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Q1 With some edits and comments from Takashi Oguchi assessment of drainage network 2 extractions in a low-relief area of the Cuvelai Basin (Namibia) from multiple sources: 3 LiDAR, topographic maps, and digital aerial orthophotographs

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ABSTRACT

Accurate delineation of drainage networks (DNs) is crucial for hydrological or hydraulic modelling, and the comprehension of fluvial processes. This task presents challenging aspects in complex lowland terrains with subtle relief and particularly for data poor-areas like the Cuvelai river basin (CRB), Namibia, where the present study takes place. In the CRB standard methods of drainage network extraction from low resolution gridded digital elevation models (DEMs) are unsuitable, hence airborne Light Detection and Ranging (LiDAR) solutions have been utilized. However, LiDAR also presents challenges to large areal applications, especially with a surface roughness exceeding the capacity of numerous algorithms. Indeed, LiDAR-based DEMs (2 and 50 m resolutions) need to be hydrologically corrected and smoothed to enable the extraction of scale-relevant geomorphologic features such as DN. In the present contribution, channels from topographic maps (blue lines) were compared to those from hydrologically corrected and uncorrected LiDAR DEMs, heads-up digitized channels from high-resolution digital aerial orthophotographs, field-mapped channels and auxiliary data. The 'maximum gradient deterministic eight (D8)' GIS algorithm was applied to the corrected and uncorrected LiDAR DEMs using two network extraction methods: area threshold support and curvature/drop analysis. Different progressive flow accumulation threshold values (12) were used to delineate channels with these methods. Validation was performed between the field-mapped channels, the modelled channels and those derived from multiple sources. Additionally, spatial and quantitative analyses were performed on geomorphologic parameters and indices. The results have shown that hydrologically corrected LiDAR DEMs offer useful details for identifying low order stream segments in headwaters, while blue lines derived from the national hydrography datasets for watersheds, located in elevated and low-lying areas of the study area, underestimated total stream lengths for field-mapped channels by – 15.3% and – 88.5%, respectively. This study also confirmed that DN can be extracted from complex low-terrain areas with standard GIS algorithms and accurate field data. The results will aid national mapping agencies in data-poor regions to modernize their national hydrography datasets and to account for changing land surface conditions that can affect channel spatial arrangements over time.

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1. Introduction

Precise delineation of drainage networks (DNs) is essential for hydraulic and hydrologic modelling, water resource management, geomorphologic change of floodplains, flood risk management and surface water mapping (Poppenga et al., 2010a,b, 2013; Ducey et al., 2012; Hohenthal et al., 2011; Jones et al., 2008; Sharon et al., 2008; Jones et al., 2007; Hollaus et al., 2005; Thoma et al., 2005; French, 2003; Moore et al., 1991). DN play an important role in computing the routine of water flow, especially in areas where long time-series data are unavailable or stream-networks are un-gauged, under-gauged, and

drainage basins are extremely large and complex. The semi-arid Cuvelai river basin (CRB; Mendelsohn and Weber, 2011), located between Angola and Namibia (Fig. 1), encompasses these and many other challenges related to flood risk management.

The CRB, where this research has taken place, displays a series of characteristics that hamper the accurate delineation of DN, when using traditional manual delineation methods: (1) very low gradients that accentuate the relative importance of numerous hydraulic obstructions such as roads, bridges and culverts (Fig. 2A, B, E); (2) lack of well-defined flood channels, which are mostly broad and shallow (Fig. 1, between Xangongo and Oshakati); (3) the semi-arid climatic conditions result in very strong seasonal variations in channel water levels which often produce inaccurate DN datasets (ephemeral, intermittent, or perennial) and are only valid for the season when the topographic data

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have been recorded (Benstead and Leigh, 2012; Directorate of Survey and Mapping [DSM], 2013; Levick et al., 2008; Stanley et al., 1997); (4) numerous natural pans, lakes and holes that are caused, in some cases, by water resource and flood risk management practices, hamper the delineation of accurate DNs (“blue lines”, Fig. 2C, D, F); (5) the absence of riparian zones and depositional characteristics that can formed as a result of in-channel migration, prevent the application of geomorphologic and vegetation-based traditional methods of channel delineation (Osterkamp and Hupp, 2010; Bendix and Hupp, 2000; Hupp and Osterkamp, 1996); (6) the complex landscape of the CRB that resulted from in-land deltaic processes (Miller et al., 2010; Mendelsohn et al., 2000; Van der Waal, 1991); (7) the scarcity of hydro-meteorological data caused by climatic conditions, lack of financial and human resources, and past war conflicts within the CRB, contributes towards the lack of accurate DNs (Zaman et al., 2012; Gebremichael and Hossain, 2010; Hughes, 2006; Wilk et al., 2006); and (8) inaccurate, outdated topographic maps (1:50000) and aerial photographs (1:60000) are unable to depict the seasonal dynamism of this drainage system (Cazorzi et al., 2013; European Space Agency [ESA], 2015).

As a result, different representations of the drainage network of the CRB have been used in studies that have tried to solve the environmental and water resource-related challenges of the CRB (RAISON, 2012; Mendelsohn and Weber, 2011; Miller et al., 2010; Mendelsohn et al., 2009; BIWAC, 2006; Hipondoka, 2005; Bittner Water Consultants,

Fig. 2. Typical characteristics that can hamper the accurate delineation of drainage networks when using traditional manual or automatic delineation methods using DEMs in the study area. (A) and (B) illustrate the low-terrain areas of the study area with a stage gauge station (telemetry) within a typical broad dry shallow channel while (C) and (D) show man-made depressions that represent water resource management practices and flood control measures. (E) shows an inundated low-terrain area partly caused by elevated hydraulic obstructions such as roads and lastly (F) shows the Ngandjela Pan (Google Earth; 18°34'12.00"S 15°15'36.00"E) in the CRB, an example of the numerous pans and lakes that hampers continuous downstream flow in this low-terrain area.

compared to manual methods. Furthermore, these new methods can be subjected to rigorous validation as well as applying refined algorithms in combination with high-resolution imagery.

Automatic delineation of drainage networks from DEMs is based on the inherent relationship between geomorphology, hydrologic and hydraulic characteristics (Moore et al., 1991). A set of morphometric properties to deterministically identify terrain features (Morris and Heerdegen, 1988; Band, 1986; Peucker and Douglas, 1975) can be used as well as a set of rules to construct relationships between hydrological features and morphometric properties (Tarboton et al., 1991, Q8 1992; Gardner et al., 1990; Band, 1986; Mark, 1984a,b; O'Callaghan and Mark, 1984). The former works well in high-terrain and steep slope landscapes where hydrological features such as channel banks, peaks and ridges are more pronounced while the latter is for hydrological modelling application. However, many hydrologic studies have been unable to provide accurate results consistently, partly because of data sources, spatial resolution of DEMs, the adopted algorithms in analysing the data (Baker et al., 2006; Gyasi-Agyei et al., 1995), unspecified flow accumulation area threshold (Chen et al., 2010) and subdued terrain with many depressions (Pan et al., 2012; Arnold, 2010).

LiDAR data have been used for process-scale studies of hillslope processes and valley network organization (Roering et al., 2013). The extraction of hydrographic features such as drainage networks is very popular due to the possibility of LiDAR to detect minor changes on low-terrain areas. Theoretically, the highest resolution data should produce the most accurate DN delineation, and should therefore allow the extraction of small channels as well as the determination of channel heads, which are essential for accurate determination of accumulation threshold values (Gonga-Saholiariliva et al., 2011; Murphy et al., 2008; Barber and Shortridge, 2005; Adams and Chandler, 2002; Bian and Walsh, 1993). Additionally, LiDAR-derived DNs have been used to map hydrology flow lines to improve and update National Hydrography Datasets (NHD), since drainage change over time is affected by changing surface conditions caused by flooding (Poppenga et al., 2013).

Studies that have used LiDAR-derived DNs compared to DNs derived from other sources have reported better results. Clarke and Archer (2009) found that small grid sizes (LiDAR DEMs) produced a quantifiable increase in hydrographic features. While studying the horizontal accuracy and completeness of DNs derived from USGS DEMs and LiDAR, Colson (2006) showed that LiDAR-derived hydrographic features have better positional accuracy compared to DEM-derived features from the USGS. Garcia (2004) also found better accuracy for LiDAR extracted headwaters DNs compared to the USGS 7.5 minute DEM-derived DNs. Miller et al. (2004) compared 1 m LiDAR with 2.5 m IFSAR LiDAR DEMs by extracting channel depth, width and cross-sectional area and found that LiDAR DEMs performed better in extracting channel depth essential in shallow, broad channels such as those of the CRB.

However, most LiDAR DEMs need preparation such as creating a 'hydrologically corrected' DEM before applying geomorphometric analysis, especially in low-terrain environments where hydraulic obstructions such as road infrastructure are accentuated (Poppenga et al., 2010a,b, Q9 2013; Amatya et al., 2013; Reuter et al., 2009; Murphy et al., 2008; Vaze and Teng, 2007). Research has also shown that LiDAR DEMs need to be resampled to coarser resolution to be more useful for the extraction of scale-appropriate hydrographic and other geomorphic features due to limitation such as the computing facilities, model run time and large file sizes of the original LiDAR data (Metz et al., 2011; Chen et al., 2010). However, with an increased coarseness of DEMs, the terrain becomes smoother, slope decreases, the length and the density of DNs decrease, the size of the watershed becomes larger and hydrologic response parameters decrease consistently (Chen et al., 2010; Liu and Lu, 2009; Wei et al., 2004). Many studies have used the D8 algorithm successfully in low-terrain areas (Lehner and Grill, 2013; Poppenga et al., 2013; Amatya et al., 2013; Liu and Zhang, 2011; Callow et al., 2007). Some have used the algorithm with high-resolution LiDAR DEMs (Liu and Zhang, 2011), while Callow et al. (2007) have used different hydrologic corrections methods such as stream burning, AGREE

and ANUDEM to assess their impact within a complex landscape similar to the CRB. Poppenga et al. (2013) have used the D8 algorithm in combination with a selective drainage method to update NHD. Amatya et al. (2013) used reconditioned culverts/bridges within LiDAR DEMs and used the reconditioned DEMs in combination with the D8 algorithm in a low-gradient coastal plain landscape. Some studies have also consistently recorded flaws with the DNs derived when the D8 algorithm is applied such as parallel flow paths in flat areas, high sensitivity to inherent DEM errors, and inaccurate flow direction on convex slopes (Jenson and Domingue, 1988; Wilson et al., 2007; Jones, 2002; Paz et al., 2008). Other studies have recommended the use of other algorithms in low-terrain areas such as multiple flow direction (MFD), deterministic-Infinity (D^∞), random-eight neighbour (Rho8) and Digital Elevation Model Networks (DEMON) to address the abovementioned flaws (Wilson et al., 2007). This paper does not address comparison between the effects of using different algorithms (SFD and MFD) to automatically delineate drainage networks from DEMs but seeks to find a framework that uses the D8 algorithm in combination with hydrological corrected LiDAR DEMs to accurately delineate DNs to help update NHD.

Research has shown that the most effective and efficient way to extract drainage networks is to start by locating the actual channel head locations which indicate the starting point of the channels (Mark, 1983; Montgomery and Dietrich, 1989). The three main approaches (Tarolli, 2014) to identify the location of channel head locations and therefore to delineate the drainage networks and catchment boundaries are: (a) a constant critical support area or threshold support area (Tarboton et al., 1991; Tarboton, 1997; O'Callaghan and Mark, 1984; Band, 1986); (b) a slope-dependent critical support area or threshold slope-area values (Dietrich et al. 1993; Montgomery and Dietrich, 1992), and (c) a threshold of local curvature or critical curvatures (Passalacqua et al., 2010; Heine et al., 2004; Rodriguez-Iturbe and Rinaldo, 1997). Hence, this study has used the D8 algorithm with hydrologically corrected LiDAR DEMs as well as with the curvature/drop analysis method (Tarboton and Ames, 2001; Tarboton et al., 1991). The central aim of this study is to use “hydrological corrected” resampled LiDAR DEMs to derive accurate DNs of the study area, because traditional photogrammetric techniques have proven ineffective to accurately mapped time-relevant hydrography (new and updates) consistently. The main objective of the study can therefore be divided between the following objectives: (1) comparing blue lines (topographic maps) with channels extracted from: hydrologically corrected and uncorrected LiDAR DEMs, field-mapped, digitized and auxiliary data; (2) calculating geomorphological parameters and indices such as number of streams, Strahler's stream orders, stream lengths, watershed's areas (km^2), and watershed's perimeters (km); and (3) performing spatial accuracy assessments and statistical analysis on the geomorphic parameters; and finally, to provide a framework that will enable the improvement, updating and validation of DNs in data-poor regions using easily accessible data sources and methods.

2. Study area

The CRB, also referred to as Cuvelai drainage system or Cuvelai–Etosha river basin (Namibia), is part of the Owambo basin that was structural in origin and is an extension of the Kalahari Basin (Mendelsohn et al., 2013; Miller et al., 2010; Miller, 1997). It has an area of 167,600 km^2 and is located between 14° and 15° E longitude, and 15° and 20° S latitude. It originates in the tropical humid highlands of Angola and terminates in Etosha Pan which forms part of the world-renowned Etosha National Park that is also the topographically lowest point (1080 m) within the Owambo basin (Fig. 1; Hipondoka et al., 2014).

The Cubango/Kavango and Kunene are the only two perennial rivers and form the borders of the CRB to the east and west, respectively (Fig. 1). They originate in the Serra Encoco region of the Angolan highlands (Wellington, 1938). The Cuvelai River has two tributaries, the

Mui-Mui and the Caundo Rivers, which also originate in Angola. These perennial tributaries have well defined channels that become diffused into a unique series of anastomosing temporary shallow channels from Ondjiva southwards (Fig. 1). This web of shallow channels is called *iishana* (sing. Oshana) in Namibia and *mulolas* in Angola (Mendelsohn and Weber, 2011; Mendelsohn et al., 2009, 2000; Cunningham et al., 1992; van der Waal, 1991).

Most studies (Miller et al., 2010; Mendelsohn et al., 2013; Cunningham et al., 1992) have emphasized the channels' distinctive characteristics as: very low gradient (approximately 1:5,300), no well-defined flood channel, covered with bushes and grasses, and meandering channels formed within a fluvial deltaic depositional system (inland). The meandering is ascribed to the topography that becomes gentler southwards, the basin effect, and frequent silting and re-routing of channels. Furthermore, due to the lack of well-defined channels, shallow depressions formed, once filled with rainfall, they connect and form broad undefined channels flowing slowly, southwards. This usually happens during a large flood known as *efundja* when rainfall occurred over the entire CRB (Mendelsohn et al., 2013; Miller et al., 2010; Mendelsohn et al., 2009, 2000; Cunningham et al., 1992).

Different width and depth measurements have been reported for these channels, some studies reported between 1 and 7 m in depth and 100 to 500 m in width while others reported widths varying from 200 to 1,750 m and depths varying from 2 m and tracts of even 4 m deep (Miller et al., 2010; Hipondoka, 2005; Barnard, 1997; Wellington, 1938). These uncertainties in the depth and width measurements greatly contribute towards the difficulty in accurately delineating major channels (thalweg).

Many attempts have been made to classify the CRB's DN. Cunningham et al. (1992) reported five distinguished zones: western oshana zone (between Oshakati and Xangongo), central oshana zone (study area) with perennial headwaters (Cuvelai–Evale–Ondjiva–Oshakati), dormant dry drainage lines – or “river valleys” called *omurambas* – (between Ondangwa/Eenhana and Tsumeb), Oponono/Ekuma zone (shallow lakes) and the Etosha Pan (Fig. 1). The central and western oshana zones are broad and flat channels which flow more frequently even though the central oshanas have perennial headwaters in Angola. The western zones are: narrow and densely spaced, mostly dormant channels that flow infrequently only under exceptional circumstances (extreme local rainfall). Most of these zones converge into the Omadhiya lakes that consist of interconnected, semi-permanent water bodies (Fig. 1). From these lakes, water will follow within the Ekuma River, in a single, well defined channel, which connects these clusters of lakes and pans to the lowest area: Etosha Pan (1080 m.a.s.l., Hipondoka et al., 2014).

The CRB primary lies on sediments of silt, clay, limestone and sandstone that was deposited by Cretaceous rivers while uplift in the Pliocene resulted in eroded sand that was washed into the basin and reworked into sand dunes during drier periods in the late Pleistocene (Miller et al., 2010; Haddon, 2005; Miller, 1997). The relationship between sandy, well-drained to sodic-clay, poorly drained soils across toposequences in the megafan palaeotopography adds another layer to the complex geological/geomorphological history of the area (Hipondoka et al., 2014; Hipondoka, 2005). Elevated areas between channels consisted of Kalahari sands and support mopane scrub and various larger trees. These elevated areas support most of the crop production in the study area which is predominantly based on subsistence and rain-fed agriculture. The southern part of the CRB is composed of very low terrain area and flattens out into saline grassland underlain with a shallow layer of saline sand hence water for domestic consumption is being brought in through an open canal for processing. Poor structure, shallow depth and high salinity of the soil prevent trees from growing in this low terrain area. The land use for this part (southern) of the catchment is mostly for grazing cattle during the rainy season. A variety of fishes are delivered during periodic flows of the oshanas (shallow channels). The abundance of the fishes depends on

the magnitude and duration of a flood event (Mendelsohn et al., 2000; Cunningham et al., 1992; van der Waal, 1991).

The Angola–Namibia border divides the CRB into two parts: areas south and north of the border. The study area is location in the southern part that is a relatively flat area (Fig. 1). Within the study area, the steepest areas (approximately 1,102 m.a.s.l.) are located to the north while the low lying areas (1,089 m.a.s.l.) to the south (Fig. 3). Three reasonable size watersheds within the study area (Watershed 1, 15; 2, 8.5 and 3, 13 km², Fig. 3) were selected. Watersheds 1 and 2 are located in the elevated parts while Watershed 3 is located in the very low relief parts. The analyses described in this study were carried out separately on these three watersheds as well as the whole of the study area (see Figs. 1 and 3).

The climate of the area can be described as semi-arid with rains falling in the austral summer months (December to April) when

temperatures are the highest. The annual rainfall in the CRB is between 900 mm in the northern part to 400 mm in the south. Water enters the study area as rainfall or flowing surface water from northern Angola and evaporates rapidly or seeps into the sandy ground. Rainfall is highly variable in the amount that falls and when it falls within the rain season (Mendelsohn et al., 2009; Engert, 1997; Department of Water Affairs, 1990; Ground Water Consulting Services, 1990, 1990, 1993; Beyers and Katsiambirtas, 1987).

3. Materials and methods

3.1. Data

This paper uses channels derived from five sources: field-mapped channels (FM), conventional hydrographic channels derived from aerial

Fig. 3. The study area with the “hydrologically corrected” 2 m resampled LiDAR DEM with a drainage network (Strahler Orders) that was produced using 0.9 km² accumulation threshold. The three watersheds as well as three stage gauge stations are shown.

photograph interpretation (DOQ), heads-up (on-screen, HDZ) digitized channels derived from various sources such as Google Earth and ArcGIS' web-based imagery, and channels modelled from hydrologically corrected and uncorrected 2 m resampled and 50 m LiDAR DEMs. These channels (Fig. 4-I) were firstly field-mapped during two field study trips: the first was from October to November 2012 while the second was from December 2013 to February 2014. A Trimble GeoExplorer 6000 series handheld GPS (post-processed), printed aerial photographs (1:60 000) and topographic maps (1:50 000) were used to map major channels in the field. These channels were walked out in the field, upstream for as far as channelized flow continued. The collected data were post-processed to increase horizontal and vertical accuracies.

The commonly used and relatively accurate channel networks are the hydrographic “blue lines” and are available from topographic maps at various map scales (Heine et al., 2004). In Namibia, the 1:50 000 topographic maps had been updated, for selected areas, using digital aerial orthophotographs derived from regional aerial surveys (Directorate of Survey and Mapping [DSM], 2013). We used these maps as the second data sources. Research has found that, however, blue lines grossly underestimate field-mapped channels (Heine et al., 2004; Montgomery and Foufoula-Georgiou, 1993; Coates, 1958; Morisawa, 1957). Instead, heads-up (or on-screen) digitizing techniques (Nardi et al., 2008; Heine et al., 2004) were used to extract channels from digital aerial orthophotographs (Directorate of Survey and Mapping [DSM], 2007a) and digital aerial imagery from ArcGIS (or Google Earth) web mapping service available only for licenced ArcGIS products (Poppenga et al., 2013); fourthly, LiDAR cloud points captured at 20 cm horizontal spacing and processed to distinguish canopy returns from ground returns were converted to gridded 50 cm ArcGIS format

tiles (National Hydrological Services Namibia [NHS], 2008). A mosaic was created from these gridded tiles that cover the study area and has a horizontal resolution of 0.5 m and a stated vertical accuracy of 2 cm (NHS, 2008). This mosaic was resampled to a 2 m gridded LiDAR DEM; fifthly, accurate and reliable orthophotographs at sub-metre horizontal resolution had been produced by regional aerial surveys in northern Namibia between 2007 and 2008. One of the products of these surveys was the 50 m LiDAR DEM regional data that had been used to update topographical maps for northern Namibia (Directorate of Survey and Mapping [DSM], 2007b; COWI, 2012, 2014). Lastly, auxiliary data such as TerraSAR-X satellite (German Aerospace Agency, [DLR], 2009) derived water mask consisting of polygons and captured during a major flood in the CRB during 2009 were also used for accuracy assessment of major flood lines.

3.2. Preparation of DEM data

Past-studies have recommended that DEMs be enhanced by applying DEM pre-processing (Fig. 4-II) algorithms (smoothing) before land-surface parameters and objects are extracted (Reuter et al., 2009). Hence, the corrected and uncorrected 2 m resampled and 50 m LiDAR DEMs (Fig. 4-IIb) were pre-processed by applying filtering and smoothing algorithms to remove typical DEM errors such as tile-boundary artefacts (or cut-line – Fig. 5C, D) and missing data (Haugerud, 2009). The pre-processing procedure was completed by an identification of sinks and filling these sinks.

Hard and soft techniques have been used together to correct DEMs hydrologically, in order to replicate known hydrological patterns (Nardi et al., 2008; Callow et al., 2007). Soft techniques used algorithms

Fig. 4. Methodological flow-chart showing the five sections the study covers. The first section list the data used; second section shows how the data were prepared for terrain analysis; and the third section shows the procedures followed under terrain analysis (III) which has two main sections A and B. Section III-A was applied to data prepared under II-b (2 and 50 m) while Section III-B was applied on DEMs from II-c (2 and 50 m). HC: “hydrological Corrected”; DNS: drainage networks.

Fig. 5. Procedures applied to produce “hydrologically corrected” LiDAR DEMs. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

to replicate known hydrology in flat terrain landscapes while hard techniques have used “stream burning” or “surface reconditioning” to physically change cell values. This paper used both techniques. The hard technique (stream burning) used in this paper burnt known main channels into the DEMs, as illustrated by Figs. 4-II and 6, while the D8 flow algorithm was applied, afterwards, for both techniques, to extract the channels. Fig. 4-III-B shows the curvature/drop analysis (soft) technique that was used to extract DNs from corrected and uncorrected 2 m resampled and 50 m LiDAR DEMs (Nardi et al., 2008; Tarboton and Ames, 2001; Tarboton et al., 1991).

The two hard techniques used have been: (1) breaching (Amatya et al., 2013; Martz and Garbrecht, 1999; Martz and de Jong, 1988) or carving (Soille, 2004a,b; Soille et al., 2003) and (2) “stream burning” (Callow et al., 2007; Hellweger, 1997). Breaching was only applied on the 2 m resampled LiDAR DEM, because high-resolution LiDAR DEMs exaggerate man-made features, such as culverts/bridges and roads (Fig. 5A). Additionally, breaching was also used to remove the digital

Fig. 6. Artefacts that hamper continuous flow within the 2 m resampled LiDAR DEM. These artefacts such as digital dams (A, B), data voids (C, D), and title boundaries (E) are shown as well as the techniques to “correct” artefacts enabling continuous flow patterns within the Hydrologically Corrected (HC) LiDAR DEMs. The small holes (E) within the channels depict holes created after the implementation of flood risk and water resource management strategies in the study area.

artefacts – like digital dams – (Fig. 5A, B) that were created at the intersection of a stream and a road (bridge or culvert), when the Fill process (Fig. 4-IIb) was performed to create smoothed corrected and uncorrected LiDAR DEMs. Fig. 6 shows the steps that were followed to produce HC corrected LiDAR DEMs (2 and 50 m):

- Firstly, breaching involves a culvert/bridge field survey as well as on-screen visual inspection using different data sources to identify, verify and record these flow controlling features. Short polylines were added using heads-up digitizing along the bridge/culverts that were aligned with the flow direction of these channels to allow flow to pass through these features (Fig. 5A).
- Secondly, the conventional aerial photograph-interpreted hydrographic “blue lines” were added.
- Thirdly, these short polylines and blue lines were converted to stream rasters. The grid cell sizes of the 2 and 50 m LiDAR DEMs

were used during the conversions. The stream rasters were superimposed on the LiDAR DEMs (2 m resampled and 50 m) by burning 7 and 100 m, respectively into pixels classified to represent blue lines and bridges/culverts. For the 2 m resampled and the 50 m LiDAR DEMs, different depths (2 m and 5, 10 and 30 m, respectively), were unsuccessfully experimented. Breaching was applied only to the 2 m resampled DEM because high-resolution of LiDAR DEMs exaggerate man-made features such culverts and bridges and also prevent continuous channel surface flow. This process replicates the effect of bridges and culverts (Fig. 5B).

'Stream burning' was applied very effectively in flatter areas such as in coastal Oregon to improve spatial accuracy of streams and watershed boundaries (Clarke and Burnett, 2003) as well as in the Kent river catchment in southwest Western Australia in an ancient and very flat landscape (Callow et al., 2007). Garbrecht et al. (2001) observed that by and large newer DEMs are hydrologically corrected and would make flow accumulation algorithms more effective in complex landscapes such as the CRB (Murphy et al., 2008; Saunders, 1999). However, many researchers have reported limitations to the stream burning method. Saunders and Maidment (1996) found that hydrography-enhanced flow direction grids produce distortions in the delineation of watershed boundaries for drainage areas especially if headwater streams (lower Strahler orders streams) are used to enhance DEMs hydrologically. Hence, this paper used the corrected and uncorrected 2 m resampled and 50 m LiDAR DEMs to extract these lower order channels (headwater streams), that are difficult to capture using traditional methods of delineation, by using principle (major) channels (blue lines, mapped and digitized; Murphy et al., 2008).

3.3. Extracting streams and drainage networks

The automatic delineation of drainage networks and watershed boundaries from DEMs is based on the inherent relationship between geomorphology, hydrologic and hydraulic characteristics (Moore et al., 1991). The most common method of comparing automatically delineated networks and boundaries is against stream networks and boundaries that are manually delineated from topographic maps (Murphy et al., 2008; Heine et al., 2004). This study used the threshold support area and the threshold of local curvature methods on corrected and uncorrected LiDAR DEMs to extract DNs. The former used surface water flow accumulation while the latter used local identification of upwards curvature to extract DNs. These methods require the calculation of surface water flow direction using a single flow direction (SFD) algorithm based on the popular deterministic eight method (D8) algorithm. The accumulation flow threshold value (threshold support area) as well as the identified local upwards curvature cells are equivalent to the amount of cells that will contribute towards a given DN. Both can be calculated in square kilometres once the gridded horizontal scale is known. Research has shown that various threshold values have different effects on the extracted DNs (Chen et al., 2010; Passalacqua et al., 2010; Tarboton and Ames, 2001).

The procedures in Fig. 4 (II, IIIA and IIIB) were followed to extract DNs from the corrected and uncorrected 2 and 50 m LiDAR DEMs using the critical support area and threshold of local curvature methods. The single flow direction (D8) algorithm was applied to the products of these methods and DNs were extracted based on the following progressive accumulation area threshold values: 0.04, 0.1, 0.27, 0.45, 0.9, 2.7, 4.5, 9, 18, 27, 45 and 54 km². The automatic extraction of an accurate DN will include many uncertainties because of the usage of the accumulation area threshold parameter; therefore nine values were selected for testing purposes to determine the optimum threshold value. The values were also selected because of the distinctive DNs they produced which had made comparison amongst them easier. Research has shown that different threshold values can be used to assess the accuracy of DEM-

derived DNs when compared to national hydrographic datasets (NHD). NHD and field-mapped channels are amongst the most accurate, hence these channels were mimicked and the resultant flow accumulation threshold value (0.9 km²) was used for comparison (Murphy et al., 2008; Heine et al., 2004). Other studies such as Saadat et al. (2008) have used three criteria to determine the threshold values: (i) 1% of the total accumulation cells which represent approximately 0.45 km² (also Dobos and Daroussin, 2005); (ii) the smallest practical area of any identifiable feature using a topographic map (1:25000) represents 0.06 km² (also Soil Survey Division Staff, 1993) and (iii) a threshold value of 4.5 km² that are used on most NHD (also Poppenga and Worstell, 2008). Liu and Zhang (2011) argued that 0.025 km² (3 m LiDAR DEM) can be used on flat terrain landscapes while this paper used 0.9 km² that corresponds to mimicking field-mapped and blue lines channels (Murphy et al., 2008; Saadat et al., 2008; Poppenga and Worstell, 2008).

DNs were derived from both 2 and 50 m LiDAR DEMs: soft, hard and uncorrected. Fig. 7 shows the results for corrected (soft and hard techniques) and uncorrected 2 m resampled LiDAR DEMs while Fig. 8 shows the results for corrected (soft and hard techniques) and uncorrected 50 m LiDAR DEM for all 12 progressive flow accumulation threshold values for the study area.

3.4. Defining parameters for drainage networks

Parameters for drainage networks were derived from multiple sources such as topographic maps (DOQ), field-mapped (FM), heads-up digitized (HDZ), and 2 m resampled and 50 m LiDAR DEMs. Parameters values were also derived from streams that were extracted using the D8 flow direction algorithm from DEMs that were: (i) hydrologically corrected (HC), (ii) uncorrected (raw) and (iii) on which the drop/curvature method (curve) were applied. The geomorphologic parameters and indices used by this study were: channel (main) length, cumulative stream length, sinuosity, and the Strahler ranking order. The length and density of drainage networks are valuable parameters to statistically quantify the accuracy of DNs. The cumulative length (L) of all the streams within a watershed was calculated as follows:

$$L = \sum_{i=1}^n l_i \quad (1)$$

where l_i is the length of streams of Strahler's order i .

The Strahler additive method was one of the geomorphic parameters that were calculated to assess the accuracy of the different LiDAR DEMs, providing a quantitative characterization of its drainage network (Strahler, 1957). Sinuosity of the main stream (highest Strahler orders or principle streams of a watershed) was calculated and used for each of the three watersheds. Sinuosity can be defined as the ratio of stream length to the straight-line distance between end-points (McCuen, 1998; Schumm, 1963; USACE, 1993). This definition can also be used to refer to the degree of meandering such as meandering length (L_m) to the straight-line distance (L_s). Sinuosity (S) can this be defined as:

$$S = \frac{L_m}{L_s} \quad (2)$$

After a polyline (principle channel) was selected, L_m was calculated using the appropriate GIS polyline length function. Afterwards, L_s was calculated using the GIS distance function. The sinuosity was then derived from Eq. (2). Sinuosity values of more than 1.5 show high sinuosity and between 1 and 1.5 indicate moderate sinuosity while values equal to 1 or less than 1 indicate a straight line. Geomorphometric properties such as enclosed area or perimeter length are commonly used to measure accuracy in DEM-derived watersheds (Oksanen and Sarjakoski, 2005; Gardner et al., 1990; Morris and Heerdegen, 1988).

Fig. 7. Drainage networks for 2 m resampled LiDAR derived with flow accumulation area thresholds of: A (0.04), B (0.1), C (0.27), D (0.45), E (0.9), F (2.7), G (4.5), H (9), I (18), J (27), K (45) and L (54 km²). Using these threshold values, twelve networks were delineated by means of three methods: hard (stream burning), soft (local upwards curvature) and uncorrected.

3.5. Evaluating accuracy of the DNs and streams

Validation of spatial patterns against observations is a key issue for assessing model capabilities and uncertainties (Güntner et al., 2004). The objective of this study was to test the accuracy of several DNs derived using different methods and from different sources at a study area and watershed level. Figs. 7 and 8, respectively, show the resampled 2 and 50 m LiDAR DEMs (soft, hard and uncorrected) that

used 12 progressive flow accumulation thresholds to enable visualization of the relation between the density of the modelled DNs and the corresponding flow accumulation threshold values.

At a watershed level, blue lines (DOQ) were compared against field-mapped (FM), heads-up digitized and LiDAR DEM-derived (2 and 50 m – hard, soft and uncorrected) channels (Fig. 4-IV). All these channels were compared visually, using a 2 m LiDAR-derived shaded relief map, to assess geo-locational accuracy using the blue lines and field-

Fig. 8. Drainage networks for 50 m LiDAR DEM derived with flow accumulation areas thresholds of: A (0.04), B (0.1), C (0.27), D (0.45), E (0.9), F (2.7), G (4.5), H (9), I (18), J (27), K (45) and L (54 km²). Using these threshold values, twelve networks were delineated by means of three methods: hard (stream burning), soft (local upwards curvature) and uncorrected.

mapped channels as references (Fig. 9; Roering et al., 2013). For quantitative comparison, values for total stream length, sinuosity and Strahler Orders were used to quantify the success of different methods and the accuracy of the different modelled LiDAR-derived DNs. The visual inspection (Podobnikar, 2009) was also used to determine the spatial pattern and magnitude of changes caused by hydrological correction of the 2 and 50 m LiDAR DEMs. Lastly, polygons (water mask), from the 2009 (6 March) flood event in northern Namibia were derived from TerraSAR-X satellite data at a spatial resolution of 6.25 m, and used as

auxiliary data to assess the spatial accuracy of channels within the 2009 flooded zones.

4. Results

4.1. Drainage networks in the study area

The DNs were delineated using various flow accumulation threshold values (Figs. 7 and 8); an increase in these threshold values resulted in

Fig. 9. Spatial comparison between blue lines (DOQ, topographic maps) and field-mapped channels (FM), heads-up digitized channels (HDZ), and hydrologically corrected (HC) and uncorrected (Raw) 2 m resampled (A) and 50 m LiDAR (B) derived channels. Watershed 1 is located in the higher elevations of the study area. Auxiliary data such as water mask TerraSAR-X satellite data from the 2009 flood event and pans/lakes from the topographic map (DOQ) are also shown.

gradual decreases in channel density (Fig. 7). Hence, there were significant differences amongst the extracted networks. Significant differences were visual in terms of the spatial accuracy amongst the hard, soft and uncorrected methods (Fig. 7). Channels (first and second Strahler orders) derived from uncorrected DEMs did not match with those derived from hydrologically corrected DEMs although the main channels matched perfectly. Fig. 7 also shows that the channels derived from uncorrected and soft methods were longer in length than those derived from the hard method, while the channels derived from the uncorrected and soft methods again matched well. The channels derived from uncorrected and soft methods consistently recorded flaws that are inherent with the D8 algorithm such as parallel flow paths in flat areas (Fig. 7A,B).

The channel networks delineated from the 50 m LiDAR DEM (Fig. 8) using the three methods mentioned above present numerous parallel flow paths in the flat area due to the coarse spatial resolution. Fig. 8 also shows that the length of channels derived from the soft method were longer compared to channels derived from both uncorrected and hard while the magnitude of the spatial accuracy between all three 50 m LiDAR DEM modelled channels were larger compared to the DNs derived from the 2 m resampled LiDAR DEMs. When comparing Figs. 7 and 8 using the same progressive threshold accumulation values, the extracted channel networks and densities for different threshold accumulation values are not similar. Hence, extracting channel networks using DEMs with different spatial resolutions as well as flow-accumulation threshold values will result in channel networks with varying spatial inaccuracies.

To quantify these inaccuracies, three watersheds were selected on which various spatial and statistical analyses were performed. Figs. 9 to 11 show the spatial analyses of watersheds 1 to 3 while Figs. 12 to 14 show the statistical analysis for various geomorphic parameters such as total length of channels, the main channels (meander and straight) and the number of streams per Strahler Order.

4.2. Watershed 1

The channel networks derived from various sources (FM, DOQ and HDZ) along with both modelled channels from the 2 m resampled LiDAR DEM (left) and those modelled from the 50 m LiDAR (right) for Watershed 1 have been drawn (Fig. 9). The spatial comparison for the channels modelled from the 2 m resampled LiDAR shows once more that high-resolution LiDAR DEMs outperformed the coarser resolution DEM (50 m). The channels modelled from the 50 m LiDAR DEM performed poorly when compared to the DOQ, FM and HDZ derived channels. Channels modelled using the curve methods were again longer in length. Fig. 12 illustrates how the DOQ underestimated the modelled channels and those derived from other sources (FM and HDZ). The underestimation was the highest for the hydrologically corrected 2 m resampled LiDAR DEM (72%) and the smallest for FM channels, confirming that LiDAR-derived channels were more accurate. Channels modelled from the raw (uncorrected) 50 m LiDAR DEM were the shortest in length for Watershed 1 (Fig. 12).

The length of the main channels modelled from the curve 2 m LiDAR DEM was the shortest due to the many upward curvature cells that resulted in many first-order channels (Fig. 9, left) and hence shorter main channels while the length of the main channel for the raw 2 m DEM was the longest. The sinuosity for the channels modelled from 2 m LiDAR DEM was surprisingly lower than those derived from the 50 m LiDAR DEM while the maximum Strahler Order for the 50 m regional LiDAR

DEM was higher compared to the 2 m LiDAR DEM. This is due to the fact that the study area is located within the central oshana zone which is the major waterway for the CRB and it has perennial headwaters upstream.

The number of Strahler first-order streams for all three watersheds and channels derived from various sources and methods have been drawn (Fig. 14). Channels modelled from the curve 2 m LiDAR DEM had the highest amount of headwater streams (1118) while the lowest were recorded from the raw 50 m LiDAR DEM.

4.3. Watershed 2

Fig. 10 shows the channel networks derived from various sources (FM, DOQ and HDZ) along with modelled channels from both the 2 m resampled LiDAR DEM (left) and the 50 m LiDAR (right) for Watershed 2. The results are similar to Fig. 9 in terms of spatial accuracy. The absence of DOQ channels in Watershed 2 resulted in limited comparisons between channels from various sources and methods (Figs. 11 to 13). However, a trend similar to Watershed 1 was observed in terms of the total channel length as well as the main channel length. Sinuosity was moderate (between 1.1 and 1.4) in Watershed 2 while the curve 2 m LiDAR DEM produced the most Strahler first order streams (Fig. 14) as expected.

4.4. Watershed 3

The channel networks that were derived from various sources (FM, DOQ and HDZ) along with modelled channels from both the 2 m resampled LiDAR DEM (left) and those modelled from the 50 m LiDAR DEM (right) for Watershed 3. Whereas Watershed 1 was located in the higher elevated areas with broad channels, Watershed 3 is located in low-terrain area with no well-defined channels (Figs. 3 and 11). Hydrologic obstructions such as roads are also visible in Watershed 3. When most channels were compared to DOQ, DOQ underestimated total length of channels in Watershed 3. For example, due to the accuracy of the HC 2 m LiDAR DEM derived channels, it recorded the highest value (124%) compared with the DOQ channels. The HC and Raw 50 m LiDAR DEM derived channels overestimated (HC LiDAR 50 m, 4%) the total channel length when they were compared to DOQ. As in Watersheds 1 and 2, the channels derived from 2 m LiDAR DEMs show the best spatial accuracy compared to channels derived from other sources. Also, as expected, the channels in Watersheds 3 derived from uncorrected LiDAR DEMs performed the worst in terms of spatial accuracy. Furthermore, field-mapped channels (Fig. 11 – left-middle) did not match well (as expected) to channels derived from other sources due to the flow accumulation threshold value of 0.9 km² that was used for this study. Fig. 11 (left) shows many more upward curvature cells due to the topography after using the curve method, even though the length of the main channels for all main channels derived from 50 m LiDAR DEMs were lower than that of the DOQ channels. As expected, Watershed 3 also had the highest number of Strahler first-order streams (2118) for channels derived from the curve 2 m LiDAR DEM. Since Watershed 3 was located in the low-terrain areas where most of the streams converge, the highest maximum Strahler order numbers occurred in Watershed 3 especially for the 2 m HC, 50 m Raw and curve 50 m LiDAR DEM derived channels. Hence, a gauge station is also located along the main channel in this watershed (Fig. 3). Lastly, the high-resolution LiDAR DEM (2 m) delineated the most accurate channel network (Fig. 13) compared to those from other sources

Fig. 10. Spatial comparison between blue lines (DOQ, topographic maps) and field-mapped channels (FM), heads-up digitized channels (HDZ), and hydrologically corrected (HC) and uncorrected (Raw) 2 m resampled (A) and 50 m (B) LiDAR DEM derived channels. Watershed 2 is located in the higher elevations of the study area. Auxiliary data such as water mask TerraSAR-X satellite data from the 2009 flood event and pans/lakes from the topographic map (DOQ) are also shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 11. Spatial comparison between blue lines (DOQ, topographic maps) and field-mapped channels (FM), heads-up digitized channels (HDZ), and hydrologically corrected (HC) and uncorrected (Raw) 2 m resampled (A) and 50 m (B) LiDAR DEM derived channels. Watershed 3 is located in the higher elevations of the study area. Auxiliary data such as water mask TerraSAR-X satellite data from the 2009 flood event and pans/lakes from the topographic map (DOQ) are also shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

Fig. 12. Graph showing the total length of channels derived from multiple sources such as topographic maps (DOQ), field-mapped (FM), heads-up digitized (HDZ), and 2 m resampled and 50 m LiDAR DEMs. The channels were extracted using the D8 algorithm from DEMs that were: (i) hydrologically corrected (HC), (ii) uncorrected (raw) and (iii) applying the drop/curvature method (curve).

and methods especially on low-relief landscapes as was also found by Liu and Zhang (2011).

5. Discussion

For the study area, Figs. 7 and 8 show the 12 progressive flow accumulation thresholds that were applied to the 2 and 50 m LiDAR DEMs using the hard, soft and uncorrected methods. The channel networks produced from both DEMs seem similar except for the 50 m LiDAR

DEM (Fig. 8), which depicts how the soft method clearly delineated more first and second order channels compared to the hard and uncorrected methods. This is an encouraging result since this method using local upwards curvature cells identified more small channels in a low-terrain area using a coarser 50 m LiDAR DEM. In contrast, the uncorrected method did not replicate accurately the channel networks, in fact, it highlighted the flaws mentioned earlier when the D8 algorithm is applied alone in low-terrain areas: parallel streams and unnaturally straight section as well as angular features (Fig. 8). For the 2 m

Fig. 13. Graph showing the main channels derived from multiple sources such as topographic maps (DOQ), field-mapped (FM), heads-up digitized (HDZ), and 2 m resampled and 50 m LiDAR DEMs. The channels were extracted using the D8 algorithm from DEMs that were: (i) hydrologically corrected (HC), (ii) uncorrected (raw) and (iii) applying the drop/curvature method (curve).

Fig. 14. Graph showing the number of first-order streams (Strahler) derived from two LiDAR DEMs sources: 2 m resampled and 50 m LiDAR DEMs. The streams (headwater) were extracted using the D8 algorithm from DEMs that were: (i) hydrologically corrected (HC), (ii) uncorrected (raw) and (iii) based on the drop/curvature method (curve). These streams were extracted from Watersheds 1, 2 and 3. The values from the 2 m resampled LiDAR DEM (Curve) are 10 times more.

LiDAR DEM, channel networks (Fig. 7) were well replicated except for the uncorrected method where the same channels did not match well with those from both the hard and soft methods.

The 12 progressive flow accumulation thresholds used were selected for testing purposes and also to understand the spatial distribution of the channel networks when applying the different progressive thresholds. This is beneficial for understanding how to update the NHD hydrology map, to create appropriate drainage densities for small, medium and large resolution scale topographic map features. This study used a threshold value of 0.9 km^2 (Figs. 7E and 8E) and produced an accurate channel network compared to the 0.025 km^2 recommended by Liu and Zhang (2011) which would have created many false channels.

At watershed scale, when comparing channels derived from the 2 and 50 m LiDAR DEMs it was found that the curvature method, again, performs equally well on both DEMs, resulting in producing more channels upslope into the landscape compared to the HC and uncorrected derived channels especially in the low-terrain areas. The HC derived channels performed the best and are in better agreement with field-mapped channels as well as the conventionally derived channels (Figs. 9 to 11). These HC channels are more accurate (DOQ underestimated by 1% for Watershed 1) than those from other data sources and they also followed flow paths of floodwaters delineated from TerraSAR-X satellite data well.

Channels derived from the uncorrected 50 m LiDAR DEM produced spatially inaccurate channels, especially in the flat terrain areas (Fig. 11), but the channels derived from the 2 m LiDAR DEM were more accurate (Fig. 11A). Obviously, this is due to the higher resolution and higher initial point density of the 2 m LiDAR DEM, which resulted in the extraction of topographic features as small as first-order stream channels. These differences have also been noted in previous studies (Moore, 1996; Murphy et al., 2008; Liu and Zhang, 2011) conducted in low-terrain areas.

Although the conventional hydrographic channels represent similar patterns to the ones mapped in the field, digitized and modelled from the 2 and 50 m LiDAR DEMs, there were significant planform differences. The Strahler first-order channels were not detected with the conventionally derived channels and for the 50 m LiDAR DEM derived channels for all methods (Fig. 14), while they were perfectly identified

by the 2 m LiDAR DEM, but over-estimated with the curve method (Fig. 14). Also, the length of the conventionally derived channels was underestimated considerably compared to the other channels.

Both the curvature method (on all DEMs) and the 2 m LiDAR DEM (all methods) predicted channels that extended upslope further than those field-mapped and conventionally derived.

The HC method (all DEMs) and the 2 m LiDAR DEM (all methods) were closer to field-mapped channels than the conventionally derived channels, although in other studies, it was found that high-resolution DEMs produced improved models of channel networks (Murphy et al., 2008; Liu and Zhang, 2011).

Significantly, channel networks that are obstructed on the LiDAR DEMs by man-made features such as culverts and roads were successfully modelled by reconditioning the LiDAR DEMs. Since previous research (Murphy et al., 2008) have also found that LiDAR DEMs significantly capture topographic details which alters flow patterns; hence, this study have demonstrated that hydrologic effects can easily be integrated (Fig. 11) into the modelling of hydrologic features such as channel networks.

In general, channel networks that were derived with the HC method were more accurate than that derived with other methods. This result is in line with the findings of Clarke and Burnett (2003) as well as Murphy et al. (2008) that drainage reconditioning of DEMs leads to superior results in terms of spatial accuracy of the modelled channel networks, better than by resampling DEMs from finer to coarser spatial resolutions. However, others have recommended that the data used in hydrologic correction need to be accurate to avoid introducing artefacts; hence, this study have demonstrated that channels derived from different sources such as HDZ and FM performed equally well and sometimes better than those obtained from convention topographic maps.

In contrast to Liu and Zhang (2011), reconditioning of LiDAR DEMs is needed (Murphy et al., 2008). This study concluded that LiDAR DEM data are not sufficiently accurate for the purpose of extracting hydrologic features such as channel networks, if reconditioning is not applied.

Overall, many studies have found that HC LiDAR DEMs improves the spatial accuracy of modelled channel networks (Callow et al., 2007; Clarke and Burnett, 2003). The results in the this study also confirmed that blue lines (DOQ) or national hydrography datasets (NHD) from national mapping agency underestimate channel data derived from other

sources such as field-mapped, digitized and modelled channels using high-resolution LiDAR DEMs (Morisawa, 1957; Coates, 1958; Heine et al., 2004; Murphy et al., 2008; Ducey et al., 2012). This study also showed that where DOQ channels are not available, field-mapped or channels digitized using online mapping services are equally good to assess the optimum flow accumulation threshold and extracted appropriate and accurate channel networks.

Comparing the results of this study to those in the southern African region, most studies in the study area have been using DNs derived for global DEM (90 m) datasets that are too coarse and not appropriate to low-terrain areas (Miller et al., 2010; Mendelsohn et al., 2009; RAISON, 2012). A new global DEM (SRTM, 30 m) is available and could be used in addition to techniques used in this study to improve these DNs. Strohbach (2008) used stream reconditioning methods such as stream burning with outdated and incomplete channel networks on the SRTM 90 m global DEM to delineate catchment boundaries and accurate continuous DNs. Using techniques presented in this study these DNs can be greatly improved. Lastly, a study in South Africa to update NHD has produced encouraging results using similar methods as this study but again the SRTM global DEM was used and it only covers the southern part of Namibia (Weepener et al., 2012) which excluded the current study area. They have also used flow accumulation threshold values appropriate to their National Hydrographic Database (NHD) which are not available in Namibia.

These results will greatly contribute towards solving spatial inaccuracies with DEM-derived DNs and overcoming the limitations of extraction of drainage networks in low-terrain environments for flood hazard mapping (Mendelsohn, 2013).

6. Conclusion

Accurate drainage networks are needed for many purposes such as analysing geomorphological change of floodplains, monitoring river corridors for natural hazard management, and water resource management and surface water mapping. Hence, time-relevant mapped national hydrography datasets (NHD) can be extracted using the latest hydrologically corrected LiDAR DEMs that have the necessary spatial resolution and vertical accuracy. Even though many advanced algorithms are available (e.g., Passalacqua et al., 2010), their applications in regions where there are chronic shortages in human, financial and computing resources are difficult. Standard terrain analysis that is available in most GIS applications can be used to develop a framework that will enable the accurate extraction of drainage networks in large low-terrain areas. This paper implemented such a framework that used the popular D8 single flow direction algorithm with hydrologically corrected LiDAR DEMs to produce an accurate drainage network.

Q16 7. Uncited references

Hengl et al., 2010
Li et al., 2003
Lin et al., 2006
Lin and Oguchi, 2004
McMaster, 2002

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at <http://dx.doi.org/10.1016/j.geomorph.2015.06.047>. These data include Google map of the most important areas described in this article.

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