Simulation of hydrological balance on experimental catchments Všeminka and Dřevnice in the extreme periods 1992 and 1997

P. Kovář[1], P. Cudlín[2], J. Šafář[1]

[1]*Czech University of Agriculture in Prague, Czech Republic*
[2]*Institute of Landscape Ecology, Academy of Sciences of the Czech Republic, České Budějovice, Czech Republic*

ABSTRACT

Hydrological research on the Všeminka and Dřevnice experimental catchments has been carried out for almost ten years. Earlier analyses on these catchments have provided many partial results in the assessment of land use on water regime and also some analysis of extreme hydrological event conditions. This paper gives attention to identification of extreme hydrological periods (i.e floods and droughts) and to the simulation of events when these catchments are in that time impacted by the torrential rainfall of design character with the periodicity P = 0.01 (N = 100 years). This is the core of the paper focusing on the analyses of extreme summer periods in 1992 (dry season) and 1997 (flood season). These 50-day periods were first reconstructed in their real existing situations with a particular reference to compute the main components of water balance. This reconstruction was implemented by the WBCM model using the parameter values derived from the optimalisation process of some annual vegetation periods in the past. These parameter values were used to simulate both extreme situations when the design rainfall impacted the experimental catchments. In the dry period of 1992, the design rainfall of 100-years caused the direct runoff increase on Všeminka for 13%, on Dřevnice for 32%. In the flood period of 1997 this increment of direct runoff should achieve 52% on Všeminka and even 93% of the existing situation on the Dřevnice catchment. The differences between two experimental catchments are caused by the different retention capacities of their active zones.

Keywords: water balance; rainfall-runoff processes; hydrological models; hydrological extremes; scenario simulations; floods; drought

The hydrological regime of a catchment is strongly influenced by the mutual interaction of its climatological and physiographical characteristics and also by land use. Implementation of water balance models provides a good tool for a quantification of a rainfall-runoff process. Former hydrological analyses on the catchments Všeminka and Dřevnice brought research results on possible reasons of a lowering water retention capacity of forest (Cudlín et al. 2000). Further, they provided the evaluation of extreme hydrological phenomena conditions (Kovář 2001, Kovář et al. 2001) and, in particular, they provided the comparison of water balance under the existing land use with those of when the different scenario land uses were implemented (Falkenmark 1999, Kovář 2001). Similarly, on these two experimental catchments Všeminka and Dřevnice some short-term rainfall runoff models were implemented for simulatiing significant direct runoff events. For these events and for the particular year 1997 (two flood waves on July 1997) the KINFIL model was implemented. This model is based on the theory of infiltration that is combined with kinematic wave simulation of direct flow from elementary subcatchments (Maidment 1993, Kovář et al. 2002). Consequently, it can be declared, that both experimental catchments were thoroughly analysed, their data was well processed using GIS techniques and the results were extensively published as their daily hydrological balance and as half-hour significant rainfall-runoff events were concerned. Nevertheless, with a more detailed analysis, the deeper knowledge on hydrological processes can be found. Thus, the aim of this work is to determine to what extent the basic components of landscape structure together with land use can influence water balance when climatic conditions (especially rainfall and temperature) are subjected to change. Therefore, in this paper, the attention is given to the identification of extreme hydrological periods (floods and droughts) and the simulation of situations when in these extreme periods the next significant rainfall struck a catchment.

MATERIAL AND METHODS

Experimental catchments

Two small-forested catchments (district Zlín) cover almost the same area and both rivers of the names Všeminka and Dřevnice flow on the left-side tributary of the Morava river. These catchments are of the 4^{th} order and while the Dřevnice catchments are more than 80% forested, the Všeminka catchment is a typical agri-forest territory with forestation less than 50%. The shape of the Všeminka catchment is longitudinal, the upper sides of the central valley are forested down from the water divide, land use on the other parts is diversified. The Dřevnice catchment is fan-shaped, highly forested, and only its part has a more structured land use. The physiographical characteristics as well as the land use are given in Table 1. Other details on the species and age structure of the forest and hydrological soil groups were described in literature (Kovář 2001).

Model WBCM-5

The WBCM model (Water Balance Conceptual model, version 5) that was implemented with the aim of quantifying the water balance on the Všeminka and Dřevnice catchments is a lumped model with a probability parameter distribution over the area. It is based on the integrated storage approach. Each storage element represents the natural storages of interception, soil surface, root (or active) zone and the whole-unsaturated zone and groundwater zone (if the latter is not very deep).

Table 1. Physiographic characteristics and land use of the Všeminka and Dřevnice catchments

Physiographic characteristics	Všeminka	Dřevnice
Catchment area (km^2)	21.51	22.58
Length of river (km)	9.2	9.1
Slope of river (%)	3.6	3.5
Catchment slopes (%)	19.4	23.0
Catchment altitude (m a.s.l.)	400.0	495.0
Land use-average state 1992–1997		
Arable land (%)	9.3	2.7
Permanent grassland (%)	24.2	9.0
Public greenery (%)	5.5	2.9
Urbanised area (%)	4.3	0.8
Riparian vegetation (%)	8.5	3.6
Forests (%)	48.2	81.0

The model with a daily step takes into consideration the storage of individual zones, and treats their daily values, including input and output rates, in line with physical regularities as reflected by the system of recurrent final difference and algebraic equations balancing the following processes (Kovář and Veselý 1998):
– potential evapotranspiration, interception and throughfall
– surface runoff recharge
– active soil moisture zone dynamics
– soil moisture content and actual evapotranspiration
– ground water dynamics, base flow, total flow

The individual parameters of WBCM-5 have the following physical meanings:
AREA – catchment area (km^2)
FC – parameter characterising the average value of the field capacity of the active zone (–)
POR – parameter characterising the average value of the soil porosity of the active zone
DROT – depth of the active zone (mm)
WIC – upper limit of interception capacity (mm)
SMAX – parameter representing the maximum capacity of unsaturated zone (mm)
ALPHA – parameter expressing non-linear filling procedure of the unsaturated zone (–)
CN – runoff curve number (–)
P1, P2, P7 – parameters affecting unsaturated zone dynamics (filling and exhausting processes) (–)
GWM – parameter expressing capacity of the active part of the ground water zone (mm)
BK – linear transformation parameter of the base flow process (days)

The water balance equation controls the volumes of the main components of the water balance:

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

where: SRAIN – rainfall depth (mm)
STF – total runoff depth (mm)
AE – actual evapotranspiration (mm)
ΔWP – change in soil moisture content (mm)
ΔWZ – change in ground water storage (mm)
ΔW – change in subsurface storage (mm)

The model was described in more details elsewhere (Kovář et al. 2001).

Selection of extreme periods

As a dry year with the least precipitation and the highest air temperature in vegetation period (April–October) in the last 20 years the year 1992 was selected in the data record of the Slušovice and Vizovice meteorological stations (for the

Všeminka catchment) and the Velíková station (for the Dřevnice catchment). Similarly, as a wet year was selected the year 1997 with the highest precipitation determined from the data record from the same stations located appropriately for both experimental catchments. However, the aim of this paper was to select two periods, one typically dry and the other typically wet. Both of the duration about 6–7 weeks when there was either no rain in the dry season or substantial torrential storms combined with regional rainfalls with their high periodicity ($P < 0.01$, $N > 100$ years) in the wet season. Thus these daily rain and corresponding daily runoff records were analysed in both characteristic years 1992 and 1997 and for the Všeminka and Dřevnice catchments the following periods were adequately selected:

Dry period 1992: July 16 to August 31, 1992 (47 days)

Wet period 1997: June 26 to August 14, 1997 (50 days)

These periods were further analysed and their daily water balance components reconstructed.

RESULTS AND DISCUSSION

Reconstruction, parameter calibration

For, the reconstruction of the selected dry and wet periods were used the WBCM model parameters calibrated earlier for the whole vegetation periods of the years 1992 and 1997 resp. (Kovář et al. 2001a, b). For the sake of clarity, referring to the cited literature above, the following data for the Všeminka and Dřevnice catchment were used:

- daily rainfall data from Slušovice, Vizovice and Velíková stations
- daily free water evaporation data from the Vizovice station
- daily runoff data from the Slušovice (Všeminka) and Kašava (Dřevnice) stations
- land use data, topographical and physiographic characteristics of the catchments, hydrological and soil parameters from maps and soil analysis, initial soil moisture contents assessed according to 30 days antecedent precipitation (March 1, 1992, 1997, respectively).

The model was implemented with the data to simulate the selected periods with the same parameters derived from the growing seasons 1982–1997 on both catchments. Table 2 provides their average values. Goodness of fit of measured and computed daily runoff values according to two criteria, i.e. coefficient of determination (efficiency coefficient) RE and coefficient of variation PE were well acceptable. The values of RE = 1.00, PE = 0.00 stand for the best fit.

Next analysis published (Kovář 2001) shows the same example given for the wet period in 1997 how values of soil moisture deficit SMD (daily differences between field capacities and soil moisture contents) are approaching to zero for the double flood wave period from July 10 to August 6, 1997. Both catchments had almost no retention capacity to accept more rainfall water to infiltrate. Conversely, the situation in 1992 was completely different and the active zone was closed to the wilting point. Daily SMD (mm) values is reciprocal to daily antecedent precipitation index values, API (mm). When we compare both experimental catchments, it is evident that the Všeminka catchment is more water keeping than the Dřevnice catchment in spite of larger forested area on the latter case. The depth of active zone on Dřevnice is shallower and its retention capacity is, therefore smaller.

A steeper trend of decreasing depletion curve gives the evidence of this phenomenon.

Table 2. The WBCM-5 parameters

Parameter value		Všeminka	Dřevnice
Non-optimised	POR (–)	0.45–0.50	0.44–0.48
	FC (–)	0.40–0.42	0.40–0.43
	DROT (mm)	300.0	300.0
	CN (–)	<62–92>	<68–94>
	WIC (mm)	2.0	2.2
	ALPHA, P1, P2, P7 (–)	1.0, 0.1, 0.2, 0.7	1.0, 0.1, 0.2, 0.7
Optimised	SMAX (mm)	582.0	600.0
	GWM (mm)	1100.0	1000.0
	BK (day)	8.5	10.0

Simulation of extreme hydrological situations

The final aim of this is to simulate the hypothetical situations how both experimental catchments respond to significant rainfall in dry and wet conditions. These rainfalls were those of the design character with the recurrence time N (years): 2, 5, 10, 20, 50, and **100** years. These rainfalls were derived for the Velíková station from the publication (Šamaj et al. 1983):

	Return period					
N (= year)	2	5	10	20	50	**100**
St. Velíková (mm)	38.9	51.7	59.9	68.4	78.9	**87.1**

For the sake of brevity, only the 100-year design rain results are given here, in the paper. This scenario-design rain was supposed to fall at the end of dry period, on August 20, 1992 as well as at the end of wet period on July 27, 1997 uniformly distributed over both catchment areas of Všeminka and Dřevnice.

In the dry period 1992 on the Všeminka catchment, the impact of 100-year rain has increased direct runoff from 0.5 mm to 7.3 mm, and on the Dřevnice catchment in the same period it varies from 4.0 mm to 32.0 mm. On both catchments this direct runoff increase has no catastrophical character, on the Všeminka catchment it was +6.8 mm, on the Dřevnice catchment +28.0 mm only.

However, during the wet period this increase was more significant. On Všeminka was +45.1 mm and on Dřevnice even +81.3 mm. It means that on the latter case of a shallow-soil catchment with fully saturated active zone, almost 93% of the rainfall can leave the catchment in the form of direct run-

Table 3. Comparative water balance on the Všeminka catchment

	Balance component (mm)	Existing situation (mm)	Scenario with 100-year rain + 87.1 (mm)
Dry period 16/7 to 31/8, 1992	rainfall RAIN	18.2	105.3
	total runoff STF	1.0	7.8
	direct runoff SOF (from STF)	**0.5**	**7.3**
	actual evapotranspiration AE	90.6	101.9
	change in subsurface storage ΔW	**–71.8**	**–4.4**
Wet period 26/6 to 14/8, 1997	rainfall RAIN	389.9	477.0
	total runoff STF	151.9	208.2
	direct runoff SOF (from STF)	**103.1**	**148.2**
	actual evapotranspiration AE	120.0	121.4
	change in subsurface storage ΔW	**118.0**	**147.4**

Table 4. Comparative water balance on the Dřevnice catchment

	Balance component (mm)	Existing situation (mm)	Scenario with 100-year rain + 87.1 (mm)
Dry period 16/7 to 31/8, 1992	rainfall RAIN	18.2	105.3
	total runoff STF	4.0	32.0
	direct runoff SOF (from STF)	**0.6**	**26.1**
	actual evapotranspiration AE	90.8	102.2
	change in subsurface storage ΔW	**–76.6**	**–28.9**
Wet period 26/6 to 14/8, 1997	rainfall RAIN	389.9	477.0
	total runoff STF	232.0	308.2
	direct runoff SOF (from STF)	**207.2**	**288.5**
	actual evapotranspiration AE	117.5	119.8
	change in subsurface storage ΔW	**39.4**	**49.0**

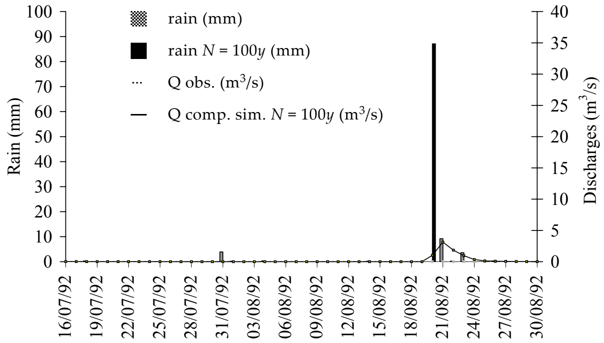

Figure 1. Hydrographs on the Všeminka catchment in the dry period 1992

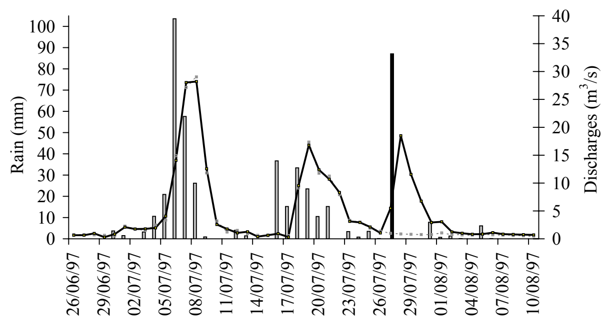

Figure 2. Hydrographs on the Všeminka catchment in the wet period 1997

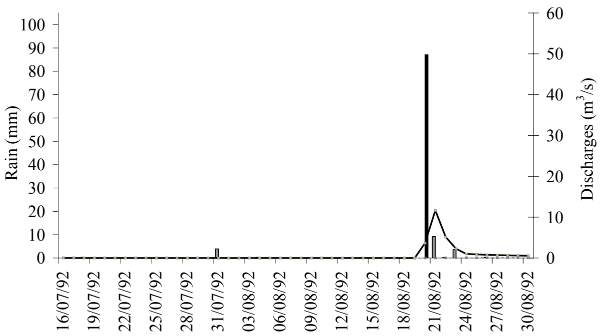

Figure 3. Hydrographs on the Dřevnice catchment in the dry period 1992

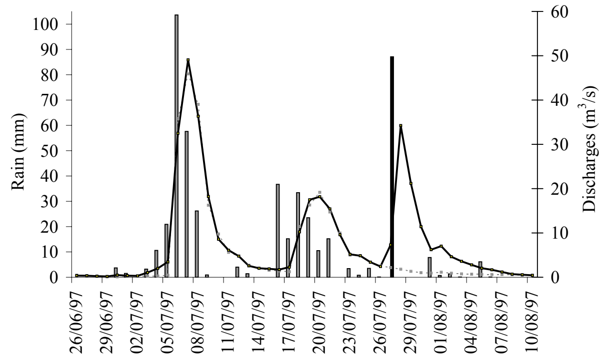

Figure 4. Hydrographs on the Dřevnice catchment in the wet period 1997

off. This could undoubtedly bring a catastrophical event. The increase of subsidy to subsurface storage is also remarkable in all four-scenario results. There the existing situation as well as the situation when the design rainfall of 87.1 mm has fallen is presented. Low values soil moisture deficit, SMD (and correspondingly high values of antecedent precipitation index, API) represent the situation when there is no more retention to replenish subsurface storages on the catchment. The situation on the Dřevnice catchment is similar, even more sensitive for faster fluctuation because of the shallower active zone. Tables 3 and 4 and also Figures 1–4 give results of the comparative water balance component values.

It can be concluded, that this paper based on the water balance of two extreme hydrological periods analysed by the WBCM model has provided the following deductions:

In dry period of the year 1992 was direct runoff from the scenario-design rainfall of 87.1 mm on the experimental catchment Všeminka 13% and on Dřevnice 32%. In the wet period of the year 1997 there was direct runoff from this rainfall on Všeminka 52% and on Dřevnice as much as 93%. A degree of situation expressed either by API or SMD is, besides the design rainfall characteristics; its depth, duration, and intensity are very substantial in a direct runoff formation process.

Changes in subsurface water subsidy are logical, the great recharge improvements in dry periods on both catchments are remarkable, and their excess in wet periods is not dangerous as groundwater flow from their subsurface storages is supposed to be not too rapid.

Small changes of actual evapotranspiration depend on an active zone and whole unsaturated soil water content. These changes are not essential.

The WBCM model can be used only for individual water balance components quantification but also for an identification of the potential harm of floods and/or droughts. This model, however, cannot reliably simulate a scenario daily hydrograph. Therefore another routing model (e.g. Fourier) was implemented as a by-tool.

REFERENCES

Cudlín P., Zemek F., Heřman M., Kovář P. (2000): Evaluation of the extreme hydrological phenomena conditions in landscape using methods of mathematical modelling and GIS. Worksh. Proc., ČVUT, Praha: 261–272. (In Czech)

Falkenmark M. (1999): Water, a reflection of land use. Swed. Nat. Sci. Res. Counc., UNESCO.

Kovář P. (2001): Use of water balance model to identify extreme hydrological situations. Worksh. Proc. ČVUT, Praha: 193–202. (In Czech)

Kovář P., Cudlín P., Heřman M., Zemek F., Korytář M. (2002): Analysis of flood events on small river catchments using the KINFIL model. J. Hydrol. Hydromech. ÚH SAV, Bratislava, *50*: 157–171.

Kovář P., Cudlín P., Korytář M., Zemek F., Heřman M. (2001): Comparative study of water balance on the experimental catchments Všeminka and Dřevnice. Rostl. Výr., *47*: 260–266.

Kovář P., Veselý R. (1998): Use of water balance model for the restoration of small catchments. Rostl. Výr., *47*: 260–266. (In Czech)

Maidment D.R. (1993): Handbook of hydrology. McGraw-Hill, Inc.

Neruda M., Kovář P. (2003): Implementation of the Fourier series model on the Ploučnice catchment. Vod. Hospod., *53*: 68–70. (In Czech)

Šamaj F., Brázdil R., Valovič J. (1983): Daily rainfalls of maximum intensity in CSSR in the period 1901–1980. Proc. Slovak Hydromet. Inst. Sbor. Prác. SHMU, Alfa, Bratislava: 19–112. (In Slovak)

Received on October 29, 2003

ABSTRAKT

Modelové simulace hydrologické bilance experimentálních povodí Všeminky a Dřevnice v extrémních letech 1992 a 1997

Hydrologický výzkum experimentálních povodí Všeminky a Dřevnice probíhá již téměř deset let. Dřívější hydrologické studie na těchto povodích přinesly dílčí výsledky hodnocení vlivu využívání pozemků na vodní režim povodí a rámcové hodnocení podmínek vzniku extrémních hydrologických jevů. Příspěvek je zaměřen na identifikaci extrémních hydrologických období (tj. povodní a sucha) a na simulaci situací, kdy v těchto extrémních podmínkách zasáhne povodí návrhová srážka s periodicitou výskytu $P = 0,01$ ($N = 100$ let), a dále na analýzu extrémních letních období roků 1992 (suché období) a 1997 (povodňové období). Tato dvě 50denní období byla nejprve rekonstruována ve stávající situaci (tj. bez návrhového deště) s cílem kvantifikovat hlavní komponenty hydrologické bilance. Tato rekonstrukce byla provedena implementací modelu WBCM s použitím hodnot parametrů tohoto modelu, získaných optimalizací různých vegetačních období několika let v minulosti. S hodnotami těchto parametrů modelu WBCM byly simulovány dvě zmíněné extrémní situace, v nichž je povodí zasaženo návrhovým deštěm. V suchém období 1992 tento návrhový déšť způsobil zvýšení přímého odtoku na Všemince o 13 % a na Dřevnici až o 32 %. V povodňovém období 1997 by tyto hodnoty dosáhly zvýšení na Všemince o 52 % a na Dřevnici dokonce o 93 %. Rozdíl zvýšení přímého odtoku mezi oběma povodími je dán rozdílnými retenčními kapacitami aktivních zón povodí. Rozdíl ve výšce přímého odtoku mezi suchým a mokrým obdobím je dán stavem předchozího nasycení povodí, hodnoceným buď indexem předchozích srážek (API), nebo deficitem půdní vlhkosti aktivní zóny povodí (SMD). Recipročně k výšce přímého odtoku je výška dotace podpovrchových vod tedy významně vyšší v suchém období. K simulaci hydrogramů denních odtoků byl úspěšně využit model Fourier (Neruda a Kovář 2003), doplňující model WBCM. Takto byl sestaven vhodný aparát, umožňující rozbor možných důsledků scénářových situací hydrologických extrémů.

Klíčová slova: hydrologická bilance; srážko-odtokový proces; hydrologické modely; hydrologické extrémy; scénářové simulace; povodně; sucho

Corresponding author:

Prof. Ing. Pavel Kovář, DrSc., Česká zemědělská univerzita v Praze, 165 21 Praha 6-Suchdol, Česká republika
phone: + 420 224 382 148, fax: +420 234 381 848, e-mail: kovar@lf.czu.cz