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Comparison of an automated and manual method for calculating storm runoff response in ungauged catchments in Serbia

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Abstract: Estimation of discharge from ungauged catchments based on rainfall-runoff analysis is a very frequent task in engineering hydrology. Very often, design discharges are needed for streams or small rivers where no streamflow data is available (river training works, culverts, small hydropower plants, etc). This study uses a well established lumped hydrologic rainfall-runoff model to compare two different approaches in data preparation. The traditional method of manual obtainment of catchment parameters was compared to a more contemporary methodology using automation with geographic information systems, digital terrain models and available datasets, with an emphasis on open-source tools and freely available datasets. Both techniques were implemented on more than 100 catchments in Serbia to calculate storm runoff response. The results show minor differences that are insignificant compared to the time and resources saved with the automated techniques. The use of such automated methods enables the hydrologist to direct more attention to other factors that influence discharge even more than catchment parameters, such as rainfall, soil and land use data.

Keywords: Hydrology; Rainfall-runoff modeling; Ungauged catchments; GIS.

INTRODUCTION

The estimation of discharge from ungauged catchments based on rainfall-runoff analysis is a very frequent task in engineering hydrology. More often than not, discharge measurements are not available for statistical analysis and estimation is based on rainfall measurements and morphometric characteristics of the catchment (among others). Some examples of this situation include design of river training works, culverts, small hydropower plants, flood hazard mapping, etc.

Although we are well into the 21st century, manual calculations of morphometric catchment characteristics from topographic maps is still common. This is usually due to either the scarcity of readily available digitized data, or sometimes the lack of expertise. Automating these techniques for extracting morphometric characteristics of catchments can greatly improve the speed and accuracy of the entire hydrologic analysis.

In this paper, an attempt was made to greatly improve the speed and efficiency of morphometric catchment characteristics extraction using existing open source software and freely available data sets. A comparison is made between calculated runoff response using manual and automatic techniques for extracting these characteristics. Over 100 catchments in Serbia, mostly of torrential nature with little urbanization and sizes varying from a few km^2 up to 300 km^2, were chosen and processed. Software used in the study is the open source geographic information system SAGA GIS (System for Automated Geoscientific Analyses), coupled with the open source programming language R.

Availability of input data

Topographic maps are still the most widely used resource for terrain data retrieval, mainly due to high availability. The most frequently used is the scale 1 : 25,000 topographic map issued by the Military Geographical Institute as the primary distributor of topographic maps in Serbia. These maps show all the necessary topographic elements for almost any hydrological analysis of ungauged catchments with satisfactory accuracy. The drawback is that in order to extract topographic information, the maps either need to be manually processed or digitized, both of which are very time-consuming.

Digital terrain models (DTMs), on the other hand, can be directly inputted to a number of geographic information system (GIS) software for further analysis, greatly improving speed and efficiency. Unfortunately, digital terrain models with nation-wide coverage are very few and very costly. An alternative to these models are digital terrain models with global (or near global) coverage, such as SRTM (Rodriguez et al., 2005) or ASTER (ASTER GDEM Validation Team, 2009). A number of studies have indicated the possibility of using the SRTM DEM for hydrologic modelling (Ludwig and Schneider, 2006; Wolf et al., 2009), and this paper continues this investigation.

In order to estimate runoff properties of a catchment, information is needed on land use, soil cover and the underlying geology. Soil maps of scale 1 : 50,000 are available, as well as geologic maps of scale 1 : 100,000 and hydrogeologic maps of scale 1 : 500,000. These maps are scanned versions of paper maps, containing much detail but they are rather difficult to incorporate into automated techniques. The CORINE Land Cover dataset (Bossard et al., 2000), on the other hand, is readily available in vector and raster format.

METHODOLOGY

Digital elevation model pre-processing

The SRTM DEM was downloaded for the entire territory of Serbia, with some margin to account for some transboundary watersheds. The resolution of this DEM is 3 arc seconds in the geographic projection (WGS84 datum), which when reprojected to the official Serbian state projection (Transverse Mercator), equals approximately 90 x 60 m. This was further resampled to a 70 m grid in order to ensure square pixels, while preserving detail.

The raw SRTM DEM data is very limited for hydrologic application without specific surface area corrections (Wolf, et al.,

2009), and a series of pre-processing steps were undertaken to obtain a "hydrologically correct" terrain model. A common problem with the SRTM dataset are patches of no data, or voids, that most frequently appear in mountainous areas due to shadowing, and in desert areas due to radar specific effects (Reuter et al., 2007). Fortunately, only a few instances of minor missing-data patches were encountered (due to mainly temperate landscape in Serbia), which were successfully filled in with simple interpolation techniques. Sink removal, on the other hand, posed a greater challenge; sink filling techniques tend to create flat regions, while drainage route deepening techniques (Hutchinson, 1989) tend to "overdeepen" routes, producing one pixel wide canyons up to 50m deep. A combination of the two was used, keeping both effects to a minimum.

Once the depressions and flat areas were treated, the flow directions and flow accumulations were determined using the Deterministic 8 method (O'Callaghan and Mark, 1984).

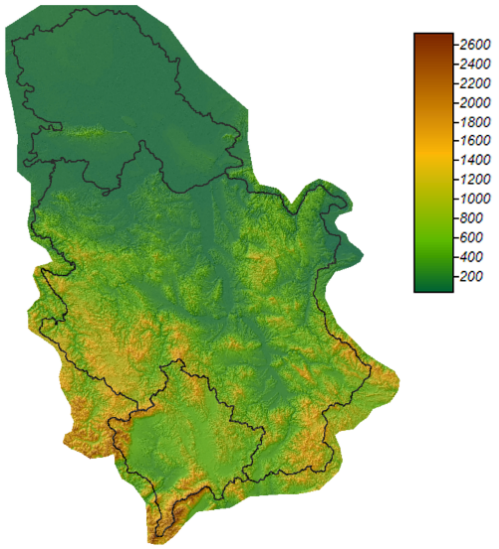


Fig. 1. Pre-processed DEM of Serbia based on SRTM data.

Morphometric Characteristics of Catchments

Catchment delineation, area (a), Perimeter (o)

The catchment area is probably the single most important watershed characteristic for hydrologic design, and along with the catchment perimeter is the most straightforward. The catchment area is the horizontal projection of the entire surface of the catchment, which is the area or reception of rainfall.

The conventional method of drainage basin delineation is using the topographic map. The basin divide is drawn starting from the outflow profile, drawing a line perpendicular to the contour lines, encompassing the headwaters and the entire stream network. This is usually done using scanned maps in CAD or GIS software, where the polygon properties can be easily calculated.

The method used in this paper uses the depressionless preprocessed digital elevation model and the calculated flow accumulation grid to determine which of the grid elements (or cells) drain into the specified output profile, or "pour point". These are the cells that comprise the catchment area, and a polygon can easily be generated for direct calculation of area and perimeter.

Mean elevation (H_{sr})

The mean elevation, or mean altitude, of a catchment is manually calculated from the weighted mean of the sum of partial volumes between contour lines (Zavoianu, 1985), expressed as:

$$H_{sr} = \frac{a_1 h_1 + a_2 h_2 + \ldots + a_n h_n}{A}, \quad (1)$$

where $a_1 \ldots a_n$ are the areas between adjacent contour lines, $h_1 \ldots h_n$ are the half-sums of the altitudes of successive contour lines, and A is the total drainage area.

This method has been used successfully for decades, and is very time consuming due to a large number of areas between contour lines that need to be calculated. The alternative to Eq. (1) is to first draw a hypsometric curve of the catchment and then obtain the value for 50% of the total surface from the chart, but this is no less time consuming.

When using digital elevation models, the calculation of mean elevation is fairly straightforward, by calculating the median of the entire sample of catchment cell elevations. Using the median value (numerical value separating the higher and lower half of the sample) corresponds to the manually calculated value in Eq. (1).

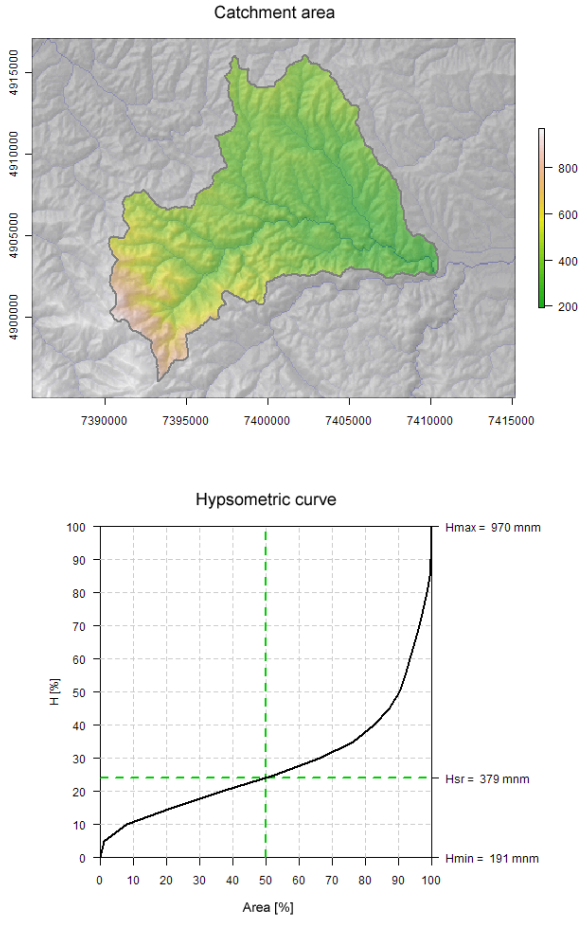


Fig. 2. Example of automatically derived catchment area and hypsometric curve.

Longest flow path (accumulated cost) (L)

The longest flow path, or length of the stream, is the distance measured along the stream channel from the source to outlet, a distance which may be measured on the topographic map. The source is generally established in a subjective manner, taking as the initial point the first perennial stream found downstream from the water divide along the channel axis.

In GIS software, the accumulated cost of travelling from the source grid cell (the outlet in this case) to each other grid cell in the raster dataset can be easily calculated. The source of the longest flow path can then be selected as the cell with the highest cost accumulation value. The distance to the outflow profile is calculated using the previously calculated flow direction grid.

Catchment slope (I_{sl})

The average slope of a catchment, as an independent variable, is calculated as the weighted mean of all the elementary surfaces between two consecutive contour lines. The following formula is used to calculate the mean slope of the catchment:

$$I_{sl} = \frac{h \cdot \left[\frac{l_0}{2} + l_1 + \ldots + l_{n-1} + \frac{l_n}{2} \right]}{A}, \qquad (2)$$

where h is the equidistance, l_0, l_1... l_n are the lengths of contour lines, and A is the catchment area (Luchisheva, 1950). This method of catchment slope calculation is also time consuming, as it requires manual measurement of total contour distances over the catchment.

On the other hand, a number of methods are available for quite fast calculation of slopes when a digital elevation model is available (Tarboton, 1997; Travis et al., 1975; Zevenbergen and Thorne, 1987). The method chosen in this paper was the "maximum slope" method, which calculates for each grid cell the maximum slope based on the surrounding 8 cells. In order to obtain an equivalent value to the one calculated (Eq. (2)), the cell values need to be integrated and area weighted. This is done by plotting the cell slope values in much the same way as the hypsometric curve (slope to percent area), then vertically dividing the area under the plotted line into two equal areas.

Profile and slope of longest flow path (I_{sr}, I_{ur})

The channel slope is an important factor in runoff calculations, and can be estimated in a number of ways (Singh, 1996), once the longitudinal profile has been defined. The manual way of defining the longitudinal profile is using a topographic map to mark each intersection of the stream with contour lines and create a plot on a separate chart. Using a DEM, this is done by starting from the cell designated as the furthest from the outlet and, with the help of the flow direction values, tracing the elevation of every downstream cell. This table can then easily be plotted.

Two distinct values of slope are used in practice. The average slope I_{sr} is defined as "rise divided by run", or the difference in elevation between the points defining the upper and lower ends of the channel, divided by the length of the channel between the same two points. However, the distance weighted channel slope I_{ur}, is more commonly used in calculations. Gray (1961) defined this slope as the slope of a line drawn along the measured profile which has the same area under it as is under the observed profile.

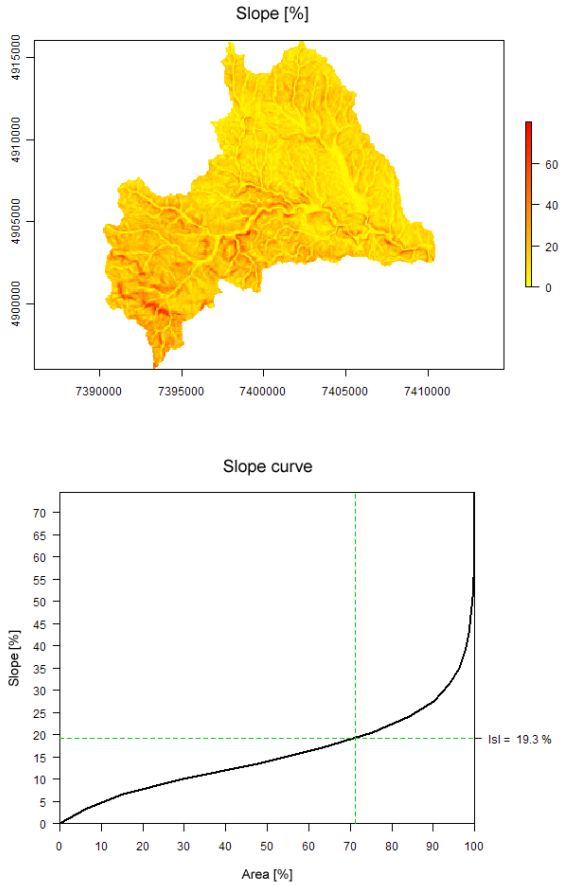


Fig. 3. Example of automatically derived catchment slope curve.

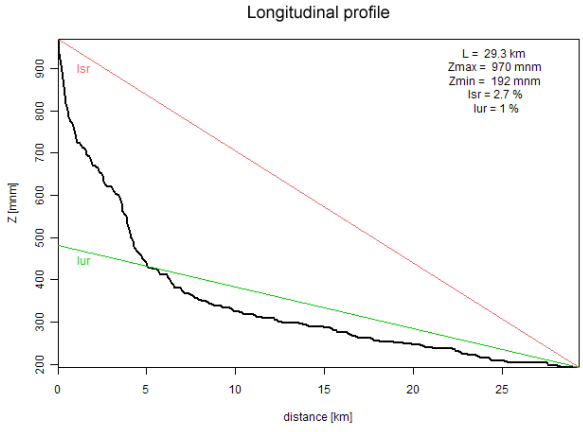


Fig. 4. Example of automatically generated channel profile, with calculated slopes.

Distance to catchment centroid (L_c)

The flow distance from the catchment centroid to the outflow profile is used in various calculations of catchment lag time. Manually, the flow path from the centroid is traced on a topographic map, following the steepest slopes (ie. perpendicular to contour lines), and along known streambeds. This is easily automated with a DEM, in much the same way as the longest flow path.

Rainfall-runoff modelling: SCS methodology

The SCS (now NRCS) method of estimating direct runoff from storm rainfall was the method of choice for rainfall-runoff calculations in this paper. This method was developed by the Soil Conservation Service (now National Resources Conservation Service) as a procedure for estimating runoff in small, ungauged agricultural watersheds (SCS, 1985), and has since become one of the most popular methods for computing surface runoff for a given rainfall event in small to medium sized watersheds (Mishra and Singh, 1999). There is a considerable amount of literature as well as review articles published on the SCS-CN method, such as an extensive overview by Ponce and Hawkins (1996). A very brief overview of the method is presented in the next few paragraphs. For a more complete description of the method, the reader is referred to the NRCS National Engineering Handbook (2002), which is available online.

The basis of the method is the runoff equation:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S}, \tag{3}$$

where Q is depth of direct runoff, P is depth of total rainfall, I_a is initial abstraction, S is potential maximum retention or infiltration. The initial abstraction, defined as the rainfall that occurs before runoff begins, is assumed to be a function of the maximum potential retention S, estimated with the following empirical relationship (Mockus, 1949):

$$I_a = 0.2S\,. \tag{4}$$

The rainfall runoff equation obtained by substituting Eq. (4) for abstraction into Eq. (3) is:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S}\,. \tag{5}$$

Maximum potential retention S is estimated using the runoff curve number CN value:

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \tag{6}$$

for obtaining S in millimeters.

The runoff curve number CN is based on the hydrologic soil group, land use, treatment and hydrological condition. Once the characteristic land cover description and hydrologic soil group have been defined, runoff curve numbers may be read from provided tables such as in the National Engineering Handbook (NEH) (NRCS, 2002).

The CN is estimated by defining each and every hydrologic soil-cover complex in the watershed, and then weighting to get the watershed average. The hydrologic soil groups are usually obtained from available soil and geologic maps, although more precise criteria for assignment of the four hydrologic soil groups are defined in the NEH. Land use information is usually obtained by manually delineating areas of similar land use from aerial or satellite images.

The CORINE Land Cover dataset was used in this paper as a means of automating the calculation of the CN. The CORINE Land Cover classification differentiates a total of 44 land cover classes, grouped in 3 levels: artificial surfaces, agricultural areas, and forest and seminatural areas. For each of these land cover classes, and for each of the four hydrologic soil groups, a CN was estimated based on well documented values in literature. The CORINE Land Cover classification was downloaded from the European Environment Agency (EEA) website in shapefile form for the same territory as the digital elevation model, and converted to raster form with 70 m cell size, also corresponding to the DEM. The hydrologic soil groups were also mapped on a 70 m raster, based on soil and geologic maps.

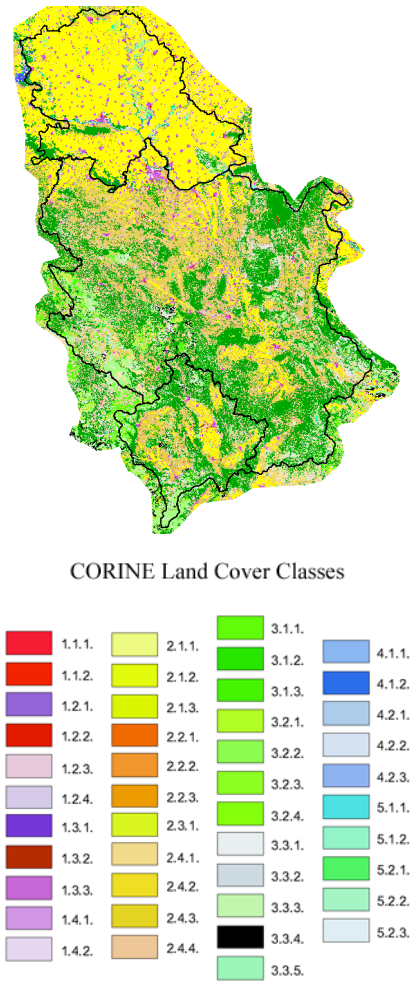


Fig. 5. CORINE Land Cover Classification for Serbia.

The transformation of excess rainfall into direct runoff was simulated using a modified SCS dimensionless unit hydrograph. This dimensionless unit hydrograph (UH) expresses the UH discharge U_t, as a ratio to the UH peak discharge U_p, for any time t, a fraction of the time to UH peak T_p. The time of peak (or time of rise) is related to the duration of the unit of excess rainfall as:

$$T_p = \frac{\Delta t}{2} + t_{lag} \tag{7}$$

in which Δt is the excess rainfall duration, and t_{lag} is the basin lag. Based on experimental data, the SCS recommends that lag time can be estimated for ungauged watersheds in direct relation to the time of concentration, as $t_{lag} = 0.6\ t_c$.

Jovanović (1989) suggested a modification of the SCS synthetic unit hydrograph based on a large number of observed watersheds in Yugoslavia, and this method has since grown much in popularity. The lag time was defined as:

$$t_{lag} = a\Delta t + t_0 , \tag{8}$$

$$t_0 = 0.4L^{0.67}\left(\frac{LL_c}{\sqrt{I_{ur}}}\right)^{0.086} , \tag{9}$$

where a is a function of catchment area and takes values from 0.3 for small catchments (smaller than 20 km^2) to 0.7 for large catchments (larger than 200 km^2), L is the longest flow path (km), L_c is the flow distance from the catchment centroid to the outlet, and I_{ur} is the distance weighted channel slope.

The peak discharge for a specific storm event is calculated by approximating the unit hydrograph with an equivalent triangular hydrograph having the same units of time and discharge, thus having the same percent of volume in the rising side of the triangle. Solving for the peak discharge in m^3/s:

$$Q_{\max} = \frac{2 \cdot A \cdot Q}{T_b} \cdot 1000 , \tag{10}$$

where A is the catchment size (km^2), Q is runoff as defined by Eq. (3) (mm) and T_b is the base of the hydrograph or time from beginning to end of the triangular hydrograph (sec). The base of the hydrograph T_b is the sum of the time of rise T_p and the time of recession of the hydrograph T_r.

The ratio of time of recession and time to peak is estimated based on a large number of observed hydrographs from catchments in Serbia, as a function of drainage area A (Jovanović, 1989). The values for K for catchments analysed in this paper range from 1.0 for small catchments (less than 5 km^2) to 2.0 for catchments with areas of 300 km^2.

Design rainfall for a catchment is usually estimated using available IDF (intensity-duration-frequency) curves from a nearby meteorological station, with correction based on rain gauges and regional dimensionless reduction curves. For comparison purposes, a rainfall event with 1 mm/min constant intensity and 60 minute duration was used for all catchments in this study. This roughly resembles a storm event of 100-year return period in the region.

RESULTS

A total of 109 catchments were analyzed in central and south Serbia, south of the Danube and Sava Rivers. These selected catchments vary in area from a few square kilometers up to 300 km^2. The locations and distribution of catchment areas are shown in Fig. 6.

For each catchment, morphometric characteristics were calculated first manually using topographic maps of scale 1 : 25,000, and then automatically using the pre-processed DEM based on SRTM data and scripting capabilities of SAGA GIS. The runoff response of these catchments to a 1 hour, 1 mm/min storm was calculated based on each set of morphometric characteristics, with emphasis on resulting maximum discharge rates (peak flow).

The comparison of resulting morphometric characteristics is shown in Fig. 7, and the comparison of calculated peak flows is shown in Fig. 8.



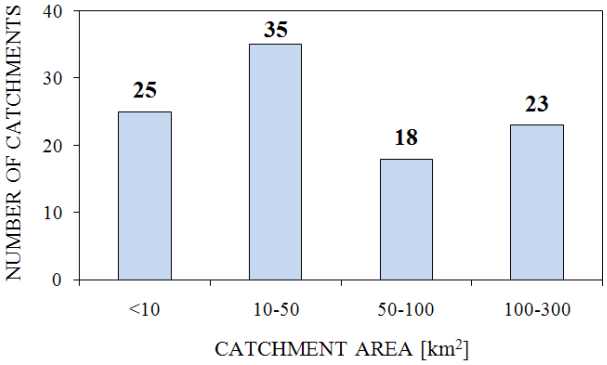


Fig. 6. Studied catchments.

DISCUSSION

As shown in Fig. 7, the catchment areas and catchment perimeters of the automatically delineated catchments based on the SRTM DEM closely resemble the same parameters which were manually extracted from topographic maps of scale 1 : 25,000. This is an excellent indicator that the automatic catchment delineation is completed successfully, and further polygon comparison confirms this. The mean catchment elevation is also closely matched for both methods, showing that the overall vertical precision of the SRTM DEM is satisfactory for spatial analysis at this scale.

The longest flow path result comparison shows that L is only slightly shorter for larger catchments when using the DEM, on average 5% shorter. This can be attributed to minor river meanders and sinuosity not being detected when using a digital elevation model of 70 m horizontal resolution, resulting in "straightened" channels. Due to the shorter flow path distance, the distance weighted channel slope I_{ur} is slightly steeper for automatically calculated catchments (less than 10%). Nonetheless, these differences do not greatly affect further calculations.

The average catchment slope, on the other hand, shows much scatter when the two methods are compared. This is attributed to the different methodologies applied. When calculating manually using topographic maps, the area between two neighboring elevation contours is treated with uniform slope, while when calculating using a DEM, slope is calculated for every grid cell thus taking into account the spatial variability of slope over the catchment area.

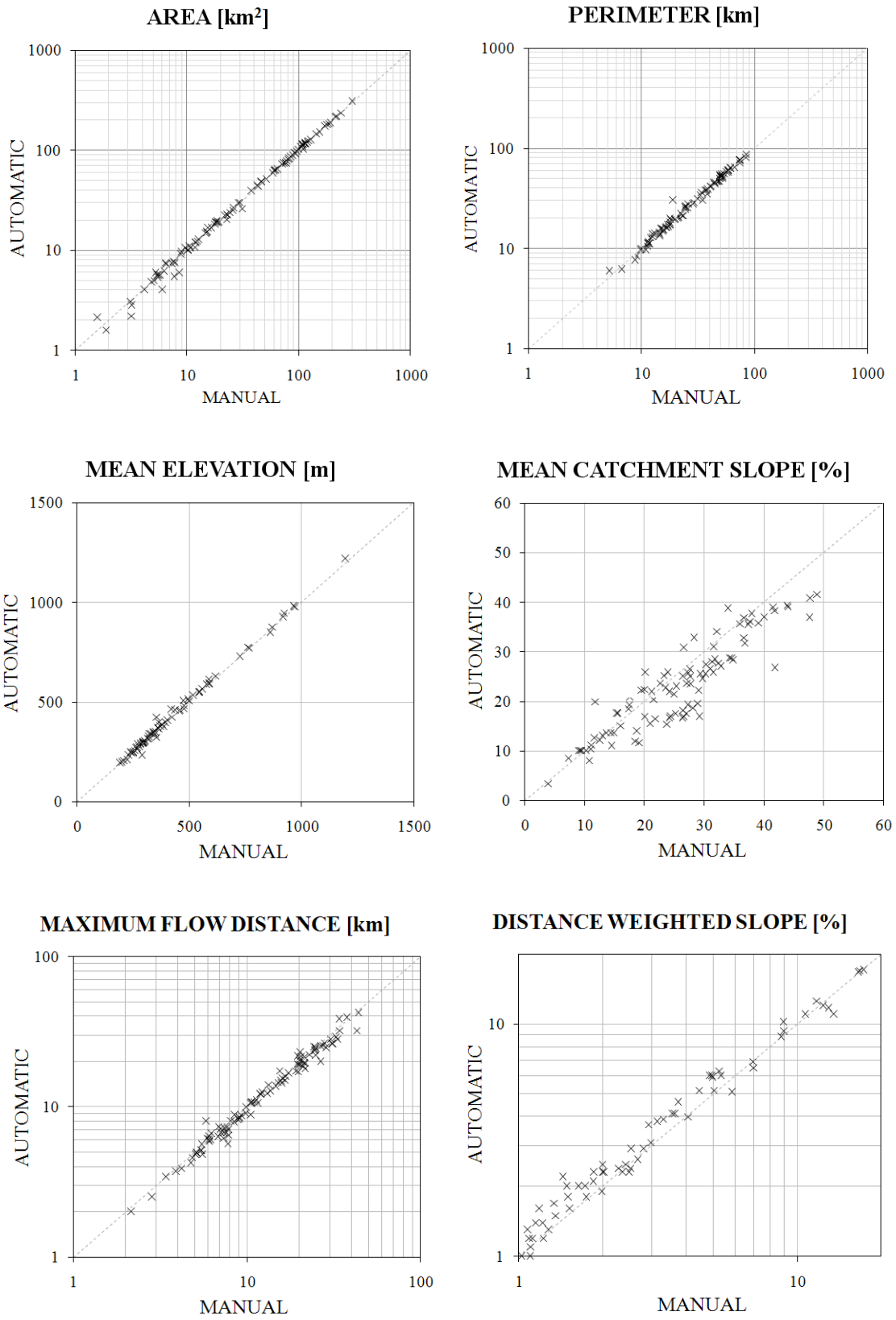


Fig. 7. Comparison of calculated morphometric characteristics.

The final result of this study is the comparison of the resulting outflows from both methods. Despite noted differences in some morphologic elements, the resulting comparison of flows calculated from manually and automatically obtained morphologic input parameters are very satisfactory. This is displayed on Fig. 8. Flow rates obtained by automated methods proved to be slightly higher than those manually obtained, although less than 5% on average.

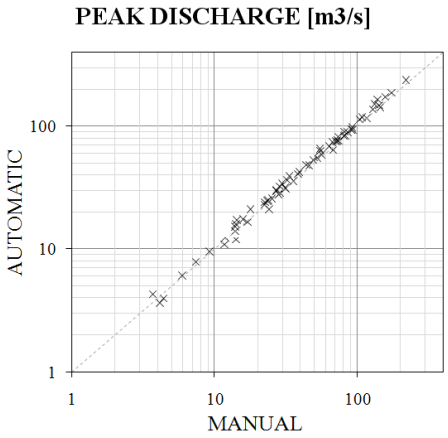


Fig. 8. Comparison of calculated maximum runoff rate.

CONCLUSION

This study has shown that the freely available SRTM digital elevation model can be successfully used for hydrological analysis of ungauged catchments, provided it is adequately pre-processed. The studied catchments vary greatly in area (from a few km^2 up to 300 km^2), with different geomorphologic characteristics.

The comparison was performed for automated and manual calculations of runoff from a specific storm. The results show that the estimation of actual runoff is much more sensitive to the quality of input data (i.e. soil, land use, rainfall etc.), than to implemented automation techniques.

In respect to time needed to perform analysis, the results are astonishing. For performing the manual calculations and extraction of catchment morphometric characteristics described in this paper, approximately 1–2 workdays are needed (for a medium-sized catchment of cca 100 km^2), at best. On the other hand, for the same analysis, the automated techniques bring the computation time down to 5–10 minutes. The input of the automated calculation technique are the x and y coordinates of the catchment outflow profile, along with previously prepared data (DEM, land use, rainfall data, etc.), allowing the method to be further scripted to process a large number of catchments at a time.

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