Drainage network extraction using LiDAR-derived DEM in volcanic plains

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Abstract

Accurate delineation of drainage networks is critical for many hydrologically related applications. The commonly used methods for drainage network extraction from digital elevation models (DEMs) have limitations in low-relief terrain areas. High-quality DEMs are required for the effective application of these methods in the extraction of drainage networks in low-relief terrains. Airborne light detection and ranging (LiDAR) offers high accuracy terrain data. With LiDAR data, high-accuracy and high-resolution DEMs can be generated. Reported here are the results of drainage network extraction for the two sub-catchments on the western Victorian Volcanic Plains (VVP). Drainage networks and some parameters describing the drainage network composition including the stream orders, the numbers of streams and the stream lengths were derived from both the LiDAR DEM and the Vicmap DEM. The LiDAR-derived DEM is shown to offer significantly more detail, especially for delineating low-order stream (headwater) segments in sub-catchments of low relief terrain.

Key words: Victoria Volcanic Plains, drainage network extraction, airborne LiDAR, digital elevation model (DEM), stream, catchment

Introduction

Pre-requisite to many catchment-based natural resource management issues is access to surface drainage network maps from which reliable hydrologic parameters such as upslope contributing area and downslope flow path for any location can be calculated (Paik, 2008). These derived data can subsequently be used to estimate rainfall runoff, predict flood levels, and manage water resources (Maune et al., 2007). Automation of drainage networks extraction from DEMs has received considerable attention (Vogt et al., 2003). The most commonly-used approach is based on the deployment of a model for surface water flow accumulation. This method, designated D8 algorithm (eight flow directions), was introduced by O'Callaghan and Mark (1984). It has become widely used (Jenson and Domingue, 1988; Martz and de Jong, 1988; Morris and Heerdegen, 1988; Jenson, 1991; Tarboton *et al.*, 1991; Martz and Garbrecht, 1992). This approach (based on a grid-based DEM) specifies flow directions by assigning flow from each cell to one of its eight neighbours, either adjacent or diagonal, in the direction with steepest downward slope (Tarboton, 1997). As the flow of water is traced downhill from a point, a counter is incremented for all the downstream points through which the water flows (Jones, 2002). The drainage network is defined by the relative counts wherever the upstream drainage area exceeds a specified threshold (Martz and Garbrecht, 1995).

A major problem in using the D8 approach to extract drainage network is the presence of sinks or depressions in DEMs (Chorowicz *et al.*, 1992; Martz and Garbrecht, 1992). Sinks are cells which have no neighbours at a lower elevation and consequently, have no downslope flow path to a neighbouring cell (Martz and Garbrecht, 1992). Sinks include both flat and depressional areas. They occur in most raster DEMs, and usually are viewed as spurious features (artefacts of the model). Truly flat surfaces seldom occur in natural landscapes. Yet when a landscape is represented as a raster DEM, areas of low relief can translate into perfectly flat surfaces (Garbrecht and Martz, 1997). Sinks may arise from input data errors, interpolation procedures, and the limited resolutions of the DEM (O'Callaghan and

Mark, 1984; Mark, 1988; Fairchild and Leymarie, 1991; Martz and Garbrecht, 1992; Martz and Garbrecht, 1998). Whatever their origin, sinks in a DEM are a problem when it comes to defining drainage, because flow directions on a perfectly flat surface are indeterminate (Tribe, 1992; Garbrecht and Martz, 1997). Special treatment is required to allow the complete definition of overland flow patterns across the DEM surface (Martz and Garbrecht, 1998).

For catchment area and drainage network analysis in areas of subdued relief, a number of methods have been developed for treating sinks in a DEM (Jenson and Domingue, 1988; Fairfield and Leymarie, 1991; Martz and Garbrecht, 1992; Tribe, 1992; Jones, 2002). Some methods assume that flat areas and depressions in a DEM are real landscape features which need to be handled in a hydrologically meaningful way during drainage analysis, while others view them as spurious features which should be corrected or removed prior to drainage analysis (Martz and Garbrecht, 1998). Most methods have typically been implemented in conjunction with the D8 algorithm, ranging from simple DEM smoothing to arbitrary flow direction assignment (Garbrecht and Martz, 1997). However, these methods have limitations. DEM smoothing introduces additional loss of information to the digital elevations while arbitrary flow direction assignment may require the modification of DEM elevations (Tribe, 1992; Garbrecht and Martz, 1997). These methods may be applicable to small flat regions, but they are not effective and less applicable to a landscape where flat regions account for a great portion of the DEM (Zhang and Huang, 2009), mainly due to the resolution limitation of the DEM (Davies and Bell, 2009). Typical low relief/flat landscapes include floodplains, coastal wetlands and lava plains, e.g., the Victorian Volcanic Plains (VVP) in Australia. Even in these areas, surfaces are not truly flat, but have a relief that is simply not detectable at the resolution of the original DEM (Martz and Garbrecht, 1992). Thus derivation of drainage networks based on such DEMs can be expected to results in inadequately-defined drainage structure (Garbrecht and Martz, 1997). Therefore, a high-resolution and high-accuracy DEM is the prerequisite to the automatic extraction of drainage networks over low relief terrains.

Under the Catchment and Land Protection Act 1994, Victoria in Australia is divided into ten catchment regions. A Catchment Management Authority (CMA) is established for each region. The CMAs govern the areas corresponding to the naturally occurring drainage basins, enabling integrated catchment management. The major tasks of CMAs are to maintain and enhance long-term land productivity while also conserving the environment, and providing services relating to integrating waterway, floodplain and drainage management. Much emphasis is given to the protection, maintenance and improvement of river health, thus ensuring that the quality of the State's land and water resources and their associated plant and animal life are monitored with a view to maintenance, and, if possible, enhancement (AustLII, 2008).

In recognition that the high resolution DEM is a key spatial dataset required for sustainable catchment management, the implementation of these tasks calls for more accuracy in digital representation of terrain shape than less. The most commonly used DEM in most catchment areas in Victoria is still the Vicmap 20 m resolution DEM. However, it is increasingly obvious that the Vicmap DEM does not offer enough terrain surface details, especially for the applications of drainage network extraction

(Liu *et al.*, 2005). The State-wide Vicmap DEM, dating from the 1990s is now being replaced by a 10 m resolution DEM in some areas. However, improved quality and coverage of DEMs is desired by many catchment management authorities (McDougall *et al.*, 2008). Indeed, the improvement and update of existing DEMs or, alternatively, the development of new high-accuracy and high-resolution DEMs has been identified as a priority by many catchment management authorities.

The Corangamite CMA is one of the pioneer LiDAR acquisition fund applicants among catchment management authorities in Australia. LiDAR data were collected to generate a high-quality DEM to address a series of environment problems in the region, many of which called for access to better-determined drainage network data, especially in the low relief areas of the VVP. Can the new high-resolution LiDAR technology meet this need? Here, we demonstrate how drainage networks and some parameters describing the drainage network composition including the stream orders, the numbers of streams and the stream lengths are derived from the LiDAR DEM and compared with those derived from the Vicmap DEM. Thus opens the way for exploration of the advantages that the use of LiDAR-derived DEMs offer in the extraction of the drainage network in the low-relief sub-catchments from which land holders, as part of climate change management, seek clarification of their rights and responsibilities, for instance, under wetland preservation legislation.

Materials and method

Study Area

The study area is in the region of Corangamite Catchment Management Authority (CCMA) in south western Victoria, Australia (Shown in Figure 1). The CCMA was established in 1997 by the Victorian Government under the provisions of the Catchment and Land Protection Act 1994 and the Water Act 1989 (Sheldon, 2006; CCMA, 2008). The mission of the CCMA is to protect and restore regional land and water resources, encourage the sustainable development of natural resource-based industries, and conserve regional cultural heritage (Sheldon, 2006). The Corangamite catchment covers an area of 13,340 square kilometres, stretching inland from Geelong to Ballarat and along the coast to Peterborough (CCMA, 2008). The region is home to about 350,000 people (Clarkson *et al.*, 2007). The catchment includes all or part of 9 local government authorities: the cities of Ballarat and Greater Geelong, the Borough of Queenscliffe and the shires of Moorabool, Surf Coast, Corangamite, Golden Plains, Colac Otway and Moyne (CCMA, 2008). The region as a whole is defined by an aggregation of its four drainage basins: the Moorabool, Barwon (draining to Port Phillip Bay) Lake Corangamite (an internal drainage basin formed because of drainage derangement by lava flows), and Otway Coast drainage basins (CCMA, 2006).

As already recognised in our research (Liu *et al.*, 2005), the sub-catchment, also called drainage basin or watershed, is one of the most important elements in hydrological analysis. Two sub-catchments in the region of CCMA that were selected as the test sites are shown in Figure 1. Sub-catchment 1, with an areal extent of 55.9 km^2 (with elevations ranging between 111 m to 158 m) is on typical volcanic plains with thinly-weathered and basalt lava flows. The landscape is still dominated by the deranged/internal drainage, typified by the lakes (ranging from the relatively large

Lake Weering to a number of smaller water bodies). The best-developed (though still only mildly incised) drainage lines are, often along the boundaries of lava flows. Discontinuous drainage lines may end at ephemeral wetlands and swamps (Robinson *et al.*, 2003). Along the south-west boundary of the sub-catchment 1 is the Woady Yaloak Diversion Channel (WYDC), one of the two artificial drainage schemes in the CCMA region. The WYDC was constructed in 1959 and was used to divert water from the Woady Yaloak River into the Warrumbine Creek which flows into the Barwon River (GHD, 2004).

In contrast to sub-catchment 1, sub-catchment 2 with an areal extent of 74.4 km^2 (with elevations ranging between 113 m to 232 m) has comparatively well-developed drainage because the basalt flows here date back to Pliocene times and so has had time to acquire a regolith/thicker soils. Very subdued terrain is still present.

[Space for Figure 1]

LiDAR Data

LiDAR data were collected using Optech ALTM 3025 laser scanner from a fixed wing aircraft at flying heights of 2,000m above ground from 19 July 2003 to 10 August 2003. The laser scanner was configured to record first and last returns with a frequency of 25 kHz (25,000 pulses per second). The laser footprint diameter at nadir is 0.6 m (AAMHatch, 2003). The primary purpose of this LiDAR data collection was to facilitate more accurate terrain pattern representation for the implementation of a series of environmentally related projects. One of the critical steps for DEM generation from LiDAR data is to separate the LiDAR points into ground (terrain) and non-ground (non-terrain) points (Liu, 2008). Several filter algorithms have been developed for automatically extracting ground points from LiDAR point clouds (Sithole and Vosselman, 2004; Silván-Cárdenas and Wang, 2006; Kobler *et al.*, 2007), among which interpolation-based (Kraus and Pfeifer, 1998), slope-based (Vosselman, 2000; Roggero, 2001; Sithole, 2001; Shan and Sampath, 2005) and morphological (Zhang *et al.*, 2003; Zakšek and Pfeifer, 2006; Chen *et al.*, 2007) are the most popular approaches (Silván-Cárdenas and Wang, 2006). The LiDAR data have been classified into ground and non-ground points by using slope-based filter algorithms across the project area. The manual checking and editing of the data led to a further improvement in the quality of the classification. The resulting data products used for the DEM generation are irregularly distributed ground 3D points, with an average spacing of 2.2 m (AAMHatch, 2003). The LiDAR data were delivered as tiles (5 km by 5 km) in ASCII files containing the x, y and z coordinates. A grid DEM with 3 m horizontal resolution was generated using the LiDAR ground points.

Method

The extraction of drainage networks from LiDAR-derived DEMs in the two sub-catchments was carried out using the Arc Hydro extension within ArcGIS (Maidment, 2002). The Arc Hydro tools are based on the most widely used D8 algorithm (O'Callaghan and Mark, 1984) as stated in the section of introduction. The main steps include sink filling, identification of flow direction, calculation of flow accumulation, and stream definition (ESRI, 2005). An important note in the above steps is the definition of a threshold. Drainage networks can be produced by applying a threshold value to the flow accumulation data (Jenson and Domingue, 1988; Dobos and Daroussin, 2005). Cells with a contributing area greater than a defined threshold are classified as part of the drainage network (Martz and Garbrecht, 2003). The density of the drainage network increases as the threshold value decreases (Jenson and Domingue, 1988). The determination of an appropriate contributing area threshold is difficult, and need take into account the DEM resolution and terrain characteristics (Dobos and Daroussin, 2005). With LiDAR-derived high-resolution DEMs over low-relief terrains, the use of a relatively small threshold can provide a detailed description of drainage networks. For the two sub-catchments in this study, the threshold area was set to 0.025 km^2 to delineate detailed drainage networks in flat areas. In order to compare the drainage networks extracted from the LiDAR-derived 3 m horizontal resolution DEM and the Vicmap 10 m horizontal resolution DEM, the same threshold value was used.

The composition of drainage network in a sub-catchment can be described quantitatively in terms of some attributes such as stream order, stream lengths and drainage density (Horton, 1945). A top-down stream order system (also called *Strahler Order*) developed by Horton (1945) and modified by Strahler (1952) is used to classify stream segments based on the number of upstream tributaries. With the Strahler system, stream order increases when streams of the same order intersect. For example, a second order stream is formed by the junction of any of two first-order streams. The intersection of two streams of different orders will not increase the stream order (Strahler, 1952). Stream ordering ranks the size and the flow regime of streams. It is a measure of the position of the stream in the tributary hierarchy and is sensitive to the accuracy of the drainage pattern delineation (Mourier *et al.*, 2008). Some characteristics of streams can be inferred from stream orders. For example, first-order streams have no upstream concentrated flow. Therefore, they are most susceptible to nonpoint source pollution problems (ESRI, 2009). In this study, the numbers of streams of different orders within each sub-catchment were also calculated. The drainage density, a measure of the length of stream per unit area of sub-catchment, was calculated with the total length of streams divided by the area of the sub-catchment. The length of streams of each order was obtained by measuring all the drainage within a sub-catchment of a given order (Schumm, 1956).

Results and discussion

Drainage networks derived from the LiDAR-derived 3m resolution DEM and the Vicmap 10m DEM for the two sub-catchments used to exemplify the approach taken here are shown in Figure 2 to Figure 5. The overview of drainage networks in Figures 2 and 3 illustrates that in sub-catchment 1, most of the streams flow to and terminate in lakes. There is no major outlet for this sub-catchment. That's why it has been called "Go Nowhere" sub-catchment. However, streams in sub-catchment 2 flow from north to south. Lakes function as staging reservoirs before discharging (if deep enough) to an outlet for the major streams.

[Space for Figures 2 and 3]

With a same contributing area threshold, both delineations (the LiDAR DEM and Vicmap DEM) were to the fifth order. However, Figures 2 and 3 show that there are some considerable differences between these two drainage network derivations. This is especially true for the first and second order streams. Some differences in the third and fourth order streams can also be observed (also circled in Figure 2 and 3). For sub-catchment 2, with a same threshold value, the streams can be delineated to the sixth order with the LiDAR DEM while the Vicmap described the streams only to the fifth order. Considerable differences in the stream networks derived from different DEMs occurred in the sub-catchment 2. These differences are not just in the low-order streams, but also the in the high-order streams which were circled in Figures 4 and 5.

[Space for Figures 4 and 5]

Visual validation of extracted drainage networks at circled locations in Figures 2 to 5 was carried out using high spatial resolution (0.35m) aerial photographs. Aerial photographs covered the two sub-catchments were all first orthorectified to produce orthoimages using the digital photogrammetric system, ERDAS Imaging software. Stereo models were built using stereo pairs of orthorectified images and displayed on an ultrasharp computer monitor. With the aid of stereo glasses, 3D terrain views over the study areas can be observed. Through visually checking at all circled locations in Figures 2 to 5 over the 3D views, drainage networks extracted from LiDAR-derived DEM coincide well with the terrains. It validates the correctness of drainage networks derived from LiDAR-derived DEM.

With the same contributing area threshold, drainage densities calculated from LiDAR-derived DEM and Vicmap DEM are 4.94 km/km^2 and 4.25 km/km^2 respectively in sub-catchment 1, and 5.84 km/km^2 and 5.82 km/km^2 respectively in sub-catchment 2. On flat terrain, e.g., sub-catchment 1, drainage densities from both LiDAR-derived DEM and Vicmap DEM are lower than those in sub-catchment 2 which exhibits a relative complex terrain pattern. The drainage density is one of the important aspects of the drainage network composition in a sub-catchment. This value is indicative of the rugged texture of the area, providing a useful numerical measure of sub-catchment dissection and runoff potential (Horton, 1945). In this study, sub-catchment 1, with its relatively incoherent drainage network, has a low drainage density value compared to sub-catchment 2 which has a relatively well developed drainage pattern. As expected, that the drainage density measure characterises the degree of drainage development within a sub-catchment (Horton, 1945). In sub-catchment 1, the drainage network derived from the LiDAR-derived DEM shows a higher drainage density than those from Vicmap DEM. In sub-catchment 2, the difference in the drainage densities obtained from the different DEMs occurred as well, but it is not significant. It gave an indication that LiDAR-derived high-resolution DEM can produce a more detailed delineation of the drainage network, especially on a flat terrain, e.g., sub-catchment 1.

The number of streams within different orders obtained from the LiDAR-derived DEM and the Vicmap DEM in both sub-catchment 1 and sub-catchment 2 are presented in Table 1, and depicted in Figure 6 as well. The total number of streams derived from the LiDAR DEM is greater than that from the Vicmap DEM for both sub-catchments, indicating that the LiDAR-derived high resolution DEM offers the capability of extracting more detailed stream networks than the Vicmap does. The number of streams within each order obtained from the LiDAR DEM is greater than the one from the Vicmap DEM for both sub-catchments, with the exception of the number of streams within order 3 in sub-catchment 1. There is a big difference in the number of streams within order 1 from different DEMs for both sub-catchments as shown in Figure 6, indicating the advantage of using high-resolution DEM to delineate the low-order streams in both poorly developed and well developed sub-catchments. The low-order streams are also known as headwaters. Accurate extraction and mapping of low-order streams is important for the physically based characterisation of hydrologic processes in sub-catchments (Tribe, 1991; Wharton, 1994).

[Space for Tables 1 and 2]

Stream lengths within each order derived from the LiDAR DEM and the Vicmap DEM for two sub-catchments are listed in Table 2. The stream lengths for different stream orders from different DEMs for two sub-catchments are plotted in Figure 7. The general trend of stream lengths within each stream order is that stream length decreases as stream order increases, except for the fourth and fifth stream orders obtained from LiDAR-derived DEM. Both the total length of streams and the stream lengths within each order from LiDAR-derived DEM are longer than those from the Vicmap DEM. The difference in the stream lengths within stream order 1 obtained from the LiDAR DEM and the Vicmap DEM for the two sub-catchments is quite significant. For sub-catchment 2, for instance, the stream length within stream order 1 derived from the LiDAR DEM is 59.54 km longer than the one derived from the Vicmap DEM, with the stream length increasing by 23.7%.

[Space for Figures 6 and 7]

Surface water flow path is one of the most important hydrological parameters. The extraction of adequate drainage networks in a sub-catchment is the first step in the simulation of hydrological and geomorphological processes (Paik, 2008). The development and the application of D8-based algorithms for automatic extraction of drainage networks from DEMs have attracted lots of research interest since the 1980s. These methods may be applicable to steep terrains, but they are not effective and less applicable to flat terrains. One of the problems in the use of these methods on flat terrains is the inadequate resolution of the DEMs. High-resolution DEMs allow for a more accurate representation of the terrain surface and make it possible to extract detailed drainage networks in low relief terrains. In this study, the analysis of some parameters of the drainage network composition in two sub-catchments demonstrated that LiDAR-derived 3 m resolution DEM provides more capability of extracting detailed drainage network compared with the Vicmap 10 m resolution DEM. The advantages of using LiDAR-derived DEM over the Vicmap DEM have been shown in terms of the stream orders, the number of streams and the stream lengths.

Conclusion

The adequate extraction and delineation of drainage networks in a sub-catchment is one of the critical steps for many geological-related applications. Determination of drainage networks over low-relief landscapes requires DEMs with higher resolution. LiDAR technology offers high-accuracy and high-density terrain data capture for detailed representation of terrain surface. From the comparison of some parameters of the drainage network composition including the stream orders, the numbers of streams and the stream lengths, this study showed that the LiDAR-derived 3m resolution DEM offers scope for drainage network delineating with more detail, compared with what can be achieved using the 10 m resolution Vicmap DEM, whether the terrain is complex or comparatively less so. The big advantage of the use of LiDAR-derived DEM is that it supports greater detail in extraction of the low-order stream (headwater) segments of drainage networks (especially in low-relief sub-catchments) than can be achieved using the conventional and state-wide Vicmap DEM.

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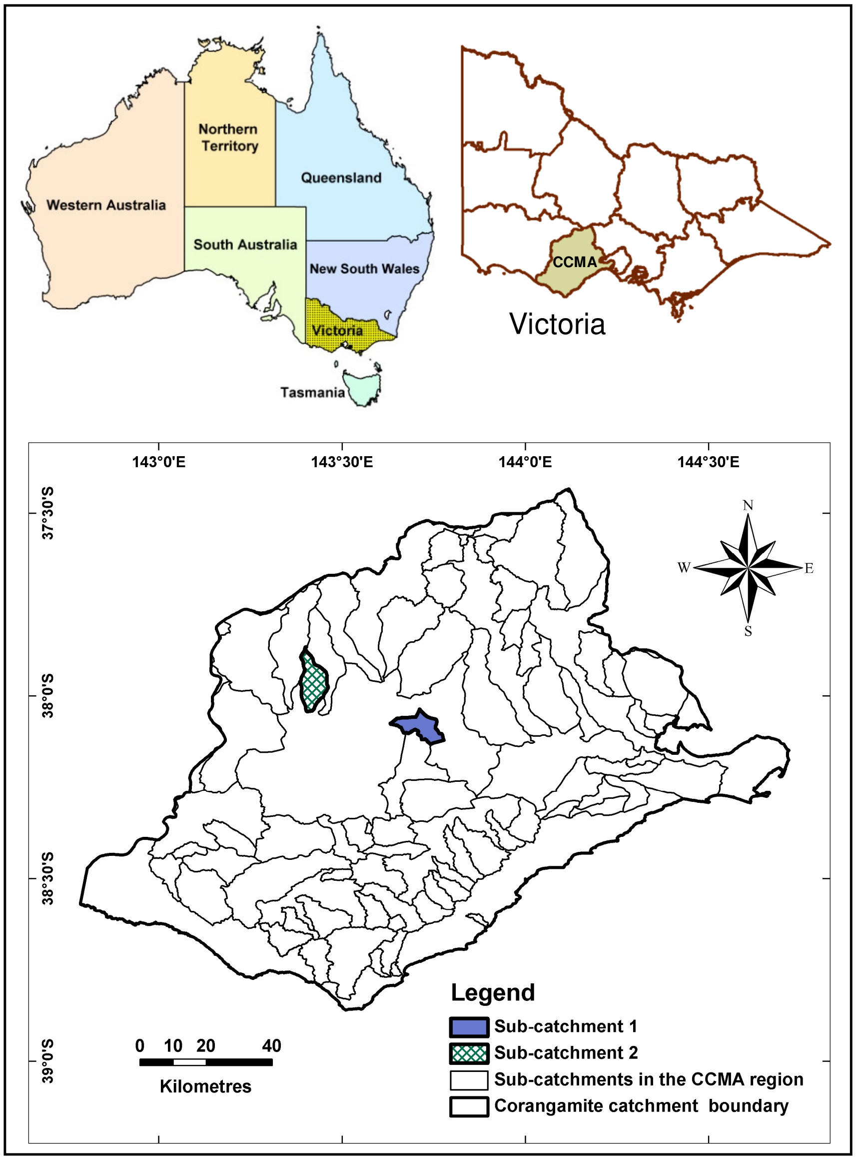

Figure 1 Locality map shows the boundary of the Corangamite Catchment Management Authority and all sub-catchments in the region. Two sub-catchments as test sites are highlighted.

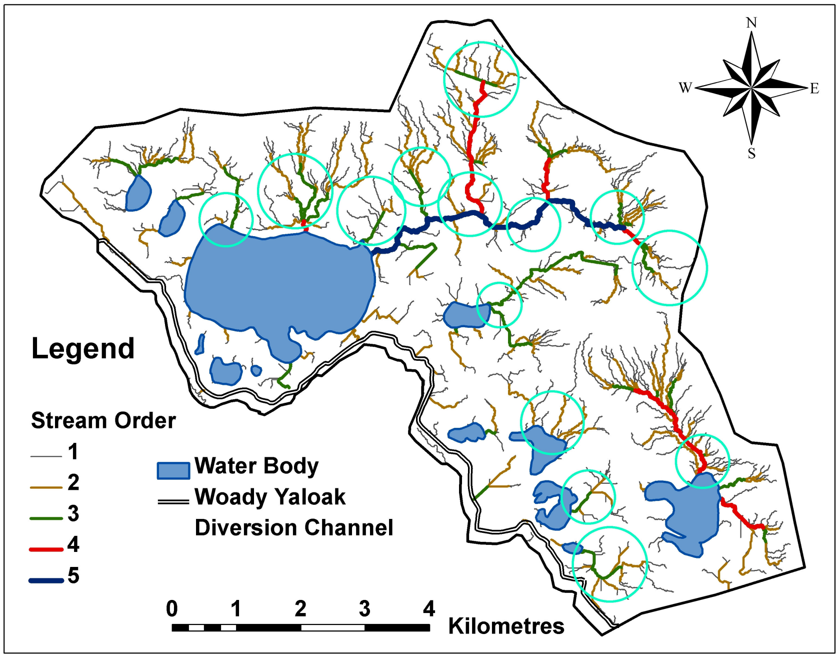

Figure 2 Drainage networks extracted from the LiDAR-derived DEM in sub-catchment 1. Considerable differences in drainage networks derived from LiDAR-derived DEM and the Vicmap are circled.

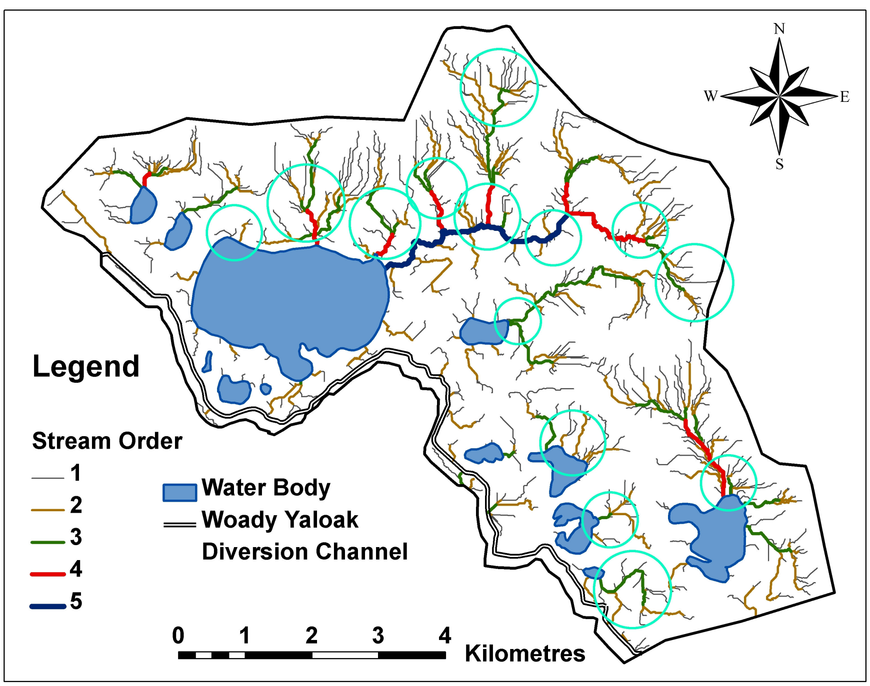

Figure 3 Drainage networks extracted from the Vicmap DEM in sub-catchment 1. Considerable differences in drainage networks derived from LiDAR-derived DEM and the Vicmap are circled.

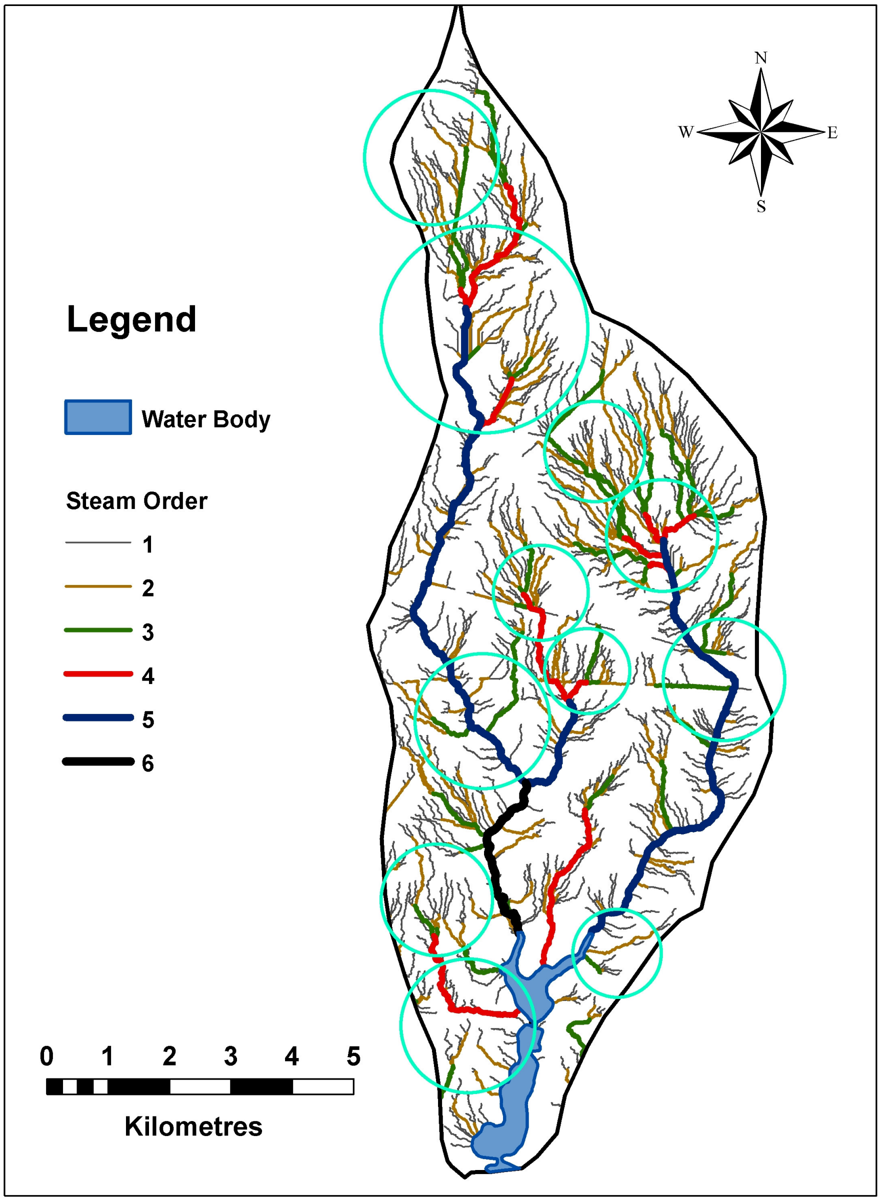

Figure 4 Drainage networks extracted from the LiDAR-derived DEM in sub-catchment 2. Considerable differences in drainage networks derived from LiDAR-derived DEM and the Vicmap DEM are circled.

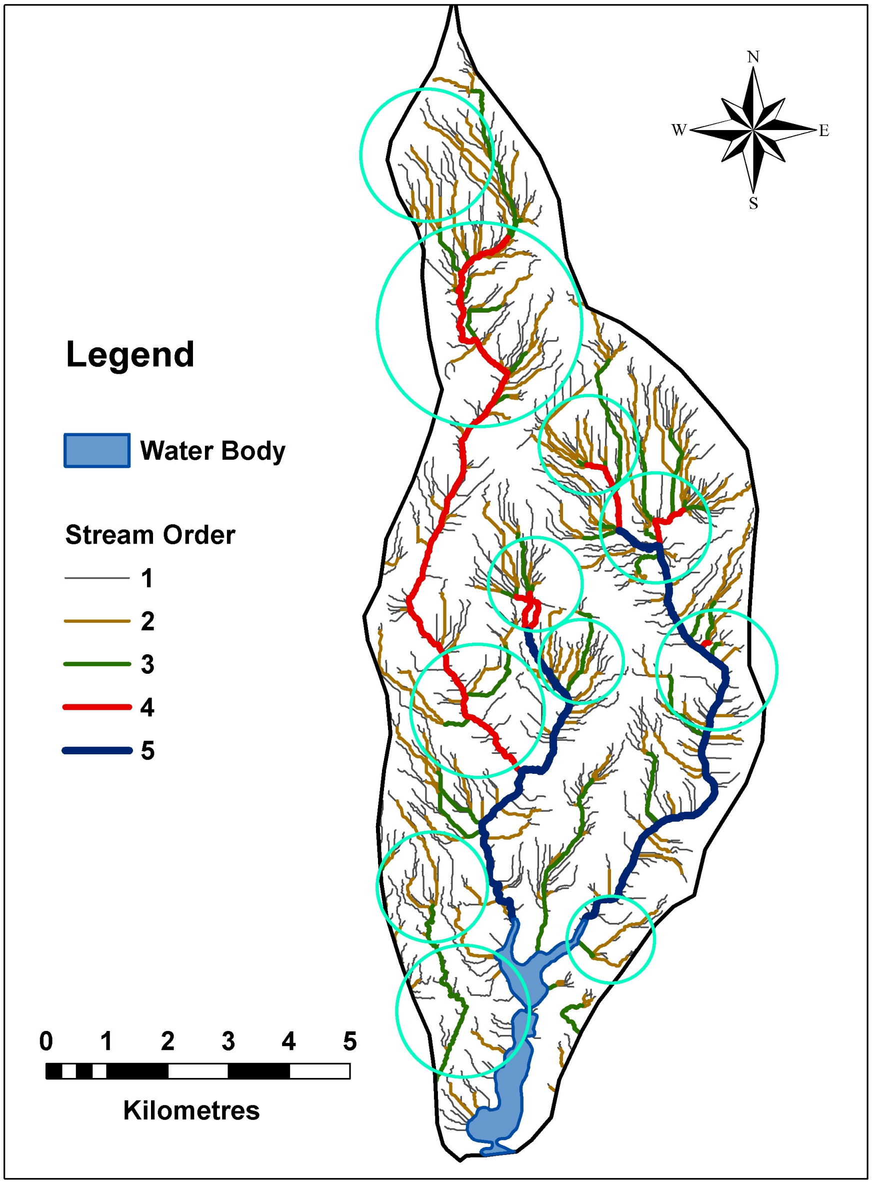

Figure 5 Drainage networks extracted from the Vicmap DEM in sub-catchment 2. Considerable differences in drainage networks derived from the LiDAR-derived DEM and the Vicmap DEM are circled.

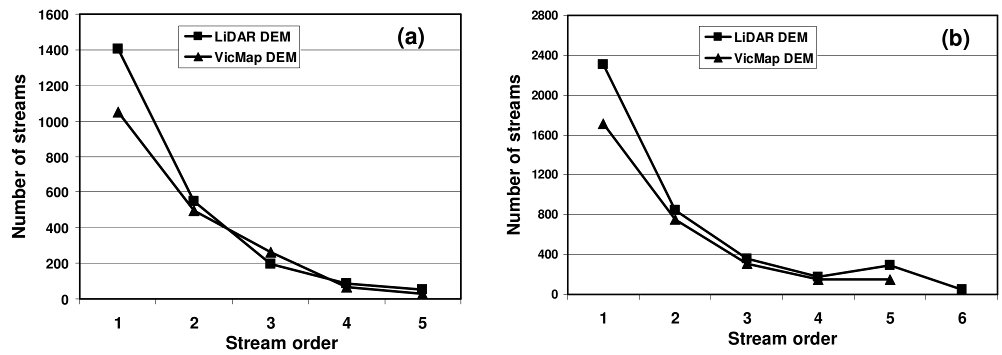

Figure 6 The numbers of streams within each stream order derived from the LiDAR-derived DEM and the Vicmap DEM: (a) in sub-catchment 1, (b) in sub-catchment 2

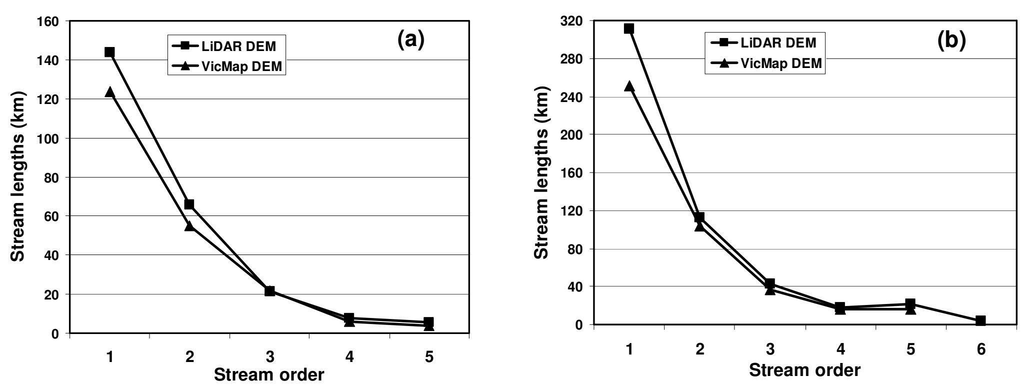

Figure 7 The stream lengths (km) within each stream order derived from the LiDAR-derived DEM and the Vicmap DEM: (a) in sub-catchment 1, (b) in sub-catchment 2

Table 1 The numbers of streams within each stream order derived from the LiDAR-derived DEM and the Vicmap DEM in two sub-catchments

Stream Order	Sub-catchment 1		Sub-catchment 2	
	LiDAR DEM	Vicmap DEM	LiDAR DEM	Vicmap DEM
1	1406	1050	2305	1712
2	551	498	848	749
3	196	264	357	310
4	88	69	174	152
5	54	30	294	151
			49	
Total	2295	1911	4027	3074

Table 2 The stream lengths (km) within each stream order derived from the LiDAR-derived DEM and the Vicmap DEM in two sub-catchments

Stream Order	Sub-catchment 1		Sub-catchment 2	
	LiDAR DEM	Vicmap DEM	LiDAR DEM	Vicmap DEM
1	143.73	123.65	311.06	251.52
2	65.83	54.85	112.21	103.25
3	21.50	21.64	43.22	36.59
4	7.74	6.16	17.46	16.01
5	5.58	3.74	21.86	15.66
6			3.75	
Total	244.38	210.04	509.56	423.03