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The potential for land use change to reduce flood risk in mid-sized catchments in the Myjava region of Slovakia

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Abstract: The effects of land use management practices on surface runoff are evident on a local scale, but evidence of their impact on the scale of a watershed is limited. This study focuses on an analysis of the impact of land use changes on the flood regime in the Myjava River basin, which is located in Western Slovakia. The Myjava River basin has an area of 641.32 km^2 and is typified by the formation of fast runoff processes, intensive soil erosion, and muddy floods. The main factors responsible for these problems with flooding and soil erosion are the basin's location, geology, pedology, agricultural land use, and cropping practices. The GIS-based, spatially distributed WetSpa rainfall-runoff model was used to simulate mean daily discharges in the outlet of the basin as well as the individual components of the water balance. The model was calibrated based on the period between 1997 and 2012 with outstanding results (an NS coefficient of 0.702). Various components of runoff (e.g., surface, interflow and groundwater) and several elements of the hydrological balance (evapotranspiration and soil moisture) were simulated under various land use scenarios. Six land use scenarios ('crop', 'grass', 'forest', 'slope', 'elevation' and 'optimal') were developed. The first three scenarios exhibited the ability of the WetSpa model to simulate runoff under changed land use conditions and enabled a better adjustment of the land use parameters of the model. Three other "more realistic" land use scenarios, which were based on the distribution of land use classes (arable land, grass and forest) regarding permissible slopes in the catchment, confirmed the possibility of reducing surface runoff and maximum discharges with applicable changes in land use and land management. These scenarios represent practical, realistic and realizable land use management solutions and they could be economically implemented to mitigate soil erosion processes and enhance the flood protection measures in the Myjava River basin.

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Key words: land use change, land use scenarios, the WetSpa model, maximum discharges, design floods

1. Introduction

Nowadays environmental protection is very important. Civil engineers try to make the world a better place and help people in their everyday lives. They should have a positive effect on nature and the environment. Therefore, they have to pay attention to nature and environmental protection from the beginning of the planning process.

Climate change affects water regimes, rainfall events, the sea level, and all the elements of the hydrological cycle. Nowadays the number of extreme floods and rainfall is increasing. Trends in flood frequencies and intensities will relate to changes in their risks in the future and risks associated with long-term climate change. Flood protection is a significant activity which can also affect nature. We usually use structural measures to regulate water or engage in flood prevention and protection. These measures have many advantages, but sometimes they can cause environmental problems as they can influence transverse and longitudinal interoperability. However, we can probably find environmentally friendly solutions such as non-structural measures.

In the past people built dams to protect their lands and buildings, but they took away some land from river areas. Because of human activities and climate change, the flood risk is increasing.

Hydrological models have been widely used to study many practical and pressing issues that arise during planning, design, operation, and management of water resources systems (*Lin et al., 2007*) and also to quantify the impacts of land use and climate change on the hydrological cycle (*Lin et al., 2010*). In the hydrological sciences there were many experiments to develop new hydrological analysis and modelling tools in the last decades of the 20th century, including massive development of complex hydrological models enabling simulation of runoff creation and erosion processes. Some of these models, which belong to a group of spatially distributed models, take into account the effect of various land use types on the simulation of catchment runoff together with individual hydrological processes. Good examples of such models include: WetSpa (*Valent et al., 2015, 2016;*

Rončák and Hlavčová, 2014; Rončák et al., 2016), SWAT (*Arnold et al., 1998*) or MIKE SHE (*DHI, 1999*). The impact of land use and also climate change on flood regimes has been an important element of research in recent years, particularly with respect to the formation of runoff (*Kostka and Holko, 2001; Hlavčová et al., 2005, 2007*). Land use and climate change directly impact key aspects of hydrological processes, such as evapotranspiration (*Vítková et al., 2015*), interception (*Bartík et al., 2016*) and runoff. There have been many studies focused on the environmental impacts of climate change adaptations on land use and water quality (*Fezzi et al., 2015; Minďaš and Škvareninová, 2016*); and other environmental or engineering aspects (*Cápayová et al., 2017*).

In this paper, we focused on the development of various scenarios for estimating potential changes, and simulation of runoff under the changed conditions in land use. A change in runoff under each scenario was compared to the current situation. We put the emphasis on comparison of changes in the depth of runoff and its related components, changes in spatial distribution of runoff in a catchment and changes in selected components of water balance.

2. Study area

The Myjava River basin has an area of 641.32 sq. km. The catchment itself is situated in the western part of Slovakia and encompasses the geomorphological units of the Myjava Hills, Chvojnica Hills, and the northern part of the Bor Lowlands (Fig. 1). Most of the slopes of the catchment are oriented towards the south and southwest as determined by the direction of the river flow. The mean altitude of the catchment is 298 m a.s.l. with the highest point at 818 m a.s.l. (Eupec) and the lowest at 164 m a.s.l. (catchment outlet). The geological structure is mainly formed by sandstones and claystones with small patches of limestones situated in the northern part of the watershed. Most of the catchment lies in warm and moderately warm regions with a mean annual air temperature of 9 °C and a mean annual precipitation amount between 550 and 700 mm (in the northern parts, as much as 900 mm). The natural vegetation is mainly represented by oak and hornbeam forests with the exception of sand-dune grasslands in the southern parts of the catchment, which are covered with pine forests (*Zaťko, 2002*).

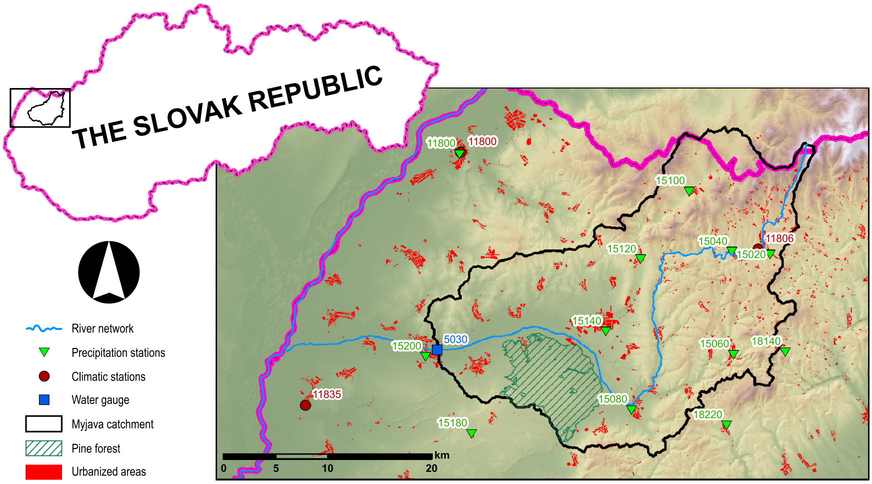

Fig. 1. The location of the Myjava River catchment within Slovakia. The larger image also displays 12 precipitation stations, 3 climatic stations and a water gauge station, which were used in the rainfall-runoff modelling, as well as the position of a large pine forest situated in the southern part of the catchment.

The Myjava River basin is typified by the formation of fast runoff processes, intensive soil erosion and muddy floods. Major stages of man-made interventions in this area include the medieval kopanitse colonization (formation of small patchy, rural settlements, deforestation, and the radical creation of agricultural fields), the socialist collectivization of agriculture, and the socio-economic changes (de-collectivization of agriculture) (*Stankoviansky, 2003*). A dense network of dry valleys concentrates the runoff, resulting in ephemeral gullying and the creation of muddy floods (*Danáčová et al., 2015*). Deforestation and extensive agricultural cultivation of originally natural areas have caused an enormous intensification of the land use and landscape-forming processes, as well as tillage erosion (*Nosko, 2016*).

3. Data analysis

To simulate the daily flow, the physically-based WetSpa rainfall-runoff model was used. The model uses geospatially referenced data as an input for deriving the model parameters, which includes most data types supported by

ArcView, such as coverage, shape files, grids and ASCII files (*Wang et al., 1996*).

The 3 basic maps used in the model are digital maps of the topography, land use and soil types, while other digital data are optional, depending upon the data available and the purpose and accuracy requirements of the project. The following hydro-meteorological data were used in the model: daily precipitation totals from spot measurements at the 12 stations and the average daily values for the air temperature at the 3 climatological stations. The location of the stations is presented in Fig. 1. The Thiessen polygon method was used for the interpolation of the rainfall data. One alternative to this method is inverse distance weighting (IDW) (*Valent and Výleta, 2015*). The flow data consisted of the average daily flows at the Myjava – Šaštín-Stráže profile. We have obtained the daily data from SHMI in the period from 1997 to 2012.

The calibration of the model requires the identification of a set of parameters that will be able to provide the best possible agreement between the measured and simulated parameters of the hydrological model in accordance with the selected criteria. Various agreement criteria were used during the calibration of the models for expressing any differences between the observed and modelled data.

In order to evaluate finally the influence of land use change on floods we had estimated the design annual mean daily maximum floods from the analysed period 2007 and 2012. Fig. 2 shows the frequency of all flood events which were observed during these years. We can see that the majority of events had less discharges than 25 m^3/s, which represents the return period lower than 2 years. Only one event was close to a 100-year flood.

4. Methods

The main aim of the study was to estimate the effect of changes in land use on the extreme runoff processes in the Myjava River basin. In order to express the changes in land use, several scenarios were created (Table 1) that assumed that we simulated runoff in a daily step for the period 1997–2012. In rainfall-runoff modelling it is essential to take into account various sources of model uncertainties that influence the quality of simulated runoff

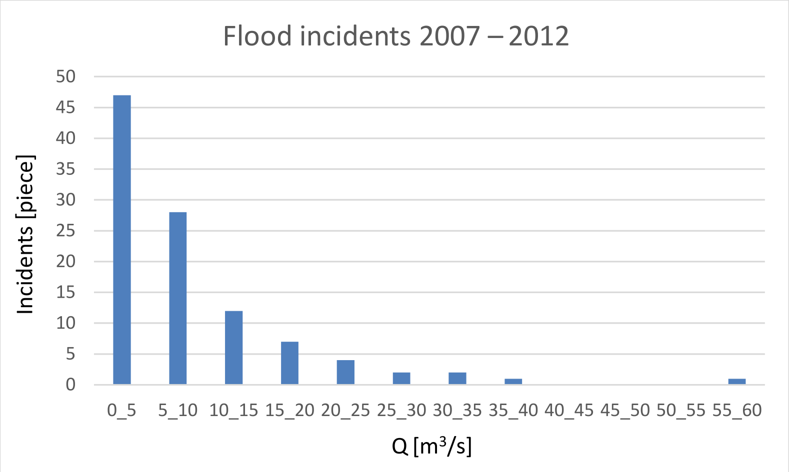

Fig. 2. Frequency of all flood events of 2007 – 2012.

from a catchment (*Valent et al., 2014*). Therefore, the first three land use scenarios were used to test the ability of the model to simulate the changes in land use. The remaining land use scenarios, which were more realistic, aimed at reducing the maximum runoff. In the 'crop' scenario, areas with short grasses were changed to cropland. In the second land use the 'grass' scenario, the cropland areas were changed to short grasses. In the third 'forest' extreme scenario, the whole of the area was afforested with the exception of urban areas.

Then we created three more realistic land use scenarios. In the 'elevation' land use scenario, the catchment area was divided into two altitudinal zones: i.e., the lowlands between 98 – 300 m a.s.l. and the low highlands between 301 – 800 m a.s.l. We covered the lowlands with cropland and the low highlands with deciduous trees. In the 'slope' scenario, we divided the catchment into 3 categories, depending on the slope characteristics. The first category was an area with a slope (0 – 12%) covered with cropland. The second was an area with a declination (12 – 20%) covered with short grasses, and the third was an area with a slope, of which more than 20% was covered with deciduous trees.

The last land use scenario, the 'optimal' scenario, was created with a combination of the slope characteristics and land use classes. The zones with slopes of less than 12% and covered with grass were changed to cropland. The areas with the declination (12 – 20%) covered with cropland were changed to grasses. The areas with over 20% slopes and where there were cropland and grasses, we changed to deciduous trees. The differences in land use classes are presented in Table 1.

Table 1. Land use classes in the current state and under the selected scenarios in % of catchment areas.

Land use [%]	**Scenarios**						
	current	**crop**	**grass**	**forest**	**elevation**	**slope**	**optimal**
crops	44.58	57.41	–	–	50.95	65.13	44.33
grassee	12.83	–	57.41	–	–	20.59	10.72
coniferous trees	9.40	9.40	9.40	–	–	–	8.11
deciduous trees	22.30	22.30	22.30	95.25	44.55	9.79	27.00
mixed trees	2.48	2.48	2.48	–	–	–	1.78
bog marsh	0.00	0.00	0.00	–	–	–	0.00
scrub	3.62	3.62	3.62	–	–	–	3.32
bare soil	0.04	0.04	0.04	–	–	–	0.04
urbanized areas	4.50	4.50	4.50	4.50	4.50	4.50	4.44

Modelling of the rainfall-runoff relationships in this study was undertaken in order to assess the impact of land use changes on runoff components and the water balance. Such an analysis requires the utilization of a distributed hydrological model which would take into an account the effect of land use on the runoff-generating processes (*Valent et al., 2016*).

For this purpose the WetSpa distributed rainfall-runoff model was used. The WetSpa model simulates runoff and river flow in a watershed in an hourly time step (*Wang et al., 1996; De Smedt et al., 2000; Liu et al., 2003; Bahremand et al., 2007*). The availability of spatially distributed data sets (a digital elevation model, land use, soil and radar-based precipitation data), coupled with GIS technology, enables the WetSpa model to perform spatially distributed calculations. The hydrological processes considered in the model are: precipitation, interception, depression storage, surface runoff, infiltration, evapotranspiration, percolation, interflow and groundwater drainage. The total water balance for each raster cell is composed of a separate water balance for the vegetated, bare-soil, open water, and impervious parts of each cell. The model predicts discharges in any location of a channel network and the spatial distribution of the hydrological characteristics.

The use of rainfall-runoff models comes with a few problems predominantly linked with a vast simplification of an otherwise complex system of the creation of runoff and the quality of the data input or with the model's calibration and finding an optimal set of parameters (*Valent et al., 2011*). Therefore, the calibration of the parameters is one of the most important parts of hydrological modelling. The calibration of the model requires the identification of a set of parameters which will provide the best possible agreement between the measured and simulated parameters of the hydrological model in accordance with the selected criteria (Fig. 3). Various agreement criteria were used during the calibration of the models to express any differences between the observed and modelled data. The period of the calibration was from 1997 to 2012. Twelve parameters for which a range of admissible values were set were optimized. The Nash–Sutcliffe coefficient was chosen as the dominant criterion in this work.

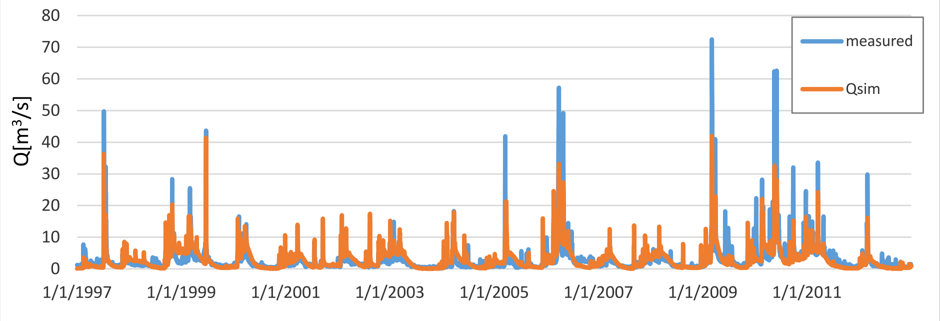

Fig. 3. Comparison of the measured and simulated runoff after the model's calibration.

5. Estimation of the design floods

To estimate the changes in the extreme runoff simulated, we conducted a statistical analysis and estimated design floods of various return periods, using the HQ-EX program version 3.0. This program computes the probabilities of maximum discharges and is based on the methodology published by Deutscher Verband fur Wasser und Kulturbau, *DVWK Regeln 101/1999 (1999).* The following three methods for estimating distribution function parameters were proposed in this methodology:

- The method of moments (MOM),
- Maximum likelihood method (ML),
- Method of probability weighted moments (PWM).

For estimating the probabilities, the following theoretical distribution functions could be used:

- E1 (Extreme Value Distribution) – parameter estimation with (MOM, ML, PWM),
- GEV (Generalized Extreme Value) – parameter estimation with (MOM, ML, PWM),
- ME – parameter estimation with ML,
- LN3 (Three-parameter Lognormal) – parameter estimation with (MOM, ML, PWM),
- P3 (Pearson type III) – parameter estimation with (MOM, ML, PWM),
- LP3 (Log-Pearson type III) – parameter estimation with (MOM, ML, PWM),
- WB3 (Three-parameter Weibull) – parameter estimation with (MOM, ML, PWM).

We estimated the plotting position according to *Cunnane (1988)* as:

$$P = \frac{m - 0.4}{n + 0.2}\,,$$

where:

- n – number of observation in years,
- m – the number of the sequence of the descending sorted data.

To test the most appropriate distribution functions, we applied the following criterion, where the following values would be minimized:

$$D + n\varpi^2 + (1 - r_p)\,,$$

- D – value of the Kolmogorov test,
- $n\varpi^2$ – differences between the theoretical and empirical distribution functions, which are calculated with the following formula:

$$\sum_{i=1}^{n} [F(x_i) - P_i]^2 + \frac{1}{12\,n},$$

where:

- x_i – discharge values, $i = 1 \ldots n$,
- F – selected theoretical distribution,
- P_i – plotting position $\quad P_i = \dfrac{i - 0.5}{n}$,
- r_p – correction coefficient.

Finally, the three best-fitted distribution functions were always used to estimate the design flood values.

6. Results

The changes in runoff were evaluated by comparing the simulated average daily flows and their statistical characteristics for the current state and land use change scenarios. We also focused on an evaluation of the individual components of runoff that form the surface, groundwater, interflow and total runoff (Fig. 4).

The water balance components (evapotranspiration and soil moisture) were also compared (Figs. 5, 6).

In the ‘crop’ scenario, surface runoff increased by +5.1% in comparison with the actual state. The other runoff components were similar. The ‘grass’ scenario showed a decrease in total runoff of −5.1% and of −14.2% in surface runoff, in comparison with the reference stage. For the ‘forest’ land use scenario, the total runoff decreased by −16% and by −70.3% in the surface runoff, in comparison with the current state. The interflow and groundwater discharges correspond with the other runoff components. The potential evapotranspiration and soil moisture in these three land use scenarios have the opposite trend as the total runoff. If the total runoff is higher, the values of the components of the water balance are lower.

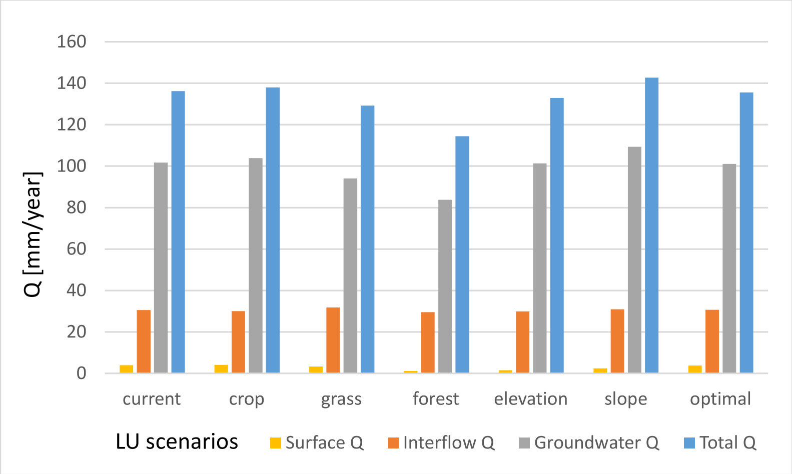

Fig. 4. Comparison of the mean annual simulated flows under the various land use scenarios runoff and the current state.

In the 'elevation' scenario, the total runoff decreased by −19%. The surface runoff significantly decreased by −59.3%, the interflow by −2.4%, and the groundwater decreased by −0.3%. The potential evapotranspiration was similar in comparison with the current state. The soil moisture

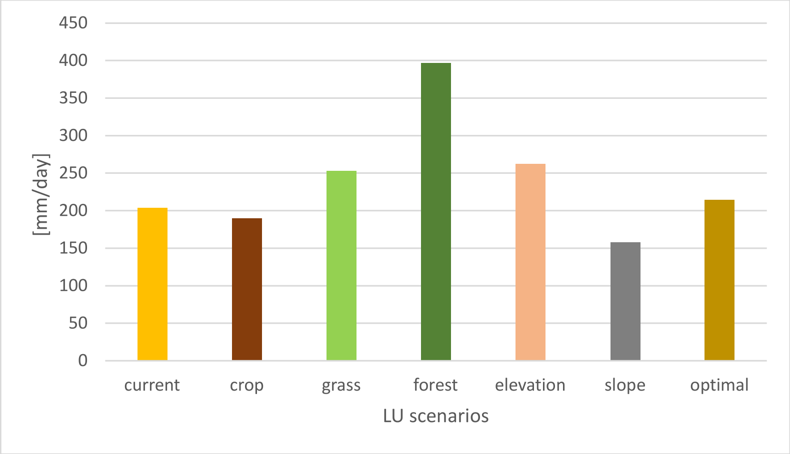

Fig. 5. Comparison of the mean daily soil moisture under the various land use scenarios and the current state.

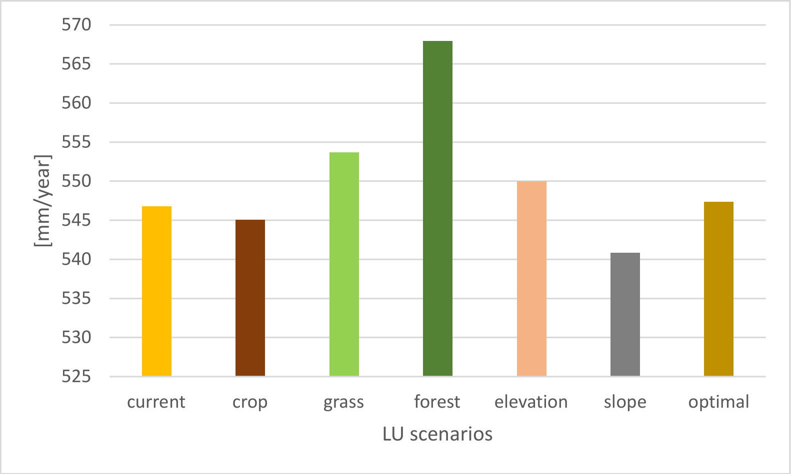

Fig. 6. Comparison of the mean annual potential evapotranspiration under the various land use scenarios and the current state.

increased by about +15% in comparison with the reference stage.

In the 'slope' scenario, the total runoff increased by about +4.7%, but the surface runoff significantly decreased by about −38.5%. The interflow was very similar to the current state, and the groundwater increased by +7.6% compared with the actual state. A noted decline in this scenario occurred in the potential evapotranspiration, which decreased by −6%, and in the soil moisture which was -17% lower compared with the actual state.

'Optimal', the last scenario, was based on actual anti-erosion measures that cost the least and had the lowest environmental impact. This basin had a reduction of the total runoff of only −0.4% compared with the current state. The surface runoff decreased by −2.1%. The other components of the runoff and individual particles of the water balance were similar.

7. Changes in design floods

We have compared the estimated values of the design annual mean daily maximum floods modelled for the six selected scenarios. The results are presented in Table 2 and in Figs. 7–9. Due to the length of the observations, the design values were estimated for a return period of 25 years, but we also presented estimates of return periods of 50 and 100 years (in grey, Figs. 7–9), which are affected by a higher degree of uncertainty due to the fact only 16 years of data were analysed. From the results, it can be concluded that, compared to the current state, some scenarios are able to reduce floods, especially the 'grass', 'forest' and 'elevation' scenarios, and to a lesser extent, the 'optimal' scenario.

Table 2. Values of the design annual mean daily floods estimated using the three best distribution functions with parameter estimation method.

Return period [years]			**2**	**5**	**10**	**20**	**25**	**50**	**100**
Current	**LN3**	WGM	25.00	36.13	44.92	54.37	57.58	68.10	79.53
	P3	MM	25.57	36.86	44.78	52.44	54.87	62.34	69.69
	P3	WGM	24.77	36.95	45.98	54.92	57.78	66.66	75.51
Return period [years]			**2**	**5**	**10**	**20**	**25**	**50**	**100**
Crop	LN3	WGM	25.44	36.95	46.67	57.58	61.38	74.12	88.42
	P3	MM	25.84	37.78	46.77	55.75	58.63	67.59	76.55
	LP3	MM	25.61	36.73	46.50	57.98	62.11	76.50	93.66
Return period [years]			**2**	**5**	**10**	**20**	**25**	**50**	**100**
Grass	ME	MLM	23.57	33.87	40.69	47.24	49.31	55.72	62.07
	P3	WGM	23.97	33.86	40.69	47.25	49.32	55.65	61.88
	WB3	WGM	23.63	33.84	40.97	47.80	49.95	56.50	62.89
Return period [years]			**2**	**5**	**10**	**20**	**25**	**50**	**100**
Forest	P3	WGM	21.73	28.88	33.45	37.68	38.99	42.95	46.78
	WB3	MLM	20.65	29.09	35.50	41.91	43.98	50.40	56.82
	WB3	WGM	21.43	28.93	33.75	38.15	39.50	43.52	47.35
Return period [years]			**2**	**5**	**10**	**20**	**25**	**50**	**100**
Elevation	ME	MLM	23.31	31.35	36.67	41.77	43.39	48.39	53.35
	P3	WGM	22.87	31.43	37.21	42.70	44.42	49.69	54.84
	WB3	WGM	22.54	31.42	37.49	43.24	45.03	50.47	55.74
Return period [years]			**2**	**5**	**10**	**20**	**25**	**50**	**100**
Slope	LN3	WGM	25.69	37.10	46.73	57.53	61.29	73.90	88.04
	P3	WGM	25.34	38.21	48.28	58.50	61.81	72.15	82.55
	WB3	WGM	25.27	37.98	48.15	58.64	62.08	72.89	83.90
Return period [years]			**2**	**5**	**10**	**20**	**25**	**50**	**100**
Optimal	P3	MM	24.80	35.58	43.26	50.76	53.14	60.47	67.74
	P3	WGM	24.21	35.90	44.53	53.06	55.79	64.24	72.66
	WB3	WGM	24.03	35.82	44.63	53.37	56.18	64.86	73.51

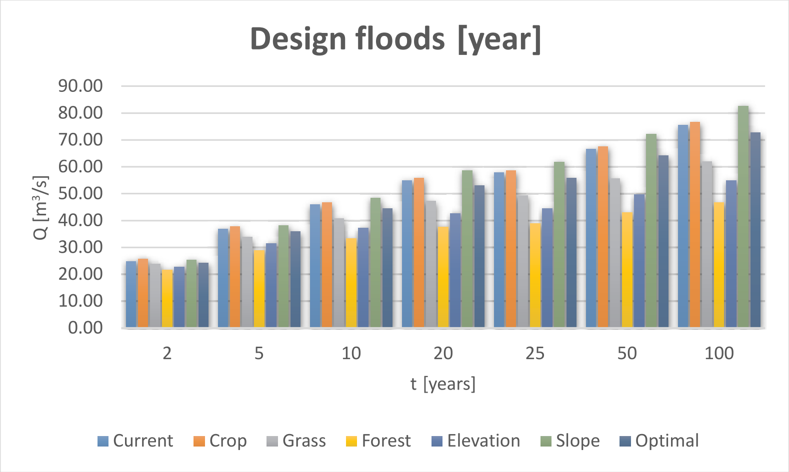

Fig. 7. Comparison of the design annual mean daily maximum floods with return periods of 2–100 years according to the scenarios analysed.

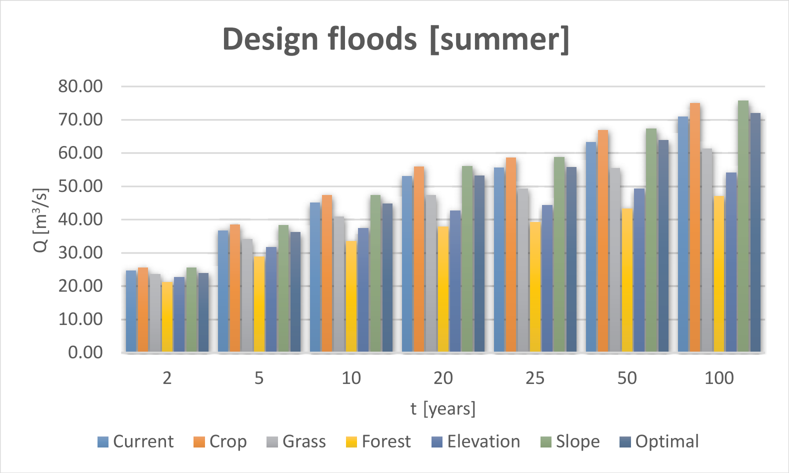

Fig. 8. Comparison of the design summer mean daily maximum floods with return periods of 2–100 years according to the scenarios analysed.

The ‘crop’ and ‘slope’ scenarios show an increase in the estimated design values. A similar conclusion can be derived for a separate analysis of the seasonal floods, which have been divided into the summer and winter seasons, Figs. 8 and 9.

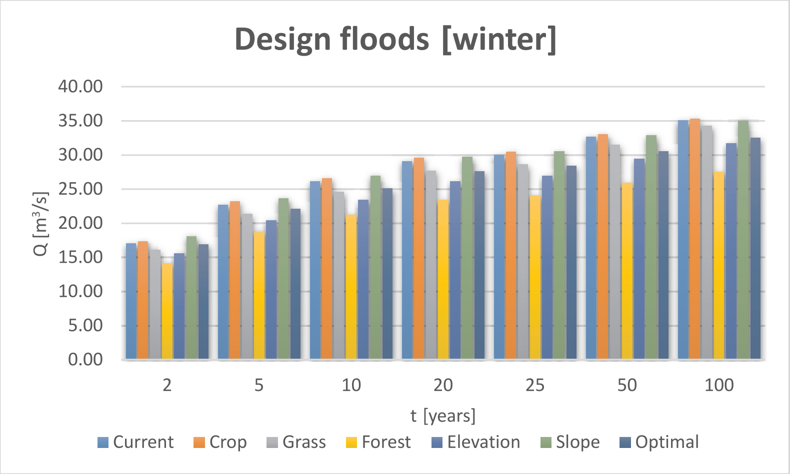

Fig. 9. Comparison of the design winter mean daily maximum floods with return periods of 2–100 years according to the scenarios analysed.

8. Conclusions

The main objective of this study was to perform an assessment of the impact of land use changes on runoff processes and the water balance. To express changes in land use, six scenarios were created ('crop', 'grass', 'forest', 'slope', 'elevation' and 'optimal').

The first three land use scenarios exhibited the ability of the WetSpa model to simulate runoff under changed land use conditions and enable the better parameterization of the land use parameters of the model. The other scenarios were more realistic. The best results from these were achieved by the 'optimal' land use scenario. The main advantage of the 'optimal' land use scenario is that it reduces not only the total runoff but also the surface runoff (Fig. 4). It could also reduce the occurrence of the soil erosion on the Myjava catchment, which is the largest problem in the basin.

The first three land use scenarios ('crop', 'grass' and 'forest') were used to test the ability of the model to simulate changes in land use. The remaining land use scenarios ('slope', 'elevation' and 'optimal'), which were more realistic, were aimed at detecting the impact on the maximum runoff and its possible reduction. We can conclude that compared to the current state, some scenarios are able to reduce floods, especially ‘grass’, ‘forest’ and ‘elevation’ scenarios, and, to lesser extent, the ‘optimal’ scenario.

The ‘crop’ and ‘slope’ scenarios showed an increase in the estimated design values of annual mean daily maximum discharges. A similar conclusion can be derived for the separate analysis of the seasonal floods divided into the summer and winter seasons.

The results could be used in integrated river basin management, especially in the organization of the river basin management process and assessments of the impacts of changes in the utilization of river basins on runoff and the extent of erosion-accumulation processes. The reliability of the results is related to the available input data and the conceptualization of the hydrological and erosion processes in the models as well as the parameterization of the environmental properties. These results also show that rainfall-runoff models with spatially-distributed parameters are an advanced tool that can be very useful in integrated water resources management in a river basin and land use planning.

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