

Determination of drainage network in digital elevation models, utilities and limitations

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Abstract

The starting point for the examination of different catchments is the determination of drainage network. This network forms the basis of many further examinations, such as the determination of subcatchments, river networks, and morphometric examinations. If there is a greater catchment area, there is a demand for a more detailed presentation and examination of the network than the automatically derived digital elevation model of the area or the hydrograph of topographic maps.

The importance of the task is shown by the fact that methods supported by the computer technology appeared as early as the beginning of relief analysis. Dozens of different algorithms have become well-known during the last fifteen years.

This presentation outlines the most important methods of the automated mapping of flow routing, highlighting their utilities and limitations. Then a complex procedure, which combines the favourable characteristics of different methods, will be presented.

The results will be demonstrated on the example of a particular catchment.

Keywords: model, hydrology, geomorphology, runoff, channel, catchment.

1. INTRODUCTION

One of the recent central topics of environmental agenda is the presence of water in our environment. Studying the causes of floods, pollution of rivers and developing prevention methods directed attention to the examination of catchment areas.

Topography plays an important role in the movement of waters flowing on the surface. Water flows downwards on the surface, towards the steepest slope. The result of defining flow direction for each point of the catchment area is the flow network of the catchment. Analysing this network we can distinguish different types of downflow. On the upper parts of catchments there are primarily surfaces and subsurfaces, with non-linear runoffs. Linear channel flows are formed by narrow channels as these waters gather on the convergent surface.

There are various methods to determine the drainage network of a given area. Based on a detailed topographic map, we can define the drainage lines from the hydrographical elements.

However, the result that we obtain is not detailed enough for large-scale examinations. The ground survey of a study area is time-consuming and expensive; furthermore the quality of the result is often not homogeneous spatially.

Nowadays, it is becoming more and more common to determine drainage networks from digital elevation models.

The first attempts at determining drainage networks (Peucker and Douglas, 1975) did not result in actual runoff, but it was also true that the capacity of computers in those days would not have been sufficient enough to allow the application of more complicated models. Several new algorithms have been presented by different authors since then. Most of these are based on cell-based grid model (Fairfield and Leymarie, 1991; Costa-Cabral and Burgess, 1994; Freeman, 1991; Lea, 1992; Tarboton, 1997), but there have also been applications of TIN (Jones et al., 1990; Nelson et al., 1994) and contour-line models, too (Moor, 1991).

Generally, these algorithms have not become widespread because of their complexity or did not provide appropriate results. Today the most commonly used method is Deterministic 8 (O'Callaghan & Mark, 1984), while other methods are mainly applied in research projects.

In this paper I will outline three different methods and their combinations for the extraction of channel networks from digital elevation models. These are the following:

- hydrological approach — flow accumulation
- morphological approach — convergence
- morphological process approach

2. METHODS

One of the most commonly used digital data model of the Earth's diverse surface is a digital elevation model (DEM), which describes the surface with elevation defined at intersection points of grid-lines. These elevation values are stored in a cell-based grid model (Fig.1, Fig. 2) Most of the hydrological models require a so-called hydrologically correct DEM, which means that starting out from any cell and following the greatest slope we can reach the edge of the DEM, consequently the DEM does not include sinks. Several methods are known for creating hydrologically correct DEM e.g. filling sinks or deepening drainage routes (Hutchinson, 1989). If the DEM contains flat areas (mostly produced by the method of filling sinks), we can't use the simple aspect based flow models. In this case we have to add some other algorithms to the flow model to handle the flat area problem. In this paper we use the method of filling sinks, which produced no flat areas (Planchon and Darboux 2002).

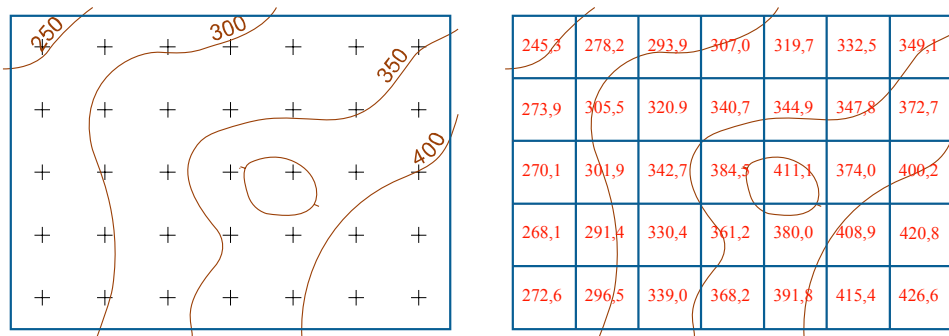


Fig. 1. Cell based digital elevation model (DEM)

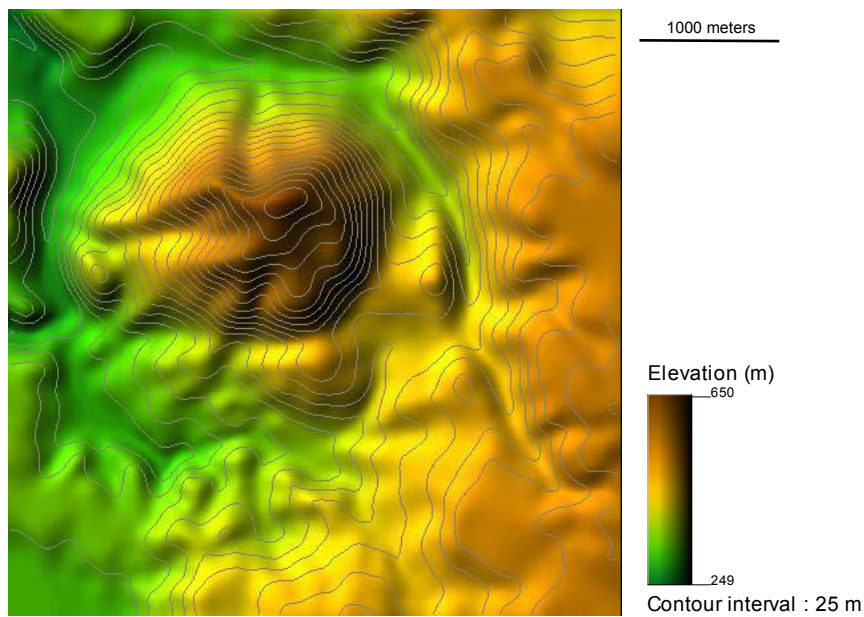


Fig. 2. Digital elevation model of the Karancs-Medves area

2.1. Hydrological approach — flow accumulation

The common characteristic of flow accumulation models is that they all determine the catchment area regarding each cell of the DEM. Those cells whose catchment areas exceed a certain size can be marked as linear flows. The difference between all the models lies in the way they determine flow direction.

Deterministic 8 (D8) model (O’Callaghan and Mark, 1984)

In this model, in the case of each cell-water can flow to the area of any adjacent cell towards the steepest slope. This model results in eight possible flow directions, which is referred to in the name of the model (Fig. 3). We determine the steepest descent slope from a cell to its steepest downslope neighbour with a simple formula taking the elevation of the adjacent cells and the distance between the centres of cells into consideration.

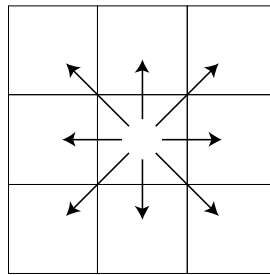


Fig. 3. The eight possible flow direction

This model is simple and traditional, therefore it is the most commonly used cell-based runoff model. General Geographical Information Systems (GIS) using cell-based models apply this model almost exclusively.

If we examine the flow accumulation result of the model, we can clearly see the main lines of the drainage network (Fig. 4). However, in the case of divergent or planar areas, where non-linear flow conditions (surface and subsurface runoffs) are prevalent, the model is not realistic. A lot of cells seem to be without inflow, although they are not situated on a drainage divide. The reason for this lies in the delimitation of flow directions to eight. On planar slopes where aspect is between two possible directions, eight directions prove to be too few. In this case we get parallel orthogonal or diagonal drainage lines, because flow direction cannot exactly match the aspect.

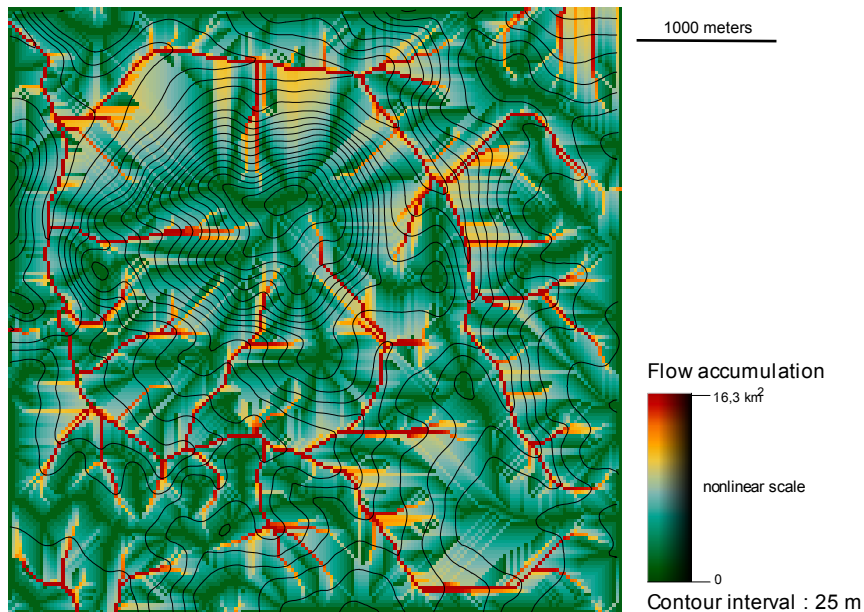


Fig. 4. The flow accumulation result of the D8 model

To obtain a channel network from the D8 model, we must define a threshold value serving as a minimum value when selecting cells with catchment areas for channels.

By analysing three different threshold values we can see that if the value we choose is too small, errors can be detected even along those channels that are correctly determined. These errors can be eliminated by increasing the threshold value, but after this modification the number of determined channels will be decreased (Fig. 5). There is no general rule to

establish threshold values. Among other things the optimal scale of thresholds may depend on the scale of the model or the morphological and geological characteristics (e.g.: drainage density, relief energy) of the area.

By edging away from the drainage divide the value of flow accumulation increases exponentially, makes establishing a correct threshold value even more problematic.

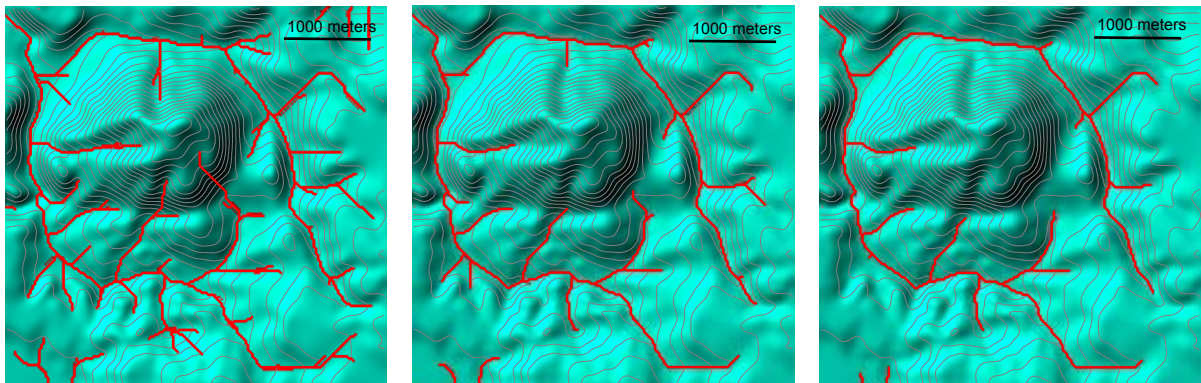


Fig. 5. The channel network from the D8 model. The threshold values are 50000 m², 150000 m² and 250000 m²

Multiple flow direction (MFD) model (Freeman, 1991)

This model considers drainage of a divergent flow, so the drainage of the particular cells flows downslope to several adjacent cells of lower elevation. The scale of divergence is determined by the slope of the cell. Similarly to the D8 model, the calculation of flow accumulation to each adjacent cells (i=1..8) is simple and is done by the following formula:

$$f_i = \frac{\max(0, S_i^p)}{\sum_{j=1}^8 \max(0, S_j^p)}$$

where S_i, S_j is the slope to adjacent cells (if cell_i is upwards, then $S_i < 0$; if cell_i is downwards, then $S_i > 0$; if the two adjacent cells have the same height, then $S_i = 0$), P is the weighting of divergence, based on the analyses the optimal value can be determined as 1.1.

Examining the result (Fig. 6) we can see that the MFD model’s result is only realistic in divergent surface and subsurface drainage circumstances, while along linear flows — especially at wide valley bottoms — the resulting divergence is not realistic. The effect is rather like a wet zone than a narrow channel. Therefore, the model cannot be applied for the threshold-based direct channel determination specified under the D8 model, since the resulting network is often unconnected.

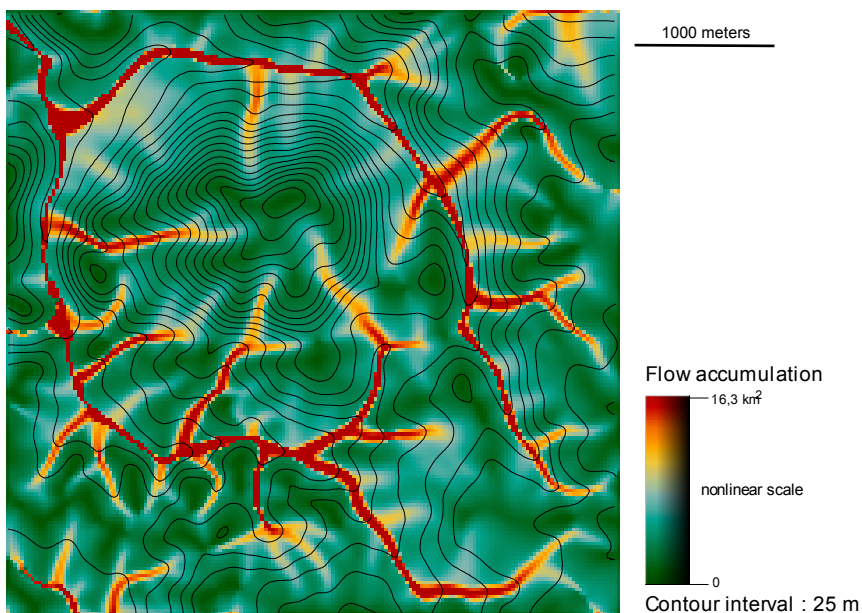


Fig. 6. The flow accumulation result of the MFD model

MFD-D8 model

Analysing the previous two models we can see that they complement each other: the divergent MFD model can be applied at the initial, upper parts of flows, while the D8 model has good results for linear flows. For the switching between the models another threshold value can be applied. The result of such a hybrid model is demonstrated on Fig. 7.

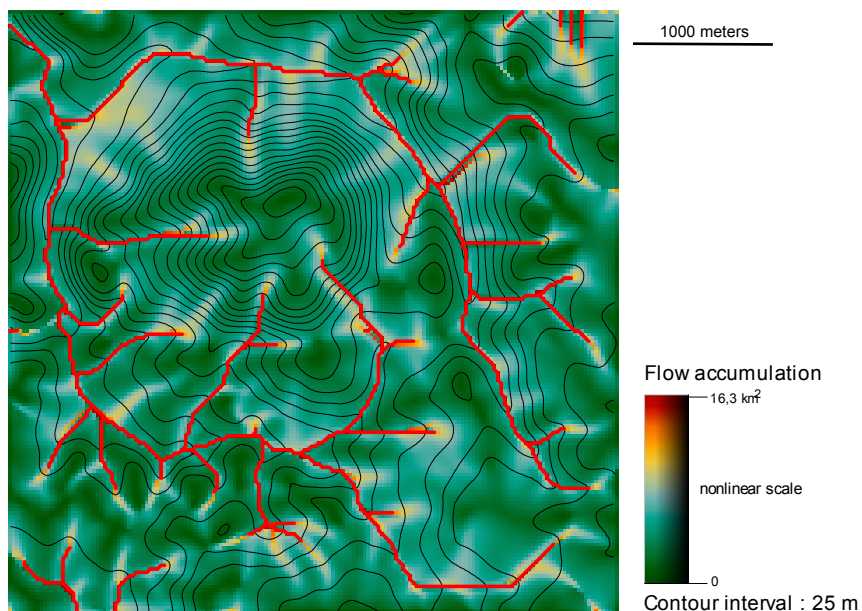


Fig. 7. The flow accumulation result of the MFD – D8 model

Assessing flow accumulation methods we can conclude that the critical point of the models is determining the threshold value for linearity.

2.2. Morphological approach: Convergence index

Several types of convergence index are known. In the following we will examine the simplest of them, which determines convergence index on the basis of aspect (Köthe and Lehmeier, 1994). The index is obtained by averaging the bias of the slope directions of the adjacent cells from the direction of the central cell, and subtracting 90 degrees. The possible values of the index range from -90° to $+90^\circ$ according to Fig. 8.

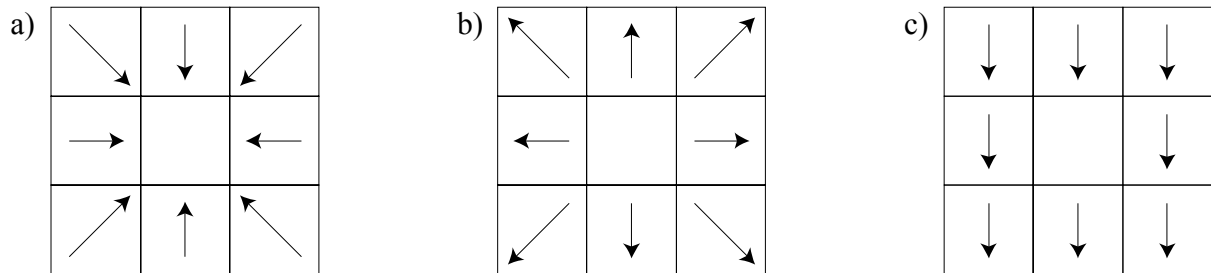


Fig. 8. Calculating the convergence index on the basis of aspect. The averages of the relative aspects are 0° (a), 180° (b), and 90° (c). The convergence indexes are -90° (a), 90° (b), 0° (c)

Figure 9 demonstrates the spatial distribution of the convergence indices on the study area. The result shows the morphological structure of the area clearly, ridges and valleys are well-defined. However, just as in the case of the MFD method, this approach is unsuitable for obtaining a drainage network.

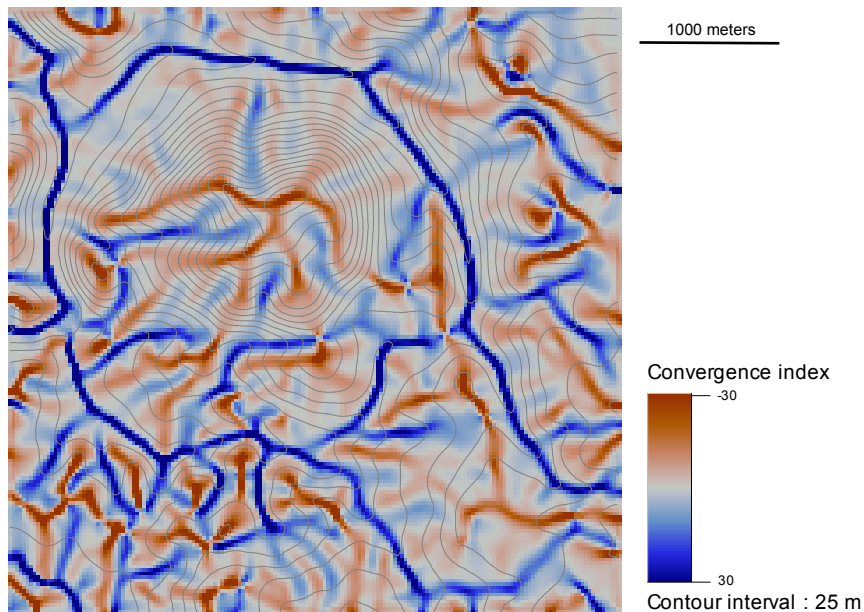


Fig. 9. The spatial distribution of the convergence index

MFD-D8-convergence threshold model

As we can see, on the basis of the convergence index we can draw conclusions concerning the nature — convergent or divergent — of the flow, and thus concerning the linearity of the flow. Therefore it can be used as a spatial threshold-value of the MFD-D8 model. The model is

structured as the following: according to the MFD model, we calculate flow accumulation values beginning from drainage divide to that point where the convergence-index is smaller than a certain threshold-value defined before. From this point we apply the D8 model. To reduce errors, as a further basic condition to linearity, we can establish the minimum length, under which the convergence value must remain under the threshold-value.

In this case we also establish the threshold-value by trial and error.

Looking at the result of the model we can see that channels are more clearly defined than in the previous models (Fig. 10). As opposed to flow accumulation models, the advantage is that we also obtain the actual channels for those catchment areas which are not fully covered by the given dataset (we can find such catchment areas at the edge of the DEM). In the case of flow accumulation models, catchment size can be calculated from the edge of the DEM, this way the calculated catchment size will be smaller than in reality.

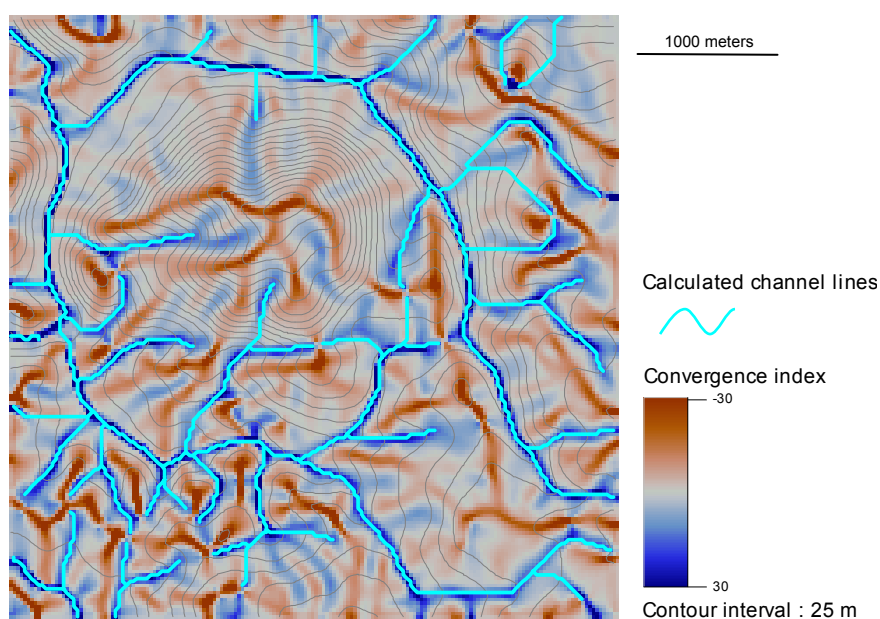


Fig. 10. The channel network determined with convergence-threshold model

2.3. Geomorphological-process competition for channel initiation

This model is based on different landscape evolution models.

The relief of the Earth was formed by the competition of different processes between hillslope and channel processes (Kirkby, 1986, 1993; Willgose et al., 1991; Howard, 1994, Tucker and Brass, 1998).

For the modelling of hillslope processes (freeze-thaw, rainsplash, bioturbation, etc) the diffusive hillslope transport model is used. According to this model the intensity of hillslope processes (H) is proportional to the degree of slope.

$$H = k_d S$$

where S is slope and k_d is a constant.

For channel processes we must differentiate between two cases: 1. if the surface is covered by easily abrading regolith, the amount of sediment flux is maximised by sediment transport capacity (transport limited model); 2. if the surface is more resistant (bedrock, dense vegetation), the scale of erosion can remain under the transportable amount of materials (detachment-limited case), and it depends on how fast the transportable materials form.

Here we model the transport limited case. According to this model, the amount of transportable material by the linear runoffs depends on the amount of water running off the surface, and the degree of slope. The following formula is used to calculate the water-borne sediment flux, Q_s (Tucker and Brass, 1998):

$$Q_s = k_f Q^m S^n$$

where Q is the total surface water discharge, S is slope and k_f, m, n are constants.

$$Q_s = k_f (PA)^m S^n$$

where A is the contributing area, P is a constant and $Q = PA$.

For a hillslope profile, the point of transition from diffusion-dominated to runoff-dominated erosion can be defined as the point at which the two processes are equally effective in transporting sediment (Howard, 1997):

$$k_d S = k_f (PA)^m S^n$$

$$\frac{k_d}{k_f P^m} = A^m S^{n-1}$$

If $\theta_l = \frac{k_d}{k_f P^m}$ and $l = n - 1$, this reduces to

$$\theta_l = A^m S^l$$

So the result is that there is transition between the processes, where $A^m S^l$ reaches θ_l value, which can be interpreted as a threshold-value for linearity.

From the model discussed above we can draw that useful conclusion that if we weigh the linearity threshold of the flow accumulation model by the degree of sloping, the result is a flow network that can reflect the recent geomorphological processes more (Fig. 11).

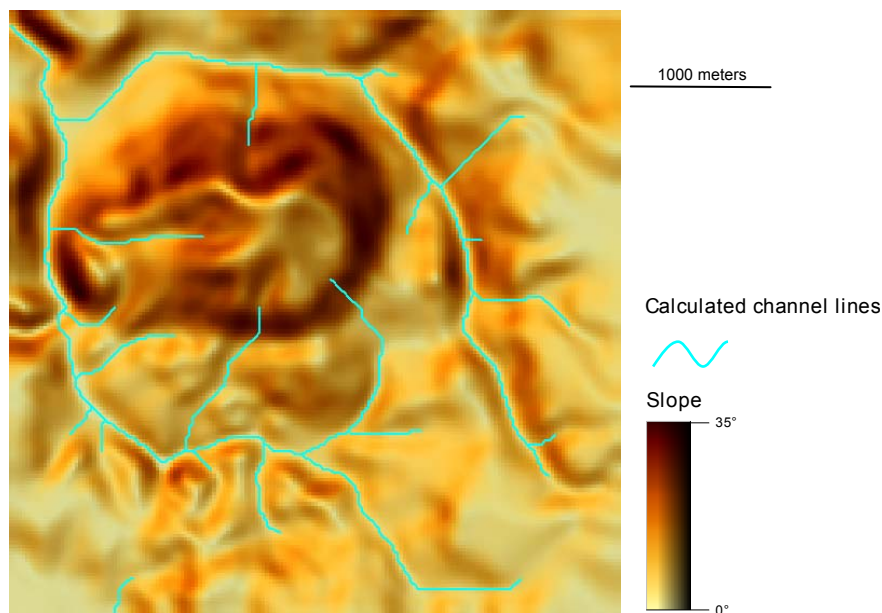


Fig. 11. The channel network determined with the Slope-Area-threshold model

3. Limitations

Models based on flow accumulation thresholds — especially if the degrees of sloping are used for determining thresholds — reflect the potential erosion work caused by the accumulated water. This many times coincides with the actual valleys, however, it is not always possible to determine a single threshold for all subcatchments, since, among other things, it depends on the spatial variability of the climate, relief, geology, vegetation and stage of evolution.

Models which use convergence index thresholds recognise evolved valleys by their shape, disregarding the amount of water running off. In this case the channels in their initial evolutionary stages may go unnoticed, and because of the DEM's resolution (usually above 10–30 m cellsize) it does not show convergence. There may be cases when due to a change in the circumstances (e.g.: climate change, capture), we get channel flows at places where the morphological conditions are given by linear runoffs (convergence), however, in reality they do not exist there.

This model also presupposes that if once the accumulated waters become linear runoffs, they keep this characteristic. This assumption is true for the upper parts of catchments with greater relief, but if we also decide to model bifurcation, we must modify the models discussed above to obtain appropriate results.

Those areas may also prove problematic where the movement of water runoff is not primarily determined by relief, because there are strong geological controls on subsurface flow. Such areas are karst landscapes, for example, where waters run dominantly under the surface, or in sandy areas, where the flow directions of ground water show the flow routes.

The results of the model are greatly affected by the spatial resolution of the DEM. The methods discussed so far apply to high-resolution DEMs (10–30 m cellsize). If we increase the cell size, we will be unable to model minor processes and forms. Since the area is more scale

invariant than the other characteristics (e.g.: slope, convergence-index) (Klinkenberg, 1992; Yin and Wang, 1999) we apply the D8 model when analysing global DEMs of larger cellsize (over 100 m). The result can be further improved if we make the best of the fractal nature of drainage system (Mandelbrot, 1982). However, the results of this are still to be improved under development.

4. Applications and results

In this part I will demonstrate the application of the drainage models discussed above through an example. The task is to draw up a water-damage prevention plan for a part of the Pannonhalma hills in Hungary. The main river of the area is the Nagy-Pándzsa. The examined area can be divided into 28 catchments (Fig. 12) — some of these are built up, some are natural areas, but most catchments are situated on areas which are the combinations of these types.

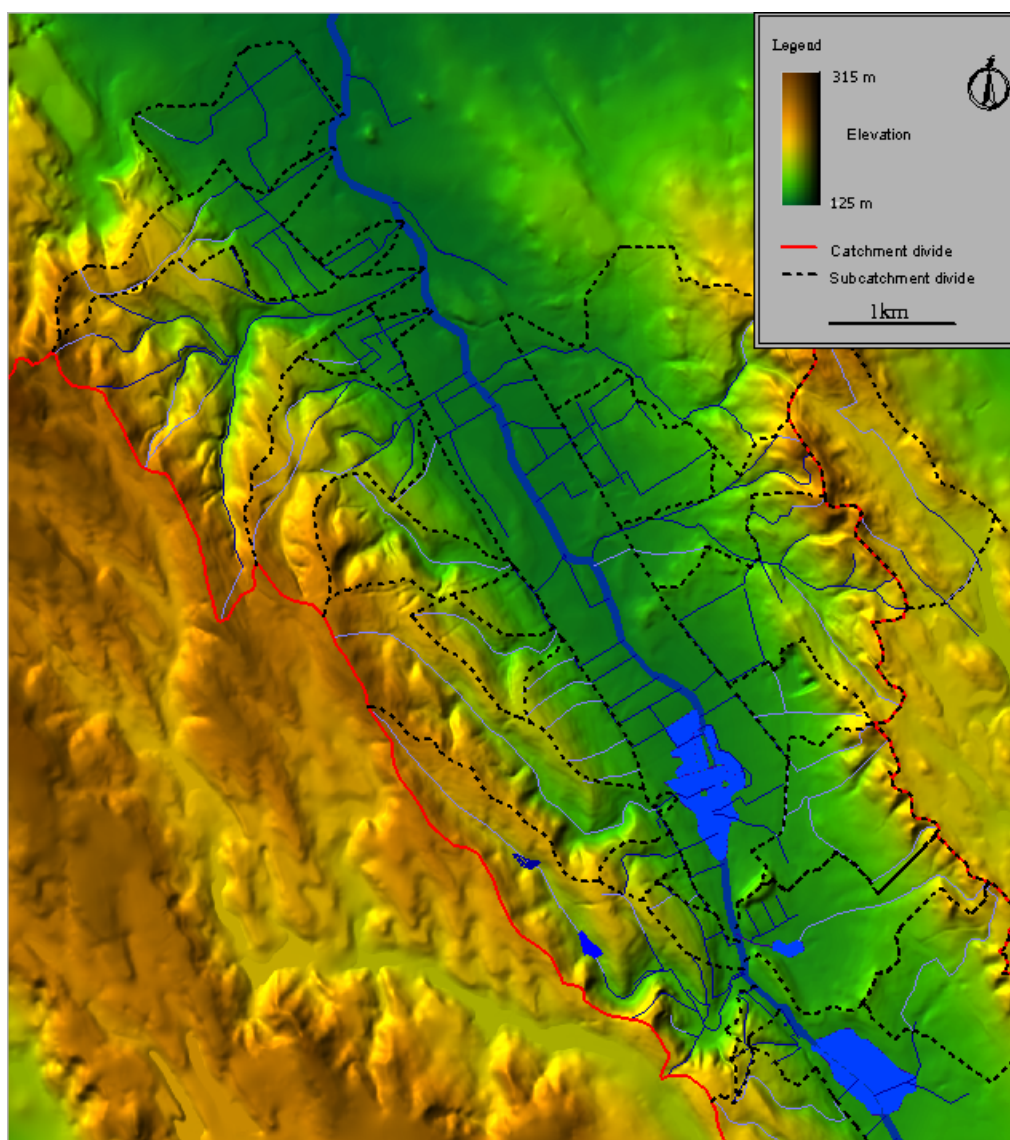


Fig. 12. The DEM and the catchments of the area

The MFD—D8 convergence-threshold index model is used as a drainage model. Ground survey has made it clear that the model cannot give a proper result on its own. The reason for this is that there are numerous artificial — mainly linear — objects on the area that do not appear in the DEM because of the scale of the map used. In some cases the objects that modify the drainage network (e.g.: canals, roads) have so strong effect on the drainage routes that subcatchment divides can be displaced (Fig.13).

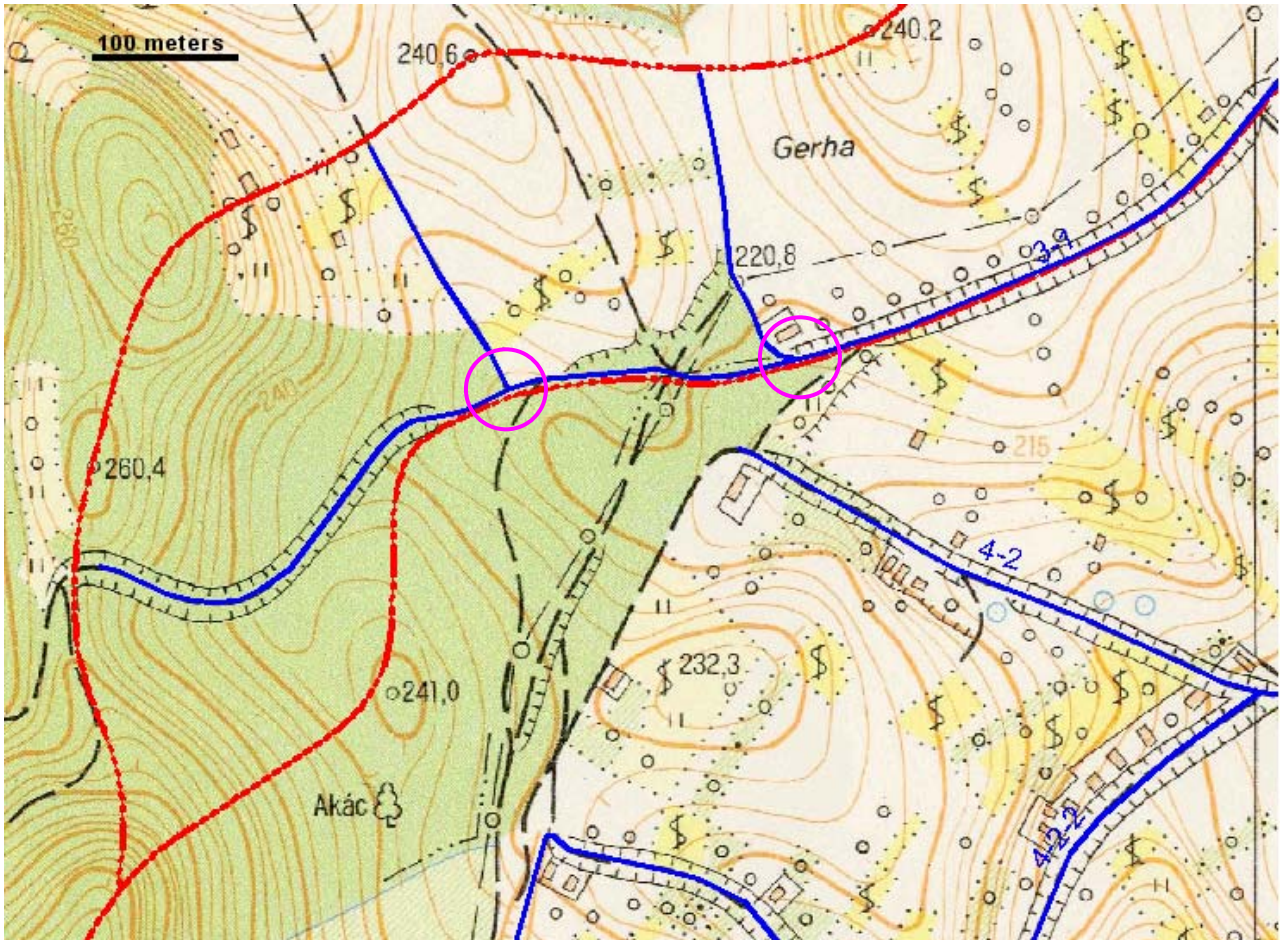


Fig. 13. Capture of a road

To correct these errors we inserted a so called 'drainage forcing' network in the model, which indicates the flow directions of artificial linear objects, too.

The catchment model that we obtain this way topologically shows subcatchments and drainage routes and it makes possible to carry out complex analyses.

The main parts of this complex engineering catchment model are the following:

- DEM
- morphometrical maps (slope, aspect)
- natural and artificial drainage routes
- parameters of artificial drainage routes and their parts (e.g.: locks, culverts etc.)
- bounded catchments, subcatchments
- landuse
- defining authoritative water amount for drainage model

On the basis of experience, automatic drainage network definition can be used on natural areas with good results, but can also prove useful in other cases. I must emphasize the importance of ground survey, since it is essential for creating a correct and reliable model.

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