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ANALIZA RAZLIK MED METODAMI AVTOMATSKEGA DOLOČANJA RAZVODNIC NA PRIMERU POVODJA ROKAVE
AN ANALYSIS OF THE DISCREPANCIES BETWEEN AUTOMATIC CATCHMENT DELINEATION METHODS IN THE CASE OF THE ROKAVA WATERSHED

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Prispevek predstavlja dva načina avtomatskega določanja razvodnic na podlagi digitalnega modela višin s prostorsko ločljivostjo 25 m. Najprej je bil uporabljen znani algoritem D8, izboljšan z novimi metodami odpravljanja lažnih depresij. Nato pa je bilo razvito še orodje na podlagi algoritma DEMON-Upslope. Ustreznost obeh postopkov je bila preverjena na povodju Rokave, kjer je bila izvedena primerjava z razvodnicami, ki so bile določene ročno na podlagi plastnic temeljnega topografskega načrta v merilu 1:5000. Oba postopka sta se ob uporabi DMV25 izkazala kot primerna za določanje razvodnic prispevnih površin do šeste ravni, zlasti v strmejšem delu povodja. Postopek D8 je dal slabše rezultate na dolgih pobočjih, ki ne potekajo v glavnih smereh neba. Povodje Rokave leži v gričevnatem svetu Slovenskega Primorja, zato so rezulati reprezentativni za dobršen del Slovenije in sredozemskega sveta, z izjemo kraškega sveta.
Ključne besede: *hidrologija, D8, DEMON-Upslope, Rokava, gričevnat svet*

The paper presents two methods for automatic catchment delineation based on a digital elevation model with a spatial resolution of 25 m. First, the D8 algorithm was used, extended with the recent false depression handling methods. Then, a tool based on the DEMON-Upslope algorithm was developed. The accuracy of the two methods was tested on the Rokava watershed. A comparison with the delineation, based on the contours of a 1:5000 topographic map, was carried out. Both methods, when used with the DEM25, turned out to be appropriate for catchment delineation up to the sixth level, especially in the steeper part of the catchment. The D8 algorithm made some mistakes on the long slopes, which run in a direction different from a cardinal direction. The Rokava catchment lies in the coastal part of Slovenia; therefore, the results are representative for the Mediterranean countries, with the exception of the karst areas.
Key words: *hydrology, D8, DEMON-Upslope, Rokava, hilly terrain*

1. UVOD

Za nekatere vrste okoljskih analiz, kot so npr. hidrološki modeli, je treba povodja deliti na prispevne površine. Način določanja razvodnic je odvisen od vsebine topografskih kart oziroma modelov površja, ki so na voljo. Digitalni modeli površja, ki so zdaj na voljo že v kar dobri prostorski ločljivosti, omogočajo avtomatsko določanje razvodnic na območjih, kjer so meje povodja odvisne od površja (t.j. na nekraških območjih).

1. INTRODUCTION

Definition of catchment boundaries and areas is a starting point for all hydrological and many ecological analyses. The method depends on the content and type of the available topographic maps and terrain models. Digital terrain models, which are now available in quite satisfactory spatial resolution, allow for automatic catchment delineation in the areas where the catchment boundaries are defined by topography (i.e. non-karst areas).

Najpogostejši načini predstavitve površja so plastnice, TIN (nepravilna trikotniška mreža, angl. *triangulated irregular network*) in pravilna kvadratna mreža oziroma raster. Tiskane karte obstajajo samo v prvi obliki. Zančilnosti in prednosti ter slabosti vsakega od teh načinov predstavitve površja za hidrološke analize so opisane v naslednjih odstavkih.

1.1 PLASTNICE

Plastnice so črte, ki tečejo vzdolž točk z enako nadmorsko višino. V digitalni obliki so predstavljene kot zaporedje vozlišč usmerjenega grafa, ki opisuje posamezno plastnico. Za uporabo v hidroloških aplikacijah lahko pravokotno na plastnice konstruiramo še črte največjih nagibov (angl. *steepest slope lines*). Tako dobimo mrežo topografsko prilagojenih elementov, ki so zgoraj in spodaj omejeni s plastnicami, ob straneh pa s črtami največjih nagibov.

Prednosti take predstavitve površja so očitne. Med črtami največjih nagibov ni pretoka, kar omogoča pregled nad kontinuiteto vodnega toka in preprosto določanje prispevnih površin. Zato je modeliranje površja na ta način najbližje bistvu fizikalnih procesov, ki so povezani s površinskim tokom vode (Menduni & Riboni, 2000). Slabost pa je zlasti v tem, da so podatki, pridobljeni s postopki daljinskega zaznavanja, kot je npr. raba tal in rastlinski pokrov, običajno v rastrski obliki. Za samo izgradnjo prostorske sheme elementov in za določanje njihovih lastnosti je torej potrebno precej dela, so pa kasneje simulacije naravnih procesov preprostejše in rezultati preglednejši.

1.2 NEPRAVILNA TRIKOTNIŠKA MREŽA

Nepravilna trikotniška mreža (TIN) je način predstavitve površja, pri katerem je površje razdeljeno na trikotnike poljubnih velikosti in oblik. Pri tem se uporablja Delaunayeva trangulacija (Delaunay, 1934). Glavna prednost tega načina je, da je mogoče površje dobro predstaviti že z zelo majhnim številom elementov: mrežo zgostimo tam, kjer je površje razgibano, kjer pa je homogeno,

The most common ways of terrain representation are contours, TIN (triangulated irregular network) and square grid (raster) cells. Printed maps exist in the first form only. The properties, advantages and drawbacks of each of the three forms of terrain representation for hydrological modelling are described in the following paragraphs.

1.1 CONTOURS

Contours are lines that connect points with the same elevation. In digital form each contour is represented as a set of vertices of an oriented graph. For use in hydrologic applications, steepest slope lines are constructed. These lines run perpendicularly to the contours. In that way, the surface is represented by topography fitted elements whose upper and lower boundaries are determined by contour lines, while the left and right boundaries are determined by steepest slope lines.

There is an obvious advantage of such a terrain model. There is no flow across the steepest slope lines, which enables a clear view of the continuity of the water flow and a simple determination of the contribution areas. Being so, modelling the surface in this way is closest to the phenomenon related to surface flow (Menduni & Riboni, 2000). The main disadvantage lies in the fact that most of the data, collected by remote sensing, e.g. land use and cover, is normally given in raster format. Therefore, for both construction of the elements and the determination of their properties, a considerable amount of work is required. However, further work is more straightforward and the results are easier to interpret.

1.2 TRIANGULATED IRREGULAR NETWORK

Representation by a triangulated irregular network means that a surface is described by triangles of any size and form. Delaunay's triangulation (Delaunay, 1934) is used to construct the triangles. The main advantage of TINs is the low number of elements that are required for a satisfactory surface representation. Where the surface is variable, small elements are used; where the surface is uporabimo večje elemente. Prednost TINov pred rastrskimi shemami je tudi ta, da lahko shranjujemo podatke o črtah spremembe naklona in višinskih točkah ter dobro opišemo tudi navpične strukture (Kvamme et al., 1997). Primer uporabe TINov za določitev hidrografske mreže in razvodnic podajata Palacios-Velez & Cuevas-Renard (1986). TINi torej predstavljajo dobro možnost za modeliranje z metodami končnih elementov, težava je le pomanjkanje fizikalnega pomena takega načina delitve površja (Menduni & Riboni, 2000). Težave nastopijo tudi v primeru interpolacije digitaliziranih plastnic, kjer se v dolinah in grebenih pojavljajo vodoravni trikotniki, če tam ne priskrbimo dodatnih točk (Clark, 1990 v Hutchinson & Gallant, 2000).

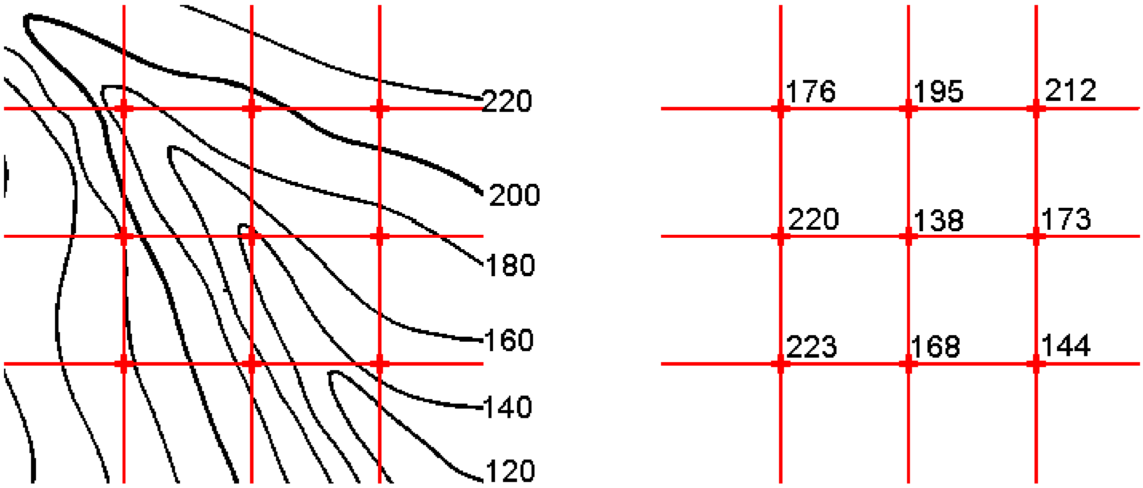
1.3 RASTER

Raster je kvadratna mreža točk, položenih čez obravnavano območje (Kvamme et al., 1997). To je najbolj razširjena oblika digitalnega modela višin (DMV). Glavni razlogi so preprosta računalniška obdelava in v določenih pogledih velika učinkovitost, poleg tega pa so podatki, povezani z ekološkimi, in torej tudi hidrološkimi, modeli, pridobljeni s postopki daljinskega zaznavanja, ter so zato največkrat v rastrski obliki (Menduni & Riboni, 2000). Po drugi strani pa so topografski podatki, to je točke izmerjenih nadmorskih višin, nepravilno razporejeni po obravnavanem območju, ker so oblike površja same po sebi neenakomerne. Zato interpolacija višin v rastrsko mrežo ne more vedno slediti izvirni informaciji. Tako v topografsko kompleksnih območjih (pečine in druga strma območja, lomi terena ipd.) primanjkuje informacij za korektno predstavitev terena. Nasprotno pa je količina informacij v topografsko nezahtevnih gladkih območjih večja od potrebne. Pogosta težava pri rastrskih modelih so tudi lažne depresije, ki povzročajo težave pri določanju smeri površinskega toka vode. Te so posledica bodisi napak DMV ali pa kvadratne razporeditve točk (Rieger, 1998). Kako v ozki dolini nastane lažna depresija zaradi kvadratne mreže, je razvidno iz slike 1. Primer uporabe rastrskega DMV za hidrološko modeliranje podajata Smith & Brilly (1992).

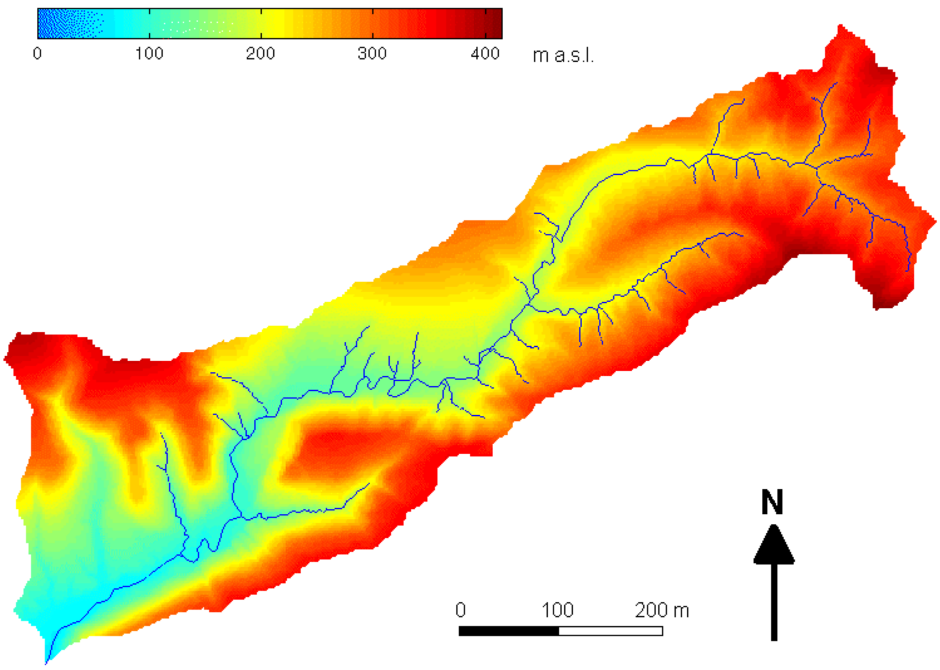
smooth, the elements can be larger. The advantage towards the square grid representation of the surface lies in the ability of the TINs to easily describe both the rapid changes in relief and the vertical structures (Kvamme et al., 1997). An example of using TINs for catchment delineation is given by Palacios-Velez & Cuevas-Renard (1986). Therefore, the TINs are suitable for finite elements modelling. However, the lack of physical meaning of such a terrain representation remains (Menduni & Riboni, 2000). Difficulties can be expected when TINs are constructed from the points of a digitised contour map, where flat triangles often appear in the valley bottoms and on the ridges (Clark, 1990 in Hutchinson & Gallant, 2000).

1.3 RASTER

The raster is a square grid of elevation points (Kvamme et al., 1997). This is the most common form of digital elevation model (DEM). The main reasons for that are the ease of computer implementation, and, in certain aspects, computational efficiency. Moreover, many of the ecologic, and among them hydrologic, data derive from the remote sensing technique and are, therefore, in raster format (Menduni & Riboni, 2000). On the other hand, the elevation data is commonly non-uniformly distributed, since the terrain features themselves are non-uniform. Therefore, the interpolation of elevation data into a regular grid point mesh cannot always honor the original information. In topographically complex areas (cliffs and other steep areas, terrain break lines, etc.), the grid based information is insufficient for correct terrain represtentation. In smooth areas, on the other hand, the amount of information is redundant. Another common problem with the grid models are false depressions that cause difficulties in determining flow direction. They are either a consequence of data errors or of the grid structure itself (Rieger, 1998), as can be seen in Figure 1. An example of a hyrological model based on raster DEM is given by Smith & Brilly (1992).



Slika 1. Lažna depresija kot posledica razporedtve točk v kvadratno mrežo: vse sosednje točke imajo večjo višino kot srednja točka. Levo - plastnice, desno - nadmorske višine.
Figure 1. False depression caused by grid structure: all neighbours have a higher elevation than the point in the center. Left – contours; right - elevation in points.



Slika 2. Povodje Rokave: relief z mrežo vodotokov.
Figure 2. Rokava catchment: Terrain model and drainage network.

2. OBRAVNAVANO OBMOČJE

Reka Rokava je levi pritok Dragonje, ki se v Sečoveljskih solinah izliva v Jadransko morje. Smer toka je v glavnem od vzhoda proti zahodu oziroma severovzhod-jugozahod. Povodje Rokave leži v osrednjem delu Slovenske Istre. To je dobro razčlenjen gričevnat svet, s srednjo nadmorsko višino 250 m. Najnižja točka je sotočje z Dragonjo (75 m NMV), najvišja pa 415 m NMV. Površina povodja je 20.4 km^2. Vzdolžni padec doline je v zgornjem delu 0.022, v spodnjem delu pa 0.014. Srednji nagib površja je 25 %. Relief z mrežo vodotokov je prikazan na sliki 2.

3. METODE ZA DOLOČANJE RAZVODNIC

3.1 ROČNO DOLOČANJE RAZVODNIC NA PODLAGI PLASTNIC (TTN 1:5000)

Prva, ki sta uporabila topografsko prilagojene elemente, določene na podlagi načrta plastnic, na področju hidrologije sta bila Onstad & Brakensiek (1968). Enako kot meje topografsko prilagojenih elementov, tudi meje prispevnih površih, t.j. razvodnice, določimo tako, da sledimo črtam največjih nagibov.

Glede na smer, v kateri iščemo največje nagibe, ločimo dva tipa črt največjih nagibov: črte največjih padcev (angl. *downslope steepest slope lines*) in črte največjih vzponov (angl. *upslope steepest slope lines*). Prve so identične tokovnim potem (angl. *flow paths*). To so črte, ki jim pri površinskem odtoku po pobočju sledi posamezen vodni delec od grebena proti dnu doline. Te črte se cepijo na grebenih in se združujejo v dnu dolin (slika 3). Na ta način dobimo informacijo o mreži odvodnikov. Nasprotno pa se črte največjih vzponov cepijo v dnu dolin in združujejo na grebenih. Na ta način dobimo informacijo o grebenih in jih zato uporabljamo pri določanju razvodnic. Črte največjih padcev in vzponov so na pobočjih, kjer se ne ene ne druge niti ne cepijo niti ne združujejo, identične.

2. DESCRIPTION OF THE AREA

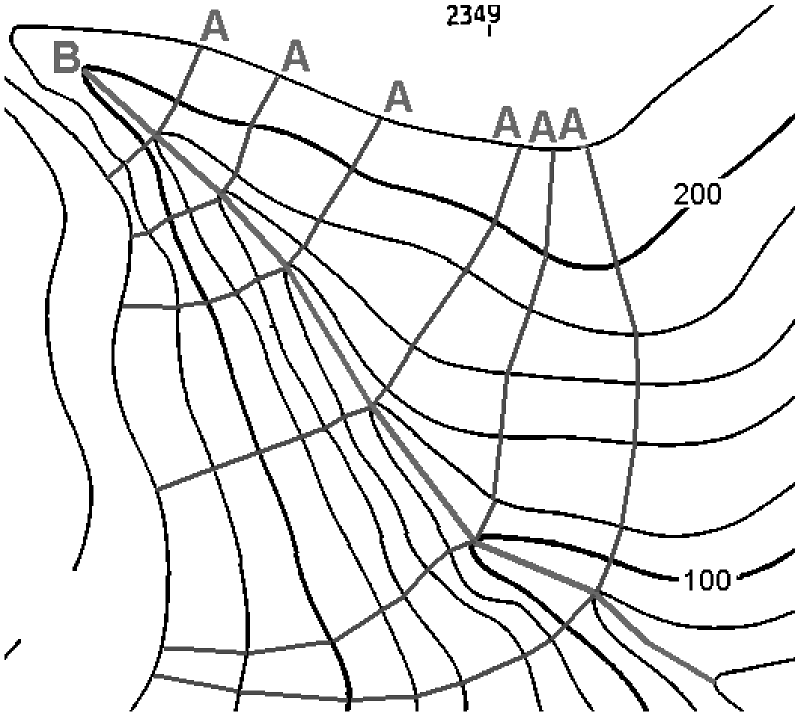
The Rokava River is a left tributary of Dragonja River, which drains into the Adriatic Sea in the Sečovlje saltworks. The river mainly flows from east to west or northeast to southwest, respectively. The Rokava catchment lies in the central part of the Slovene part of the Istria peninsula. This is a predominantly hilly terrain with mean elevation of 250 m. The lowest point is the confluence with the Dragonja (75 m a.s.l.); the highest peak is 415 m a.s.l. The catchment area amounts to 20.4 km^2. The longitudinal slope of the valley is from 2.2 % in the upper part to 1.4 % in the lower. The mean slope of the area is 25 %. The terrain model and drainage network are given in Figure 2.

3. METHODS FOR CATCHMENT DELINEATION

3.1 CATCHMENT DELINEATION BASED ON TOPOGRAPHIC MAP 1:5000

In the field of hydrology, Onstad & Brakensiek (1968) were the first to use topographically fitted elements. Catchment delineation follows the same principles as topographically fitted elements construction, i.e. following the steepest slope lines.

Depending on the direction in which the steepest slopes are searched for, two kinds of steepest slope lines can be determined: downslope steepest slope lines and upslope steepest slope lines. The first are identical to flow paths, i.e. the lines that the surface flow follows from the ridge to the valley bottom. These lines diverge on the rides and converge in the valley bottoms (Figure 3). In this way the information about the drainage network can be obtained. On the other hand, the upslope steepest lines diverge in the valley bottoms and converge on the ridges. In this way the information about the ridges can be obtained. Therefore, the latter ones are used for catchment delineation. On the hillslopes, neither downslope nor upslope steepest slope lines converge or diverge. In this case, they are identical to each other.



Slika 3. Črte največjih vzponov (A) in padcev (A in B) v dnu doline.
Figure 3. Downslope (A and B) and upslope (A) steepest slope lines in a valley bottom.

Odsek črte največjih nagibov med dvema plastnicama idealno zadošča naslednjim trem pogojem (Menduni & Riboni, 2000): je pravokoten na nižje in višje ležečo plastnico in je najkrajša razdalja med njima. Ker med dvema plastnicama nimamo dodatnih informacij o površju, so črte največjih nagibov med dvema plastnicama ravne. Zato večinoma ne morejo zadostiti vsem trem omenjenim pogojem. Pri ročnem določanju se lahko o najustreznejšem merilu odločamo za vsak primer posebej. Za avtomatsko (računalniško) določanje se uporabljata dve merili: najkrajša razdalja ali pa pravokotnost na nižje ležečo plastnico (Hutchnison & Gallant, 2000; TOPOG WWW; TAPES WWW).

V okviru te naloge so bile razvodnice določene ročno z risanjem črtovja na skaniran načrt plastnic. Uporabljen je bil programski paket AutoCAD (Autodesk, 1997). Kot podlaga so bili vstavljeni skenirani temeljni topografski načrti merila 1:5000 (vir: GURS). Najprej so bile s plasti "vode" digitalizirani vodotoki. Kjer je bilo ob ogledu terena ugotovljeno, da se voda površinsko steka v cestne jarke, so bili tudi ti upoštevani kot del

Ideally, the segment of a steepest slope line between two contours satisfies the following conditions (Menduni & Riboni, 2000): they are perpendicular to both upslope and downslope contours, and are the shortest distance between them. Since there is no information about the terrain surface between two contours, the segments are straight. For this reason, they cannot satisfy all the above mentioned conditions. If lines are drawn by hand on a map, the most suitable criteria can be selected, depending on the specific case. For automatic determination of the lines, one of the two following criteron can be applied: the shortest distance, or the perpendicularity to the downslope contour (Hutchnison & Gallant, 2000; TOPOG WWW; TAPES WWW).

In the framework of this project, the lines were determined non-automatically by drawing polylines over a scanned contour map. An AutoCAD (Autodesk, 1997) software package was used. The scanned contour map for the scale 1:5000 was obtained form GURS. First, the blue lines were digitised from the layer "water". During field visits, the road ditches that intercept some surface runoff were evidented and considered as part of the mreže odvodnikov. Ceste s prepusti so bile digitalizirane s plasti "naselja in promet". Digitalizacija je potekala vektorsko, digitalizirani material pa je prikazan an sliki 4. Nato so bile po opisanem postopku črt največjih vzponov na podlagi plasti "relief in plastnice" vrisane izbrane razvodnice. Izbor razvodnic je bil tak, da je bilo z njim povodje deljeno do šestega nivoja po šifrantu KSH (Šraj, 2000).

drainage network. The roads and culverts were digitised from "settlements and traffic" layers. The digitised material was of vector format and is given in Figure 4. Then, following the above described procedure, the selected upslope steepest lines were drawn based on the "contour" layer of the map. The selection of the lines was done so that they determine the catchment partitioning to the sixth level of the KSH coding system (Šraj, 2000).

Slika 4. Digitalizirani vektorji hidrografske (polne črte) in cestne (črtkane črte) mreže.
Figure 4. Digitised vectors of drainage network (solid lines) and road system (dotted lines).

3.2 AVTOMATSKO DOLOČANJE RAZVODNIC NA PODLAGI DMV25

3.2.1 OCENA TOČNOSTI IN PRIPRAVA DMV25

Digitalni model višin v prostorski ločljivosti 25 m (DMV25), uporabljen v tej nalogi, je pripravila Geodetska uprava Republike Slovenije (GURS). Izdelan je bil na podlagi ortofotografskih snemanj. Višine so podane v centimetrih. Povprečna višinska točnost podatkov, kot jo je podal GURS, je podana v preglednici 1.

3.2 AUTOMATIC CATCHMENT DELINEATION BASED ON DEM25

3.2.1 ASSESSMENT OF ACCURACY AND PREPARATION OF THE DEM25

The digital elevation model with a spatial resolution of 25 m (DEM25) that was used in this project was published by the Surveying and Mapping Authority of the Republic of Slovenia (GURS). It was derived from an orthophoto survey. Elevations are given in centimeters. The average accuracy of the elevation data, as given by GURS, is given in Table 1.

Preglednica 1. Povprečna višinska točnost podatkov DMV25 (vir: GURS).
Table 1. Average accuracy of elevation data of DEM25 (source: GURS).

raven teren / *flat terrain*	1.5 m
razgiban relief / *smooth terrain*	3 m
hribovit relief / *hilly terrain*	6 m
poraščena območja / *forrested areas*	5 m

Najprej je bilo celotno območje pregledano s ciljem odkrivanja grobih napak. Za grobo napako bi veljal vsak podatek, ki se od povprečja svojih štirih sosedov razlikuje za več kot 12.5 m, kar je polovica razdalje med celicami; vendar grobih napak po tem merilu nismo odkrili.

Nadalje je bila točnost preverjena tako, da so bile iz DMV s programskim paketom MATLAB (MathWorks, 1997) zgrajene plastnice. Te smo primerjali s plastnicami temeljnega topografskega načrta, ki je bil uporabljen za ročno določanje razvodnic. Odstopajna so bila opazna zlasti na dnu ozkih dolin, na pobočjih pa je bilo ujemanje zadovoljivo.

Na ta način je bila istočasno ugotovljena tudi grobost oziroma gladkost modela. Pri modelu, ki je preveč grob, prihaja do nenaravnih nezveznosti v nagibih. Pri preveč zglajenih modelih pa se izgubljajo topografske značilnosti terena, kot so manjše doline in grebeni. Za primerjavo smo model zgladili s filtrom šibkega glajenja (Kvamme et al., 1997), ki je podan v preglednici 2. Pokazalo se je, da je že izvorna oblika reliefa dovolj gladka in je nadaljnje glajenje nepotrebno in povzroča le izgubo topografskih informacij.

First, the entire area was checked for gross errors. Each elevation data that was more than 12.5 m (half of the grid cell side) different from the average of its four cardinal neighbours was considered a gross error. Using this criterion, no gross errors were detected.

Another way of checking the accuracy was implemented. From the supplied DEM, contours were constructed using MATLAB software (MathWorks, 1997), and overlayed over the "contour" layer of the topographic map that was used in Chapter 3.1. Some discrepancies could be noted in the bottoms of the narrow valley, while on the slopes, the two maps matched well.

Simultaneously, the robustness of the model was assessed. If a model is too robust, an unnatural discontinuity in slope can appear. If a model is smoothed too much, some topographic features such as small narrow valleys and ridges can be lost. To check the robustness, the model was filtered by a weak filter (Kvamme et al., 1997) given in Table 2. It turned out that the original model was smooth enough. Further smoothing was unnecessary, and would have caused loss of topographic information.

Preglednica 2. Filter šibkega glajenja.
Table 2. Weak filter.

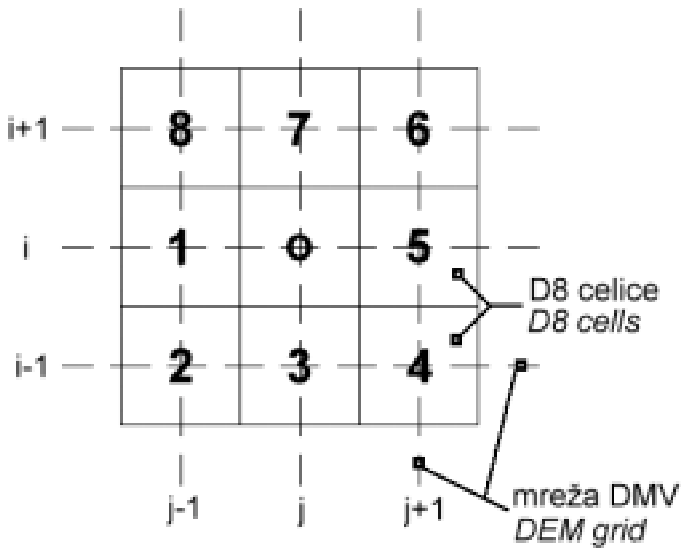
$$\begin{bmatrix} 0.025 & 0.075 & 0.025 \\ 0.075 & 0.600 & 0.075 \\ 0.025 & 0.075 & 0.025 \end{bmatrix}$$

3.2.2 ALGORITEM D8

Pri algoritmu D8 (O'Callaghan & Mark, 1984) imajo računske celice središče v točkah digitalnega višinskega modela. Tokovne poti določamo po metodi osmih sosednjih celic (slika 5). Najprej za vsako celico določimo gradiente do vsake od njenih osmih sosed. Nato določimo smer toka tako, da voda odteka v celico v smeri najmanjšega gradienta. Ko so smeri določene, lahko za vsako celico določimo prispevno območje ter vrsto drugih hidroloških parametrov. Algoritem lahko uporabimo tako za naravna kot tudi urbanizirana povodja (Smith & Vidmar, 1994).

3.2.2 ALGORITHM D8

In algorithm D8 (O'Callaghan & Mark, 1984), computational cells are centered in the grid points of the digital elevation model. Flow paths are determined using the method of eight neighbours (Figure 5). First, gradients to each of the eight neighbours are calculated. Then the flow direction is determined so that the water flows to the neighbour cell to which the gradient is lowest. When the flow directions for all cells are determined, contribution areas and other hydrologic parameters can be calculated. The algorithm can be applied to both natural and urbanised watersheds (Smith & Vidmar, 1994).



Slika 5. Osem sosednjih celic v pravokotni mreži.
Figure 5. The eight neighbours in a rectangular grid.

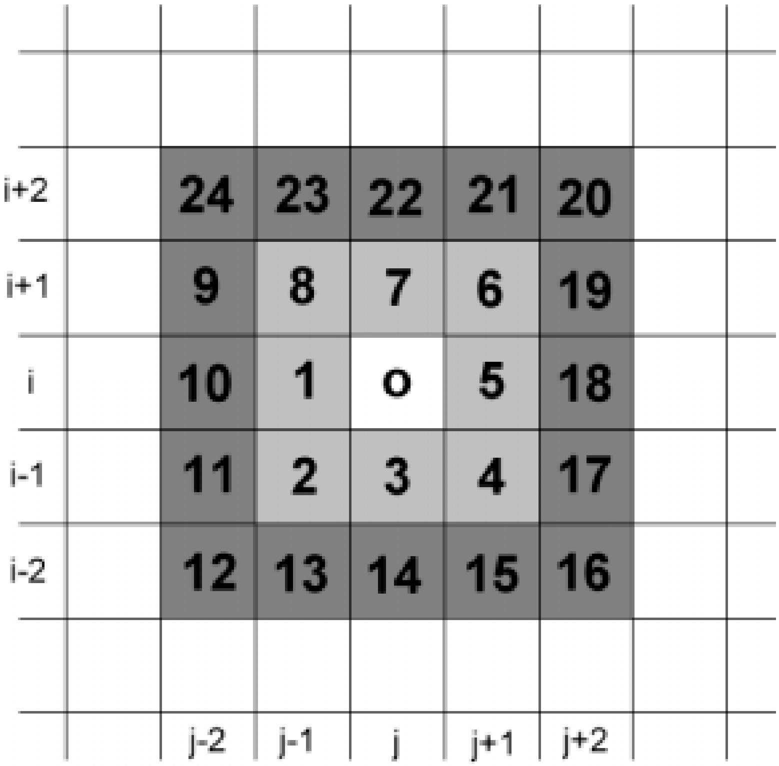
Glavna prednost algoritma D8 je preprostost. To je razlog, da je kot ena od možnosti vgrajen v večino sistemov za hidrološko analizo površja, kot sta npr. TAPES (TAPES WWW) in RiverTools (Research Systems, 2001). Slabosti algoritma izvirajo iz dveh lastnosti. Prvič, možne smeri toka so vnaprej določene, in sicer so to mnogokratniki kota 45°. Drugič, dvodimenzijske površine računskih celic so, kot viri toka, obravnavane kot točke (točkovni oziroma ničdimenzijski vir). Posledice so napačno določene smeri toka in napačne prispevne površine. Primere navajata Costa-Cabral & Burges (1994).

The main advantage of the algorithm D8 is the simplicity of the method. For that reason, it is incorporated into many of the hydrologic and terrain analysis systems, such as TAPES (TAPES WWW) and RiverTools (Research Systems, 2001). There are also disadvantages, mainly caused by two algorithm properties. First, the possible flow directions are predetermined: only the directions that are multiplies of 45° are possible. Second, the surface of the two dimensional cells is considered as points (point or zero dimensional source). The consequence of these two properties are: incorrectly determined flow directions and contribution areas.

Podlaga za uporabo algoritma je brezdepresijski (angl. *depressionless*) model višin. Odprava depresij je mogoča na več načinov. Obstoječi modeli (TAPES, RiverTools) odpravljajo depresije tako, da jih napolnijo do višine najnižje sosednje točke, ki ima smer toka stran od depresije. Pri tem postopku torej točke dvigujemo. Rieger (1998) pa je raziskal tudi vzroke za t.i. lažne depresije. Ugotovil je, da so ena od možnosti napake DMV. Navaja, da so višinske točke DMV v dolinah pogosto precenjene. Zato priporoča ohranjanje višin v točkah z nizkimi vrednostmi in njihovo povezovanje tako, da zmanjšamo vrednosti v vmesnih točkah. Druga možnost za nastanek lažnih depresij je kvadratna mreža, kot način razporeditve višinskih točk (slika 1).

Examples are given by Costa-Cabral & Burges (1994).

A basis for the application of the algorithm is depressionless DEM. Depressions can be handled in two ways. Existing models (TAPES, RiverTools) handle depressions by filling them until the outlet is reached. The elevations of the points are therefore raised. Rieger (1998) performed research about the appearance of so-called false depressions. His conclusion was that the elevations in a narrow valley are often overestimated. Therefore, he recommends lowering the points between the depression and the nearest lower point rather than raising the points within the depressions. The other possibility for the appearance of a false depression is the square grid structure itself (Figure 1).



Slika 6. Prvi (svetlosivo) in drugi (temnosivo) krog sosednjih točk.
Figure 6. First (light gray) and second (dark gray) round of neighbours.

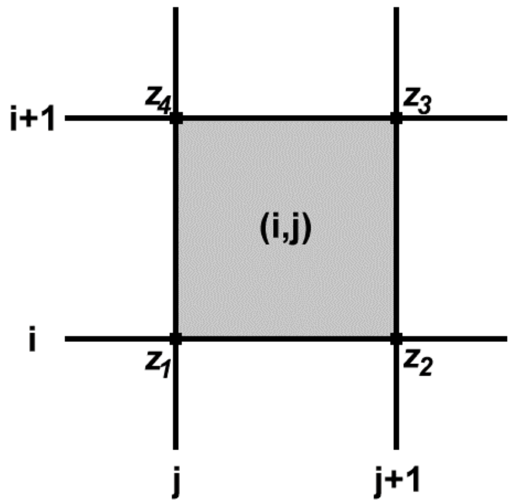
V tej nalogi sta bila za določanje odtoka iz depresij uporabljena dva postopka. V ozkih dolinah nastanejo depresije predvsem kot posledica kvadratne razporeditve višinskih točk. V tem primeru je bil uporabljen prvi postopek, razširjeno iskanje do drugega kroga sosednjih točk (slika 6). Če je v tem krogu

For the purpose of this project, two ways of routing the flow from depressions were used. In narrow valleys, where false depressions are mostly caused by the square grid structure, extended search in the second round of neighbours was applied (Figure 6). If, within the second round, a point with lower elevation obstajala vsaj ena točka z nižjo nadmorsko višino, je bila izvorni celici določena smer toka v tisto celico drugega kroga, v smeri katere je gradient najmanši. Če rešitev na ta način ni bila mogoča, je bil uporabljen drugi postopek, povezovanje do najbližje nižje točke. DMV je bil popravljen tako, da je bila vmesnim točkam prirejena nižja višina tako, da je bil gradient na vsej poti kostanten.

Na podlagi algoritma D8 so se razvile številne izpeljanke, kot so Rho8, FD8 in FRho8 (Gallant & Wilson 2000), ki bolje ocenjujejo prispevno površino posamezne celice, vendar ne omogočajo določanja razvodnic, pa tudi ne nekaterih drugih hidroloških parametrov, kot so najdaljša pot toka do celice, srednji padec itd.

existed, the flow direction was determined towards the second-round point of the lowest gradient. If no possible connection was found, the method of connecting a depression to the nearest lower point was used. In this case, the DEM was changed so that the points on the path between the depression and the nearest lower point were lowered. The new elevations were calculated so that the gradient on the entire path was constant.

Several algorithms, derived from D8, such as Rho8, FD8 and Frho8 (Gallant & Wilson 2000), exist. They are better in terms of the contribution area of a single cell, but they do not enable catchment delineation, nor the determination of some other hydrologic parameters, such as upslope flow path, average upslope slope, etc.



Slika 7. Celice pri algoritnu DEMON.
Figure 7. Cells for the DEMON algorithm.

3.2.3 ALGORITEM DEMON

Algoritem DEMON (Digital elevation model networks; Costa-Cabral & Burges, 1994) predstavlja znatno izboljšavo algoritma D8 in njegovih izpeljank, je pa uporaba postopka DEMON tudi bistveno zahtevnejša.

Za razliko od algoritma D8, ki površje obravnava kot množico točk, algoritem DEMON obravnava površje kot množico površin. Celice niso centrirane v točkah mreže DMV, pač pa tvorijo točke mreže njihove vogale (slika 7). Površje vsake celice je ravnina, dobljena z lokalno regresijo.

3.2.3 DEMON ALGORITHM

The introduction of the DEMON algorithm (Digital elevation model networks) by Costa-Cabral & Burges (1994) was a significant improvement in hydrologic modelling. However, the implementation of the DEMON algorithm is more complex.

DEMON treats the terrain surface as an array of surfaces, rather than as an array of points. The DEM grid points are not centres of the cells, but their corners (Figure 7). The surface of each cell is a plane obtained by local regression.

Za določanje razvodnic prispevnih površin se uporablja metoda največjih vzponov. Začnemo na najnižji točki prispevne površine (spodnji presek). Kadar je ta sotočje z drugim vodotokom, jo določimo tako, da sledimo črtama največih padcev vzdolž strug obeh vodotokov do presečišča obeh tako konstruiranih črt. Nato lahko pričnemo z razmejitvijo prispevne površine tako, da sledimo levobrežni in desnobrežni črti največjega vzpona v smeri največjega gradienta **g**. Ta v posamezni celici poteka v smeri:

For the determination of the contribution area, the method of steepest slope lines is used. The line starts at the lowest point of the contribution area (outlet cross section). When the lowest point is a confluence, it is determined by following the steepest downslope lines along the two valleys. The intersection of these two lines is the confluence. Then the contribution area of a selected watercourse can be determined by following the left and the right steepest upslope line that in each cell runs in the direction of the maximum gradient **g**:

$$\mathbf{g} = g_x \cdot \mathbf{e_x} + g_y \cdot \mathbf{e_y} \tag{1}$$

kjer je (glej sliko 7):

where it is (see Figure 7):

$$g_x = \frac{dx}{2}\left(-z_1 + z_2 + z_3 - z_4\right) \tag{2}$$

$$g_y = \frac{dy}{2}\left(-z_1 - z_2 + z_3 + z_4\right) \tag{3}$$

Tako dobimo levo in desno razvodnico. Razvodnice se zaključijo v točki, ki je lokalni maksimum (vrh). Če se tako dobljeni razvodnici ne končata na istem vrhu, moramo poiskati vmesno sedlo, teh je lahko tudi več, in od tam slediti črtam največjih vzponov proti obema vrhovoma.

Algoritem DEMON v različici DEMON-Downslope je vgrajen v programski paket za analizo okoljskih in hidroloških parametov TAPES (TAPES WWW). Ta različica omogoča izračun prispevnih površin in specifičnih prispevnih površin za vsako celico, ne omogoča pa določanja razvodnic in nekaterih drugih hidroloških parametrov. Zato je bil v ta namen razvit lasten računalniški program, ki temelji na različici DEMON-Upslope.

Following both the left and right lines, the contribution area can be delineated. The lines end in a point that is a local maximum (peak). If both lines do not end in the same point, the saddle (or more of them) lying between them must be detected. From the saddle, the upslope steepest line must be followed towards both peaks.

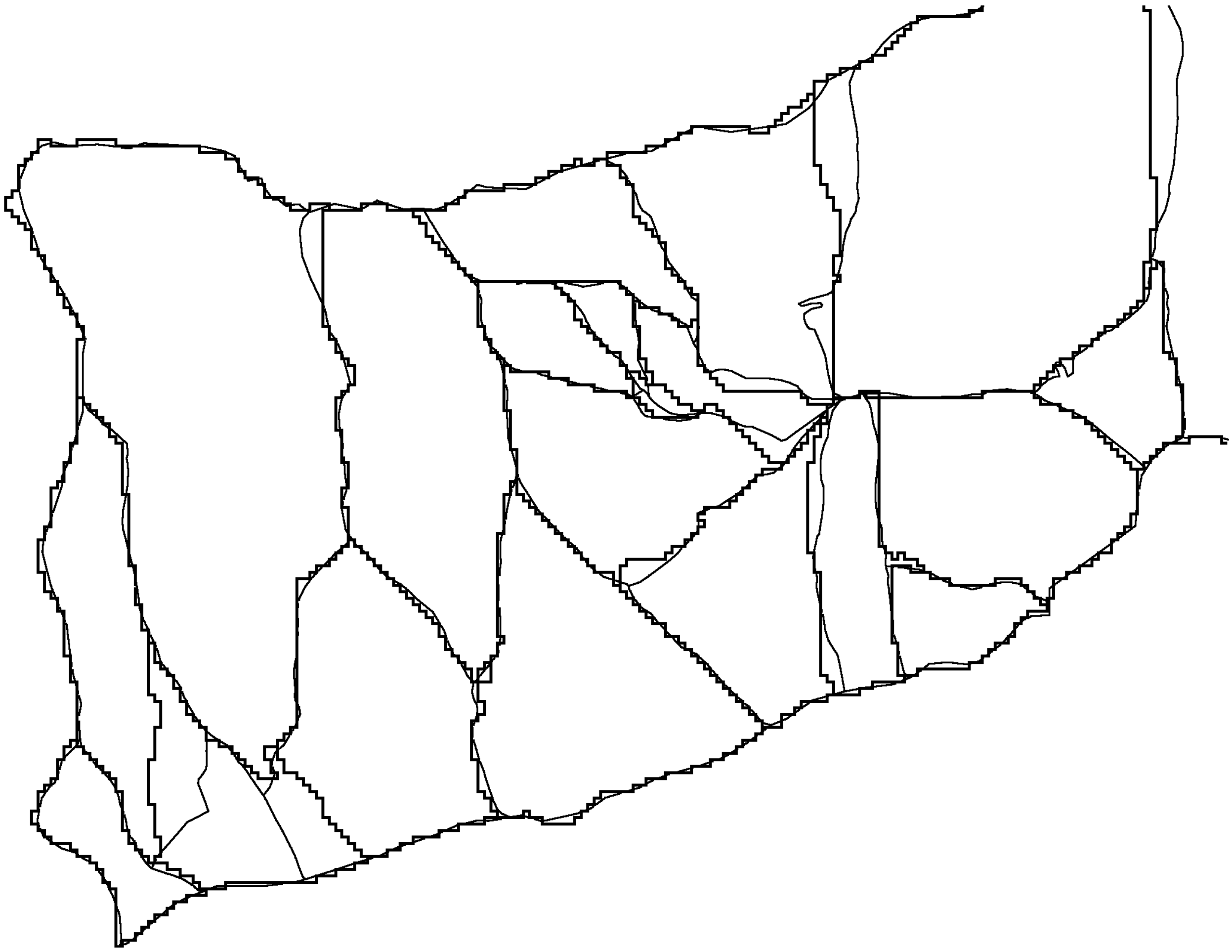
The DEMON algorithm exists in two variants. The DEMON-Downslope is implemented in the TAPES (TAPES WWW) terrain analysis program for the environmental sciences. This variation can be used for the computation of catchment areas and the specific catchment areas of a single cell, but does not enable catchment delineation and the calculation of some other hydrologic parameters. Therefore, a tool based on DEMON-Upslope had to be developed.

4. REZULTATI

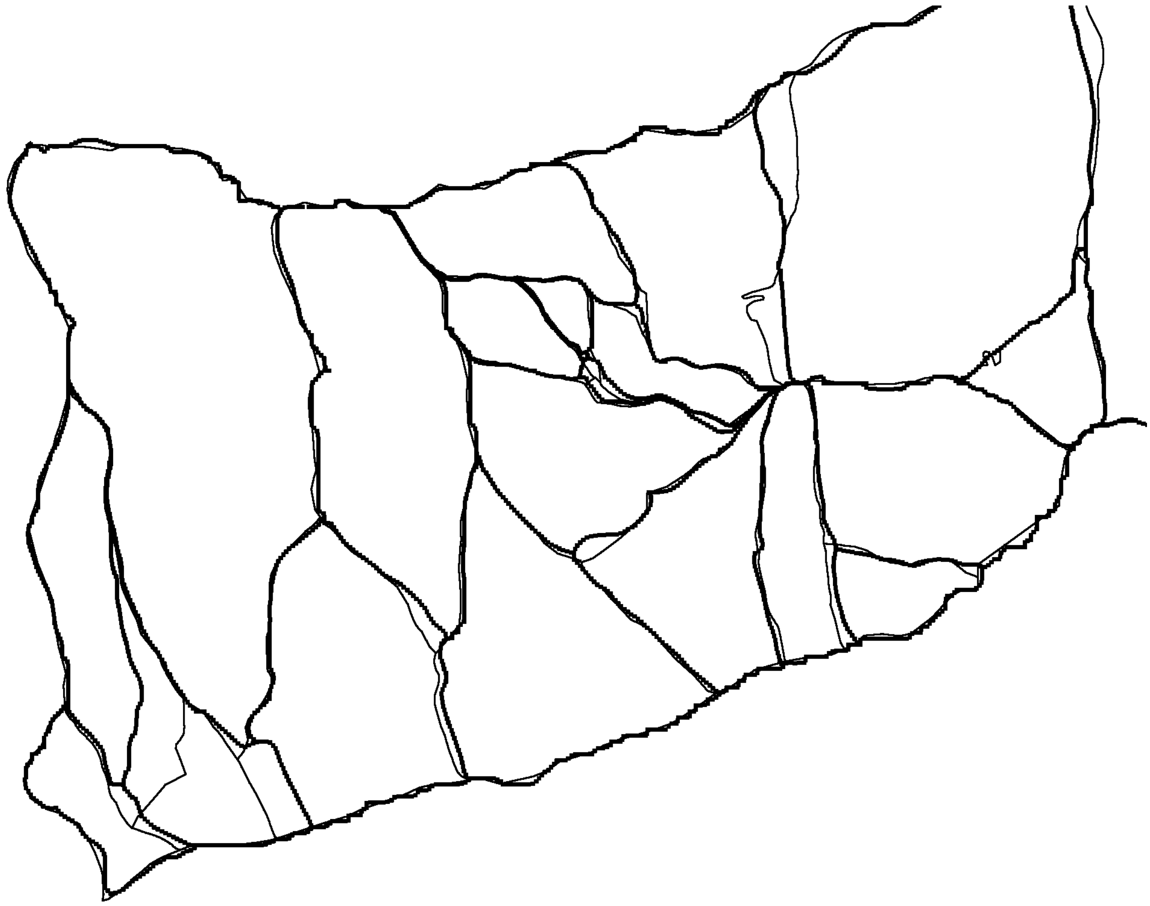
Grafična primerjava referenčne delitve, ki je ročna delitev na podlagi plastnic, z avtomatskima načinoma, je podana na slikah 8 in 9. Razvodnice predstavljajo delitev povodja do šeste ravni šifranta KSH (Šraj, 2000).

4. RESULTS

A graphical comparison of the reference delineation, i.e. lines drawn over the scanned contour map, with the two automatic delineation methods, is given in Figures 8 and 9. The lines represent the partitioning of the catchment to the sixth level of the KSH coding system (Šraj, 2000).



Slika 8. Primerjava razvodnic, določenih ročno iz plastnic (tanka črta)
in razvodnic, dobljenih po metodi D8 (debela črta) za spodnji del povodja.
Figure 8. Catchment partitioning: lines determined from a contour map (thin line)
And a D8 algorithm (thick line). The lower part of the catchment is shown.



Slika 9. Primerjava razvodnic, določenih ročno iz plastnic (tanka črta, enako kot na sliki 8) in po metodi DEMON (debela črta) za spodnji del povodja.
Figure 9. Catchment partitioning: lines determined from the contour map (thin line, the same as in Figure 8), and by the DEMON algorthm (thick line). The lower part of the catchment is shown.

5. RAZPRAVA

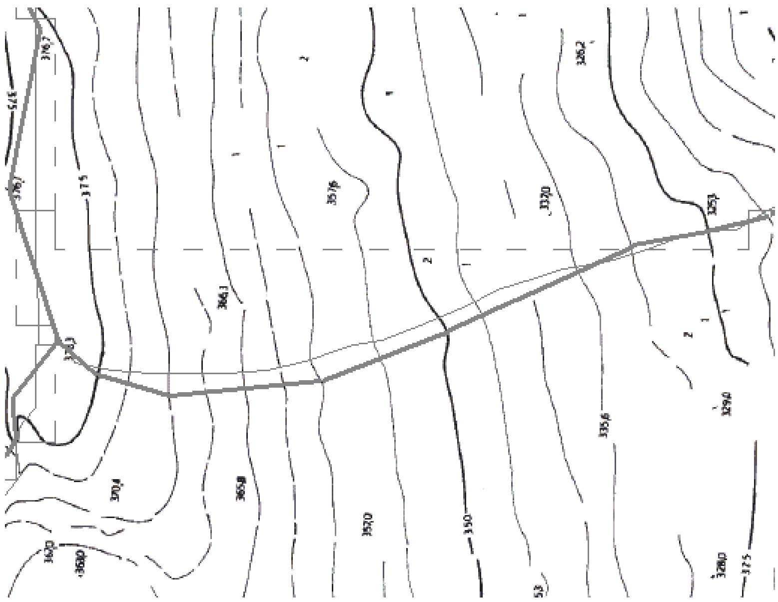
Oba algoritma, tako D8 kot DEMON, sta ob uporabi DMV25 dala na peti ravni dobre rezultate. Na šesti ravni so rezultati še vedno zadovoljivi, pri čemer pa je opazna razlika med zgornjim in spodnjim delom povodja. V zgornjem delu in na nižje ležečih, strmejših površinah, so rezultati zelo dobri, kar še zlasti velja za algoritem DEMON. V spodnjem delu se pojavlja več napak. Napake so posledice naslednjih vzrokov: pri algoritmu D8, zaradi vnaprej določenih možnih smeri toka, pri obeh algoritmih pa zaradi pomanjkljive resolucije DMV in napak v ravninskih delih.

Slika 10 prikazuje napako algoritma D8 pri določanju razvodnic zaradi vnaprej določenih možnih smeri toka. V primeru, ko je azimut pobočja vmesna vrednost med večkratniki kota 45°, prihaja do napak. Te so posebej očitne, kadar se pobočje vzpenja v isti smeri na daljši razdalji. Zato je algoritem D8 ustrezen na območjih z razgibanim reliefom, ne pa tudi tam, kjer so pobočja dolga in tečejo enakomerno.

5. DISCUSSION

Both D8 and DEMON algorithms, used with the DEM25, gave good results on the fifth level. On the sixth level the results were still satisfactory, but a difference in quality between the upper and lower part can be noted. In the upper part and some steeper parts of the lower part, the results are good, which is especially true for the DEMON algorithm. In the lower part, some errors can be noted. The causes for the errors were the following: for algorithm D8, the before mentioned predetermined flow directions; and for both algorithms, insufficient spatial resolution and the data errors of the DEM.

Figure 10 shows the error of the D8's delineation because of the predetermined flow direction. The errors appear in cases where the azimuth of the hillslope is not a multiplier of 45°. These are most obvious when a slope runs in the same direction for a long distance. Therefore, tha D8 algorithm is more appropriate in cases where the azimuth of the slopes changes, than in the cases of long slopes with a uniform azimuth.



Slika 10. Primer napake algoritma D8 pri določanju razvodnic. Črte predstavljo razvodnice: debele neprekinjene črte so določene ročno na podlagi načrta plastnic, tanke neprekijene z algoritmom DEMON, tanke črtkane pa z algoritmom D8.

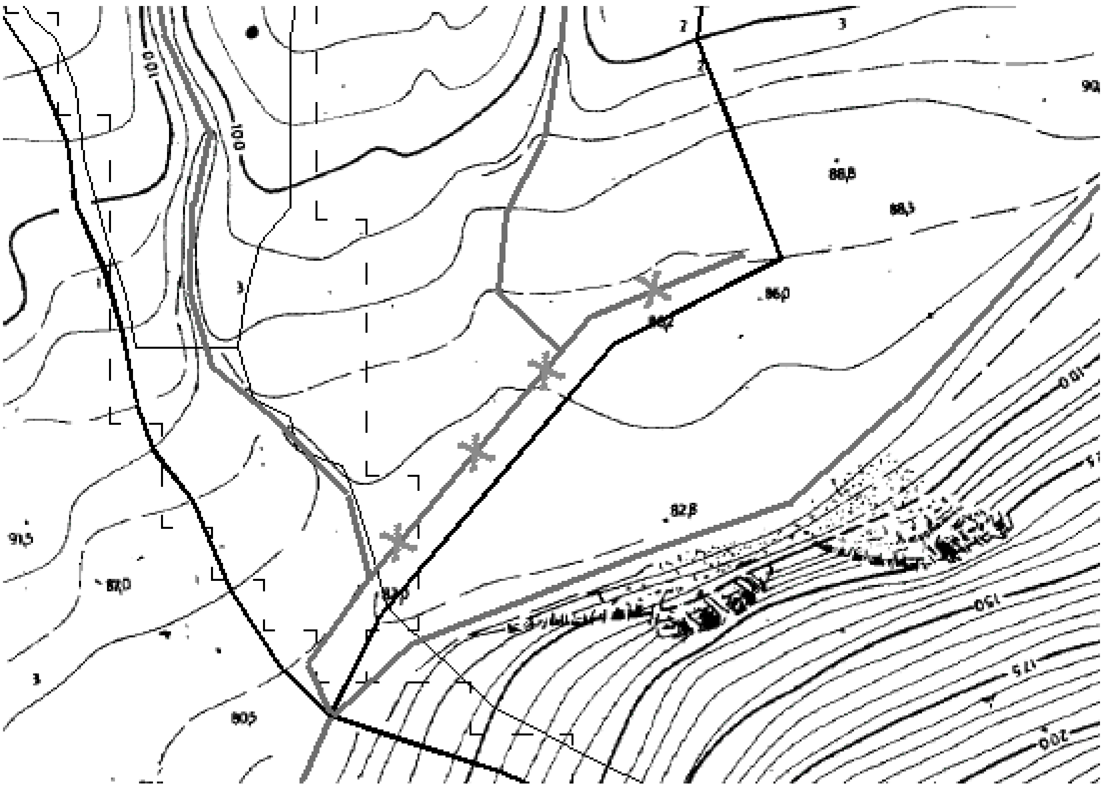
Figure 10. An example D8's error in determining contribution area. The thick solid lines divide contribution areas obtained from the contour map; the thin solid lines were obtained by Demon; and the thin dashed lines, by D8.

Drugi vir napak je dejstvo, da uporabljeni model terena ne zajema manjših odvodnikov, kot so npr. cestni jarki. Razlog ni le prevelik prostorski korak mreže višinskih točk. Ti jarki so namreč običajno obraščeni in skriti v vegetaciji, zato jih iz zračnih posnetkov ni mogoče zanesljivo določiti. Slika 11 prikazuje primer ceste in cestnega jarka, ki potekata skoraj vzporedno s plastnicami, in tako povečujeta površino, s katere se odvaja voda v spodnji presek prispevne površine.

Tretji vir napak določanja razvodnic so višinske napake v dolinah, posledica katerih so napačno določene struge in sotočja. Ker je napačno določen spodnji presek prispevne površine, so napačno določene tudi razvodnice (slika 12).

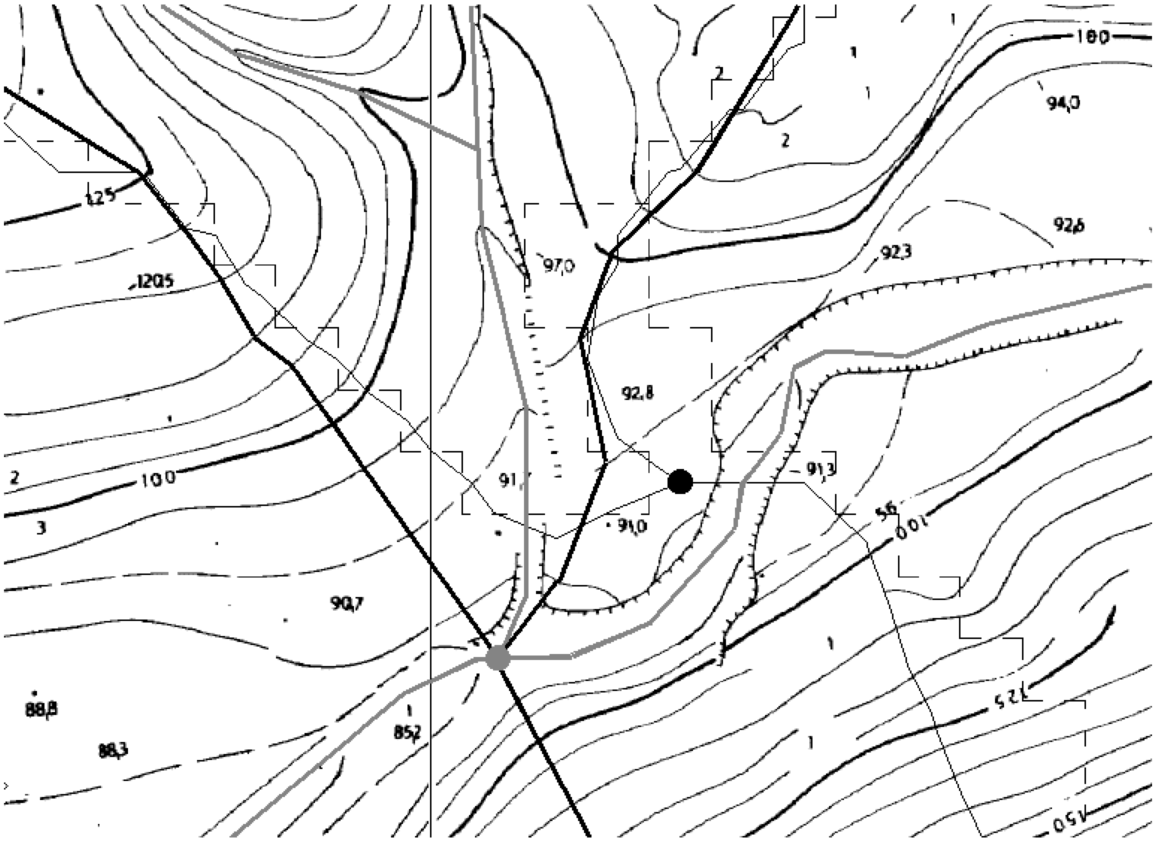
The second source of errors is the fact that the complete drainage network cannot be reproduced from the DEM, e.g. the road ditches are missing. Not only does the insufficient resolution contribute to this incompleteness, but also the fact that the ditches are hidden below the vegetation cover. Figure 11 shows an example of a road and a road ditch that run nearly parallel to the contours, and thus enlarge the contribution area of the outlet profile.

The third source of errors are the errors in the elevation data in the valleys which lead to erroneously determined thalwegs and confluences. If the outlet profile is misplaced, then the delineation is obviously wrong (Figure 12).



Slika 11. Napaka v določitvi prispevne površine zaradi cestnega jarka (X), ki ga model terena DMV25 ne zajema. Sive črte so hidrografska mreža, ostalo kot na sliki 10.

Figure 11. Error in the delineation of the contibution areas. The road ditch (X) cannot be reproduced from the DEM25 terrain model. The drainage network is coloured grey; the rest is the same as in Figure 10.



Slika 12. Napačno določeno sotočje zaradi napak DMV. Posledica so napačno določene razvodnice. Sivi krog je dejansko sotočje, črni krog je sotočje, kot ga določita algoritma D8 in DEMON. Ostalo kot na sliki 10.

Figure 12. Error in the determination of the location of the confluence. A consequence is an error in the contribution area delineation. The grey circle is the actual confluence; the black circle, the confluence as predicted by D8 and DEMON. The rest is the same as in Figure 10.

6. ZAKLJUČEK

Za celotno Slovenijo imamo na voljo digitalne modele višin (DMV) v rastru 25 m. Meje elementov hidrološkega ali okoljskega modela (običajno prispevnih območij) je mogoče na območjih, kjer je prevladujoč vpliv površinskega toka, iz takega modela reliefa generirati tudi avtomatsko. Na voljo sta metoda D8 in algoritem DEMON-Upslope.

Prva metoda je preprostejša za uporabo, a ima tudi kar nekaj pomanjkljivosti. Te se pokažejo zlasti na dolgih enakomernih pobočjih, ki tečejo v smeri, ki ni mnogokratnik kota 45°, in pa pri majhnih nepravilnih prispevnih površinah. Druge napake izvirajo iz načina predstavitve površja in so iste kot pri algoritmu DEMON.

Algoritem DEMON odpravlja mnoge od teh pomanjkljivosti. Še vedno pa je odvisen od kakovosti predstavitve površja, to je tako od prostorske resolucije rastrske mreže višinskih točk kot od njihove točnosti. Na obravnavanem območju nismo našli grobih napak DMV. Manjše napake v dolinah, ki povzročajo nastanek umetnih depresij, pa so bile popravljene po postopku, ki ga predlaga Rieger (1998). Kljub temu se je v spodnjem toku primerilo, da so bile struge in sotočja na napačnih mestih. To je imelo za posledico napačno določene prispevne površine. Podobno se je zgodilo v primeru cestnih jarkov, ki jih v DMV25 ni zaznati.

Sklenemo lahko, da je določanje razvodnic na avtomatski način ob uporabi DMV25 v gričevnatem in hribovitem svetu mogoče najmanj do pete ravni, ob popravkih zaradi cestne mreže in napak v določanju sotočij pa tudi do šeste ravni. To ustreza velikosti prispevne površine reda 0.1 km^2. Najpriporočljiveje je uporabiti algoritem DEMON, čeprav tudi preprostejši D8 pogosto daje dobre rezultate.

6. CONCLUSION

For the entire territory of Slovenia, digital elevation models (DEM) in the resolution of 25 m are available. The delineation of the elements of a hydrological or environmental model (usually contribution areas) can be generated automatically from such a terrain model, where the overland flow is predominant. D8 or DEMON-Upslope algorithms can be used.

The former algorithm is easier for implementation, but has some considerable drawbacks. These are best shown on long slopes running in a direction that is not a multiplier of the angle of 45°, and on small irregular surfaces. Other errors of the method are due to the terrain model, and are same as for the DEMON algorithm.

The DEMON algorithm improves the automatic catchment delineation significantly, but still depends on the quality of the terrain representation, which means both the spatial resolution and the accuracy of the DEM. In the research area, no gross errors were found. Smaller data errors in the valleys that caused false depressions were handled by the procedure recommended by Rieger (1998). In spite of that, channels and confluences in the lower part were misplaced on a few occasions. Therefore, the contribution areas were delineated incorrectly. Similarly, the delineation was wrong in the case of the road ditches that cannot be reproduced from the DEM25.

In a hilly terrain, the delineation of the contribution areas up to the fifth level is possible using the DEM25 and one of the mentioned automatic methods. If the channel locations are corrected in the DEM, an accurate delineation of the contribution areas to the sixth level (ca 0.1 km^2) is also possible. The DEMON algorithm proved to be a bit better, although the simpler D8 also often yields good results.

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