Extracting Drainage Network from High Resolution DEM in Toowoomba, Queensland

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Keywords: digital elevation model, drainage network, stream order, Toowoomba, Condamine catchment, Murray Darling Basin

Abstract

Detailed delineation of drainage networks is the first step for many natural resource management studies. Compared with field survey and interpretation from aerial photographs or topographic maps, automation of drainage network extraction from DEMs is an efficient way and has received considerable attention. Toowoomba City is the principal activity centre for the Darling Downs, Queensland. The development of the Surat Energy and Resource Province will continue to drive population growth in Toowoomba, placing high pressure on water and other resources in the region. This study aims to extract drainage networks from a high resolution DEM to support the strategy for improving the management of the impacts of stormwater, flooding, bank stability, pollutants, water quality and creek health in Toowoomba City. Composition parameters of the drainage network including the numbers of streams and the stream lengths are derived from the high resolution DEM. Contributing area thresholds and their impacts on the extraction of drainage networks are also discussed.

Introduction

Accurate delineation of drainage networks is a prerequisite for many natural resource management issues (Paik, 2008; Liu and Zhang, 2010). Drainage network is one of the main inputs for estimating rainfall runoff, predicting flood levels and managing water resources (Maune *et al.*, 2007). Automation of drainage networks extraction from Digital Elevation Model (DEM) has received considerable attention. 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) and 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; Fairfield 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 drainage network extraction, a number of methods have been developed for dealing with sinks in a DEM (Jenson and Domingue, 1988; Fairfield and Leymarie, 1991; Martz and Garbrecht, 1992; Tribe, 1992; Jones, 2002). 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). No matter what method is used, the quality of the DEM is critical for the automatic extraction of drainage networks.

With the D8 algorithm, drainage networks are 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 needs to take into account the DEM resolution and terrain characteristics (Dobos and Daroussin, 2005).

Toowoomba is located at the western edge of the south east Queensland region. Toowoomba City sits in two catchments, with the eastern flowing into south east Queensland, and with the western flowing into the Condamine catchment in the Murray Darling Basin. Toowoomba City is also the principal activity centre for the sub-region and services the Darling Downs and Surat Basin. The development of the Surat Energy and Resource Province will continue to drive population growth in Toowoomba, placing high pressure on water and other resources in the region. In order to support efficient natural resource management and sustainable development, high resolution elevation data were acquired for the area of Toowoomba City. This study aims to derive drainage networks and some parameters describing the drainage network composition, including the stream orders, the numbers of streams and the stream lengths from the high resolution DEM. Contributing area thresholds and their impacts on the extraction of drainage networks are also discussed.

Materials and method

Study Area

The study area is in the region of Toowoomba Regional Council, covering the area of the Toowoomba City. The Toowoomba City is the regional centre of the Darling Downs, located approximately 130 km out of Brisbane, Queensland, Australia (ANRA, 2009). The city sits on the crest of the Great Dividing Range, around 700 metres above sea level. The majority of the city is west of the divide. It occupies the edge of the range and the low ridges behind it. The area of Toowoomba City is on the edge of the Condamine Catchment and is also part of the Murray-Darling Basin in southern Queensland. The study area, shown in Figure 1, covers an area of 265.97 square kilometres, with elevations ranging between 234 metres to 722 metres. It is at the headwaters of a number of drainage systems (ANRA, 2009). Two valleys run north from the southern boundary, each arising from springs either side of Middle Ridge near Spring Street at an altitude of around 680 m. These waterways, East Creek and West Creek flow together just north of the CBD to form Gowrie Creek. Gowrie Creek drains to the west across the Darling Downs and is a tributary of the Condamine River, part of the Murray-Darling Basin. The water flowing down Gowrie Creek makes its way some 3000 km to the mouth of the Murray River near Adelaide in South Australia.

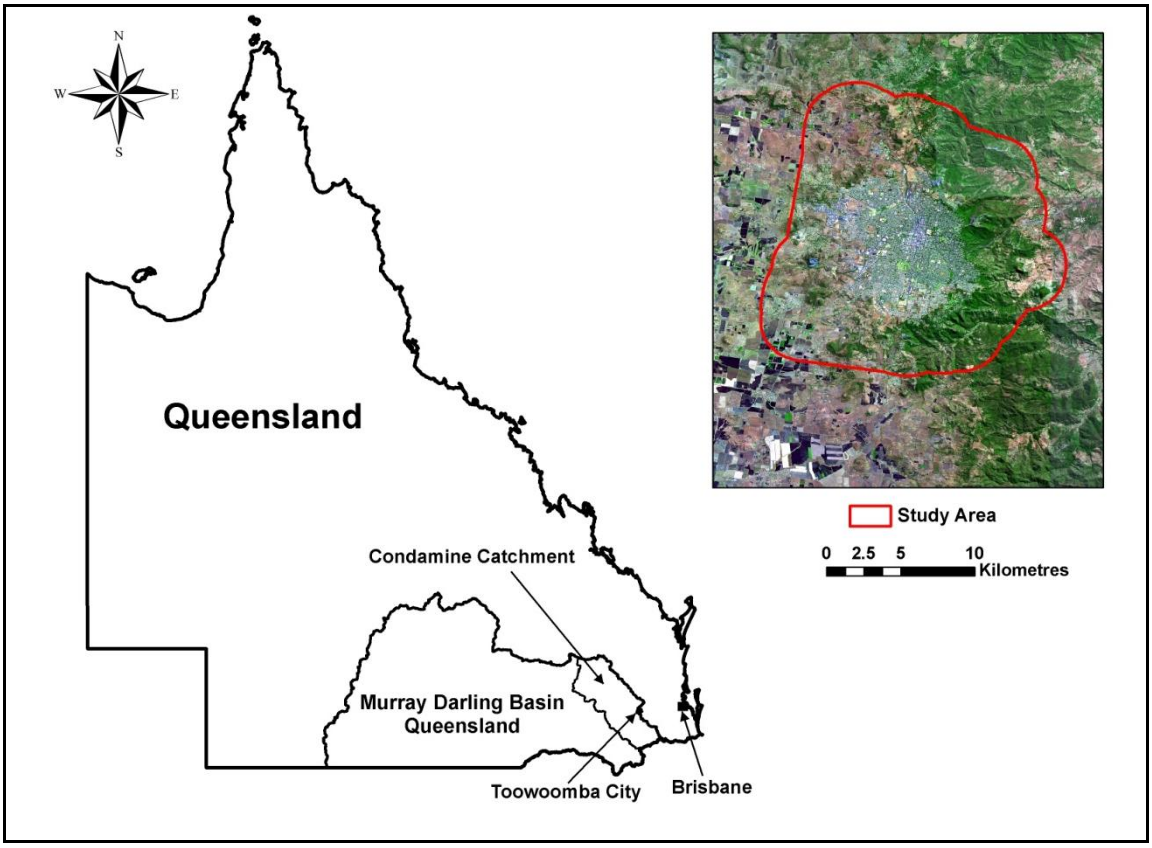

Figure 1. Study area

Data

As part of the strategy for improving the management of the impacts of stormwater, flooding, bank stability, pollutants, water quality and creek health in Toowoomba City, the digital elevation data in the Toowoomba City area was acquired in 2006. These data were generated from orthorectified digital colour aerial photography, and provided with 1m grid elevation points. Vertical accuracy was estimated as 0.5m in standard error. In this study, a 5-m resolution (grid) DEM was generated from these elevation data and shown in Figure 2.

Method

The extraction of drainage networks from the DEM in the study area was carried out using the Arc Hydro extension within ArcGIS (Maidment, 2002). Arc Hydro tools are based on the most widely used D8 algorithm (O'Callaghan and Mark, 1984). 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 as stated in the introduction section. With the high-resolution DEM over the study area, the use of a relatively small threshold can provide a detailed description of drainage networks. In this study, the threshold areas with 0.5, 0.25, 0.125, and 0.05 square kilometres were tested for the delineation of drainage networks in the study area.

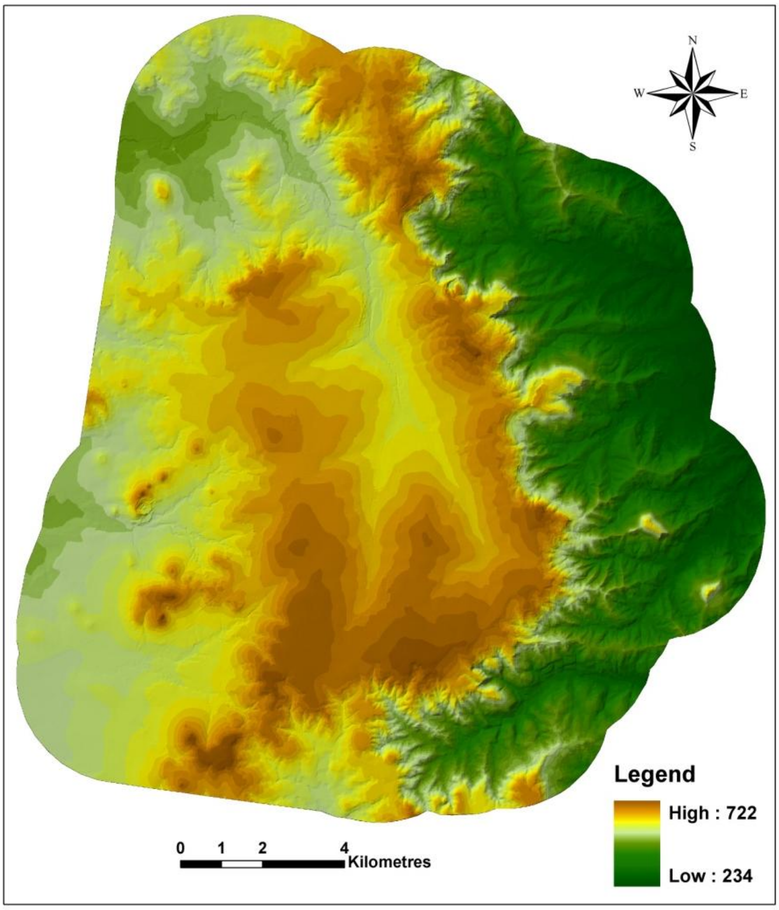

Figure 2. 5-m resolution DEM in the study area

The composition of a drainage network 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 in the study area were also calculated. The drainage density, a measure of the length of stream per unit area, was calculated with the total length of streams divided by the study area. The length of streams of each order was obtained by measuring all the drainage in the study area of a given order (Schumm, 1956).

Results and discussion

Drainage networks extracted from the DEM using different thresholds are shown in Figure 3. The overall view of drainage networks in the figure illustrates that the area of the Toowoomba City is at the headwaters of a number of drainage systems. Water from the study area drains to all directions: east into the Lockyer Creek system, south into the Hodgson Creek system, west into the Westbrook Creek system and north into the Gowrie Creek system. The majority of the streams flows to the north into the Gowrie Creek, which is located in the headwaters of the Murray Darling Basin (ANRA, 2009).

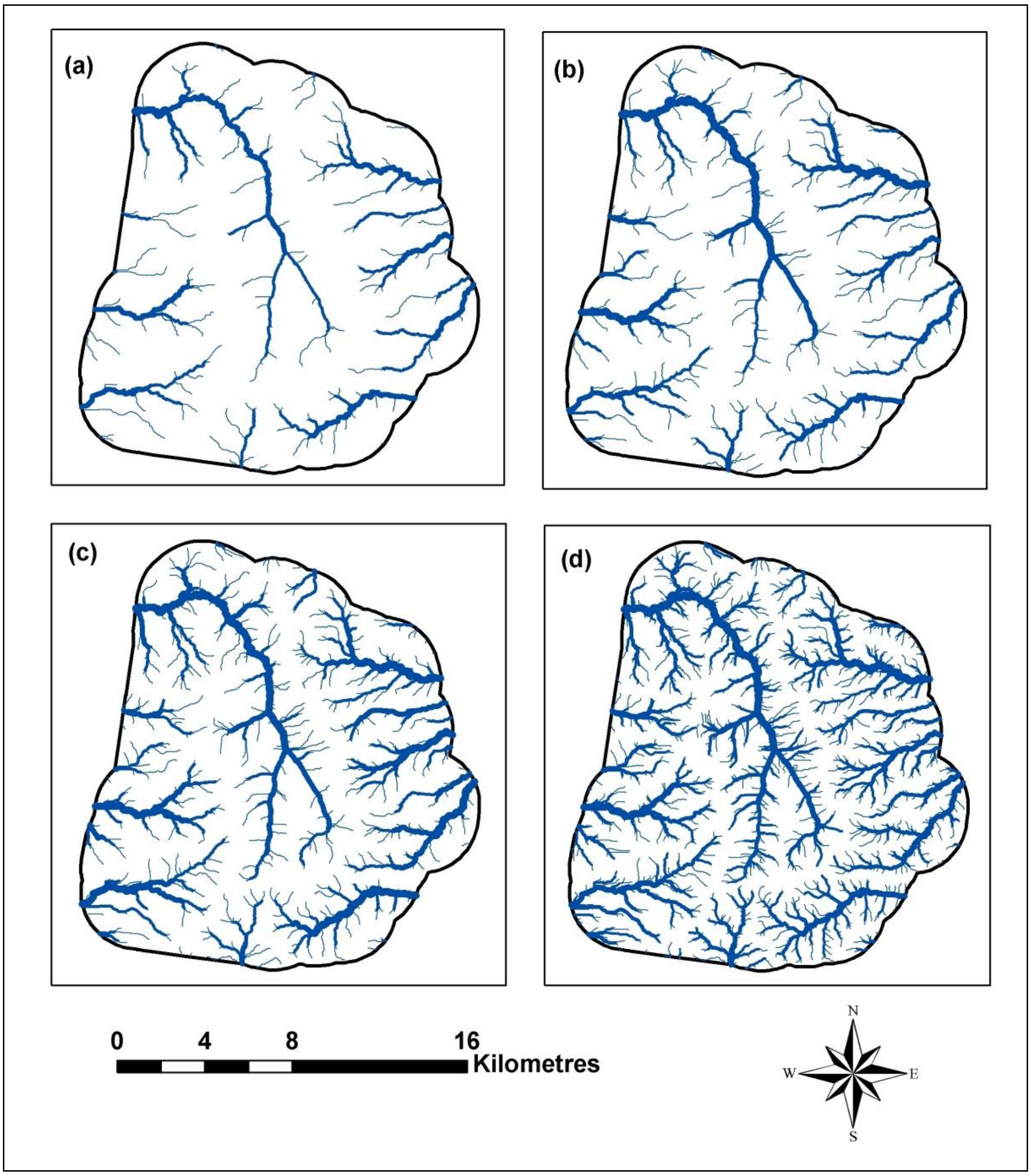

Figure 3. Drainage networks derived from the DEM using different threshold areas: (a) using 0.5 km^2 threshold, (b) using 0.25 km^2 threshold, (c) using 0.125 km^2 threshold, and (d) using 0.05 km^2 threshold.

The use of a small contributing area threshold can produce a more detailed delineation of the drainage network, but obviously, smaller threshold value is only applicable to high resolution DEMs. The determination of an appropriate contributing area threshold is dependent on the DEM resolution and the application. With the decrease of the threshold value, the density of derived drainage network increased. Drainage density is one of the important aspects of the drainage network composition, which measure the degree of drainage development within a region. This value is indicative of the rugged texture of the area, providing a useful numerical measure of dissection and runoff potential for a region (Horton, 1945).

Table 1. The stream lengths (km) within each stream order derived from the DEM using different threshold areas

Stream order	Threshold 1 (0.500 km^2)	Threshold 2 (0.250 km^2)	Threshold 3 (0.125km^2)	Threshold 4 (0.050km^2)
1	123.11	189.59	265.98	394.91
2	64.14	89.03	116.43	200.48
3	42.5	38.54	50.67	97.05
4	1.89	22.78	40.92	44.1
5	0	0	0	22.84
Total	231.64	339.94	474.00	759.38

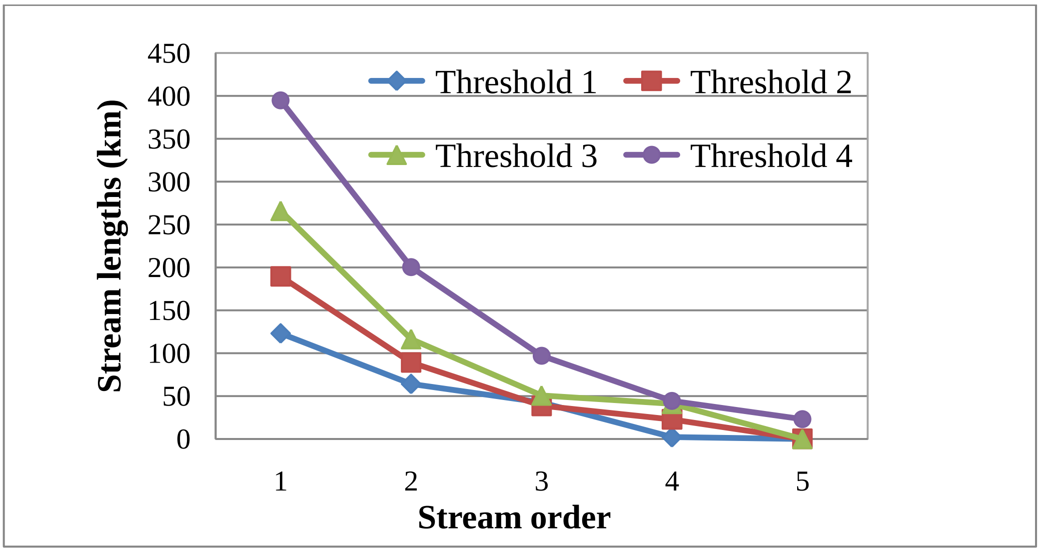

Figure 4. The stream lengths (km) within each stream order derived from the DEM using different threshold areas

Stream lengths within each order derived from the DEM using different threshold areas in the study area are listed in Table 1, and are plotted in Figure 4 as well. The general trend of stream lengths within each stream order is that stream length decreases as stream order increases no matter what threshold area is used. The total length of streams increases with the decrease of threshold area. When the threshold area increases, the stream lengths within each order also increase, except for the third order using threshold 2. With small threshold area, the details of the description of low-order streams increase. 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 (Tribe, 1991; Wharton, 1994).

Table 2. The numbers of streams within each stream order derived from the DEM using different threshold areas

Stream order	Threshold 1 (0.500 km^2)	Threshold 2 (0.250 km^2)	Threshold 3 (0.125km^2)	Threshold 4 (0.050km^2)
1	256	514	1349	5313
2	107	229	608	2044
3	93	124	199	953
4	4	83	254	446
5	0	0	0	180
Total	460	950	2410	8936

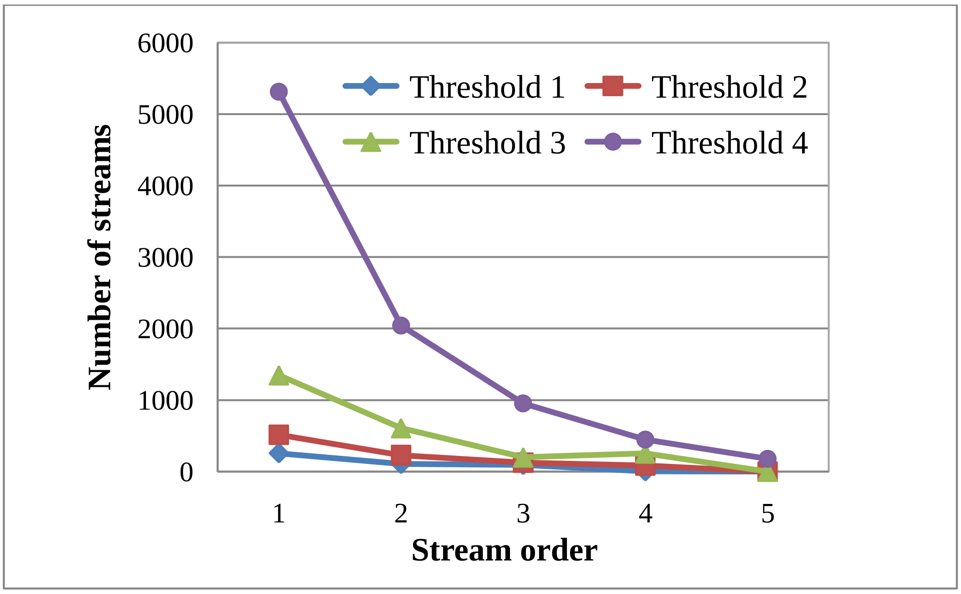

Figure 5. The numbers of streams within each stream order derived from the DEM using different threshold values

The number of streams within different orders obtained from the DEM using different threshold areas in the study areas are presented in Table 2, and depicted in Figure 5. The decrease of the threshold areas leads to the increases of both the total number of streams and the numbers of streams within each stream order in the study area. As we can see from the Figure 5, there is a significant increase in the numbers of low-order streams when using small threshold value (0.05km^2 in this study). Generally speaking, the use of a bigger threshold area can derive an overall pattern of drainage networks while a smaller threshold area can give more detailed description for the drainage networks, especially for the low-order streams (headwaters). It should be noted that the use of a small threshold area require a high resolution DEM.

Over-land (or surface) water flow path is one of the most important hydrological parameters. The extraction of adequate drainage networks is usually 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. One of the problems in the use of these methods 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 this study, the analysis of some parameters of the drainage network composition demonstrated that the high resolution DEM provides capability of extracting drainage networks at different detail levels when using different threshold values.

Conclusion

The adequate extraction and delineation of drainage networks is one of the critical steps for many geological-related applications. Determination of detailed drainage networks requires DEMs with higher resolution. From comparing some parameters of the drainage network composition including the stream orders, the numbers of streams and the stream lengths, this study showed that the high resolution DEM offers scope for drainage network delineating at different detail levels when using different threshold values. With a high resolution DEM, it is possible to use smaller threshold values for the delineation of the drainage networks and some composition parameters such as the numbers of streams and the stream lengths. High resolution DEMs support greater detail in the extraction of the low-order stream (headwater) segments of drainage networks for the applications in the physically-based hydrologic processes (Giertz *et al*., 2006; Tague and Pohl-Costello, 2008).

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