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An integrated design discharge calculation system for small to mid-sized ungauged catchments in Serbia

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Abstract. This study deals with the application of freely available datasets on the global and local level coupled with open source GIS software in hydrological modelling, greatly improving cost and time effectiveness of hydrological analyses of ungauged catchments. The automated calculation system was developed as an extremely useful tool for hydrologists for the quick estimation of design discharges. The morphometric module of the calculation system showed excellent results, saving a great deal of time that would otherwise been spent on manual processing of geospatial data. Using the automated calculation system, the methodologies currently in use in hydrological practice in Serbia were evaluated. The distributed velocity method was introduced as a way of calculating hydrograph lag time. The comparison between design discharges calculated by rainfall-runoff analysis and by frequency analysis yielded very good resemblance. Examples of real-world application for over 2500 catchments are shown.

1 Introduction

In Serbia, catchments with area less than $100\,\mathrm{km}^2$ are for the most part ungauged, and a good number of larger catchments remain ungauged. Very often, design discharges are needed for these rivers where no streamflow data is available, for various applications. Examples include river training works for flood protection measures or erosion control, culvert design, small hydropower plants etc.

Current hydrological practice still mainly relies on numerous manual methods of handling data and calculations. This is partly due to the segregation and inadequate form of the necessary data, and partly due to experts lacking the GIS skills needed for the efficient manipulation of spatial data.

The purpose of this study is to: (1) identify datasets that can readily be used for hydrological modelling, to overcome data availability issues, (2) create an integrated design discharge calculation system, to greatly speed up the modelling process, (3) evaluate the existing methodologies used for predicting discharge in ungauged catchments, and (4) introduce modifications to the methodology in order to improve accuracy.

2 Study area

Serbia is located at the crossroads of Central and Southeast Europe, covering the southern part of the Pannonian Plain and the central Balkans. A landlocked country, Serbia borders Hungary to the north; Romania and Bulgaria to the east; Macedonia to the south; and Croatia, Bosnia, and Montenegro to the west; it also borders Albania through the disputed territory of Kosovo.

The study area of this study is the region of Serbia south of the Danube and Sava rivers (Fig. 1). This area is predominantly hilly and mountainous, with a moderately dense network of rainfall and water level gauging stations, making it suitable for rainfall-runoff analysis of small-to-mid sized catchments.

Out of a total of 28 gauged catchments in this region with area less than $500\,\mathrm{km}^2$, 21 have been chosen for the study. The criteria for choosing the catchments were: (1) natural catchment hydrology is dominant, (2) the actual catchment area corresponds to topographic catchment area, (3) sufficient time series of data are available, and (4) there have not been major changes in the catchment during the course of observations that influence catchment runoff.

Figure 1. Location of Serbia, with study area outlined in red (basemap source: The World Factbook, 2017).

3 Data

The SRTM DEM (Shuttle Radar Topography Mission Digital Elevation Model) (Rodriguez et al., 2005), with a resolution of 3 arcsec, was downloaded for the entire territory of Serbia, with some margin to account for some transboundary basins. The downloaded original digital elevation model was pre-processed using void-filling interpolation and a combination of sink filling and drainage route deepening techniques in order to obtain a hydrologically correct DEM that is capable of correctly representing riverbeds.

The CORINE (Coordination of Information on the Environment) Land Cover dataset (EEA, 2000), developed by the European Environment Agency (EEA) and made available online, was used in this study. The dataset was downloaded for the entire country and converted to raster form to facilitate calculations.

Soil data was obtained from soil maps. Two different sets of soil maps were used in this study. To represent the currently used methodology, the soil map of scale 1 : 1 000 000 (developed in 1959 by the Yugoslav Society of Soil Science) was used. As an improvement to the methodology, the soil maps of scale 1 : 50 000 (developed between 1958 and 1982 by the Soil Institute of Serbia) were introduced. All maps were manually digitized and classified. The implemented datasets are shown in Fig. 2.

The hydrological and meteorological data used in this study were obtained from the Hydrometeorological Service of Serbia (HMSS). Rainfall data included: mean annual rainfall at 704 rain gauges, maximum daily rainfall at 433 rain gauges, intensity-duration-frequency (IDF) curves at 26 main meteorological stations. Mean annual air temperature data was acquired for 81 stations. Discharge data was acquired in the form of maximum annual instantaneous discharge and mean annual discharge, for the 21 reference catchments, from the beginning of measurement for each discharge station up to 2011. The locations of the used meteorological data are shown in Fig. 3.
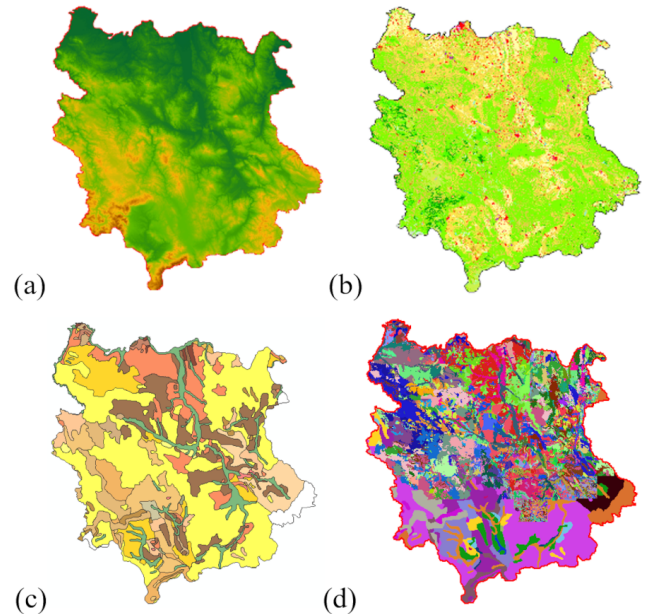

Figure 2. Overview of used datasets: **(a)** Pre-processed DEM, **(b)** CORINE Land Cover, **(c)** digitized soil map of scale 1 : 1 000 000, and **(d)** digitized soil map of scale 1 : 50 000.

4 Theory and methodology

4.1 Automation of Currently Used Methodologies

The Soil Conservation Service (now National Resources Conservation Service) Curve Number method, developed at the United States Department of Agriculture (USDA) during the 1950s, is the method most frequently used for estimating direct runoff from storm rainfall in ungauged catchments in Serbia today. 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 Curve Number (CN) was estimated using the CORINE Land Cover dataset and the digitized soil map of scale 1 : 1 000 000. The soils were categorized into hydrologic soil groups (A, B, C and D) based on criteria from the Soil Conservation Service and soil characteristics. The classes of the CORINE Land Cover classification system have each been assigned a Curve Number for every hydrologic soil group. The complex Curve Number for the entire catchment was computed using the weighted CN method, following the identification of all hydrologic soil-cover complexes.

The transformation of excess rainfall into direct runoff was simulated using a modified SCS dimensionless unit hydrograph. Jovanović (1989) documented a modification of the SCS synthetic unit hydrograph based on a large number
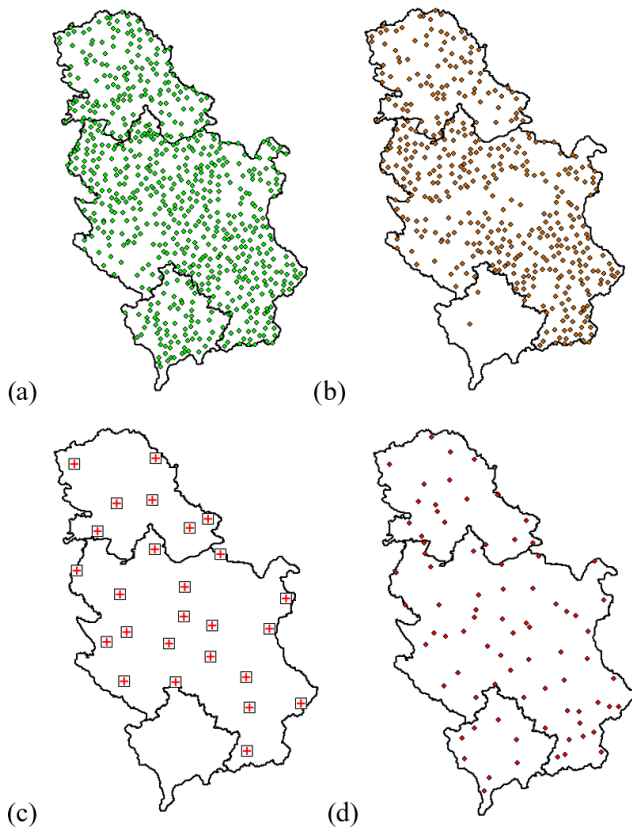
Figure 3. Availability of meteorological data: **(a)** mean annual rainfall, **(b)** maximum daily rainfall, **(c)** IDF curves, and **(d)** mean annual air temperature.

of observed catchments in Yugoslavia, and this method has since grown much in popularity. This method defines the dimensionless unit hydrograph based on the duration of rainfall and certain morphometric characteristics of the catchment (catchment area, longest flow path, flow distance from the catchment centroid to the outlet and 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.

Design rainfall for flood discharge estimation is most often based on the premises that an event with rainfall intensity of a certain probability of occurrence will cause runoff with the same probability of occurrence. These rainfall events were estimated using available IDF (intensity-duration-frequency) curves from the nearest meteorological station for each catchment. When performing calculations, each combination of rainfall duration and intensity (for a certain probability of occurrence) is evaluated, and the combination which yields the highest runoff is chosen.

4.2 Proposal for Improvement of Methodology

In an attempt to improve the results of current methodologies, two modifications were made to the calculations: an update of soil data and the introduction of a distributed velocity method for calculating catchment lag time.

The soil database was updated to include available soil data from soil maps of scale 1 : 50 000. All available soil maps were digitized and classified into hydrologic soil groups. As soil maps at this scale do not cover the entire study area, the gaps were substituted by previously used soil data (from the smaller scale 1 : 1 000 000 maps). This way, all of the study area was covered with the best available soil data.

A more hydraulic and deterministic approach was taken to estimate hydrograph lag time, improving upon current empirical methods relating hydrograph lag to longest flow path length and average slope, length of flow path from the catchment centroid and rainfall duration. The motivation to the suggested improvement was to utilize the computing power of GIS to achieve a more process-based, distributed approach that accounts for spatial variability of flow, while still implementing the unit hydrograph methodology (as a lumped model).

The distributed velocity method for estimating hydrograph lag time developed in this work estimates flow velocities on every flow path within a catchment (in this case in every grid cell), then sums travel times along the hydraulically most distant path. Catchment areas were characterized by driving processes into three flow types: sheet flow, shallow concentrated flow, and open channel flow.

Sheet flow is defined as flow over plane surfaces, which usually occurs in the headwaters of a stream near the ridgeline that defines the catchment boundary. Sheet flow was calculated using a simplified version of Manning's kinematic solution. Shallow concentrated flow was defined as flow that follows sheet flow, but lacks a well-defined channel, and was calculated using an empirical relationship between velocity, land cover and slope. Open channel flow, defined as a stream (or river) with a clearly defined channel, was calculated using Manning's equation. The value for Manning's roughness n was estimated using Jarrett's formula, while the hydraulic radius R was estimated based on the assumption of a trapezoidal channel cross section.

A flow velocity raster is created by calculating the flow velocities in every cell of the catchment based on flow type, slope and estimated roughness. After the flow velocity raster has been calculated, travel times are also computed using the aspect raster. Examples of the flow velocity and time to outlet rasters are shown for the Obnica River in Fig. 4.
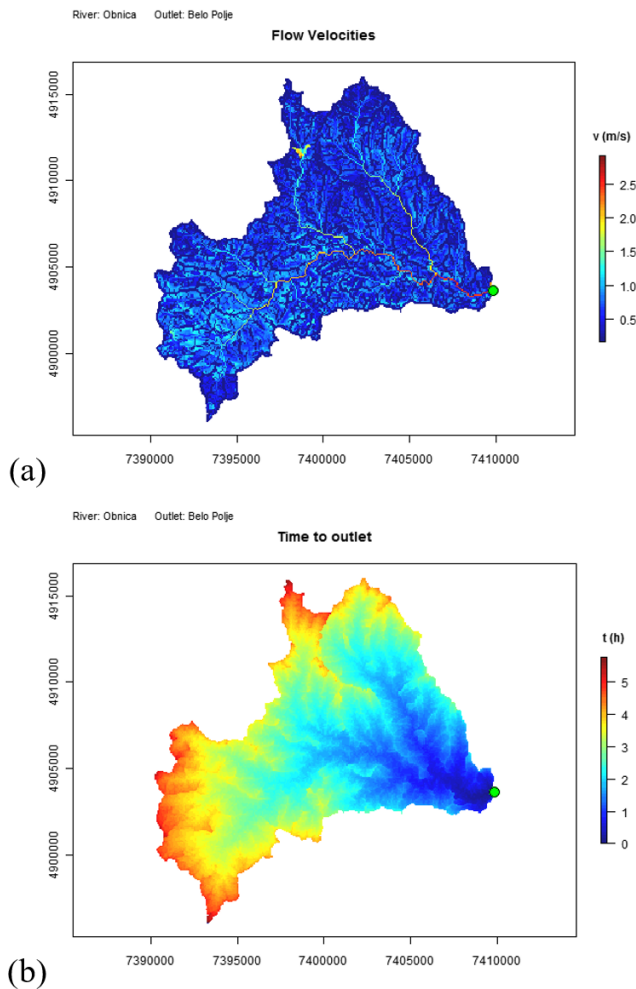
(a)

(b)

Figure 4. Example of flow velocity (**a**) and time to outlet (**b**) rasters.

4.3 Validation of Flow Prediction in Reference Catchments

To validate discharge prediction methods applied in ungauged catchments in Serbia, 20, 50, 100 and 1000 year return period discharges predicted in 21 reference (gauged) catchments were compared to results obtained by frequency analysis of annual maximum discharge. To test the impact of improved soil data and the distributed velocity estimation of hydrograph lag time, discharges were predicted using both standard and improved methods. Frequency analysis included Generalized Extreme Value (GEV) and Gumbel (Extreme Value Type I) distributions, where parameters were estimated using L-moments.

5 Results

Comparison of predicted discharges and those derived from frequency analysis (Figs. 5 and 6) indicate that the methodology applied is likely acceptable for deriving design dis-
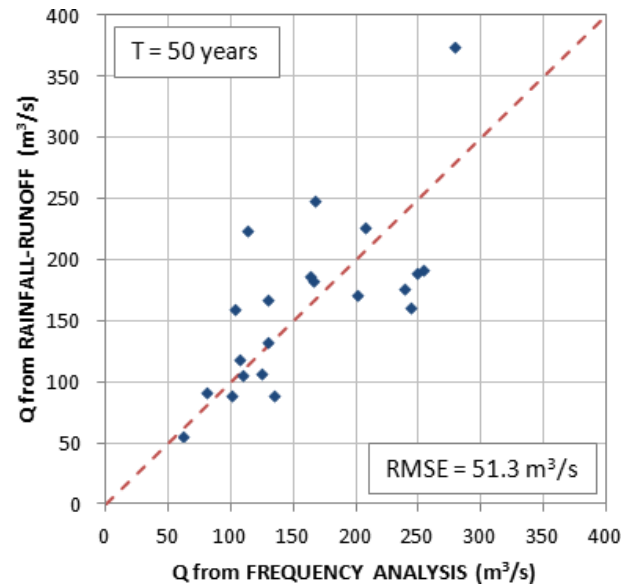
Figure 5. Comparison of calculated peak discharges and statistical design discharges, BEFORE methodology improvements, for 50-year return period.
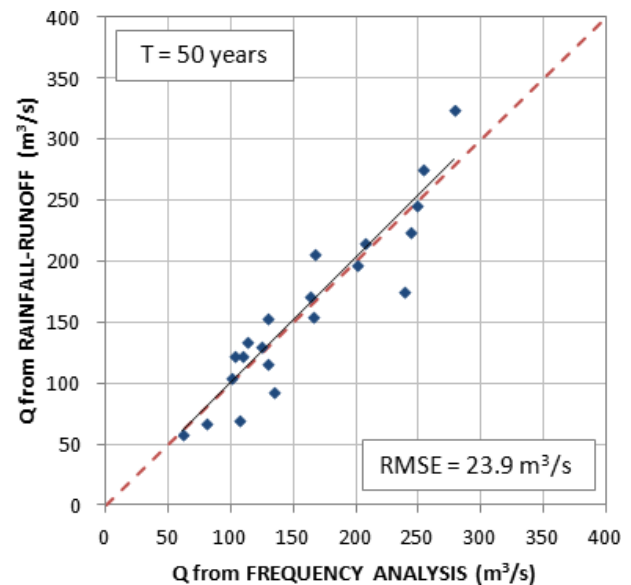
Figure 6. Comparison of calculated peak discharges and statistical design discharges, AFTER methodology improvements, for 50-year return period.

charges for ungauged catchments in Serbia. Improvements of improved soil data and the distributed velocity estimation of hydrograph lag time greatly reduce residuals (Fig. 7), indicating much better model performance. Greater improvements were associated with lower return periods, while the level of improvement for the 1000-year return period was insignificant. No clear link between rate of improvement and geographic characteristics of the catchments was found.
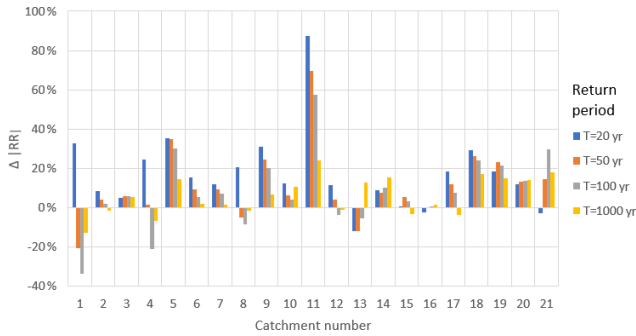
Figure 7. Difference in absolute value of relative residuals for all catchments before and after implementing methodology improvements (greater values indicate more improvement).

6 Example of application

The methodology presented has been successfully applied to calculate design flood flows for over 2500 catchments in Serbia for numerous design projects (roads, railways, pipelines, etc.), with the results shown in Fig. 8 as a plot of specific discharge (defined as the discharge per catchment area) of the 100-year flood and catchment area, comparing calculated results with verified results. The term "verified results" is used for results that correspond to the results of statistical analysis of observed values (where available).

7 Conclusion and recommendation

The automated calculation system presented in this study is one way of creating an extremely useful tool for hydrologists for the quick estimation of design discharges. The morphometric module of the calculation system showed excellent results, saving a great deal of time that would otherwise have been spent on manual processing of geospatial data. This type of automated analysis presented in this study will enable a much quicker hydrologic analysis on multiple catchments, while the methodology improvements introduced in this study will help to provide better estimates of predicted runoff.

Further work could include an even more distributed approach to modelling runoff (as opposed to the lumped unit hydrograph method used in this study) to better take into account the spatial variability of runoff. Unfortunately, more accurate datasets are currently unavailable, most notably soil and rainfall data, which are all limiting factors in achieving a closer resemblance of calculated results to observed values.
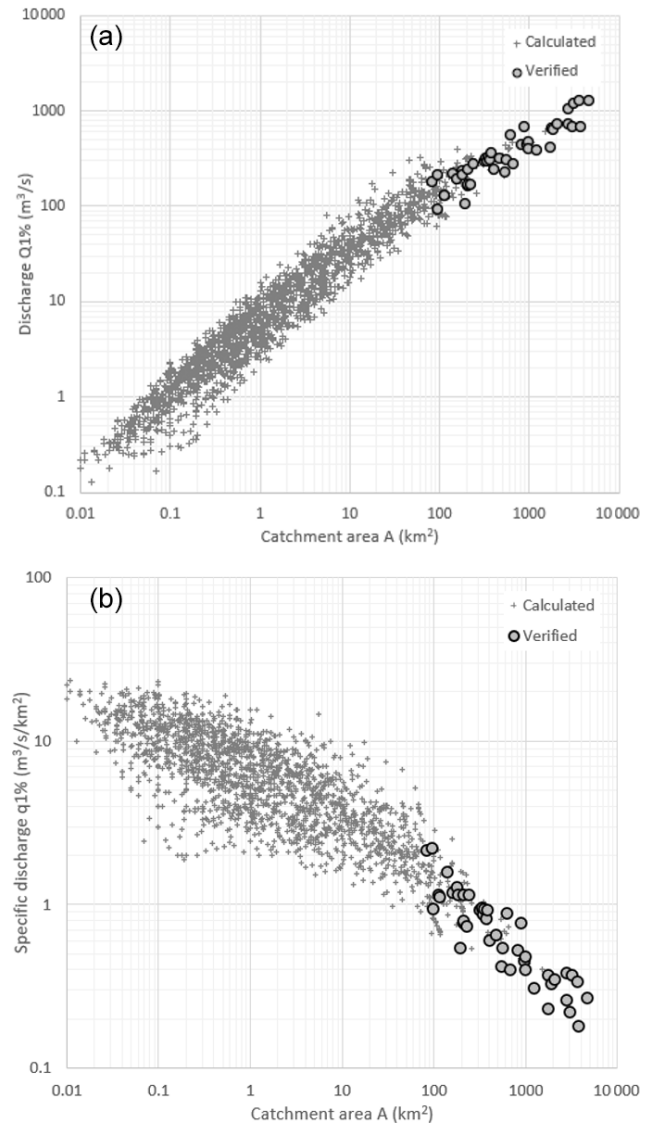
Figure 8. Results of calculation of 100-year floods on over 2500 catchments, presented as discharge values (above) and specific discharge values (below) compared to values verified with statistical analysis.

and the R programming language (R Core Team, 2021) for running the calculations.

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