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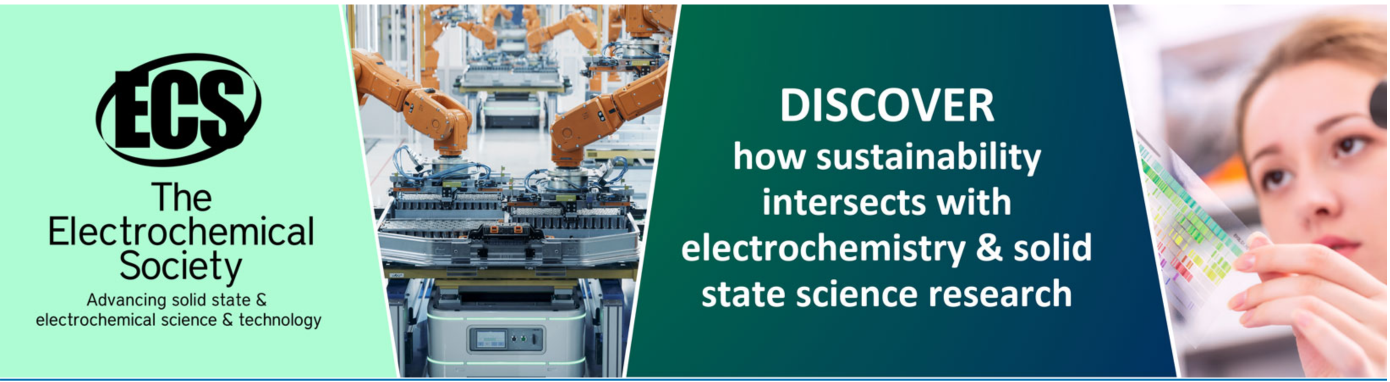

Land use and climate change impact on runoff in a small mountainous catchment in Slovakia

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Abstract. The paper focuses on the changes in runoff caused by changes in land use and climate. The study was performed in the Boca River basin, which is located in the Low Tatra National Park in Slovakia. This area has been affected by several severe windstorms in recent decades, which had a significant impact on the changes in forest cover in the Boca River basin occurred in 2004 (Alžbeta) and 2007 (Kyrill and Filip). The bark beetle outbreak followed these windstorms. The first part of the paper focuses on the changes in runoff caused by changes in land use for the period from 1990 to 2018. The design values of short-term rainfalls from actual observations and Corine Land Cover land use are used for the calculation of design floods. The second part focuses on the changes in runoff caused by climate change. The climate change is represented by data from Regional Climate Model (RCM) scenario. The estimation of runoff change is provided for the period 2070 – 2100. These results are compared with the results from actual observations. The design floods are calculated using the Soil Conservation Service - Curve Number method.

1. Introduction

In the last decades, extreme flash floods caused by short-term rainfall have become one of the most common natural threats in Europe, as well as in Slovakia, which is reflected in a large number of studies on extreme rainfall, flash floods and flood protection, such as seasonal characteristics of flood regimes across the Alpine–Carpathian range [1], flash floods in urban areas in Reggio Calabria (Italy) region [2], the impact of extreme rainfall and flash floods on the flood risk management process and geomorphological changes in small Carpathian catchments in Poland [3], post-event analysis and flash flood hydrology in Slovakia [4] and the land use change impact studies from Myjava River basin in Slovakia [5].

These extreme events have raised the need to improve hydrological methods for natural flood protection, especially in small agricultural and forested mountainous catchments. For successful risk management of these extreme events, it is essential to know if they were (or to what extent) affected by land-use changes and practices. Although the rainfall is the most important external factor that affects the occurrence of floods, the scale, and slow land-use changes, such as changes in forestry, increased protection of ecosystems and natural measures to capture water, changing vegetation in response to climate and ecological changes and many more, also require attention. Unlike slow land-use changes, there are also sudden, local factors such as forest fires and severe windstorms and blizzards that are more difficult to predict.

Changes in land use and runoff formation in connection with forestry have also been brought to the attention. The relationship between a forest and the runoff from a catchment area was confirmed by an experiment at the beginning of the 20th century by Professor C. Bourgeois of the Swiss Federal Institute for Forest, Snow and Landscape Research. Bourgeois started systematic measurements of runoff on two small river basins, Spelbergraben, and Rappengraben, with different forest densities [6]. In 1927 Zdeněk Válek [7] started similar research in an area located at the Slovak and Czech border [8]. The results of these experiments confirmed the influence of the forest on runoff and showed that the substantional flood flows were reduced.

Experiments involving deforestation and afforestation, have been carried out on slopes and permanent forests. Many authors have focused their research on this study, and there are many publications on this topic, such as, the hydrological impact of the Mediterranean forests in France [9], role of the forest in hydrological cycle and runoff [10], land use effects on flood generation – considering the soil hydraulic measurements in modeling [11], etc.

This article is focused on an assessment of the impact of the climate and land use (especially forest composition) changes on runoff. The changes in runoff are presented as the changes in design floods. The design floods are calculated using the Soil Conservation Service - Curve Number method and the design rainfall intensity values from the Liptovska Teplička station. In the first part of the paper, changes in runoff caused by changes in land use for the period from 1990 to 2018 are calculated and analyzed. The design values of short-term rainfall were divided from actual observations using the simple scaling method. The second part of the study focuses on the changes in runoff caused by climate change. The climate change is represented by data from Regional Climate Model (RCM) scenario, for the period 2070 – 2100.

2. Methodology

2.1. Simple scaling

To process rainfall data for a period of time shorter than one day, a simple scaling method is used. It is used for determination of the design values for a duration shorter than one day and for a selected time period by using daily rainfall records that are commonly available. Simple scaling method can be applied ti the relationship between the intensity, duration, and periodicity properties (IDF properties) of the precipitation. The general shape of the determination of the scaling properties of the precipitation is based on the following IDF formula [12]:

$$i=\frac{a\,(T)}{b\,(d)}, \tag{1}$$

where: T–return period function, b(d) – duration function of the rain given by the formula:

$$b(d)=(d+\theta)^{\eta}, \tag{2}$$

where: θ, η–parameters, determined by the estimation $\theta > 0$, $0 < \eta < 1$.

In this paper, the simple scaling for the scaling of the statistical moments was applied. The scaling exponent was estimated with a linear regression from the slope between the logarithmic moment values and the scaling parameters for the different order of the moments. A linear dependence between the scaling exponent and the moment order is a scaling exponent of the first order. This property is assigned to as "wide sense simple scaling". The following formula is used for deriving the scaling coefficients [13,14]:

$$E[I_{\lambda d}^{n}]=\lambda^{\beta_n}\mathrm{E}[\mathrm{I}_{\mathrm{d}}^{\mathrm{n}}], \tag{3}$$

where: $\beta n = n\beta$ – the scaling exponent of the n-th order.

2.2. The Soil Conservation Service – Curve Number (SCS-CN)

The SCS – CN method is used for estimating the volume of direct surface runoff characteristics in small rural catchments where there are no measurements or/and observations of direct flow [15]. This method is used to predict direct surface runoff volume for a given rainfall event, as well as to estimate the volume and peak rate of surface runoff [15]. Curve Number (CN) is the main parameter in this model, and it is based on an empirical study of runoff in small watersheds and hill slopes [16]. Parameter CN depends on land surface characteristics and hydro-soil conditions. As shown in Mishra and Singh [17], the SCS

– CN method is based on a water balance equation (4) and two hypotheses. The first hypothesis, as shown in equation (5), 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, as shown in equation (5), relates the initial abstraction (Ia) to the maximum potential retention.

$$P = Ia + F + Q, \tag{4}$$

$$\frac{Q}{P - Ia} = \frac{F}{S}, \tag{5}$$

$$Ia = \lambda \cdot S, \tag{6}$$

where: P–total rainfall [mm], Ia–initial abstraction [mm], F–cumulative infiltration excluding Ia [mm], Q–direct runoff [mm], λ–initial abstraction coefficient [-], S–maximum potential retention or infiltration [mm].

3. 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 Malužiná station has the basin area of 81.93km^2, and it is a left tributary of the Váh River.

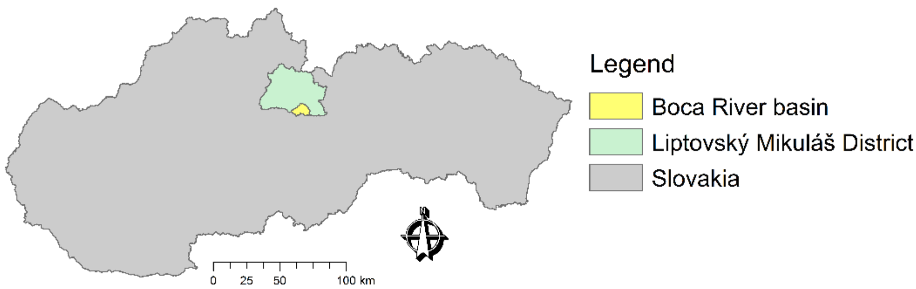

Figure 1. Location of the Boca River basin.

For the analysis of the runoff changes caused by land use impacts the actual measured and simulated data of rainfall were used. The historical observation of rainfall was provided by the Slovak Hydrometeorological Institute. The data consists of the hourly rainfall intensities for the 1995-2009 period.

Secondly, the rainfall data used in the analysis for the future changes in run-off caused by climate change were created by a CLM simulation and were provided by Dr. Martin Gera from Comenius University in Bratislava, Department of Astronomy, Physics of the Earth, and Meteorology. The Regional Climate Scenario (RCM) used consists of the rainfall intensities for the future period (2070-2100). The RCM scenario selected for the simulation of the climate was the SRES A1B scenario, which is a semi-pessimistic scenario with an increase in the global warming temperature of about 2.9° by the year 2100. This scenario relates well to the current processes in the atmosphere.

The inputs for the estimation of the design floods consists of following digital maps:

- raster map of the Digital Elevation Model (DEM), with a grid size of 20 x 20 m;
- vector map of the types of soil;
- Corine Land Cover (CLC) vector land use maps for the year 1990 and 2018 (Figure 2) [18];
- raster maps with a scale of
- 1:25 000 created according to the basic database for the Geographic Information System (ZBGIS®) [19].

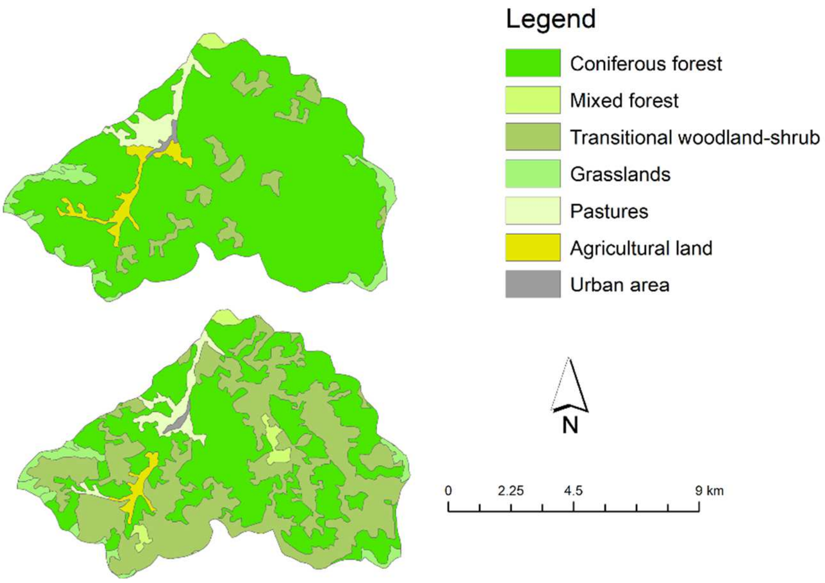

Figure 2. Land use maps of the Boca River basin in the 1990 and 2018.

4. Results of estimation of the changes in design floods

4.1. Land use change impact

The study aimed to compare the impact of land use change from 1990 to 2018 on the design floods (QN) for 1990 and 2018, for the return periods of 10, 20, 50, and 100 years using the actual measured data (total rainfall). When applying the SCS-CN method, the initial abstraction coefficient is equal to zero. The values of the main parameter CN that depends on land surface characteristics and hydro-soil conditions were selected from the CN table values [20].
The calculation and results of the estimation of the design floods using the design values of rainfall intensities for the actual period are shown in Table 1 and Table 2.

Table 1. Estimation of the design floods for the Boca River basin in the year 1990 using the actual design values of rainfall.

N [year]	P [mm] for t_c = 79.61 min	Weighted average CN value [-]	S [mm]	Q_N [$m^3 \cdot s^{-1}$]
10	29.32	55.99	199.65	42.93
20	31.78			49.90
50	34.69			58.72
100	36.65			65.00

Table 2. Estimation of the design floods for the Boca River basin in the year 2018 using the actual design values of rainfall.

N [year]	P [mm] for t_c = 79.61 min	Weighted average CN value [-]	S [mm]	Q_N [$m^3 \cdot s^{-1}$]
10	29.32	60.26	167.53	49.94
20	31.78			57.94
50	34.69			68.05
100	36.65			75.22

When the results from the Table 1 and 2 are compared, the values of the design floods increased by 14.02% in the case of the return period 10 years, by 13.88% in the case of the return period 20 years, by 13.70% in the case of the return period 50 years, and by 13.60% in the case of the return period 100 years. This increase in the designed floods was caused because of land use change. Figure 3 shows the percentage of certain land use covers. The forests in the Boca River basin have decreased by 43.5% since the year 1990. This deforestation was most probably caused by the Alžbeta, Kyril and Filip windstorms and has affected the design floods.

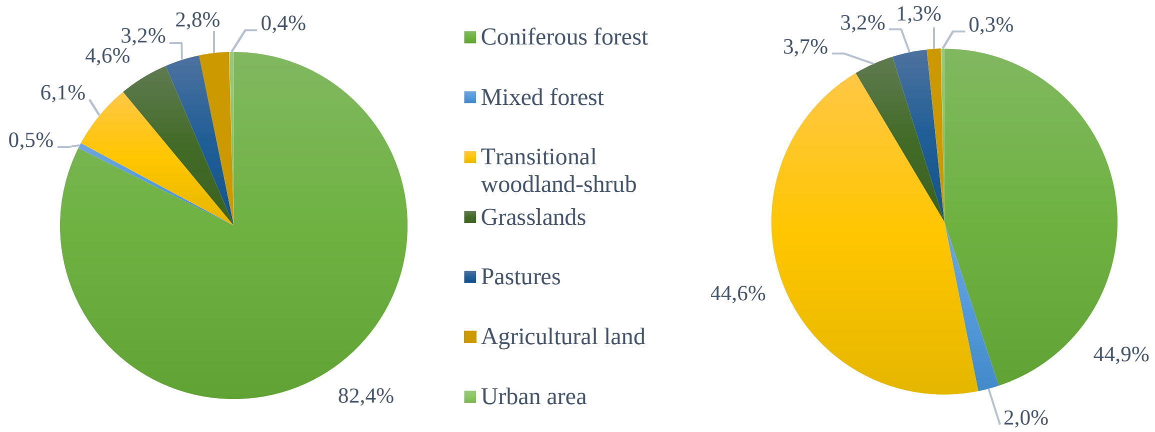

Figure 3. Percentage of the land use cover for the year 1990 (left) and 2018 (right).

4.2. Climate change impact

The second part of the study focuses on the changes in runoff caused by climate change, using the latest available land use (from 2018) and the future prediction of rainfall data created by a CLM simulation (2070-2010 period). Downscaled design values of the short-term rainfall depths are radically higher than the actual measured rainfall depths. For the future period, the difference between the amounts of precipitation seems to be two times higher.

The design flood QN, for the 2100 year was calculated for the return periods of 10, 20, 50, and 100 years. Except for the total rainfall values, all inputs data were the same as in calculation in Table 2. The calculation and results of the estimation of the design floods using the downscaled data from future scenario are shown in Table 3. The comparison of the results from a calculation using the actual design values of rainfall intensities and design values of rainfall intensities from the future scenario are shown in Table 4.

Table 3. Estimation of the design floods for the Boca River basin using the design values of rainfall intensities from the future scenario.

N [year]	P [mm] for t_c = 79.61 min	Weighted average CN value [-]	S [mm]	Q_N [$m^3.s^{-1}$]
10	37.58	60.26	167.53	78.72
20	45.63			111.69
50	56.37			162.27
100	64.08			202.71

Table 4. Comparison of the design floods using the actual design values of rainfall intensities and design values of rainfall intensities from the future scenario.

N [year]	Q_N [m^3.s^{-1}]	
	actual period	future period
10	49.94	78.72
20	57.94	111.69
50	68.05	162.27
100	75.22	202.71

5. Summary

The paper provides basic information about the simple scaling methodology and the SCS-CN methodology that was used to estimate changes in the design floods.

When the land use from 1990 and 2018 are compared (Figure 2 and 3), it is noticeable even by eye that the land use has visibly changed over the period. The forest has decreased by 43.5%. When the results from 1990 and 2018 are compared, the values of the design floods increased by 14.02% in the case of the return period 10 years, by 13.88% in the case of the return period 20 years, by 13.70% in the case of the return period 50 years, and by 13.60% in the case of the return period 100 years. This was most probably caused by deforestation, which can be the result of the severe windstorms and by the bark beetle outbreak in the year 2004 and 2007.

When the results from a calculation using the actual design values of rainfall intensities and design values of rainfall intensities from future scenario are compared, it can be seen that results predict even more increased values of the design floods. The calculation of design floods using the design values of rainfall intensities from future scenario was performed on the land use form the 2018 year, and results were compared to the results from the calculation of the design floods using the actual design values of rainfall and land use from the 2018 year. From results, is expected that the design floods will increase by 36.57 % in the case of the return period 10 years, by 48.12% in the case of the return period 20 years, by 58.06% in the case of the return period 50 years, and by 62.90% in the case of the return period 100 years.

As the results show, the changes in the land-use and also the change in the rainfall intensities, have a significant impact on the runoff, for the future will be necessary to re-evaluate the flood protection measures and the water management in the area.

Acknowledgments

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References

[1] Parajka J et al G 2010 *J. Hydrol.* **394** (1–2)
[2] De Franco M, Minniti M, Versaci R, Foti G, Canale C and Puntorieri P 2018 *Int. Conf. on Urban Drainage Modelling* Springer 441–6
[3] Bryndal T, Franczak P, Kroczak R, Cabaj W and Kołodziej A 2017 *Nat. Hazards* **88** (1) 95–120
[4] Hlavčová K, Kohnová S, Borga M, Horvát O, Šťastný P, Pekárová P, Majerčáková O and Danáčová Z 2016 J. *Hydrol. and Hydromech* **64** (4) 304-15
[5] Valent P, Rončák P, Maliariková M and Behan Š 2016 *SJCE* **24** (4) 15–26
[6] Minďáš J and Škvarenina J 2010 Forests of Slovakia and water (in Slovak) (Zvolen: Technical University in Zvolen)
[7] Válek Z 1953 *Water Manag.* **10** 293–6
[8] Mráček Z and Krečmer V 1975 The importance of the forest for human society (in Czech) (Prague: State Agricultural Publishing House)
[9] Cosandeya C, Andréassian V, Martin C, Didon-Lescot J F, Lavabre J, Folton N, Mathys N and Richard D 2005 *J. Hydrol.* **301** (1-4) 235–49

IOP Conf. Series: Earth and Environmental Science **444** (2020) 012036 doi:10.1088/1755-1315/444/1/012036

[10] Kostka Z and Holko L 2006 *Meteorol. J.* **9** (3) 143-8
[11] Wahren A, Feger K H, Schwärzel K and Münch A 2009 *Adv. Geosci.* **21** 99–107
[12] Koutsoyiannis D, Kozonis D and Manetas A 1998 *J. Hydrol.* **206** 118–35
[13] Menabde M, Seed A and Pegram G 1999 A simple scaling model for extreme rainfall
[14] Yu P S, Yang T C and Lin C S 2004 *J. Hydrol*. **295** (1–4) 108–23
[15] Boughton W C 1989 *Australian J. of Soil Research* **27** (3) 511–23
[16] Fan F, Deng Y, Hu X and Wenig Q 2013 *Remote Sensing* **5** (3) 1425–38
[17] Mishra S K and Singh V P 2003 Soil Conservation Service Curve Number (SCS-CN) Methodology Springer
[18] Copernicus land monitoring service, CLC. Available on: https://land.copernicus.eu/pan-european/corine-land-cover
[19] ZBGIS - The Geodesy, Cartography and Cadaster Authority of the Slovak Republic, Available on: https://zbgis.skgeodesy.sk
[20] USDA-SCS 1989 *Eng. Hydrol. Training Series*. Module 104 - Runoff Curve Number Computations. Study Guide. 2. Washington DC