

Limitation of 90 m SRTM DEM in drainage network delineation using D8 method—a case study in flat terrain of Bangladesh

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Received: 4 April 2009 / Accepted: 8 March 2010 / Published online: 13 April 2010
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Abstract Bangladesh is the deltaic flood plain located in the lower ridge of the Ganges Brahmaputra and Meghna basins. The country is very flat having 40% of its landmass up to 10 m above the mean sea level. Shuttle Radar Topography Mission (SRTM) 90 m, i.e., 3-arc second digital elevation model (DEM) is being widely used to delineate river network and to extract catchment information using hydrology tool of ArcGIS. The hydrology tool uses the D8 method for extraction of drainage pattern. The study was carried out to find the limitation and suitability of 90 m SRTM DEM data in flat terrains especially in Bangladesh using ArcGIS. Twelve catchments of varying geomorphology were chosen from five hydrological zones of Bangladesh. Basin characteristics such as bifurcation ratio, drainage density, and channel slope of the catchments were estimated and analyzed to evaluate the suitability of 90 m SRTM DEM. The delineated catchments of slope 1:3,600 or more flat shows large deviation in river network alignment when compared with the digital river network developed by Bangladesh Water Development Board and with Google Earth's images. The catchments having slope

1:2,850 and more steep were delineated correctly. The conclusion could not be established between slopes 1:2,850 and 1:3,600. The study also revealed that the catchment characteristics other than the slope have no effect on river network delineation.

Keywords 90mSRTM DEM · River network · Delineation · Spatial-deviated alignment · Flat-steeper slope · Morphological parameters

Introduction

In recent years, digital elevation model (DEM) data derived from remote sensing data have been widely used in estimating catchment characteristics. National Aeronautics and Space Administration is providing 90 m (3-arc second) DEMs for about 80% of the globe (CGIAR-CSI 2008) under the program Shuttle Radar Topographic Mission (SRTM). The mission provides near-global topographic coverage of the Earth's surface with unprecedented consistency and accuracy, which is used widely for large-scale hydrologic studies (Bhang and Schwartz 2008). The DEM data is available in public domain on the website of the Consortium for Spatial Information of the Consultative Group for International Agriculture Research (CGIAR) (<http://srtm.csi.cgiar.org>).

In hydrological studies, DEMs are often used for delineation of drainage network, catchment boundary, and in estimation of various catchment parameters such as slope, contours, aspects, etc. The accuracy of typical geomorphological and hydrological descriptors (e.g., stream networks, watershed areas, area slope, aspect, etc.) in a rugged terrain were examined with the 90 m SRTM DEM data set which indicates that stream networks and

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watersheds can be easily identified accurately (Hancock et al. 2006).

Alarcon and O'Hara (2006) conducted a research where Interferometric Synthetic Aperture Radar and 30 m SRTM DEM data were used to delineate a portion of the Saint Louis Bay watershed (MS). In addition to these, two digital elevation databases, the National Elevation Data (NED) and the United States Geological Services' Digital Elevation Model (USGS-DEM) were also used for delineation. They found that 30 m SRTM DEM produced optimum delineation results comparable to NED when areas and sub-basin perimeters were compared.

The computation for DEM pixels are based on the flow routing model introduced by O'Callaghan and Mark (1984) and referred as the D8 Method. In this D8 method, each pixels discharges in to one of its eight neighbors in direction of steepest descent. In the beginning, this method was problematic when grid cells lacking a down slope neighbor occurred in the DEM referred to as a "sink", resulted in flow paths that terminated at the grid cell with the lowest elevation, producing a discontinuous drainage pattern. Jensen and Domingue (1988) developed a new procedure to eliminate all "sinks" prior to the assignment of flow directions. This method is being widely used in ESRI products ArcView, ArcGIS, and Arc Info and established in Arc Hydro (Maidment 2002).

The D8 approach has limitation arising from the discretization of flow into only one of eight possible directions, separated by 45° (Fairfield and Leymarie 1991; Quinn et al. 1991). Moore and Grayson (1991) pointed out that D8 method allows flow which originates over a two-dimensional pixel is treated as a point source (non-dimensional) and is projected down slope by a line (one-dimensional). Costa-Cabral and Burges (1994) also pointed out that the flow direction in each pixel is restricted to eight possibilities. Costa-Cabral and Burges (1994) then developed a new approach named DEMON (digital elevation model network), having an advantage like contour-based models (Moore et al. 1988), and represents varying flow width over nonplanar topography. Tarboton (1997) described that the best fit plane cannot pass through only four corner elevations, which may be inconsistent or counterintuitive flow directions that are a problem in DEMON.

Tarboton (1997) developed a new procedure based on representing flow direction as a single angle taken as the steepest downward slope on the eight triangular facets centered at each pixels. He demanded that different methods give different results and differences increases with the increases of resolution of DEM and argued that his method is simple effective approach. Orlandini et al. (2003) described that method proposed by Tarboton (1997) constitutes a reasonable compromise between the simplicity

of the D8 method and the sophistication introduced in more recent formulations to improve the precision with which drainage directions are resolved by the D8 method. He also mentioned that a certain degree of dispersion is maintained by Tarboton's method.

Orlandini et al. (2003) proposed path-based methods for the determination of nondispersive drainage directions in grid-based digital elevation models. The path-based methods extend the descriptive capabilities of the classical D8 method by cumulating the deviations between selected and theoretical drainage directions along the drainage paths. It cannot eliminate the bias at the local level; it provides nonlocally constrained drainage paths which may improve significantly the nondispersive description of drainage systems. Orlandini et al. (2003) also gave reasons of this bias which has an effect in the field of terrain analysis applied to geomorphology and hydrology. Seibert and McGlynn (2007) proposed new triangular multiple flow direction algorithm (MD ∞) which combines the advantages of the multiple flow direction algorithm as proposed by Quinn et al. (1991) with the use of triangular facets as in the approach described by Tarboton (1997).

Thus, many researchers studied to improve the D8 method proposed by O'Callaghan and Mark (1984) but the same has since been traditionally used in ESRI GIS software (ArcView, ArcGIS, and ArcInfo) as well as in Arc Hydro. This study is also concerned with this traditional D8 method, and findings may be related with the method's uncertainty or morphological characteristics of used DEM. The findings may be changed with respect to change of software or resolution of DEM.

However, while conducting a hydrological study of river Jamuneswari in Bangladesh, it was found that the river network is poorly delineated using the popular and widely used GIS software ArcGIS (version 9.3) that uses the D8 method for determination of the network when the result compared with Google Earth images and observed network received from Bangladesh Water Development Board (BWDB). This led to carry out an extensive analysis to find the limitations of use of 90 m SRTM DEM in hydrological applications using ArcGIS in flat terrain especially in Bangladesh.

Description of the study area

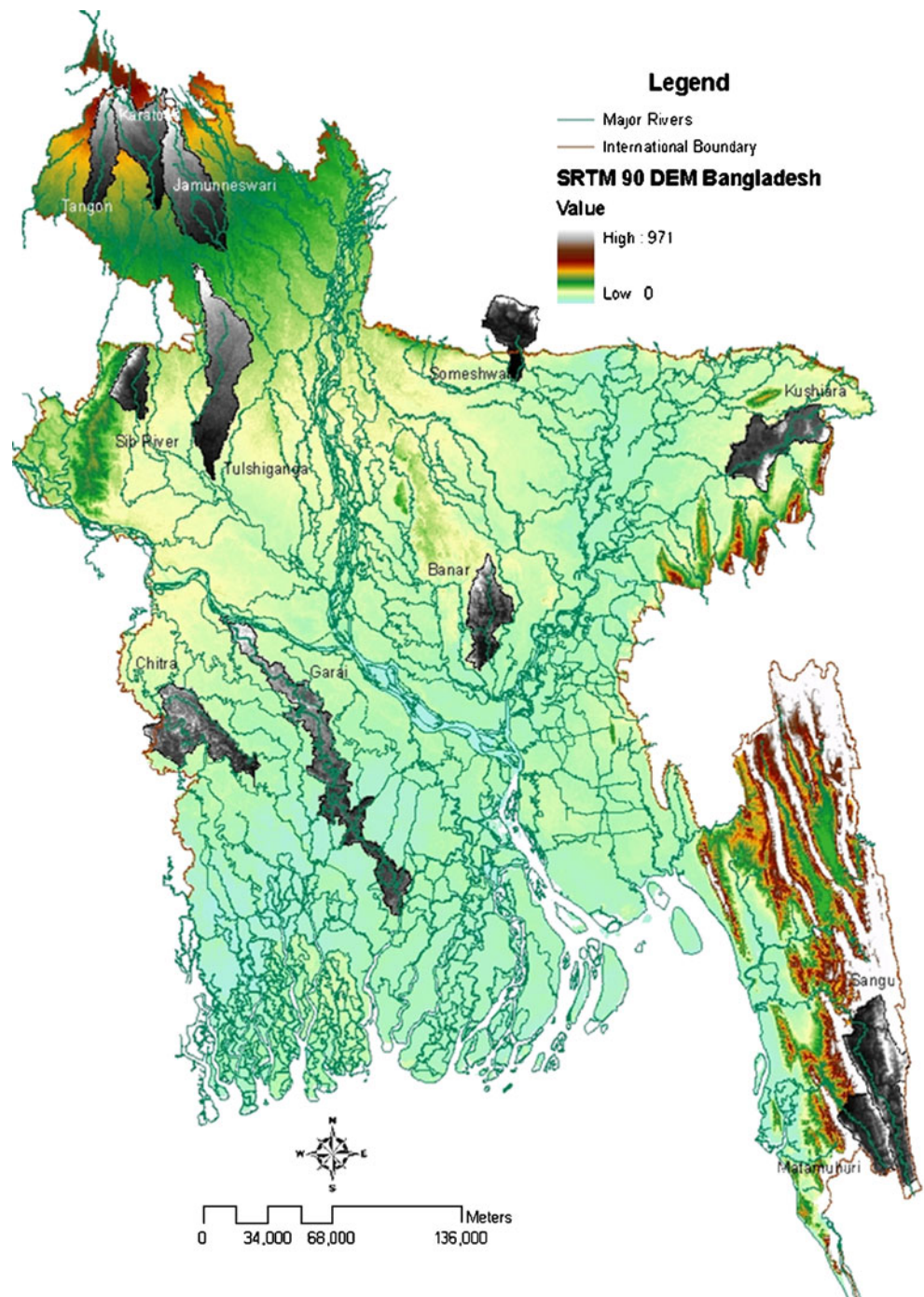
Bangladesh is located in the lowest ridge of Hindu Kush Himalayan Region, which makes the country geographically unique. Land is mainly flat, with 40% of its landmass up to 10 m above mean sea level. The confluence of the Ganges, Brahmaputra, and Meghna rivers and their criss-crossed tributaries and distributaries are shown in Fig. 1. The catchment area of Ganges basin is 1,087,300 km²;

Brahmaputra basin is 552,000 km², and Meghna basin is 82,000 km² (Lettenmaier 2005 and Jorgensen and Host-Madsen 1997) out of which only 7% of the total lies in Bangladesh. Heavy rainfall over the catchment of these rivers produces an average monsoon runoff of about 1,009,000 million m³. Bangladesh would be flooded to a depth of 8 to 10 m if the water is not drained off by these rivers to the Bay of Bengal (Alam 2000).

A total of 12 catchments namely Matamuhuri-Upper, Tulshi-Ganga, Tangon-Upper, Karatoya, Sangu-Upper, Jamuneswari, Kushiara, Garai-Madhumati-Kaliganga, Chitra, Sib, Someswari, and Banar River were chosen to analyze the delineation accuracy. The locations of these catchments are shown in Fig. 1 in gray shades.

The guiding criteria for selection of the catchments were slope, drainage density, and proximity to the rivers. It is

Fig. 1 Location of various rivers of Bangladesh and selected catchments having DEM in the background



worth mentioning here that Bangladesh is divided in five hydrological zones viz., Northeastern Zone (NEZ), Northwestern Zone (NWZ), Central Zone (CZ), Southeastern Zone (SEZ), and Southwestern Zone (SWZ). The NEZ has hilly terrain and located in the hydrological region of world's highest rainfall intensity causing frequent flash floods in the region. The slope of this zone suddenly becomes very flat (roughly 1:10,000 to 1:20,000) when it reaches the plain land immediately after hilly terrain. The NWZ is located in the non-hilly terrain having moderately steeper slope than all other plain lands of Bangladesh. Often, floods are observed in this NWZ. The SEZ is located in the hilly as well as coastal plain land. The river network causes both the storm surge and flash flood in this zone. The SWZ is coastal plain land of Ganges Delta without any hilly terrain. The tidal rivers cause storm surge due to cyclone in this SWZ. The CZ is mainly the flood plain of three major rivers Ganges, Brahmaputra, and Meghna. The land pattern is comparatively low-lying, through which all the flood waters pass towards the Bay of Bengal. The representative catchments Kushiara and Someswari were chosen from NEZ; Tangon-Upper, Karatoya, Jamuneswari, Sib, and Tulshi-Ganga were chosen from NWZ; Matamuhuri-Upper and Sangu-Upper were chosen from SEZ; Garai-Madhumati-Kaliganga and Chitra were chosen

from SWZ, and Banar was chosen from CZ hydrological zone. The locations of the catchments are shown in Fig. 1.

Data used

DEM data

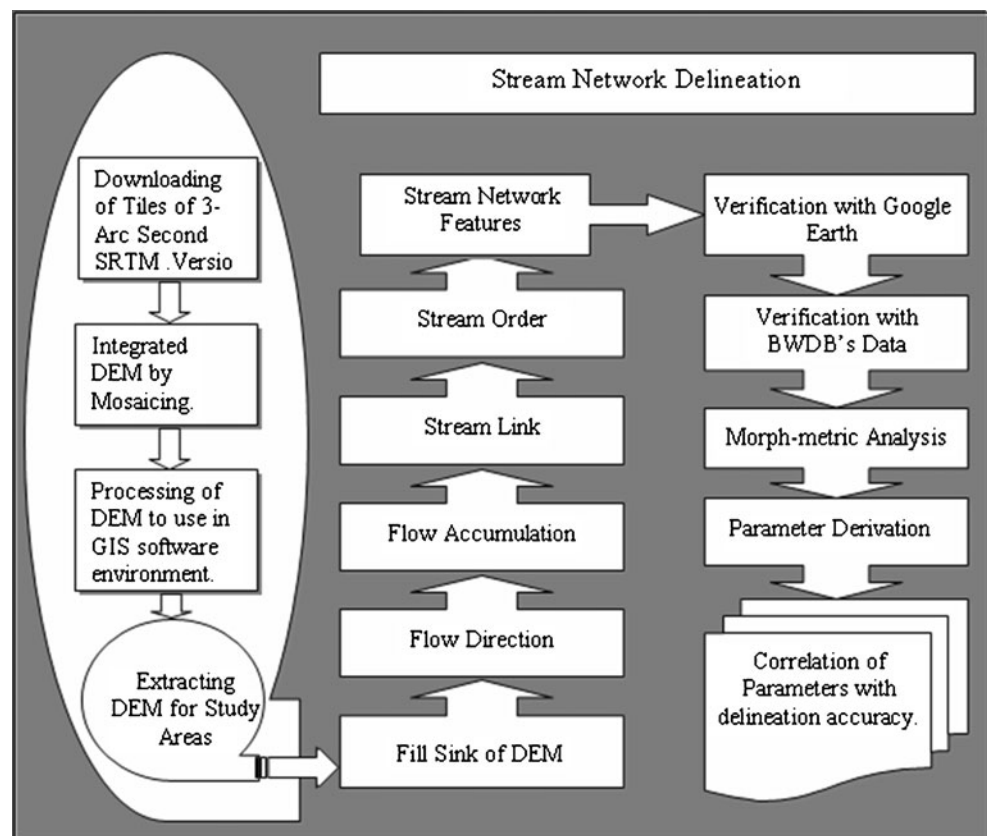
Three-arc second (90 m) SRTM digital elevation model data (version-3 and version-4) were used in this study. The data set were downloaded from the CGIAR website (<http://srtm.csi.cgiar.org/>).

Verification data

Two types of reference data were used to verify the results as given below:

1. Google Earth images Google Inc (2008)
2. Bangladesh Water Development Board's (BWDB) data: BWDB digitized river network (having more than 100 m width) using SPOT multi-spectral images (scale 1:50,000) of 1989, topographic maps from Survey of Bangladesh of 1:50,000 scale (1961), and LANDSAT TM (Thematic Mapper) images 1997 (WARPO 2008).

Fig. 2 Flow diagram of the methodology adopted for delineation of stream network using SRTM DEM



Methodology

The stream networks for each river catchment were delineated using the hydrology tool of Spatial Analyst

extension of ArcGIS 9.3 ESRI Inc (2007) by filling the sinks, finding the flow direction, estimating the flow accumulation, and delineating the stream line, and watershed. The flow directions are determined by

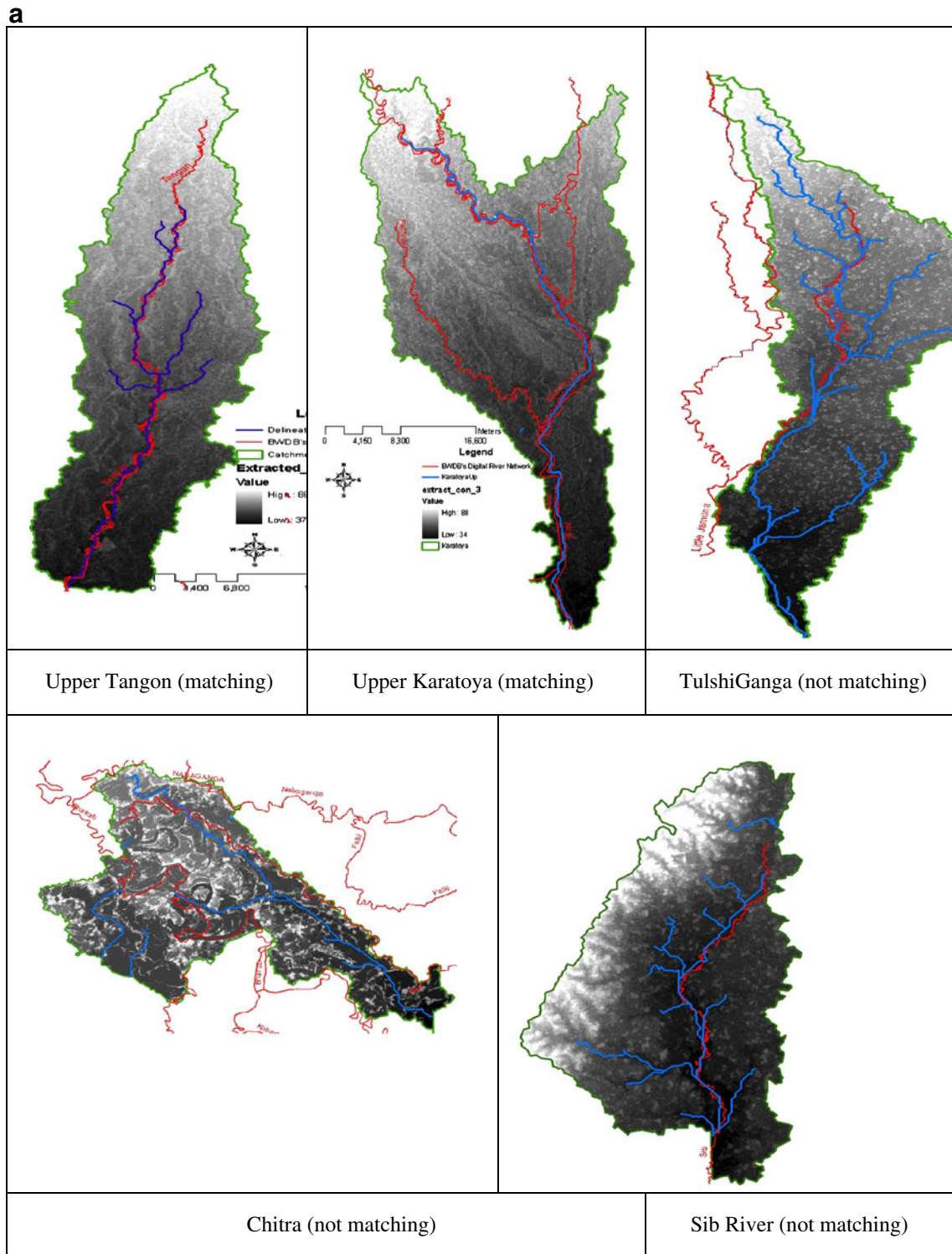


Fig. 3 **a** Delineated catchments (blue color for delineated and red color for reference data obtained from BWDB). **b** Delineated catchments (blue color for delineated and red color for reference data obtained from BWDB)

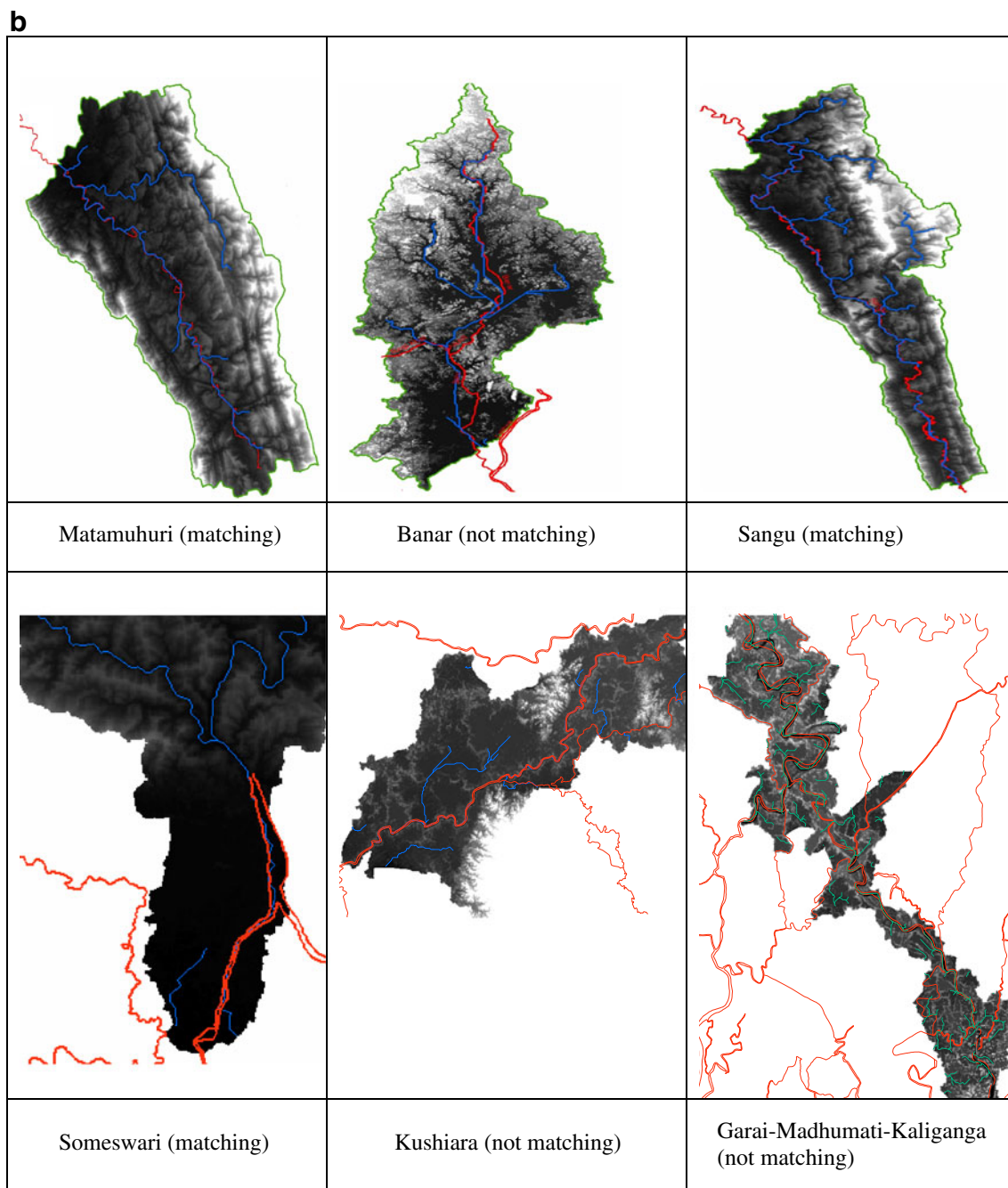


Fig. 3 (continued)

identifying the neighboring cells which has the highest positive distance weighted drop (Jensen and Dominique 1988). Flow accumulation is determined as the sum of the flow accumulation values of the neighboring cells which flow into it (Venkatachalam et al. 2001). The stream order is also defined using Strahler's classification (Strahler 1952). A step by step methodology used for drainage network delineation is shown in Fig. 2.

The delineated drainage pattern and the watersheds were then compared with the BWDB data and further verified by

exporting the data to Google Earth. In order to study the effect of other catchment parameters like slope, bifurcation ratio, width, and drainage density, these parameters were also estimated.

The distance between delineated river network and BWDB's observed network was measured in number of equal intervals using ArcGIS 9.3. The interval was taken less than 1 km for each catchment. This measured distance is the alignment error in river network delineation in both right (considered as +ve) and left side (considered as -ve) of the

original river network. The mean absolute error (MAE) and standard deviation were computed for quantification the error in network alignment. MAE is preferred because absolute error measures are less dominated by a small number of large errors, and thus, it is a more reliable indicator of typical error magnitudes (Lettenmaier and Wood 1993). The equation to calculate MAE is

$$MAE = \frac{1}{n} \sum_{i=1}^n |O(x_i y_i) - D(x_i y_i)| \tag{1}$$

Where,

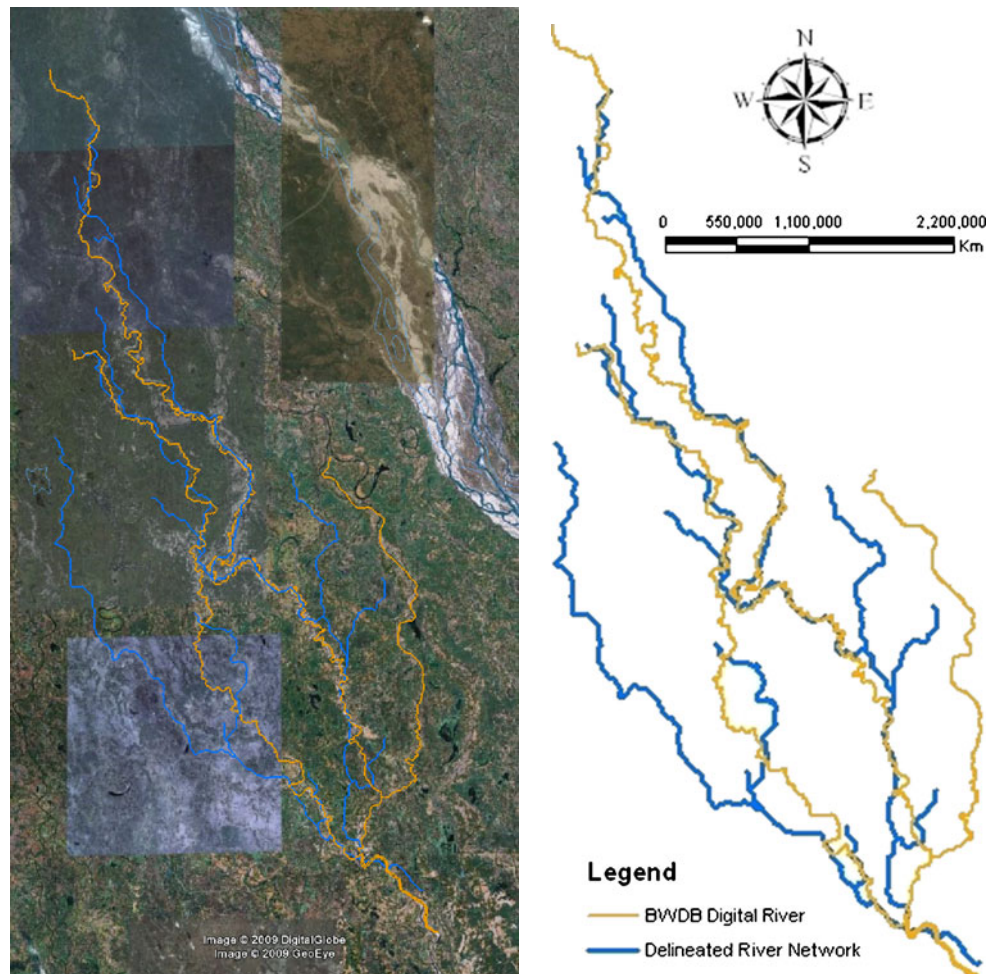
- $O(x_i y_i)$ is the location of observed river alignment at the rate of i^{th} interval
- $D(x_i y_i)$ is the location of delineated river network at the rate of i^{th} interval, and
- N is the total number of intervals

Results and discussion

The drainage network and watersheds were delineated following the methodology as described above. All the delineated catchments are shown in Fig. 3a, b. Drainage network of the Jamuneswari River is shown in Fig. 4. The delineated network and BWDB network were overlaid and are shown in Fig. 4a. The figure shows that the BWDB drainage network follows the river/stream network as seen in Google Earth images, and the delineated network deviates significantly from the streams as seen clearly in Fig. 4a. Delineated networks along with the BWDB drainage network is also provided in Fig. 4b which clearly shows the deviations in network delineation.

The range of deviation is from 0 to 5,000 m for all the catchment. A catchment is classified as matching when the minimum deviation is 0 and maximum deviation is less than 500 m. The same analysis was done for all catchments, and the results are presented in Table 1.

Fig. 4 Comparison of the delineated river network of the Jamuneswari River with BWDB river network and Google Earth images



(a)

(b)

Geomorphological parameters namely the bifurcation ratio (Rb), drainage density (Dd), and channel slope of the 12 catchments were estimated to find if there exists any relationship between the geomorphological parameters and suitability of the 90-m SRTM DEM data for automatic delineation of drainage network using hydrology tool of ArcGIS. The Dd is the ratio of the total length of streams to the total area of the watershed. The drainage density performs a rapid storm response. A value typically ranges from 0.94 to 3.5 km/km² (MSU 2008). The Rb is defined as the ratio of the number of streams of any order to the number of streams of the next highest order (Horton 1945). Values of Rb typically range from the theoretical minimum of 2 to around 6 and typically, the values range from 3 to 5 (MSU 2008). Normally, the main stream is delineated, and the slope is

computed as the difference in elevation (ΔE) between the end points of the longest flow path divided by the hydrologic length of the flow path.

The values of the geomorphological parameters have been calculated using inputs from delineated drainage network. Table 1 shows a comparison of the geomorphological parameter with the deviation of the catchment. The comparison shows that, among the catchment parameters like slopes, bifurcation ratio, and drainage density, only slope is the main governing parameter. All other catchment characteristics other than the slope have no effect on river network delineation. The delineated catchments of slope 1:3,600 or more flat shows enormous error in stream delineation. Large deviations in delineated river network are seen when compared with the digital river network of BWDB and with Google Earth's images. The catchments

Table 1 Comparison of river network delineation for different catchments of Bangladesh

River name	Slope of the river bed ^a	Bifurcation ratio, Rd	Average width of the river (m) ^a	Drainage density, D_d ($\sum L, A$)	Deviation of the alignment	Remarks
01	02	03	04	05	06	07
Matamuhuri-Upper	1:500	3.25	200 to 300=250	0.15 (97 km, 658 km ²)	Matches (maximum 322 m deviation, no breaking of stream line exists)	Slope $\leq 1:2,850$
Tangon-Upper	1:2,000	7.00	200 to 700=450	0.15 (92 km, 669 km ²)	Matches (maximum 500 m deviation, no breaking of stream line exists)	Slope $\leq 1:2,850$
Sangu-Upper	1:1,000	3.17	300 to 1,000=625	0.16 (238 km, 1,535 km ²)	Matches (maximum 500 m deviation, no breaking of stream line exists)	Slope $\leq 1:2,850$
Karatoya	1:2,600	3.25	>50 to 450=250	0.10 (92 km, 954 km ²)	Matches (maximum 300 m deviation, no breaking of stream line exists)	Slope $\leq 1:2,850$
Someswari	1: 2,850	2.50	250 to 550=400	0.18 (122 km, 665 km ²)	Matches (maximum 200 m deviation, no breaking of stream line exists)	Slope $\leq 1:2,850$
Jamuneswari	1:3,600	2.41	100 to 650=375	0.18 (245 km, 1,373 km ²)	Does not match (maximum 2,100 m deviation, no breaking of stream line exists)	Slope $\geq 1:3,600$
Chitra	1:13,000	4.00	150 to 350=259	0.12 (139 km, 1,187 km ²)	Does not match (maximum 5,000 m deviation, no breaking of stream line exists)	Slope $\geq 1:3,600$
Sib_river	1:5,000	3.85	600 to 1,200=900	1.94 (89.25, 46.05 km ²)	Does not match (maximum 1,000 m deviation, no breaking of stream line exists)	Slope $\geq 1:3,600$
Garai-Madhumati-Kaliganga	1:32,000	2.00	250 to 650=450	0.05 (95 km, 1,930 km ²)	Does not match (maximum 2,300 m deviation and breaking of stream line exists)	Slope $\geq 1:3,600$
Kushiara	1:13,000	4.5	150 to 300=225	0.13 (139 km, 1,038 km ²)	Does not match (maximum 550 m deviation and breaking of stream line exists)	Slope $\geq 1:3,600$
Banar River	1:7,000	3.25	300 to 1,000=650	0.14 (106 km, 772 km ²)	Does not match (maximum 2,600 m deviation and no breaking of stream line exists)	Slope $\geq 1:3,600$
Tulshi-Ganga	1:9,000	5.5	400 to 1,000=700	0.15 (240, 1,550 km ²)	Does not match (maximum 2,500 m deviation and breaking of stream line exists)	Slope $\geq 1:3,600$

$\sum L$ total length, A area

^a Measurement has been taken from pixel value of the processed SRTM DEM

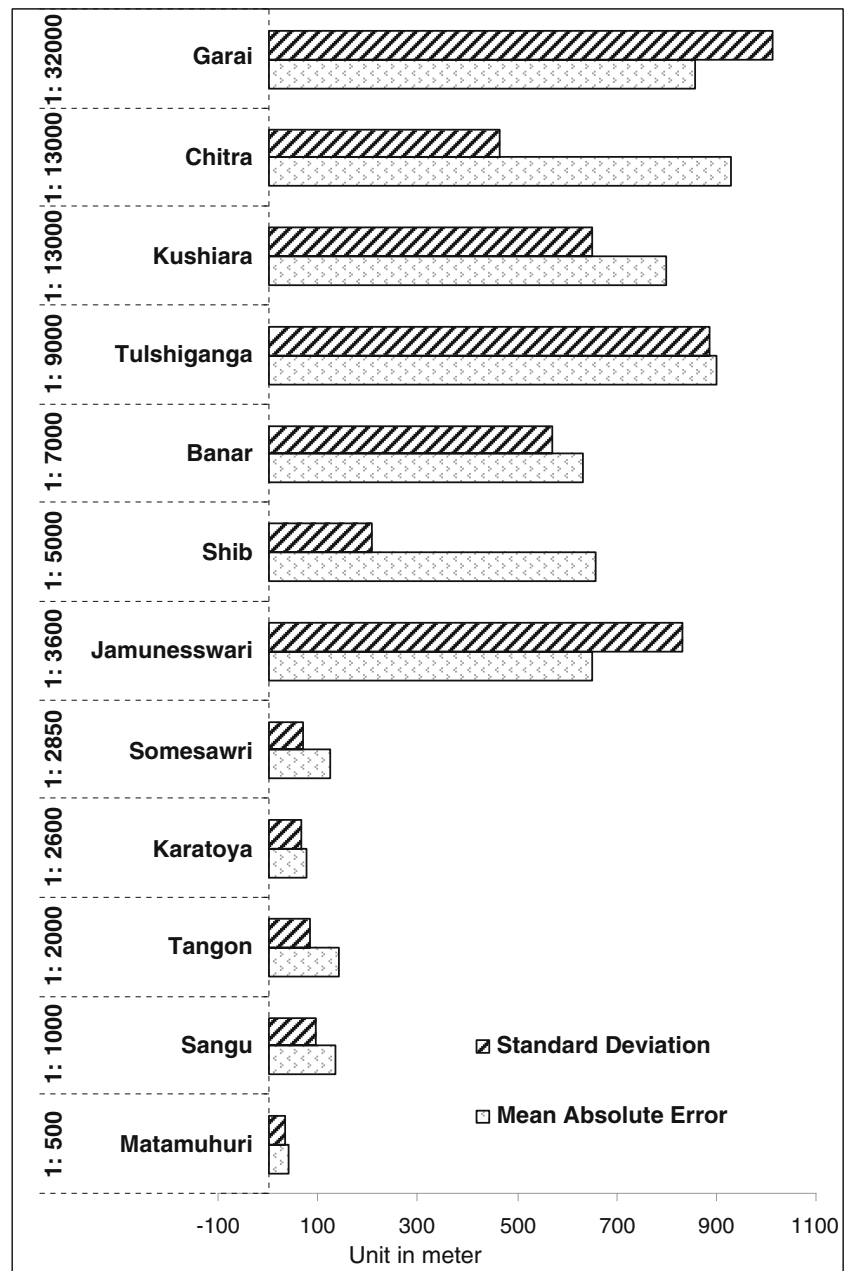
having slope 1:2,850 and more steep were delineated correctly. However, a conclusion could not be established between slopes 1:2,850 and 1:3,600. The calculated MAE of all the catchments shows that it increases with respect to decrease of slope as seen in Fig. 5.

Conclusion

A study was undertaken to evaluate the performance of 90-m SRTM DEM in delineation of drainage network using

hydrology tool of ARCGIS, in the flat terrain of Bangladesh. Twelve catchments were selected from the five hydrological zones of Bangladesh. It is concluded that, in flat terrains having a slope flatter then 1:2,850, delineation of drainage network must be carried out carefully using the hydrology tool of ArcGIS software that uses the D8 method for delineation of drainage pattern and catchments. It is also recommended that other techniques excluding D8 method as implemented in ArcGIS, should be experimented before a general conclusion about the use of SRTM data in flat terrains could be drawn.

Fig. 5 Comparison of mean absolute error with the catchment slope. The figure shows clearly that the error is increasing significantly with the increase in slope



Acknowledgement The authors thankfully acknowledge the constructive suggestions received from the anonymous reviewers.

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