Hydrological Research in China: Process Studies, Modelling Approaches and Applications (Proceedings of Chinese PUB International Symposium, Beijing, September 2006). IAHS Publ. 322, 2008.

Appropriate contributing area threshold of a digital river network extracted from DEM for hydrological simulation

LI LI[1,2], JIAHU WANG[1,2] & ZHENCHUN HAO[1]

1 *State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, No. 1 Xikang Road, Nanjing, China*
llwjh@163.com
2 *National Weather Center, University of Oklahoma Norman, Oklahoma 73019, USA,*

Abstract Contributing area threshold is an important parameter of extracting digital river networks (DRNs) from digital elevation models (DEMs). Impact of its change on runoff concentration, methods of determining it, and its spatial distribution are studied in this article. Conclusions showed that with the increase of contributing area threshold, basin mean concentration time of flood became longer and flood peak decreased, while the time of peak was almost unchanged. It meant that the runoff concentration of the hydrological model was sensitive to the contributing area threshold. A new approach was developed, in which the river system in digital maps was considered as the correct river network (CRN) while that extracted from DEM was called the digital river network (DRN). Drainage density and fractal dimension of DRNs derived from different thresholds were compared with that of CRN to choose the best one. Contributing area thresholds of 60 catchments were estimated using this method. It was found that the spatial distribution of them followed some rules, e.g. it changed approximately with power function of upslope gradient in areas with the same vegetation. It would be of benefit to take into account its spatial variation during extracting catchment properties and simulating hydrological processes.

Key words digital river network; DEM; contributing area threshold; catchment properties

INTRODUCTION

Distributed hydrological models have been widely used in hydrological simulating and studies of impact of climate change on water resources. Extracting catchment properties from DEM is usually the beginning of developing a distributed hydrological model based on DEM. A variety of algorithms (Band, 1986; Tribe, 1992; Garbrecht & Martz, 1997) have been reported in the literature and the most pertinent problems have been highlighted. These are related to the treatment of flat areas and to the location of the channel heads. The former has been researched extensively and some methods have been developed (Hutchinson, 1989; Martz & Garbrecht, 1998; Turcotte & Fortin, 2001). However, studies about the latter are far fewer than the former. In the following channel heads are discussed, including sensitivity of flow concentration to them and the methods of determining it.

In geomorphology, the head location of the channel is a concept related to river erosion, so it is described as the result of sediment transport and erosion processes. The contributing area of all grids can be obtained after pit filling and flow direction calculation during the period of extracting the river network from DEM. Grids with a larger contributing area more possibly belong to channels. Based on this concept, a common approach of extracting drainage networks from a DEM is to consider a grid cell as being part of a channel if its contributing area is larger than a defined contributing area threshold (O'Callaghan *et al.*, 1984). The threshold is also called a critical contributing area. It is considered as a parameter of digital river network extraction and distinguishes stream processes from flow concentration of hillslopes.

The structure of stream networks, such as river density, classification of streams and partition of sub-basins, may be different with different threshold (Baxter *et al.*, 2004). Impacts of its change on landscape properties (length of streams, main channels and drainage paths) and scale properties (Horton law and Strahler law) can also not be ignored (Roger *et al.*, 1996). Some studies showed that its change would influence width function (Yang *et al.*, 2000) and basin geomorphologic instantaneous unit hydrograph (Liu *et al.*, 2003). So the change of contributing area threshold would affect the proportion of overland and channel processes, and as a consequence, would affect the basin flow concentration in hydrological modelling.

Copyright © 2008 IAHS Press

The contributing area threshold varies with local climate, soil, geology, vegetation, and landscape (Martz *et al.*, 1992). A lot of literature (Giorgio *et al.*, 1996; Karea *et al.*, 1996) has declared that there was a relationship of power function between contributing area (A) and local slope (S). The threshold value can be evaluated from the plot of slope *vs* area. This approach is based on the premise that there will be a single inflection point in the longitudinal profile near the head of a channel. Moreover, it is expected that the slope will reach its maximum value at this inflection point. So a single value is usually applied due to the lack of more detailed information, ignoring its spatial distribution with change of hydrology, geology, relief and climate (Carpenter *et al.*, 2001). The underlying hypothesis is applied to find the location of channel heads, that channel heads are located in zones where fluvial transport becomes dominant over diffusive transport, corresponding to the spatial transition from convex to concave slope profiles (Jürgen *et al.*, 2003). Some authors get it from a log–log plot of local slope against contributing area (Tarboton *et al.*, 1992) or relationship between drainage density and corresponding assumed area threshold (Kong, 2003). Others get it by photointerpretation techniques (Dennis & Arthur, 1997; Lopez & Camarasa, 1999).

Unfortunately, there is a considerable scatter in these slope/area plots and furthermore the network identified in this way shows a constant drainage density. Forced by the need to obtain a non-uniform drainage density in the different parts of the catchment, as expected in natural basins, some authors assumed contributing area as a surrogate variable for discharge (Rodriguez-Iturbe *et al.*, 1992) and used a threshold of AS^k to identify channel network (Giannoni *et al.*, 2000).

In order to study impact of contributing area threshold on basin runoff concentration, two small catchments (named as Sta1 and Sta22, respectively; their details are listed in Table 1) lying in the middle reach of the Yellow River Basin were selected in this study. Some approaches in common use to evaluate contributing area threshold are discussed, taking the two catchments as examples. A new method was proposed to estimate the threshold according to drainage density of the correct river network. Finally, the contributing area thresholds of 60 catchments were evaluated and analysed to obtain their distribution rules. Both the GTOPO30 USGS DEM and digitized river network from 1:250 000 topographic maps of China were used during the study.

Table 1 Information of the two catchments.

ID	Information of outlets			Information of catchments	
	Long. (East)	Lat. (North)	Altitude(m)	Number of grids	Area of catchment (km^2)
Sta1	112.363	36.413	1006	285	197
Sta22	110.329	34.171	1013	937	664

SENSITIVITY OF BASIN FLOW CONCENTRATION TO CONTRIBUTING AREA THRESHOLD

The digital river system, flow path network and their slope describe the properties of basin runoff concentration if ignoring the non-uniformity of the underlying surface. Variation of them implies the changed response of the basin to flow concentration process in distributed hydrological simulation. The reservoir action of the watershed can be presented as the translation and flattening-out of the flood hydrograph. Consequently, different contributing area thresholds may result in change of concentration time and flood hydrograph.

Change of basin mean concentration time

The concentration time of each water drop in one watershed is different from others because of their varied flow velocity and path. Similarly, the concentration time of flow in each grid is different to others in distributed hydrological simulations because grids are considered as minimum units. In the study, concentration time of each grid from its centre to the outlet was evaluated by equation (1):

$$T_i = \sum_{j=1}^{M_i - 1} t_j \,;\, t_j = \frac{l_j}{v_j} = \frac{l_j}{K_V S_j^{\frac{1}{2}}} \tag{1}$$

where, T_i is the concentration time of flow from centre of the ith grid to the outlet, M_i is the number of grids it passes through, t_j is the time it needs from the jth grid to the next downstream grid, l_j is the surface distance, v_j is average flow velocity, S_j is gradient, and K_V is defined as the velocity constant, implying the effect of hydraulic factor, such as roughness and hydraulic radius, on flow velocity.

Basin mean concentration time is defined as the average concentration time of all water drops. In distributed hydrological modelling, it is defined as that of all grids. In order to study its universal change, define:

$$Kv_{channel} = \beta Kv_{slope};\ \tau = \frac{1}{Kv_{slope}} \tag{2}$$

where, $Kv_{channel}$ and Kv_{slope} are the velocity constant of channel and overland runoff, respectively, and β is a constant. They change with different stream and underlying surface. In this study, they are assumed to be invariable for the same basin. So t_j for channel grids and slopes may be expressed as:

$$t_j = \frac{l_j}{Kv_{channel} S_j^{\frac{1}{2}}} = \frac{l_j}{\beta Kv_{slope} S_j^{\frac{1}{2}}} \text{ and } t_j = \frac{l_j}{Kv_{slope} S_j^{\frac{1}{2}}} \tag{3}$$

So basin mean concentration time can be calculated with the following equations:

$$T_i = \tau \left(\sum_{j=1}^{m_i} \frac{l_j}{S_j^{\frac{1}{2}}} + \sum_{j=1}^{n_i - 1} \frac{l_j}{\beta S_j^{\frac{1}{2}}} \right) = \tau \alpha_i \,;\ T = \frac{1}{N} \sum_{i=1}^{N} T_i = \frac{1}{N} \sum_{i=1}^{N} \alpha_i \tau = (\frac{1}{N} \sum_{i=1}^{N} \alpha_i) \tau \tag{4}$$

where, N is the number of grids in the basin, m_i is the number of slope-grids passed through by runoff from the ith grid to the outlet-grid, n_i is that of channel-grids. The concentration time of each grid to the outlet is the function of τ. It is convenient to calculate mean basin concentration time and compare it with that of different conditions.

Impact of surface roughness on overland runoff is larger than that of channel runoff because flow in the channel is deeper. So the velocity constant of channel, $Kv_{channel}$, is larger than that of overland Kv_{slope}. They would vary with the change of conditions. For example, the value of Kv_{slope} is about 0.21 for forested surface and 1.5 for farmland (Li *et al.*, 2003). While the value of $Kv_{channel}$ may reach 89.9 in the Xiaoli River, which is a branch of the Yellow River, according to its flow velocity of 6.67 m/s and mean gradient of 5.5‰. Upon that, the value of constant β was assumed as 10, 50 and 100, respectively, in the study. The change of river basin mean concentration time with critical contributing area in the two studied catchments is shown in Fig. 1, in which the y-coordinate means the relative increment of basin mean concentration time *vs* that when critical contributing area was one grid. It shows that basin mean concentration time becomes longer with the increasing contributing area threshold. With the increase of β, basin mean concentration time is also longer. Furthermore, the sensitivity is related to basin area. Its change is more apparent when basin area is smaller because of the larger percentage of slope grids.

Change of flow hydrograph

The reservoir action of the basin would also change with the variation of contributing area threshold. Assume that net precipitation (R) occurs on a basin uniformly in one time-step Δt and the runoff concentration of each grid is independent of others. Linear reservoirs are applied to simulate runoff concentration from each grid to the next downstream grid. These reservoirs for channel or overland runoff both assume no change along the flow path. The difference of runoff

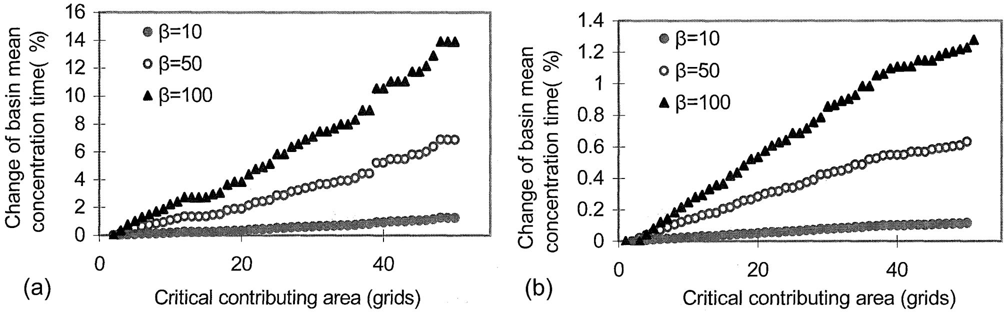

Fig. 1 Relative change of basin mean concentration time with critical contributing area: (a) Sta1 basin area, 197 km^2, (b) Sta22 basin area, 664 km^2.

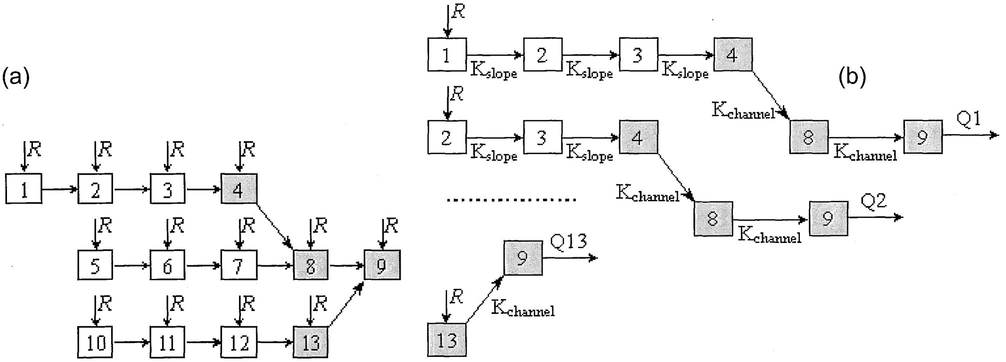

Fig. 2 Sketch map of basin flow routing; the number in grids is the ID of each grid, white grids mean slope grids and grey grids mean channel grids: (a) flow path network and net precipitation, (b) flow routing simulation of each grid.

concentration process between channels and hillslopes lies on the value of outflow coefficient K. Figure 2 illustrates this, in which, $K_{channel}$ is the outflow coefficient of channel and K_{slope} is that of hillslopes. So the flood hydrograph at the outlet can be obtained by adding up that of each grid:

$$Q_{out} = Q_1 + Q_2 + \cdots\cdots + Q_N \tag{5}$$

where, Q_{out} is the total runoff at outlet, Q_i is the outlet runoff contributed from the ith grid.

The percentage of overland and channel runoff is different, with the change of critical contributing area, which results in the change of flow hydrograph and flood peak. Flow hydrographs of Sta1 and Sta22 with different outflow coefficients were calculated to investigate its sensitivity to contributing area threshold. Figures 3 and 4 show when the value of K_{slope} and $K_{channel}$ were 0.2 and 0.6, respectively. The threshold is 10, 15, 20, 25, 30, 35 or 45 grids. With increasing contributing area threshold, the outflow of basins became slower, discharge of flood peak was decreasing and the recession period became longer, while the time of flood peak changed slightly.

NEW APPROACH TO THRESHOLD EVALUATION

The impact of the digital river network on basin runoff concentration is due to its characteristics, such as contributing area, channel length and slope, drainage density and morphology. Change of river network caused by different contributing area thresholds embodied in its statistical properties, such as density, and morphology properties. In this study, drainage density was applied to evaluate threshold and river system in digital maps was considered as the correct river network

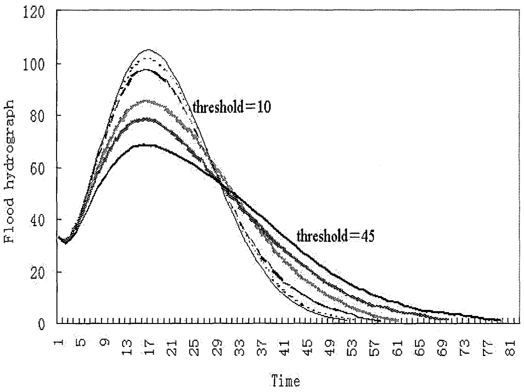

Fig. 3 Change of flood hydrograph in Sta1.

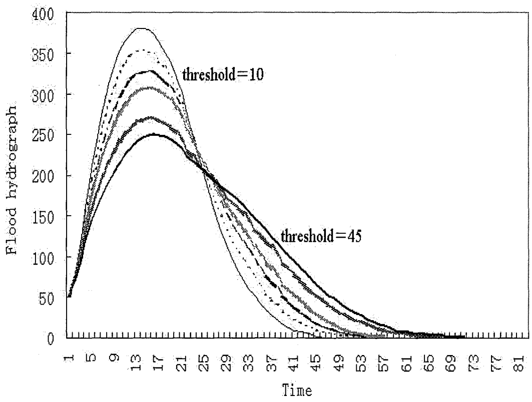

Fig. 4 Change of flood hydrograph in Sta22.

(CRN). Drainage density of correct and digital river networks with different contributing area thresholds were calculated and compared, selecting the one closest to that of the correct river system as the right one. The relevant contributing area threshold is also considered as the reasonable value.

The river system in digital maps was preprocessed first as shown in Fig. 5, in order to calculate its characteristics automatically. In the figure, "gridding" means partitioning the channel of the river system into grids according to cells of DEM, which can be accomplished by some GIS software. "Vectoring" means determining flow direction of grids with channel segments based on their elevation (Wang *et al.*, 2005). "Single-gridding" means making channels be single-grid width, which makes characteristics of the correct river system comparable with that of the digital river.

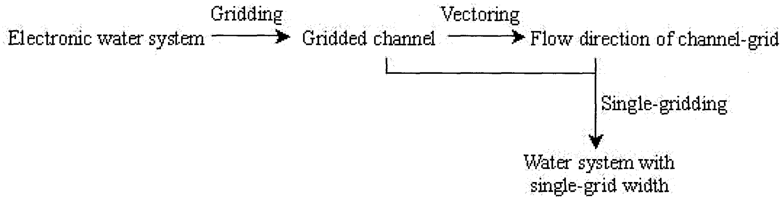

Fig. 5 Preprocessing of correct river system.

Table 2 Characteristics comparison of correct and digital river system.

Characteristics	Sta1			Sta22		
	Correct	Digital	Error	Correct	Digital	Error
Drainage density (km/km^2)	0.222	0.226	1.80	0.387	0.397	2.58
Fractal dimension	1.089	1.137	4.41	1.460	1.478	1.23

Drainage density of CRNs in Sta1 and Sta22 were 0.222 km/km^2 and 0.387 km/km^2, respectively, the evaluated threshold with this method being 21 and 8 grids. Drainage density and fractal dimension were applied to judge the similar degree between correct and digital river network for the former showed the density of channel, and the latter described its morphology and growth (Jin *et al.*, 2000). Some of their characteristics are listed in Table 2. Table 2 shows that fractal dimension of digital and correct river network were close when making thresholds 21 and 8 in Sta1 and Sta22, respectively. It implies that they were similar in morphology characteristics and development, as well as in density of channels.

SIMPLE ANALYSIS ABOUT SPATIAL DISTRIBUTION OF THRESHOLD

Contributing area threshold locates the point where overland runoff becomes channel runoff. As mentioned before, it is different not only with landscape and relief, but also with geology, hydrology and climate. Spatial distribution of contributing area threshold exhibits that of river characteristics. It would benefit to improve the precision and rationality of digital river networks to take into account its distribution. The spatial distribution of threshold was discussed after evaluating the basin mean contributing area threshold. Thresholds of 60 small catchments located in the Sanmenxia-Huayuankou region of the Yellow River were evaluated with the above method based on the assumption of contributing area threshold being equal in the same catchment. It is the reason for choosing small catchments in this study. Density of channel head and fractal dimension of digital river system in each catchment were also calculated at the same time. Compare them with that of the correct river network and similarly estimate thresholds corresponding to channel head density and fractal dimension. Basins in which the three thresholds being similar were sought out for later study while they were different, sometimes due to errors coming from preprocessing of correct river network, digital channel extraction and resolution of DEM. Twenty five catchments were sought out and their thresholds were analysed to find the spatial distribution rules. Conclusion of a simple analysis showed that thresholds of these catchments were related to vegetation and mean gradient of hillslopes. The main vegetation of the study area is woods and farmland. The relationships between contributing area threshold and mean gradient of hillslopes with different vegetation are shown in Fig. 6. They are both in power law. But there were three

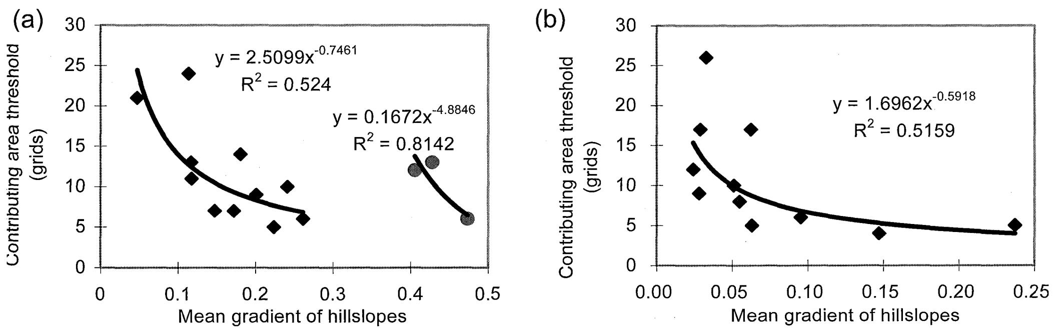

Fig. 6 Relationship between thresholds and mean gradient of hillslopes: (a) in woods, (b) in farmland.

catchments deviated from the main relationship in Fig. 6(a), which may be related to other factors, such as geology and soil.

CONCLUSION

Contributing area threshold is an important parameter during the extraction of the digital river network, which determines the basin runoff concentration of distributed hydrological models by partitioning the proportion of overland and channel runoff processes. Studies of the sensitivity of watershed runoff concentration on contributing area threshold showed that flood peak and hydrograph changed, apparently with different threshold. Appropriate thresholds will describe the obtained digital channel and flow path characteristics of basin runoff concentration better and help to decrease the uncertainty of hydrological simulation. A new method of estimating thresholds based on correct river networks was suggested after testing some methods in common use. The result obtained using the new method was similar, to the correct river network in morphology characteristic and development. Simple analysis of its spatial distribution showed that a power law existed between contributing area threshold and mean gradient of hillslopes. Furthermore, the relationship was related to vegetation and other factors.

REFERENCES

Band, L. E. (1986) Topographic partition of watersheds with digital elevation models. *Water Resour. Res.* **22**(1), 15–24.

Baxter, E. V., Zhengtao C. & Anubhav, G. (2004) Evaluation of a physics-based distributed hydrologic model for flood forecasting. *J. Hydrol.* **298**, 155–177.

Carpenter, T. M., Georgakakos, K. P. & Sperfslage, J. A. (2001) On the parametric and nexrad-radar sensitivities of a distributed hydrologic model suitable for operational use. *J. Hydrol.* **253**, 169–193.

Dennis, L. J. & Arthur, C. M. (1997) A spatially distributed hydrologic model utilizing raster data structures. *Computers & Geosci.* **23**(3), 267–272.

Garbrecht, J. & Martz, L. W. (1997) The assignment of drainage direction over flat surfaces in raster digital elevation models. *J. Hydrol.* **193**, 204–213.

Giannoni, F., Roth, G. & Rudari, R. (2000) A semi-distributed rainfall–runoff model based on a geomorphologic approach. *Phys. Chem. Earth (B)* **25**(7–8), 665–671.

Hutchinson, M. F. (1989) A new procedure for gridding elevation and stream line data with automatic removal of spurious pits. *J. Hydrol.* **106**, 211–232.

Jin, D., Chen, H. & Guo, Q. (2000) An experimental study on influence of materiel component to non-linear relation between sediment yield and drainage network development. *Acta Geographica Sinica* **55**(4), 439–448.

Jürgen, V. V., Roberto C. & Francesca B. (2003) Deriving drainage networks and catchment boundaries: a new methodology combining digital elevation data and environmental characteristics. *Geomorphology* **53**, 281–298.

Kong, F. (2003) Distributed watershed hydrological model and flow concentration based on digital technique. PhD Thesis, Hohai University, Nanjing, China.

Li, L. (2003) Extraction of catchment properties from DEM and its using in hydrologic simulation. MSc Thesis, Hohai University, Nanjing, China.

Liu, Y. B., Gebremeskel, S. & De Smedt, F. (2003) A diffusive transport approach for flow routing in GIS-based flood modelling. *J. Hydrol.* **283**, 91–106.

Lopez, G. M. J. & Camarasa A. M. (1999) Use of geomorphological units to improve drainage network extraction from a DEM: Comparison between automated extraction and photointerpretation methods in the Carraixet catchment (Valencia, Spain). *Int. J. Applied Earth Observation & Geoinformation* **1**(3/4), 187–195.

Martz, L. W. & Garbrecht, J. (1992) Numerical definition of drainage network and subcatchment areas from digital elevation models. *Comput. Geosci.* **18**(6), 747–761.

Martz, L. W. & Garbrecht, J. (1998) The treatment of flat areas and closed depressions in automated drainage analysis of raster digital elevation models. *Hydrol. Processes* **12**, 843–855.

O'Callaghan, J. F. & Mark, D. M. (1984) The extraction of drainage networks from digital elevation data. *Computer Vision, Graphics & Image Processing* **28**, 323–344.

Rinaldo, A., Rigon, R., Vogel, G. K. & Rodriguez-Iturbe, I. (1995) Can one gauge the shape of a basin? *Water Resour. Res.* **31**(4), 1119–1127.

Rodriguez-Iturbe, I., Rinaldo, A., Rigon, R., Bras, R. L., Marani, A. & Ijjasz-Vasquez, E. (1992) Energy dissipation, runoff production, and the three-dimensional structure of river basins. *Water Resour. Res.* **28**(4), 1095–1103.

Roger, M. & Claude, B. (1996) Fractal analyses of tree-like channel networks from digital elevation model data. *J. Hydrol.* **187**, 157–172.

Roth, G., La Barbera, P. & Greco, M. (1996) On the description of the basin effective drainage structure. *J. Hydrol.* **187**, 119–135.

Tarboton, D. G., Bras, R. L. & Rodriguez-Iturbe, I. (1992) A physical basis for drainage density. *Geomorphology* **5**, 59–76.

Tribe, A. (1992) Automated recognition of valley lines and drainage networks from grid digital elevation models – a review and a new method. *J. Hydrol.* **139**, 263–293.

Turcotte, R., Fortin, J.-P., Rousseau, A. N., Massicotte, S. & Villeneuve, J.-P. (2001) Determination of the drainage structure of a watershed using a digital elevation model and a digital river and lake network. *J. Hydrol.* **240**, 225–242.

Vandaele, Karel, Poesen, Jean, Govers, Gerard & van Wesemael, Bas (1996) Geomorphic threshold conditions for ephemeral gully incision. *Geomorphology* **16**, 161–173.

Wang, J., Hao, Z. & Li, L. (2005) Method for automatic determining the flow direction of raster river network. *J. Hydraul. Engng* **36**(8), 972–977.

Yang, D., Herath, S. & Musiake K. (2000) Spatial resolution sensitivity of catchment geomorphologic properties and the effect on hydrological simulation. *Hydrol. Processes* **15**, 2085–2099.