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MODIFICATION OF DIRECT RUNOFF IN A SMALL FOREST CATCHMENT OF THE KRAJEŃSKIE LAKELAND AS A RESULT OF THE WATERCOURSE DEVELOPMENT

Summary

The field investigations were carried out in a small forest catchment situated in the area of the Krajeńskie Lakeland, in the Lipka Forest District, the Biskupice Forest Range. The catchment covers the area of 182 ha; 95% is covered by forests and 5% by arable land and meadows. Field measurements comprised continuous recording of water level at the Thompson's weir and weekly measurements of groundwater levels in ten wells. Construction development was introduced in the area of the watercourse during the conducted research: six damming devices (installations) constant weirs - were constructed there. The annual outflow coefficient from the catchment equals to 0.330. It confirms the necessity of developing the discussed watercourse in order to create the so-called small retention. However, no significant influence was found of the development on the water balance components of the catchment. The influence of the watercourse bank development can be clearly described by conducting an analysis of direct runoff. 14 recorded large floods were subject to analysis; 6 prior to the development and 8 following it. Each of the waves was described by applying Nash's conceptual model. A constant number of 2 reservoirs in a cascade was assumed. Means of time-constants for high water waves after the development were higher by approx. 50% than for the waves prior to the construction. Resulting from it a hypothesis can be constructed here stating that the time of runoff water deposition in the catchment as a result of the weir development was significantly prolonged. It can be thus assumed that systems of small and basic weirs should be applied in forest small retention programmes.

Key words: forest catchments, small retention, runoff modelling

INTRODUCTION

Shortages of water resulting from unfavourable water balances are found in the area of almost the whole country, including forest areas. It may result in degradation of some forest habitats e.g. those particularly precious to preserving forest marshy habitat biodiversity. Programmes of small retention are aimed at preventing the occurrence of the unfavourable phenomenon. Synthesizing the problem, the actions within the frame of the programmes are supposed to lengthen the route and time of water circulation in catchments alongside with ensuring water self-purification. The aim of the work is to present the influence of a watercourse bank development with a weir cascade on the outflow in a small forest catchment situated on the Krajeńskie Lakeland. Such a modification of outflow can be best described by analysing the observed runoffs prior to and after the development. Nash's model was suggested to describe runoff in order to carry out their effective analysis. Effective rainfall for the successive high water stages were calculated on the basis of the direct runoff coefficients i.e. quotients of indices of the direct runoff and sums of precipitation bringing about the runoffs.

MATERIALS AND METHODS

Description of the catchment

Hydrological measurements began in April 2002 in a small catchment situated in the Krajeńskie Lakeland in the area of the Lipka Forest District, the Biskupice Forest Range. The measurements comprise a continuous recording of water levels at Thomson's overflow and weekly measurements of groundwater levels in 10 wells. The catchment covers the area of 182.26 ha; 174.02 ha – 95% covered by forests, and 8.24 ha – 5% arable land and meadows. The investigated catchment can be regarded as representative of the Lipka Forest District since both the dominant forest habitat types (fresh coniferous and fresh mixed coniferous forests) and dominant soils (rusty soils) are similar. The length of the watercourse channelling the water from the catchment is 1540 m. The course has no local name, and is marked in the register as 17-86-1. Its beginning is found on a forest meadow and it flows directly into the Gwda river. The elevation, where the watercourse source is located is 110 m a.s.l., whereas its mouth elevation is 97.5 m a.s.l. The course gradient is uneven in full length. The course in its upper reaches is characterized by insignificant gradients reaching 0.38%, whereas the 350 m section, directly before the mouth, equals to 1.6-2.8% limits. There is a drainage ditch in the upper reaches of the course. A mean daily specific discharge in the catchment in focus equalled to 6.4 $l/s/km^2$, and the maximum and minimum respectively 2.5 and 25.5 $l/s/km^2$. The levels of ground water of the 17-86-1 ditch oscillated within 60-280 cm, and at mean 166 cm u.g.l.

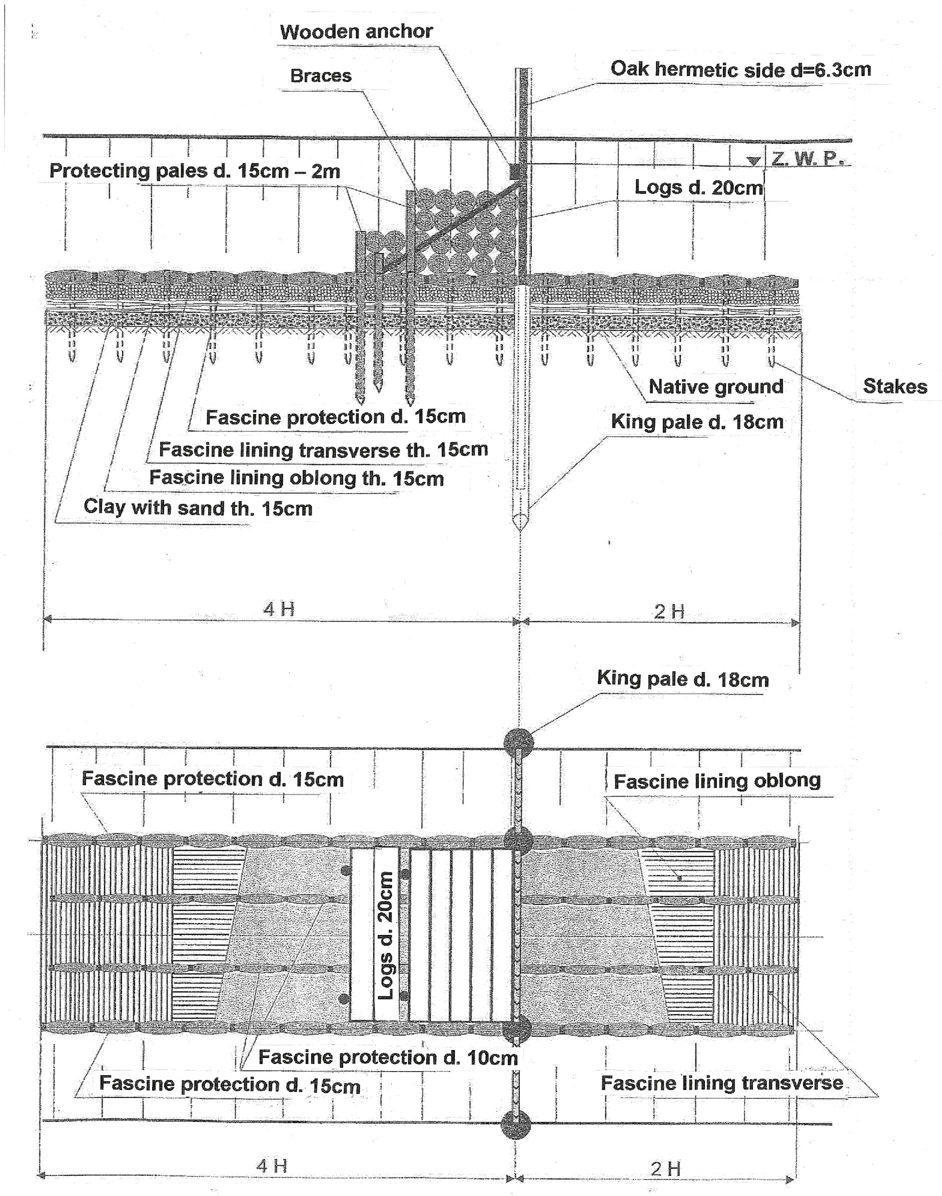

Figure 1. Project of constant type ZW weir, worked out by Natural Historians Club from Świebodzin, used at developing of damming devices on watercourse 17-86-1

Between 4-11 December, 2004, within the framework of the project devoted to marshy habitat protection in the Gwda river basin, 6 damming devices were constructed on the 17-86-1 watercourse. The development was meant to limit surface water runoff from the area in focus, and to prevent from further drying of the marshy areas in the neighbourhood of the watercourse. The damming of water proceeded through application of simple wooden type ZW weirs having a constant damming gradient (Fig. 1).

The hermetic weir walls were dug to the double damming depth and additionally reinforced with anchors. A log cascade was constructed on the water side; the logs were fixed to the ground applying pales in order to minimize the power of water overflowing the weirs; the banks were strengthened with a fascine, and the watercourse bottom was reinforced in front of and behind the damming.

The weirs were placed at the following distances measured from the mouth (Fig. 2):

– weir 1 – 270 m, damming height H = 0.8 m, the expected range of backwater L = 25 m,

– weir 2 – 360 m, H = 0.7 m, L = 160 m,

– weir 3 – 520 m, H = 0.7 m, L = 140 m,

– weir 4 – 690 m, H = 0.6 m, L = 120 m,

– weir 5 – 810 m, H = 0.6 m, L = 140 m,

– weir 6 – 1210 m, H = 0.5 m, L = 110 m.

As far as weir 2 is concerned the backwater gets as far as weir 3, similar situation occurs in case of weir 4. Moreover, in the neighbourhood of weir 3 a small pond fed by the watercourse, 200 sq m area and 1m deep, was created as a result of soil removal.

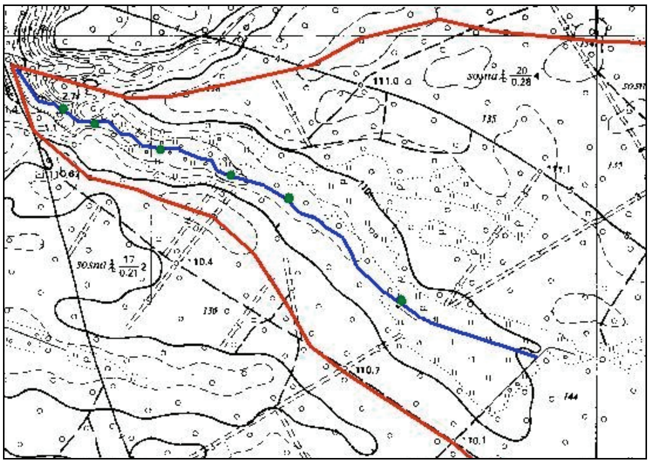

Figure 2. Part of topographical map with marked border of the catchment (red colour), watercourse (blue colour) and location's of dams (green points)

Nash's model

A cascade of *N* linear, identical reservoirs having a constant time (inertia) *T* (Nash 1958) is a conceptual catchment model frequently used in engineering hydrology. The input signal is effective rainfall (bringing about the high water wave) while the output signal is direct runoff identified with the volume of the high water wave. Hyetograph of the effective rainfall *Pe(t)* can be described by the dependence:

$$Pe(t) = \sum_{i=1}^{M} x_i \cdot (\eta(t-(i-1)) - \eta(t-i)), \quad \text{(Fig. 3)} \qquad (1)$$

where:

M – denotes the number of rainfall impulses – rectangular signals with a unitary time duration (1h is accepted here as the time unit)

x_i – amplitude of the i-tly rainfall impulse,

$\eta(t)$ – function of Heaviside step function,

t – time,

i – current variable, i = 1,2…,M.

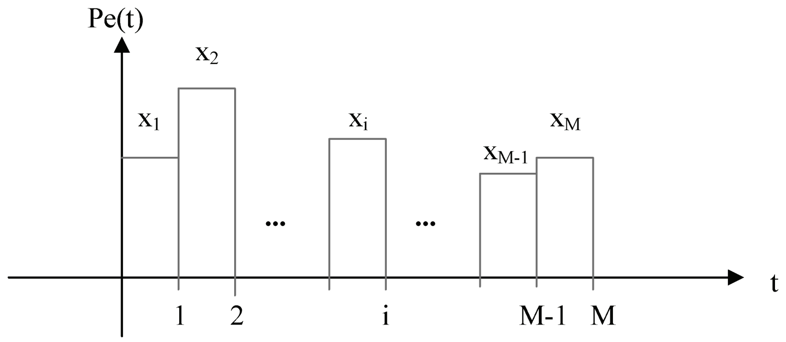

Figure 3. Hyetograph of effective rainfall

The maximum number of reservoirs in a cascade *N* may reach 3 for the very small catchment (the area of approx. 2 km^2) analysed in the paper. It can be estimated from the dependence:

$$N = 3.329 \cdot (R_B / R_A)^{0.744} \cdot R_L^{0.072}, \qquad (2)$$

where:

R_B – index of bifurcation,

R_A – index of catchment area,

R_L – index of watercourses length [Ostrowski 1987-88].

Mean values of geomorphological indices $\overline{R_B}$ and $\overline{R_L}$ for small catchments of the Wielkopolska region (with an area smaller then 350 km^2) reach respectively the values to 3.68 and 2.28 [Miler 1994a]. The dependence between an average watercourse length $\overline{L}$ and average cachment area $\overline{A}$ is as follows:

$$\overline{L} = 1.40 \cdot \overline{A}^{0.568} \text{ [Eagleson 1978].} \tag{3}$$

An average catchment area index $\overline{R_A}$ can be thus evaluated from the dependence:

$$\overline{R}_A = \frac{\overline{A_{i+1}}}{\overline{A_i}} = \left(\frac{\overline{L_{i+1}}}{\overline{L_i}} \right)^{\frac{1}{0.568}} = \left(\overline{R}_L \right)^{1.761} = 4.27\,. \tag{4}$$

What is obtained from dependence (2) equals to N = 3.16 for catchments even 100 times bigger than the analysed one. Ostrowski's calculations (1987-88) indicate that the lower constant N is in the smaller the area of a catchment. And thus accepting the highest N value as 3 seems fully justified.

It can be proved that the index of direct runoff H is expressed by the below dependence:

for N = *1*

$$H(t = m) = \sum_{i=1}^{m} x_i \cdot (e^{-\frac{m-i}{T}} - e^{-\frac{m-i+1}{T}})\,, \tag{5}$$

for N = *2*

$$H(t = m) = \sum_{i=1}^{m} x_i \cdot ((1 + \frac{m-i}{T}) \cdot e^{-\frac{m-i}{T}} - (1 + \frac{m-i+1}{T}) \cdot e^{-\frac{m-i+1}{T}})\,, \tag{6}$$

for N = *3*

$$H(t=m) = \sum_{i=1}^{m} x_i \cdot ((1 + \frac{m-i}{T} + \frac{(m-i)^2}{2 \cdot T^2}) \cdot e^{-\frac{m-i}{T}} - (1 + \frac{m-i+1}{T} + \frac{(m-i+1)^2}{2 \cdot T^2}) \cdot e^{-\frac{m-i+1}{T}})\,, \tag{7}$$

where:

m – discrete time moments, m = 1,2,3, …

More general results – for optional N, as well as rainfall impulses with a changeable duration are given by Miler [1994b].

RESULTS AND DISCUSSION

Table 1 presents the equilibrium water balance for the researched catchment for the 2004/2005 hydrological year. The year is an average one considering the annual atmospheric precipitation total, as well as mean annual air temperature; the values are in the adequate intervals of 90-110% of the multi-annual mean values.

Table 1. Equilibrium water balance of the investigated catchment in hydrological year 2004/2005

Components of balance [mm]	Months											
	XI	XII	I	II	III	IV	V	VI	VII	VIII	IX	X	Year
Precipitation	49	53	81	36	35	14	113	30	48	45	26	21	**551**
Evaporation	13	9	16	10	19	37	45	54	60	56	38	23	**380**
Outflow	10	12	20	20	27	22	22	15	10	10	7	8	**182**
Change of water storage	33	50	52	11	38	-41	-5	-66	-38	-24	-11	-11	**-11**

The sums of precipitation and indices of outflow presented in Table 1 were calculated on the basis of direct measurements. Daily evapotranspiration was calculated according to Konstantinow method, and next its monthly and annual sums were calculated [Miler 1997]. Changes in water storage were calculated on the basis of the groundwater levels measurements.

The annual outflow coefficient equals to 0.330. It justifies the 6-weir cascade development of the watercourse aiming at creating conditions for the so-called small retention. No clear influence of the watercourse development was found on the fluctuations of groundwater table in the shallowest wells situated in the closest neighbourhood of the course. Groundwater level fluctuations run almost simultaneously in all the ten wells (Fig. 4). Analysing the value of outflows, it is difficult to prove any influence of the watercourse development on the outflow.

The influence of the 17-86-1 watercourse development can be clearly proved analysing direct runoffs. And thus 14 observed high water waves were analysed – 6 prior to and 8 after the course development (Table 2). Each high water wave was described with the two-reservoir Nash model ($N = 2$). Assuming a constant number of reservoirs $N = 2$ is conditioned by two factors:

– the parameter should be constant for a given catchment (e.g. Ostrowski 1987-88),

– calculations for $N = 1$ and $N = 3$ presented a lower coincidence of measured and simulated direct runoffs.

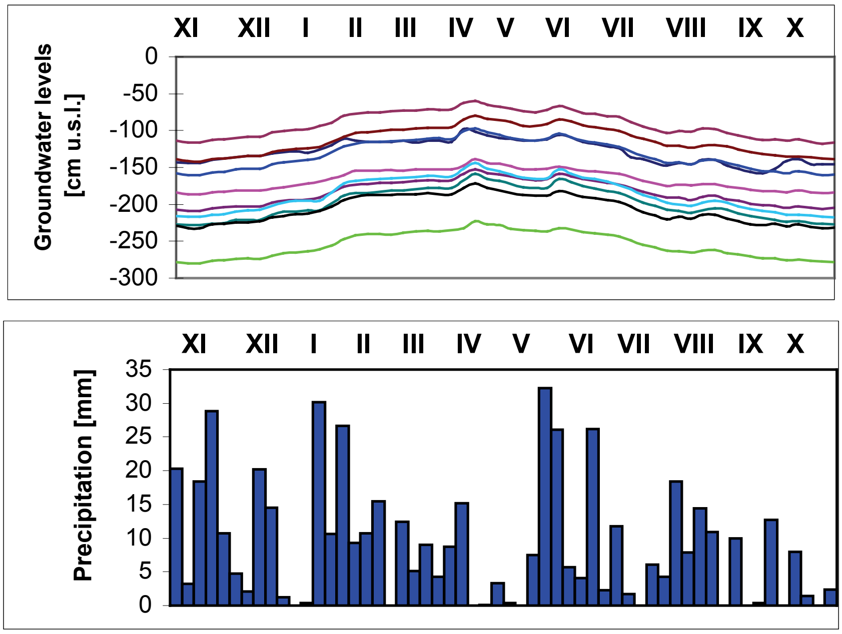

Figure 4. Groundwater levels in 10 wells vs. precipitation in hydrological year 2004/2005

Table 2. Characteristics of high water stages in the investigated catchment

Time interval		Outflow [mm]	Rainfall [mm]	Initial outflow [mm]	Effective rainfall [mm]	Outflow coefficient [%]	Time constant for Nash model [hour]
Before watercourse development	2 V 2004	0.37	6.7	0.26	0.11	1.67	**2.5**
	9 V 2004	2.26	44.3	1.49	0.77	1.74	**3**
	23 VI 2004	0.43	5.9	0.32	0.11	1.80	**2**
	21 VII 2004	0.53	13.7	0.23	0.30	2.21	**3**
	13 VIII 2004	0.79	10.7	0.29	0.50	4.71	**2**
	27 X 2004	0.33	11.4	0.24	0.09	0.80	**4**
After watercourse development	4 V 2005	0.96	20.0	0.49	0.47	2.35	**4**
	8 V 2005	1.68	23.2	1.11	0.57	2.47	**3**
	30 V 2005	0.54	13.2	0.37	0.17	1.30	**3**
	21 VII 2005	0.71	19.8	0.46	0.25	1.25	**3**
	3 VIII 2005	0.89	12.3	0.44	0.45	3.65	**5**
	30 IV 2006	1.69	17.1	1.21	0.48	2.79	**3**
	13 V 2006	0.96	9.6	0.55	0.41	4.26	**4**
	28 V 2006	2.13	17.1	1.27	0.86	5.01	**8**

The values of optimum time constants T for the successive high water waves are collected in Table 2. Optimum values T are the ones that show the highest coincidence of both measured and simulated high water waves (for the constant $N = 2$). Demonstration modelling results of high water waves prior to and after the watercourse development are presented in Figs. 5 and 6 respectively. Hourly indices of outflows [mm/h] were converted into discharges [l/s].

The mean value of time constant T for high water waves before the watercourse development equalled to 2.75 h while after it 4.13 h. It means that the time constant T connected with the catchment inertia increased by 50%. As a result a hypothesis can be formulated that the time of high water deposition in the catchment was significantly prolonged owing to the 6-weir watercourse development.

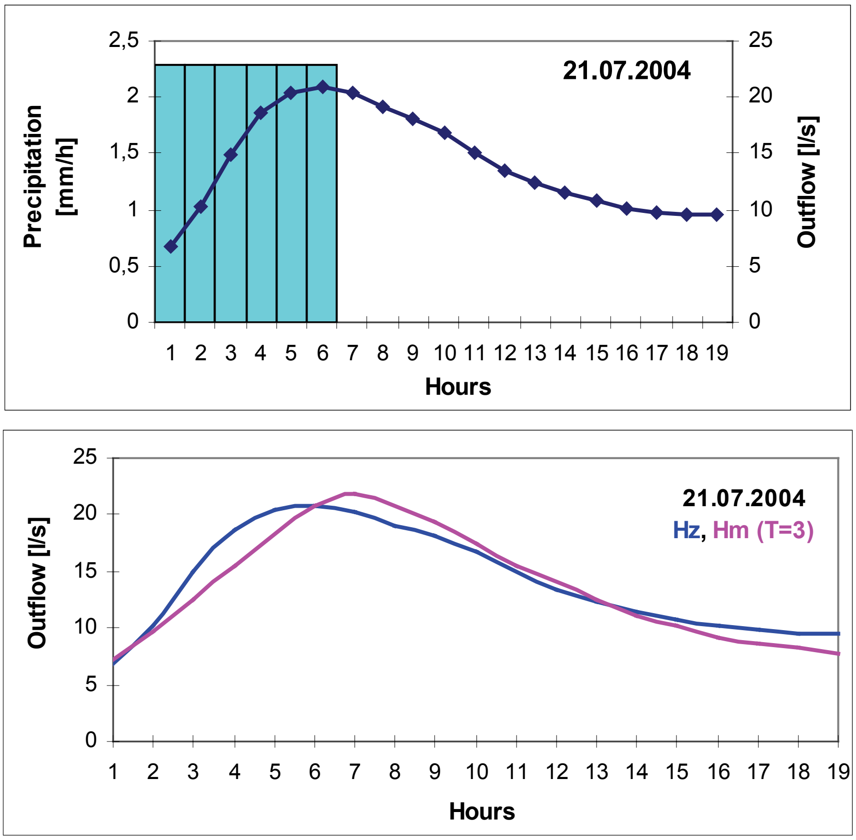

Figure 5. High water wave before watercourse 17-86-1 development
(Hz – measured outflow, Hm – simulated outflow)

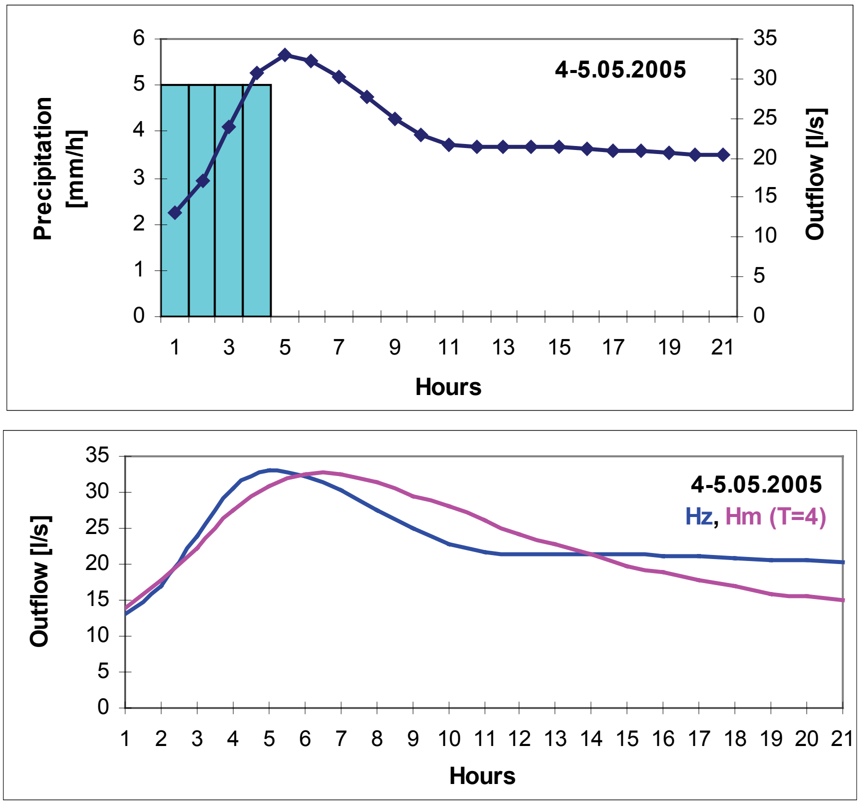

Figure 6. High water wave after watercourse 17-86-1 development
(Hz – measured outflow, Hm – simulated outflow)

CONCLUSIONS

The six weirs cascade development of the 17-86-1 watercourse was proved justified. It can be hypothesised that the storage capacity of the catchment was increased in this way. The catchment inertia to the direct runoff water increased by about 50%. Constructing such an evaluation was possible owing to a description (modelling) of the observed high water waves prior to and after the watercourse development with the two-reservoir Nash model. Constructing watercourse developments with systems of small simple weirs seems justifiable in the so-called small retention programmes for forests.

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