TOWARDS GLOBAL RIVER DISCHARGE ASSESSMENT USING A DISTRIBUTED HYDROLOGICAL MODEL AND GLOBAL DATA SETS

CAMINO A LA ESTIMACION DE CAUDALES DE LOS RIOS EN EL MUNDO USANDO MODELOS HIDROLOGICOS DISTRIBUIDOS Y FUENTES DE DATOS GLOBALES

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ABSTRACT

To improve global water resource assessment, quantification of the global river discharge while considering the effect of slopes is required. Rainfall patterns need to be transformed into discharge by hydrological models like a distributed hydrological model (DHM). This model is expected to represent the spatial variation in aspects of digital global mapping such as land use, land cover, vegetation and elevation. Particularly, a digital elevation model (DEM) is crucial for tracking the flow direction and defining the river network in a basin. In this study, the performance of a 1-km resolution DHM is compared with that of a 90-m resolution DHM in simulating the discharge of the Meghna River in Bangladesh. The input rainfall was obtained from the Tropical Rainfall Measuring Mission (TRMM). The TRMM raw data was improved using available rain gauges over Bangladesh employing correcting factors. These correction factors were then also extended over India where rain gauge data was not available. In summary, the simulation of river discharge using the 1-km resolution model gave reasonable results even though the condition of the slope was limited. Therefore, the procedure here shows the feasibility of modeling global river discharge using global mapping data set. In future development, after setting thresholds at different control points, the potential flood damage to population centres can be evaluated for sound decision making.

RESUMEN

De manera de mejorar la estimación de los recursos hídricos, la cuantificación de los caudales de los ríos en el mundo considerando los efectos de pendientes es necesaria. La distribución espacial de las lluvias necesita ser transformada en caudales por Modelos Hidrológicos Distribuidos (DHM de sus siglas en inglés). Se espera que estos modelos representen la variación espacial usando mapas digitales globales como ser uso de suelo, cobertura, vegetación y elevación. En particular, el modelo de elevación digital (DEM de sus siglas en inglés) es vital para definir la dirección del flujo y la red hidrográfica en la cuenca. En este estudio, la efectividad de un modelo DHM con 1km de resolución ha sido comparada con otro DHM de 90m para simular caudales en el Rio Meghna en Bangladesh. Los datos de entrada de precipitación han sido obtenidos del proyecto "Tropical Rainfall Measuring Mission" (TRMM). Los datos de TRMM han sido mejorados usando mediciones disponibles en pluviómetros sobre Bangladesh y aplicando factores de corrección. Estos factores fueron luego expandidos sobre la región de India, cabeceras del Rio Meghna, donde no se disponía de datos pluviométricos. En resumen, la simulación de los caudales usando un modelo DHM con 1km de resolución ha proporcionado resultados satisfactorios a pesar que las limitaciones de las condiciones de pendiente. Por tanto, el procedimiento descrito en este estudio muestra la factibilidad de la modelación de caudales de ríos en el mundo usando fuentes de datos globales. En avances futuros, después de definir niveles clave en puntos de control, el daño potencial por inundaciones a los centros poblados puede ser evaluado para la toma de decisiones apropiadas.

1. INTRODUCTION

The assessment of global water resources is becoming even more relevant due to growing population, water demands, and the effects of global warming. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) summarized and projected that the frequency of heavy precipitation events has increased over most land areas, consistent with warming and observed increases of atmospheric water vapour. And, it is very likely that heavy precipitation events will continue to become more frequent [1]. Quantitative information on the global water cycle, as a basis for sound and effective water management, is thus required. River discharge is a crucial state variable that needs to be estimated to provide information for the study of potential water use and water disasters. Efforts to determine river discharge have been reported. For example, it was developed a total runoff integrating pathway (TRIP) network at $1° \times 1°$ resolution [2], and later on improved [3], [4]. However, the effect of slope has not yet been considered in these

approaches. This study attempts to route water from upstream relying on digital elevation models using hillslope elements to simulate the hydrological processes.

To capture rainfall patterns and simulate river discharge within a basin, a distributed hydrological model is recommended. The model requires spatially distributed input data such as land cover and elevation data. Nowadays, a number of initiatives offer global geographical data but few of them gather under common standards for societal benefits. An example would be the efforts of Global Mapping initiative that develops global scale geographic information through international cooperation. One of its interests is the prediction of global water resources for preventing water-related disasters. A hydrological model would be very useful for assessing and preventing disasters at a basin scale while using global data set.

A key component of the water cycle is precipitation, but not all basins are well gauged at the surface. The TRMM multi-satellite precipitation analysis (TMPA) carries out estimations from satellite measurements. In most cases a ground validation might be required. Only a few works on this topic in Asia have been reported. For example, it was used 1º × 1º boxes over Thailand at monthly and daily scales to evaluate TRMM predicted rainfall against rain gauge measurements [5]. It was found TRMM 3B42 V6 performed better than the 3B43 product when evaluated against gauge measurements. Moreover, high correlation was found for 3 days using the spatial average of 50 boxes. This latter study was limited to evaluation without the proposal of a validation method. Similarly, it was compared the performance of TRMM products against ground-based gauge measurements over Bangladesh [6]. The analysis was made on a point-by-point basis at five selected gauges for the period 1998–2002. It was confirmed that 3B42 V6 performed better than other TRMM products. Moreover, they reported that using spatial averages at a country level reduces biases compared with analysing on a point basis. Again, it would be interesting to include a validation procedure on top of the evaluation. The present study, different from the previous two, proposes correction factors for TRMM products using the available ground measurements at basin scale for hydrological purposes.

In Asia, cooperation among 18 countries has been established as the Asian Water Cycle Initiative (AWCI). The objective of the initiative is to promote integrated water resources management by making usable information from the Global Earth Observation System of Systems (GEOSS) to address common water-related problems in Asia. The key aspects of the AWCI are convergence of satellite observations, data integration, open data and source policies, and capacity building. Under this initiative, each member country proposed one demonstration river basin. In central Vietnam, a hydrological model of a small basin was set up to predict floods using forecasted and observed rainfall [7]. TRMM products were used successfully without corrections; however, the results should be confirmed in larger basins with few gauging stations. The present study attempts to use satellite measurements over the Meghna River, GEOSS/AWCI demonstration basin, in Bangladesh to assess river discharge.
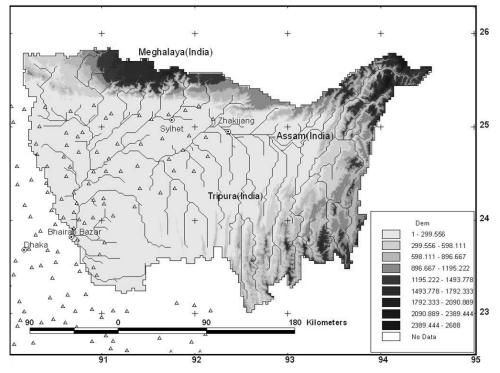
In summary, the goal of this paper is to contribute to river discharge assessment using available global datasets through an application to a large river basin. Since datasets might show constraint at coarse resolution, a ground validation is proposed.

2. STUDY AREA

Bangladesh is a land of rivers. This small country with an area of about 144 000 km^2 happens to be the meeting point of three major rivers: the Jamuna-Brahmaputra, the Padma-Ganges and the Meghna. The majority of the country is characterized by flat terrain, and the small areas of non-flat terrain lie to the northeast and southeast. Owing to this terrain structure, even though the rest of the country experiences prolonged flooding, the population living downstream of the Meghna basin experience flash flooding. Damage due to flash flooding in this region has drawn the attention of researchers and modellers for some time.

The Meghna River basin extends between Bangladesh and India. About 35 % of the basin area falls within the Bangladesh borders and the remaining 65% lies within India. Specifically, the basin encompasses the Assam and Tripura mountain regions of India down to the agricultural area of Bangladesh at latitude of 23–26ºN and longitude of 90–95ºE as seen in Figure 1. Downtown Dhaka is located 50 km southwest of the outlet of the simulation, Bhairab Bazar. The total river system basin area is approximately 64 000 km^2; about 62% of the area comprises forested mountainous and hilly terrain. On the other hand, 29% comprises irrigated cropland and pastures. The basin altitude varies from 1 m to 2 688 m with a mean of 362 m a.s.l., and the average basin slope is 1.3%.

The main river channel runs northeast–southwest towards Bhairab Bazar. The topography of the basin changes rapidly in northern and eastern areas as shown in Figure 1 with dark shading. The high runoff in the rainy season creates large amounts of discharge. However, the central part of the basin comprises plains and gentle hills and is highly susceptible to flooding. The Meghalaya mountainous area has recorded high rainfall exceeding 5 500 mm per year. The Meghna River is a main source of irrigation for agriculture and aquaculture, which shift with the rainy season. The year can be

divided into April–May as the pre-monsoon season, June–September as the monsoon season and October–November as the post-monsoon season [6]. December–March is the dry season during which there is only small amount of rainfall.

Figure 1 - Study area and distribution of rain gauge (triangles) over Bangladesh.

3. METHODOLOGY

To transform rainfall patterns into river discharge while considering the effect of slope, a physically based distributed hydrological model (DHM) was selected. A brief description of the model, the required input data and the methods undertaken to validate the global dataset are described in this section.

- **Distributed Hydrological Model**

A DHM was used to simulate the spatially distributed hydrological processes in the study area and the routing of water in the river network system. The DHM employed in this study is a grid-based geomorphology-based hydrological model (GBHM) where the computational unit is a geometrically symmetrical hillslope [8]. This element is viewed as a rectangular inclined plane with a defined length and unit width. The inclination angle is given by the surface slope, and bedrock is assumed to be parallel to the surface. The GBHM solves the governing equations using two models. First, a hillslope model evaluates hydrological processes such as canopy, interception, evapo-transpiration, infiltration, surface flow, and subsurface flow, as well as exchanges between groundwater and surface water using governing equations. Second, the water routing of the river network is determined using a kinematic wave approach.

- **Topography**

The first step in building the described model is to delineate the modelling area from a digital elevation model (DEM) using a geographic information system (GIS). The DEM is crucial in tracking the flow direction and defining the river network in the basin. Two different sources for the DEM were employed. A 90-m DEM resolution product was employed. It is produced by the Shuttle Radar Topography Mission (SRTM) and it can be accessed at http://seamless.usgs.gov/. The SRTM is a joint project between the National Aeronautics and Space Administration (NASA) and the National Geospatial-Intelligence Agency to map the world in three dimensions. The Global Map project archives a global 30 arc-second (around 1-km) DEM in geographic projection available at http://www.iscgm.org. The objective of Global Mapping is to bring all nations and concerned organisations together to develop and provide easy and open access to global digital geographic information at a scale of 1:1 million. There are mainly two types of dataset, namely global and country specific data in raster and vector form. In addition to the global elevation, land use, land cover and vegetation are available. At country level, transportation, boundaries, drainage and population centres are defined as common information among participating countries.

Once both datasets (90-m & 1-km DEM) were downloaded, two different 2700-m DEM models were prepared by aggregating their original elevation resolutions using the TOPOGRID command in Arc/Info version 8.2. This command allows the generation of hydrological correct elevation from the river network (in vector format). This layer can be generated from a finer DEM and/or digital streams. The river network obtained using a 90-m DEM did not show relevant differences with the actual river network. There were some grids with no data that were corrected using a base layer. This layer was created by averaging surrounding grids and then using the FILL command in Arc/Info. On the other hand, the new DEM obtained using the 1-km DEM was far from representing the actual stream network. Therefore, the digital drainage layer of Bangladesh provided by the Global Mapping dataset was used as input in the TOPOGRID generation. The results of the first attempt and the corrected 1-km DEM are displayed in Figure 2.

It can be seen that the main constraint was the flow direction at low elevations where streams did not converged at Bhairab Bazar. Using the surface hydrologic analysis with Arc/Info, two watersheds were delineated. They were then divided into sub-basins, as shown in Figure 3, using the Pfafstetter scheme [9]. The resolution of the source data is reflected by the morphology of the streams, which are straighter using the 1-km DEM. The total drainage area using the 1-km DEM and 90-m DEM reached 63 277 km^2 and 64 495 km^2, respectively. The discrepancy for both watersheds was 1.89%.
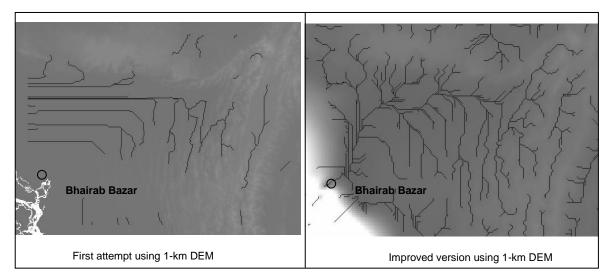

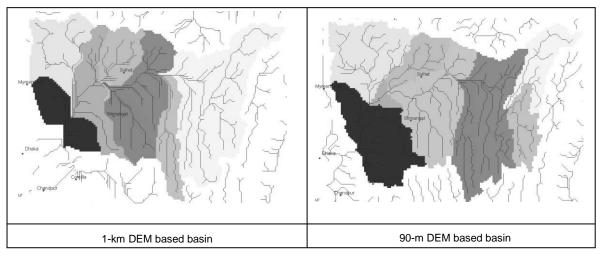Figure 2 - River network from the 30 arc-second DEM.

Figure 3 - Watershed delineations.

- **Other Spatial data**

Global land cover characteristics at 1-km resolution were prepared and clipped to the delineated watersheds using GIS tools. The dominant land use is forest with 62% coverage and 29% corresponds to irrigated cropland and pastures. Additionally, the vegetation raster data from Global Mapping was used to define the percentage of tree coverage for each land use type.

The soil type was determined from the Food and Agriculture Organization global soil maps [10], which include derived soil water parameters associated with each soil unit (available at: http://www.fao.org/AG/agL/agll/dsmw.stm). The parameters used were the saturated hydraulic conductivities, saturated and residual water content, and Van Genuchten's constants. Similarly as for land use, the soil unit data was clipped to the delineated watersheds using GIS.

Sub-grid parameterization was carried out using the original grid size resolution to consider the heterogeneity of land use and the length of hillslope elements in the 2 700-m grid models. In the case of land use, the percentage of coverage was applied. The total length of a hillslope in a 2 700-m grid was extracted from small hillslope lengths of the DEM following the reported literature [11, 12]. The distribution and depth of topsoil play key roles in determining the simulated discharge, since subsurface depths and initially saturated zones are defined by topsoil depth. For instance, forested areas with loose material and gentle slopes are most likely to have greater topsoil depths than other combinations [13].

▪ **Precipitation data**

Once the drainage area of the basin was defined, observed time series data were prepared. The rainfall amounts recorded by the rain gauge network, indicated with triangles in Fig. 1, were used as input data for the model. The values are daily and the coverage is only over the Bangladeshi area. Besides observed values at the surface, observed satellite values from the TRMM were also used. The TRMM is a joint mission between NASA and the Japan Aerospace Exploration Agency to monitor and study tropical rainfall and energy exchange [14]. The satellite has been in orbit for more than 10 years. The efforts to improve estimations of TRMM multi-satellite precipitation analysis (TMPA) with different applications was reported [15]. The 3B42 version 6 product was used in this study which includes calibration with monthly merged rainfall from Global Precipitation Climatology Project (GPCP). The temporal resolution is 3h and spatial resolution 0.25° and it can be downloaded free of charge from http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=TRMM_3-Hourly. This webpage also allows interactive visualization of spatial and temporal sub-sets.

▪ **Improvement of Satellite Precipitation**

The gauges located within the modelling domain were selected and given a systematic code. First, the 3-hourly 3B42 V6 product was aggregated into daily values. Second, these daily values were averaged over the same month using TRMM and gauge data. Third, at each gauging station, mean values $daily\_mean_{TRMM}$ and $daily\_mean_{Gauge}$ were obtained for each month. According to the overestimation or underestimation, a correction factor was then used at each gauge:

$$correction\,factor_{Gauge\_month} = 1 + (1 - \frac{daily\_mean_{TRMM}}{daily\_mean_{Gauge}}) \; ; \; daily\_mean_{Gauge} > 0 \tag{1}$$

For example, overestimation of TRMM by 20% would be denoted as 1.2; the correction factor would then be 0.8 and vice versa. Note that equation (1) is only valid when the daily rainfall is greater than zero to avoid infinite magnitudes. Moreover, the lower and upper boundaries of the correction factor are defined as 0.5 and 1.5 respectively. As a matter of fact, the correction of TRMM values cannot exceed 50% of values at the surface. After applying equation (1), at each gauging station a different factor is obtained according to the month. However, the DHM model requires the rainfall amounts at each computing grid. The factors are applied to those grids covered by each gauging station defined by Thiessen polygons. This procedure is valid within model grids in the Bangladesh area; however, the factors are extrapolated to India area using measurements from the nearest gauges. The new TRMM values at each grid were obtained using the correction factors as:

$$Rain_{New\_TRMM} = Rain_{TRMM} * correction factor_{Gauge} \tag{2}$$

4. MODEL APPLICATION

This study targeted the rainy season running from April to November for the years 2001, 2002, 2003 and 2004 owing to the availability of input data. The situation before and during main floods was targeted. The hydraulic conductivities of top soil layers, surface storage and anisotropy were calibrated by running the DHM for the rainy season of 2001. April was used for model initialization and May and June for evaluation. July was then considered for validation using rainfall measurements from observed rain gauges. The calibrating method was trial-and-error reduction of the root mean square difference between simulated and observed river discharges.

Within the monsoon season of 2004, the highest flood peak events of mid September and November were targeted at Zhakiganj (intake of Upper Meghna) and Bhairab Bazar (outlet of the model) as seen in Figure 4.
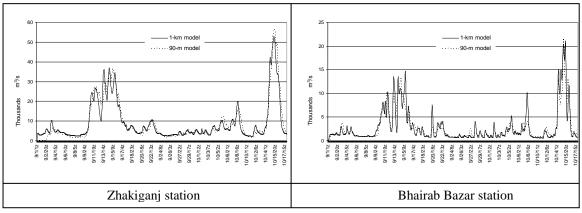
Figure 4 - Simulation comparison for 2004.

The 1-km model gave reasonable results even though the condition of the slope was limited. Next, the 1-km DEM based model was run using TRMM raw data and the improved TRMM data. This shows the availability of water resources during the rainy season.
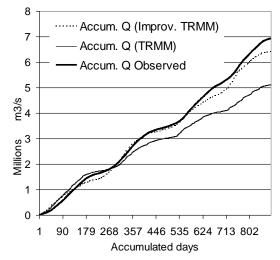

Figure 5 - Discharge at Bhairab Bazar for rainy seasons 2001-2004.

5. DISCUSSION & OUTLOOK

The river network of the Meghna River, a demonstration basin for GEOSS/AWCI, was obtained using global datasets. The typical limitations of using a 1-km DEM in flat areas were overcome using national drainage data from the Global Mapping project. The delineated area obtained using the 1-km DEM was very close to that obtained using a fine DEM. The simulated discharge obtained using the 1-km DEM within the river network was validated by comparing with the finer DEM results even though there were slope constraints. The 3-hourly TRMM 3B42 V6 product was then improved using correction factors for each month within the rainy season. These factors were obtained at each gauging station then transferred to each grid according to Thiessen polygon areas of influence. The performance of the improved TRMM product was evident when plotting the accumulated discharge. The present river routing model should be improved in future development in order to simulate inundations. In addition, after setting a threshold discharge, the potential flood damage to population centres should be evaluated for flood hazard predictions and warnings.

The spatial and temporal ground validation of TRMM products is crucial. In the present study, a sampling approach uses available measurements at the surface. The correction factors were applied to the Thiessen polygon influence area as a first attempt. Alternatively, the influence areas can be detected as fringe zones in latitude and longitude. Moreover, the effect of topography and proximity to the ocean over the gauging locations could be analyzed. Regarding the temporal variation, the daily average over a month was calculated over four years. TRMM data are archived from 1998, so about 10 years of data could be evaluated. The TRMM sensor will last for a couple of years more considering the remaining fuel aboard. However, the launch of the Global Precipitation Mission (GPM) sensor is expected for 2013 and the mission will have an increased global coverage up to 95%. With the use of the Dual Precipitation Radar, the spatial resolution is to be as fine as 0.1°. TRMM and GPM data could be very useful for measurements of poorly gauged or un-

gauged basins. In these cases, the neighbouring basins should be used to validate the satellite measurements.

The International Steering Committee for Global Mapping is currently entering its third phase, which involves further upgrades of global maps and the expansion of the country-level dataset. At the time of writing, 164 countries share their national data according to digital standards. It would be desirable that Bolivia also joins the group sharing the national digital maps to enable the set-up of Bolivian rivers using the global data set fully as showed in this study.

The obtained results are promising for the simulation of other large river basins of the world. River discharge measurements are needed to assess water resources at basin scale. Mainly in areas where no *in situ* measurements are available, TRMM precipitation data can be very useful providing rainfall patterns. An example of such use would be the Predictions in Ungauged Basins (PUB) initiative supported by the International Association of Hydrological Sciences [16]. The information derived from the simulations is crucial for planning water usage and reducing the extent of disasters such as floods and droughts. Particularly, the hydrological modelling of large trans-boundary river in South America such as Amazon and La Plata basins would be feasible using the presented approach. For example, La Plata basin covering 3.2 millions km^2 with very localized rain gauge network mainly over Brazilian territory where calibration of TRMM satellite data could be done. Then, those correction factors could be applied over large areas but with less observation coverage like in Bolivia and Argentina.

6. ACKNOWLEDGMENTS

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