PARAMETER ESTIMATION OF HYDRO-RECULTIVATED MINING PITS USING WATER BALANCE MODEL[*]

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Restoration of pits, left after surface mining, by filling them with water in order to provide landscape improvement, recreation and often even irrigation opportunities is currently desired recultivation technology. This paper proposes a general solution for the water balance in man-made catchment areas created mostly by coal mining in deep depressions without any runoff. This paper briefly describes the project of hydro-recultivation, which involves the CSA mine situated on the boundary between the Most and Chomutov districts, in both the extreme years in terms of rainfall (dry and wet) and the average years. The water balance results simulated by the WBCM-5 model (Water Balance Conceptual Model) were used as basic data for finding the optimum open water level for damming up, with respect to the dry, i.e. not flooded, part of the catchment area, and then for determining the time required to fill the reservoir.

WBCM-5 model; time to fill the reservoir; extreme hydrological years

INTRODUCTION

In the 1990's the first projects of hydro-recultivated mining pits in the area of Chomutov-Most (Czech Republic) were conceived, where surface mining was carried out to a great extent in the past. Hydro-recultivation means filling up a mining pit with water for better landscape, fish breeding and recreation purposes. Studies were conducted at the Benedikt reservoir, Ležáky mine (both on the Most district), and also, more recently, at the largest mine pit called CSA (Czechoslovak Army Pit) on the border of the districts of Most and Chomutov (Fig. 1). The purpose of these projects was to find water balance of precipitation, runoff and evapo- transpiration. Subsequent computation has shown that external water inflow is necessary to fill in the space-capacity of huge mine pits. Hydrometeorological data was expected to be implemented through a water balance model simulating a water filling process. The purpose of this simulation was to determine daily and monthly values of water balance components in order to have an idea of how much time is needed for filling the pit. After the first computations it was evident that without external

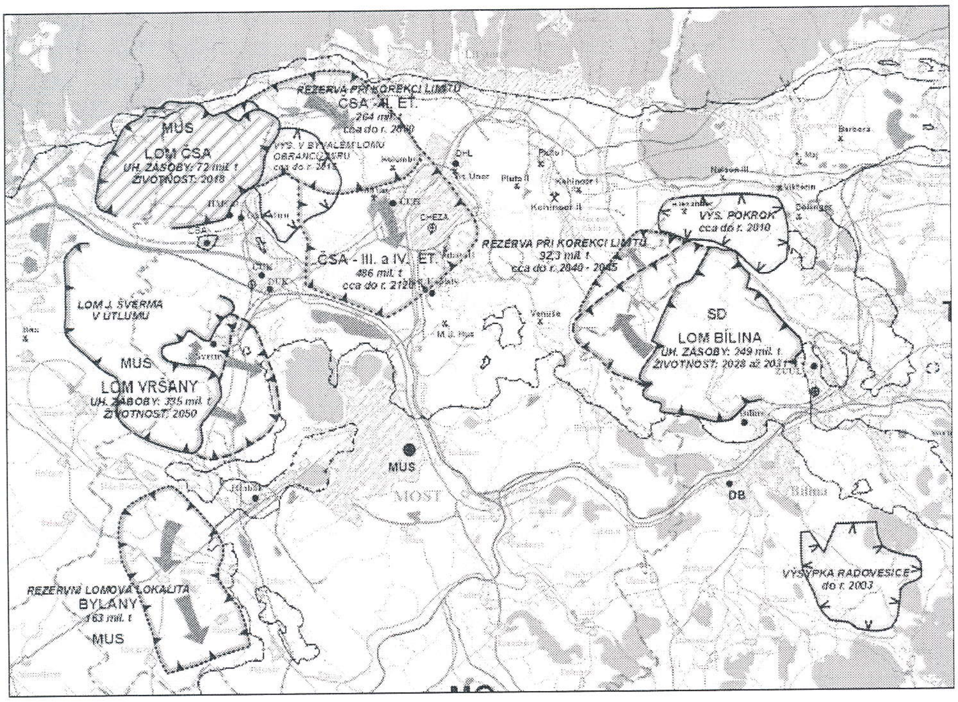

Fig. 1. Situation of significant surface mines in Northern Bohemia

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inflows from Krušné hory (Ore Mountains) brooks and also from the Bílina river a significant filling with water could never be achieved. The main purpose of this paper was to produce a feasibility study of the water balance model WBCM-5 (Water Balance Conceptual Model) for the natural hydrological balance, together with man-made water resources manipulations (Kovar, 2004).

MATERIAL AND METHODS

The catchments of the CSA pit have partly a former natural geography, however, their greater part has been formed by surface mining with slopes of natural stability creating an about 120 m deep pit with an almost flat bottom in an altitude elevation of 105 to 110 m a.s.l. The purpose of this study is to determine the water balance for three precipitation/temperature characteristic years – normal, wet and dry – with the final water level in the pit as high as 230 m a.s.l. that corresponds with the pits' upper banks. Consequently, for this computation it was necessary to collect data on deep seepage, formerly pumped out of the pit during surface coal mining, and also runoff data of four brooks that had been drained out by an artificial gallery before the mining started late in the 1950's.

Table 1. Land use in km^2 and adjoined CN-values (Curve Numbers)

CN	100	73	71	85		
Elevation (m a.s.l.)	Water area	Forest	Meadows	Urban areas	Dry area	Average CN of dry areas
110	0.15	20.45	4.00	1.50	25.95	73.4
140	2.33	18.27	4.00	1.50	23.77	73.4
170	5.85	14.75	4.00	1.50	20.25	73.5
205	10.91	9.69	4.00	1.50	15.19	73.7
230	14.21	6.39	4.00	1.50	11.89	73.8

Catchment

A detailed drawing of the water divide was done by land surveying, the catchments area was derived from a map in a ratio scale 1: 10 000. The catchments' characteristics were determined as follows:

- Total catchment area: $F_c = 53.1$ km^2
- Mining catchment area: $F_m = 26.1$ km^2
- Pit area F_p: 23.0 km^2 (to natural geomorphology)
- Highest geographical elevation: 753 m a.s.l.
- Lowest geographical elevation: 105 m a.s.l.

Table 2. Land use in dry areas in %

Elevation (m a.s.l.)	Forest	Meadows	Urbanized areas
110	78.8	15.4	5.8
140	76.9	16.8	6.3
205	63.8	26.3	9.9
230	53.7	33.6	12.6

- Average pit bank slopes: 5–10%

More detailed catchment physiographical characteristics are provided in Tables 1 and 2. The runoff curve numerical values were determined for individual land use from standard tables (Boonstra, Ritzema, 1994; Ponce, Hawkins, 1996), assuming the hydrological soil group "C" (U.S. SCS, 1986, 1992). As the water area changes with its depth, the dry area in the mining part of the catchment changes too, while their absolute area values remain unchanged.

Characteristic properties of earth material

Dumped earth material has a granular character, inner friction angle $\varphi \cong 30^{\circ}$. Deposited earth material has a minimum hydraulic conductivity close to day. Typical granulometric curves are described elsewhere (Kovář, Kuna, 1998). At the present stage the average CN values vary between 85 to 92, after fundamental agri-forestry recultivation the CN values for individual land use can be estimated as CN = 73 (forest), CN = 71 (meadows) and CN = 85 (urbanized area) (Table 1). The recultivation plan has been designed by Báňské projekty Teplice, Co. Ltd. and was used for the WBCM model parameter estimations (interception depth and root zone depth).

Hydrometeorological data

Daily data files have been recorded at the hydrometeorological station at Kopisty (CHMI Ústí n. L.) (Czech Hydrometeorological Institute) as follows:

- Daily precipitation (mm)
- Average daily temperature (°C)
- Sunshine duration (hrs)
- Average wind speed (m.s^{-1})
- Average relative, air humidity (%)

The daily data files were assessed for a period of 20 years (1975–1995) with selection of the following characteristic years:

- 1976 as dry year
- 1979 as normal year (average year)
- 1981 as wet year

Water resources data

The basic water resources information for water balance calculation is given in the form of bathygraphical

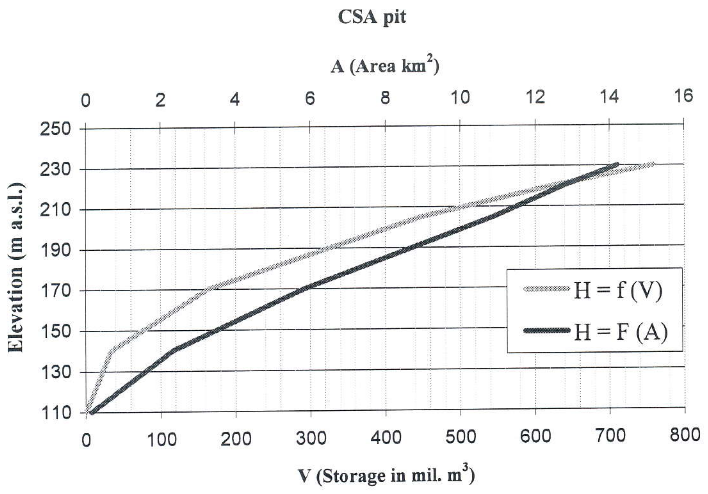

Fig. 2. Bathygraphical curves of the CSA pit

curves of the CSA pit (Fig. 2), as shown in Table 3. Average groundwater inflow volumes pumped from the pit are shown in Table 4.

Model WBCM

The WBCM model (version 5) that was implemented with the aim of quantifying the water balance on the CSA pit catchment 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 storages of interception, soil surface, root (or active) zone, the whole unsaturated zone and groundwater zone (if the latter is not very deep). The model takes into consideration the storage of individual zones and assesses 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 (Kovar, 2004, 2006):

- 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

Table 3. Bathygraphic ordinates of areas and volumes of the CSA pit

Elevation (m a.s.l.)	Area (km^2)	Volume (mil. m^3)	Ground water inflow (l/s)
110	0.15	0.528	25.0
140	2.33	33.977	25.0
170	5.85	162.815	22.0
205	10.91	448.238	15.5
220	12.76	623.773	13.0
230	14.21	758.179	11.0

The modified Monteith-Penman method, as well as the Priestley-Taylor method, or alternatively the Hamon method, were used for assessing daily values of potential evapotranspiration computation. The selection of one of these methods depended on input data availability. The model unit that computes actual interception and throughfall is based on the simulation of irregular distribution of local interception capacities around their mean value, WIC (WBCM model parameter). These capacities oscillate between zero (bare soil) and a multiple of WIC. To avoid an abrupt threshold concept, a linear distribution around the WIC-value was accepted.

For quantifying direct runoff recharge the US Soil Conservation Service (SCS) method based on Curve Number (CN) assessment was used. 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 active (root) and thus of all unsaturated zones depends greatly on the previous soil moisture content, and is controlled by a field capacity (FC) parameter.

Simultaneously, exhaustion from this zone by evapotranspiration was computed. In order to simulate this procedure, an approach was applied, which takes into account the proportion between actual and potential evapotranspiration according to the soil moisture contents and according to the particular physical properties of the soil.

The saturated zone is filled with groundwater recharge and depleted through base flow. This is simulated only within the framework of short-term groundwater participation in the water balance. The William's method (Tallaksen, van Lanen, 2004) was applied here. In cases where possible control of model efficiency can be achieved either through runoff or through ground water table fluctuations, automatic optimisation was applied. Three parameters were optimised by minimising the sum of least squared differences between the computed and

Table 4. Pumped volumes of deep ground water from CSA pit

Year	1993	1994	1995	1996	1997
Volume (m^3)	2 727 721	3 865 459	3 943 086	3 407 764	2 694 584

observed 10-day runoff depths on the experimental gauged catchments.

Thus, the water balance equation controls the volumes of the main components of the water balance (Lal, 2000):

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

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)

RESULTS AND DISCUSSION

Model based calculations of the hydrological balance were made for each damming from 105 m a.s.l. to 230 m a.s.l. with changes of water level in an interval of 5.0 m. In this paper cumulative tables were shown only for damming water in reservoirs of 110 m, 140 m, 170 m, 205 m and 230 m a.s.l. In this section of the calculation the WBCM-5 model was used for assessing evaporation from a free water surface E_v and evaporation from the terrestrial section of the catchment ("dryland") E_p. The total evapotranspiration (territorial evapotranspiration) thus amounts to:

$$E = E_v + E_p \quad (2)$$

The runoff section of the model is the solution of the runoff from the terrestrial section of the catchments O_P, which means the solution of the dynamics of surface runoff O_{PP}, and runoff from the saturated zone O_{PN}:

$$O_P = O_{PP} + O_{PN} \quad (3)$$

Expressed by the equation of hydrological balance this means:

$$\Delta W = P + O - E \quad (4)$$

where: ΔW – change in reservoir volume
P – precipitation
O – total runoff
E – territorial evapotranspiration

Water management balance

In contrast to hydrological balance, water management balance includes also components influenced by man-made activities, i.e. groundwater inflows caused by a morphological depression – mine waters O_{PD} (data supplied by BP Teplice a.s.) and external surface inflow (i.e. inflow of the brooks from the Krušné hory – Ore Mountains region) O_{PP} (data CHMU). Inflow of the Bílina river is not included. After modification the equation (3) will be:

$$O = O_{PP} + O_{PD} + O_{PT} \quad (5)$$

Table 5 comprises a section of the hydrological balance which does not include any external inflow. For full damming of the water surface to the maxima level of 230 m a.s.l. (water volume aprox. 760 million m^3) components of hydrological balance were calculated and furthermore external inflow from Krušné hory brooks were taken into account.

Figs 3 and 4 provide water balance of the characteristic years dry 1976 and wet 1981.

Table 5. Hydrological balance of the CSA mine watershed in characteristic years

Month	Hydrological components in characteristic years								
	Dry (1976)			Normal (1979)			Wet (1981)		
	P (mm)	E (mm)	O_P (mm)	P (mm)	E (mm)	O_P (mm)	P (mm)	E (mm)	O_P (mm)
1	63.1	23.7	11.2	19.8	8.6	3.0	41.9	13.1	9.2
2	6.7	15.8	1.3	27.9	10.0	7.4	14.0	17.9	1.7
3	13.7	29.2	2.2	27.3	23.7	4.8	45.8	36.9	10.8
4	17.4	39.6	1.9	30.0	37.6	4.3	30.3	42.9	4.7
5	24.4	55.1	1.7	17.5	62.7	1.9	53.6	65.2	10.4
6	16.6	55.3	2.8	67.4	65.3	13.4	14.9	62.5	2.0
7	17.3	45.6	0.4	39.9	4.7	5.2	20.1	51.4	21.3
8	61.3	37.3	6.2	40.8	36.5	5.3	57.3	46.4	14.8
9	18.7	20.9	0.9	74.3	26.2	11.4	59.9	27.3	7.5
10	27.5	13.4	3.0	14.8	15.0	2.1	92.6	26.7	11.0
11	23.1	12.3	1.3	45.6	14.1	4.8	40.8	24.2	5.0
12	7.4	6.9	0.4	45.4	9.1	5.1	37.4	9.8	5.5
Σ	297.2	355.1	33.3	450.7	357.5	68.7	608.6	24.3	103.9
ΔW = –24.6 mm			ΔW = 161.9 mm			ΔW = 288.2 mm			

Explanations: P – precipitation, ΔW – change of reservoir volume, O – total runoff level of damming – 230.0 m a.s.l., E – territorial evapotranspiration

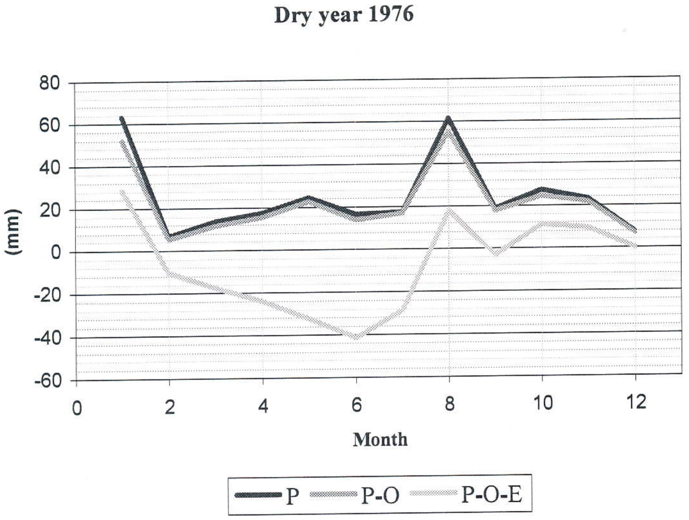

Fig. 3. Water balance – dry year 1976

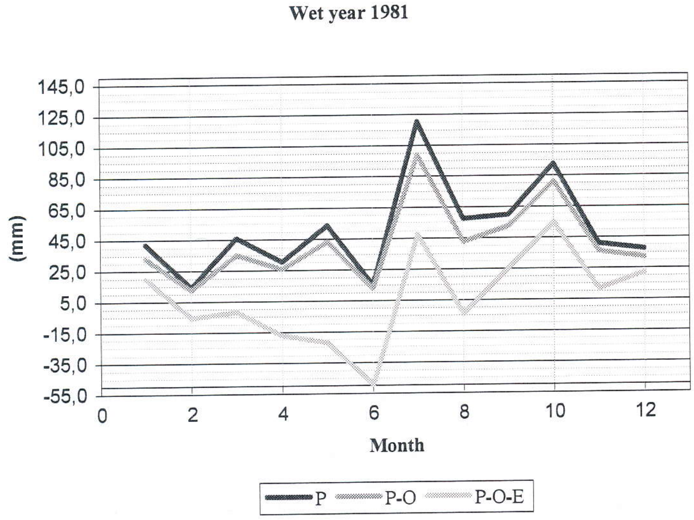

Fig. 4. Water balance – wet year 1981

In the initial study (Kovář, Kuna, 1998) selected catchments were chosen with regard to the present topographical situation, from which water could be diverted to the CSA quarry pit, on the condition of eliminating shifting brooks and cross connecting galleries. This concerns the river basins of the Kundratický, Vesnický, Šramnický and Černický brooks (in the case of Šramnický and Černický brooks the name changes to Albrechtický brook after their confluence). Furthermore, it would be possible to influx the quarry pit with waters drained by the Jiřetín brook, which at present is artificially diverted along the rim of the quarry. In Table 6 the area of each river basin and expected average yearly flow of water volumes is indicated.

It is necessary to mention here that the indicated values have been created from isolinear maps of average specific elementary runoff (TP 34, 1969). As the accuracy of this data is not very high, more precise and accurate measurements, or other calculation methods, should be implemented.

It should be noted that the revitalization of the mentioned four main small rivers would undoubtedly contribute to the revitalization of the region and bring it closer to the original state, yet with considerable investments involved. An average yearly volume of 7.1 million m^3 (after subtracting 10% of the necessary discharge) would be quite radical. Table 7 further describes the overall water management balance for maximum inflow of reservoir in an average (normal) year from own catchment sources.

On the basis of this data we may derive an idea on the time needed for filling the reservoir including the possibility of further inflow of water from Krušné hory (Ore Mountains) brooks and the river Bílina. The balance of precipitation corresponds to the normal year (1979), the balance of terrestrial evaporation of a dry year (1976). Thus we consider as likely, due to the fact that the comparison of the average temperatures in the years 1976–1996 indicates the normal precipitation year 1979 had an under average level of evaporation because the assessed data, needed for measuring daily evaporation, were under average (lower day temperatures, less sun hours, lower average wind speed, higher relative humidity). In fact 1976 should be an average evaporation year and therefore it has been used in the balance indicated in Table 7. From on analysis of water balance, accomplished with the model WBCM-5, it is also possible to assess the so called

Table 6. Characteristics of brooks in Krušné hory (Ore Mountains)

River basin	Surface (km^2)	Average specific elementary runoff (l.s^{-1}.km^{-2})	Average yearly discharge Q_r (l/s)	Average yearly runoff O_r (10^3. m^3)
Kundratický b.	4.77	7.5	36	1128
Vesnický b.	4.05	7.5	30	958
Albrechtický b.	16.38	7.5	123	3874
Jiřetínský b.	8.16	7.5	61	1930

Table 7. Water management of increment of the CSA mine watershed in an average year. Proposed year: 1979 (precipitation), 1976 (evaporation)
Annual sum of precipitation: 450.7 mm
Annual evaporation: 550.1 mm
Annual inflow from terrestrial part of river basin: 67.5–68.7 mm (according to damming level)

Level (m a.s.l.)	Water area (km^2)	Surface of terrestrial river basin (km^2)	Influents				Inflows total in (10^3.m^3)	Losses total E (10^3.m^3)	Variation in volume ΔW (10^3.m^3)
			P_v* (10^3.m^3)	O_P (10^3.m^3)	O_{PD} (10^3.m^3)	O_{PT}** (10^3.m^3)			
110	0.15	25.95	68	1752	788	–	2608	83	2525
140	2.33	23.77	1050	1604	788	–	3442	1282	2160
170	5.85	20.25	2637	1375	694	–	4706	3218	1488
205	10.91	15.19	4917	1044	489	–	6450	6002	448
220	12.76	13.34	5751	916	410	–	7077	7019	58
230	14.21	11.89	6404	817	238	–	7459	7817	–358

* P_v – precipitation on water surface
** Influx of rivers from Krušné hory (Ore Mountains) was not included: ($O_{PT} = 0$)
$O = O_P + O_{PD} + (O_{PT})$
$\Delta W = P_v + 0 - E$

"small" variation, wherein an inflow of waters from Krušné hory (Ore Mountains) brooks would bring an equilibrium of the water surface within levels varying from 200–205 m a.s.l. in 50 years. However, the situation requires to fill the reservoir up to 230 m a.s.l. as a watel level should reach the banks. Shortening of this time could be expected with the inflow of waters from the Ohře river, yet this would surely cause many landscape as well as ecological problems. A possible climate change that causes less water available might still worsen this situation (Pretel, 2006; Kabat, Schaik, 2003).

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Využití hydrologického modelu pro stanovení parametrů rekultivace zbytkových jam zatopením.

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Rekultivace zbytkových jam po těžbě uhlí zatopením vodou a jejich využití pro krajinotvorné, rekreační a mnohdy i hospodářské účely je v dnešní době běžnou a v rozumné míře i žádanou technologií. Příspěvek uvádí obecné řešení hydrologické bilance těžbou uměle vytvořených, antropogenizovaných povodí většinou v bezodtokových depresích. Vedle dřívějších studií hydrologické bilance umělých nádrží v lokalitách Ležáky a Benedikt na Mostecku byly zpracovány studie hydrorekultivace lomu ČSA na pomezí okresů Most a Chomutov vždy v letech srážkově extrémních (suchých a mokrých) i v letech průměrných. Účelem těchto studií (1999–2000) bylo určení hlavních složek hydrologické bilance na cílových kótách stálého udržení včetně bilance terestrické části povodí. Výsledky bilance simulované modelem WBCM-5 slouží jako podklad k nalezení optimální hladiny nadržení s ohledem na náročnost rekultivace nezatopené části povodí, dobu napouštění akumulačních prostor a potřeby externích vod pro nalepšení procesu napouštění nádrže. Z důvodu omezeného rozsahu je příspěvek zaměřen pouze na vodní bilanci lokality lomu ČSA.

Konkrétním úkolem studie byl výpočet hydrologické bilance nově vzniklého jezera v lokalitě povodí zbytkové jámy lomu ČSA. Povodí je dotvářeno výsypkami a z malé části též původním rostlým terénem, když po douhlení lomu se předpokládá vytváření jezera zprvu bezodtokového (během napouštění) a potom průtočného s využitím vnějších přítoků. Bylo tedy zapotřebí zjistit složky hydrologické bilance pro rok srážkově normální, suchý a mokrý a pro finální stav napuštění jámy na dílčí vodní stavy a finální stav až na cílovou kótu 230 m n. m. s ohledem na dobu, kdy může být tohoto stavu dosaženo. Návazně bylo zapotřebí vodohospodářské bilance se započtením hloubových průsaků měřených v minulosti a porovnaných s hodnotami ročně čerpaných objemů vody a také se zahrnutím průměrných odtoků z potoků stékajících z Krušných hor, kdyby připadalo v úvahu jejich zaústění do prostoru jámy lomu.

Modelové výpočty hydrologické bilance byly provedeny pro jednotlivé stavy nadržení od 105 m n. m. do 230 m n. m. při změnách kót v intervalu 5,0 m. V příspěvku jsou uvedeny souhrnné tabulky pouze pro kóty nadržení vody v nádrži: 110 m, 140 m, 170 m, 205 m a 230 m n. m. V této části výpočtu bylo použito modelu WBCM-5 pro řešení výparu z volné vodní hladiny E_V a výparu z terestrické části povodí („pevnina“) E_p.

Vodohospodářská bilance oproti bilanci hydrologické ještě navíc obsahuje komponenty ovlivněné antropickou činností, tj. přítoky podzemních vod vzniklé depresí morfologickou – důlní vody O_{PD} (údaje dodány BP Teplice, a.s.) a externí přítoky (tj. přítoky podkrušnohorských potoků) O_{PT} (údaje ČHMÚ). Dotace z řeky Bíliny počítána není.

Tab. 5 obsahuje část hydrologické bilance, která nezahrnuje žádný externí přítok. Pro plné nadržení vodní hladiny na maximální kótu 230 m n. m. (objem vody cca 760 mil m^3) byly vypočteny komponenty hydrologické bilance a dále byly zohledněny možnosti externí dotace vod z krušnohorských potoků.

V tab. 6 jsou přehledně uvedeny plochy jednotlivých povodí a předpokládané průměrné roční objemy vod, které jimi tečou. Zde je třeba podotknout, že uvedené hodnoty vycházejí z mapy izolinií průměrných specifických elementárních odtoků, jejich přesnost není vysoká a měly by být zpřesněny měřením nebo jinými výpočtovými metodami. Tab. 7 obsahuje celkovou vodohospodářskou bilanci pro maximální dotaci nádrže pro průměrný (normální) rok z vlastních zdrojů povodí. Z těchto údajů lze odvodit představu i o době plnění nádrže včetně nutnosti další dotace vod z krušnohorských potoků i z řeky Bíliny.

Z rozboru bilance, provedené modelem WBCM-5, je rovněž možné usuzovat na tzv. „malou“ variantu, kdyby se s dotací vod z krušnohorských potoků rovnovážná hladina ustálila v rozmezí kót 200–205 m n. m. za cca 50 let. Zkrácení této doby by pak bylo pravděpodobné účinnou dotací vod z řeky Ohře, což by jistě přineslo i řadu krajinářských a ekologických problémů.

model vodní bilance WBCM-5; doba napouštění zbytkových jam; vodohospodářská bilance; hydrologická bilance; extrémní hydrologické roky

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