# Comparison of SRTM and ASTER Derived Digital Elevation Models over Two Regions in Ghana – Implications for Hydrological and Environmental Modeling

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## 1. Introduction

A Digital Elevation Model (DEM) refers to a quantitative model of a part of the earth's surface in digital form (Burrough and McDonnell, 1998). A DEM consists of either (1) a two-dimensional array of numbers that represents the spatial distribution of elevations on a regular grid; (2) a set of $x$, $y$, and $z$ coordinates for an irregular network of points; or (3) contour strings stored in the form of $x$, $y$ coordinate pairs along each contour line of specified elevation (Walker and Willgoose, 1999). Though there are some disadvantages (Gao, 1997), regular grid DEMs are nowadays the most popular due to their computational efficiency. The use of DEM in this paper, therefore, refers to a regular gridded DEM.

DEMs are useful for many purposes, and are an important precondition for many applications (Kim and Kang, 2001; Vadon, 2003). They are particularly useful in regions that are devoid of detailed topographic maps. DEMs have been found useful in many fields of study such as geomorphometry, as these are primarily related to surface processes such as landslides which can directly be depicted from a DEM (Hengl and Evans, 2009), archaeology as subtle changes due to previous human activity in the sub surface can be inferred on detailed DEMs (Menze *et al*., 2006), (commercial) forestry, e.g. height of trees and relation to preferred tree stem size (Simard *et al*., 2006), hydrology, like deriving drainage network and overland flow areas that contribute to (suspended) sediment loads (Lane *et al*., 1994) and analysis of glaciers (movement of glaciers using multi temporal DEM's) and glaciated terrains (change of glacier thickness by comparison of multi temporal DEM's) (Bishop *et al*., 2001). Thus for a whole range of different studies, typically topics of interest to geomorphologists, DEMs that provide a good representation of the terrain, are of utmost importance as a starting point for further analysis.

DEMs can be generated using several methods, with varying degrees of accuracy and cost (Flood and Gutelius, 1997). Traditionally, they have been derived from contours that are extracted with photogrammetric techniques from aerial stereo photographs using the parallax displacement on the overlapping images, in conjunction with the flight parameters, to derive elevation information (X,Y,X, Omega, Phi and Kappa) (Petrie and Kennie, 1990). Currently using digital photogrammetric software, when the 6 orientation parameters are recorded during the flight (using an inertial measurement unit (IMU) in conjunction with GPS), direct georeferencing is possible and the initial DEM extraction can be achieved directly. Further post processing might be required though. DEMs are also generated from optical satellite images using similar elevation extraction methods (Jacobson, 2003). In 1986, SPOT was the first satellite to provide stereoscopic images that allowed the extraction of DEMs (Nikolakopoulos *et al*., 2006). Advances in space technology have now resulted in many more satellites - ASTER, IKONOS, Quickbird and IRS-1C/1D (etc.) - producing stereoscopic images facilitating the extraction of DEMs, both relative, using only orbital information or absolute, integrating also known ground control points. The last procedure is done through provision of actual ground locations in X,Y,Z.

Use of satellite images for DEM generation have a tremendous advantage over traditional methods in that DEMs over large and inaccessible areas can nowadays be easily produced (near) real-time and within a relatively short time and at remarkable cheaper costs. A disadvantage, however, is that optical spectral range requires a cloud free view and appropriate (time of the day) light conditions in order to generate a good quality and high resolution (in accordance with flight parameters) DEM. Radar Interferometry or Interferometric Synthetic Aperture Radar (InSAR) have recently become popular in extracting elevation data. This technique uses two or more Synthetic Aperture Radar (SAR) recordings to generate DEMs, using differences in the phase of the waves returning to the satellite or airborne platform (Rosen *et al*., 2000). Radars have two main advantages over optical techniques (Massonnet and Feigl, 1998): (1) as an active system, they self-transmit and receive electromagnetic waves. This means image acquisition is independent of natural illumination and therefore images can be taken at night. (2) Observations are not affected by cloud cover since the atmospheric absorption at typical radar wavelengths is very low. National Aeronautics and Space Administrations' (NASA) Shuttle Radar Topographic Mission (SRTM), which produced a near-global DEM, followed this methodology. This system applied a so called single overpass technique using a dual antenna setup. Two systems recorded different wavelength bands (the German Space Research Centre, DLR, operated an X band and NASA a C-band InSAR). For each wavelength, the two antennas' on board of the shuttle were displaced by a certain baseline distance (60 m). When using single overpass, dual antenna techniques, images are recorded at the same time. Using different overpasses from different orbits, recording the same area, mostly the dielectric properties at the Earth surface have changed (given the fact that environmental conditions have changed with respect to a next overpass!) the initial interferogram might show low correlations for locations where environmental conditions have changed in the mean time and therefore the actual elevation might not be properly extracted for these locations.

Another method currently popular in the US and Europe is the Lidar or Airborne Laser Scanning. Due to the fact that these types of recordings are not readily available over Western Africa they are not further discussed here.

Irrespective of the method used, generated DEMs are inevitably subjected to errors, mainly due to the methodology followed (see above) or the various post-processing steps the models have to undergo (e. g. interpolation). It is, therefore, imperative that errors are quantified so as to provide users with first hand information on the accuracy of the DEM.

SRTM and ASTER-derived DEMs are two post-processed elevation datasets that are frequently used for a wide range of applications due to their near-global coverage (Nikolakopoulos and Chrysoulakis, 2006). Dozens of researchers have, over the past few years, carried out a series of global and local assessments of these products. Rodriquez et al. (2006) performed a global validation of the SRTM product using globally distributed set of ground control points derived from Kinematic Global Positioning System (KGPS) transects and National Geospatial-Intelligence Agency's (NGA) level 2 Digital Terrain Elevation Data (DTED). They concluded that SRTM has an absolute height error that exceeds the mission's goal of 16m (90%) often by a factor of two. Hofton et al. (2006) also used data from NASA's Laser Vegetated Imaging Sensor (LVIS) to assess SRTM's accuracy at study sites of variable relief and landcover (i.e. vegetated and non-vegetated terrain). They found out that, under "bare earth" conditions, SRTM data are accurate measurements of LVIS data whereas in vegetated areas, SRTM fell above the ground but below the canopy top, indicating an increase in the vertical offset between SRTM and the LVIS ground data. Jarvis et al. (2004) examined relative and absolute differences between SRTM DEM and a cartographically derived (TOPO) DEM using 1:50,000 scale contours digitized for all Honduras. They validated the two datasets using fifty-nine (59) high accuracy GPS points derived from the National Geodetic Survey (NGS) GPS database from the Central America High Accuracy Reference Network project (NGS, 2003). They also computed slope, aspect, curvature and Pearson's Correlation Coefficient. Their analysis revealed that, SRTM DEM has an average error of 8m as opposed to 20m for the TOPO DEM, although some systematic errors were identified in the SRTM data, related to aspect. They, therefore, concluded that SRTM is more accurate than the 1:50,000 scale cartographically derived DEM for Honduras. Slater et al. (2009) conducted an evaluation of the new ASTER Global Digital Elevation Model (GDEM) using 20 sites in 16 countries. Datasets used for comparison (reference data) with the ASTER GDEM are (1) level 1 and 2 DTED data and (2) control points data (GCPs) photogrametrically derived from satellite imagery. Standard DEM-to-DEM comparisons and DEM-to-control-point comparisons as well as detailed visual analyses of the data were conducted. It was found out that, in almost every area, the mean ASTER GDEM elevations are lower than the reference DEM elevations (biased negatively). The mean ASTER elevations are also lower than the GCPs in every area. Most of the assessments conducted have reported on an absolute accuracy assessment though.

In this study, the C-band SRTM - and ASTER – derived DEMs are compared and validated against a reference DEM for two regions in Ghana. Next to an absolute accuracy assessment also a relative assessment has been conducted. For many environmental and hydrological processes, even if the absolute elevation is not correct, relative to its surrounding regions it might for example exhibit the appropriate flow direction which is the basis of many GIS routines to derive a hydrological network. The reference DEM used was generated using data from a 1:50 000 scale contour map with the TOPOGRID function in the ArcInfo™ software (Hutchinson, 1988, 1989).

### 1.1 Objectives

In short, the objectives of this work are to:

- Assess how the elevation data from SRTM and ASTER do compare in an absolute manner with respect to a contour based "traditionally derived" elevation model in an absolute comparison. DEMs over different topography and land cover have been selected.

- Derive the "behavior" of the DEMs over different terrain, using multiple tests, to observe their "internal coherence", which is referred to here as "relative assessment". This assessment is especially relevant to geomorphologists, as actual land surface processes do not have a direct bearing on absolute elevation alone, these can also be appropriately studied if relatively to each other the individual elevation grids resemble appropriate elevation change! This topic has hardly been addressed in literature so far!
- Determine implications of the accuracy of the products for hydrological and environmental modeling.

### 1.2 Study sites

The study is conducted for two sites in Ghana (Figure 1). These sites fall in different agro climatic zones, have different elevation ranges and differ in landcover. Site 1, which climatologically falls in the Guinea Savannah zone (northern Ghana), has an elevation range of about 400 m. It is fairly flat, with an average slope of $0.9^0$. The major landcover types are deciduous woodland (55 %) and shrubland (36 %). Site 2 lies between two climatic zones – moist semi-deciduous forest and transitional zones. It has an elevation range of about 780 m, with an average slope of $3.3^0$. Though also fairly flat, this site has a range of mountains that borders the Volta Lake. The dominant landcover types are forest (52 %) and woodland/shrubland (34 %).

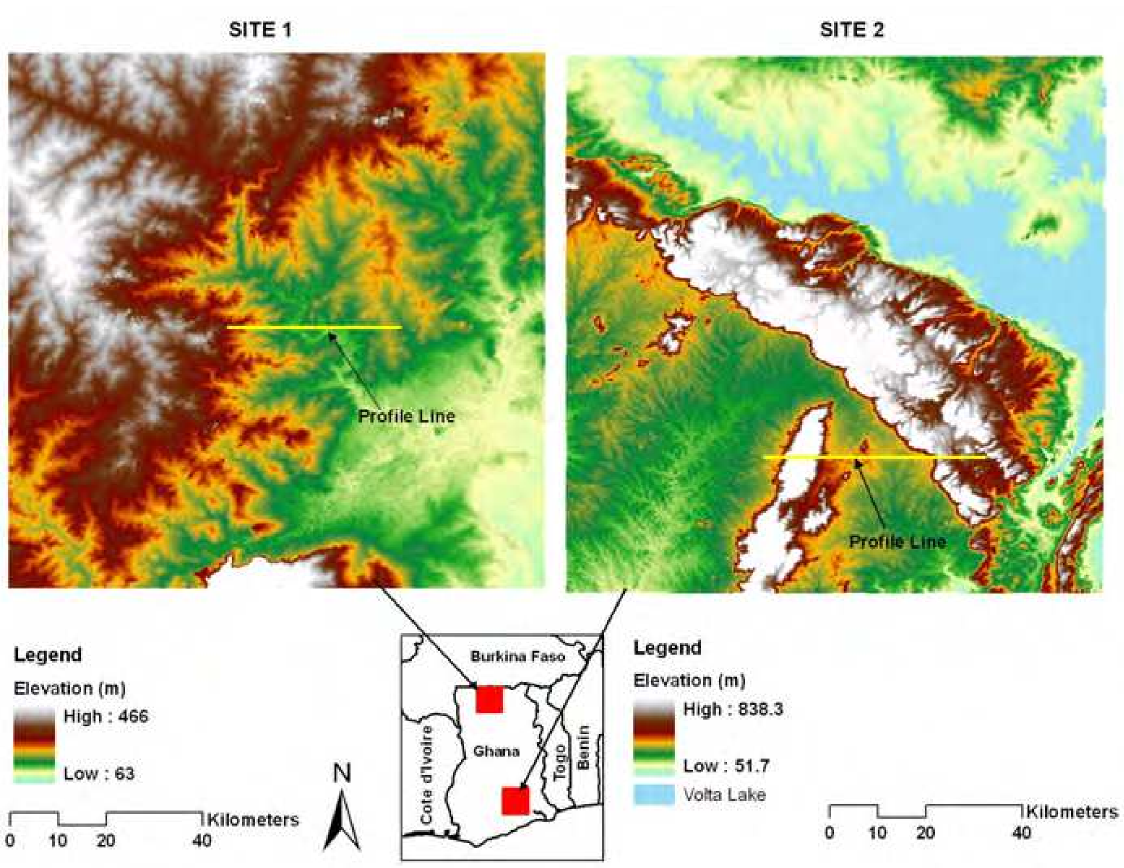


Fig. 1. Map of the study sites

## 2. Data

### 2.1 Aster GDEM

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) is an advanced multispectral imager that was launched onboard NASA's Terra spacecraft in December, 1999. ASTER has three spectral bands in the visible near-infrared (VNIR), six bands in the shortwave infrared (SWIR), and five bands in the thermal infrared (TIR) regions, with 15-, 30-, and 90-m ground resolution, respectively (Yamaguchi *et al.* 1998). The VNIR subsystem has one backward-viewing (27.7$^0$ off-nadir) instrument for stereoscopic observation in the along-track direction, making imagery acquired by this satellite suitable for DEM generation. Other important properties that make ASTER data suitable for DEM generation are the platform altitude (705 km) and its base-to-height ratio of 0.6 (Abrams 2000; Hirano *et al*. 2003).

The Ministry of Economy, Trade and Industry of Japan (METI) and the United States NASA recently released a global DEM (ASTER GDEM) derived from ASTER images acquired since its launch (1999) to the end of August, 2008. It covers land surfaces between 83$^0$ N and 83$^0$ S, comprising of 22 600 1$^0$ –by- 1$^0$ tiles. The GDEM is provided at a one arcsec resolution (30 m) and referenced to World Geodetic System (WGS) 1984. Elevations are computed with respect to the WGS 84 EGM96 geoid. The vertical accuracy of the DEM data generated from the Level-1A data is 20 m with 95% confidence without ground control point (GCP) correction for individual scenes (Fujisada *et al*., 2005).

METI and NASA acknowledges that Version 1 of the ASTER GDEM is "research grade" due to the presence of certain residual anomalies and artifacts in the data that may affect the accuracy of the product and hinder its effective utilization for certain applications. For this study, two 1$^0$ –by- 1$^0$ tiles in Ghana (see figure 1) were download from NASA's Warehouse Inventory Search Tool (WIST - https://wist.echo.nasa.gov/api/)

### 2.2 SRTM DEM

The SRTM (Werner, 2001; Rosen *et al*., 2001a), undertaken by NASA and the NGA, collected interferometric radar data which has been used by the Jet Propulsion Laboratory (JPL) to generate a near-global (80% of earth's land mass) DEM for latitudes smaller than 60$^0$. SRTM has been the first mission using space-borne interferometric SAR (InSAR). The SRTM mission has been a breakthrough in remote sensing of topography (van Zyl, 2001), producing the most complete, highest resolution DEM of the world (Farr *et al*., 2007). An extensive global assessment revealed that the data meets and exceeds the mission's 16m (90 percent) absolute height accuracy, often by a factor of two (Rodríguez *et al*., 2006). Since its release in 2005, the user community has embraced the availability of SRTM data, using the data in many operational and research settings.

SRTM data for this study was downloaded from the website of the Consultative Group on International Agricultural Research Consortium for Spatial Information (CGIAR-CSI - http://srtm.csi.cgiar.org). Data available from this site has been upgraded to version 4, which was derived using new interpolation algorithms and better auxiliary DEMs. This version, thus, represent a significant improvement from previous ones.

### 2.3 Reference DEM

The reference DEM was generated from the hypsographic (contours) and hydrographic (rivers/streams) data in the 1:50,000 topographical map series produced by the Survey Department of Ghana (SDG). The contours used have an interval and vertical accuracy of 50 feet (≈ 15m). This accuracy supersedes that of the 16m and 20m of SRTM and ASTER respectively, hence its use as a reference. Map sheets covering the study sites were merged prior to generating the DEM.

The SDG, in January 2009, adopted the WGS 1984 (UTM) coordinate system (Daily Graphic, 14th October 2008). Prior to this, the department's maps (including the ones used in this study) were produced based on a local datum and the "war office" ellipsoid. Thus, there was the need to transform the data from the old system (Ghana grid) into the new adopted system (WGS 84 UTM). Table 1 shows the transformation parameters, as published by the SDG, used for the conversion.

The TOPOGRID function in the ArcInfo™ software was used to interpolate the transformed contour data into a DEM. There are many interpolation methods used to generate a DEM from contour data (Hengl and Evans, 2009). Comparison of these techniques has been extensively carried out by many researchers (Wise, 2000). Li *et al*. (2005) points out that there is no universal interpolation technique that is clearly superior, and appropriate for all sampling techniques and DEM applications. Despite this conclusion, Hengl and Evans (2009) recommend that, where possible, algorithms that can incorporate secondary information (such as layers representing pits, streams, ridges, scarps or break lines) should be implemented for DEM interpolation. One such method, and the one used in this study, is the ANUDEM algorithm by Hutchinson (1988, 1989), and implemented as the TOPOGRID function in the ArcInfo™ software. ANUDEM is based on the discretized thin-plate spline technique (Wahba, 1990), and is an iterative DEM generation algorithm that produces hydrologically correct DEMs. The algorithm starts with a coarse grid, and then enforces drainage conditions, the spatial resolution is increased, and then drainage enforcement is performed again, and so on, until the desired resolution is reached (Hengl and Evans, 2009).

| Local Datum | Geodetic | Transformation Parameters | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Name | Code | Pub. Date | $\Delta X$ | $\Delta Y$ | $\Delta Z$ | Rx (Rads) | Ry (Rads) | Rz (Rads) | Scale factor | Xo | Yo | Zo |
| Ghana | GHA | 2008 | -196.58 | 33.383 | 322.552 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |

Source: Daily Graphic of Ghana, 14th October 2008

Table 1. Transformation parameters (War Office to WGS 84)

The grid resolution chosen for the reference DEM was based on equation (1). In cases where a DEM is based on contours, a suitable grid resolution can be estimated from the total length of the contours (Hengl and Evans, 2009). It is important to choose a grid resolution that optimally reflect the complexity of the terrain and represent the majority of the geomorphic features (Smith *et al*., 2006).

$$\Delta S = \frac{A}{2.\sum L} \tag{1}$$

where "A" is the area of the study site (km²) and "L" is the cumulative length of all contour lines (km).

Table 2 shows the implementation of equation (1) for both study sites and the resultant grid resolution. Based on these results, a cell size of 90 m was chosen in generating the reference DEM. The choice of a 90 m spatial resolution reflects the complexity of terrains for both study sites and allows direct comparison with the 90 m SRTM data.

| Site | Area (Km²) | Length of contours (km) | Grid resolution (m) |
|---|---|---|---|
| 1 | 12100 | 21736.0 | 278.3 |
| 2 | 12100 | 61875.6 | 97.8 |

Table 2. Suitable grid resolution for the Reference DEM

## 3. Methodology

### 3.1 Data preparation

DEMs of the study sites were transformed into the same projection system – Universal Transverse Mercator (UTM) zone 30 north. WGS 1984 was selected as both datum and spheroid. Part of the Volta Lake falls within site 2. For this reason, a mask was prepared and used to mask out the lake area on all DEMs (ASTER, SRTM and Reference). The original 30 m resolution of the ASTER GDEM was resampled to 90 m to enable comparison with the other DEMs. After resampling, a low pass 3 x 3 filter was applied to all DEMs to remove possible outliers still remaining in the data. In practice, smooth models of topography and a small amount of smoothing of DEMs prior to geomorphometric analysis have proved more popular among geomorphometricians, although no single smoothing approach is absolutely superior for all datasets and study areas (Hengl and Evans, 2009). No misalignment between DEMs was observed, thus co-registration was not necessary. Table 3 presents summary statistics of the DEMs compared for both sites.

### 3.2 Comparison of DEMs

Two main approaches were used to compare and validate the elevation products against the reference. These are: (1) determining the accuracy of the *elevation values* of the products (absolute accuracy) and (2) determining the accuracy of terrain derivatives of the products (relative accuracy).

#### 3.2.1 Accuracy of elevation values

This was achieved by performing DEM differencing, profiling and correlation plots.

- **DEM differencing**: This was performed to derive elevation error maps. Root mean square error (RMSE), a common measure of quantifying vertical accuracy in DEMs, was calculated for each error map. In addition, skewness and kurtosis (King and Julstrom, 1982) was calculated for each error map. Skewness is a unitless measure of asymmetry in a distribution (Shaw and Wheeler, 1985). Negative skewness indicates a longer tail to the left, while positive skewness indicates a longer tail to the right. Excess kurtosis is a unitless measure of how sharp the data peak is. A value larger than zero (0) indicates a peaked distribution, while a value less than zero (0) indicates a flat distribution. Percentage of pixels falling within different error ranges was also determined.

- **Profiling**: Horizontal profiles were created on the DEMs and compared. Profile lengths were 35 km and 45 km for site 1 and 2 respectively. A graph of elevation against distance was produced for comparison. Figure 3 (*a* and *b*) shows profile graphs for sites 1 and 2.
- **Correlation scatter plots**: This was performed to assess the level of correlation between the DEMs. It was difficult making a scatter plot from all the pixels in a DEM, as each DEM contained over a million pixels. For this reason, the scatter plots are based on randomly selected points/pixels. In all, about 6000 points/pixels were randomly selected from each DEM. They are an aggregation of pixels randomly selected from different landcover types identified in each site. For each site, two scatter plots were produced and correlation coefficient determined.

| Dataset | **Description** | **Min** | **Max** | **Mean** | **Standard deviation** | **Skewness** | **Kurtosis** |
|---|---|---|---|---|---|---|---|
| | **Site 1** | | | | | | |
| *Reference* | **Elevation** | ***105*** | ***463*** | ***213.0*** | ***63.2*** | ***0.45*** | ***2.3*** |
| | Slope | *0* | *30.2* | *0.86* | *0.94* | *9.5* | *183.6* |
| *SRTM* | **Elevation** | ***111*** | ***467*** | ***216.9*** | ***63.5*** | ***0.45*** | ***2.4*** |
| | Slope | *0* | *31.9* | *0.97* | *0.9* | *11.1* | *240.6* |
| *Aster* | **Elevation** | ***77*** | ***464*** | ***209.87*** | ***64.8*** | ***0.4*** | ***2.3*** |
| | Slope | *0* | *29.9* | *1.06* | *0.9* | *9.3* | *182.2* |
| **Site 2** | | | | | | | |
| *Reference* | **Elevation** | ***44.8*** | ***836.0*** | ***238.9*** | ***139.8*** | ***1.2481*** | ***3.8751*** |
| | Slope | *0* | *45.1* | *3.3* | *4.2* | *2.523* | *10.758* |
| *SRTM* | **Elevation** | ***51.7*** | ***838.3*** | ***241.0*** | ***139.7*** | ***1.2499*** | ***3.9459*** |
| | Slope | *0* | *47.1* | *3.5* | *4.1* | *2.5949* | *11.311* |
| *Aster* | **Elevation** | ***41.3*** | ***848.7*** | ***235.6*** | ***139.6*** | ***1.2479*** | ***3.9275*** |
| | Slope | *0* | *44.3* | *3.7* | *4.0* | *2.4926* | *10.561* |

Table 3. Summary statistics of DEMs analysed for both sites

### 3.2.2 Accuracy of terrain derivatives

In this assessment, the three DEMs were first preprocessed to obtain a hydrologically consistent elevation model (filling local depressions). Flow direction, using a Deterministic-8 flow direction algorithm, flow accumulation and drainage maps were subsequently generated. Next, a common outlet location was used to extract an upstream catchment area from the DEMs and the attributes of the derived catchments compared. This analysis was conducted for site 1 alone due to two main reasons: (1) the location of the Volta Lake within site 2 would result in a large number of relatively small catchments that directly drain into the lake, and (2) the relief of site 1 is relatively gentle (average slope = $0.9^0$) and for the accuracy of terrain derivatives this is critical since in steeply sloping terrain the flow direction is assigned correctly. Using statistics extracted, the following analyses and comparisons were performed.

- **Longitudinal Profiles**: these were extracted at 500m interval, along the longest flow path, with the respective depression- filled DEMs as source. Profiles of the three DEMs were plotted and compared.
- **Horton Plot:** In hydrology, the geomorphology of the watershed, or quantitative study of the surface landform, is used to arrive at measures of geometric similarity among watersheds, especially among their stream network. The quantitative study of stream networks was originated by Horton. Horton's original stream ordering was slightly modified by Strahler, and Schumm added the law of stream areas. Number of streams of successive order, the average stream length of successive order and the average catchment area of successive order is found to be relatively constant from one order to another. Graphically this can be visualized by construction of a Horton plot. The Horton plots show the relationship between Strahler order and total number of Strahler order stream segments for a given order, average length per Strahler order and average catchment area per Strahler order, as well as the bifurcation (Rb), channel length (Rl) and stream area ratio's (Ra), by means of a least square regression line. Using the extracted drainage data from the three DEMs, Horton's statistics were derived and the results graphically displayed by plotting Strahler order on the X-axis and the number of drainage channels, stream length and stream area on a log transformed Y axis.
- **Geomorphological Instantaneous Unit Hydrograph (GIUH)**: The GIUH model is based on the theory proposed by Rodriquez-Iturbe and Valdes and its subsequent generalization by Gupta. According to the theory, the unit input (unit depth of rainfall) is considered to be composed of an infinite number of small, non-interacting drops of uniform size, falling instantaneously over the entire region. The basin geomorphology plays an important role in the transition of water from the overland region to channels (streams) and also from the channels of one order to the other (Bhadra *et al.*, 2008). Using extracted statistics such as Horton's ratios, length of highest order stream, maximum order, etc., a GIUH was calculated, assuming identical effective precipitation and effective holding capacity for each of the datasets. No infiltration was assumed. A user-friendly event based computerized GIUH model, "GIUH_CAL" (Bhadra *et al.*, 2008) was applied to derive the direct runoff hydrograph of an assumed uniform storm event for all three DEMs and compared.
- **Topographic Index (TI)**: TI is a topography-based concept for watershed hydrology modeling which has been widely used to study the effects of topography on hydraulic processes (Wolock and McCabe, 1995). The TI, $ln(a/tan\ b)$, is the natural logarithm of the ratio of the specific flow accumulation area "$a$" to the ground surface slope "$tan\ b$". Surface slope can be evaluated from DEMs. The specific flow accumulation area is the total flow accumulation area (or upslope area) "$A$" through a unit contour length "$L$".

When using a DEM, *L* can be defined as being equal to the horizontal resolution of the DEM (Pan *et al*., 2004). In this study, the algorithm applied uses a Deterministic-8 flow direction algorithm to obtain the (specific) flow accumulation area. The continuous Topographic Index data range obtained for each of the DEMs was classified into integer classes and plotted for comparison purposes.

## 4. Results and discussion

### 4.1 Accuracy of elevation values

Table 4 presents the statistics of the error maps obtained for both sites, whereas figure 2 (*a* - *d*) shows the spatial distribution of the errors and the percentage of pixels that falls in different error ranges. It is quite evident that better results were obtained for site 1 than site 2. This is manifested in the RMSEs obtained for site 1. Although all RMSEs fall within predefined vertical accuracy specification (Slater *et al*., 2006; Fujisada *et al*., 2005), results for site 1 indicate that the products (of site 1) are three-times better than that of site 2. This could be due to the physical characteristics of site 1, which has a relatively flat terrain with a mean slope of about $0.9^0$. It can, thus, be said that both products do better on flat and less complex terrain than would do on hilly and mountainous terrain as in site 2.

| Difference Map | Min | Max | Mean | Standard deviation | RMSE | Skewness | Kurtosis |
|---|---|---|---|---|---|---|---|
| **Site 1** | | | | | | | |
| *ASTER - Reference* | *-82.92* | *118.01* | *-3.30* | *6.05* | *5.46* | *1.4326* | *20.884* |
| *SRTM - Reference* | *-70.96* | *143.57* | *3.67* | *5.70* | *4.95* | *2.3606* | *43.820* |
| **Site 2** | | | | | | | |
| *ASTER - Reference* | *-245.56* | *233.78* | *-3.323* | *20.41* | *18.76* | *-0.4743* | *10.512* |
| *SRTM - Reference* | *-229.89* | *204.44* | *2.089* | *16.08* | *14.54* | *-0.7992* | *15.054* |

Table 4. Difference statistics of the study sites

Table 4 further reveals that, compared to the reference DEM, SRTM has a better vertical accuracy than the ASTER GDEM. In both sites, a smaller RMSE was obtained for SRTM than ASTER GDEM. This finding is in line with the pre-launch vertical accuracy of 16m for SRTM (Hensley *et al*., 2001) and 20m for ASTER GDEM (Fujisada *et al*., 2005; Slater *et al*., 2009).

Figures 2*a* and 2*b* shows the spatial distribution of errors in the ASTER GDEM for both sites. The graphs and statistics indicate that ASTER GDEM elevations are generally lower, compared to the reference DEM (i. e biased negatively). In other words, the ASTER GDEM underestimates elevation on both sites. Statistics from site 1 indicate that 74% of pixels fall below zero (0), whereas 58% of pixels fall below zero (0) in site 2. This further reveals that, though ASTER GDEM generally underestimates elevation, this underestimation is more pronounced on flat and less complex terrains (as in site 1) than in hilly and complex terrains.

Figures 2*c* and 2*d* shows that SRTM have the directly opposite characteristic – overestimates elevation. Elevation differences are positively biased, resulting in majority of pixels being greater than zero (0). Statistics from site 1 indicate that about 78% of pixels were greater than zero (0), whereas about 60% was greater than zero (0) in site 2. This overestimation may be partly due to the fact that SRTM records the reflective surface and, thus, may be positively biased with respect to the bare earth when foliage is present. This under- and overestimation of ASTER GDEM and SRTM respectively has been noted in previous studies (Slater *et al.*, 2009).

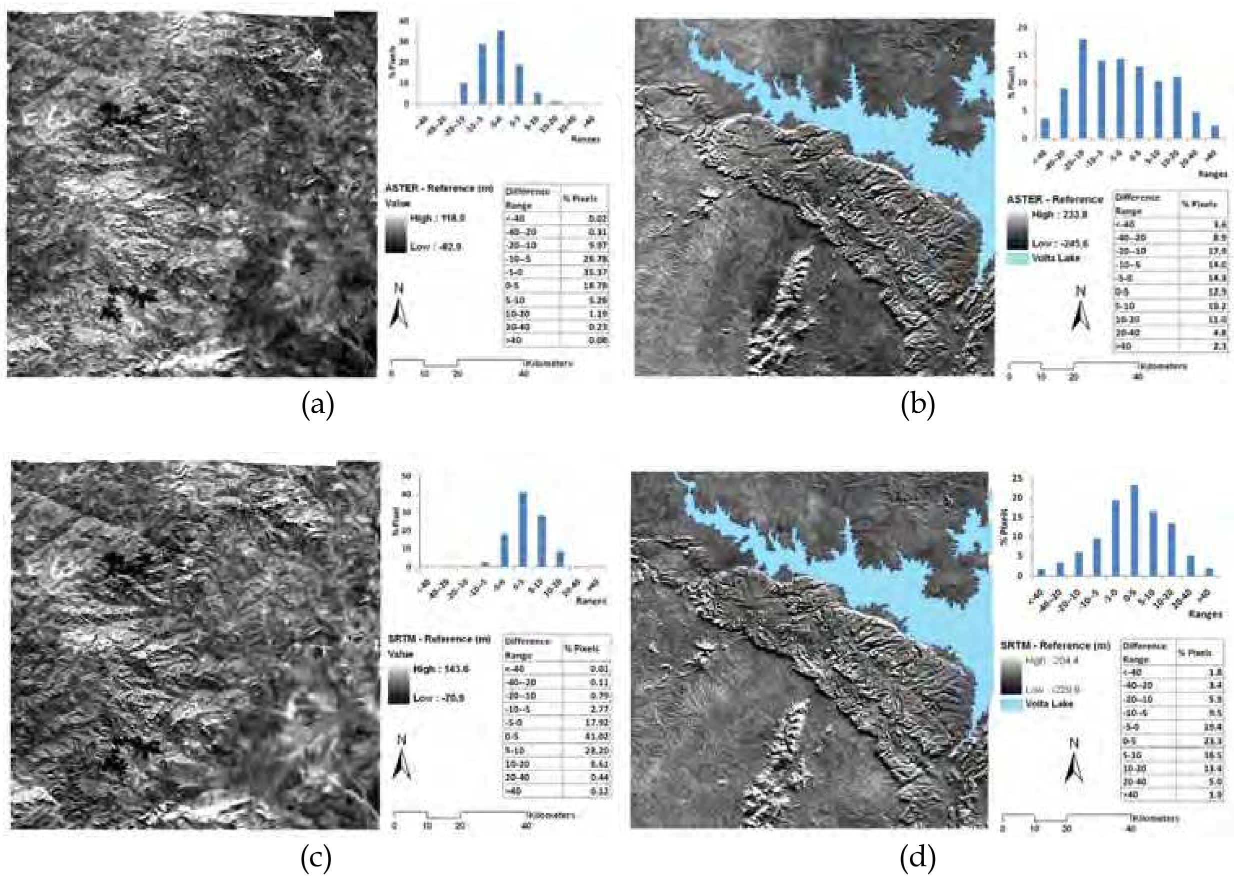


Fig. 2. Difference maps computed for the two study regions. (a) ASTER minus Reference (Site 1). (b) ASTER minus Reference (Site 2). (c) SRTM minus Reference (Site 1). (d) SRTM minus Reference (Site 2).

Apart from generating error maps, horizontal profiles were created on the DEMs using the 3-D analyst extension in ArcGIS®, and the data exported to excel for comparison. Figure 1 above shows the location of the profile lines, whereas figure 3 (*a* and *b*) below shows the comparison between the three (3) DEMs for both sites. The results obtained in this section further confirm the earlier finding that ASTER GDEM underestimates elevation whereas SRTM overestimates. Figure 3*a* clearly shows how bad ASTER GDEM performs on lowlands – its profile line is consistently below that of SRTM and the reference DEM. A visual inspection of figure 3 reveals that, the magnitude of overestimation of SRTM is less than the magnitude of underestimation of ASTER GDEM. In other words, SRTM is “closer” to the reference than ASTER GDEM. This further confirms that SRTM has an accuracy superior to ASTER.

Figure 4 (*a* – *d*) shows the correlation plots obtained for both sites. As stated earlier, these plots are based on a random selection of points representing different land covers. Results from site 1 indicate that both products have the same correlation coefficient with the reference DEM, which is slightly different from earlier results discussed above. This could be due to the number and distribution of points selected (i. e. 6000 out of over a million points). The plot for site 2, however, indicates that SRTM is slightly better correlated to the reference than ASTER GDEM.

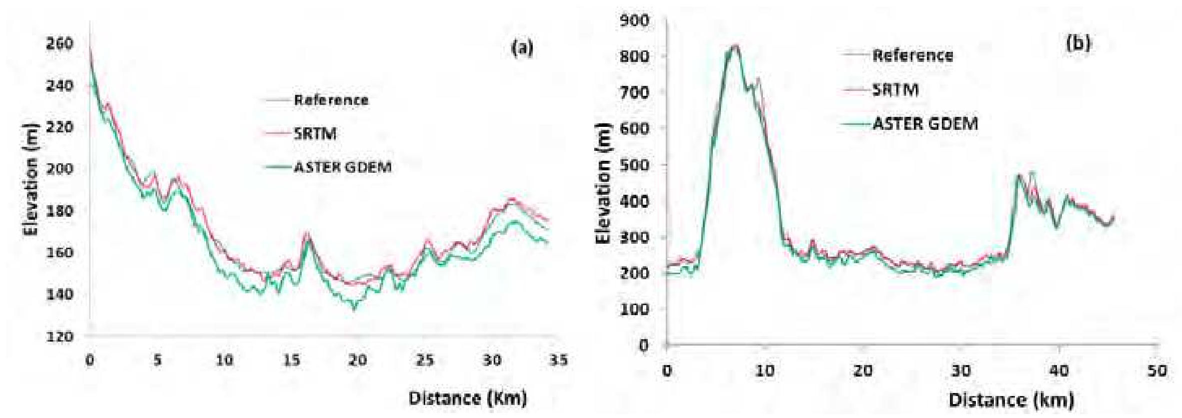


Fig. 3 (a). Comparison of profile lines derived from all DEMs for site 1. (b). Comparison of profile lines for site 2

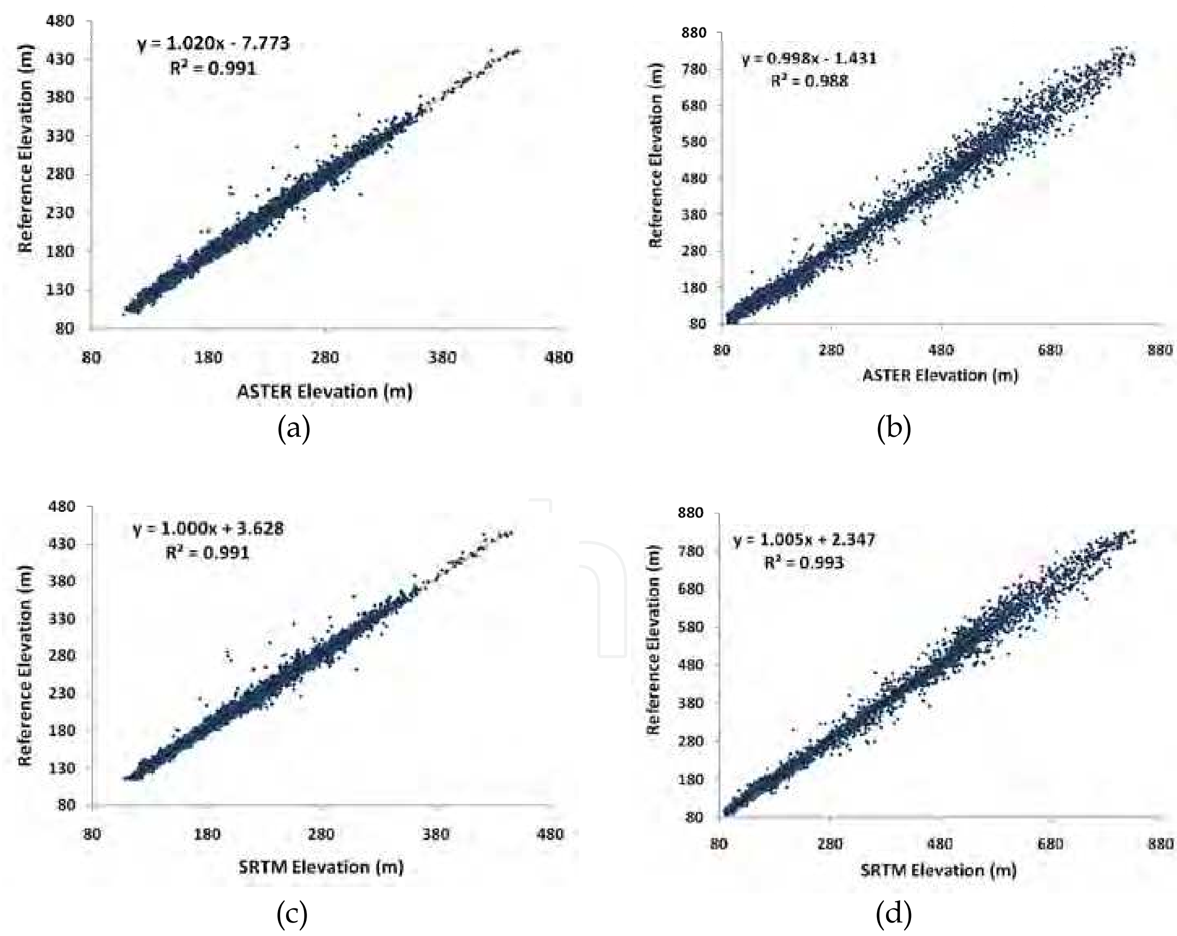


Fig. 4. Correlation plots for the two study sites. (a) ASTER versus Reference (Site 1). (b) ASTER versus Reference (Site 2). (c) SRTM versus Reference (Site 1). (d) SRTM versus Reference (Site 2).

### 4.2 Accuracy of terrain derivatives

Results of the hydro-processing to extract catchments and drainage information, using a common outlet, from the three DEMs are shown in Table 5. The upstream catchment area extracted for a common outlet location is largest for the Reference DEM, the catchment areas of ASTER and SRTM are -1% and -0.7% respectively. Although the same flow accumulation threshold map has been used for all DEMs, larger differences appeared during the drainage extraction process. This resulted in the largest deviations with respect to the Reference DEM of the drainage length and drainage density for the SRTM DEM, +7.6% and +4.5% respectively.

| **Catchment characteristics** | **Reference** | **ASTER** | **SRTM** |
|---|---|---|---|
| Area (km2) | 7,189.97 | 7,118.36 | 7,140.06 |
| Perimeter (m) | 442,767.37 | 475,829.21 | 463,395.49 |
| Total Drainage Length (m) | 2,725,840.8 | 2,890,504 | 2,911,511.2 |
| Drainage Density (m/km2) | 379.12 | 406.06 | 407.77 |
| Longest Flow Path Length (m) | 189,275.21 | 194,572.84 | 197,697.76 |
| Longest Drainage Length (m) | 186,556 | 192,018.2 | 194,910.4 |
| Sinuosity | 1.787 | 1.816 | 1.864 |

Table 5. Attribute values for extracted catchments and longest flow path

Figure 5 shows the longitudinal profiles extracted at 500 m interval along the longest flow path, with the various depression-filled DEMs as the elevation source. The graph confirms results of the absolute accuracy assessment, i.e. ASTER's underestimation and SRTM's overestimation of elevation.

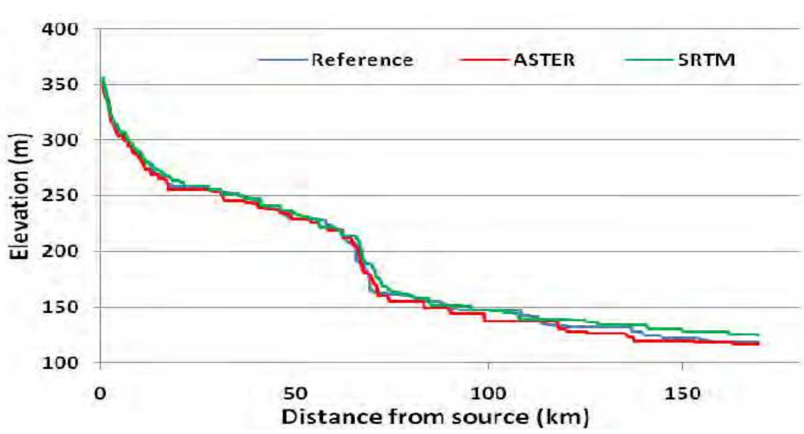


Fig. 5. Longitudinal profiles extracted from the three DEMs

Horton statistics were computed using the extracted drainage data from the three DEMs. The statistical values are shown in Table 6 while Figure 6 shows the resulting Horton plot for Strahler stream orders 1 to 5. The Strahler order is plotted on the "X" axis while the number of drainage channels, stream length and stream area are plotted on a log transformed "Y" axis. According to Horton's law the values obtained should plot along a straight line and this can be used as an indicator that the parameters used for drainage extraction are properly selected (Chow *et al*., 1988).

SRTM and ASTER have a larger number of drainage lines per Strahler order, especially for the lower order streams and therefore the stream length per order is less for SRTM and ASTER compared to the Reference DEM. The stream area shows a similar tendency. The stream lengths for the fifth and sixth order are the main deviating phenomena; smaller and larger for the Reference DEM, compared to ASTER and SRTM respectively. The Horton ratio's, calculated excluding the lowest and highest stream orders, shows that SRTM has slightly higher ratio values compared to those derived from the Reference DEM for all ratio's. ASTER derived ratio's for "Rb" and "Rl" are in between, the area ratio of ASTER is strongly deviating, only 3.99. In general the trend of the ratios as plotted in Figure 6 show a similar geomorphological structure for ASTER and SRTM and only deviates notably with respect to the Reference DEM for the Length Ratio. The "Rb", "Rl" and "Ra" values vary normally between 3 and 5 for "Rb", between 1.5 and 3.5 for "Rl" and between 3 and 6 for "Ra" (Rodrıguez-Iturbe, 1993). For all DEMs the derived ratios are within the ranges given.

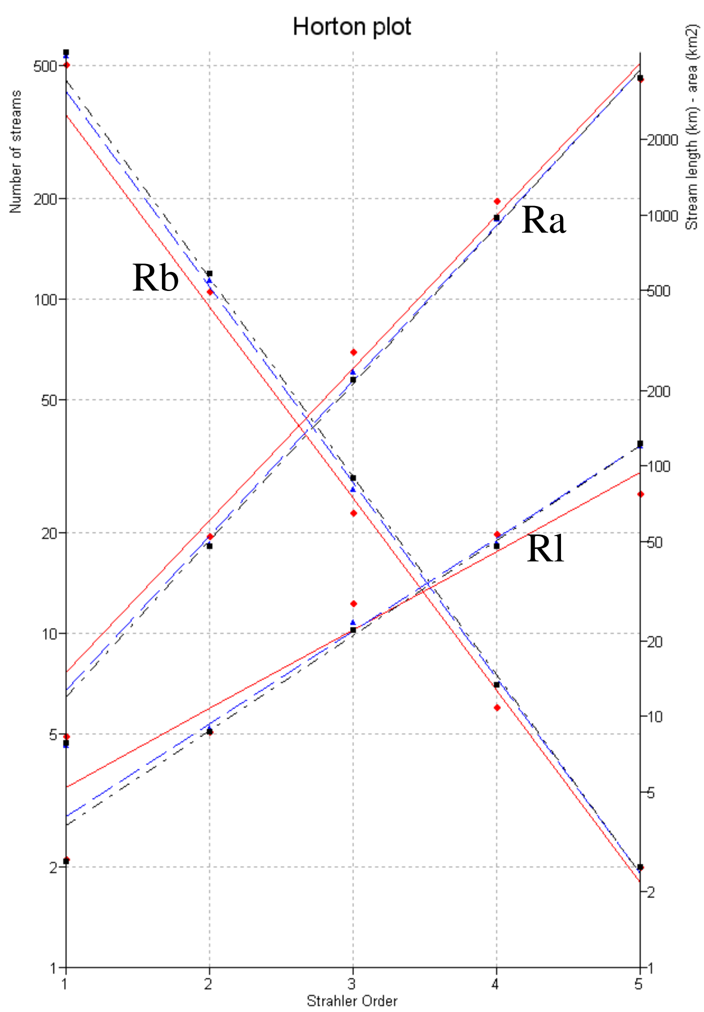


Fig. 6. Horton plot (Legend: Red = Reference; Blue = ASTER; Black = SRTM)

| | Reference | | | ASTER | | | SRTM | | |
|---|---|---|---|---|---|---|---|---|---|
| Order | No. of streams | Length (km) | Area (km2) | No. of streams | Length (km) | Area (km2) | No. of streams | Length (km) | Area (km2) |
| 1 | 502 | 2.7 | 8.34 | 537 | 2.66 | 7.72 | 550 | 2.63 | 7.84 |
| 2 | 105 | 8.66 | 52.55 | 114 | 8.93 | 48.83 | 119 | 8.67 | 47.59 |
| 3 | 23 | 28.2 | 284.62 | 27 | 23.79 | 237.75 | 29 | 22.03 | 221.73 |
| 4 | 6 | 53.7 | 1146.61 | 7 | 49.48 | 972.54 | 7 | 47.88 | 975.53 |
| 5 | 2 | 77.42 | 3496.54 | 2 | 120.9 | 3540.11 | 2 | 123.14 | 3549.87 |
| 6 | 1 | 172.09 | 7190.37 | 1 | 145.98 | 7138.2 | 1 | 148.56 | 7154.38 |
| **Horton Ratio's (calculated excluding lowest and highest stream order)** | | | | | | | | | |
| | Ratio Reference | | Ratio ASTER | | Ratio SRTM | | | | |
| Rb | 3.55 | | 3.61 | | 3.64 | | | | |
| Rl | 2.22 | | 2.26 | | 2.28 | | | | |
| Ra | 4.55 | | 3.99 | | 4.6 | | | | |

Table 6. Horton statistics

### 4.3 Implications for hydrological and environmental modeling

The reported accuracies and geomorphological behavior of the studied DEMs have numerous implications for hydrological and environmental modeling in the study regions. Topography is a crucial land surface characteristic and controls many earth processes (Hutchinson, 1996). For this reason, topography needs to be adequately represented (as in the form of a DEM) to ensure that modeling results, e.g. predicting surface/ sub-surface runoff, erosion estimates, etc. are as much as possible close to observed values. The implications of using inappropriate DEMs in hydrological and environmental modeling have been amply studied and reported in the literature. For example, Datta and Schack-Kirchner (2010), in reviewing erosion studies conducted in the Indian lesser Himalayas, attributed the large variations in the range of soil loss estimates chiefly to poor description of the terrain in the form of a DEM. They compared erosion relevant topographical parameters – elevation, slope, aspect and LS factor – derived from DEMs of different source and accuracy and concluded that the choice of a DEM for soil erosion modeling has a significant impact on the relevant topographical parameters and, consequently, on the modeling results. In a related study, Rojas et al. (2008) studied the effects of DEM grid sizes – 30m, 90, 150, 210, 270 and 330 - on results of modeling upland erosion and sediment yield from natural watersheds. They found that using different resolution DEMs (30m – 330m) significantly reduces land surface slopes and channel network topology, resulting in varied upland erosion estimates. Walker and Wildgoose (1999) studied the implications of using different source DEMs – cartometric, photogrammetric and ground truth - of varying resolution and accuracy on key hydrologic statistics. They found catchment sizes and stream networks derived from the cartometric and photogrammetric DEMs to be significantly different from that of the ground truth. This was particularly the case in smaller catchments where a localized error in elevation may direct a major stream line in a wrong direction. They concluded that the use of published DEMs for determining catchment boundaries and stream networks must be done with care by comparing results with that of a ground truth DEM or a higher accuracy DEM.

In light of the above, this study computed two indices - GIUH and TI – to assess the suitability of using the published elevation products under consideration in hydrological and environmental modeling. A GIUH enables the determination of the hydrological response of a catchment to rainfall by taking into consideration its geomorphology. The runoff volumes generated at the outlet of a catchment and time-to-peak are dependent on the topography of the overland regions as well as the transmission surfaces. The reliability of these parameters (runoff & time-to-peak) is, therefore, dependent on how well a catchment's terrain (landform) is represented by the underlying elevation product (DEM). A GIUH was calculated using the three DEMs and their responses compared. Apart from changing the Horton statistics for the respective DEMs, all other variables, such as the rainfall intensity and a mean holding time of 5 hours, remained constant. Result of the GIUH analysis is shown in Figure 7. The figure shows that the direct runoff hydrographs for the Reference DEM and SRTM DEM are comparable with respect to the volume as well as the timing (i.e. time to peak). The ASTER DEM, however, shows a delay in the rising limb and a higher peak discharge. Considering that Horton statistics are the only variable in the analysis (with all others remaining constant), the behavior of ASTER can be attributed to its representation of the catchment's geomorphology. Although ratios obtained in the Horton analysis fall within acceptable ranges, the stream area ratio (Ra) obtained for the ASTER DEM (3.99), which strongly deviates from that of the other two DEMs, is believed to have caused the noted delay in rising limb and higher peak discharge.

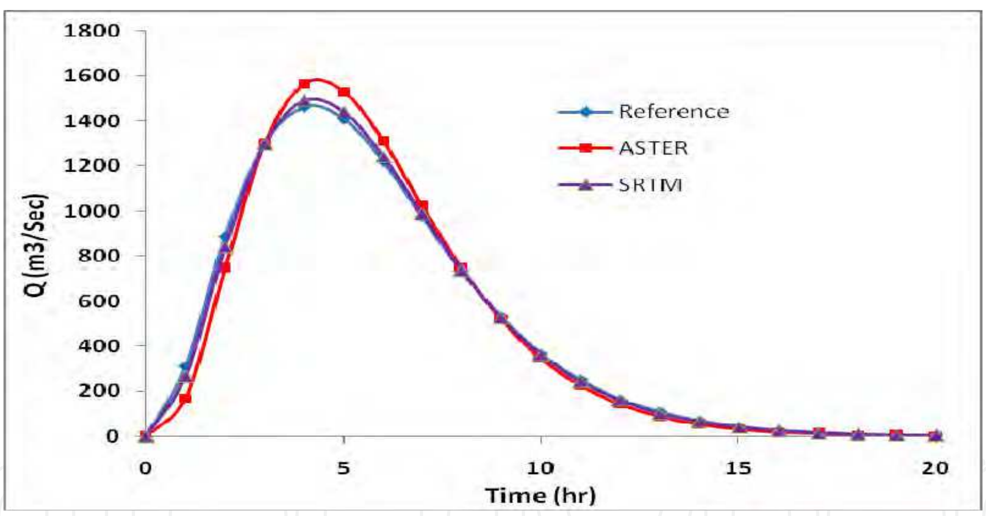


Fig. 7. Direct runoff hydrographs for the three DEMs

Figure 8 shows results of the TI analysis. Continuous Topographic Index data range obtained for each of the DEMs was classified into integer classes, and the percentage of pixels falling in each was determined and plotted. The graph shows a notable difference between the reference DEM and the two global DEMs. In order to attribute reasons for the results obtained, slope maps of the three DEMs were created and analyzed. Slope was chosen and analyzed due to the fact that TI is a function of the local slope angle acting on the pixel. The analysis revealed that, the distribution of slopes was quite different in all three DEMs. The reference DEM was found to have about 67% of its area having slopes up to $1^0$, while for the ASTER and the SRTM DEMs, this slope class accounted for nearly 50% and slightly over 50% respectively. In the case of SRTM the radar reflective surface seems to cause a more “rough” topography and the difference with respect to ASTER may be attributed to the resampling of the original 30m to 90m for purposes of comparison with the other DEMs. Previous studies, e.g. Rojas et al. (2008), have noted that resampling DEMs to coarser resolutions generally reduces surface slopes and changes channel topology. Slopes have also been found to be highly sensitive to varying DEM resolution and accuracy (Datta and Schack-Kirchner, 2010). Zhang and Montgomery (1994), in their investigation of the effect of grid size on TI concluded that increasing DEM grid sizes results in increased mean TI due to increased contributing area and decreased slopes. This fact was also emphasized by Wilson et al. (2000). A reasonable conclusion can, thus, be drawn that the low percentage of pixels up to $1^0$ in ASTER, and the resultant TI curve, could be attributed to the resampling of the DEM from the original 30m to 90m. The similarity between the ASTER and SRTM curves indicate that SRTM failed to produce the desired slope compared to the reference.

Results obtained in the GIUH and TI analysis is a clear demonstration of the effects of topography on hydrological processes and the need to select the right DEM (resolution and accuracy) for hydrological and environmental modeling. Use of a DEM that does not adequately represent the surface landforms of a catchment has the tendency of producing erroneous modeling results. With the exception of the TI, the comparison in this study consistently revealed SRTM to have a superior accuracy compared to ASTER DEM, although its resolution is coarser. This is in line with results of previous studies (Datta and Schack-Kirchner (2010).

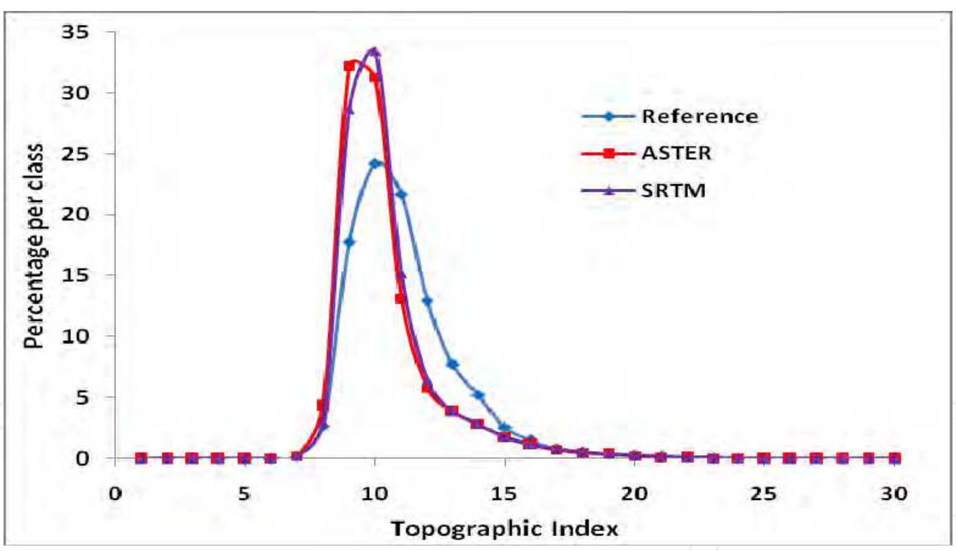


Fig. 8. Comparison of Topographic Index classes for the DEM’s

## 5. Conclusions

In this study, two near-global DEMs - SRTM and ASTER – are compared and validated against a reference DEM for two sites in Ghana. The reference DEM used was generated using hypsographic and hydrographic data from a 1:50 000 topographical map produced by the SDG. DEM differencing, profiling, correlation plots, extraction of catchment area and drainage network, computation of Horton statistics and GIUH are some of the methods employed in the comparison.

Results obtained indicate that, for the two sites selected, both SRTM and ASTER GDEM meet their predefined vertical accuracy specifications of 16m and 20m respectively. This is in line with results of previous studies (Fujisada *et al.*, 2005; Rodriquez *et al.*, 2006). It was realized that SRTM has a higher vertical accuracy (in terms of RMSE) than ASTER GDEM for both sites. RMSEs ranged between 4.9 and 5.5 (site 1) and 14.5 and 18.8 (site 2) for SRTM and ASTER respectively. The vertical accuracy of both products, thus, increases (by a factor of 3) on flat and less complex terrain (i.e. site 1). Analyses conducted revealed that ASTER GDEM underestimates elevation (i.e. negatively biased), even if fill routines are applied. SRTM, on the other hand, overestimates elevation, which may be partly due to the fact that SRTM records the reflective surface and, thus, may be positively biased with respect to the bare earth when foliage is present. The underestimation of ASTER is more pronounced on flat and less complex terrain (site 1), and of a greater magnitude than the overestimation of SRTM. Results of horizontal profiling on site 1 showed that the elevation of ASTER GDEM is consistently lower than that of the other two. In areas that are heavily vegetated, the effect of the under- and overestimation of ASTER and SRTM respectively can be reduced by constructing an average DEM (i.e. ASTER+SRTM/2), which will have an absolute accuracy between that specified for the two global DEMs.

In the relative accuracy assessment, the Horton plot revealed that SRTM and ASTER DEMs have a similar geomorphological structure as compared to the Reference DEM. The main deviation is with respect to the stream area ratio (Ra) of ASTER. All other ratio values extracted are within the ranges as given for the various ratio's (Rodrıguez-Iturbe, 1993). The calculated direct runoff hydrograph showed similar response for the Reference and SRTM DEMs. ASTER DEM, however, showed a delayed rising limb and a higher peak discharge. This might be due to the deviating area ratio obtained for ASTER DEM. The calculated Topographic Index for the DEMs showed a substantial difference between the global DEMs and the Reference DEM. This difference is to be attributed to the gentle slopes that prevail in the area (site 1) analyzed.

In summary, the study has revealed that SRTM is "closer" to the Reference DEM than ASTER, although both products are useful and are an excellent replacement for local 1:50 000 hypsographic data both in absolute and relative terms. The relative assessment further confirms that various surface processes can be appropriately studied when using these global elevation data sets, which is a great asset to geomorphologists. Here the relative assessment conducted is more focused to hydrological processes, one of the terrain processes important in geomomorpholgy.

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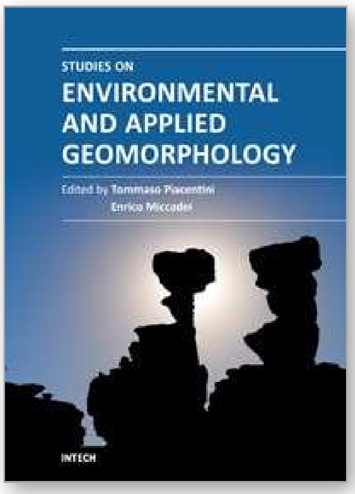


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