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Enhancing digital elevation models for hydraulic modelling using flood frequency detection

Georgina Ettritch[a,*], Andy Hardy[a], Landing Bojang[b], Dónall Cross[c], Peter Bunting[a], Paul Brewer[a]

[a] Department of Geography and Earth Sciences, Aberystwyth University, Aberystwyth, United Kingdom
[b] Department of Water Resources, the Gambia
[c] Institute of Biological, Environmental and Rural Sciences, Aberystwyth University, Aberystwyth, United Kingdom

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ABSTRACT

Medium-resolution DEMs have limited applicability to flood mapping in large river systems within data sparse regions such as Sub-Saharan Africa. We present a novel approach for the enhancement of the SRTM (30 m) Digital Elevation Model (DEM) in The Gambia, West Africa: A time-series analysis of flood frequency and land cover was used to delineate differences in the vertical limits between morphological units within an alluvial floodplain. Combined with supplementary river stage data and vegetation removal techniques, these methods were used to improve the estimation of bare-earth terrain in flood modelling applications for a region with no access to high-resolution alternatives. The results demonstrate an improvement in floodplain topography for the River Gambia. The technique allows the reestablishment of small-scale complex morphology, instrumental in the routing of floodwater within a noise-filled DEM. The technique will be beneficial to flood-risk modelling applications within data sparse regions.

1. Introduction

In data sparse regions (such as sub-Saharan Africa), hydraulic flood modelling applications are limited to the use of medium-resolution (~30 m) Digital Elevation Models (DEMs) including the Shuttle Radar Topography Mission (SRTM: NASA JPL), ASTER Global DEM (GDEM: NASA JPL), and most recently, the ALOS Global Digital Surface Model (AW3D30: JAXA). These products have been implemented within 1D/2D flood modelling applications across large river reaches (typically exceeding 10,000 km^2 in domain extent) to basin-scale and region-scale analysis (covering multiple basins) (e.g. da Paz et al., 2011; Neal et al., 2012; Wilson et al., 2007; Biancamaria et al., 2009; Amarnath et al., 2015; Lewis et al., 2013). A large domain extent requires the resampling of DEM data at coarser resolution (e.g. through mean pixel aggregation) or the use of low-resolution data (e.g. Biancamaria et al., 2009) to reduce the computational demand on flood model performance (Amarnath et al., 2015) (Table 1). Increasing computational efficiency through coarse resolution resampling is particularly important for large-scale rivers, where flood pulses are extensive not just in space, but also in time (da Paz et al., 2011).

Coarse resolution resampling can, in itself, be viewed as a DEM enhancement technique: SRTM, as the most commonly used product in large-scale flood modelling and the primary subject of this investigation, contains a high level of pixel-to-pixel noise, known as the short-wave error component (Rodriguez et al., 2006). The smoothing effect of pixel aggregation works to lower the vertical error margin of the DEM relative to the vertical range of floodplain morphology and flood wave amplitude (e.g. Wilson et al., 2007; Neal et al., 2012). Recent improvements in hydraulic modelling have been made specifically in relation to large-scale flood mapping at resolutions below the native grid spacing of a DEM. For example, the development of the sub-grid channel mode in LISFLOOD-FP allows the inclusion of channel geometry at the sub-grid level. As such, DEM resolution for the 2D component can be coarsened without impacting upon the representation of channel flow in the 1D component (Neal et al., 2012; Lewis et al., 2013).

However, care must to be taken to ensure that DEM coarsening is not detrimental to model performance, particularly when floodwater routing is controlled primarily by floodplain topography. For example, DEM aggregation has been found to lead to the eradication of key regions of riparian floodwater storage, fundamental to the accurate simulation of flood wave travel time (Horritt and Bates, 2001). Pixel aggregation has also been found to limit processes of floodplain dewatering and the representation of low water inundation extent

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* Corresponding author.
E-mail addresses: gee25@aber.ac.uk (G. Ettritch), ajh13@aber.ac.uk (A. Hardy), dec8@aber.ac.uk (D. Cross), pfb@aber.ac.uk (P. Bunting), pqb@aber.ac.uk (P. Brewer).

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Table 1
Examples of the use of medium to low-resolution DEMs in flood modelling and associated resampling of raster-based elevation data relative to model domain extent.

Study	DEM	Original (m)	Resampled (m)	Domain (km^2)	Scale
Neal et al. (2012)	SRTM	90	905	210,389	Sub-basin
Wilson et al. (2007)	SRTM	90	270	13,000	Sub-basin
Biancamaria et al. (2009)	ACE	1000	1000	790,000	Sub-basin
da Paz et al. (2011)	SRTM	90	2000	219,514	Sub-basin
Komi et al. (2017)	SRTM	30	30–960	72,000	Basin
Lewis et al. (2013)	SRTM	90	900	223,000	> Basin
Sampson et al. (2015)	SRTM	90	1000	–	Global

through the removal of complex, small-scale topography (Wilson et al., 2007). Overall, optimal DEM resolution is a compromise between: 1) Accounting for flood wave amplitude and the complexity of floodplain topography (e.g. Wilson et al., 2007), 2) The vertical accuracy of the DEM relative to the above and 3) Optimising computational efficiency of the flood model relative to study domain extent and flood wave temporality.

1.1. Methods of DEM enhancement

The relative/absolute vertical error of medium-resolution DEMs (e.g. SRTM with an absolute vertical error > 5 m in regions with slopes of < 10° (Gorokhovich and Voustianiouk, 2006)) will often exceed the vertical range in floodplain morphology and flood wave amplitude. Therefore, medium-resolution DEMs are often considered to be unsuitable for use in the modelling of overbank flow controlled by floodplain topography, without modification (Bates, 2012). Furthermore, large river systems contain complex flow networks that control the routing of water/sediment across the floodplain (Lewin and Ashworth, 2014). Many small-scale features instrumental in floodwater routing will be missed by medium-resolution DEMs in the first instance, a problem exacerbated further by coarse resolution resampling, as outlined above. In addition, the presence of closed canopy vegetation, such as mangrove forests, can mask the bare earth terrain below (Sun et al., 2003; Yastikli et al., 2006; Tighe and Chamberlain, 2009). This is problematic for the majority of large tropical floodplains where vegetation cover is often dense, continuous and does not experience the leaf-off conditions typically associated with winter months in temperate regions. As such, an estimate of bare-earth terrain under vegetation using Earth Observation data is limited. Tidally-influenced tropical regions are particularly problematic as saline-tolerant species will persist throughout the hydrological year and may experience only limited periods of die-off and subsequent exposure of the underlying surface. The following literature review is a brief account of techniques available to the end-user for the enhancement of SAR-based or optical-based elevation data.

Common DEM enhancement techniques include data fusion (i.e. hybridisation), waterbody masking, void filling, stream burning and vegetation removal. Data fusion is typically conducted at the landscape-scale. For example, SRTM can be fused with ASTER GDEM to capitalise on the relative differences in sensor performance over mountain slopes, valleys and floodplains for respective SAR and optical-derived DEMs (e.g. Tran et al., 2014). However, this technique has also been effective at improving topography within the floodplain. For example, 2.5 m Cartosat-1 data (Patel et al., 2016) was combined with 90 m SRTM data to form an 8 m hybridised DEM that compensated for the limited performance of the Cartosat-1 DEM over paddy fields (Sanyal et al., 2014).

InSAR-derived DEMs such as SRTM produce a noisy water surface with a high density of data voids due to the specular reflection of C-Band microwave energy over water (Lehner et al., 2008) and side-looking angles of spaceborne/airborne radar systems. Waterbody masking applies a constant elevation value over an open water surface and allows the removal of elevation anomalies and data voids associated with these regions. SRTM has been improved at global-scale through the use of the auxiliary water mask: SWBD (SRTM Water Body Data). A similar dataset AWBD (ASTER Water Body Dataset) has also been applied to GDEM version 3 (Abrams, 2016).

Data voids are negative relief features of internal drainage that include single-cell/double-cell sinks and larger regions. These features are easily resolvable using common fill techniques that raise the elevation of an internally draining region to the level of its peripheral pour point (e.g. Jenson and Domingue, 1988; Planchon and Darboux, 2001; Wang and Liu, 2006). Fluvial erosion generally dictates a hydrologically connected landscape (Wang and Liu, 2006; Mark, 1988) suggesting that the majority of such features are erroneous and should be eliminated from the topographic profile (Mark, 1988; Senevirathne and Willgoose, 2013; Lindsay and Creed, 2005a, 2005b). However, larger features may in fact be natural regions of negative relief (e.g. de Carvalho Junior et al., 2014; Siart et al., 2009; Smith et al., 2013). In a fluvial context, negative relief formations may include: palaeochannels, riparian lagoons and pools, that will remain inundated following floodwater recession (Lewin and Ashworth, 2014; Smith et al., 2013). Removal of these features may contribute to inaccuracies in the calculation of floodwater storage within the floodplain. Some negative relief features that are hydrologically connected to the main trunk stream maybe inaccurately presented as internally draining features. In such cases, a breaching algorithm (e.g. Martz and Garbrecht, 1999) can be used to eliminate anomalous topographic highs and allow hydrological reconnection.

Stream burning also facilitates a hydrologically connected surface within a DEM, thereby, improving floodwater routing within a 2D hydraulic model. Depending on DEM resolution river channels may become disconnected or are too narrow to be detected as a negative relief feature in the first instance. Automated stream burning procedures (Lindsay, 2016) can directly modify channel elevation within a DEM, based on a predefined flow path. One example is the AGREE method for DEM surface reconditioning (Hellweger, 1997). The technique generates a trench along a given stream vector, while eliminating proximal parallel flow paths through a lateral smoothing procedure. In data sparse regions, streams are typically generated by lowering channel cells by a constant value (representative of predicted channel depth), relative to adjacent floodplain cells (representative of river bank height) (Lindsay, 2016). In doing so, the integrity of channel geometry estimation is inherently dependent upon the vertical accuracy of the DEM. If bank height above river bed is distorted by riparian vegetation cover, channel bed elevation, relative to local floodplain level will be overestimated.

Furthermore, in lowering channel cells by a constant value it is assumed that the DEM surface is representative of channel bed gradient in the first instance. However, this is unlikely to be the case, particularly within gently sloping regions where vertical error typically exceeds topographic variation within a DEM. As such, stream burning procedures often incorporate interpolation techniques that linearly recondition channel bed elevation between predetermined values in the downstream direction. For example, LISFLOOD-FP (1D/2D mode) applies linear interpolation between discrete cross-sections of known width and bed elevation. Using bank height as an approximation of channel depth, the estimated geometry is burned directly into the DEM,