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Comparison of Water Regimes of Two Dump Catchments in the Krušné hory Mts. (Czech Republic) in Dry Years Using a Hydrological Balance

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Abstract

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The dump catchments water regime optimization is one of fundamental recultivation operations in areas devastated after surface coal mining. Two dump catchments (at Radovesice and Loket in the Krušné hory Mts., Czech Republic) were selected to study whether their hydrological balance allows to keep life in them on a sufficiently natural level. The WBCM-6 water balance model was implemented. Different hydrological conditions of the mentioned dump catchments located ca. 90 km apart were compared. The Radovesice catchment lies in a precipitation shadow and suffers from a much greater precipitation deficiency than the Loket one. Its long-term annual precipitation deficit makes about 100 mm. Based on the analysis of the dry year 2003 growing season, biotechnical hydrological measures, in particular cascades of small reservoirs, were proposed.

Keywords: biotechnical measures; landscape improvement; mining dump; water balance model

The concept of recultivation after surface mining in the North-West Bohemian Brown Coal Basin requires studies of water regimes in support of future restoration processes. The WBCM-6 hydrological model has been applied to exploited areas of the Loket and Radovesice dump catchments (Figure 1). The 1000 ha Radovesice dump catchment (Teplice district) stretching at an elevation of 200–400 m a.s.l. (Figure 2) is the largest dump in the Most region. Its area is 1653 ha and the average thickness is 50–70 m. Some parts have already been recultivated, part of the dump has been left for spontaneous succession. It belongs to the B2 climatological region (moderately warm, moderately dry, mainly with moderate winter) and partly to the B3 region (moderately warm, moderately wet, with moderate winter, hilly). The average long-term temperature is 8–9°C and annual precipitation does not exceed 500 mm. The Radovesice dump catchment has the lowest number of snow days (ca. 40) of all catchments in Bohemia. Due to prevailing winds, the water regime tends to be very dry.

The Loket dump catchment (over 50 ha) lies in the eastern part of the Sokolov district, its characteristic shape is elliptical, with a longer axis in the east-west direction (Figure 3). The land use is mostly forest that was recultivated in the past. It belongs to the B1 (moderately warm, dry, with moderate winter), and B2 climatological regions (moderately warm,

Figure 1. Locations of the Radovesice and Loket dump catchments

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moderately dry, mainly with moderate winter). The average long-term temperature is 7–8°C, and the annual average precipitation does not exceed 700 mm. A study project in 1985 dealt with recultivation of the whole dump complex as a unit, with the aim of creating an ecologically well-balanced locality, a landscape suitable for agriculture, providing good living conditions for the inhabitants.

MATERIAL AND METHODS

The WBCM-6 model. Conceptual models are frequently applied in operational practice. However, they usually neglect the spatial variability of the parameters and state variables. They are often calibrated using measured stream flow data. Models of this type include HBV (Bergström 1995), SAC-SMA (Burnash 1995), TOPMODEL (Beven *et al.* 1995), SWAT (Arnold *et al*. 1998), and AFFDEF (Moretti & Montanari 2007). The parameters of these models often cannot be measured in the field, or lack physical meaning. These models also suffer from lack of parameter identifiability, and from equifinality.

Recharge estimation is essential for proper management of a catchment area. There is a group of water balance models based on the water balance equation, e.g. simplified DHVSM model (Andrew & Dymond 2007), HIDROMORE (Sánchez *et al.* 2010), and WBCM-6 model (Kovář & Vaššová 2010). The WBCM-7 model (Kovář *et al.* 2016) can be applied to improve water regimes quantitatively with the use of water reservoirs.

This paper provides a comparison of the water balance in the growing season (April 1 to October 31) with the decadal balance in the dry year 2003 for both dump catchments similarly with the exception of precipitation component. However, a higher difference in water balance components was in the normal growing season 2004 on the Radovesice dump catchment, and also with the decadal water balance in normal year 2006 on the Loket dump catchment. A growing season is the most importatnt part of a hydrological year (November 1 to October 31). The same year does not always indicate a property of a growing season in a normal year. Different hydrological conditions and the distance between both hydrometeorological stations (Bílina and Karlovy Vary) are the circumstances that do not allow using a growing season in one normal year. The water balance for a particular area in a given time span can be described by the equation (in mm):

$$SP = STF + SAE + ASM + GWR - BF \tag{1}$$

where:
SP – rainfall (mm)
STF – total runoff ($STF = SOF + BF$) (mm)
BF – baseflow (mm)
SOF – direct runoff (mm)
SAE – actual evapotranspiration (mm)
ASM – change in soil moisture content (mm)
GWR – groundwater recharge (mm)

The net difference in groundwater storage is *SNGWR*, and it is calculated from (in mm):

$$SNGWR = SGWR - BF = ASM + GWR - BF \tag{2}$$

where:
$SNGWR$ – net change in subsurface storage (after subtracting BF) (mm)
$SGWR$ – change in subsurface storage (mm)

The variable DGWR (change in subsurface storage, i.e. soil water) is calculated as:

$$DGWR = ASM + SNGWR \tag{3}$$

Figure 2. Radovesice dump catchment area

Figure 3. Loket dump catchment area

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The aim of implementing the WBCM-6 model was to quantify the water balance. It is a combined model with the unsaturated soil zone as a distributed part and the other zones conceptually structured. In principle, it is based on the integrated storage approach. Each storage element represents the natural storages of interception, the soil surface, the root zone, the whole unsaturated zone, and the active ground water zone. The model with a daily step computes the storage of each zone and treats the daily values, including the 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 *et al.* 2004; Kovář 2006): (1) potential evapotranspiration, interception and throughfall, (2) surface runoff recharge, (3) root soil moisture zone dynamics, (4) soil moisture content and actual evapotranspiration, and (5) groundwater dynamics, baseflow, and total flow.

We carried out a three-year project (i.e. 2009–2011, MZe QG92091) which highlighted hydrology. The land use on both catchments and with large areas without proper cultivation are spontaneously and irregularly changing. In 2003–2006 the parts of forested and ploughed land were almost the same but due to lesser tillage applied in the past 10 years the percentage of cultivated land slowly lowers and only pastures remain. Therefore we have applied the Curve Number (CN) methodology that is closer to hydrology (e.g. Radovesice CN = 77, Loket CN = 72). Some water pool areas in depressions on the Loketský dump catchment grow more spontaneously due to a seasonal rainfall component in the water balance. Such a previous idea has been confirmed.

The WBCM-6 model has 11 parameters, but only three of them are to be optimized (Kulhavý & Kovář 2000): SMAX (mm), a parameter representing the maximum capacity of the unsaturated zone; GWM (mm), a parameter representing the maximum capacity of the saturated zone; and BK (days), the transformation parameter of the base flow.

The individual parameters have the following physical meaning:

AREA – catchment area (km^2)
FC – average field capacity of unsaturated zone (–)
POR – average total porosity (–)
KS – hydraulic conductivity (mm/h)
DROT – average depth of root zone (mm)
WIC – upper limit of interception (mm)
ALPHA – non-linear filling function exponent (–)
SMAX – maximum capacity of unsaturated zone (mm)
GWM – maximum capacity of groundwater zone (mm)
BK – baseflow transformation parameter (day)
CN – Curve Number (US SCS NRSC 1986, 1992) (–)

The modified Penman-Monteith method (Penman 1963; Monteith 1965), the Priestley-Taylor method (Priestley & Taylor 1972), and the Turc method (Turc 1961) are used for computing the daily potential evapotranspiration values. The model unit that computes the actual interception and throughfall is based on a simulation of the irregular distribution of the local interception capacities around their mean value, WIC.

The US Natural Resources Conservation Service method, based on CN assessment (US SCS NRCS 1986), was used for quantifying direct runoff. The standard procedure for the initial CN value was accepted, and the daily storages of the active zone (SS), were computed by this procedure. The recharge of the root zone, and thus of all unsaturated zones, depends greatly on the previous soil moisture content, and is controlled by the KS of the FC parameters. The evaluation procedure is based on the assumption that the distribution of the local FC values around their average is linear.

The exhaustion function with negative input represents the prevailing evapotranspiration in the daily step. This is applied to the root zone and also to the lower layer of unsaturated soil. Parameters P2 and P7 are based on particular soil retention curves: P2 = 0.2, P7 = 0.7 (loamy soils), 0.6 for clay soils, and 0.8 for sandy soils. Parameter P1 = 0.1 describes very dry conditions for stomata transpiration. Linear retention curves can be substituted by a non-linear curve introducing parameter ALPHA.

The WBCM-6 model describes deep infiltration that recharges a groundwater zone and base flow while the upward capillary flux evaporates when evaporative conditions are favourable. Simultaneously, the exhaustion from this zone due to evapotranspiration is computed. To simulate this procedure, use is made of the proportions between the actual evapotranspiration and the potential evapotranspiration, according to the soil moisture content and according to the particular physical properties of the soil. The saturated zone is filled with groundwater recharge and is depleted through the base flow. Automatic optimization of parameters SMAX, GWM, and BK is applied where the efficiency of the model can be controlled by minimizing the sum of least squared differences between the computed decades and the observed decades (periods of 10 days) of the annual water balance or of the vegetation period water balance (Rosenbrock 1960).

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Table 1. Seasonal hydrological balance of the Radovesice dump catchment in 2003 (dry year) and in 2004 (normal year) in mm

Water balance component (1/4–31/10)	2003	2004
Rainfall (*SP*)	243.9	340.9
Total runoff (*STF*)	31.4	53.3
Surface runoff (*SOF*)	16.6	27.6
Basic flow (*BF*)	14.8	25.7
Potential evapotranspiration (*SPE*)	516.5	422.7
Actual evapotranspiration (*SAE*)	341.6	336.5
Infiltration recharge (*SRECH*)	180.5	245.6
Difference in soil moisture (*ASM*)	–171.4	–123.2
Groundwater recharge (*SGWR*)	56.3	100.2
Net groundwater recharge (*SNGWR*)	41.4	74.4

Table 2. Seasonal hydrological balance of the Loket dump catchment in 2003 (dry year) and in 2006 (normal year) in mm

Water balance component (1/4–31/10)	2003	2006
Rainfall (*SP*)	315.3	419.3
Total runoff (*STF*)	54.4	78.7
Surface runoff (*SOF*)	23.1	25.2
Basic flow (*BF*)	31.3	53.5
Potential evapotranspiration (*SPE*)	390.2	378.3
Actual evapotranspiration (*SAE*)	312.2	329.7
Infiltration recharge (*SRECH*)	221.2	299.7
Difference in soil moisture (*ASM*)	–116.5	–98.4
Groundwater recharge (*SGWR*)	93.3	161.5
Net groundwater recharge (*SNGWR*)	62.0	108.0

RESULTS

The water balance was simulated for both areas for a growing season 2003 (dry), in the form of decadal monthly water balances for 2004 (normal) on the Radovesice dump catchment (Table 1) and for 2006 (normal) on the Loket dump catchment (Table 2). Our interest was focused on dry years, as the aim of our study is to protect the water balance of dump catchments, in particular the water balance of the Radovesice dump catchment. The water balance simulation of the vegetation periods in the dry year 2003 is the most important episode in our study. This year shows the importance of precipitation as the fundamental component of the water balance equation.

The differences in rainfall (*SP*) and in water deficits between potential and actual evapotrans- piration (*SPE – SAE*) show clearly the character of each period (dry or normal). The second indicator is the net change in subsurface storage (*SNGWR*), which is a figure that usually expresses a deficit in growing periods. Table 3 presents an overview of the decade (10 days) values in 2003 on the Radovesice dump catchment, and Table 4 presents the values on the Loket dump catchment. These tables are computed by subtracting the components of the water balance equation.

The graphs presented in Figures 4 and 5 express the decade water balance for the tested growing seasons. They are arranged sequentially step-by-step as graphs subtracting the water balance components on the right side of the equation for each decade, i.e. (1): *SP*, (2): *SP – SAE*, (3): *SP – SAE – STF*, (4): *SP – SAE – STF – DGWR*. The last component, *DGWR*, expresses the subsurface water storage as the sum of the water in both the unsaturated zone and the

Table 3. Deductible decade water balance of the Radovesice dump catchment in dry year 2003 (1/4–31/10, 2003)

Decade	*SP*	*SAE*	*STF*	*DGWR*
	(mm)			
1	3.30	–10.90	–11.70	–23.50
2	17.30	–1.50	–3.20	–4.61
3	1.80	–15.10	–16.20	–31.21
4	20.70	–5.10	–7.40	–13.71
5	20.10	3.60	1.00	–1.96
6	0.70	–25.50	–26.30	–51.69
7	7.20	–22.80	–23.20	–46.13
8	14.60	–11.60	–14.00	–27.20
9	12.80	–11.20	–13.40	–26.09
10	43.40	28.80	22.30	–2.03
11	7.40	–9.20	–10.30	–19.90
12	50.40	33.80	26.90	–1.80
13	0.00	–18.60	–19.50	–38.07
14	3.30	–18.30	–18.40	–36.63
15	1.40	–14.40	–14.40	–28.78
16	1.10	–8.90	–8.90	–17.70
17	9.50	1.70	1.40	–0.12
18	0.00	–6.60	–6.60	–13.22
19	15.90	9.60	9.10	0.63
20	7.50	2.90	2.30	–0.97
21	4.00	1.00	0.90	–0.08

SP – rainfall; SAE – actual evapotranspiration; STF – total runoff; DGWR – change in subsurface storage, i.e. soil water

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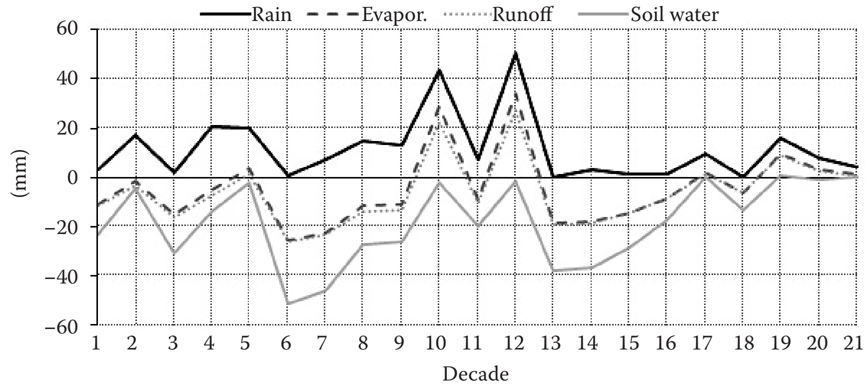

Figure 4. Deductible decade water balance graph of the Radovesice dump catchment in the growing season of 2003

saturated zone (*ASM* + *SNGWR*). Negligible imbalances can be observed in several decades, when they are considered separately. These imbalances (*DIF*) are computed by:

$$DIF = SP - SAE - STF - DGWR \quad (4)$$

Table 4. Deductible decade water balance graph of the Loket dump catchment in the dry year 2003 (1/4–31/10, 2003)

Decade	*SP*	*SAE*	*STF*	*DGWR*
	(mm)			
1	10.70	–1.30	–2.30	–8.60
2	14.00	–6.50	–8.20	–14.80
3	2.70	–10.40	–11.70	–21.70
4	5.00	–17.40	–17.70	–34.90
5	29.40	12.70	9.00	–3.10
6	24.00	5.00	–3.10	–4.40
7	5.00	–17.10	–17.80	–34.90
8	38.60	16.70	7.50	–3.60
9	0.70	–21.30	–22.20	–43.50
10	37.90	22.20	16.40	–3.70
11	3.80	–14.10	–14.50	–28.60
12	51.50	31.50	23.80	–2.30
13	0.00	–17.60	–19.80	–37.30
14	2.70	–14.30	–14.40	–28.70
15	2.80	–11.10	–11.10	–22.30
16	8.50	–1.40	–1.60	–3.10
17	17.30	9.80	7.50	–1.00
18	1.10	–6.40	–6.50	–12.90
19	27.00	21.50	19.50	0.30
20	23.00	17.80	12.10	–4.20
21	9.00	5.90	5.10	–1.20

SP – rainfall; SAE – actual evapotranspiration; STF – total runoff; DGWR – change in subsurface storage, i.e. soil water

The very small differences (*DIF*) are due to the fact that all balance components are calculated independently by the model, without forcing the balance processes to close at the end of each day. However, these imbalances, with values lower than 1.0%, which are usually observed for the entire vegetation periods, indicate that the parameterization of the model is satisfactory.

The sum of the imbalances (i.e. the differences) is then expressed by:

$$SDIF = \sum_{i=1}^{N} DIF_i \quad (5)$$

where:

SDIF – total difference between the left and the right balance equation for the annual growing period (mm)

DIF_i – difference between the decadal left and right balance equation in a decade *i* (mm).

These differences can also be expressed as a percentage.

The difference in the water balance equation for the Radovesice dump catchment in 2003 is *SDIF* = 0.90 mm (0.37%), and for the Loket dump catchment the difference is *SDIF* = –0.27 mm (–0.05%).

The rainfalls are by 23% higher on the Loket dump catchment area than on the Radovesice catchment (Table 5). For this reason, other major water balance components are also considerably higher there. Other components of the water balance are therefore hardly able to improve the water regime on the Radovesice catchment. Biotechnical measures are needed to improve retention and accumulation. This situation calls for more advanced "water harvesting" technologies. For example, a system of small reservoirs can be constructed, infiltration ditches can be managed, and other water regime improvement measures can be introduced.

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Table 5. Major component water balance differences between the Radovesice and Loket dump catchments in the dry period 2003 (1/4–31/10, 2003)

Water balance component	Radovesice catchment (mm)	Loket catchment (mm)
Rainfall (*SP*)	243.9	315.3
Total runoff (*STF*)	31.4	54.4
Actual evapotranspiration (*SAE*)	341.6	312.2
Difference in soil moisture (*ASM*)	–171.4	–116.5
Net groundwater recharge (*SNGWR*)	41.4	62.0

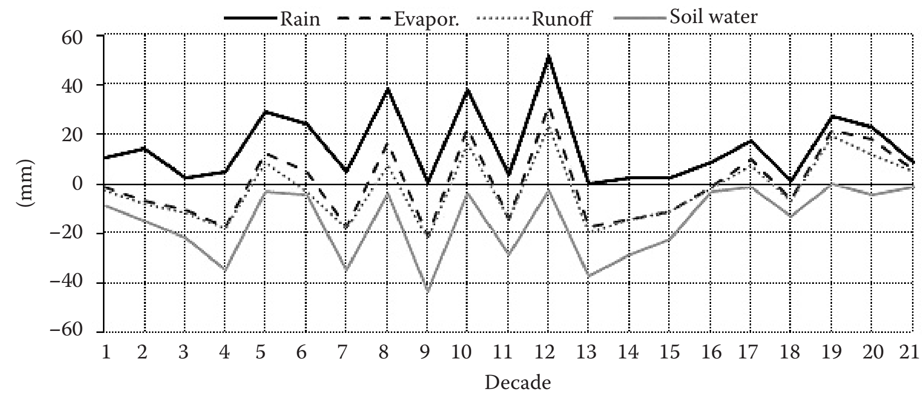

Figure 5. Deductible decade water balance graph of the Loket dump catchment in the growing season of 2003

DISCUSSION

The analysis of the water balance equation leads to the mass conservation equation, which can be derived from Eq. (1):

$$(ASM + GWR) = SP - STF - BF - SAE \quad (6)$$

All variables are understood to be functions of time, averaged over the whole catchment area (Kirchner 2009). According to Kirchner's analysis, Eq. (6) should take into account how its individual terms can be measured to find the degree of uncertainty of their values. The precipitation (*SP*) calculations are local, and are consequently loaded with the highest bias; the *SAE* data depend on the evapotranspiration method that is used. However, global radiation data and unsaturated soil moisture parameter measurements ensure reliability only when they are measured in areal transects that are reasonably well selected. The soil moisture dynamics (*ASM*) is then computed by data calculations. The direct runoff component (*SQ*) and the baseflow component (*BF*) cannot be calculated directly. Instead, we applied the measured groundwater tables. These values also depend on the selection of borehole sites. This problem was also described by Banks *et al.* (2011), who assessed the spatial and temporal connectivity between surface water and groundwater in a regional catchment. Implementation of soil moisture assimilation data was also described in a similar way by Han *et al.* (2012), who investigated how surface layer soil moisture data affect all hydrological processes at catchment scale.

CONCLUSIONS

The present study has compared the water balance in the growing seasons in a distinctly dry year (2003) with the water balance in two normal years (2004 and 2006). The water balance data were measured on the Radovesice and Loket dump catchments in the Krušné hory Mts. The hydrological balance was computed using the WBCM-6 model. The following innovations in water balance modelling were introduced:

– The climate data measurements and the data collection were done using state-of-the-art technology. Data from the CHMI meteorological stations at Bílina and Karlovy Vary equipped with an automatic measurement system were used. There was a charger connected to a solar panel. For the WBCM-6 model, the climate data was measured with a time step of 1 h.

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– Measurement of daily input climate data (by CHMI Ústí nad Labem: precipitation, air temperature, air humidity, solar radiation, daily duration of sun shine, wind speed) and soil hydrology (by the Faculty of Environmental Sciences, Czech University of Life Sciences Prague: soil moisture in a root zone, Curve Number (CN), water storage due to CN, initial soil moisture, average total porosity, average field capacity, assessment of the major parameters SMAX, GWM, and BK (as the starting values)).

This specific hydrological study provides background information for reclamation in an engineering system project planned for improving the water regimes in the area. Due to biotechnical measures a growing period, it has been given preference to study drought.

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