The extent of land use impact on water regime

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ABSTRACT

The paper is focused on the impact of land use changes on water regime. First, an emphasis was given to what extent the main components of the water balance on the experimental catchment Všeminka (region Vsetínské Hills) were influenced. For this reason, the WBCM-5 model was implemented for the period of 10 years in a daily step with a particular reference to simulate the components of direct runoff and of subsurface water recharge. In the selected years of the period 1990–2000, the major changes were made in land use and also the significant fluctuation of rainfall-runoff regimes were observed (e.g. dry year 1992 and flood year 1997). After WBCM-5 parameter calibration it was found that some water balance components can change in relation to substantial land use changes even up to tens of percent in a balance-consideration, i.e. in daily, monthly and yearly or decade values, namely the components of interception and also of direct runoff and of subsurface water recharge. However, a different situation appears when investigating significant short-term rainfall-runoff processes. There were about seven real flood events analysed using the model KINFIL-2 (time step 0.5 hr) during the same period of about 10 years on the same catchment. Furthermore, some land use change positive or negative scenarios were also analysed there. As opposed to long-term water balance analyses, there was never achieved any greater differences in the hydrograph peak or volume than 10%. Summarising, it is always important to distinguish a possible land use change impact in either long-term balance or short-term runoff consideration, otherwise a misunderstanding might be easily made, as can often be found when commenting on the impact on floods in some mass media.

Keywords: land use change; water balance; rainfall-runoff event

The principle question "How much can water regime be impacted by change of land use" is often discussed by hydrologists (Falkenmark et al. 1999) as well as by the public, particularly after flood events. Therefore, it is very appropriate to investigate this problem more deeply when the common rural EU policy leads to massive land use changes.

First, it should be clear that the most important factors affecting direct runoff is the rainfall depth and duration, and then other factors, namely climatic and physiographic conditions, land use, etc. Which of these factors could influence the rainfall-runoff process to a greater or lesser degree, was the aim of this paper, in general. This investigation focused on specific land use changes. There were two major approaches used:

– Water balance analysis of long-term period of rainfall, runoff and free water evaporation on the Všeminka experimental catchment in the period 1990–2000 with particular emphasis on land use change on significant water balance components.
– Rainfall-runoff analysis of isolated short-term events investigating the influence of land use changes on direct runoff hydrograph, its shape and peak.

Both approaches were applied through the implementation of the adequate mathematical models.

MATERIAL, METHODS AND RESULTS

Experimental catchments

Data from ten Czech experimental catchments were analysed to reconstruct and to simulate both water balance of a long time series and the selected isolated flood events of short time duration. The selected data from the following catchments was then used:

Table 1. Land use and physiographic characteristics of the Všeminka catchment

Land use	Physiographic characteristics
Arable land 10%	river length 9.2 km
Permanent grassland 36%	average river slope 3.6%
Forested area 48%	average catchment slope 19.4%
Urbanized area 6%	average altitude 400 m a.s.l.

Jizerské hory: Černá Nisa (Uhlířská), Černá Desná (Jezdecká), Kamenice (Josefův Důl), Smědá (Bílý Potok)
Železné hory: Dolský potok, Kotelský potok
Vsetínské vrchy: Všeminka, Dřevnice

Next to this, the catchments of Rusava (in two outlets: Chomýž and Třebenice), the experimental catchments of Jeseník, Orlice and Opavice.

This paper summarises the results of some catchments mentioned above. However, the main emphasis was put on the catchment Všeminka, which was explored deeply in detail, and also for other similar projects in forest hydrology and water resources management (Kovář et al. 2002, 2004).

Introducing briefly, the Všeminka catchment has a hilly topography with an area of 21.5 km^2. Its land use and the main physiographic characteristics are given in Table 1.

Other characteristics, such as hydrological soil groups, their physical properties, land use mosaic pattern, forest species, etc. are published elsewhere (Kovář et al. 2001).

Water balance modelling

The simulation of water balance on the Všeminka catchment for the sake of water regime dependence on land use change was implemented by the WBCM-5 model (Kovář et al. 2001, 2004). The structure of the model is physically based with a mathematical description of the mutually interconnected hydrological processes in the time step Δt = 1 day, as follows:

– potential evapotranspiration, PE
– interception AIR
– direct runoff generation and its transformation, SOF
– soil moisture dynamics of the upper soil zone (active zone SMC)
– unsaturated zone dynamics ΔWP and actual evapotranspiration AE
– saturated zone dynamics ΔWZ, groundwater flow GWF, total flow STF

Volumetric fit of all water balance storages is controlled through the water balance equation:

$$SRAIN = AE + STF + (\Delta WP + \Delta WZ) \quad (1)$$

where: SRAIN is rainfall depth (mm), AE actual evapotranspiration (mm), STF total runoff (mm), ΔWP change of soil moisture content of unsaturated zone (mm), ΔWZ change of subsurface water, there: ΔW = ΔWP + ΔWZ (mm).

The core of WBCM-5 model is unsaturated soil water dynamics (its filling and exhaustion), which is described by the Richards equation, numerically solved in the form of finite differences:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta).\left(\frac{\partial H}{\partial z} - 1\right)\right] \quad (2)$$

where: θ – soil moisture (–), H – pressure height (m), z – depth of infiltration front (m), t – time (s), $K(\theta)$ – unsaturated coefficient of hydraulic conductivity (m/s)

The WBCM-5 model was used for the simulation of five scenarios, representing the changes of land use on the Všeminka catchment with data of the flood year 1997. The changes of main water balance components, i.e. total runoff STF, direct runoff SOF, actual evapotranspiration AE, total interception AIR, and changes of subsurface water storage ΔW, have been published earlier (Kovář et al. 2004). There are only three basic scenarios of land use change in this paper as follows:

Scenario 0: The existing situation according to the measured hydrometeorologic data on daily values of rainfall (Slušovice), free water evaporation (Vizovice) and runoff at the outlet (Slušovice).
Scenario A: The situation of the Všeminka catchment after 50% deforestation when cutting forest more than 40 years old on slopes steeper than 20%.
Scenario E: It is representing the target situation when, 155 ha of arable land is grassed and 171 ha of meadows is afforested.

Table 2 provides the changes of the WBCM-5 model parameters which reflect land use changes. The physical meaning of those parameters is the following:

DROT – depth of "active zone" that basically reflects direct runoff formation (mm)
CN – curve number of the catchment (according to the U.S. Soil Conservation Service) (–)
WIC – upper limit of the interception canopy (mm)

Table 2. The WBCM-5 parameter values for various scenario situations on the Všeminka catchment

WBCM-5 parameters	Scenarios		
	0	A	E
DROT (mm)	600.0	500.0	680.0
CN (–)	72.0	76.0	69.5
WIC (mm)	2.0	1.2	2.6
BK (days)	8.5	7.0	13.0

SMAX = 582 mm, GWM = 1100 mm
remain constant due to the calibration

The CN values above were determined according to the U.S. SCS method; however their daily values are variable depending on the upper soil layer (DROT) saturation

BK – coefficient of the master depletion curve of the catchment (days)

Table 3 gives the value of the main components of water balance in the existing situation (calibrated values) and in both scenarios (A, E) for flood year 1997.

The changed values of the most important water balance components, i.e. direct runoff SOF and subsurface water storage ΔW (printed below in bold) provide the graph on Figure 1.

The results achieved in various implementations of the water balance model WBCM-5, clearly shows that the total flow STF and direct flow SOF are in logical relationships with land use changes, scenario A varies up to +22%, and scenario E as much as –29%, in each case when compared to the existing status, i.e. scenario 0. The practical impact of scenario E is evident in the context of non-structural flood measures. The changes of subsurface water storage ΔW are important too, namely from the water balance viewpoint when the variance between the preferred scenario E, and least-preferred scenario A, differs by up to 65 mm. On the other hand, the values of actual evapotranspiration AE do not differ significantly (to 10 mm only) because of the non-homogenous character of the catchment.

Isolated rainfall-runoff events

Another tool in the form of the KINFIL-2 model was used for the simulation of short isolated rainfall-runoff events on small catchments. This model is based on the solution of infiltration process using the Green-Ampt approach according to the Morel-Seytoux method (Morel-Seytoux and Verdin 1981):

$$K_s\left[\frac{z_f + H_f}{z_f}\right] = (\theta_s - \theta_i)\frac{dz_f}{dt} \quad (3)$$

$$S_f = (\theta_s - \theta_i).H_f \quad (4)$$

$$t_p = \frac{S_f}{i\left[\frac{i}{K_s} - 1\right]} \quad (5)$$

where: K_s – saturated hydraulic conductivity (m/s), z_f – depth of the infiltration front (m), θ_s – saturated soil moisture content (–), θ_i – initial soil moisture content (–), H_f – saturation pressure below the infiltration front (m), I – rainfall intensity (m/s), S_f – storage suction factor (m), t_p – ponding time (s), t – time (s)

The basic task, when implementing the KINFIL-2 model, is the determination of soil parameters K_s and S_f (at field capacity FC value) which correspond to their conceptual values CN = f(K_s, S_f) (Morel-Seytoux and Verdin 1981, Kovář et al. 2001). The second component of the model is its runoff part simulating the propagation and transformation of direct runoff by kinematic wave:

Table 3. The main components of water balance (mm) of the Všeminka catchment in 1997

	Scenarios		
	0	A	E
Rainfall (RAIN)	713.0	713.0	713.0
Total runoff (STF)	272.8	288.7	215.6
Direct runoff (SOF)	**79.3**	**96.6**	**56.2**
Actual evapotranspiration (AE)	422.9	417.3	424.9
Interception (AIR)	171.4	105.6	224.4
Change subsurface water storage (ΔW)	**18.3**	**7.0**	**72.5**

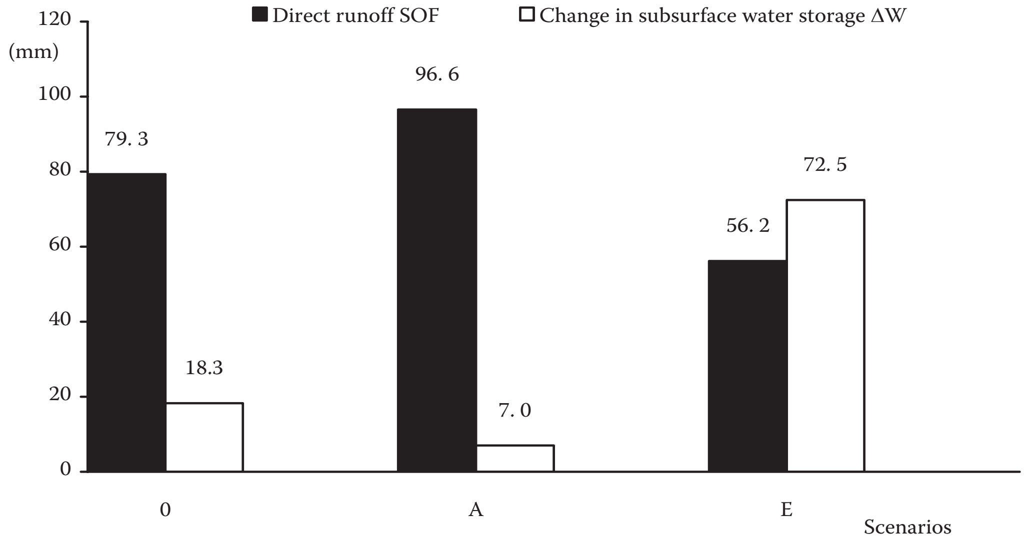

Figure 1. The changed values of the water balance components SOF and ΔW according to various scenarios of the WBCM-5 model

$$\frac{\partial h}{\partial t} + \alpha m h^{m-1} . \frac{\partial h}{\partial x} = r_e(t) \qquad (6)$$

where: h, t, x – ordinates of depth, time, and position (m, s, m), α, m – hydraulic parameters (m^{2-m}/s, –), r_e – effective rainfall intensity (m/s)

Eq. (6) is a core of the direct runoff component of the KINFIL-2 model, and in its programmed version is solved using the Lax-Wendroff explicit scheme after transforming it into the finite difference form. Both models, KINFIL-2 as well as WBCM-5 were first used for the reconstruction of the rainfall-runoff events of the year 1997. However, as opposed to the WBCM-5 model implemented throughout the whole year, the KINFIL-2 model was only used for two significant flood events in July 1997. Table 4 provides the most important characteristics of both flood waves when antecedent catchment saturation was on the 3^{rd} degree, i.e. on the field capacity of upper soil layer.

The resulting hydrographs of both reconstructed flood waves by the KINFIL-2 provide Figure 2a,b. The fit of measured and computed hydrographs is very close which testify how well the model parameters are calibrated. This high degree of fit has encouraged the next step, which was a scenario simulation. For this, the same scenarios, A (50% forest cut) and E (target optimal land use) as in the WBCM-5 model were implemented. Table 5 below shows the changes of the KINFIL-2 parameters reflecting the corresponding changes in land use on the Všeminka catchment.

Besides the reconstructed hydrographs, Figure 2a,b also provide the designed scenario hydrographs deterministically corresponding to the changed land use on the Všeminka catchment. The changed discharges, in coincidence of the analyses made on other experimental catchments, are not significant and they do not exceed the differences higher than 10% in hydrograph peaks as well as in runoff volume.

Table 4. Characteristics of the flood waves in July 1997 on the Všeminka catchment

Characteristics	Wave 1	Wave 2
Beginning of causal rainfall	July 6, 6.00 a.m.	July 18, 2.00 a.m.
End of causal rainfall	July 8, 10.00 p.m.	July 22, 1.00 a.m.
Total depth of causal rainfall H_s	123.3 mm	70.4 mm
Depth of effective rainfall H_o	61.4 mm	53.0 mm
Flooding rainfall H_p	4.0 mm/hr	1.6 mm/hr
Flooding time T_p	2.0 hr	1.0 hr

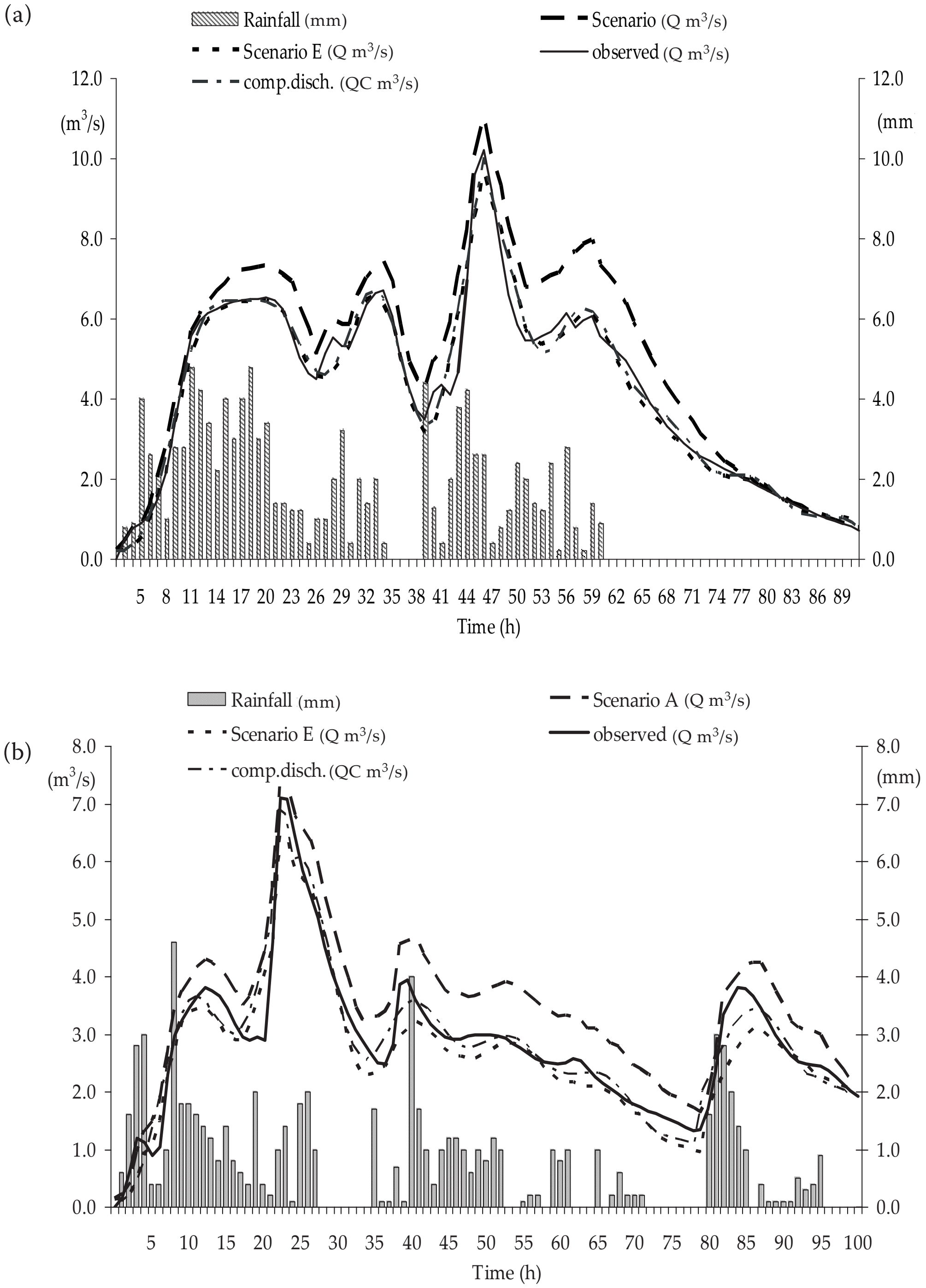

Figure 2. Comparison of ordinates of observed and reconstructed discharges (including scenarios) on the Všeminka catchment

DISCUSSION

This paper is the last result from the series of experiments that focused on scenario simulations of land use and their rainfall-runoff reactions. Short-term flood events investigated on several experimental catchments (Jizerské hory – Černá Nisa and Kamenice, Železné hory – Dolský potok, Kotelský potok), particularly Dřevnice and Všeminka (Vsetínské vrchy) were tested by the KINFIL-2 model with the short time step Δt = 0.5 hr. None of the realistic land use changes, including very robust impacts (50% deforestation), caused the increase of peak discharges of more than 10% (exceptionally 15%) on more than 30 examined events. There were a few exceptions (three only) of between 10% and 15% increase on the catchments Všeminka and Rusava. All "positive

Table 5. The KINFIL-2 parameter values for the scenario simulation on the Všeminka catchment

Parameter	Land use scenarios		
	0 (existing)	A (50% forest cut)	E (optimum)
Conceptual K_s (mm/hr)	1.25–1.35	1.35–1.40	1.20–1.30
Conceptual S_f (mm)	18.0–22.0	26.0–32.0	15.0–20.0
Interception limit WIC (mm)	2.0	1.2	2.6
Manning roughness *n*	0.20–0.30	0.25–0.35	0.20–0.30

scenarios" representing the change of arable land to permanent grassland or afforestation might decrease peak discharges to 5%–10% (e.g. Černičí catchment with 8.2% to 8.6%).

Long-term water balance simulation, with the time step Δt = 1 day on the same catchments, however, have shown that the major water balance components usually change depending on land use changes much more significantly even in the order of tens of percent. In particular, total runoff and specifically direct runoff components are sensitive to land use changes in a long-term scale similarly, infiltration, recharging subsurface water storage is usually in a reciprocal relation with direct runoff. These two last components are very important as a criterion of positive or negative impact of land use change. Furthermore, it is very logical in water balance accounting, that interception component, in general, depends on a vegetation stage and on canopy quality. Therefore, deforestation, specifically before a substitutive weed-herb canopy has grown, affects actual evapotranspiration.

It is evident that, through implementation of both models, KINFIL-2 and WBCM-5, it has been found that the changes of the major balance components in the tested periods were much greater than those in short flood events in reaction to land use changes. In particular, direct runoff in a long-term balance scale can be affected by expressive land use even to several tens of percent, while in the short-term, flood events as mentioned above, to a maximum of only 10% to 15%. Therefore, it is necessary to distinguish clearly whether runoff of events, or of balance-periods as a reaction of land use change, is to be separately evaluated.

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Received on October 17, 2005

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