Impact of resolution of DEM on the calculation of design floods in a small mountainous basin

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Abstract. A Digital Elevation Model (DEM) is a powerful tool for representing the surface of a particular area of interest. The containing data in the DEM is used for determining the characteristics of the surface. The main factor regarding the quality of such data is the resolution of the DEM. In this paper, the authors focus on the impact of the resolution of the two DEMs that were used to calculate a design flood in the Boca River basin. The Boca River basin is a small mountainous catchment located in the Low Tatras National Park in Slovakia. The authors have used digital elevation models of the Boca River basin with a 20 x 20 m and 1 x 1 m resolution of the raster and the S-JTSK coordinate system. The DEMs were downloaded from the Basic Database for GIS (ZBGIS®) which is a part of the spatial database of the cadastral information system in Slovakia. The design values of short-term rainfalls from actual observations from the Kráľová Lehota – Čierny Váh climatological station and the Corine Land Cover land use map for 2018 were used as an input for the calculation of the design floods. The design floods (QN) were estimated for the return period (N) of 10, 20, 50 and 100 years, using the Soil Conservation Service - Curve Number method, and ArcGIS software and raster tools. The peak design floods were estimated by calculating the time concentration, the maximum potential river basin retention, the design rainfall intensity, the depth of the runoff, and the volume of the flood wave. The aim of the paper was to compare the results of these calculations when the two different quality resolution DEMs are used. The results show that the design floods calculated using the more precise DEM with a 1 x 1 m raster were lower by 3.9% than the design floods calculated using the DEM with the 20 x 20 m raster.

1. Introduction
When it is talked about Digital Elevation Model (DEM), the meaning is linked to a form of digital representation of surface and topography of a particular area of interest. By manipulating with such a model user gets to know elevation, slope, and aspect of any point represented in a particular area. Digital Elevation Model is found to be very helpful in hydrology analysis, such as to study water flow direction or visibility analysis. For hydrology purposes, DEM is used for flood-prone area mapping or the calculation of the design floods, such as the calculation that is made for the small mountainous basin in Slovakia.

For this study, authors have chosen to research possibilities in variations in the results of calculating the design flood for catchment located in Slovakia using two different Digital Elevation Models with the resolutions 20 m and 1 m. Used DEMs are made as a product of the National Office
for Geodesy, Cartography, and Cadastre, free and open for use and downloading [1]. Data used throughout the calculations are in the form of raster with the earlier mentioned resolutions. Raster data consisted of a matrix of cells often-called pixels that are organized into rows and columns that carry information about the height of terrain or temperature in particular points, and so more. Each raster is defined by the size of the cell that is consisted. This means that size of the raster used in DEMs in this paper are representing the area size of 20 x 20 m and 1 x 1 m. The starting hypothesis behind this paper is to explore the changes between the calculation process and the gained results in the process of designing floods in the small mountainous basin when different resolution DEMs are used.

2. The issue of the variety of the DEM resolutions
Nowadays, technology and computer development enabled many to strive for using more quality and accurate datasets. LiDAR (Light Detection and Ranging) technology is used to represent and create a digital elevation model with a high vertical resolution (up to 10 cm) [2]. With such a high spatial resolution of the DEM, it is essential to find the right balance between the quality of the data and the need for reliable output.

It is known that the higher level of the detail represented by the raster’s cell size takes much more storage space and memory. Besides, the processing time of the calculations is more extended than with the same process by using the low-resolution raster data. Comparing to the low-quality resolution of the DEM, the smaller cell size provides high resolution of the represented occurrence and higher feature spatial accuracy. On the downside, displaying such data is much slower as well as processing it, and there is a larger file size [3].

Slow processing of the data showed its downsides when authors were trying to do the flow accumulation of the 1 m resolution DEM. Then the calculation was nearly as three times slower as the calculation of the 20 m resolution DEM. For this study, the authors aimed to estimate the benefit of such high-quality DEMs that are free to use. The main issue is finding the right balance between the purpose of the calculation, such as design floods and the spatial resolution of the given DEM.

3. Methodology
3.1. The Soil Conservation Service – Curve Number (SCS - CN)
The Soil Conservation Service Curve Number (SCS - CN) method was developed in 1954 and published by the Soil Conservation Service (now called the Natural Resources Conservation Service), U.S. Department of Agriculture in 1956 [4, 5].

The SCS - CN is used in small ungagged rural catchments where there are no (or limited) measurements/observations of direct flows or discharges [6]. It is used for estimating the volume of the direct surface runoff characteristics from rainfall data, predicting direct surface runoff volume for a given rainfall event, and estimating the volume and peak rate of surface runoff [7, 8].

The primary reason for the broad applicability and acceptability of the SCS-CN method lies in the fact that it accounts for most runoff - producing watershed characteristics, e.g., soil types, land use/treatments, surface conditions, and antecedent moisture conditions. Soil properties can have a significant influence on the amount of runoff [9].

As shown in Mishra and Singh [4] and USDA National Engineering Handbook [10], the SCS – CN method is based on a water balance equation (1) and two hypotheses. The first hypothesis (2) equates the ratio of the actual amount of direct runoff ($Q$) to the total rainfall ($P$) to the ratio of the amount of actual infiltration ($F$) to the amount of the maximum potential retention ($S$). The second hypothesis (3) relates the initial abstraction ($I_a$) to the maximum potential retention.
\[ P = I_a + F + Q \]  
\[ Q = \frac{F}{P - I_a} \]  
\[ I_a = \lambda \cdot S \]

where:
- \( P \) – total rainfall [mm],
- \( I_a \) – initial abstraction [mm],
- \( F \) – cumulative infiltration excluding \( I_a \) [mm],
- \( Q \) – direct runoff [mm],
- \( \lambda \) – initial abstraction coefficient [-],
- \( S \) – maximum potential retention [mm].

The maximum potential retention \( S \) is related to the \( CN \) value:
\[ S = \frac{25400-254*CN}{CN} \] (4)

The Curve Number (\( CN \)) is the main parameter in this methodology that depends on land surface characteristics and hydro-soil conditions [11], and is determined using the \( CN \) table of values [7]. This method allows for the calculation of a design peak flood \( Q_n \) by calculating the time concentration \( t_c \) (an indication of the time required for the flow of water from the farthest point of the river basin to its outlet [12]), the maximum potential retention or infiltration \( S \), the design rainfall intensity \( H_z \) with duration equal to the time of concentration (representing the input rainfall - \( P \)), the depth of runoff \( H_0 \), and the flood wave volume \( V \). For the purpose of this study, the initial abstraction \( (I_a) \) is equal to zero. A similar calculation with detailed formulas is described e.g., in publications [13–15].

4. Study area and input data
The area of interest is the Boca River basin, which is located in the Liptovský Mikuláš district (figure 1) in the Low Tatras National Park in Slovakia. The Boca River basin, with its outlet at the Malužíná station, has the basin area of 81.9 km², and it is a left tributary of the Váh River.

![Figure 1. Location of the Boca River basin](image)

For the analysis of the quality of DEM resolution, two DEMs with a raster size 20 x 20 m and 1 x 1 m were used (figure 2).
In order to calculate the design floods using the SCS-CN methodology, the following input data was used:

- vector map of soil types (figure 3a) was used to determine the hydrologic soil group. According to figure 3a, all soil types can be classified as hydraulic soil group B;
- Corine Land Cover (CLC) vector land use map for 2018 (figure 3b) was used to determine the CN values (table 1) [16];
- the actual design rainfall intensity data for the Kráľová Lehota – Čierny Váh climatological station (figure 4) divided from the one-day design values by a simple scaling method [17]. The historical observation of rainfall was provided by the Slovak Hydrometeorological Institute.
Figure 3. a) The map of soil types, and b) Land use map

Figure 4. The actual design rainfall intensity values for the Kráľová Lehota – Čierny Váh climatological station
Table 1. Selected CN values according to land use

| Land use                     | Area [km²] | CN [-] |
|------------------------------|------------|--------|
| Coniferous forest            | 36.78      | 60     |
| Mixed forest                 | 1.60       | 60     |
| Transitional woodland-shrub  | 36.51      | 65     |
| Grasslands                   | 3.04       | 58     |
| Pastures                     | 2.64       | 69     |
| Agricultural land            | 1.08       | 77     |
| Urban area                   | 0.25       | 74     |

weighted average CN value = **62.71**

5. Calculation and results

This study aimed to estimate and compare the design floods \( Q_N \) for return periods of 10, 20, 50, and 100 years, calculated using the DEMs with two different types of quality.

Using the DEM and spatial analysis tools in GIS, the longest runoff path was determined for each DEM resolution (figure 5). In this step of the calculation, the effect of the DEMs different quality can be noticed. The longest runoff path determined using the DEM with 20 x 20 m raster resolution is 12919 m long, while the longest runoff path determined using the DEM with 1 x 1 m raster resolution is 15112 m long. The runoff path was divided into the runoff on a hill slope, in a valley, and a river channel. The mean runoff velocity along the runoff path was determined using specified values from tables of runoff velocities [18]. The mean runoff velocity depends on the slope of the terrain and the land use along the hill slope and valley path.

![Figure 5. The longest runoff paths](image)

After velocities were selected, the time of concentration \((t_c)\) was calculated. In the case of the DEM, 20 x 20 m raster resolution time of concentration is equal to 67.83 min, while in the case of DEM with 1 x 1 m raster resolution time of concentration equals 72.59 min. These durations allowed the determination of the rainfall intensities, according to figure 4.
The design peak floods were estimated by applying the formulas from the SCS-CN methodology. When applying the SCS-CN method to calculate the design peak floods ($Q_N$) in the final profile of the river basin, we assumed that the river basin is affected by precipitation with the same statistical significance as the design floods and with duration equal to the time of concentration. For this study, the initial abstraction ($I_a$) is equal to zero. The results of the estimation of the design floods for return periods 10, 20, 50, and 100 years are shown in table 2.

**Table 2.** Estimation of the design floods ($Q_N$) for the return period ($N$) od 10, 20, 50, and 100 years

| Return period [year] | Weighted average CN value [-] | Rainfall intensity [mm] for $t_c = 67.83$ min (20x20 DEM) | $Q_N$ [m$^3$.s$^{-1}$] for $t_c = 72.59$ min (1x1 DEM) |
|----------------------|-------------------------------|----------------------------------------------------------|----------------------------------------------------------|
| 10                   | 62.71                         | 26.69                                                    | 53.78                                                    |
| 20                   |                               | 29.66                                                    | 65.33                                                    |
| 50                   |                               | 33.77                                                    | 82.81                                                    |
| 100                  |                               | 36.12                                                    | 93.51                                                    |

From the results it follows that estimated design floods were affected by the change of DEM resolution. The values of design floods calculated using the DEM with the size of raster 20 x 20 m ($Q_{10} = 55.78$ m$^3$.s$^{-1}$; $Q_{20} = 65.33$ m$^3$.s$^{-1}$; $Q_{50} = 82.81$ m$^3$.s$^{-1}$; $Q_{100} = 93.51$ m$^3$.s$^{-1}$) are higher than the values of design floods calculated using the DEM with 1 x 1 m raster ($Q_{10} = 51.79$ m$^3$.s$^{-1}$; $Q_{20} = 62.89$ m$^3$.s$^{-1}$; $Q_{50} = 79.69$ m$^3$.s$^{-1}$; $Q_{100} = 89.97$ m$^3$.s$^{-1}$) for all return periods.

6. Conclusions
The paper provides a short overview of an assessment of the impact of DEM resolution on the estimation of design floods, and the SCS-CN methodology used to estimate the design peak floods. From the results, we can conclude that the design flood calculation was affected by the DEM resolution. When results are compared, the design floods calculated using the more precise DEM with a 1 x 1 m raster were lower by approximately 3.9% for all return periods, than the design floods calculated using the DEM with the size of raster 20 x 20 m. The resolution of DEM affected the estimation of the longest runoff path and the time of concentration. Therefore, it affected the determination of the rainfall intensities that are a significant input in the calculation of design floods.

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