USE OF WATER BALANCE MODEL FOR ESTIMATION OF ANTECEDENT MOISTURE CONDITIONS

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Abstract: Use of water balance models gives opportunities to identify extremes of rainfall-runoff processes namely a degree of the saturation in the active zone on small catchments as a potential scale-distress danger of floods or draughts, respectively. The active zone is the most upper layer of soil (0,20 - 0,50m) on a catchment which strongly influences a formation of direct runoff particularly when its soil moisture content is close to saturation, and on the other hand, it causes drought, when the water content is exhausted.
The paper gives the results of hydrological balance implementation using the WBCM-5 model (Water Balance Conceptual Model, version 5) running in one-day step on two experimental catchments: Vseminka and Drevnice in the Czech Republic. Conceptual soil moisture content in the active zones has been related to antecedent precipitation index. Then extreme summer season data of the year 1992 was reconstructed to simulate the dry season and both summer periods 1992 and 1997 data were used to simulate a situation when the extra torrential rainfall of design character with recurrence time N=100 years fell.
In the period of 1992, the design rainfall of 100-year caused the direct runoff increased on Vseminka for 13%, on Drevnice for 32%. In the flood period of 1997 this increment of direct runoff should achieve 52% on Vseminka and even 93% of the existing situation on the Drevnice catchment. The differences between two experimental catchments and between the years 1992 and 1997 are caused by very different retention capacities of their active zones.
Key words: water balance model, antecedent moisture conditions, hydrological extremes, soil moisture deficit, scenario simulation.

Zusammenfassung: Die Anwendung des hydrologischen Bilanzmodells bietet günstige Bedingungen zur Identifizierung extremer Niederschlags-Abfluss-Prozesse, insbesondere zur Bestimmung des Wassersättigungsgrades der aktiven Bodenzone von kleinen Einzugsgebieten, als einen Maßstab für die Bedrohung durch Hochwasser oder Trockenheit. Die aktive Bodenzone ist die oberste Bodenschicht (mit einer Dicke von 0,20 - 0,50 m), die im Einzugsgebiet einen bedeutenden Einfluss auf die Gestaltung des Direktabflusses hat, insbesondere falls sich ihre Sättigung durch Niederschläge dem kapillaren Sättigungsgrad nähert, oder in Trockenperioden, wenn ihr Feuchtigkeitsvolumen erschöpft ist.
Der Artikel stellt die Ergebnisse des hydrologischen Bilanzmodells WBCM-5 (Water Balance Conceptual Modell, Version 5) vor, das mit einem Zeitschritt von 1 Tag auf zwei Experimentaleinzugsgebieten in der Tschechischen Republik - Vseminka und Drevnice - angewandt wurde. Die konzeptuelle Feuchtigkeit der aktiven Zonen wurde mit den Indexwerten der vorherigen Niederschläge konfrontiert.

Ferner wurden mit Hilfe des Modells ausgewählte extreme Abschnitte des Sommers 1992 zur Simulierung einer typischen Trockenperiode rekonstruiert und andererseits wurde eine ähnliche Datenreihe aus dem Jahre 1997 zur Simulierung eines typischen von Hochwasser geprägten Zeitabschnitts herangezogen. Für beide dieser Zeitabschnitte wurde eine Szenario-Simulierung des Abflusses und eines Ein-Tages-Bemessungsniederschlags mit einer Periodizität von N=100 Jahre vorgenommen. Im Zeitabschnitt 1992 verursachte dieser Bemessungsniederschlag einen Anstieg des Direktabflusses gegenüber der existierenden gemessenen Situation am Gewässer Vseminka um 13%, am Gewässer Drevnice um 32%. In der Hochwasserzeit des Jahres 1997 war jedoch der Anstieg des Direktabflusses auf Grund der Sättigung der aktiven Zone bei Vseminka um 52%, im Einzugsgebiet von Drevnice sogar um 93% höher. Diese Unterschiede zwischen den

einzelnen Jahren und den Einzugsgebieten wurden eindeutig durch den sehr unterschiedlichen Zustand der Retentionskapazitäten der aktiven Zonen verursacht.

Schlüsselworte: Hydrologisches Bilanzmodell, vorherige Bodenfeuchtebedingungen, hydrologische Extreme, Bodenfeuchtendefizit, Szenario-Simulierung.

1. Introduction

Water regimes of a catchment can be well quantified by an analysis of water balance components with reference to direct runoff and subsurface water recharge. In particular, the upper soil layer in a catchment is extremely important, as its moisture content predetermines possible floods or droughts according to its soil moisture deficit value (Maidment, 1993). Therefore, this layer (usually 0.20m to 0.50m in depth) is known as the **active zone**. The impact of land use on the water balance in an active zone is also a matter of great importance in water resources management and flood control (Falkenmark, 1999).
A case study based on water balance computation has been carried out using data from two small catchments **Vseminka** and **Drevnice** in Moravia. The aim of this study, in a broader sense, is to investigate the effect of soil, physiographical factors and land use on water retention capacities in the active zones of the catchments.

2. Experimental catchments

Both Moravian experimental catchments covering similar areas have suffered at least twice from floods during recent years (1997, 2001). Fig. 1 gives a general view of the situation of the catchments. The shape of the Vseminka catchment is longitudinal, the upper sides of the central valley are forested down from the water divide, and land use on the other parts is diversified. The Drevnice catchment is fan-shaped, highly forested and only its lower part has a more structured land use. The soil characteristics of the catchments are given in Table 1 a, b. The soil groups have been selected in accordance with methods widely used (U.S. SCS, 1986). The land use and physiographic factors are presented in Table 2.

Fig. 1: Situation of the experimental catchments

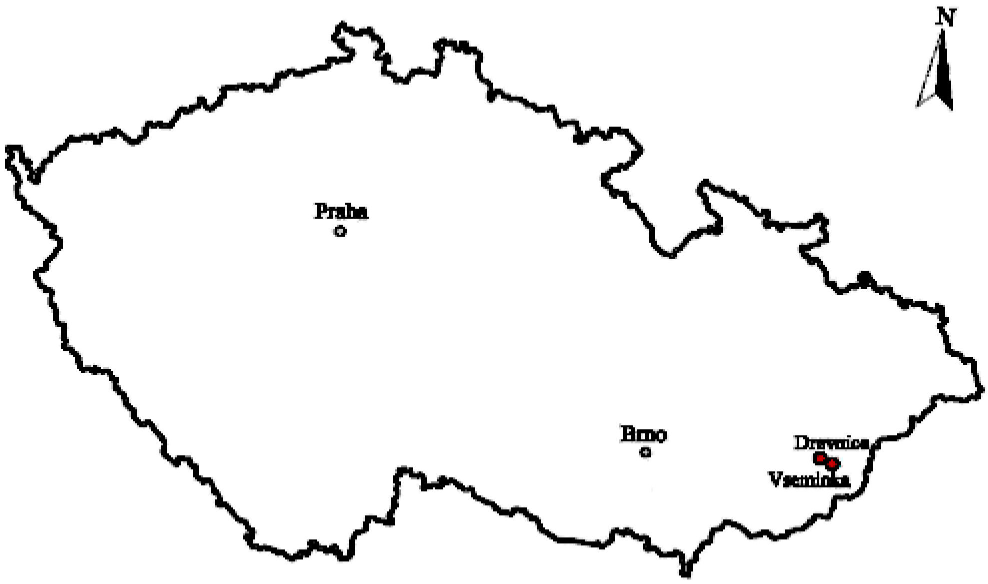


Table 1a. Catchments soil characteristics:

Catchment name	Area (km²)	Average field capacity FC (-)	Average porosity POR (-)	Depth of active zone DROT (mm)	Saturation content Q_{SAT} (mm)
Vseminka	21.51	0.40-0.42	0.45-0.50	300.0	123.0
Drevnice	22.58	0.40-0.43	0.44-0.48	300.0	125.0

Table 1b. Catchment hydrological soil groups:

Soil group	Vseminka	Drevnice
A	0.0%	5.1%
B	10.8%	30.5%
C	46.1%	39.0%
D	43.1%	25.4%

Note: Water permeability decreases from A to D.

3. Model

The WBCM model that was implemented with the aim of quantifying the soil moisture dynamics of the experimental catchments is a lumped model with probability parameter distribution over the area. It is based on the integrated storage approach. Each storage element represents the natural storage interception, soil surface and active zone. In this version not all the unsaturated and ground water zones were used, however only a recharge to them was considered as an output from the active zone in the form of deep infiltration.

The model with daily step input/output rates simulates the following processes (Kovar 1999, Kovar 2000):

- potential evapotranspiration, interception and throughfall
- direct runoff
- active soil moisture zone dynamics

Note: Soil moisture content of the whole unsaturated zone, ground water dynamics, base flow and total flow were computed only for the process of parameter calibration.

The modified Monteith-Penman method was used for computing **potential evapotranspiration**. A linear distribution of local interception capacities was in principle used for **actual interception** and **throughfall**. For quantifying **direct runoff**, the US Soil Conservation Service, SCS method based on runoff curve number (CN) assessment was used. The **recharge of the active zone** and its **depletion** depend mostly on soil parameters (field capacity FC, porosity POR, hydraulic conductivities, KS), on soil moisture content and on potential evapotranspiration conditions. For this computation, the one-dimensional Richards equation is used in the finite difference form (Kovar, 2001).

Table 2. Catchment land use and physiographic factors

LAND USE	**VSEMINKA**	**DREVNICE**
Arable land	9.3%	2.7%
Meadows, pastures	24.2%	9.0%
Wild greenery	14.0%	0.8%
Forest	48.2%	81.0%
Others	4.3%	6.5%
PHYSIOGRAPHIC FACTORS	**VSEMINKA**	**DREVNICE**
Length of river	9.2 km	9.1 km
Average river slope	3.6%	3.5%
Average catchment slope	19.4%	23.0%
Average catchment altitude	400 m a. s. l.	495 m a. s. l.

Table 3. Major data on floods in 07/1997

Catchment	**Date**	**Flood peak Q_{max} ($m^3.s^{-1}$)**	**Causal rainfall (mm)**	**Initial SMD (mm)**	**Antecedent precipitation index API_{30} (mm)**	**Final SMD (mm)**
Vseminka	4/7-10/7	11.4	123.3	37.8	30.0	1.2
	18/7-27/7	7.3	70.4	10.8	87.8	0.0
Drevnice	4/7-10/7	11.2	160.6	36.1	35.9	0.8
	18/7-27/7	5.3	90.1	12.4	127.2	0.0

4. Results and Discussion

The model has been implemented annually since 1992 to compute the water balance components. Thus the model parameters had already been calibrated. The aim of this paper is to study two pre-flooding periods in July 1997 with reference to soil moisture content in the active zones of both experimental catchments. There were two flood waves over the territory of Eastern Bohemia and Moravia (4/7 to 10/7 and 18/7 to 27/7/1997). The major data on these floods is shown in Table 3. Then, the WBCM-5 model was implemented to compute soil moisture content fluctuation in the form of daily moisture deficit values (SMD), as well as the daily antecedent precipitation index (API). Figures 2 a, b give the daily values of rainfall, runoff, SMD, and API. These graphs plotted for the period of June 1 to September 3, 1997, show how dangerous flooding situation appears when the SMD values drop below 10 mm and even lower and the catchments have no more retention capacity to store next rainfall. In particular, the period 5/7 to 7/8/1997 on the Vseminka and Drevnice was the most hazardous. The result was a flood close to 100-year return period, which caused major loss in human life and in property.

Figure 2a: Soil moisture deficits on the catchment of Vseminka

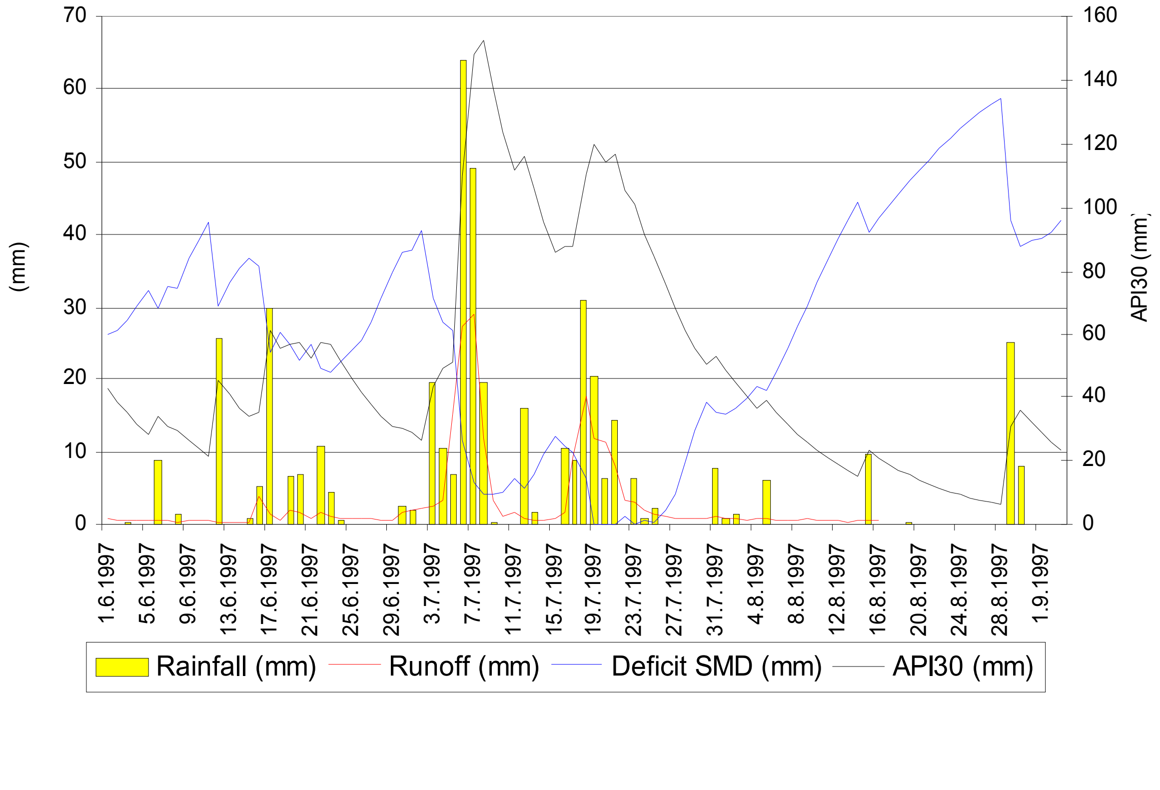
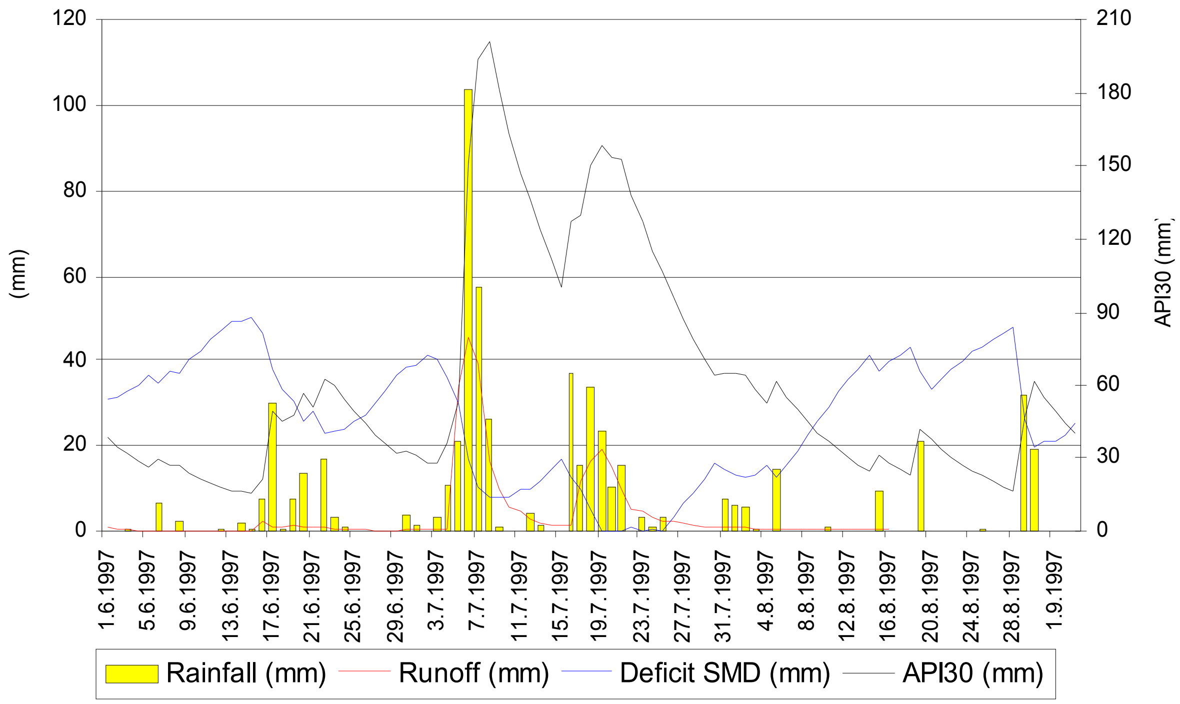


Figure 2b: Soil moisture deficits on the catchment of Drevnice



The second part of this research was to select two extreme periods: dry and wet ones of about the same duration. 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. 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 next aim of this paper was to select two periods, one typically dry and the other typically wet, both of the duration about 6 to 7 weeks when there was either no rain in 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 Vseminka and Drevnice 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. 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. (Kovar et al, 2001).

Next to the previous analysis of the situation in 1997 the situation in 1992 was completely different and the active zone was closed to the wilting point. Daily SMD (mm) values are reciprocally to daily antecedent precipitation index values, API (mm). When we compare both experimental catchments, it is evident that the Vseminka catchment is more "water keeping" than the Drevnice catchment in spite of larger forested area on the latter case.

The final aim of this work was 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 (Samaj, et al,1983):

	Return period N – year					
N =	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 Vseminka and Drevnice.

In dry period 1992 on the Vseminka catchment, the impact of 100-year rain has increased direct runoff from 0.5 mm to 7.3 mm, and on the Drevnice 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 Vseminka catchment it was +6.8 mm, on the Drevnice catchment + 28.0 mm only.

However, during the wet period this increase was more significant. On Vseminka was +45.1mm and on Drevnice even +81.3mm. It means that on the latter case on a shallow–soil catchment with fully saturated active zone, almost 93% of rainfall can leave the catchment in the form of direct runoff. 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 87.1mm has fallen are 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 Drevnice catchment is similar, even more sensitive for faster fluctuation because of the shallower active zone. Tables 4 and 5 and also Figures 3, 4, 5 and 6 give results of the comparative water balance component values.

Table 4. Comparative water balance on the **Všeminka catchment**
dry period 16/7 to 31/8/1992, wet period 26/6 to 14/8/1997

Water balance component	**Dry situation 1992**	**Wet situation 1997**	**Scenario with 100-year rain 1992**	**1997**
(mm)	**(mm)**	**(mm)**	**(mm)**	**(mm)**
Rainfall, RAIN	18.2	389.9	105.3	477.0
Total runoff, STF	1.0	151.9	7.8	208.2
Direct runoff, SOF	**0.5**	**103.1**	**7.3**	**148.2**
Actual evapotranspir., AE	90.6	120.0	101.9	121.4
Change in storage ΔW	**-71.8**	**118.0**	**- 4.4**	**147.4**

Table 5. Comparative water balance on the **Dřevnice catchment**
dry period 16/7 to 31/8/1992, wet period 26/6 to 14/8/1997

Water balance component	**Dry situation 1992**	**Wet situation 1997**	**Scenario with 100-year rain 1992**	**1997**
(mm)	**(mm)**	**(mm)**	**(mm)**	**(mm)**
Rainfall, RAIN	18.2	389.9	105.3	477.0
Total runoff, STF	4.0	232.0	32.0	308.2
Direct runoff, SOF	**0.6**	**207.2**	**26.1**	**288.5**
Actual evapotranspir., AE	90.8	117.5	102.2	119.8
Change in storage ΔW	**-76.6**	**39.4**	**-28.9**	**49.0**

5. Conclusions

The data on hydrometeorological observations, soil, land use and on watershed management were checked for reliability and then spatially processed by ARC/INFO on the catchments of Vseminka and Drevnice. Then, after implementing the WBCM-5 model on that data, the resulting outputs were analysed and the following conclusions can be made:

•Comparing rainfall-runoff events in July 1997 on the experimental catchments, in spite of the relatively greater percentage of forestation in the Drevnice catchment (81.0% against 48.2% on Vseminka), the **depth of rainfall** (Drevnice about 30% higher than those on Vseminka) and its **intensity** are **more important factors than land use** in a flood consideration.

•Water balance modelling such as implementing only "upper layers" (i.e. active zones) on catchments **can easily quantify daily soil moisture deficit (SMD) values** which signalize a **degree of water saturation**

•In dry period of the year 1992 was direct runoff from the scenario–design rainfall of 87.1mm on the experimental catchment Všeminka 13% and on Dřevnice 32%. In wet period of the year 1997 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, very substantial in a direct runoff formation process.

Figure 3: Hydrographs on the Všeminka catchment in the dry period 1992

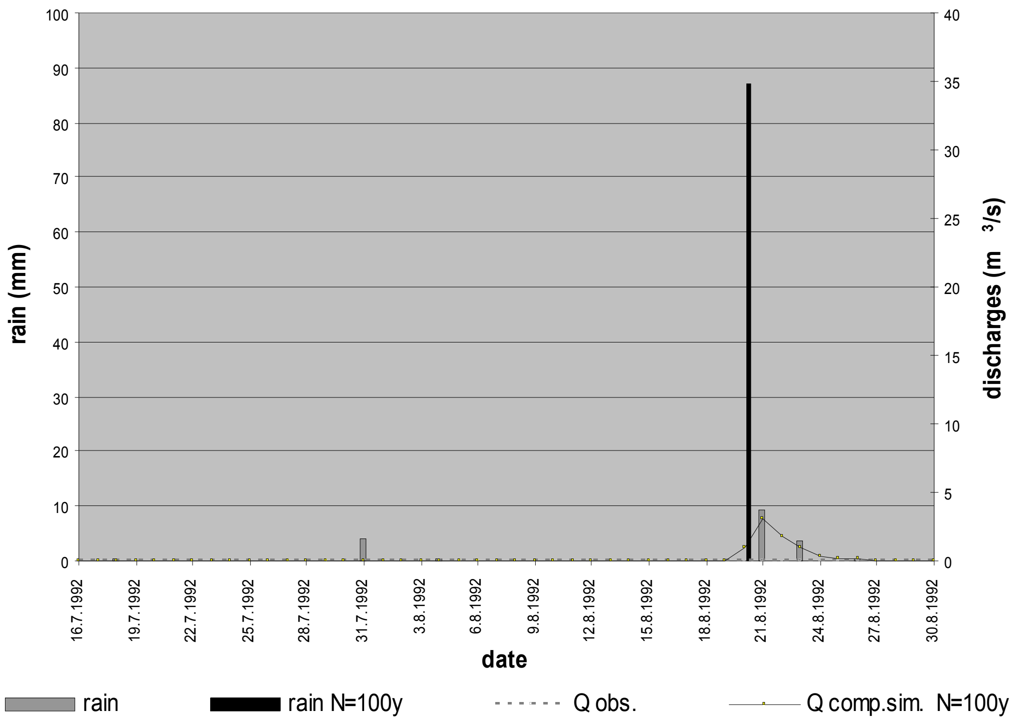


Figure 4: Hydrographs on the Všeminka catchment in the wet period 1997

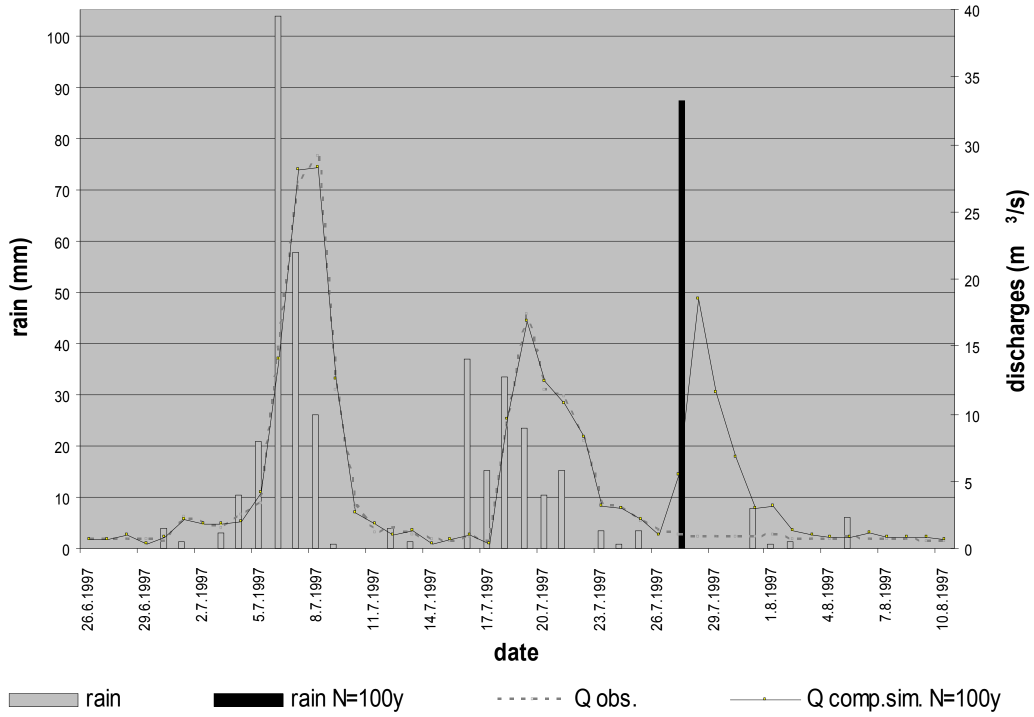


Figure 5: Hydrographs on the Dřevnice catchment in the dry period 1992

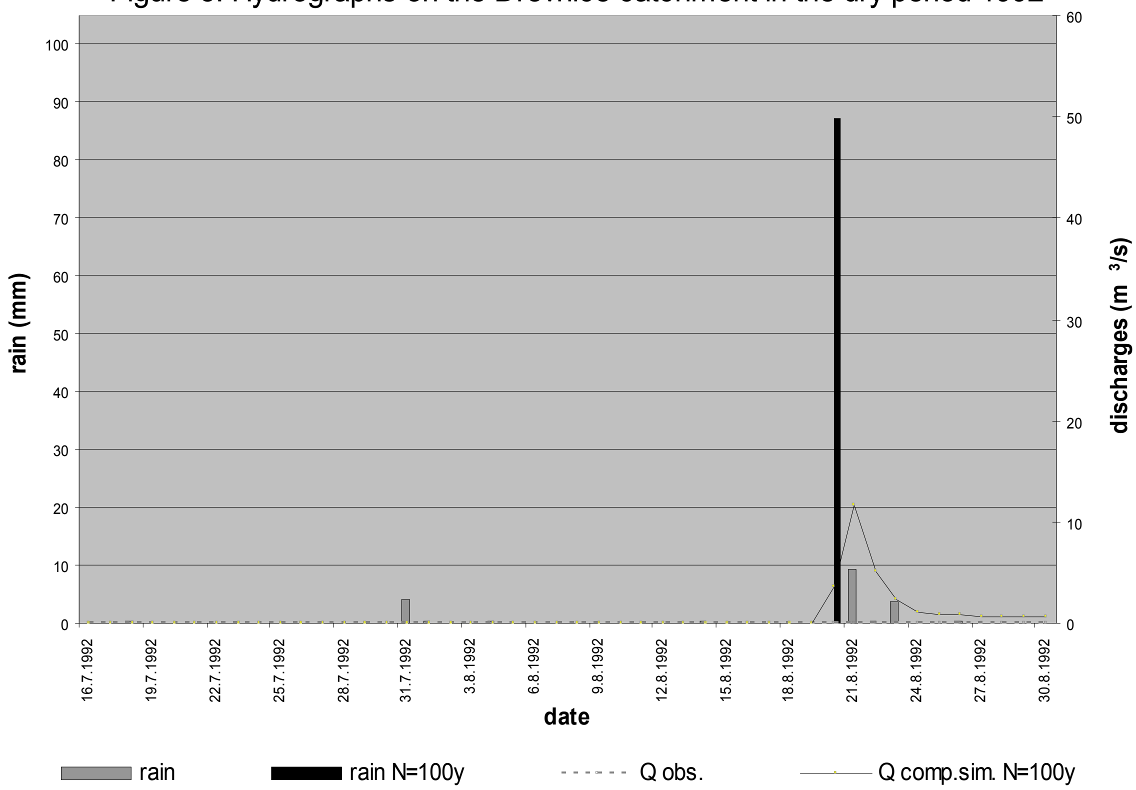
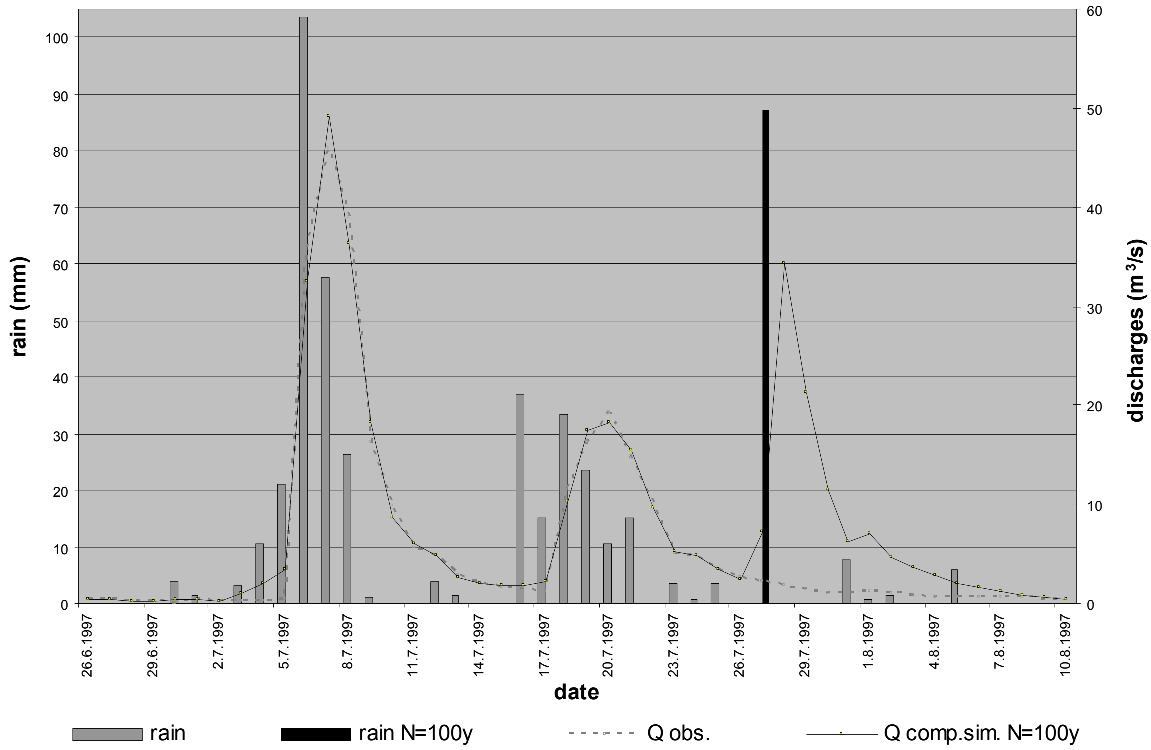


Figure 6: Hydrographs on the Dřevnice catchment in the wet period 1997



•Changes in subsurface water subsidy are logical, the great recharge improvements in dry periods or both catchments are remarkable, their excess in wet periods is not dangerous as groundwater flow from their subsurface storages is supposed as 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.

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6. References

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