Impact of Landuse on Runoff in Mountain Catchments of Different Scales

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Abstract: The paper presents two approaches to the analysis of the impacts of landuse changes on hydrological regime in mountain catchments of northern Slovakia. An intersite comparison of measured data along the Jalovecký creek was used to test whether different landuse can be identified by means of water balance data and characteristics of runoff events. Although the comparison provided extended knowledge of the catchment, the only characteristic which might indicate possible impact of different landuse is the ratio of peakflow to flow at the beginning of the event. Simulations by means of spatially distributed hydrological model showed that different (extreme) scenarios resulted in relatively subtle impacts compared to uncertainties connected with hydrological modelling.

Keywords: hydrological regime; landuse change

Big floods that occurred in the last decade intensified discussions on the role of vegetation, especially forest in mitigation of floods. This topic is not new. In fact, it gave birth to experimental research in small catchments already over a century ago. In the 1900 the measurements in two small catchments of Sperbelgraben (0.6 km^2, 99% forested) and Rappengraben (0.7 km^2, 69% pastures, 31% forests) were established to study the influence of the forest on runoff (Engler 1919). Similar studies were later performed all over the world. In Czechoslovakia they started in 1927 in the Jeseníky Mountains (Válek 1953). The research finished after three decades, but similar research started in the Beskydy Mountains in 1953 where it continues until today (Bíba *et al.* 2006). McCulloch and Robinson(1993) grouped catchments studies into three main types:

– correlation studies in which the streamflow is compared between different catchments which are as similar as possible in all respects other than vegetation
– single catchment studies in which the streamflow behaviour is statistically related to climatic variables before the land cover is changed
– paired catchment experiments composed of two similar catchments one of which is subjected to a change after the calibration period

Another potential option in catchment studies, which is an alternative of the first group studies defined by McCulloch and Robinson (1993), is the study of runoff characteristics along the rivers. Jones (2005) argues that despite the common view that it is impossible to gain insights about hydrologic mechanisms from rainfall-runoff data, a lot can be learned from intersite comparisons. We think that intersite comparisons may be represented also by comparisons along the streams within the same catchment.

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Vegetation influences hydrological cycle by its participation in certain processes (e.g. interception, evapotranspiration, infiltration). Thus, the research of the role of vegetation in these processes represents another direction in better understanding of the impacts of vegetation on hydrological cycle and specifically on the runoff (e.g. Calder 2003).

Application of the knowledge from catchment and process studies resulted in development of tools that are used in estimation of the impacts of vegetation change on hydrological cycle. They are represented by empirical relationships between the water balance components (e.g. Zhang *et al.* 2001) and by hydrological (rainfall-runoff) models of varying complexity. It should be noted that different terminology is often used in various studies, mixing the terms vegetation change, landcover change and landuse change. These terms are not always synonymous. While the landcover change represents the change of vegetation, the landuse change has a broader meaning than just the change of vegetation. The landuse change implies also a change of human activities, e.g. from forestry to agriculture.

This paper summarizes the results of various analyses performed in the mountain areas of northern Slovakia. In the first part we wanted to test whether the intersite comparison of runoff characteristics (along the stream) can indicate the influence of different landuse\landcover. In the second part we present results of simulation of the impacts of landcover\landuse changes on hydrological cycle of mountain catchments of different scales.

METHODS AND DATA

The analyses were performed in the basin of the upper Váh river, northern Slovakia. Several catchments were selected according to the purpose of the study.

Comparison of measured runoff characteristics in two subcatchments with varying natural conditions

Paired catchments experiments mentioned above represent an approach which can not be applied easily. Comparison of runoff characteristics along the streams flowing through different lansdcapes is a more common opportunity. We have used this opportunity in the Jalovecký creek catchment. The catchment has two parts – a mountain and a foothill one (Figure 1, Table 1).

Stream gauges exist at the outlets of both parts of the catchment which have approximately the same area. The two parts of the catchment have different natural characteristics. The mountain part is formed by crystalline rocks covered by Quaternary sediments. Mean elevation is 1500 m a.s.l. and the mean slope is 30°. It is densely forested (forest 44%, dwarf pine 31% of catchment area) and except tourism there are almost no other human activities. The foothill part is formed mostly by the Paleogene rocks (impervious) which are covered by the alluvium of the Jalovecký creek. The subcatchment is relatively flat. Coniferous forests and the dwarf pine cover about 32% of the catchment, urbanized zones, agricultural land and meadows cover 9%, 37% and 18%, respectively.

Water balance for period 1989–2005 was used to quantify the contribution of both parts of the catchment to runoff. Despite different opinions on the influence of vegetation (forest) on runoff (forest as a "pump" versus forest as a "sponge", e.g. Jewitt 2005) it can be expected that the proportions of the long-term values of runoff and evapotranspiration would be different in catchments with extremely different landcover (e.g. forested, deforested). Calculation of the long-term water balance for both parts of the catchment was used as a first indicator of possible impacts of landuse on the hydrological cycle. First, the runoff coefficients were calculated for the mountain part of the catchment and for the whole catchment. Runoff from the foothill part was calculated on the basis of the difference between discharge in profiles Ondrašová and Dolina (0.356 m^3/s) and area of the foothill part for the catchment. We believe that such a calculation is correct because there are no important tributaries of the Jalovecký creek below profile Dolina. Runoff coefficient for the foothill part was then calculated and the contributions of both parts to total catchment runoff were compared.

Second analysis consisted in comparison of rainfall-runoff events from the warm period of a year (June–September) using hourly discharges. For each event we have determined time of the beginning, time of peakflow and time of the end, concentration time (= time to peakflow), duration of the event, volume and peakflow. The same characteristics were determined for both profiles.

Table 1. Selected characteristics of the Jalovecký creek catchment and its two parts and the upper Váh river catchment (profile Liptovský Mikuláš); *P*, *R* and *Q* are the long-term (1989–2005) annual precipitation, runoff and discharge, respectively

Studied catchment	Area (km^2)	Elevation (m a.s.l.)			*T* (°C)	*P* (mm)	*R* (mm)	*Q* (m^3/s)
		min	max	mean				
Jalovecký creek – mountain part	22.20	820	2178	1500	3.1[3]	1562	1015	0.715
Jalovecký creek – foothill part	22.65	560	1606	806	6.1[4]	858	496[2]	
Jalovecký creek – the whole catchment	44.85	560	2178	1166		1206[1]	753	1.071
Upper Váh river	1095	560	2494	1090	4.2	1046	598	20.76

[1]precipitation for the whole catchment was calculated as a weighted mean taking into account precipitation and areas in both parts; [2]runoff from the foothill part was calculated from the difference between discharges at stream profiles 1 and 2 (see Figure l); [3]mean annual air temperature at 1500 m a.s.l., [4]mean annual air temperature at 750 m a.s.l.

Time of the beginning of the event was determined as the hour in which the first increase of discharge was recorded. Duration and volume of selected single events (i.e. not events composed of several successive events) were determined on the basis of runoff separation. Graphic filter Bflow (Arnold *et al.* 1995; Arnold & Allen 1999) was used to separate the events into two components – baseflow and direct flow. The separation method does not have any physical background related to runoff generation. However, the comparisons with the method based on the relationship between groundwater tables and stream discharge (the Kliner-Kněžek method) we have made (unpublished data) showed that the filter provides reasonable results. Separation of flow components was used just to determine the end of the event using a method that provides repeatable results. Hourly precipitation was not available for the analysis. Daily precipitation was determined to allow correlations with characteristics of runoff events.

Simulation of the impact of landuse change by means of distributed hydrological model

Spatially distributed hydrological model WaSiM-ETH (Schulla 1997) was used to simulate the impact of landuse changes at several scales. The small scale was represented by the Jalovecký creek catchment (area 22.2 km^2, Table 1). Mesoscale was represented by the upper Váh river catchment (area 1095 km^2, mean elevation 1090 m a.s.l., coniferous forests 47%, dwarf pine 8.7%, mixed forest 1.2%, meadows 21.6%, arable land 16.1%). The model was run in daily step. In the Jalovecký creek we used data from hydrological years 1989–2001, in the upper Váh river catchment we used data from hydrological years 1962–2001. The model was

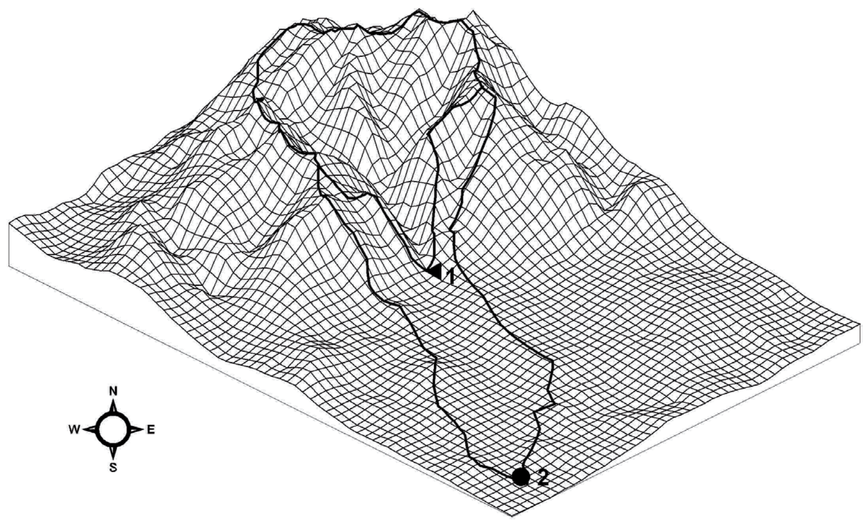

Figure 1. The Jalovecký creek catchment; its mountain and foothill parts; 1 – stream profile Dolina; 2 – stream profile Ondrašová

calibrated and validated in both catchments against measured discharges and snow water equivalents. Then the parameters of the model that represent landuse in the model (surface resistance, albedo, leaf area index, effective height of the vegetation, root depth, surface coverage) were changed according to several scenarios. The model was run again for the entire period of the input data and the results were compared with the results obtained from calibrated model. The following scenarios of landuse change were used:

– total afforestation of catchments by the coniferous forest (CON),
– total afforestation of catchments by the deciduous forest (DEC),
– total deforestation, i.e. meadows in the catchments (MEAD),
– extention of arable lands in the upper Váh river cachment over the whole Liptov valley (up to 900 m a.s.l.) and total deforestation at higher elevations; altitudinal shift of the forest in the Jalovecký creek catchment – mixed forest up to 1800 m a.s.l., coniferous forest above it (EXT).

Spatially distriuted hydrological model WaSiM-ETH was developed to simulate the water balance and discharge for daily or shorter time intervals. It schematizes current hydrological knowledge. The input data in this study were represented by the time series of meteorological data (precipitation, air temperature, air humidity, sunshine duration and wind speed). Spatial data consisted of the maps of elevation, soils and landuse.

RESULTS AND DISCUSSION

Comparison of measured runoff characteristics in two subcatchments with varying natural conditions

The long-term water balance. Values of the main water balance elements for period 1989–2005 are shown in Table 1. Runoff coefficient for the mountain part of the catchment is 0.65, for the whole catchment 0.62. Runoff coefficient for the foothill part is 0.57. Thus, the evapotranspiration in the deforested and warmer foothill part which has less precipitation is 8% larger than in the more forested, but colder and wetter mountain part. Such a difference lies within the interval of measurement errors of precipitation in the mountains. It can be concluded that the contribution of the foothill part to catchment runoff roughly corresponds to that of the mountain part. Proportion of the long-term mean values of the water balance components did not help in indication of the influence of different landuse and landcover.

Analysis of runoff events at hourly time step

Although we had hourly discharge data from 16 years, we could use the data from just 6 years (Figure 2). For other years the discharge plots indicated problems with measured data in Ondrašová. Totally, 125 events occurred in the 6 analysed years. Generally, the events occurred in all months except December (Table 2), but most of them occurred in the spring (May) and summer (July). Totally, 68 flood events were analysed in the warm period of the year (June–September). Some of them were rather small and some were rather complex, i.e. they were composed of several events (e.g. event No. 12 in Figure 2), but the time lags between the beginning of the event and the peakflow were analysed for all of them. The mean time lag between the beginning of the event was almost 2 hours. The mean time lag between the peakflows was 4 hours. The time lags between the beginning of the event and flow peaks were different for all but 4 events. It indicates that the events are transformed in the foothill part of the catchment and not just routed in the Jalovecký creek. This finding is not an indication of the landuse effect. Instead of that we can hypothesize about the role of the alluvium of the Jalovecký creek in delayed arrival of peakflows to profile Ondrašová. It was proven by current metering that the Jalovecký creek infiltrates into the alluvium as soon as it leaves the narrow valley of the mountain part of the catchment and that only further downstream the discharges start to increase along the stream.

Table 2. Seasonal distribution of the 125 runof events observed in the Jalovecky creek catchment in hydrological years 1996, 1997, 2001, 2002, 2004 and 2005

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
%	0.8	0.8	4.8	12.0	21.6	12.0	22.4	12.8	7.2	4.0	1.6	0.0

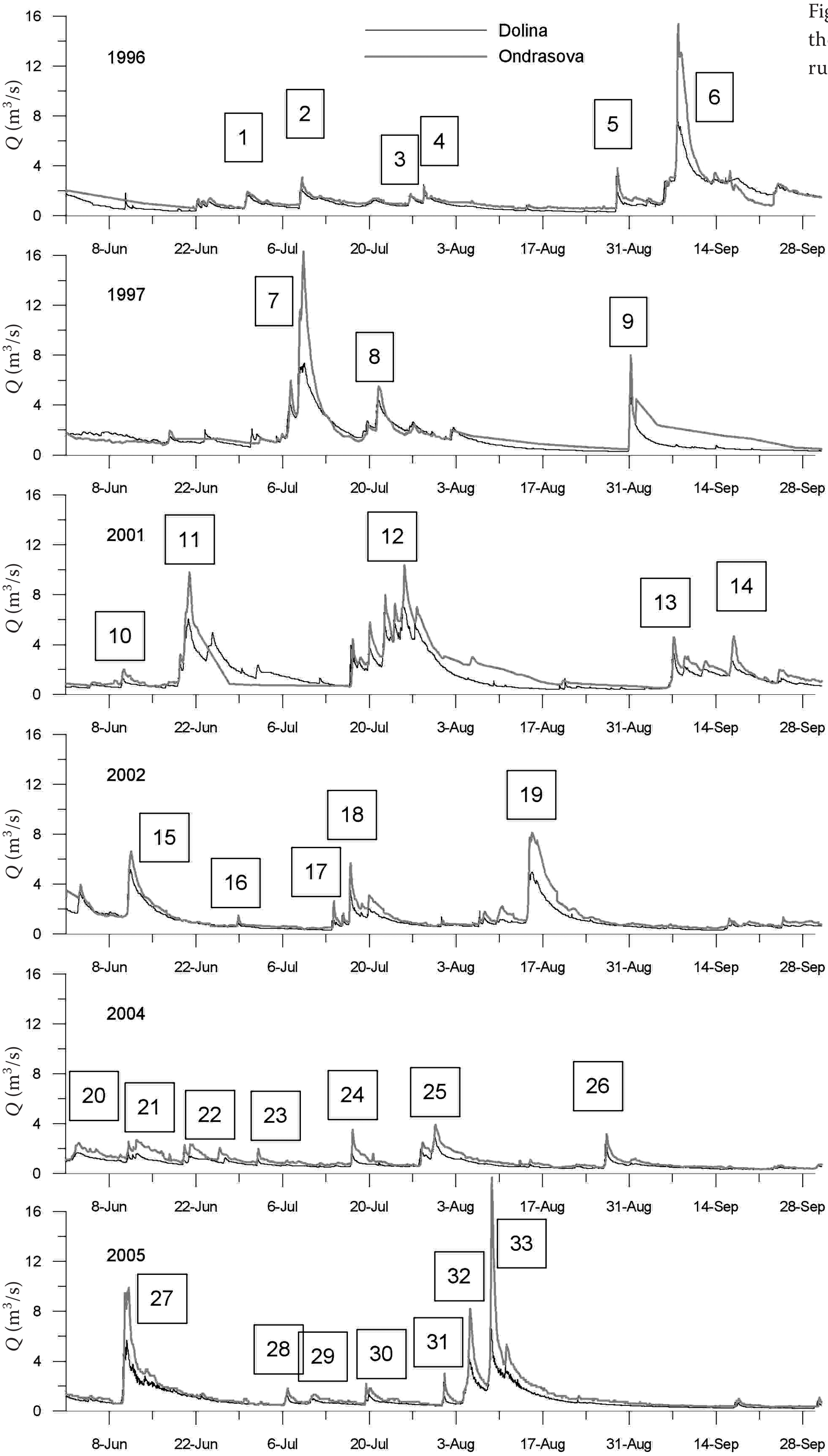

Figure 2. Hourly runoff in the years with analysed runoff events

This way the alluvium could affect also the travel time of peakflow.

The concentration times were analysed only for the simple events (i.e. not composed of several events). Concentration times were shorter in the mountain part of the catchment (about 5 h on average) than in the foothill part (about 8 h on average). In both parts of the catchment about ¼ of the events had long concentration times (about 18 and 20 h, respectively).

Neither other comparisons of events measured at the two profiles proved the influence of different landuse. The only characteristic which might reflect possible impact of the landuse was the ratio of peakflow to flow at the beginning of the event. The ratio was always higher at profile Ondrašová. Runoff events at both profiles often indicated the impact of slower flow components (e.g. event 27 in Figure 2) when the discharge after the recession was higher than before the event. Despite we had only daily precipitation, runoff characteristics (e.g. Q_{max}, Q_{max}/Q_0, concentration time) were reasonably correlated only with precipitation volume. Other influences, such as the wetness state at the beginning of the event represented by discharge Q_0 did not have good correlations with runoff characteristics. These findings extended our knowledge of hydrological regime in the catchment. However, the impact of vegetation on runoff was not indicated.

Simulation of the impact of landuse change by means of distributed hydrological model

The differences in the mean runoff and actual evapotranspiration for the different landuse scenarion are shown in Figure 3. It can be seen that the impacts of landuse changes are rather subtle compared to the uncertainties that result from the input data (e.g. measurement errors of precipitation, number of stations in the catchment, calculation of catchment values of the input data) and model (any model represents just a schematization of the nature). Because of that the results should be considered rather as scenarios (a "what if" kind of analysis) than forecast. Runoff is usually measured with the error below 5%. Errors of precipitation measurements can be much larger. If the difference between the values of 10% is chosen as a threshold, then a significant change (increase) of runoff in the Jalovecký creek would happen only if current vegetation would be substituted by deciduous forest

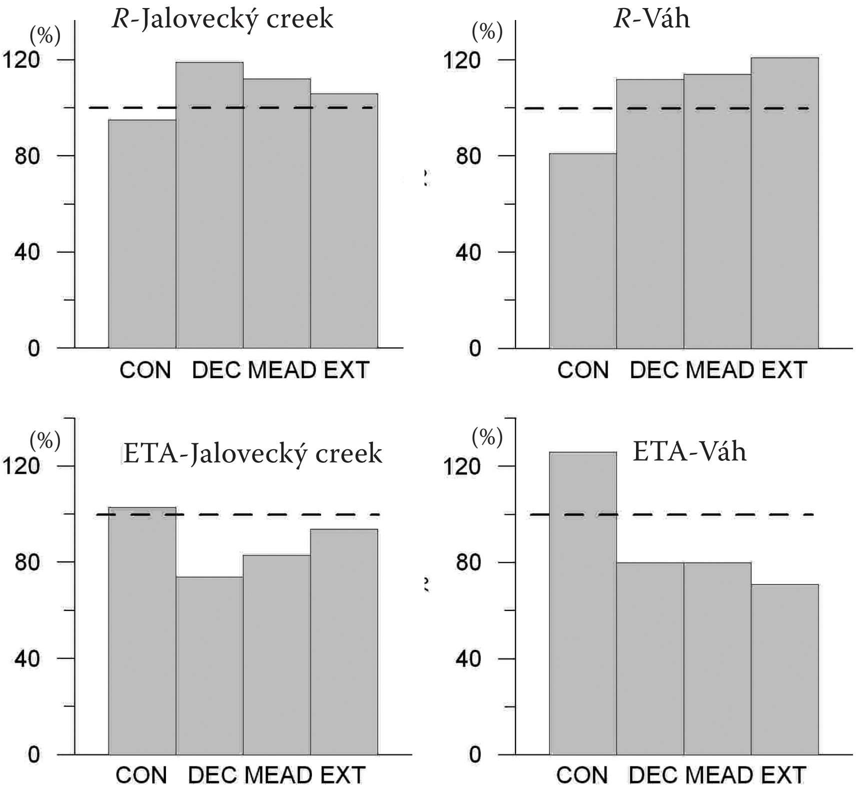

Figure 3. Changes of mean runoff (*R*) and actual evapotranspiration (ETA) in the Jalovecký creek and the upper Váh river catchments simulated for different landuse scenarios; the dashed line represents 100%, i.e. current state

or meadows. Total afforestation of the catchments by coniferous forests or upward shift of the forest would not significantly affect the long-term runoff. Such a result seems to be reasonable. If coniferous forests and the dwarf pines at present cover 75% of the catchment, the increase of their area should have relatively smaller impact than afforestation by a totally different vegetation (deciduous forest or meadows). Applying the same threshold, runoff in the Váh river catchment would be significantly affected under all scenarios. Significant changes of actual evapotranspiration in the Jalovecký creek catchment were simulated for the same scenarios as for runoff, i.e. for DEC and MEAD. In the Váh river

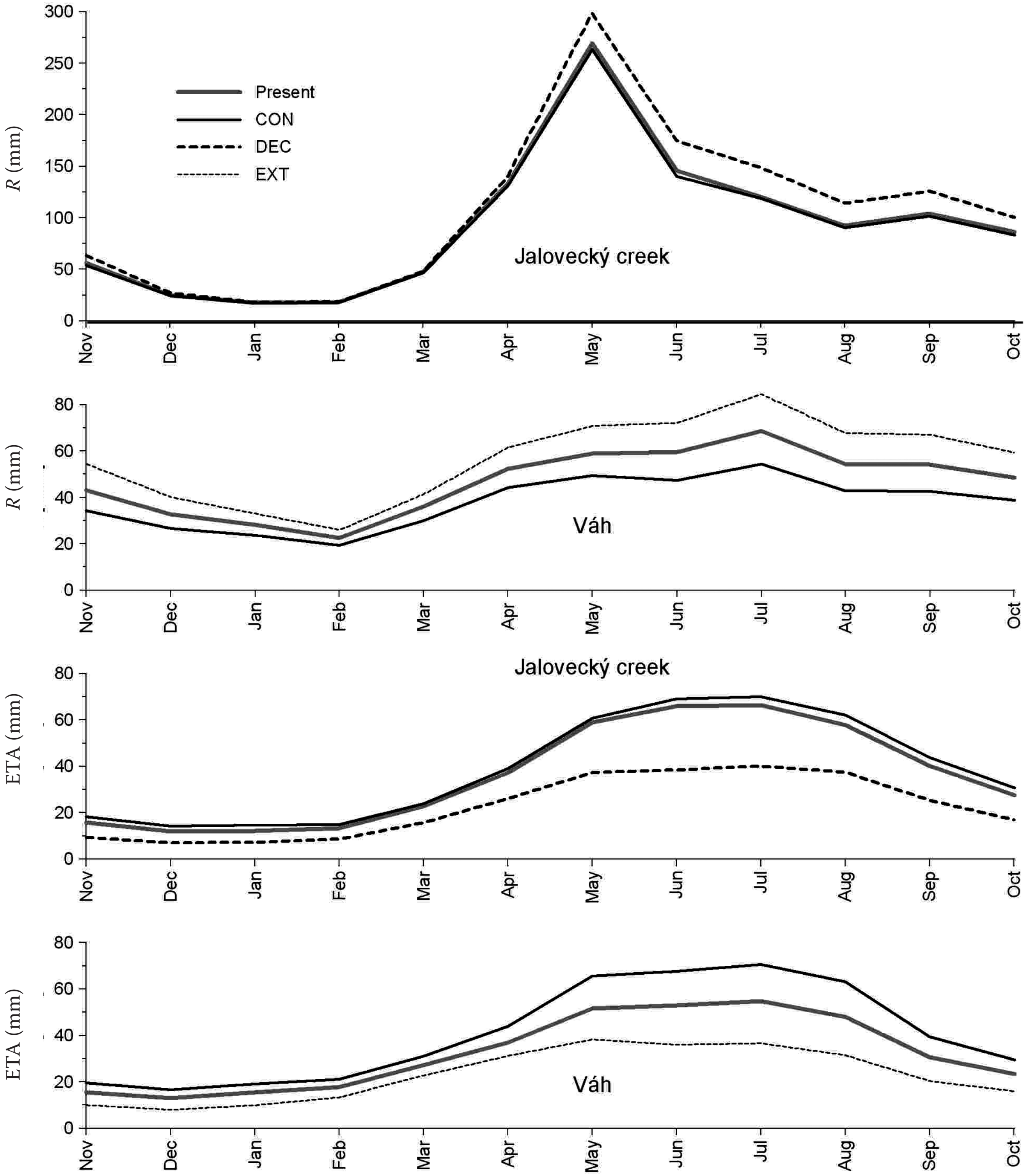

Figure 4. Mean monthly runoff (R) and actual evapotranspiration (ETA) for the Jalovecký creek and the upper Váh river catchments simulated for different landuse scenarios; only the most extreme scenarios are shown together with present conditions to show the range of the results

catchment all scenarios would result in a significant change of actual evapotranspiration. It should be noted that the results represent the mean changes of the main water balance components. In reality, the changes would not remain stable. They would very with further evolution of landuse, e.g. growth of new forest after total deforestation.

Simulated mean seasonal changes of runoff and actual evapotranspiration are shown in Figure 4. For the Jalovecký creek catchment the results indicate small differences among scenarios and similar seasonal distribution of runoff. Larger differences were simulated for actual evapotranspiration. Especially for scenario DEC simulated actual evapotranspiration was significantly lower than for other scenarios. The impact of scenarios on runoff in the Váh river catchment were larger than in the Jalovecký creek catchment. Scenario CON resulted in changed seasonal variability when the runoff peak in summer was less pronounced compared to present conditions due to higher actual evapotranspiration.

CONCLUSIONS

The intersite comparison of the water balance and discharge data did not indicate impacts of the landuse in the Jalovecký creek catchment. However, it indicated the role of the alluvium in transformation of runoff events. Simulations of the impacts of the landcover/landuse changes for two mountain catchments of different scales resulted in relatively smaller changes for the small catchment compared to the mesoscale catchment. Because of relatively subtle impacts of landuse compared to other factors, the assessment of the impacts of landuse changes on hydrological regime was performed only for the long-term mean values. Application of the hydrological model for the assessment of the impact of landuse on rainfall-runoff events should be based on hourly data which are not easily available.

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