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PÔVODNÁ PRÁCA – ORIGINAL PAPER

Effect of deforestation on watershed water balance: hydrological modelling-based approach

Vplyv odlesnenia na vodnú bilanciu povodia: prístup na báze hydrologického modelovania

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Abstract

Changes in land cover, including deforestation, can have significant effect on watershed hydrology. We used hydrological model with distributed parameters to evaluate the effect of simulated deforestation on water balance components in the watershed Ulička (97 km^2, 84.3% forest cover) located in the eastern Slovakia. Under the current land cover, average interception accounted for 21.1% of the total precipitation during the calibration period 2001–2013. Most of the precipitation (77%) infiltrated into the soil profile, and less than half of this amount percolated into the ground water aquifer. The surface runoff accounted for 1.2% of the total precipitation only, while the interflow accounted for ca. 12%. The largest proportion of the precipitation contributed to the base flow (23%). Watershed`s deforestation induced significant decrease in the interception and evapotranspiration (by 76% and 12%, respectively). At the same time, total runoff, surface runoff, interflow and base flow increased by 20.4, 38.8, 9.0 and 25.5%, respectively. Daily discharge increased by 20%. The deforestation significantly increased peak discharge induced by a simulated extreme precipitation event with the recurrence interval of 100 years. In the deforested watershed, the peak discharge was higher by 58% as compared with the current land cover. Peak discharge occurred in 432 minutes with the current land cover and in 378 minutes with deforestation, after the precipitation event had started. The presented assessment emphasized the risk of adverse effect of excessive deforestation on watershed hydrology. At the same time, the developed model allows testing the effect of other land cover scenarios, and thus supports management in the investigated watershed.

Key words: forest hydrology; runoff; flood risk; hydrological model; calibration

Abstrakt

Zmeny vo vegetačnom kryte a využívaní krajiny, vrátane odlesnení, môžu mať významný vplyv na hydrologickú bilanciu povodí. V tejto štúdii bol na analýzu vplyvu simulovaného odlesnenia na jednotlivé zložky vodnej bilancie použitý hydrologický model s distribuovanými parametrami. Výskum bol realizovaný v povodí Ulička na východnom Slovensku (97 km^2, lesnatosť 84,3 %). Pri súčasnom využívaní krajiny pripadalo na intercepciu v priemere 21,1 % z celkového úhrnu zrážok počas kalibračného obdobia 2001 – 2013. Najväčší podiel zrážok (77 %) bol infiltrovaný do pôdneho profilu a necelá polovica z tohoto množstva prenikla do vodonosnej vrstvy podzemnej vody. Zatiaľ čo podpovrchový odtok tvoril z celkového úhrnu zrážok približne 12 %, v prípade povrchového odtoku išlo len o 1,2 % podiel. Najvyššia časť úhrnu zrážok prispela k tvorbe základného odtoku (23 %). Simulované odlesnenie povodia vyvolalo významný pokles intercepcie (o 76 %) a evapotranspirácie (o 12 %). Celkový, povrchový, podpovrchový a základný odtok zároveň vzrástli o 20,4; 38,8; 9,0 a 25,5 %. Denný prietok sa v priemere zvýšil o 20 %. Odlesnenie významne ovplyvnilo kulminačný prietok vyvolaný simulovanou extrémnou zrážkovou udalosťou s pravdepodobnosťou výskytu 100 rokov. V odlesnenom povodí bol kulminačný prietok o 58 % vyšší v porovnaní s prietokom pri súčasnom využití územia. Kulminačné prietoky sa vyskytli po 432 minútach od začatia zrážkovej udalosti pri súčasnom využití územia a po 378 minútach v prípade scenára odlesnenia. Prezentované výsledky poukázali na riziko nepriaznivého vplyvu rozsiahlych odlesnení na hydrologické procesy v povodí. Vyvinutý hydrologický model zároveň umožňuje testovanie vplyvu rôznych scenárov využívania krajiny, čím podporuje manažment lesa a krajiny v skúmanom povodí.

Kľúčové slová: hydrológia lesa; odtok; povodňové riziko; hydrologický model; kalibrácia

1. Introduction

Interactions between ecosystems and hydrological cycles have been among the central topics of hydrology and ecosystem research for long. In particular, forests have been recognized to regulate the water cycles at various scales (Lee 2005; Sun et al. 2001, 2005), and their proper management is thought of as capable to mitigate the effect of adverse hydrological events such as floods and droughts (Calder & Aylward 2006; Calder et al. 2007). Forest ecosystems accumulate 80% of Earth`s total plant biomass (Kindermann et al. 2008), which affects actively the water cycle

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through the modification of soil properties and water flows, or the evapotranspiration of substantial amounts of water. The importance of forest water regulatory effects has been increasingly recognized in the context of climate change (Sun et al. 2005; Calanca et al. 2006; Hlavčová et al. 2007) and water-friendly forest management is expected to be able to moderate some climate change-mediated adverse effects on water cycles (Stohlgren et al. 2007; Fezzi et al. 2015).

Moreover, a growing rate of forest disturbances (Seidl et al. 2014) or improper forest management has generated concerns about the effect of regional water balance, which still remains largely unexplored (but see e.g. Uunila et al. 2006; Alila et al. 2009). A study of Langhammer et al. (2015) showed that a combined effect of forest disturbances and recent climate warming induced significant inter-seasonal changes in water balance components, including doubled frequency of peak flow events as compared with the period before 1980.

Effect of changes in forest cover induced by both natural disturbances and human interventions has been explored for long using paired-watershed experiment (Hewlet 1982) and numerous modelling studies (e.g. Brown et al.; Wagener 2007; Kostka & Holko 2007; Hlavčová et al. 2009). Among the most important paired watershed-experiment, which significantly extended our understanding, belong the studies, for example, by Hornbeck et al. (2014) from the Hubbard Brook watershed, Henry (1998) and Lewis et al. (2000) from the Caspar Creek watershed or Rao et al. (2011) from the Coweeta watershed.

A synthesis of a number of such studies suggested that hydrological responses to deforestations are highly variable, and often difficult to interpret. Anyway, the obvious finding is that the deforestation increases and reforestation decreases the annual flow. At the same time, deforestation increases flood peaks and volumes (Andréssian 2004), while forested catchments have greater infiltration rates, which may decrease catchment runoff (Zhang et al. 2014).

Forest effect on watershed hydrology has been questioned in some studies, and the disparity between the public expectations and real effects has been highlighted (e.g. Andréssian 2004; Kostka & Holko 2006). In this study we strive to contribute to this discussion and explore how changes in forest cover affect the hydrological balance of a highly forested watershed in Slovakia. At the same time, we test the applicability of the newly developed hydrological model ISSOP (Integrated System for Simulation or Runoff Processes) in the assessment of effects of land cover changes on watershed`s hydrology. In particular, we strive to:

– calibrate the hydrological runoff-rainfall model so as it reliably reproduces the measured daily and hourly discharges in the model watershed;
– use the calibrated model to simulate the main hydrological processes during a 13-year period under the current land cover (the reference state simulations); and
– evaluate the changes in water balance components, including those related to the simulated flood volume and peak discharge, in response to deforestation of the studied watershed.

We test the effect of forest removal and its permanent substitution by a grassland (i.e. the deforestation). Although such a development is rather unrealistic in Central Europe, this theoretical experiment shows the worst-case scenario of the total forest removal, for example, in the period following large-scale disturbances and the removal of dead trees. At the same time, the experiment shows the maximum effect, which the forest might have in the investigated watershed, and thus supports the evaluation of this forest function. Such investigation is intended to add to the current knowledge of forest effects on watershed hydrology, and support the integrated watershed management through the well-founded description of hydrological responses to land cover changes.

To help a reader unfamiliar with hydrological terms to understand the article, we provided a brief glossary in the Appendix 1.

2. Data and methods

2.1. Model watershed

The model watershed Ulička lies in the Bodrog basin in the north-eastern Slovakia (Bukovské vrchy Mts.). Watershed`s area is 96.6 km^2, elevation range 244–1,177 m a.s.l., average slope 16.0° and river network density 2.3 km km^{-1}. The mean annual discharge is 1.54 m^3 s^{-1}. The catchment has a moderately warm to moderately cool, very humid climate, with a mean annual precipitation between 920–1,220 mm and a mean annual air temperature ranging from 4.5°C to 7.8°C (data for the period 1961–1990). The watershed`s rock substrate consists of the flysh strata with low permeability. The positive landforms developed on the strata mostly built of sandstones, while valleys were formed on predominantly claystone strata. The soils are skeletal, loamy and silt-loamy, relatively shallow with depth up to 40 cm. Cambisols and rankers are the main soil types.

Forests cover 84.3% of the watershed, with the dominance of broadleaved trees (mainly European beech, *Fagus sylvatica* L.), which account for 79.4% of the total forest cover; coniferous forests account for 2.1% and mixed for 2.8%. The other land cover types are grasslands (12%), arable land (2%) and transitional woodland-shrub (0.6%) (Fig. 1). As the current study aims to evaluate the effect of deforestation on watershed`s hydrology, we present in Table 1 both the current proportion of land cover categories and the proportion after the simulated deforestation.

2.2. Meteorological and land cover data

Daily meteorological data for the period 2001–2013 were collected at 19 stations measuring precipitation and 4 climatological stations measuring air temperature. Daily discharge data were collected in hydrological station Ulič (245 m a.s.l.) in the catchment outlet. Hourly meteorological and discharge data were collected for year 2013 to perform model`s calibration that allows the hourly-scale simulation.

Three main sources of data used to define the watershed parameters in the hydrological model were digital elevation model, map of soil types and map of land cover categories. Data on forest tree species composition were extracted from the forest management plans archived in the National For-

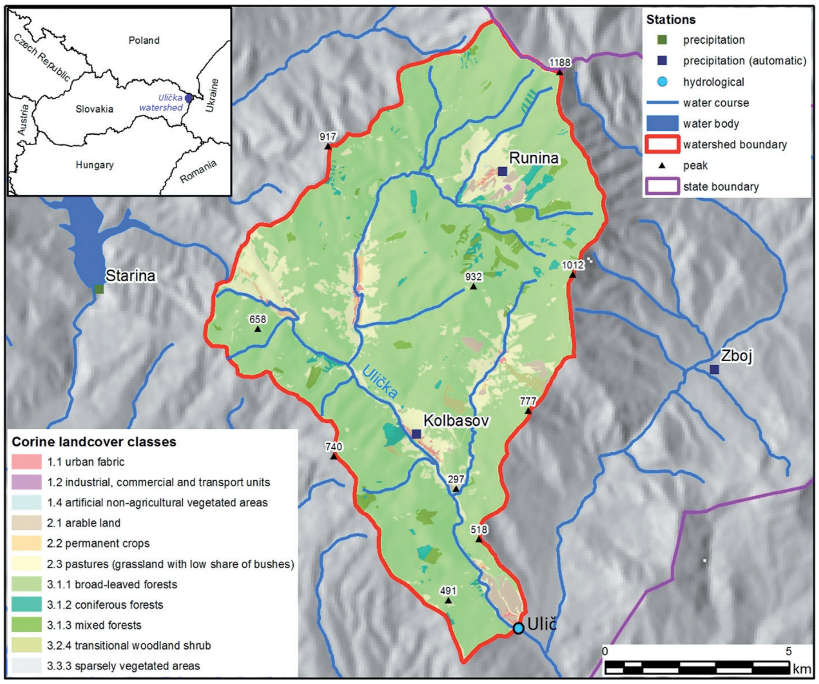

Fig. 1. Main land cover types of the Ulička watershed and river network. The position of meteorological and hydrological stations is indicated as well.

Table 1. The proportion of the current land cover categories and categories after watershed`s deforestation.

Land cover category	Current coverage	Deforestation scenario	Difference
		[%]	
1.1 urban fabric	0.55	0.55	0.00
1.2 industrial, commercial and transport units	0.03	0.03	0.00
1.4 artificial non-agricultural vegetated areas	0.02	0.02	0.00
2.1 arable land	1.98	1.98	0.00
2.2 permanent crops	0.57	0.57	0.00
2.3 pastures (grassland with low share of bushes)	11.98	96.81	84.83
3.1.1 broad-leaved forests	79.35	0.03	−79.32
3.1.2 coniferous forests	2.09	0.00	−2.09
3.1.3 mixed forests	2.82	0.00	−2.82
3.2.4 transitional woodland shrub	0.61	0.00	−0.61
3.3.3 sparsely vegetated areas	0.01	0.01	0.00

est Centre, Slovakia. The land cover types other than forest were extracted from the ZB GIS base maps (ZB GIS®), and the Corine Land Cover nomenclature (EEA 2006) was used (Table 1). Elevation was described using a digital elevation model with spatial resolution 20 m. Forest soil data were taken from the national forestry database supervised by the National Forest Centre (internal data) and derived from the geological maps with the scale of 1:50,000 (Malík et al. 2007) for the non-forest land.

2.3. Used hydrological model and calibration procedure

We used the Integrated System for Simulation of Runoff Processes (ISSOP), which is an advanced form of the physically-based models WetSpa (Wang et al. 1997; Liu & De Smedt 2004) and FRIER (Hlavčová et al. 2007; Horvát 2008). The ISSOP is a physically based hydrological model with distributed parameters that simulates the water balance components and water flows in grid-represented watersheds. The simulated hydrological system consists of plant canopy layer, soil surface, root-zone profile, and saturated groundwater aquifer. Soil water content is the superior variable that controls particular hydrological processes, i.e. the runoff, evapotranspiration, interflow and percolation into the ground water. Basic hydrological parameters of the land cover are indicated in Table 2; some forest-related parameters were adjusted using the long-term forest monitoring data collected in the frame of the ICP Forests monitoring programme (Pavlenda et al. 2013).

The model uses the calibration procedure that allows estimating the global calibration parameters (i.e. those specific to the entire watershed, Appendix 2) so as the difference between measured and simulated discharges is minimized. We used the Shuffled Complex Evolution method (SCE-UA; Duan et al. 1992; Vrugt et al. 2003), which was found efficient in locating the optimal model parameters of a hydrological model. The Nash-Sutcliff coefficient (Nash & Sutcliff 2006) and other statistics are used to assess the predictive

Table 2. Selected hydrological parameters of land cover categories occurring in the model watershed.

Land cover category	Manning	Interc_min	Interc_max	PET_coeff
1.1 urban fabric	0.10	0.00	0.00	0.90
1.2 industrial, commercial and transport units	0.10	0.00	0.00	0.90
1.4 artificial non-agricultural vegetated areas	0.40	0.50	1.50	1.05
2.1 arable land	0.35	0.00	1.00	1.10
2.2 permanent crops	0.35	0.50	1.50	1.15
2.3 pastures (grassland with low share of bushes)	0.30	0.10	1.00	1.00
3.1.1 broad-leaved forests	0.80	0.50	3.00	1.20
3.1.2 coniferous forests	0.40	2.00	4.00	1.15
3.1.3 mixed forests	0.55	1.00	3.50	1.18
3.2.4 transitional woodland shrub	0.40	0.10	1.50	1.15
3.3.3 sparsely vegetated areas	0.10	0.00	0.10	0.95

Abbreviations: Manning – Manning's Roughness Coefficient [-], Interc_min and Interc_max – minimum and maximum interception capacity [mm], PET_coeff – potential evapotranspiration coefficient [-].

power of the model in terms of the degree of match between measured and simulated discharges (Appendix 3).

2.4. Design of precipitation event with 100-year recurrence interval

Additionally to simulations based on the meteorological and hydrological data measured during the period 2001–2013, we tested the hydrological response to the theoretical precipitation event with the recurrence interval of 100 years. Such evaluation shows how the deforestation can affect the culmination discharges occurring during extreme floods. The precipitation intensity (mm h^{-1}) was proposed using a simplified approach based on the map of 100-year daily precipitation (Remiášová 2010) and scaling coefficients proposed by Bara (2009). We assumed the recurrence interval of the extreme precipitation is equal to the interval of peak discharge (i.e. the recurrence interval of a flood wave). Further, we assumed that the precipitation duration needed to initiate a flood wave with a given return time is equal to the so-called time of concentration, which is the time during which a water particle moves from the hydrologically most distant part of a watershed to watershed`s outlet (hence, the concentration time depends on the land cover). For the Ulička watershed, the design precipitation intensity was 10.39 mm h^{-1} with the concentration time 260 minutes for the current land cover, and 200 minutes for the deforestation scenario (see also Table 6).

3. Results

3.1. Model calibration

Model calibration based on daily discharges in the period July 1, 2001– December 31, 2013 was used to estimate the global calibration parameters specific to the investigated watershed (Table 3). The Nash-Sutcliffe coefficient reached value 0.819, what suggest good model` performance in terms of ability to reproduce the observed discharges. Parameters estimation based on the hourly data in year 2013 was satisfactory as well, and the coefficient reached value 0.809. The other statistical indicators of the match between measured and simulated discharges are given in Appendix 3; all of them suggest good model`s performance.

To illustrate the effect of calibration, we show the match between hourly simulated and measured discharges in the period May–July 2013, when an extreme precipitation amounting for 23.2 mm day^{-1} occurred (May 26, 2013), with maximum rainfall of 7.5 mm $hour^{-1}$ (June 18, 8:00 PM) (Fig. 2). Simulated discharge (Qs) reached the maximum of 15.74 $m^3 s^{-1}$ on 4 June at 02:00 PM, while the maximum measured discharge (Qm) was slightly lower (15.68 $m^3 s^{-1}$) and occurred 5 hours later (07:00 PM). In this day, the sum of precipitation was 22.1 mm, with maximum hourly amount 7.3 mm. As can be seen, the pattern of observed discharges is reproduced by the simulated data very well, though minor underestimation of peak discharges and certain shift in the timing of peak flows are apparent.

3.2. Hydrological simulations

3.2.1 Current land cover

A high share of forest cover and the dominance of broadleaved trees caused that the interception loss accounted for 21.1% of the total precipitation. Most of the precipitation (77%) infiltrated into the soil profile, and less than half of this amount percolated into ground water aquifers. The surface runoff accounted for 1.2% of the total precipitation only, while the interflow accounted for ca 12%. The largest proportion of the total precipitation contributed to the base flow (23%) (Table 4). A minor difference between the total

Table 3. The results of model calibration in the Ulička watershed. The values of global model parameters and a degree of match between measured and simulated discharges in terms of the Nash-Sutcliffe (NS) coefficient are indicated. Parameters abbreviations are explained in the Appendix 2.

Parameter	NS	K_run	P_max	T0	K_snow	K_rain	K_imp	K_ss	K_ep	K_i	K_g	G0	G_max
Unit	[-]	[-]	[mm d^{-1}]	[°C]	[mm $°C^{-1} d^{-1}$]	[mm $°C^{-1} d^{-1}$]	[-]	[-]	[-]	[-]	[-]	[mm]	[mm]
Daily, 2001–2013	0.82	6.50	70.00	0.1	4.0	0.2	0.6	0.80	0.80	0.48	0.02	145.0	90.0
Hourly, 2013	0.81	3.70	18.50	0.1	4.0	0.3	0.6	0.61	0.35	0.84	0.03	15.5	125.1

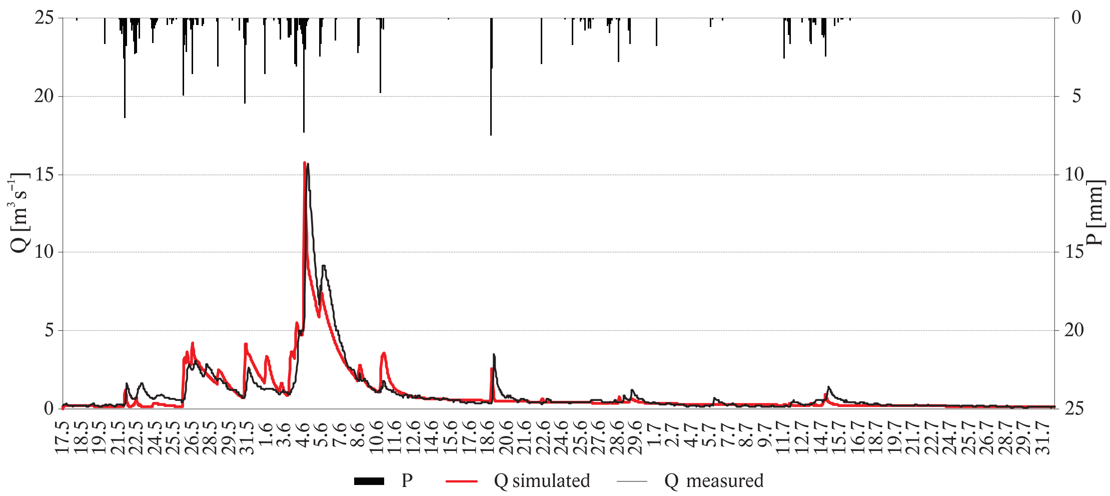

Fig. 2. Comparison of simulated and observed hourly discharges (Q) in the period May–July 2013. Hourly precipitation totals (P) are displayed as well.

Table 4. Simulated annual averages of the hydrological balance components during the period 2001–2013 in the Ulička watershed (mm year^{-1}) under the current land cover.

	Mean annual totals [mm]								
Component	P	I	In	Ep	Pe	R	G	B	T
Current landcover	1 000.5	211.5	770.4	623.1	357.1	12.1	122.3	231.8	366.1

precipitation amount and the sum of interception, infiltration and surface runoff (1,000.5 vs. 994 mm) accounts for the water accumulated in the surface depressions that evaporates.

Hourly-scale simulations allowed investigating a more detailed response of discharges to precipitation events. Investigation during the period May–July 2013 showed that the discharge sharply increased in response to the precipitation events that occurred from May 20 to June 4 (the sum of 127 mm); the rising limb of the hydrograph was formed mainly by runoff, followed by slightly delayed interflow (Fig. 3). This finding implies that while the surface runoff accounts for a minor proportion of the long-term water balance, its importance increases in culmination events. The recession limb of the hydrograph was formed by the ground flow (Qg) fed by the water from the saturated zone (aquifer); the base flow response to the precipitation event was not significant.

3.2.2 Effect of deforestation

The deforestation induced a substantial decrease of interception, which reached only 24.4% of the interception under the current land cover (i.e. 21.1% of the precipitation sum with the current land cover vs. 5.2% with the deforestation); however the effect on the total discharge was not that significant because of the minor relative effect of the interception on the total water budget with the current land cover (Table 4). The deforestation induced an increase in the total runoff by 20.4%, surface runoff by 38.8% and the base flow by 25.5% (Table 5).

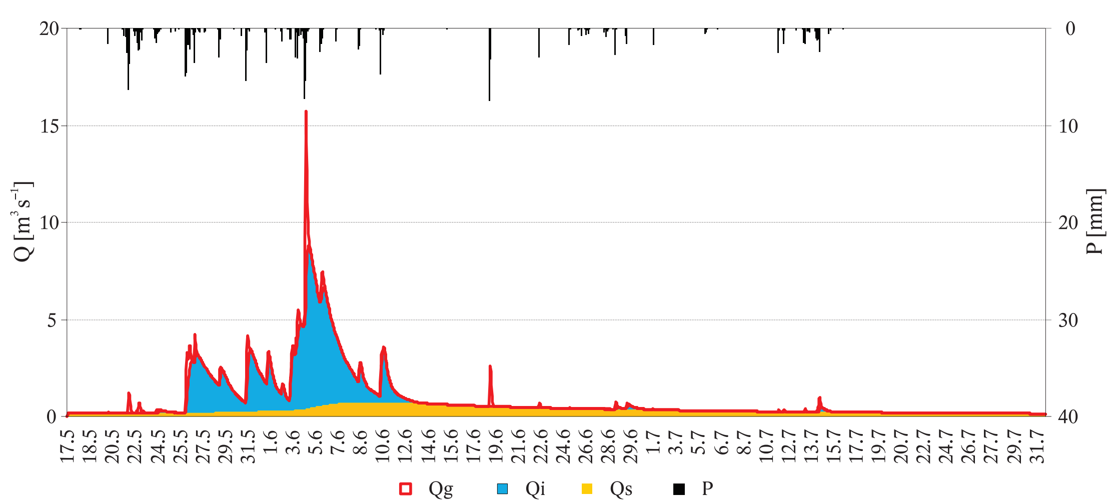

Fig. 3. Hourly hydrograph of the simulated water balance components in the Ulička watershed during the period May–July 2013.

Table 5. Simulated annual averages of the hydrological balance components during the period 2001–2013 in the Ulička watershed (mm year^{-1}) with the deforestation scenario. The comparison with simulation outputs generated with the current land cover (Table 4) is indicated as well.

	Mean annual totals [mm]								
	P	I	In	Ep	Pe	R	G	B	T
Deforestation scenario	1 000.5	51.6	928.4	551.5	413.3	16.8	133.2	290.9	440.9
Difference [%]	0.0	−75.6	20.5	−11.5	15.7	38.8	8.9	25.5	20.4

Abbreviations: P – precipitation, I – interception, In – infiltration, Ep – evapotranspiration, Pe – percolation, R – surface runoff, G – interflow, B – base flow, T – total runoff.

As we presented in the previous chapter, the surface runoff is the main driver of culmination discharges. Therefore, the increase in the surface runoff by 38.8% caused peak discharges to rise as well; the maximum daily discharge in the studied period increased in response to the deforestation by 20%, from 20 to 24 m^3 s^{-1}. In addition, the discharge was found to increase also in the rainless periods by 316%, what is mainly the effect of reduced evapotranspiration (Appendix 4).

The hourly-scale simulations during two time periods in May and July 2013 (Fig. 4) showed that the deforestation affected the pace of culmination, which occurred two hours sooner as compared with the original land cover. At the same time, the rise of discharge was significantly sharper in the deforested watershed; this is due to a higher velocity of the runoff on deforested slopes as well as a higher share of the runoff in the total flow. In case of a smaller precipitation, the delayed increase of discharge was also affected by the interception loss in the beginning of the precipitation event (Fig. 4).

3.3.3 Peak discharge response to extreme precipitation

We simulated the hydrological response to the precipitation event with intensity of 10.4 mm hour^{-1} with duration (i.e. the time of concentration) 260 minutes with the current land cover and 200 minutes with the deforestation scenario; such precipitation is likely to initiate a flood wave with the recurrence interval of 100 years (Table 6, Section 2.4).

We found that the simulated deforestation significantly affected peak discharge induced by the simulated precipitation event. In the deforested watershed, the peak discharge was higher by 58% as compared with the current land cover (0 vs. 84% of forest cover). The peak discharge occurred in 378 and 432 minutes, respectively, after the precipitation event had started (Table 6). With the current land cover the discharge maximum was 77 m^3 s^{-1}, while with the deforestation scenario the maximum was 121.2 m^3 s^{-1} (Fig. 5).

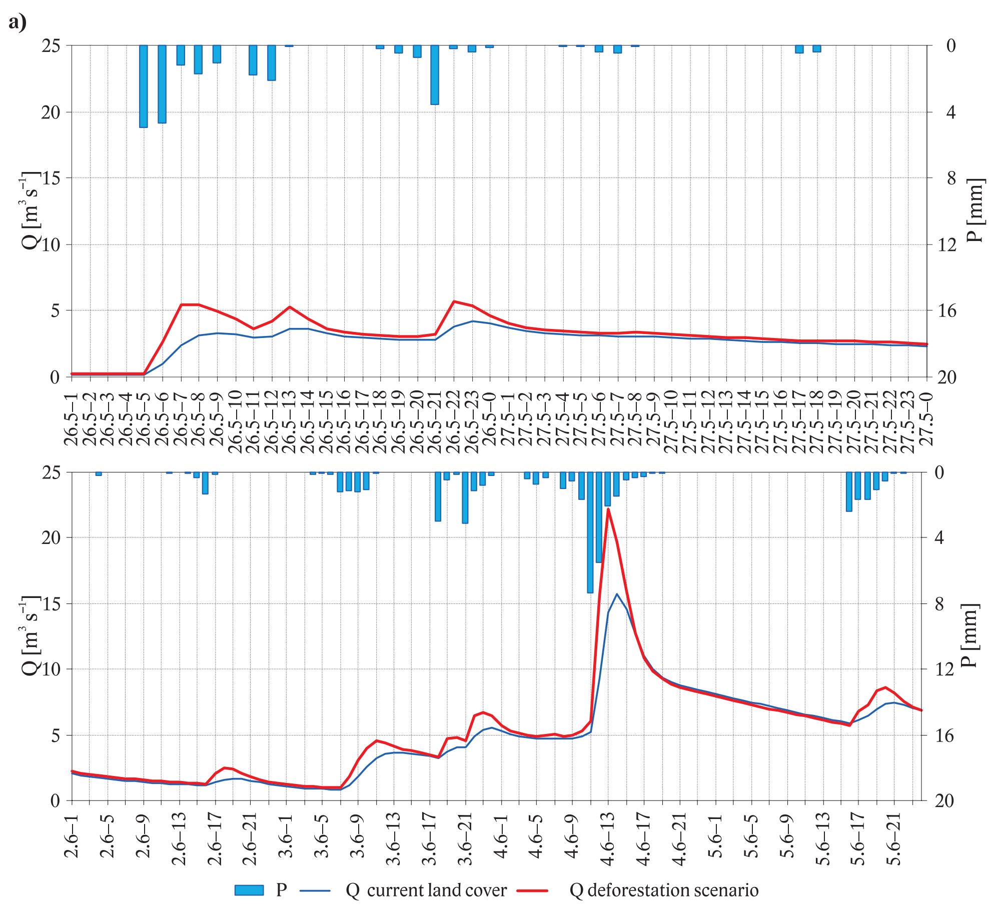

Fig. 4. The comparison of simulated hourly discharges (Q) under the current land cover and the deforestation scenario. Two time periods are presented: May 26 – 27 2013 (a) and July 2 – 5 2013 (b).

Table 6. The comparison of peak discharge response to the precipitation with the recurrence interval of 100 years with the current land cover and with the deforestation scenario.

Indicator	Unit	Current land cover	Deforestation scenario	Difference [%]
Time to culmination	[hour]	7.20	6.30	−12.5
Time of concentration	[hour]	4.33	3.33	−23.1
Design rainfall intensity	[mm h^{-1}]	10.39	10.39	0.0
Design discharge Qn	[m^3 s^{-1}]	76.96	121.18	57.5
Design wave volume	[th m^3]	2 326	2 765	18.9

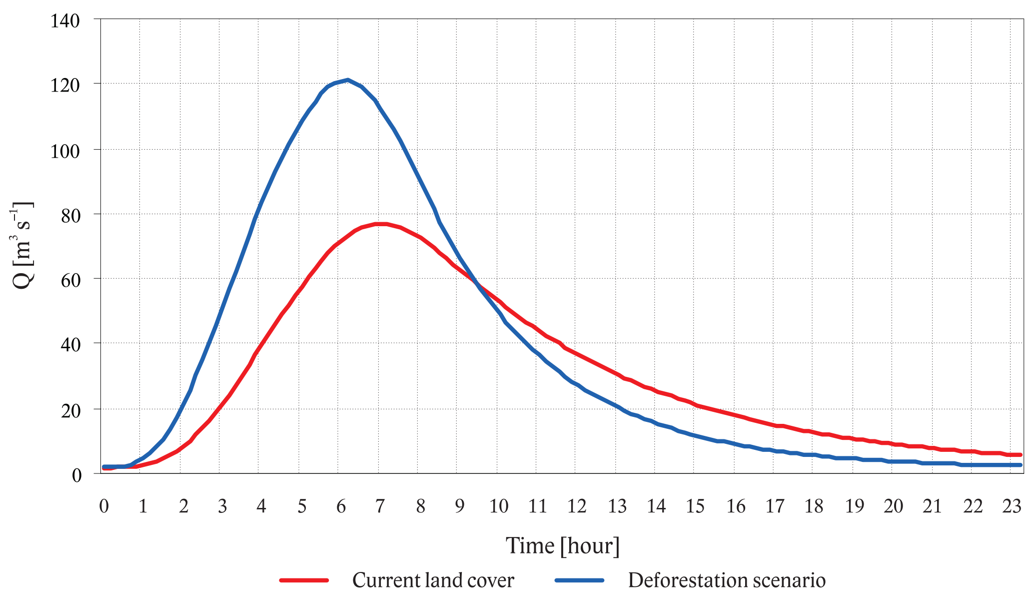

Fig. 5. The response of peak discharge (Q) to the precipitation with the recurrence interval of 100 years under the current land cover and the deforestation scenario. The X-axis shows the time from the beginning of the precipitation event.

4. Discussion

This study adds to the current knowledge on forest-water relationship in that it investigates, using a modelling exercise, the effect of deforestation on hydrological processes in watersheds. We focused on deforestation, which is particularly important land-cover change because of remarkable regulatory effect of forests with respect to water, air quality or climate (Messerli & Ives 1997; FAO 2005, 2010; de Groot et al. 2012).

Such issue`s importance is underscored by an increasing frequency of large scale disturbances (due to windthrow, wildfires, bark-beetle infestation etc.; Seidl et al. 2014), which may have adverse effect on water cycles in many regions (Vörösmarty & Sahagian 2000). As the current understanding of anticipated responses of water cycles to such events is insufficient, modelling studies, such as that presented in the current study, can inform the decision-making in forest and landscape management. We showed in the model watershed that total deforestation (i.e. the theoretical substitution of the forest covering 84% of the watershed by a grassland) increased the total runoff by 20.4%. Such effect was apparent mainly during discharge culminations, when regulatory effect of forest is particularly important (Calder 2007; van Dijk & Keenan 2007). Although the surface runoff accounts for a minor proportion of the long-term water balance (12.1 mm of the 1,000.5 mm of precipitation, Table 4), it occurs episodically in response to intensive precipitation and thus it contributes effectively to culmination discharges.

The interception loss in the current study accounted for ca. 21.1% of the total precipitation with the current land cover (i. e. with the forested watershed), and decreased to 5.2% in response to the theoretical substitution of the forest by a grassland. The simulated interception of the forested watershed (21.1%) is relatively low when compared with other studies (e.g. Augusto et al. 2005; Nisbet 2005), who suggested that forest interception may account for 20 to 40% of the precipitation, and can be high even in grasslands (Tate 1996). For example, the long-term observations (1997–2013) in the adult beech stands Svetlice (plot code 208) and Turová (plot code 206) in Slovakia (operated in the frame of the ICP Forests monitoring programme) showed that the interception loss accounted for 31–33% of the precipitation. Such a difference between observed and simulated values can be attributed to several factors. First, there are conceptual differences in methods of interception measurement in a stand and interception algorithm implemented in the hydrological model. Second, the simulated value represents the interception of the entire watershed with 84% forest cover; the remaining watershed area is covered by surfaces with a lower interception capacity.

The effect of forest on the moderation of effects of intensive precipitation was mainly related to the decrease of the total runoff in response to the increased interception and evapotranspiration, which accounted for 75.6% and 11.5% of the annual precipitation, respectively. Evaluation of the hydrological response to the simulated extreme precipitation showed that forest significantly modified surface parameters and water flow paths, and affected the time needed for the simulated flood wave to reach the catchment outlet; the difference between the current land cover and the deforestation scenario was 54 minutes. At the same time, the size of flood wave was smaller with the current land cover by 58% than with the deforestation. Such a difference is greater than differences reported in other studies. We, however, argue that our study showed an extreme case example, in which the watershed was almost saturated with water, and the design precipitation with the duration equal to the time of concentration occurred constantly across the entire watershed. In addition, there is substantial difference in runoff coefficients for forest and grassland in case of maximum soil saturation (Liu & De Smedt 2004), which further amplified the difference in culmination discharges between the two land covers.

Niehoff et al. (2002) pointed out that the influence of land-use on storm-runoff generation depends on the rainfall event characteristics and on the related spatial scale. In particular, land cover mainly affects small-scale convective storm events with high precipitation intensities. In contrast, effect of land cover on the runoff diminishes in long-lasting large-scale advective windstorms.

Land abandonment and agriculture land overgrowth by woody plants frequently occurs in many European region (Elfert et al. 2010; Mueller et al. 2009), and such a development is likely to initiate opposite responses of water cycles than those observed with deforestation. For example, land abandonment related to agriculture decline and social changes typically occurs in the watershed investigated in this study. In the view of the current large share of forest cover (ca. 84%), however, such changes are not likely to induce any significant changes in watershed`s hydrology. Indeed, this fact also relates to the sensitivity of the hydrological model. A high frequency of afforestation or conversion of agriculture land into forests initiated researches on the effect of such a conversion on water cycles. Verbunt et al. (2005) suggested that changing grasslands into forests results in an increase in evapotranspiration, especially at` the valley bottom. Modelling study from the eastern Slovakia (the Hornád watershed) showed that 50% increase in forest area decreased the peak discharge by 12%, and delayed the culmination by 14 hours as compared with the current land cover (Bahremand et al. 2006). Area of the investigated watershed is, however, much bigger as compared with the watershed in the current investigation, hence the limited comparability.

The removal of large forest tracts in central Europe is mostly related to the effect of natural disturbance, which substantially affect the regional forest dynamics (Kuemmerle et al. 2007). As reforestation often follows such events, the effect on watershed`s hydrology does not persist for a long time. Such a fact limits the inferences based on our study as we simulated an extensive deforestation, which, however, persisted during the simulation period, and was not followed by natural forest development supported by active human interventions, as would the case in reality.

The reliability of results obtained using the hydrological model depends on a number of factors (Wagener 2007; Caldwell et al. 2015). While calibration during the adequately long period supports the inferences based on simulation outputs, availability and quality of the input data or conceptualisation and parameterisation of processes represented by the model can be limiting. An important source of uncertainty in model outputs in the current study was related to a sparse network of climatological stations in the watershed. Such effect could have been seen in some discharge patterns, which were not adequately associated to the recorded precipitation.

A review of the literature shows a high degree of uncertainty in the parameterisation of land cover types (Eckhardt et al. 2003). As for the parameterisation of land cover types in the hydrological model ISSOP, we modified the original parameters of some forest categories. We used the long-term empirical data of the stand-scale forest hydrology collected in a number of forest stands across Slovakia within the ICP Forests monitoring programme (Pavlenda et al. 2013; Michel et al. 2014). Such a re-parameterisation can enhance models` suitability in forestry research and applications in the Central European temperate forests, which the used parameterisation data can be representative for. Although watershed scales and forest stand scales are not compatible, and transfer of knowledge between the scales is not that straightforward, hydrological modelling studies can benefit from the forestry field research in some respects.

5. Conclusions

Our simulations emphasized the importance of forest in water-regime regulation in a highly forested watershed in the eastern Slovakia. At the same time, the developed model allows testing the effect of land cover scenarios other than the total deforestation, and thus support management in the investigated watershed. Specifically, effect of forest disturbances, which affect the forest stands selectively (i.e. based on stand and site characteristics), can be tested and effects on water balance components can be evaluated.

The results contribute to the growing interest in the multifunctional forest management with respect to forest water-regulatory functions. The developed model and presented simulation outputs can be used in complex decision-support systems dealing with the trade-offs between the provisioning of diverse ecosystem services such as wood production, flood regulation and biodiversity maintenance.

Finally, the current study explored the options for the use of a newly developed hydrological model ISSOP using the theoretical example of extensive deforestation. The model`s well-performing calibration supports the validity of inferences based on model`s outputs and gives opportunities for next studies exploring the effect of intervention, which commonly occur in the central European forests and landscapes.

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Appendix 1. Key hydrological terms used in the study.

Term	Description
Base flow:	That part of the stream discharge that is not attributable to direct runoff from precipitation or melting snow; it is usually sustained by groundwater discharge
Discharge (or water flow):	Volume of water passing through a given point at a given time
Groundwater:	That part of the subsurface water that is in the saturated zone. All water which occurs below the land surface. It includes both, water within the unsaturated and saturated zones
Hydrograph:	Graph showing the variation in time of some hydrological data such as stage, discharge, velocity, sediment load, etc. (hydrograph is mostly used for stage or discharge)
Infiltration rate:	The rate at which a soil or rock under specified conditions absorbs falling rain, melting snow, or surface water expressed in depth of water per unit time
Interflow (syn. subsurface flow):	That portion of the precipitation which has not passed down to the water table, but is discharged from the area as subsurface flow into stream channels
Outlet:	Lowest point on the boundary of a watershed
Peak discharge (syn. peak flow):	Maximum instantaneous discharge of a given hydrograph
Percolation (syn. filtration):	Percolating water that recharges the aquifer. Percolation rates where flow is dominated by gravity.
Saturated zone:	That part of the earth's crust beneath the regional water table in which all voids, large and small, are filled with water under pressure greater than atmospheric.
Surface runoff (syn. surface flow):	That part of precipitation that appears as streamflow.
Unsaturated zone:	The zone between the land surface and the regional water table. Generally, water in this zone is under less than atmospheric pressure, and some of the voids may contain air or other gases at atmospheric pressure.

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Appendix 2. List of global calibration parameters used in the Integrated System for the Simulation of Runoff Processes.

Global parameters	Abbreviation	Unit	Description
Precipitation	K_run	[-]	Factor reflecting the effect of the rain intensity on runoff
	P_max	[mm d^{-1}, mm h^{-1}]	Maximum intensity of rainfall, at which K_run = 1
Formation of solid precipitation or snow melt	T0	[°C]	The limit temperature for the formation of snow reserves, at T0-value the rain changed to snow
	K_snow	[mm °C^{-1} d^{-1}]	A temperature degree-day coefficient for calculating snowmelt
	K_rain	[mm °C^{-1} d^{-1}]	A rainfall degree-day coefficient determining the rate of snowmelt caused by rainfall
Landuse	K_imp	[-]	Coefficient of relative representation of impermeable surfaces on urbanized areas
Soil moisture	K_ss	[-]	Relative initial soil moisture expressed as a ratio to field water capacity
Evapotranspiration	K_ep	[-]	Corrective coefficient for the values of actual evapotranspiration
Subsurface runoff	K_i	[-]	Scaling factor for subsurface runoff is the ratio between horizontal and vertical hydraulic conductivity, reflecting the impact of organic matter and root systems in the uppermost soil layer
Groundwater flow	K_g	[-]	Coefficient of groundwater outflow line expresses regime decline of groundwater for average subcatchments, the total area is divided into the several subcatchments
Ground water reserve	G0	[mm]	Initial amount of groundwater
	G_max	[mm]	Maximum amount of groundwater

Appendix 3. Statistical results of model calibration – detail overview.

	Watershed	Rain season	Dry season	Spring III–V	Summer VI–VIII	Autumn IX–XI	Winter XII–II
RMSE	1.136	1.321	0.882	1.470	0.696	0.916	1.766
r	0.959	0.952	0.978	0.981	0.899	0.943	0.967
R2	0.920	0.906	0.957	0.962	0.808	0.889	0.935
NS	0.819	0.812	0.823	0.808	0.793	0.817	0.803
NSL	0.913	0.895	0.928	0.925	0.915	0.868	0.852
NSH	0.813	0.810	0.805	0.794	0.822	0.832	0.795

Abbreviations: RMSE – Root Mean Squared Error, r – Pearson correlation coefficient, R2 – R-square, NS – Nash-Sutcliffe model efficiency, NSL – Modified Nash-Sutcliffe for low flows, NSH – Modified Nash-Sutcliffe for high flows.

Appendix 4. Effect of deforestation on water balance components in the Ulička watershed – detail overview.

		Current land cover		Deforestation		
	Precipitation [mm]	Runoff [mm]	Discharge [$m^3.s^{-1}$]	Runoff [mm]	Discharge [$m^3.s^{-1}$]	Difference [%]
Sum	12 222.8	4 758.4	—	5 764.2	—	21.1
% *	—	38.9	—	47.2	—	21.1
Mean	2.7	1.0	1.2	1.3	1.4	21.2
Min	0.0	0.0	0.0	0.0	0.0	300.0
Max	61.3	18.6	20.8	22.3	24.9	19.8
Rain season						
Sum	12 222.8	3 084.9	—	3 714.5	—	20.4
%	—	25.2	—	30.4	—	20.4
Mean	5.0	1.3	1.4	1.5	1.7	20.4
Min	0.0	0.0	0.0	0.0	0.0	300.0
Max	61.3	18.6	20.8	22.3	24.9	19.8
Dry season						
Sum	0.0	1 673.5	—	2 049.7	—	22.5
%	—	—	—	—	—	—
Mean	0.0	0.8	0.9	1.0	1.1	22.4
Min	0.0	0.0	0.0	0.0	0.0	316.7
Max	0.0	4.7	5.2	5.4	6.0	16.3
Spring III–V						
Sum	3 119.6	1 409.2	—	1 625.1	—	15.3
%	—	45.2	—	52.1	—	15.3
Mean	2.7	1.2	1.4	1.4	1.6	15.3
Min	0.0	0.2	0.2	0.2	0.2	33.1
Max	54.8	11.2	12.5	14.2	15.9	27.3
Summer VI–VIII						
Sum	4 037.3	664.1	—	991.4	—	49.3
%	—	16.4	—	24.6	—	49.3
Mean	3.3	0.5	0.6	0.8	0.9	49.4
Min	0.0	0.0	0.0	0.0	0.0	300.0
Max	61.3	18.6	20.8	22.3	24.9	19.8
Autumn IX–XI						
Sum	2 822.9	1 168.1	—	1 433.3	—	22.7
%	—	41.4	—	50.8	—	22.7
Mean	2.4	1.0	1.1	1.2	1.4	22.7
Min	0.0	0.0	0.0	0.0	0.0	223.1
Max	38.9	9.0	10.1	10.5	11.7	15.6
Winter XII–II						
Sum	2 242.9	1 517.0	—	1 714.4	—	13.0
%	—	67.6	—	76.4	—	13.0
Mean	2.1	1.4	1.6	1.6	1.8	13.0
Min	0.0	0.3	0.3	0.4	0.4	37.6
Max	34.0	9.6	10.7	11.0	12.3	14.3