured framework for Global Flood Monitoring (GFM) that integrates the TRMM-based multi-satellite forcing data (Huffman et al., 2007) with a simplified hydrological model (Hong et al., 2007b), which can be parameterized by a tailored geospatial database, in an effort to evolve toward a more hydrologically-relevant flood modeling system with direct rainfall input from real-time satellite nowcasting or quantitative precipitation forecasting (QPF). This system is now running in real-time in an experimental mode with results being displayed on the TRMM web site, specifically [http://trmm.gsfc.nasa.gov/publications\\_dir/potential\\_flood\\_hydro.html](http://trmm.gsfc.nasa.gov/publications_dir/potential_flood_hydro.html). A major outcome of this framework is the availability of a global overview of flooding conditions that quickly

disseminate through an open-access web-interface. We expect these developments in utilizing satellite remote sensing technology to offer a practical solution to the challenge of building a cost-effective early warning system for data-sparse and under-developed areas. Additionally, through the use of more hydrologically relevant approaches, we hope this framework will spur meteorologists engaged in satellite rainfall data production to communicate more effectively with hydrologic modelers for development of GPM satellite rainfall algorithms (Hong et al., 2006; Hossain and Lettenmaier, 2006).

### **Figure 1**

## **2. A Quasi-GLOBAL SATELLITE-BASED FLOOD MONITORING Framework**

Shown in Figure 2 is the conceptual framework for the GFM that puts forward a computationally simplified hydrological model to predict floods quasi-globally using a combination of data from the TRMM-based multi-satellite products, Shuttle Radar Topography Mission (SRTM), and other global geospatial data sets such as soil property and land cover types. This framework is modular in design with the flexibility that permits changes in the model structure and in the choice of components. Four major components included in the framework are 1) multi-satellite high-resolution precipitation products; 2) characteristics of land surface including elevation, topography-derived hydrologic parameters such as flow direction, flow accumulation, basin, and river network; 3) spatially distributed hydrological models to infiltrate rainfall and route overland runoff; and 4) an implementation interface to relay the input data to the models and display the flood inundation results on website. The simulation results must be updated at regular intervals (~3hr), requiring computational efficiency in transferring space-borne observations into the operational web-based flood mapping interface, even at the expense of some loss of detail and

accuracy. Another note is that the flexible module-structured framework also allows for optimal use of grid-based precipitation flux fields from multiple sources, including *in situ*, satellite, and numerical model forecasts.

### ***2.1 Precipitation Input***

Precipitation displays high space-time variability that requires frequent observations for adequate representation. Such observations are not possible through surface-based measurements over much of the globe, particularly in oceanic, remote, or developing regions (Huffman et al., 2007). Continued development in the estimation of precipitation from space has culminated in sophisticated satellite instruments and techniques to combine information from multiple satellites to produce precipitation products at long-term coarse scale (Adler et al., 2003) and short-term finer time-space scales useful for hydrology including flood analysis (Sorooshian et al. 2000; Kidd et al. 2003; Joyce et al. 2004; Hong et al., 2004; Turk and Miller 2005; Huffman et al., 2007). The key data set used in the framework is the TRMM Multi-satellite Precipitation Analysis (TMPA; Huffman et al. 2007), which provides a calibration-based sequential scheme for combining precipitation estimates from multiple satellites, as well as gauge analyses where feasible, at fine scales ( $0.25^{\circ} \times 0.25^{\circ}$  and 3-hourly) over the latitude band  $50^{\circ}\text{N-S}$  (<http://trmm.gsfc.nasa.gov>). The TMPA is a TRMM standard product computed for the entire TRMM period (January 1998-present) and is available both in real time and retrospectively. Although Huffman et al. (2007) verified that the TMPA is successful at approximately reproducing the surface-observation-based histogram of precipitation, as well as reasonably detecting large daily events, properly characterizing the impact of the rainfall estimation error structure on hydrological response uncertainty at small scales remains to be carried out.

Over much of the globe, remote sensing precipitation estimates may be the only available source of rainfall information, particularly in real time. Correspondingly, remote sensing has increasingly become a viable data source to augment the conventional hydrological rainfall-runoff simulation, especially for inaccessible regions or complex terrains, because remotely sensed imageries are able to monitor precipitation and identify land surface characteristics such as topography, stream network, land cover, vegetation etc. Artan et al. (2007) demonstrated the improved performance of remotely sensed precipitation data in hydrologic modeling when the hydrologic model was re-calibrated with satellite data rather than gauge rainfall over four subbasins of the Nile and Mekong Rivers.

## ***2.2 A Central Geospatial Database***

A central geospatial database describing the land surface (topography, land cover, and soils etc.) is needed to derive comprehensive parameter sets for linking the precipitation input with hydrological flood simulation models. The basic topography data considered in this system include NASA SRTM (<http://www2.jpl.nasa.gov/srtm/>) and U.S. Geological Survey's GTOPO30 (<http://edcdaac.usgs.gov/gtopo30/gtopo30.html>). The 30m horizontal resolution provide by SRTM data is a major breakthrough in digital mapping of the world, particularly for large portions of the developing world. The digital elevation data are used to derive topographic factors (slope, aspect, curvature etc) and hydrological parameters (river network, flow direction, and flow path). Global soil property data sets are taken from Digital Soil of the World published in 2003 by the Food and Agriculture Organization of the United Nations (<http://www.fao.org/AG/agl/agll/dsmw.htm>) and the International Satellite Land Surface Climatology Project Initiative II Data Collection (<http://www.gewex.org/islscp.html>). The soil

parameters used in this study are soil property information (including clay mineralogy and soil depth) and 12 soil texture classes, following the U.S. Department of Agriculture soil texture classification (including sands, loam, silt, clay, and their fractions). The Moderate Resolution Imaging Spectroradiometer (MODIS) land classification map is used as proxy of land cover/uses at its highest (250-meter) resolution (Fridel et al. 2002). Figure 3 lists several parameters, flow direction and river basins, derived from the geospatial database. A large proportion of the supporting data for implementing the hydrological models is also available from the NASA Goddard Global Land Data Assimilation System (Rodell et al., 2004).

### ***2.3 A Cost-Effective Hydrological Simulation Model***

Many hydrological models have been introduced in the hydrological literature to predict runoff (Singh, 1995) but few of these have become common planning or decision-making tools (Choi et al., 2002), either because the data requirements are substantial or because the modeling processes are too complicated for operational application. Our initial pool of candidate hydrological simulation models included a number of distributed hydrological models (Singh, 1995; Chen et al., 1996; DHI, 1999; Liang et al., 1994; Beven and Kirkby, 1979; Coe, 2000 etc.). However, many of these models are extremely time-consuming when used to update global flood simulation results at sub-daily scale. They require not only more parameterization of the hydrological processes, but additional climate variable such as air temperature or net radiation, vapor pressure and wind speed, which are not always available in real time and also introduce uncertainty due to their unknown error characteristics. Trade-offs between efficiency and complexity in terms of the quantity and quality of the data available to meet model input requirements and the modeling components to implement (Choi et al., 2002) argue for a simplified model in the current works that:

- (1) Treats only the most important processes related to the hydrological problem to be considered (i.e., flood);
- (2) Allows the model to evolve as more data become available or as the modeler gains insight during the modeling process; and
- (3) is ready to use, accepting a certain loss of detail and accuracy.

In fact, such simplification is already an accepted methodology among hydrologists to allow the hydrologic modeling effort evolve to the global solution through an iterative process (Klemes, 1983). Additionally, for rainfall-runoff simulation alone, parsimonious models often perform as well as sophisticated ones (Jian et al., 1992; Duan et al., 2003). Hence, we adopt the Hydrologic Engineering Center (HEC) Hydrologic Modeling System (HMS) developed by US Army Corps of Engineers (USACE, 2002). The HEC-HMS improves upon the capability of the predecessor HEC-1, providing additional capabilities for distributed modeling and continuous simulation (USACE, 2002).

### Figure 2: Framework

## **3. A Cost-Effective Hydrological Model**

### 3.1 HEC-HMS and NRCS-CN

The HEC-HMS improves upon the capability of the predecessor HEC-1, providing additional capabilities for distributed modeling and continuous simulation (USACE, 2002). Its simplicity is especially critical for the vast un-gauged regions and geopolitically trans-boundary basins of the world. In a literature review, Choi et al. (2002) concluded that NRCS-CN has useful skill because it responds to major runoff-generating properties including soil type, land/use/treatment, and soil moisture conditions. They point out that it has been successfully applied to situations that include simple runoff calculation (Heaney et al., 2001), assessment of long-term

hydrological impact on land use change (Harbor, 1994) for tens of years, stream-flow estimation for watersheds with no stream flow records (Bhaduri et al., 2000), and comprehensive hydrologic/water quality simulation (Srinivasan and Arnold, 1994; Engel, 1997; Burges et al., 1998; Rietz and Hawkins, 2000). Recently, Curtis et al. (2007) used satellite remote sensing rainfall and gauged runoff data to estimate CN for basins in eastern North Carolina. Harris and Hossain (2007) found that simpler approaches such as the NRCS-CN method to be more robust than more complicated schemes for the levels of uncertainty that exist in current satellite rainfall data products. On the other hand, we note the risks of implementing this, or any other method without fully understanding its associated ‘uncertainty’. As such, we adopt the NRCS-CN method to estimate a first-cut global runoff by taking advantage of the multiply years of rainfall estimates from the Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA; Huffman et al., 2007). The NRCS-CN method generates runoff as a function of precipitation, soil property, land use/cover, and hydrological condition. The later three factors are empirically approximated by one parameter, CN. Following methodology adopted from the standard lookup tables in USDA (1986) and NEH-4 (1997), we derived a global CN map from infiltration characteristics of soils classified by USDA-NRCS (2005) and the MODIS land cover classification, at long-term averaged soil wetness conditions (Hong and Adler, 2008). The NRCS-CN values are updated by using a 5-day normalized Antecedent Precipitation Index (API) from TRMM as a proxy of antecedent moisture conditions (Hong et al., 2007b).

### **3.2 Mapping NRCS-CN**

One distinct advantage of HEC-HMS is a multi structured hydrologic modeling that allows selection of a variety of rainfall-runoff modeling schemes (USACE, 2002). For our framework

we use the US Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) method of gridded Curve Number (NRCS-CN; USDA, 1986) for excess rainfall generation component and the ModClark (Feldman, 2000) method for sub-basin surface runoff routing through gridded river networks. USGS research groups have proved that the NRCS-CN method is cost-effective to simulate surface runoff process in their Geospatial Stream Flow Model (Artan et al., 2001; Asante et al., 2007). The data sets (i.e., precipitation, soil information, and land cover) required by the NRCS-CN runoff generation scheme are all available globally with a well-established record in Earth system analysis (Fekete et al., 2000). Information on soil properties is obtained from the Digital Soil of the World published in 2003 by Food and Agriculture Organization of the United Nations (<http://www.fao.org/AG/agl/agll/dsmw.htm>). The Moderate Resolution Imaging Spectroradiometer (MODIS) land classification map is used as a surrogate for land use/cover, with 17 classes of land cover according to the International Geosphere-Biosphere Programme classification (Fridel et al., 2002). Routing information is taken from the HYDRO1k (<http://lpdaac.usgs.gov/gtopo30/hydro/>), which provides global coverage of topography such as elevation, slope, and flow direction etc. These geo-referenced datasets are of value for users who need to run hydrologic models on both regional and global scales.

The NRCS-CN estimates surface runoff as a function of precipitation, soil type, land cover, and antecedent moisture conditions. The latter three factors are usually approximated by one parameter, the CN (USDA, 1986). In this case, the set of Equations (1-2) is used to partition rainfall into runoff and infiltration:

$$Q = \frac{(P - IA)^2}{(P - IA + PR)} \quad (1)$$

$$PR = \frac{25,400}{CN} - 254 \quad (2)$$

where  $P$  is rainfall accumulation (mm/day);  $IA$  is initial abstraction;  $Q$  is runoff generated by  $P$ ;  $PR$  is potential retention;  $CN$  is the runoff curve number, with higher  $CN$  associated with higher runoff potential; and  $IA$  was approximated by  $0.2PR$ .

$CN$  values are approximated from the area's hydrologic soil group (HSG), land use/cover, and hydrologic condition, the two former factors being of greatest importance in determining its value (USDA, 1986). First, following the USDA (1986) handbook, a global HSG map is derived from the digital soil classification which includes 13 textural classes, an important indicator for infiltration rate (Table 1). Given “fair” moisture condition (defined below), the MODIS land cover classification and the HSG map are used to estimate  $CN$  by indexing into the standard lookup tables in USDA (1986) and NEH-4 (1997). Thus, for a watershed on a coarse grid, a composite  $CN$  can be calculated as:

$$CN_{com} = \frac{\sum A_i CN_i}{\sum A_i} \quad (3)$$

In which  $CN_{com}$  is the composite  $CN$  used for runoff volume computations;  $i$  = the index of subgrids or watershed subdivisions.  $A_i$  = the drainage area of area  $i$ .

### 3.3. Time-variant NRCS-CN and Runoff Simulation

Note that the  $CN$  values obtained from Equations 1-3 are for the “fair” hydrologic condition from standard lookup tables, which are used primarily for design applications. However, for the same rainfall amount there will be more runoff under wet conditions than under dry. In practice, lower and upper enveloping curves can be computed to determine the range of  $CN$  according to the Antecedent Moisture Conditions (AMC):

$$CN_i^I = \frac{CN_i^{II}}{2.281 - 0.01281CN_i^{II}} \quad (4)$$

$$CN_i^{III} = \frac{CN_i^{II}}{0.427 + 0.00573CN_i^{II}} \quad (5)$$

Where upper subscripts indicates the AMC, *I* being dry, *II* normal (average), and *III* wet (Hawkins 1993). The change of AMC is closely related to antecedent precipitation (NEH-4, 1997). We apply the concept of an Antecedent Precipitation Index (API) to provide guidance on how to estimate the variation of CN values under dry or wet antecedent precipitation conditions. Kohler and Linsley (1951) define API as:

$$API = \sum_{t=-1}^{-T} P_t k^{-t} \quad (6)$$

Where T is the number of antecedent days, k is the decay constant, and P is the precipitation during day t. The model is also known as “retained rainfall” (Singh 1989). Decay constant *k* is the antilog of the slope on a semi-log plot of soil moisture and time (Heggen, 2001). API practice suggests that k is generally between 0.80 and 0.98 (Viessman and Lewis 1996). Here we use decay constant k as 0.85 for demonstration purpose. API generally includes moisture conditions for the previous five days (or pentad; NEH-4, 1997). In order to obtain time-variant CN, the site-specified API is first normalized as:

$$NAPI = \frac{\sum_{t=-1}^{-T} P_t k^{-t}}{\bar{P} \sum_{t=-1}^{-T} k^{-t}} \quad (7)$$

Where T=5 for pentads, the numerator is API, and the denominator is a normalizing operator with two components: average daily precipitation  $\bar{P}$  and the  $\sum k^{-t}$  series. The “dry” condition is

defined as  $NAPI < 0.33$ , the “wet” condition is defined as  $NAPI > 3$ , and the intermediate range  $0.33 \sim 3$  is the “fair” hydrological condition. By definition, the surface moisture conditions are delineated as dry (or wet) if any pentad API is less than one third (or larger than three times) of the climatologically averaged pentad API, and fair conditions for all others. Summarizing, the CN can be converted to dry, fair, or wet condition using Equations 4-7 according to the moisture conditions approximated by the pentad NAPI. Using the multi-year (1998-2006) satellite-based precipitation dataset from NASA TRMM, the 9-year climatological pentad API is shown in Figure 3a. Thus, given any date, the pentad NAPI can be determined and thus CN can be updated with Equations (4)-(7). For example, on Aug. 25<sup>th</sup>, 2005, the pentad rainfall accumulation, pentad NAPI, resulting hydrological conditions (dry, fair, or wet), and the updated CN on the same date are shown in Figures 3b, 3c, 3d, and 3e, respectively. Note that part of text in Section 3.2 and Section 3.3 are from previous publication by Hong et al., 2007b.

### **Figure 3**

## **4. IMPLEMENTATION OF THE GFM**

### **4.1 Retrospective Simulation**

The global CN map enables estimation of runoff by partitioning gridded satellite-based precipitation estimates, particularly useful at places lacking in-situ gauge data. After that, the ModClark is used for routing the overland flow based on first-order linear differential equations (Olivera et al., 2000). Surface topography data from the geospatial database are used to define river networks and sub-catchments on a global basis (e.g. Fig. 4). Information regarding soils, land cover, and topography from the geospatial database is used for delineating and parameterizing catchments and basin reaches, and the precipitation data is from TMPA.

#### Figure 4: Global Basins and River Networks

Driven by multiyear remote sensing rainfall, the NAPI and NRCS-CN methods are first used to compute the surface runoff for each grid independently and to subsequently route the surface runoff to the watershed outlet through downstream cells [U.S. Army Corps of Engineers, 2000]. Quasi-global runoff data are thus simulated from this framework over the entire time span (1998-2006) of TMPA dataset at 3-hour time scale and simulation results were compared to Global Runoff Data Center (GRDC) rainfall and runoff data, which are quality controlled and objectively analyzed to a  $0.5^\circ \times 0.5^\circ$  latitude-longitude grid (Fekete et al., 2000). Finally, simulated quasi-global runoff is evaluated with Global Runoff Data Center (GRDC) observed runoff (B. M. Fekete et al., Global Composite Runoff Data Set (v1.0), Complex System Research Center, University of New Hampshire, Durham, 2000, available at <http://www.grdc.unh.edu>, hereinafter referred to as Fekete et al., Global Composite Runoff Data Set (v1.0), 2000) and water balance model-simulated runoff [Thorntwaite and Mather, 1955; Steenhuis and Van der Molen, 1986; Vorosmarty et al., 1998].

The TRMM-simulated runoff (TRMM-CN) is compared with the three sets of GRDC annual runoff fields: observed (OBS), water balance model (WBM)-simulated, and composite (CMP) from the OBS and WBM (Fekete et al., Global Composite Runoff Data Set (v1.0), 2000). The WBM used the water balance model of Thorntwaite and Mather [1955] with a modified potential evaporation scheme from Vorosmarty et al. [1998], driven by input monthly air temperature and precipitation from Legates and Willmott [1990a, 1990b]. Note that the three GRDC runoff data span a period of incomplete data records (1950–1979), while the TRMM-CN runoff is simulated for 9 years (1998–2006) of satellite rainfall with complete spatiotemporal coverage. One assumption here is that the change of rainfall between the two time periods is

small enough so that the resulting runoff climatology is spatially consistent. Table 1 shows that the TRMM-CN runoff corresponds more closely with the WBM, having a relatively high correlation and low error. An intercomparison with the GRDC runoff observation demonstrates that the WBM has a moderate advantage over the TRMM-CN runoff: The correlation and root-mean-square difference (RMSD) between the GRDC OBS and WBM are 0.81 and 159.7 mm/yr (or 0.44 mm/d), respectively, which is slightly better than for the TRMM-CN case (Table 1).

Table 1 TRMM-CN Runoff Climatology in the Latitude Band 50S–50N Compared to GRDC Observed, Water Balance Model, and the Later Two Composite Runoff<sup>a</sup>

	GRDC Runoff Climatology		
Statistics	OBS	WBM	CMP
Corr. Coef.	0.75	0.80	0.79
Bias ratio	1.28	1.12	1.12
RMSD	0.56mm/day	0.48mm/day	0.51mm/day

<sup>a</sup>Abbreviations are OBS, observed; WBM; water balance model; CMP, composite; and RMSD, root-mean-square difference [Source: Hong et al., 2007b].

Figure 5a shows the annual mean runoff (mm/yr) driven by TRMM daily precipitation for the same 9-year period in comparison with the GRDC-observed runoff climatology (Figure 5b). Note that the gray areas indicate no data or water surface in Figures 5a and 5b. By averaging areas covered by both TRMM-CN and GRDC runoff data, Figure 5c shows the TRMM-CN runoff zonal mean profile against the OBS, WBM, and CMP. In general, the TRMM-CN zonal mean runoff follows more closely the three GRDC runoff profiles in the Northern Hemisphere than in the Southern Hemisphere. We believe that this difference is the result of having many more samples in the Northern Hemisphere as well as more accurate GRDC data. Considering the TRMM-CN runoff difference as a function of basin area shows the TRMM-CN performance

deviates more for basins smaller than 10,000 km<sup>2</sup>, with significantly better agreement for larger basins (Figure 6).

Figure 5

Figure 6

Fig. 7a shows the locations of GRDC gauge stations, which represents 72% catchment coverage of actively discharging land surface (excluding Antarctica, the glaciated portion of Greenland and the Canadian Arctic Archipelago). Fig. 7b provides the scatterplot for all annual mean rainfall and runoff matchups of GRDC and TMPA. Both the rainfall and runoff scattergrams are quite consistent, with correlation coefficient above 0.8. However, it also indicates that TMPA overestimated at high range of rainfall and low range of runoff values, causing positive bias 0.57% and 7.74% comparing to GRDC, respectively. The likely explanation is that a wind loss correction is applied to the gauge data used in the TMPA, but not to the GRDC. In contrast to the point comparison in Fig. 7, basin-averaged runoff scattergrams in Fig. 6 show that TRMM runoff significantly underestimated runoff over small basins and increasingly performed better for larger basins. For more evaluation results of this simulation framework, please refer to Hong et al., 2007b.

Figure 7

#### **4.2 Implementation Interface**

Since 2007, the GFM trial version has been operating at near real-time on NASA TRMM website in an effort to offer a practical cost-effective solution to the ultimate challenge of building flood early warning systems for the data-sparse regions of the world. A hydrograph of rainfall-runoff time series is simulated for each grid and basin; and the hydrograph estimates are the basis for a web-based interface that displays color-coded maps of flood potentials by

comparing current surface runoff with a predefined water depth or bankfull flow value. The interactive GFM website shows close-up maps of the flood risks overlaid on topography and integrated with the Google-Earth visualization tool ([http://trmm.gsfc.nasa.gov/publications\\_dir/potential\\_flood\\_hydro.html](http://trmm.gsfc.nasa.gov/publications_dir/potential_flood_hydro.html)).

Shown in Fig.8 are examples of flood events detected and displayed by the framework. As shown in the example in Fig. 8, the GHS-Flood diagnosed flooding events in Mozambique in Feb. 2007 as the result of tropical cyclone Favio. This event was verified by Reuters News reports: 69+ dead and more than 120,000 lives affected. The hydrograph estimates are the basis for a Web-based interface that displays color-coded maps of flood risk by comparing current surface runoff in each grid box with a predefined water depth or bank-full flow value. Figure 8c shows a map of excess water depth due to heavy rainfall from tropical cyclone George that caused widespread flooding in the northwestern Northern Territory, Australia, on March 5, 2007. This event is shown as an example of the current Web interface: a quasi-global interactive map with flood potential areas highlighted in red and close-up maps of the flood potential overlaid on topography or integrated with Google-Earth visualization tools.

Shown in Fig. 8d is the 9-year rainfall-runoff simulation results over the Limpopo Basin, Southern Africa. The runoff spikes in Feb. 2000 indicate the catastrophic Mozambique flood disaster within the TMPA's limited 9-year span. On February 27, floods inundated low farmlands in the worst flooding event in Mozambique for last 55 years (ARPAC, 2000). Two million people were affected by the floods, 50,000 lost homes, and about 800 were killed. The flood also had a tremendous effect on agriculture in Mozambique, destroying 1,400 square kilometers of cultivated and grazing land, leaving 113,000 small farming households with nothing, and damaging 90% of the country's functioning irrigation infrastructure. One year later,

another severe flood occurred in late February, 2001, caused by heavy seasonal rains (Fig. 7d), which killed 52 people and displaced almost 80,000 in the central Zambezi Valley of Limpopo basin (FAO, 2001). Fig 8b shows the 2007 flood in Mozambique, which worsened when Category 4 Cyclone Favio made landfall on February 22. The United Nations Office for the Coordination of Humanitarian Affairs reported approximately 121,000 people displaced. However, U.S. Agency for International Development (USAID) cited Mozambique's response to 2007 flood as a success: "Deaths from this year's disasters were kept to a minimum – less than 100 -- due largely to the timely response and efficiency of Mozambican emergency operations", according to USAID regional director, Jay Knott in Mozambique. Overall, U.S. humanitarian and development aid to Mozambique amounted to \$150 million in 2006, with \$200 million sought by the Bush administration for 2007. The TRMM website (<http://trmm.gsfc.nasa.gov>) provides more extreme rainfall and flooding examples.

Figure 8

## **5. SUMMARY AND DISCUSSION**

### **5.1 Summary**

Satellite rainfall observations acquired in real time are valuable in improving our understanding of the occurrence of flood hazardous events and in lessening their impact on the local economies and reducing injuries around the world. This chapter describes a practical modular-structured framework, Global Flood Modeling (GFM) that predicts surface runoff by incorporating NASA TRMM-based multi-satellite real-time precipitation estimates into a cost-effective hydrological model that includes parameters from high-resolution topography and other geospatial data sets. As shown in Figure 2, this framework includes four major components: (1) a real-time satellite-

based precipitation measuring system; (2) a geospatial database containing global land surface characteristics; (3) a spatially distributed hydrological model; and (4) an open-access web interface.

Given the increasing availability of global geospatial data describing land surface characteristics, we adopt the Hydrologic Engineering Center (HEC) Hydrologic Modeling System (HMS) developed by US Army Corps of Engineers (USACE, 2002). The HEC-HMS improves upon the capability of the predecessor HEC-1, providing additional capabilities for distributed modeling and continuous simulation. The runoff generation method is the NRCS-CN that determines runoff as a function of precipitation, soil property, land use/cover, and hydrological conditions. The later three factors are empirically approximated by one parameter, the CN. First, this study estimated a global CN map primarily based on soil property and land use/cover information under the “fair” moisture condition. Then using Antecedent Precipitation Index (API) from TRMM rainfall as a proxy of initial moisture conditions, this study further estimated time-variant CN values bounded by dry and wet moisture conditions approximated by pentad normalized API (Hong et al., 2007b). Finally, driven by 3-hour TMPA precipitation estimates, quasi-global runoff was simulated with this framework for period of 1998-2006. Compared to GRDC runoff, this framework provides consistent estimation of runoff at both stations and medium-to-large basins. Currently, the framework operationally runs in near-real-time and updates flood conditions every 3 hours with the most current satellite-based rainfall maps ([http://trmm.gsfc.nasa.gov/publications\\_dir/potential\\_flood\\_hydro.html](http://trmm.gsfc.nasa.gov/publications_dir/potential_flood_hydro.html)).

## **5.2 Discussion and Future Work**

Our effort is a first approach to understanding a challenging problem that lies ahead in advancing satellite-based global runoff monitoring. Thus, the use of NRCS-CN should not be construed as a call for replacement of other more advanced methods for rainfall-runoff simulation. We expect that the successes and limitations revealed in this study will lay the basis for applying more advanced methods to capture the dynamic variability of the hydrologic process for global runoff monitoring in real time. Although this study is able to demonstrate the potential of using this framework for quasi-global flood monitoring when driven by satellite-based rainfall estimates, there remain several unanswered questions: First, among many methods to estimate CN values, Hawkins (1993) recognized that remote sensing data may not be adequate to define the “true” value of a CN. Thus, field surveys of basin characteristics should be conducted where feasible in order to obtain “true” soil and land cover data. Second, while this study recognized the uncertainty of the estimates of actual CN values and assumed that they likely fall within the enveloping wet (upper) and dry (lower) conditions approximated by the 5-day Normalized API, it may be possible to adjust the CN more precisely to account for local or regional information. Finally, one major unaddressed hydrological concern for rainfall-runoff applications of remotely sensed precipitation is the thorough evaluation of satellite-based rainfall estimation error and its nonlinear influence on rainfall-runoff modeling uncertainty in varying landscapes and climate regimes (Hong et al., 2006; Hossain and Anagnostou, 2006; Villarini and Krajewski, 2007). Thus, while we conclude that this cost-effective framework seems to provide a reliable tool when using coarse resolution satellite precipitation data, we also urge similar studies using more sophisticated hydrological models, particularly seeking to serve the vast un-gauged regions and geopolitically trans-boundary basins of the world.

As an initial step to evolve toward a more hydrologically-relevant approach that can make better use of the valuable information contained in the state-of-the-art satellite precipitation data, the modular-structured framework allows the use of new components and the integration of locally existing flood management tools into a global flood alert system. One on-going activity is to continue calibrating and regionalizing this system with local in-situ data when they become available. Additionally, more complex hydrological models can be modified and implemented at regional or local scales by subsetting the TRMM rainfall input data. An important improvement to the GFM will be to link it to the NASA Land Information System (LIS; Peters-Lidard et al., 2004), allowing for use of LIS databases, local in-situ data, and various hydrological models. Particularly, we will utilize the LIS platform to improve/regionalize the land surface modeling capability (e.g. VIC) and the associated meteorological data. The LIS will provide three types of inputs for local regionalization: 1) Initial conditions, which describe the initial state of the land surface; 2) Boundary conditions, which describe both the upper (atmospheric) fluxes or states also known as "forcings" and the lower (soil) fluxes or states; and 3) Parameters, which are a function of soil, vegetation, topography, etc., for the selected land surface models in order to predict terrestrial rainfall-runoff processes. Early results of TMPA real-time rainfall application in VIC model show that the TMPA-driven VIC hydrological model simulations were able to capture the flooding events and to represent low flows, although peak flows tended to be biased upward (Su et al., 2008). After the successful launch and operation of the Regional Visualization and Monitoring System (SERVIR) for Mesoamerica ([www.servir.net](http://www.servir.net)), the NASA Applied Science program has again partnered with United States Agency for International Development and The Africa Regional Centre for Mapping of Resources for Development (RCMRD) to implement an operational flood warning system as part of the SERVIR-Africa project. The

ultimate goal of the project is to build up disaster management capacity in East Africa by providing local governmental officials and international aid organizations a practical decision-support tool in order to better assess emerging flood impacts and to quantify spatial extent of flood risk, as well as to respond to such flood emergencies more expediently. Although the results (Li et al., 2008) suggest that TMPA real-time data can be acceptably used to drive hydrological models for flood prediction purpose in Nzoia basin at resolution of 1-km grid scale after downscaling, continuous progress in space-borne rainfall estimation technology toward higher accuracy and higher spatial resolution is highly appreciated.

The current GFM uses normalized 5-day antecedent precipitation index as a proxy of antecedent moisture conditions to provide initial soil wetness information. In the future, we will explore use of the daily AMSR-E soil moisture data as initial soil condition instead of the normalized antecedent precipitation index. One additional capability of the framework under consideration is to incorporate quantitative precipitation forecasts (QPF) from NOAA Global Forecast System (GFS) or other global forecasts to predict runoff within the short to medium ranges of lead time. The increased lead time provided by this framework will be a major improvement over in-situ monitoring infrastructures that may have to wait for delayed transmission of rainfall information from upstream countries and may be defeated by severe weather. We expect work reported here to become increasingly fruitful and practical with the advent of GPM-related products and research collaborations.

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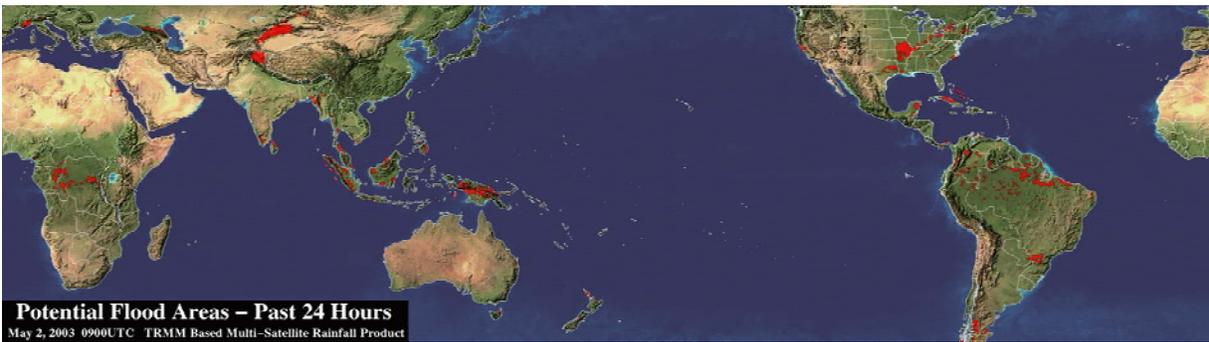
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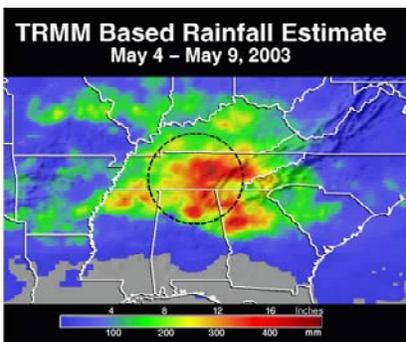
Figure 1 TRMM rainfall threshold-based flood potential Map.

- (a) Example 1-day flood potential map; red regions show areas that have received a 24-hour rainfall accumulation (May 2, 2003) greater than 35 mm.
- (b) Spring flooding in the Southeastern US: Data from the TMPA estimated more than 400mm of rainfall in the red areas of the top map (TN, AL, GA) during May 4-9, 2003, from spring storms.
- (c) Left graph shows rain rates as high as 35 mm hr<sup>-1</sup> over the 5-day period. Right graph shows that after 85 hours, rain totaled 472.7 mm (18.6 inches) within a 200 km (77 mile) radius surrounding Nashville, TN.

(a)



(b)



(c)

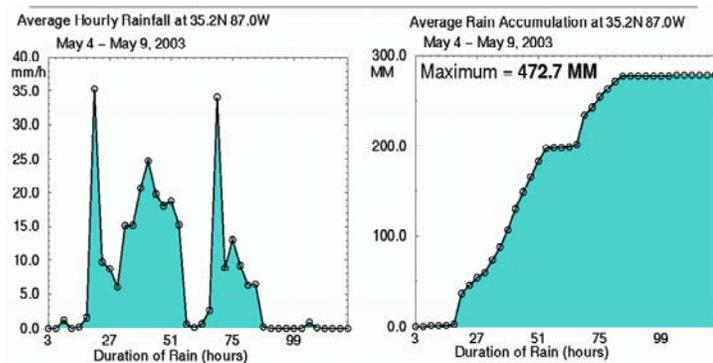


Figure 2 A modular structured framework for global flood monitoring system: (1) precipitation input; (2) surface geospatial database; (3) hydrological models; and (4) an implementation interface.

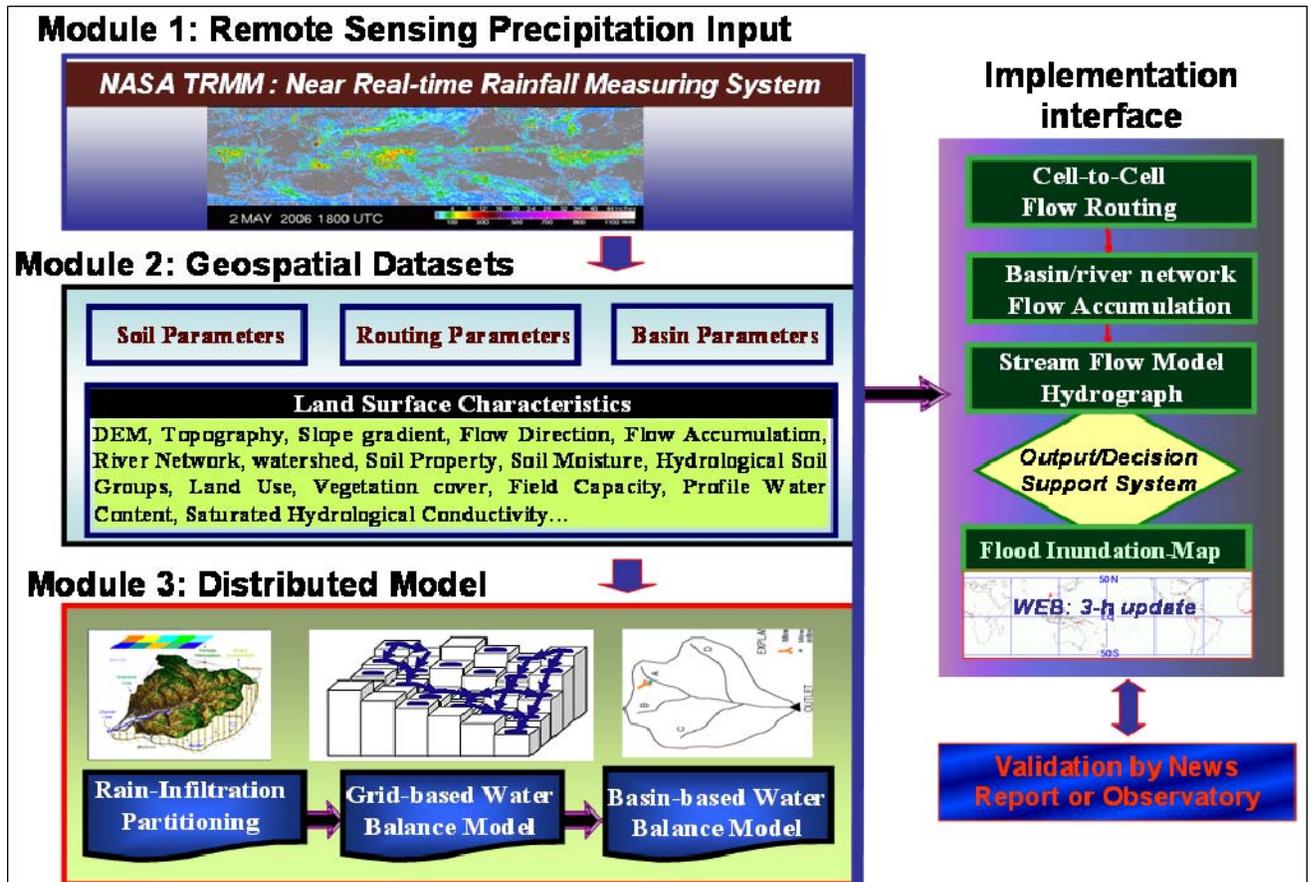


Figure 3 (a) Climatological pentad antecedent precipitation index (API) averaged over 9 years (1998–2006). (b) Pentad antecedent rainfall accumulation (mm) ending on 25 August 2005. (c) Pentadnormalized API (NAPI) on 25 August 2005. (d) Hydrological condition, with  $-1$ ,  $0$ ,  $1$ , and  $2$  corresponding to no data, dry, fair, and wet conditions, respectively, determined by NAPI as of 25 August 2005. (e) Updated CN on 25 August 2005. [image source: Hong et al., 2007b]

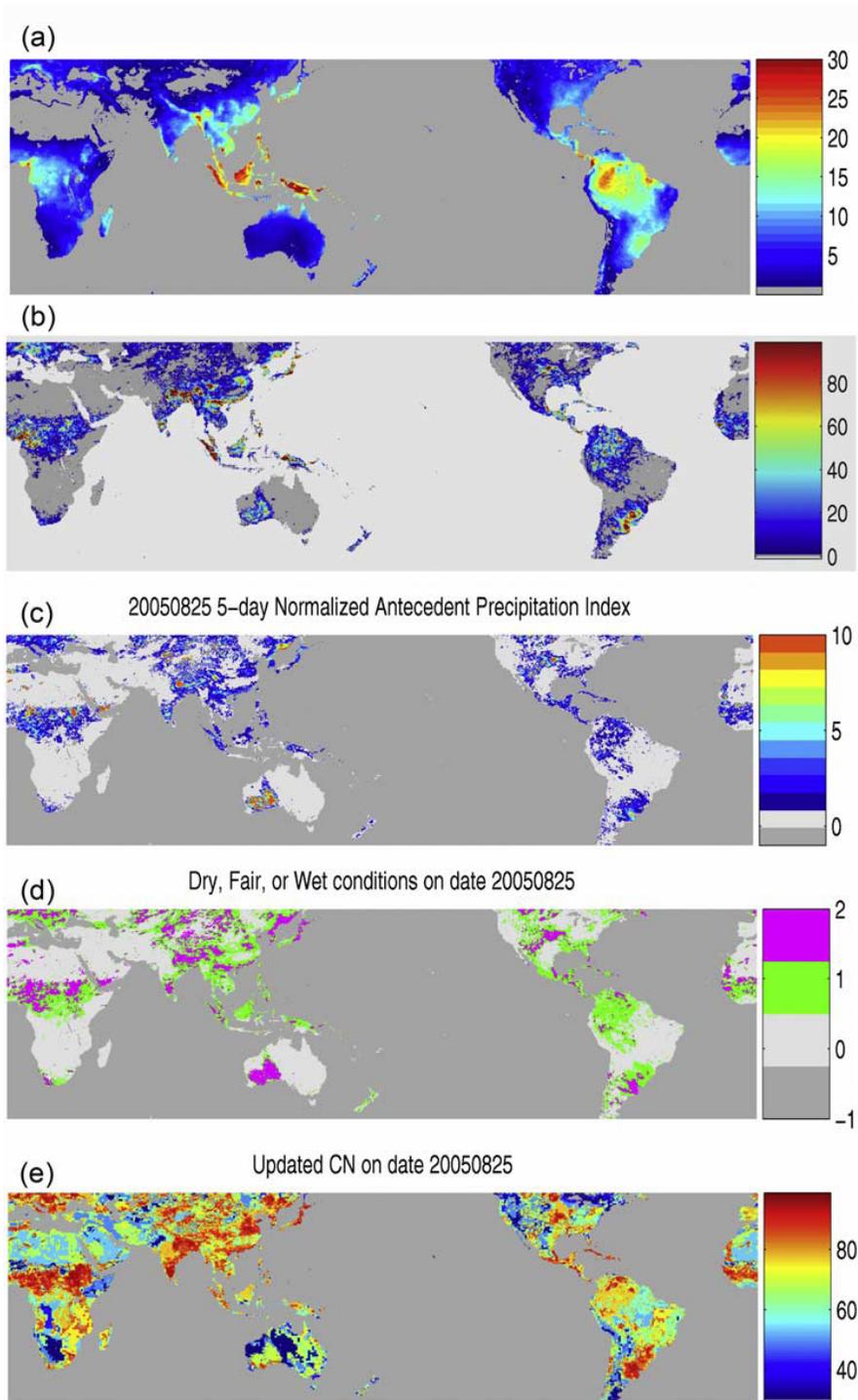


Figure 4 Global Basins and River Networks

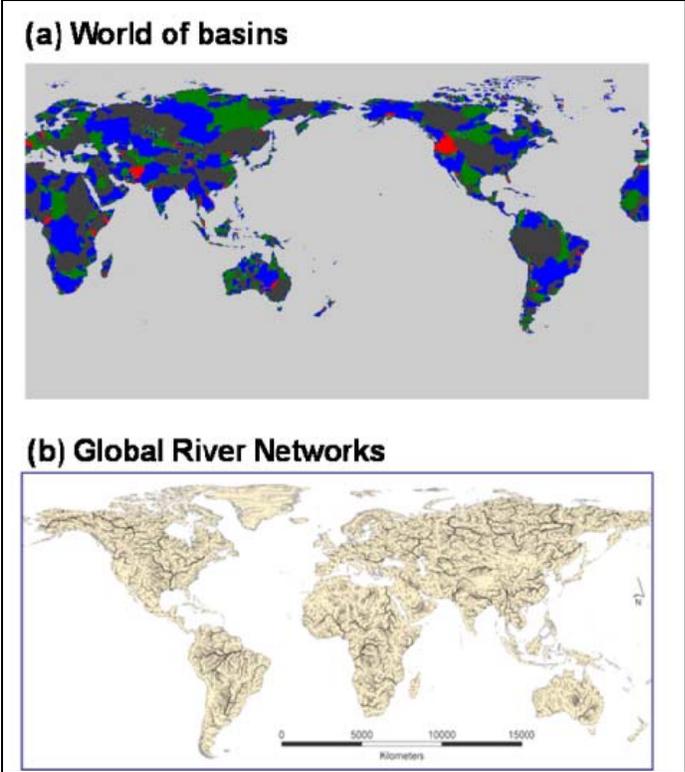
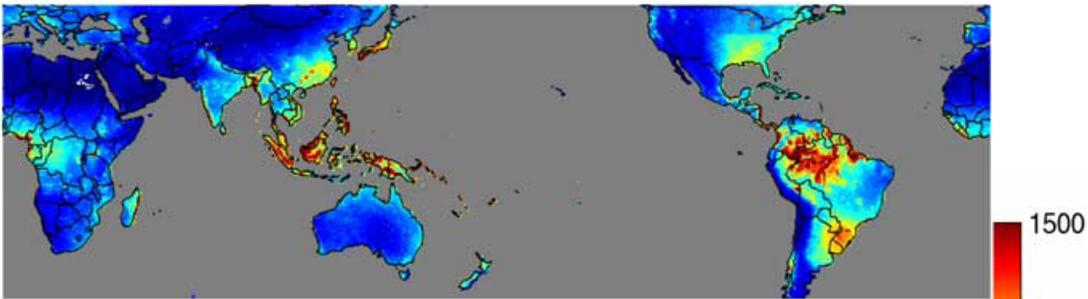
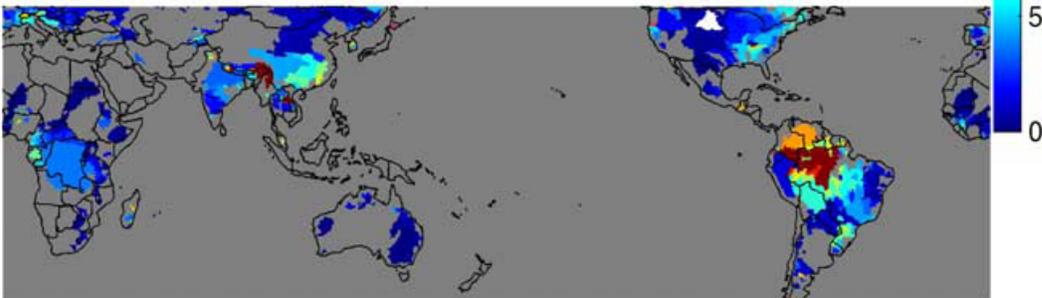


Figure 5. (a) Annual mean runoff (mm/yr) simulated using NRCS-CN methods from TRMM estimates for the period 1998–2006. (b) GRDC-observed runoff (mm/yr). (c) Runoff zonal mean profiles comparing TRMM precipitation (green) and simulated runoff (red) to GRDC runoff (blue) from the (left) observed, (middle) WBGs, and (right) composite data sets. Note the gray areas in Figures 3a and 3b indicate no data or water surface. [image source: Hong et al., 2007b]

**(a) TRMM Rainfall derived Runoff Climatology**



**(b) GRDC Observed Runoff Climatology (mm/yr)**



**(c) Runoff Zonal Mean Comparison (mm/yr)**

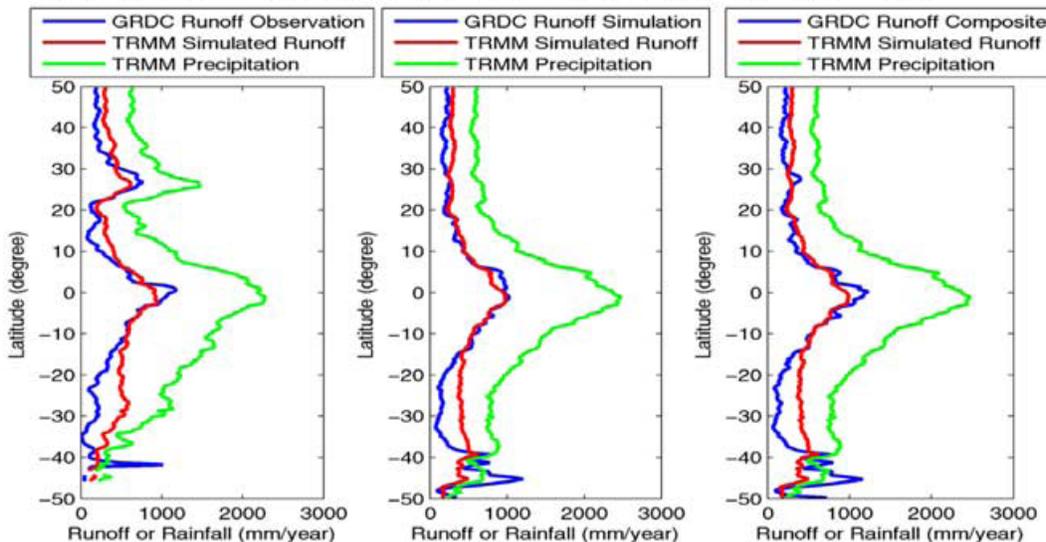


Figure 6. TRMM-CN (a) runoff difference distribution and (b) root-mean-square difference (RMSD) as a function of basin area. [image source: Hong et al., 2007b]

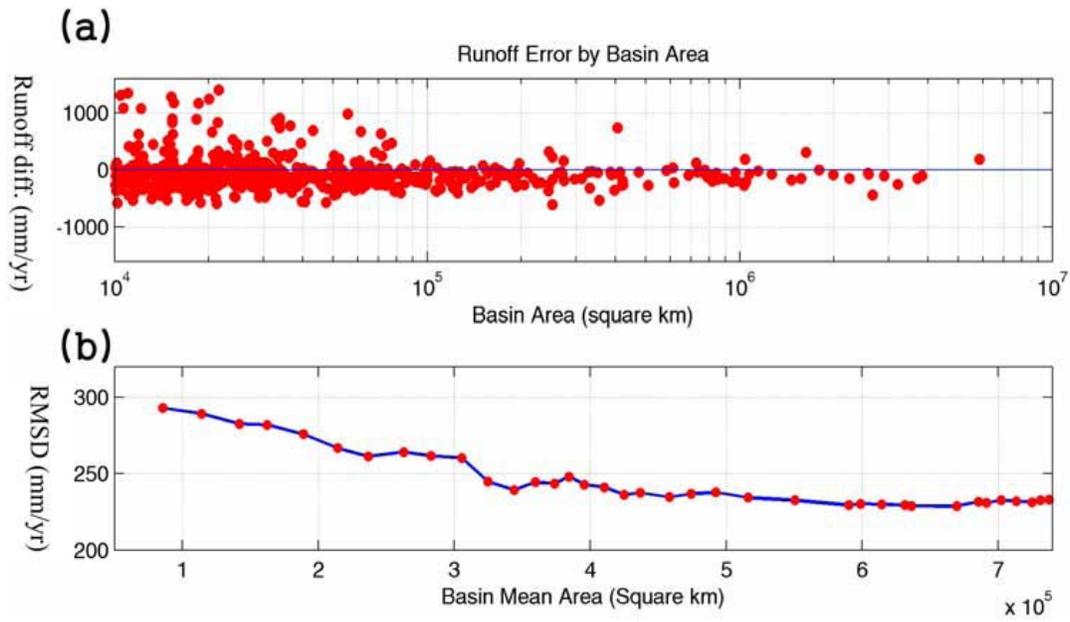


Figure 7 Comparison of TRMM-CN Annual Runoff with GRDC gage stations

### GRDC Gauge Stations (488)

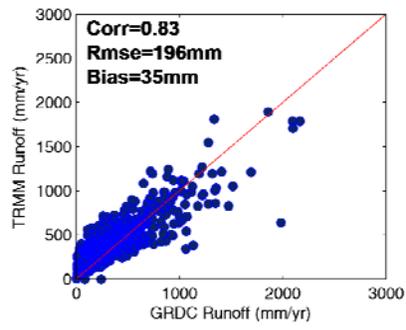
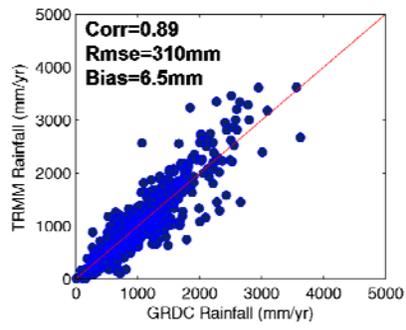
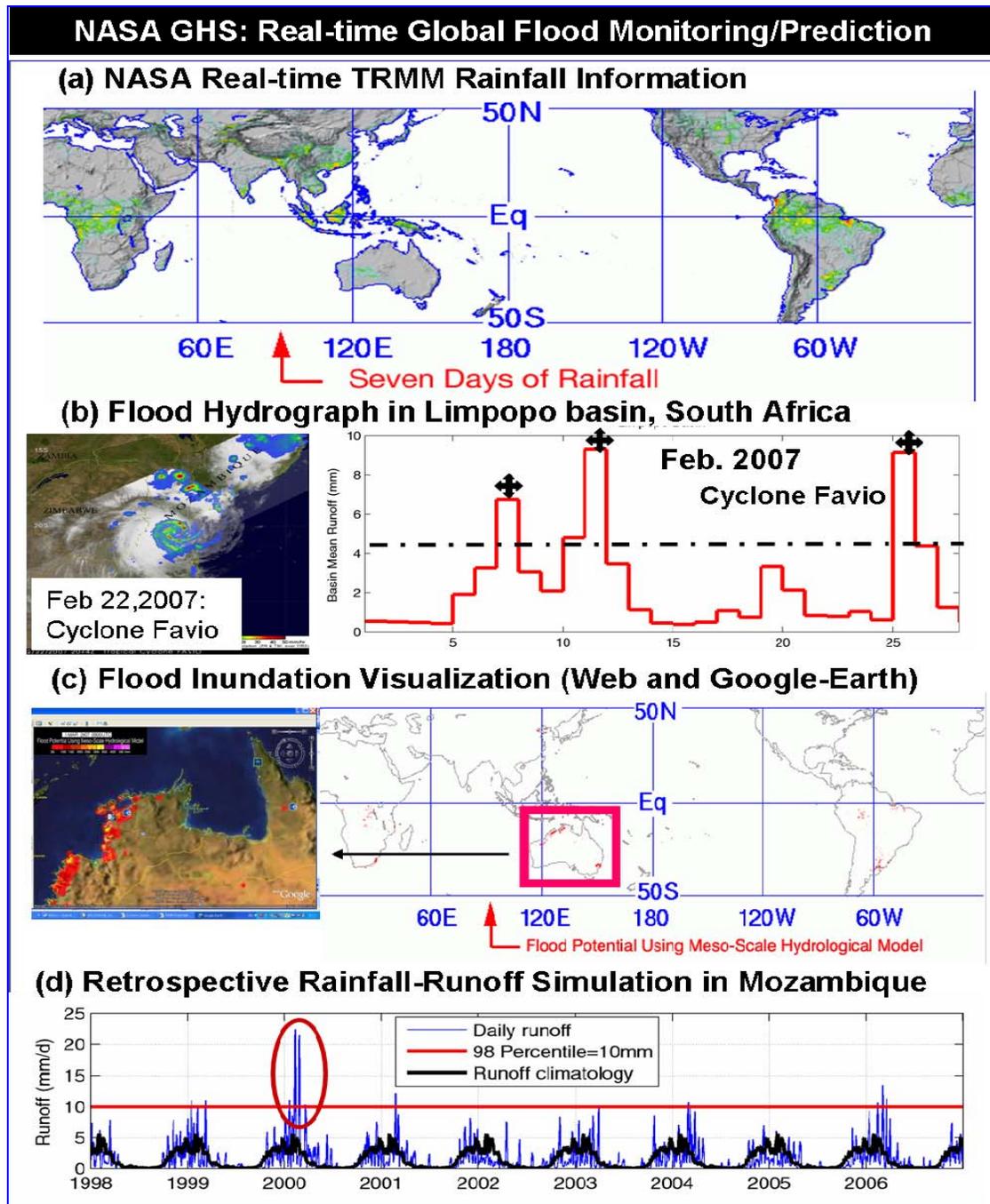


Figure 8: Implementation of GHS-Flood: (a) Example of 7-day accumulation of real-time TRMM rainfall, and (b-d) examples of GHS-Flood detection/visualization results.



## **Applications of TRMM-based Multi-satellite Precipitation Estimation for Global Runoff Simulation: Prototyping a Global Flood Monitoring System**

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### ***Popular Summary***

Flooding driven by excessive rainfall is one of the most routine, yet devastating natural disasters to occur around the world, taking thousands of lives and damaging huge amounts of property every year. Practically every nation around the world could benefit from improved flood information, whether dealing with very localized flash flooding or inundations by major rivers that take days or weeks to grow and then recede. It has been hard to make progress in flood forecasting in many parts of the world because it is difficult to gather enough ordinary rainfall measurements, mainly raingauges and radars, quickly enough to quantify rainfall with the necessary detail in space and time. However, modern satellite precipitation observations are now capable of providing the necessary detail quickly, although we have to accept a fair amount of uncertainty. We use these relatively new data to develop an experimental flood alert system that starts with current rainfall data and results in alerts on a Web page for the possibility of flooding. The system is referred to as the Global Flood Monitor (GFM)

This new experimental system required us to draw on several different technical specialties: satellite precipitation estimates, land surface data, computer models of flooding, and Web site development. First, we assemble a detailed analysis of land surface characteristics around the globe, showing for each location what is covering the land surface, what the soil is like, and where water will flow. Second we bring in precipitation estimates that are created by the NASA Tropical Rainfall Measuring Mission (TRMM) about 9 hours after the data are observed using the TRMM Multi-satellite Precipitation Analysis. Third, we use a simple computer model to show what happens to rain when it falls on that landscape. In particular, we can track how much runoff occurs, and where it goes, allowing us to estimate flooding. Fourth, we post these flood alerts on our public GFM Web site. When we tested the GFM by running it with data observed during 1998-2006 it was clear that the system performs consistently both at individual stations and averaged across river basins.

The GFM Web site is intended as an early example of a natural disaster early warning system for the data-sparse regions of the world. The site is interactive, showing close-up maps of current flood risks drawn on top of land-surface and population maps. It is also possible to display the flood information in Google Earth. In the near future we plan to run the GFM with precipitation estimated by weather forecast models. This will allow us to issue flood alerts further into the future than is possible with observed data alone.