ACCURACY OF DEM-BASED TOPOGRAPHIC DATA IN FLOOD INUNDATION MODELLING: A CASE OF WAMI RIVER, TANZANIA

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ABSTRACT

The objective of this paper is to evaluate and further comment on the accuracy of the DEM-based topographic data as input in flood modelling. Recent studies have indicated that hydraulic parameters of the modified cross sections based on high resolution DEM are geometrically and hydraulically similar to the measured ones. In the current study hydraulic modelling was intended to guide a development project whereby a floodplain protection embankment is contemplated. Therefore, accuracy in terms of positioning/alignment of natural features such as river banks and heights/elevations was imperative to attain. In order to achieve these, accuracy of various topographic data sources were qualitatively and/or quantitatively analysed before and after hydraulic modelling. As the study river reach is ungauged, the hydraulic model was verified and validated with field observations, readily available information and professional judgement. Based on error analysis, it was found that uncalibrated 90-m resolution STRM DEM-based topographic data are biased, i.e., 80% of the error mass is negative. The error increases with elevation. The final input to the hydraulic model was a composite/hybrid DEM derived after merging geometric data from four representative field-measured cross sections, a 2-m interval contour map covering part of the river valley, and calibrated 90-m resolution DEM. Although, calibration improves the data, it does not remove completely the inherent bias. Further to DEM calibration, it was therefore recommended to include an elevation uncertainty value of -0.5 m, as derived from topographic analysis, into simulated water surface profiles elevations. The hydraulic model satisfactorily simulated flood inundation extent after considering the elevation uncertainty. In order to improve the findings further studies should use adequate measured cross sections and DEM of higher resolutions.

***Keywords**: Error analysis, DEM, Flood inundation, Hydraulic modelling, Topographic data.*

INTRODUCTION

Understanding how changes in river flow regime affects river valley geometry/geomorphology requires an understanding of hydraulics, which refers to water depth, velocity, shear stress, wetted perimeter, and width of the water surface. Hydraulic conditions are determined by the interaction between channel cross-section geometry and flow. For a particular cross-section, the hydraulic conditions depend on channel hydraulic roughness, channel morphology comprising slope, and channel geometry.

It should be reiterated that topographic data are key input to a hydraulic model as they determine conveyance, flow direction, and path. Besides, the hydraulic energy of the flowing river is determined by the difference of thalweg elevations between successive cross sections. A good number of studies on various aspects of river hydraulics have been carried out for last two decades (eg., Gichamo *et al.*, 2012; Pramanik *et al.*, 2010). However, studies on hydraulic modelling are limited in most developing countries such as Tanzania due to unavailability of good quality measured topographic data (eg., Gichamo *et al.*, 2012; Pramanik *et al.*, 2010, Ndomba, 2010).

Some previous studies have revealed that freely available Shuttle Radar Topography Mission Digital Elevation Model (STRM DEM) based extracted river cross-sections could be used to simulate river flow hydraulics with satisfactory performance using scarce measured geometric data (Pramanik *et al.*, 2010). It is noteworthy that the data sources and processing methods for generating DEMs have also evolved rapidly from ground surveying and topographic map digitization to remote sensing, and more recently to Light Detection And Ranging (LiDAR) and RAdio Detection And Ranging (RADAR). Airborne LiDAR combines cost efficiency, high degree of automation, high point density of typically 1–10 points per m^2 and height accuracy of better than ±15 cm. LiDAR is therefore known for derivation of precise Digital Terrain Models (DTM) as an input to hydrodynamic models (Mandlburger *et al.*, 2009).

Researchers such as Nelson *et al.* (2009) have categorized three technologies/sources used to develop DEMs:- i) ground survey techniques; ii) existing topographic maps; and iii) remote sensing both airborne and satellite photogrammetric/ stereo methods, airborne laser systems, and both airborne and satellite radar using interferometry.
Field measurements of river cross-sections are known to be labour intensive, expensive and sometimes are logistically impossible (Pramanik *et al.*, 2010, Ndomba, 2010, Gonga-Saholiariliva *et al.*, 2011). The existence of large volumes of hardcopy topographic maps provides a source of primary input in the form of contours which can be digitized and used for Digital Terrain Model (DTM) generation purposes. However, such an approach has been used by some researchers as means of generating low cost DTMs where elevation data is not readily available in digital form and when the accuracy of the output is not a dominant factor (Forkuo, 2008).

To the best of the knowledge of the author, to date, the strengths and weaknesses of remote sensing based DEMs are inadequately documented to warrant general applications in real life development projects. Other researchers have cautioned that whatever the data source that is selected some preprocessing will usually be required no matter what the source or intended application (Gichamo *et al.*, 2012; Hengl *et al.*, 2010). As reported by various studies processing approaches require huge computational resources and thus prohibitive in some parts of the world (Hengl *et al.*, 2010; Gonga-Saholiariliva *et al.*, 2011). In respect of the current study, it should also be noted that a number of studies have already been carried out that try to deal with topographic data scarcity in river flood modeling (Gichamo *et al.*, 2012). The approaches include integration of Geographic Information System (GIS) with DEMs and use of data assimilation techniques towards generating synthetic cross-section that is geometrically and hydraulically equivalent to the studied river geometry (Gichamo *et al.*, 2012; Gonga-Saholiariliva *et al.*, 2011). In similar studies satellite images provided the locations and types of structures in the area of interest and spatial flood extent and its quantified damage (Gichamo *et al.*, 2012).

A hydraulic model coupled with GIS uses global digital elevation model (DEM) to extract river cross-sections, which define the geometry of the river. The extracted river cross-sections are then used in the hydraulic model for computations of water level and flow. However, low resolution and inadequate vertical accuracy of such global data presents difficulties in differentiating features of hydraulic importance (Gichamo *et al.*, 2012; Hengl *et al.*, 2010). Based on the author experience and surveyed literature, the automatic extraction always bring problems as it often results into unrealistic cross-sections. That is why, for flood modeling purposes, many researchers elsewhere are recommending corrections for vertical and horizontal biases of these global topographic data (Vaze *et al.*, 2010; Gichamo *et al.*, 2012). Besides, the methodology for the construction of synthetic cross-sections can hardly be implemented in a gauged river reach with at least in-bank rating curve either at the upstream or downstream end of the river reaches.

Admittedly, errors in DEMs are inevitable, even if they are produced using highly accurate techniques such as LiDAR (Hengl *et al.*, 2010; Gonga-Saholiariliva *et al.*, 2011). It has been established by other researchers that hydraulic modelling results are substantially affected by quality of surface details (Mandlburger *et al.*, 2009). The knowledge of errors in the hydraulic model inputs are undeniably imperative, especially in guiding environmental decisions and engineering applications (Gonga-Saholiariliva *et al.*, 2011). However, literature on DEM quality in terms of geomorphological reliability indices is inadequate (Vaze *et al.*, 2010).
So far based on the background thereof and author's personal experience it seems that accuracy achieved by using DEM based topographic data is uncertain for real life development projects such as flood protection levees/embankments construction projects. Therefore the objective of this study is to evaluate and further comment on the accuracy of DEM based topographic data as input into flood modelling using a case study of Wami River in Tanzania.

MATERIALS AND METHODS

Description of the Study Area

The study area extends 23 km from Kikwate to Gama village (Fig. 1), within the Wami River sub-basin in the North-Eastern part of Tanzania. The maximum elevation upstream at Kikwate village is 50 m.a.s.l. while the minimum is around 10 m.a.s.l. at Gama Village downstream giving a general slope of 0.001. The varying elevations within the environment through which the river passes results into pronounced meanders and many depositional features. These are found almost throughout the banks of the river. According to Mwanukuzi (2007), the Wami River valley at Matipwili village generally could be characterised as unconfined floodplain that is flooded annually. Geomorphologic units are plain bed with sand, run and backwater while the channel type is alluvial composed of sand and silt as perimeter material. The channel appears active, shifting laterally through lateral erosion. Bank erosion ranges from 0 to 10%, which is predominantly caused by river bank undercutting. Mwanukuzi (2007) further described the river reach in the study area as of a winding channel type.

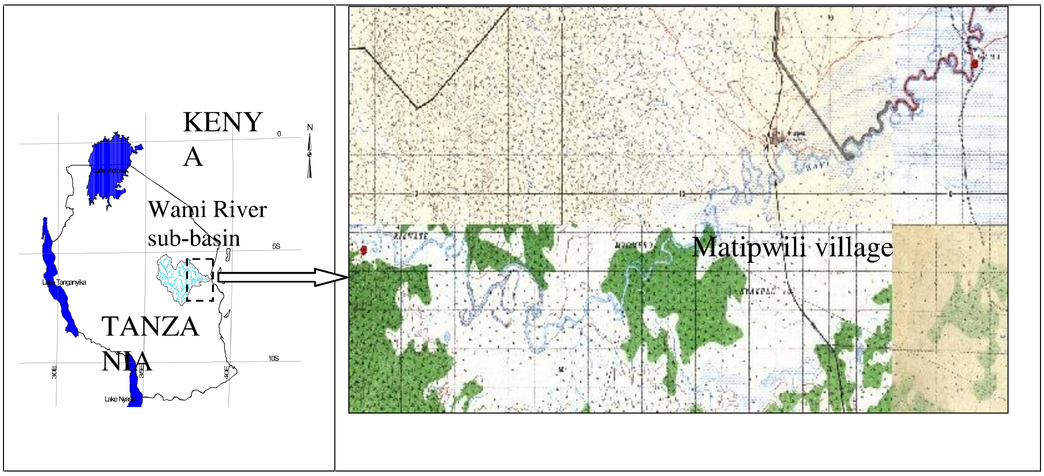

Figure 1: A location map of the study area, Wami River at Matipwili village

The study area is located within the coastal plain. The plain is an important source of suspended sediments. Materials in the plains are thick deposit silt-clays. The suspended sediments are also supplied by the bank erosion. There are limited supplies of bed load at Matipwili. Therefore the scouring of the channel and lateral erosion are other processes that remobilize the fine particle that are carried as suspended load. The bed deposit is largely sands derived after long conveyance of sediments from middle river reaches of Wami River sub-basin. Due to limited supply of sediment, the river mouth of Wami is an estuary. The riverine wetlands comprise of main River Wami and seasonally inundated floodplain. The Wami River flows from eastwards within the study area turning north-eastwards to discharge into the Indian Ocean. Apart from direct runoff from a limited catchment area, the river at the study area has no major tributaries.

Information on hydrology of the river (*i.e.*, stream flows data, water levels, floods) is not available for this site as there is no nearby operating gauging station. The river branches into a delta as it approaches the sea. Alternating confined and unconfined valley reaches characterize the geomorphology of the river reach. In the confined valley reaches, the left flood plain is narrow, whereas the right flood plain is extensive. The channel is characterized as meandering with moderate sinuosity. The river banks are elevated with localized low lying banks. The latter is mostly located where the old river crosses the new river channel. These are found dominantly on the right banks. The channel reach of the study site is primarily a plain sandy bed with pools and point bars occurring at the meanders. In the dry season, the flows are low with translucent waters. It appears that channel modification is primarily through floodplain cultivation on one side, and vegetation removal leading to extensive bank erosion (Mwanukuzi, 2007). Fluvial bank erosion as a result of undercutting and slumping is occurring along 10-33% of the bank, leading to an active channel tending to shift towards the side of cultivation. Through interviewing people with familiarity of the study area (elderly, railway staff, and farmers) they indicated that the river flows overtop the banks every other year (approximately every 2 years). This is equivalent to global average bankful discharge recurrence interval (EPA, 2012). The low lying banks are overtopped seasonally almost every year.

Overview of HEC-RAS Model

HEC-RAS model, a modelling framework which suits large scale project area, data limitations/requirements, computational resource and scope, was used to model the Wami River hydraulics. The HEC-RAS system contains four one-dimensional river analysis components for: i) Steady flow water surface profile computations; ii) Unsteady flow simulation; iii) Movable boundary sediment transport computations; and, iv) Water quality analysis. A key element is that all four components use a common geometric data representation and common geometric and hydraulic computation routines (Brunner, 2010). Furthermore, HEC-RAS is designed to perform one-dimensional hydraulic calculations for a full network of natural and constructed channels. The steady flow system is designed for applications in flood plain management and to evaluate floodway encroachments. In steady flow water surface profiles component, water surface profiles are calculated for steady gradually varied flow. The steady flow component is capable of modelling subcritical, supercritical, and mixed flow regime water surface profiles. To get a proper model it is necessary to divide the cross sections into parts that have homogeneous hydraulic properties in the direction of the flow (**Fig. 2**). The direction of flow is perpendicular and into the paper. It should be noted that, mainly homogeneity is governed by variation of hydraulic roughness properties. The cross-section subdivisions are usually the left/right overbanks and the main channel. It is assumed that there is no exchange of energy across the boundaries. Both the water Surface elevation and the total energy head are assumed to be constant at the whole cross section. Such an assumption partly helps to reduce data requirement such as observed water surface for calibration. Practically, it is difficult under field conditions to capture small changes in water surface elevation between the inner and out banks at the meander as it is theoretically idealized.

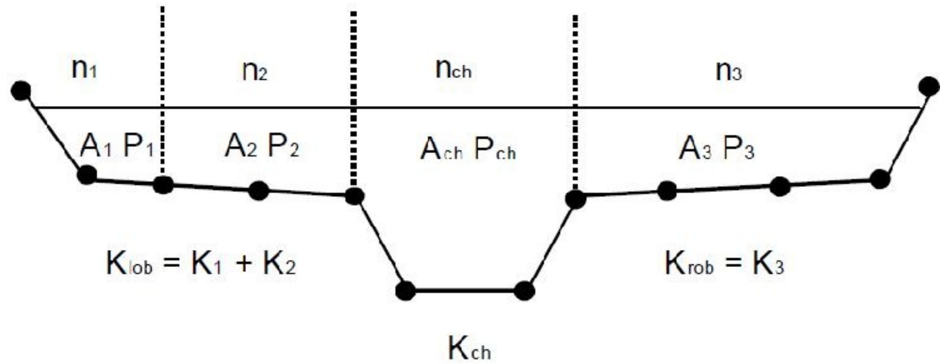

Figure 2: HEC-RAS model cross section subdivided into parts that have homogeneous hydraulic properties as adopted from Brunner (2010). (Note: K is conveyance factor; n is Manning's roughness number; P is wetted perimeter; and A is flow area).

The basic computational procedure is based on the solution of one-dimensional energy equation. Energy losses are evaluated by friction (Manning Equation) and contraction/expansion (coefficient multiplied by the change in velocity head). The momentum equation is utilized in situations where the water surface profile is rapidly varied (*i.e.*, hydraulic jumps, hydraulics of bridges, stream junctions). The effects of various obstructions such as bridges, levees/embankments, and other structures in the river valley may be considered in the computations.

It should be noted that geometric data such as cross section geometries, stream centreline, flow path centrelines, ineffective flow areas, storage areas, and alignment of hydraulic structures are entered/edited into the HEC-RAS model through either a manual or an automated procedure. In the automated procedure topographic data inputs are pre-processed in HEC-GeoRAS ArcView GIS extension (Ackerman, 2009) before it is exported to HEC-RAS. HEC-GeoRAS requires a Digital Terrain Model (DTM) in the form of a Triangular Irregular Network (TIN). TIN could be derived from DEMs, dense elevation data points, or contour maps. DTM must be representative of both the land surface of the channel bottom and adjacent floodplain areas to be modelled. Because all cross-sectional data are extracted from the DTM, only high-resolution DTMs should be considered for hydraulic modelling (Brunner, 2010). Measurement units used are relative to those in the DTM. Once the hydraulic computations are performed, exported water surface and velocity results from HEC-RAS may be imported back to the GIS using HEC-RAS for spatial analysis. The DTM is also used for determining floodplain boundaries and calculating inundation depths. Therefore, it is critical to emphasize that only DTMs describing channel geometry with high accuracy and resolution should be considered for the basis of performing hydraulic analysis (Brunner, 2010). With such favourable functionalities of the model as described above that is why HEC-RAS is widely used for flood inundation modelling (Bates et al., 1997; Bates and De Roo, 2000). It is worth noting further that a number of studies showed that, when the hydraulic problem at hand is not dominated by specific 2D phenomena (e.g. inundation caused by dam breaches or levee failures), HEC-RAS is rather suitable for providing an accurate reproduction of the flood propagation and inundation extent (Bates et al., 1997). HEC-RAS provides an accurate reproduction of the hydraulic behaviour of natural rivers (Castellarin et al. 2009).

Data Types and Data Processing

To calculate water surface profile the HEC-RAS model needs mainly geometric and hydrological (streamflows) data which include i) Geometric data: River schematic network, cross-section geometry, reach length and energy loss coefficients; ii) Hydrological data: Streamflows (discharges), flood discharges. You will note that geometric data analysis is a key activity in this study and thus it is given due weight in the following sections. It entailed analyzing data gaps, overlaps and inconsistencies.

Hydrological Information Retrieval and Processing

Hydrological information (*i.e.,* floods magnitudes, floods recurrence intervals, highest water marks, *etc.*) were also key data for this study. Streamflows (river discharges) were obtained from Water Resources Engineering Department (WRED) database at the University of Dar es Salaam. The data spans over a period of 57 years, *i.e.*, between June 9, 1954, and August 25, 2010. These data were of various return periods including 1, 2, 10 20, 30, 50, 100, 200, 500, and 1000 years. Flood magnitudes were determined using GEV/L-Moments procedure (Valimba, 2007).

The upstream and downstream boundary conditions are as stipulated in Table 1.

Table 1: Estimated flood discharges of Wami River at Mandera Bridge gauging station (upstream boundary condition)

Return period [years]	1G2 Floods (upstream boundary condition) [m^3/s] (Valimba, 2007)	Indian ocean maximum tide level (as downstream Boundary condition) [m]
1**	93.3	4.25
2**	329.8	
5	493	
10	611.3	
20	732.9	
25	773.2	
50	903.1	
100*	1041.0	
200	1188.0	
500	1397.0	
1000	1567.0	

Source: As adopted from Valimba, 2007)
* 100 years return period flood was used for model calibration
** 1 and 2 years return period floods were used for model validation

Other useful hydrological data include measured water surface level and discharges at Matipwili village, rating curves at Wami-Mandera gauging station (1G2) and historical flood levels at various locations within the study area. For hydraulic model calibration, streamflow characteristics of discharge, velocity, depth, wetted perimeter, *etc.,* are sometimes required at locations within the study reach. Measurements of these parameters were carried out at Matipwili Village in the past (Ndomba, 2007). The sea level gauging station is located at time Indian Ocean coastline, zone 03:00, Latitude 06^o 50'S, Longitude 039^o 17'E at Dar es Salaam harbour. The times and heights of high and low waters data are recorded daily at a frequency of 4 in a day with temporal resolution of 6 hrs. The data used spans over a period of 2 years from January, 2011 to December, 2012. The mean, standard deviation of daily maxima and the largest heights are 3.40, 0.45 and 4.25 m, respectively. The heights varied from 0.0 to 4.25 m. The highest tides occurred in the month of April. It should be noted that April is the wettest month on the Wami River Sub-basin. As presented in Table 1, the downstream boundary condition of 4.25 m is used as it coincides with wettest month in the study area. Therefore, flooding critical condition extent was envisaged to be simulated.

DEM Based Topographic Data Retrieval and Processing

In this study digital elevation models, i.e., ASTER GDEM ver.2 at 30 m spatial resolution and SRTM DEM ver.4 at 90 m were evaluated. Qualitatively, the ASTER GDEM seemed not to work due to holes and large values that are not representative of the terrain in the flood plain particularly banks of the river. The performance of SRTM DEM was further quantitatively evaluated despite the fact that some vertical bias was observed. As expected, the vertical bias is the result of spatial and spectral limitation of the remote sensor on board satellite and the vertical datum anomalies. Therefore, this model was used as one of sources of elevation information for the study area.

The SRTM DEM tiles ($1^o \times 1^o$) of resolution 90 m × 90 m were downloaded from the website of the National Map Seamless Server, Earth Resources Observation and Science (http://seamless.usgs.gov/). The DEM tiles were made mosaic to get the complete DEM of the study area. The DEM is available in 90 meters resolution and is formatted in 1 x 1 degree tiles as GeoTIFF files. The original DEM was processed to fill the voids before the extraction of river cross-sections. For filling the voids, contours were derived from the DEM and a fresh DEM without any void was prepared using the contour map. First of all the DEM and the topographic map were geometrically corrected with same projection system and datum (Arc 1960, UTM zone 37 S) with the help of ERDAS IMAGINE 8.7.

Contour Map Based Topographic Data Retrieval and Processing

An aerial photogrammetry technology generated a 2-m contour interval map that was used in this study. It entails four main processes: i) overlapping aerial photography that involves taking aerial photos with 60-80% overlap and 20-30% side lap; ii) model restitution that involves construction of the 3-D model of the earth's surface. The process further includes restoration of the internal and external geometry of the taking camera during photography; iii) Data extraction from the 3-D model constructed from which the X, Y, Z coordinates are extracted. This process can be fully or semi automated. The resulting coordinates list is usually used to generate DEM; and iv) DEM generation using dedicated software with spatial interpolation methods are available for generating DEM. It should be noted that, however, that river schematic network was traced (screen digitized) from the topographic maps of scale 1:50,000. Other pertinent data collected are lineage of the spatial dataset used to generate a 2-m interval contour map. The lineage include but not limited to the specific date of dataset acquisition; the type of reference surface to which the elevations were referred, *i.e.*, Tanzania M.S.L, or EGM96 or Arbitrary; and the coordinates for all reference points used to generate the elevation data as photographed.

Cross Section Geometric Data Measurements and Processing

Since the river valley is extensive, logistically, cross section geometry surveying was limited to a few transects. However, tentatively, in order to capture spatial variability of typical valley geometry and considering limited time and financial resource 4 transects were measured. The geometric data collected from these representative transects was used to modify the DEM-based developed cross sections as discussed later in this paper. The main focus on geometric data survey was on low banks and the micro channel. They represent river reaches of Mvomero, upstream of Matipwili Bridge, Downstream of Matipwili Bridge and Gama (Fig. 3). The geometric data includes transverse (cross section) and longitudinal profiles for selected representative river reaches and depths for the bed topography of the open water plains.

During cross section surveying, a GPS technology (Leica System 500 GPS) in Real Time Kinematic (RTK) was used. The instrument gives position up to 0.001 m accuracy. The measured elevations were tied to the previously established reference points by Photomap International Inc. within the Wami River flood plain between July and August, 2007. The reference receiver was set at PH 8 that was identified by Hand Held GPS Map 76 cx. The rover receiver was also configured to store 3 D positions at 0.050 m precision. The observation rate was set to 1 second interval. Depending on the availability of satellites required to resolve 3-D position, several observations were done on a single position.

Development of a Composite or Hybrid DEM

As the valley terrain is flat with extensive floodplains with localized low lying banks featuring the old river channel crossing the Wami River, a combination of high, medium and course spatial resolution DEMs had to be explored to capture the same. The high resolution DEM was developed from the contour map (2 m contour interval). The medium resolution DEM in this context was the DEM generated from data collected from the STRM DEM. An hybrid DEM was generated from a combination of two DEMs. Quality assessment, quantification and visualization were adhered to at all stages of data processing and parameter estimation. The cross validation of the hybrid DEM was conducted through the field cross section survey and available reference points.

Error Analysis of Developed DEM and its Vertical Error Correction

The error analysis of the DEM was performed by comparing the elevations of 530 grid points distributed throughout the DEM with corresponding spot heights taken from the 2-m contour map/topographic map of the study area. The basic descriptive statistics related to the errors were calculated. RMSE-based comparison of DEM elevation values with sample values from another, more accurate source seems to be the most appropriate way of providing error estimation (Gonga-Saholiariliva *et al.*, 2011). RMSE is the square root of the variance of a distribution (Equation 1). DEM error analysis integrates errors relating to interpolation methods and to geographical position in X, Y and Z. Note that RMSE has been used successfully by other researchers as well as a threshold criterion for testing the accuracy of elevation (Gonga-Saholiariliva et al., 2011).

$$\mathrm{RMSE}_{\mathrm{DEM}} = \sqrt{\frac{\sum_{i-1}^{N}\left(E_{Ri} - E_{DEMi}\right)^2}{N}} \quad ....(1)$$

Where E_R denotes the reference elevation data that is, the spot heights in the topographic map, E_{DEM}: is the elevation data as provided by SRTM DEM; and N is the total number of reference data points used.

The steps followed to extract all the river cross-sections from the DEM are described in this section (Fig. 3). Figure 3 presents the locations where the cross sections were extracted from the DEM. The extracted cross-sections were modified using the $\mathrm{RMSE}_{\mathrm{DEM}}$ values computed for different elevation ranges. It is assumed that the hydraulic parameters such as hydraulic radius and conveyance of the modified cross sections are the same as for measured ones as supported by other studies (Pramanik *et al.*, 2010).

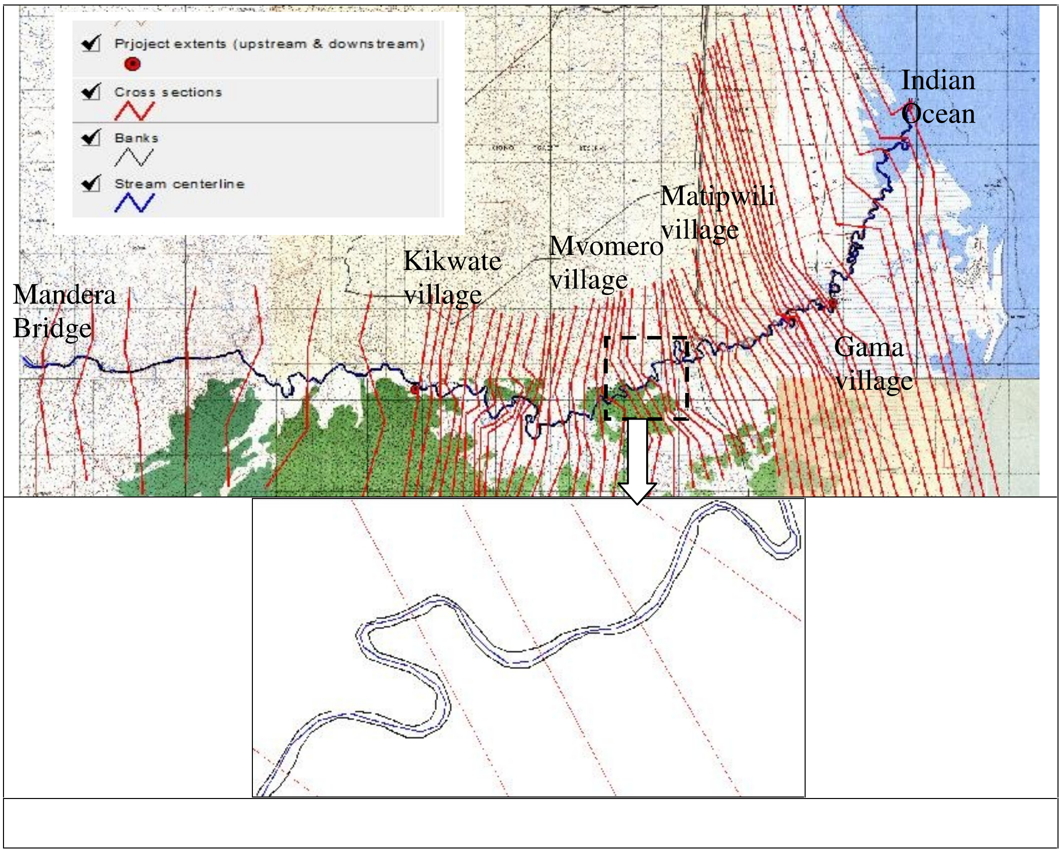

Figure 3: The map presents the locations where the cross sections were extracted from the DEM

Model Schematization and Assumptions Made

Although the entire study area is located within a coastal plain that it is expected to have similar geometric and fluvial/hydraulic characteristics, the spatial variability of these characteristics as observed from the site reconnaissance visit needed to be captured. A river network for the study reach is a main river reach of Wami River. The river reach extends 23 km from Gama to Kikwate villages (Fig. 3). It was assumed that gullies and intervening catchment do not contribute significant runoff to the study river reach. Several river bottom points referred to as *stations* describe the properties of each cross section (Fig. 2). The points were defined by the horizontal distance from the left river bank (with respect to looking in the downstream direction) and the bottom elevation above Indian Ocean mean water level as datum. The cross sections are normal to the direction of the flow and they were located at places where the river properties change. The order of numbering the cross sections is from the downstream end to the upstream end, in which the distance between two cross sections is the reach length. A reach length was required for the main channel as well as for the overbanks. The differences in the three reach lengths may reflect a river patterns such as meandering and straight (Fig. 3).

River reach lengths are downstream distances between adjacent cross sections. The downstream cross section reach lengths describe the distance between the current cross section and the next cross section downstream. The most downstream cross section has zero reach length. Cross section reach lengths are entered in meters. The Manning's n is the most important coefficient to get a proper water surface profile. It has to be estimated or determined by calibrating the model according to known water surface profiles. The adopted coefficients were defined for the main channel and floodplains. An initial value for channel Manning's roughness coefficient, *n*, for use in the model was determined from reported literature values (Chow, 1959) corresponding to roughness condition of Wami River sub-basin study reach. The manning values were estimated based on characteristics of the material forming the channel banks and floodplains (*i.e.*, fine-grained particles comprised mainly of clay and silts) and vegetation cover (*i.e.*, open bush to dense grass). The estimated initial "*n*" values range from 0.030 to 0.045 as the surface condition of the river reach could be characterized as alluvial sand. The contraction coefficient ranges between 0 and 0.6 while the expansion coefficient range is 0.0-0.8 with adopted default values in HEC-RAS of 0.1 and 0.3 for contraction and expansion coefficients, respectively.

To use available spatial data (*i.e.*, satellite images, DEM and land use map) and output hydraulics (inundated surface area, depth, *etc.*), the hydraulic model was linked to GIS based software, HEC-GeoRAS. The model was set up by 57 cross sections, on average, spaced at 1.36 km interval. They represent most of cross section features including freeboard, floodplains, old river channels, wetlands, and main channels. The cross sections were placed strategically at locations as per model requirement and project objectives while the modelled river reach spans about 95.3 km. Although, the study reach spans only 23 km long, the extension of the modelling river reach to downstream, the Indian Ocean shore line, and further upstream, at Wami-Mandera Bridge gauging station, was inevitable in order to capture the pre-assumed boundary conditions and hydraulic controls for the modelling purpose (Fig. 3). The upstream and downstream boundary conditions are located about 10 km and 15 km away from the study river reach, respectively. As the contemplated flood protection embankments segment length will be determined by the spacing of cross sections, so dense cross sections were mainly placed on flooding potential reach, low lying banks, as the case of Matipwili village river reach, which is between Mvomero and Gama villages. The shorter the reach length the shorter will be the embankment lengths. The upper reaches such as in Kikwate village. In gorge river section, the cross sections were sparsely placed.

The upstream boundary condition was the floods magnitudes, estimated using streamflow data historically observed at Wami at Mandera Bridge gauging station (1G2). Indian Ocean tides levels were used as the downstream boundary condition for the study reach. It was hypothesized that backwater curve from sea might influence hydraulic regime of the Wami River at the study area. The observed water surface level of 4.25 m, as highest tide of month of April for the last two years (2011-2012), was used as downstream boundary condition. The maximum tide was used in order to simulate the critical/worse conditions expected at the study reach. Railway Bridge at Matipwili village was also implemented in the hydraulic model. The channel constriction at the bridge was considered to alter hydraulic regime upstream in form of a backwater. Uniform flow condition in the river reach is manifested when gravity and friction forces are equal. It should be noted that computations in the model started from downstream and proceeded upstream direction as the state of flow in the reach was characterized as subcritical.

Model Calibration and Validation

The model calibration was achieved by qualitatively matching the simulated and observed flood plain inundation area and flood levels as reported by villagers and observed during field visit, respectively. Although in various applications water level/depth is the most reliable hydraulic data for calibrating hydraulic models, in this study flood extent was used, instead. The uncertainty of floods extent data is relatively small compared to that of water level especially for extensive floodplains like that of Wami River at the study area. Considering the spatial scale of the study and logistical issues flood extent geographical locations of recent extreme floods of year 1997/98 (El Nino) were captured. Such extreme hydrological events were also witnessed by youngsters who could be mobilized easily, as field Assistants, for this study. The El Nino flood was estimated to have a period recurrence interval of 100 yrs. Besides, note that other researchers elsewhere have linked an area affected by a 100-year flood to play an essential role for flood mitigation planning in many countries in the world (Mandlburger *et al.* 2009). The calibration was achieved by mainly adjusting Manning's values, n, in specific cross sections. The coefficient was defined for the main channel and floodplains. The model was run under subcritical state of flow where the computation starts from downstream and proceeding upstream using a standard step method.

The model performance was validated qualitatively using professional judgment. Based on the field visits findings it was learned that the banks of river are overtopped approximately intra-annually with exception of low lying banks which are overtopped seasonally. Therefore, floods of return periods of 1 and 2 were used for validation to represent seasonal (low lying bank) and intra-annual (elevated bank), bankfull discharge. It was anticipated that the entire river reach in the study area will accommodate the flood of 1 year return period within the micro-channel. Besides, most of the river reach with exception to low lying banks will accommodate the flood of 2 years return period. Further validation was based on the physical characteristics of the material forming the bed. With the presence of sand bars on the river bed and meanders, the Wami River system in the study area was characterised as "Old River" with a low gradient and low erosive energy. It was therefore anticipated that the hydraulic model would simulate and mimic low tractive shear stresses on the river bed.

RESULTS AND DISCUSSIONS

The key results presented in this paper are performances of a calibrated composite DEM and the hydraulic model developed. The prospects and limitations of the DEM-based extracted topographic data are also discussed in detail.

Performance of Calibrated DEM

Error analysis of the DEM was performed by comparing the elevations of the DEM grids and topographic map spot heights at 530 points. The elevation points plotted around the 1:1 line (Fig 4) indicated that the deviation in the elevation values between the DEM and spot heights were higher for elevation values above 60 m.a.s.l. The points having elevation magnitudes of less than 60 m were found to be plotted closely around the 1:1 line. The basic statistics of the errors (Table 2) indicate propagation of the magnitudes of the errors with the increase in the elevations (Fig. 5) and the frequency distribution of the errors (Fig. 6). It is observed that the magnitudes of the errors are higher for higher elevations (Fig. 5). It is further observed that a majority of the 530 error values are negatives, which indicates that the elevations of SRTMDEM points are higher than those of the spot heights (Fig. 6).

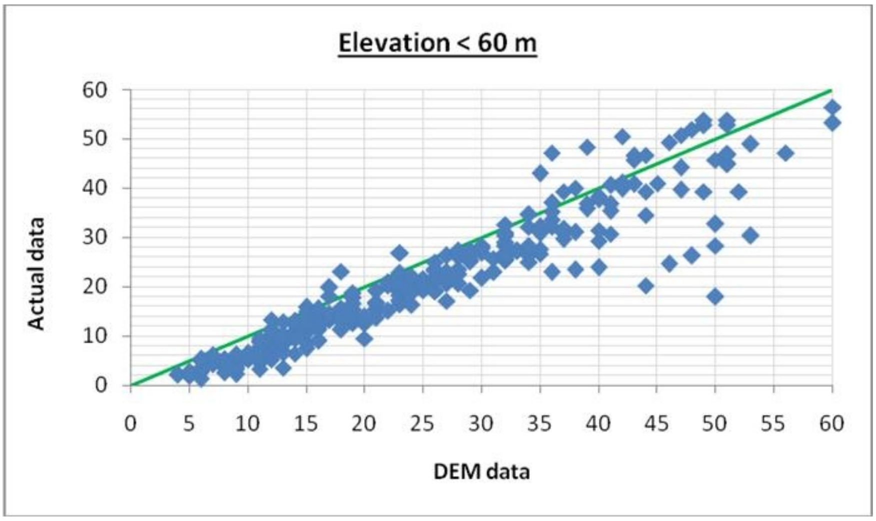

Figure 4: Scatter plot of DEM against Actual Elevations Data

Table 2: Basic Statistics of the DEM Errors

Number of data points	530
Minimum (m)	4.000
Maximum (m)	291.0
Mean (m)	62.1
Standard deviation (m)	58.2
Variance (m^2)	3385.0
Coefficient of Variation (%)	93.7
Standard error of the mean (m)	2.5

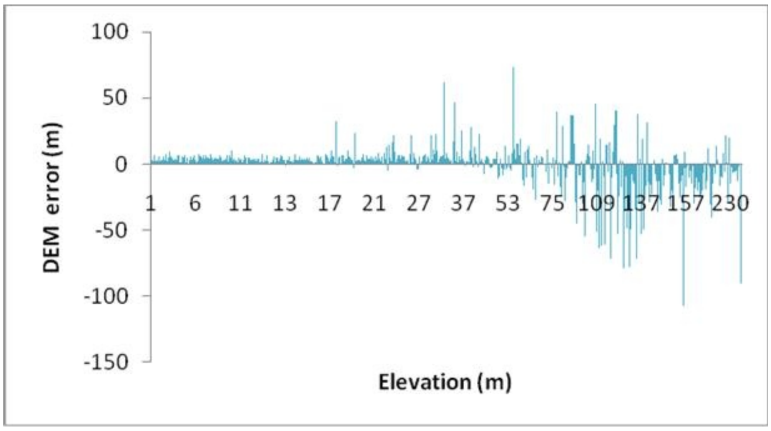

Figure 5: Error Propagation in SRTMDEM with Increase in Elevation

The error-frequency plot (Fig. 6) shows that 80% of the error mass is negative. Therefore it was decided to subtract the error values from the elevations of the DEM-extracted cross-sections to bring geometries of the extracted cross sections as close as possible to the measured cross sections. To assess the accuracy of the SRTMDEM, $RMSE_{DEM}$ was calculated for different elevation ranges (Table 3).

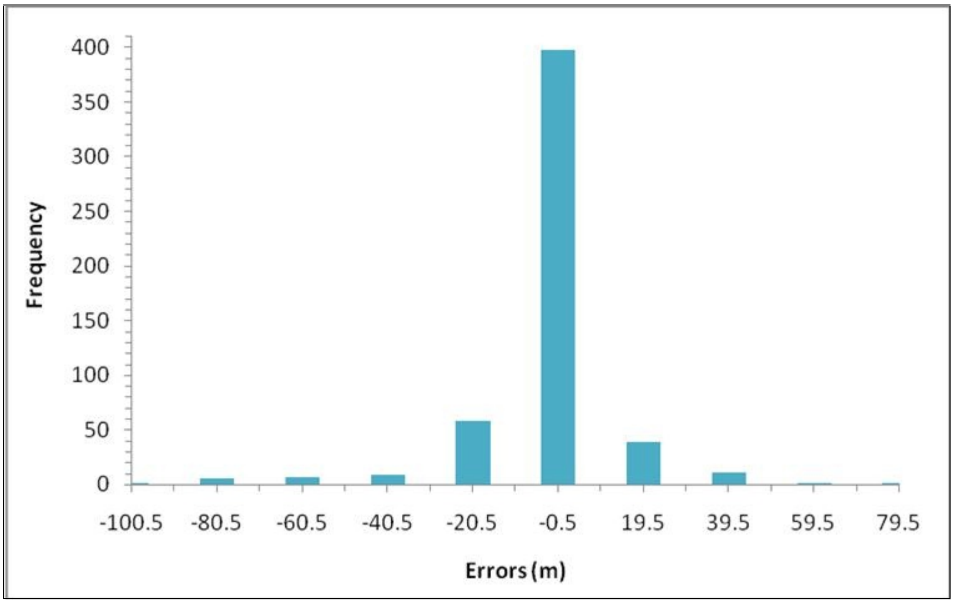

Figure 6: Error-frequency Plot of SRTMDEM Elevations

Table 3: Computed RMSEDEM, RMSE values of the DEM for different elevation ranges

Ranges of Elevation			$RMSE_{DEM}$
0	to	2.3	0.000
2.4	to	5	2.415
6	to	10	3.685
11	to	15	4.178
16	to	20	4.242
21	to	29	4.579
30	to	42	6.367
43	to	60	11.536
61	to	135	27.695
136	to	250	19.396

Although other researchers such as Vaze et al. (2010) used higher DEM resolutions, DEM resampling was necessary for comparison purposes with coarse measured topographic data. The resampling in this study has been done with ArcView GIS version 3.2 using the resample function. The resampling algorithm used was the "NEAREST", which assigns the nearest neighboring value for the output cell. Such an operation is known to influence the elevation derivatives. It should be noted however that elevation is independent of DEM mesh size (Vaze *et al*., 2010). Accordingly, for the RMSE calculation resampling procedures were performed on each DEM by transforming cell size to the reference size, i.e. 90 m. As recommended in Gonga-Saholiariliva *et al.* (2011) work the quality of DEM data used in this study was considered good as the maximum RMSE computed (27.695 m) is less than half a pixel size (i.e., < 45 m).

Based on the foregoing analysis and discussion, the unmodified DEM-extracted cross-sections would have resulted in overestimation of simulated water level because of their higher elevation values. Another notable observation is that the vertical error is spatially variable changing with elevation range. Such variability, as ascertained by other researchers elsewhere, will have an effect on geomorphological reliability, indices such as slope and hydrographic characteristics (Vaze *et al*., 2010). Based on the error analysis, it was decided to adopt a simple method of modifying the DEM by subtracting the values of $RMSE_{DEM}$ (Table 3) from the elevation values of the DEM. Note that modification of the DEM by subtracting the RMSE values did not ensure complete matching of the geometry as it was observed that the modified DEM was still higher than datum (i.e., the mean sea level) by 1 m. So the modified DEM was post-processed by subtracting its elevation values by 1 m throughout. As discussed earlier in this paper the river cross sections geometries used for modelling are the composite of 4 surveyed micro-channels and the modified DEM-based extracted cross section geometries. The Cross sections are presented in Figure 7 on one graph for two purposes: i) to indicate the channel geomorphologic variability; and ii) to check the trend of thalweg elevations (lowest cross section elevation points). The latter is expected to fall downhill from upstream to downstream. An outlier in elevation data beyond the left river bank at Kikwate village is observed. This is attributed to partly due to inherent DEM data uncertainty. Besides, one would note that Kikwate and Mvomero cross sections depict a gorge valley (narrow and deep valley), whereas Matipwili and Gama cross sections are the typical alluvium floodplain geometries characterised by shallow channel and extensive flood plains as observed in the field.

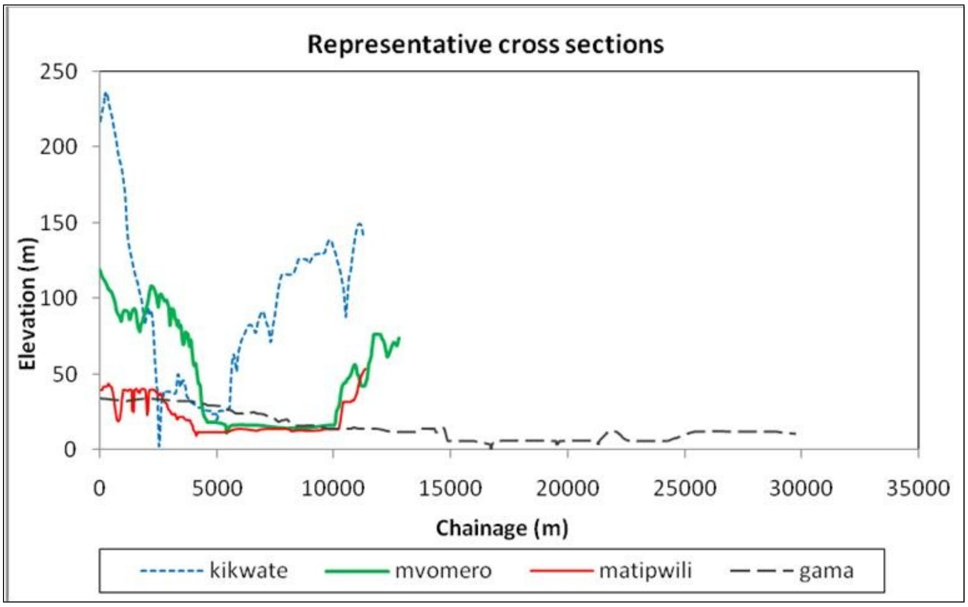

Figure 7: Modified DEM-based Extracted Cross Section Geometry

This approach of DEM composite/hybrid derivation is similar to what other researchers have had proposed (Mandlburger *et al.* 2009). In Mandlburger *et al.* (2009) they recommended the use of LiDAR as geometric input. However, the application of LiDAR goes with problems. Contrary to traditional manual data acquisition techniques like stereo-photogrammetry or tachymetry, LiDAR data includes both terrain and off-terrain points on buildings, vegetation, power lines, etc. The quality of the derived DTM depends crucially on how well off-terrain points have been eliminated within the filtering process. Another issue besides filtering is the fusion of LiDAR and river bed data. This involves the derivation of the water-land-boundary and the interpolation of river bed cross sections (Mandlburger *et al*., 2009).

Performance of the Flood Hydraulic Model
Performance evaluation of the flood hydraulic model was used as a means of validating the accuracy of topographic inputs while keeping other factors constant. A good performing model was expected to simulate a known and observed hydraulic regime of the Wami River. General hydraulic results are presented qualitatively in form of a map (Fig. 8) and quantitatively in tabular format (Table 4) for a flood discharge of 100 years return period. This is one of the flood events when the whole river valley, main channel and flood plain, is actively conveying the flow downstream. It is an event when the contemplated flood protection embankment will be functional or reached by the encroaching floods. Note that inundation width increases towards downstream in the study area, between Kikwate (< 1 km) and Gama Village (> 6 km), (Fig. 8 & Table 4). The flood extends mostly to the right bank floodplain with low lying river banks. One will also note that the flooding zones are not continuous. This could be explained by presence of isolated higher grounds as well as elevation errors as discussed earlier. Some portions of the river reach are hardly overtopped and inundated. As described earlier these are river sections with elevated banks and/or confining floodplains and gorge river section.

From Table 4 one will note that the hydraulics vary spatially from Kikwate to Gama village. Maximum velocities and shear stresses in the channels of less than 0.5 m/s and 4 N/m^2, respectively, are experienced by the middle river reaches between Mvomero and Matipwili villages. Such river regime could be characterized as aggradation (depositional). Elsewhere, the river could be regarded as degrading (eroding). Throughout from Kikwate to Gama village, the floodplain maximum velocities and shear stresses are lower than critical incipient velocity and shear stress of 2 N/m^2, respectively.

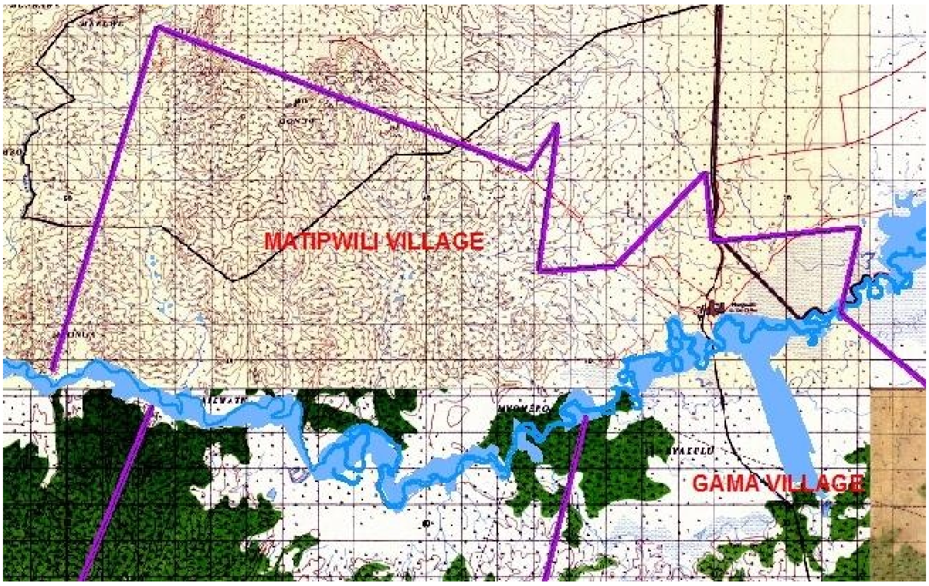

Figure 8: Flooding spatial pattern at the study area under natural condition with 100 years return period

Table 4: Simulated Hydraulics for a Flood of 100 Years Return Period along the Wami River in the Study Area

Hydraulics	Location			
	Kikwate	**Mvomero**	**Matipwili**	**Gama**
Max. channel velocity (m/s)	0.95	0.27	0.18	0.66
Max. floodplain velocity (m/s)	0.29	0.19	0.12	0.16
Max. channel Shear stress (N/m^2)	9.71	0.89	0.30	6.01
Max. floodplain Shear stress (N/m2)	1.34	0.40	0.13	0.59
Top width (m)	860	4655	6256	6490

Further analysis indicates that water levels increase with increasing flood magnitudes as expected. The water levels near Gama Village are influenced by Indian Ocean backwater curve. Upstream reaches of Wami River are not affected by the same. Velocities in the main channels are a bit higher, compared to total average velocities along the study area, but still similar hydraulic regimes are reflected. Velocities increase linearly with flood discharge. On both sides of the river the flood plain velocities are lower than 0.5 m/s, suggesting for aggradation regime. There is insignificant increase in velocity with discharge at Matipwili. This could be explained by the fact that flow area increases substantially with discharge. At Gama river reach right overbank velocities vary non-linearly in the discharge range of 80 to 773.2 m^3/s. This might be explained by presence of depression in the right flood plains which get filled up with increase in discharge. The total shear stresses for reaches of Matipwili and Gama are below 2 N/m^2. Such a threshold is only exceeded at upper reaches, near Kikwate Village. Again, though elevated, there is no much difference between total shear stress and channel shear stresses experienced in the study area. Mostly depositional regime prevails, especially at Matipwili village. Upstream river reaches might be in an equilibrium regime. Such regimes would depend very much on the sediment supply side from catchment or upper reaches. The shear stresses on the left and right floodplains are relatively low to warrant deposition even during extreme floods.

Considering the simulated hydraulics, this study confirms that the Wami River at the study area is under equilibrium/transport and depositional/degradation regimes at Kikwate/Mvomero and Matipwili villages, respectively. The occasional banks erosion observed at the study area are, mainly, attributed to river bank cultivation. Water levels near Gama Village are influenced by Indian Ocean backwater curve. Upstream reaches of Wami River are not affected by the same. Although the performance was generally good, model uncertainties revealed in some parts of the study area are attributed to inherent DEM uncertainty. Therefore, the model results should be applied cautiously especially when intended to be used for planning purposes in low lying floodplain protection embankments.

CONCLUSION AND RECOMMENDATIONS

This study used river cross-sections from a SRTM DEM of 3-arc second for hydraulic modelling studies. Error analysis of the SRTM DEM showed that elevations of DEM grids are higher than those of the corresponding measured spot heights. The present approach of modifying the extracted river cross-sections based on $RMSE_{DEM}$ values for different elevation ranges have improved the performance of DEMs as input to hydraulic model unlike similar studies done previously in Tanzania. The error in the elevation values of the extracted cross-sections could be further minimized using relatively finer resolution DEM and obtaining the $RMSE_{DEM}$ values from a large number of spot heights. The hybrid DEM based hydraulic model satisfactorily simulated the observed and known hydraulic regime of Wami River in the study area. Performance of the hydraulic model was further ascertained based on professional judgement as the calibrated roughness coefficient was found to be within the prescribed range of 0.03 and 0.045.

Notwithstanding the satisfactory performance of the developed model, this study was conducted under various assumptions and limitations. The reader needs to know that impact assessment of the channel modification, as a basis for evaluating ability of the model to mimic the hydraulic regime in the study area, was conducted with limited data on Particle Size Distribution (PSD) of material forming the channel bed and floodplains. Furthermore, a limited number of measured cross sections were used to represent the varying micro-channel geometries of Wami River in the study area. And model schematization was simplified considering high computation resource requirements, limited accessibility and other logistical issues. The modeling framework was limited to 1-D model and the channel was modeled as a fixed bed. Besides, the hydraulic model used only topographic inputs derived from a composite/hybrid DEM.

ACKNOWLEDGEMENTS

The Author is indebted to EcoEnergy Ltd for allowing him to participate in the planning of the contemplated project. The Directorate of Research of the University of Dar es Salaam is also acknowledged for supporting the preparation and publication of the manuscript. Lastly, further appreciations are extended to a couple of individuals; Dr. Valimba, Patrick, Mr. Ijumulana Julian, Mr. Wambura Frank, and Dr. Kahimba Fredrick; for either participating in the fieldworks or sharing data or reviewing the draft paper.

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