USING A WATER BALANCE MODEL FOR HYDRO-RESTORATION OF MINING PITS*

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This paper presents results of water balance modelling in a catchment where a mining pit left after surface exploitation lies in a deep depression without runoff. The purpose was to determine all major water balance components, including those coming from the terrestrial part of the catchment and a possible supply of deep mining groundwater. The water balance was simulated by WBCM (Water Balance Conceptual Model). The results are used for finding adequate scenarios of pit filling, including the appropriate mixing of water coming from the local catchment and the acid deep mining water with surface water coming from a distant catchment. The paper is focused on the Medard mining pit in the Sokolov region (West Bohemia).

water balance; time to fill mining pits; extreme hydrological years

INTRODUCTION

The foothills of the Krušné Hory (Ore Mountains) on the western border of the Czech Republic has been for many decades negatively impacted by surface mining of brown coal. However, all mining companies must make provisions for restoration of the exploited territory, using proper techniques. This may imply restoration of agricultural land, reforesting, landscape remolding or so-called hydro-restoration, i.e. the filling abandoned mining pits with water and thus creating artificial lakes that can serve water accumulation, industrial and municipal purposes, recreation, sports and landscape improvement, including microclimate amelioration. The hydro-restoration becomes an increasingly important restoration measure. In this connection, the question of quantity and quality of water intended to fill the mining pits must be addressed. This water may come from local precipitation, shallow groundwater, deep mining groundwater or external catchments.

First mining pits hydro-restoration projects in the Ústí nad Labem and Karlovy Vary regions (Czech Republic) were conceived in the beginning of the 1990's. The sites to be restored were heavily modified by surface mining. Some artificial lakes have been successfully created in this way (Ležáky near Most, Michal near Sokolov, Milada near Chabařovice), while others are under construction at present and still others are planned to appear on the territories where brown coal is still being mined.

All such lakes have to meet the requirements of the EU Framework Directive (EU FD 2000/60/EC), as well as those of Czech legislation on water quality and environmental impact assessment, requiring, among other things, appropriate living conditions for fish and invertebrates to be created. Hence, hydro-restoration costs are usually higher than the costs of agricultural or forest land restoration. Generally, water scarcity and low quality of water available are among the most common problems encountered when mining pits are to be filled (Vlasák et al., 2009). In the past, the river network of the Krušné hory foothills, making left-side tributaries to the Ohře river, were not allowed to flow through the mining area but were diverted away to a safe distance from the mining works. These alterations, together with large-scale surface excavation, have drastically changed the landscape character. The naturally meandering river beds were abandoned and rivers became canals. Today, after closing down of many mining works, this river network deserves to be restored. This restoration, including the biotechnical measures for stabilization of slopes, the revetment of lake banks, the sealing of the lake bottom by clay layers and other expensive measures, must be implemented before water starts to fill the pit. These engineering measures obviously increase hydro-restoration costs. Moreover, water from external sources is expensive (Stiebitz, 2001). Specifically, the creation of the artificial lake Medard, fed prevailingly with water from the Ohře river, appears to be complicated and financially demanding. Without the external water supply, the project could hardly be implemented. A water balance computation, aimed at saving as much external water supply as possible, is therefore needed. The main purpose of this paper is to present a feasibility study of the use of WBCM (Water Balance Conceptual Model) for the natural hydrological balance of the pit being gradually filled, also allowing for man-made water resources manipulations (Kovář, 1981, 1997, 2006;

* Field studies, assessment and evaluation have been carried out within the research project NAZV QH 92091, financially supported by the Ministry of Agriculture of the Czech Republic.

K o v á ř , N o v o t n á , 2007). In this study, we attempt to quantify the contribution of the Medard-pit's own catchment and to calculate how much water will be needed to fill the pit from external sources.

MATERIAL AND METHODS

The task was to compute water balance using the WBCM model. All significant water balance components were computed on the basis of hydrological data in daily steps for the local catchment of the Medard pit, available for three characteristic years: 2001 (normal year), 2002 (wet year) and 2003 (dry year).

Catchment

The catchment of the Medard-Libík pit has partly preserved its former natural geography. However, a greater part of the area has been remolded by surface mining. The pit slopes are designed to preserve the natural stability of the soil. The pit is approximately 50 m deep and has an almost flat bottom. The final water level of the artificial lake will be situated at an altitude of 400.00 meters a.s.l. Fig. 1 presents a map of the mining pit.

A detailed identification of the water divide was done by land surveying. The catchment area of the Medard-Libík pit was then obtained from the ZABAGED map system at the scale 1:10 000. The catchment characteristics are as follows:

Total catchment area	$F_C = 14.6\ km^2$
Lake area (after filling)	$F_L = 4.9\ km^2$
Lake length	$L_L = 4.0\ km$
Lake width	$L_W = 1.5\ km$
Maximum depth	$D_M = 50\ m$
Water volume in the lake	$V = 120\ mil.\ m^3$
Bank line length	$B_L = 12.4\ km$
Planned water level elevation	$H = 400.0\ m\ a.s.l.$

The land use characteristics and the corresponding runoff curve number (*CN*) values are presented in Table 1. The *CN*-values for individual land use categories were taken from standard tables (J a n e č e k et al., 2002; P o n c e , H a w k i n s , 1996), assuming the prevailing hydrological soil group *"C"* (USDA SCS, 1985; USDA SCS, 1986). As the lake water area will change with the rise of water level, the lake water balance was computed for the present water level in 2010 (when the water depth is about one third of the expected final water depth), for the final water level and for several intermediate levels, while the dryland parameters (except for its area) remained unchanged. Fig. 2 presents the actual stage of the lake filling in 2010.

The major soil parameters were taken as varying within the following limits: Field capacity: $33\% < FC < 38\%$, total porosity: $42\% < P < 48\%$, saturated hydraulic conductivity: $0.03 < K_s < 0.08\ mm \cdot min^{-1}$.

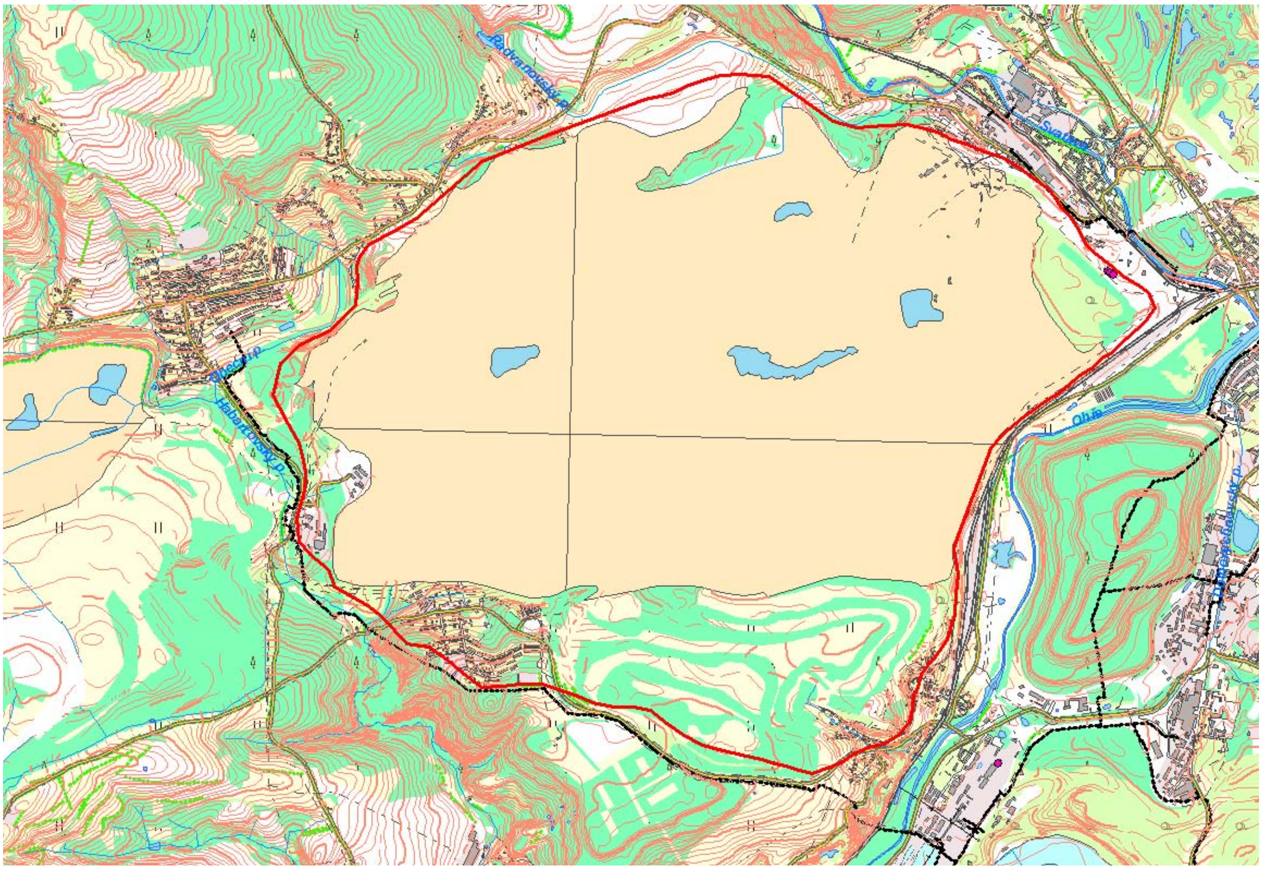

Fig. 1. Situation of the mining pit Medard-Libík

Fig. 2. Panoramic view of the Medard lake in the initial phase of its filling

Table 1. Land use and associated Curve Number (CN) values in the Medard lake catchment at different stages of filling

CN	100		85		73		71		CN weighted mean
Water table elevation	Water surface		Industrial and bare soil		Forest		Permanent grassland		
m a.s.l.	km^2	%	km^2	%	km^2	%	km^2	%	(–)
350	0.1	0.7	11.4	78.1	2.0	13.7	1.1	7.5	82.4
360	1.0	6.9	10.5	71.9	2.0	13.7	1.1	7.5	83.3
370	1.9	13.0	9.6	65.8	2.0	13.7	1.1	7.5	84.3
380	2.8	19.2	8.7	59.6	2.0	13.7	1.1	7.5	85.2
390	3.9	26.7	7.6	52.1	2.0	13.7	1.1	7.5	86.3
400	4.9	33.6	6.6	45.2	2.0	13.7	1.1	7.5	87.3

Climatological and hydrological data

The following daily weather data of three hydrological years (from 1/11 to 31/10), namely 2001 (normal year), 2002 (wet year) and 2003 (dry year) measured by the Czech Hydrometeorological Institute Plzeň (weather station Citice) were available:

- Precipitation (mm)
- Average air temperature (°C)
- Sunshine duration (hrs)
- Average relative air humidity (%)
- Average wind speed ($m \cdot s^{-1}$)

These data were used for daily potential evapotranspiration estimation (see below) and then for actual evapotranspiration estimation depending on the available soil moisture content resulting from the water balance model.

Basic hydrological data were provided by the Czech Hydrometeorological Institute (Plzeň). This data set was derived from measurement made at the Citice weather station during the period 1931–80. The data set included the minimum m-day discharges (Q_m), but not the maximum N-year discharges (Q_N). The most important catchment data are as follows: the annual average precipitation P = 610 mm, the long-term annual discharge $Q_a = 74 \text{ l} \cdot s^{-1}$ and the minimum discharge $Q_{min} = 8.5 \text{ l} \cdot s^{-1}$.

The water balance for the catchment reads (Lal, 2002):

$$SP = SAE + SOF + SBV + (ASM + GWR) \quad (1)$$

$$\text{or } SP = SAE + STF + \Delta W \quad (2)$$

where SP is the rainfall or snowmelt depth (mm), SAE is the actual evapotranspiration (mm), SOF is the direct runoff depth (mm), SBF is base flow depth (mm), ASM is the change in soil moisture content (mm) and GWR is the change in groundwater storage (mm). $SOF + SBF$ create together the total runoff depth STF (mm). Similarly, $ASM + GWR$ create the total change in subsurface water storage ΔW. The daily values of SP and SAE affect the other components. SOF depends on CN-values, while SBF, ASM and GWR values are governed by hydrological processes simulated by the model. The model parameters were set up according to field soil tests and known catchment parameters.

Water from precipitations is not the only water appearing in the pit. Additional water comes from the local mining drainage system (the pumping station Medard-Josef) where the previous pumping of mining water out of the pit was stopped on 1 July 2008. In 2009, the deep mining water from two neighboring pumping stations (Lomnice and Rafanda) was pumped into the Medard lake. The inflow of deep mining water does not only speed up the filling of the lake but, in particular, improves water quality in the lake, controlling the growth of algae by increasing water acidity. Table 2 presents the history of deep mining water inflow/outflow in the 2006–2009 period, wherein the outflow includes the former pumping out of the lake (stopped in 2008) and the inflow includes the pumping from external sources (Lomnice and Rafanda) and the Medard's local source (station Josef). Since June 2010 it has become technically possible to fill the lake from the Ohře river through a hydraulic intake. However,

Table 2. Recent history of mining water inflow/outflow (in 10^3 m^3)

Year	Inflow of mining water to the lake	Outflow of mining water from the pit	Water volume
in the lake			
2006	–	6 531	–
2007	–	6 478	–
2008	81	2 834	3 200
2009	161 + (1 728)*	–	10 072

* inflow of mining water from the external pumping stations Lomnice and Rafanda

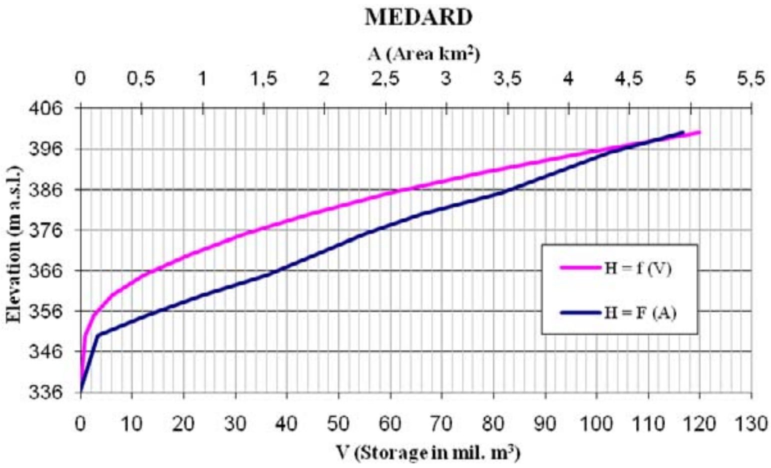

Fig. 3. Bathygraphic curves on the Medard lake

at the moment of writing this paper, it is only the subsurface river bank infiltration water from this river that is reaching the lake. The bank infiltration capacity is not high. The delay in opening the intake is caused by the necessity of improvement works being undertaken on the banks of the lake.

The pit geomorphology was surveyed, which resulted in the bathygraphic curves relating the volume, area and depth of the lake (Fig. 3).

Model

The WBCM model (Water Balance Conceptual Model, Kulhavý, Kovář, 2000; Kovář, 2006) is a lumped model with either linear or non-linear probability distribution over the catchment area (Bultot, Dupriez, 1976). It is based on the integrated storage approach, assuming that each storage element of the model represents the cumulative storage capacity (of a particular reservoir) for the entire catchment. Individual storage elements simulate the effects of interception, soil surface storage, root zone (or active zone), the whole unsaturated zone and the groundwater zone (if the latter is not very deep). The model was developed for simulation of water balance in daily steps. Relevant interactions between the zones listed above are taken into account.

The model considers the actual storage depths in individual zones and assesses their daily values and the corresponding input and output rates in accordance with the underlying physical principles. Mathematically, the simulation consists in solving recurrently a system of finite difference equations, together with algebraic equations balancing the partial processes (Kulhavý, Kovář, 2000). The processes modeled include:

- Potential evapotranspiration, interception and throughfall,
- Snow melting,
- Surface runoff and infiltration,
- Active soil moisture zone dynamics,
- Soil moisture content and actual evapotranspiration,
- Groundwater dynamics, base flow and total runoff.

There are 13 parameters in the WBCM model:

AREA – the catchment area (km^2),
FC – the parameter characterizing the "average" value of the root zone field capacity (–),
POR – the parameter characterizing the average value of the root zone soil porosity (–),
DROT – the root zone depth (mm),
WIC – the upper limit of the interception capacity (mm),
SMAX – the parameter representing the maximum capacity of the unsaturated zone (mm),
ALPHA – the parameter expressing the non-linear filling procedure of the unsaturated zone (–),
CN – runoff curve number (–),
P1, P2, P7 – the parameters affecting the unsaturated zone dynamics, namely, its filling *(P2)* and exhausting *(P1* and *P7)* (–),
GWM – the parameter expressing the maximum active capacity of the saturated zone in the neighborhood of the water stream (mm),
BK – the parameter transforming groundwater recharge into base flow (day).

Three of them, *SMAX*, *GWM* and *BK* are normally supposed to be calibrated within the reconstruction, when observed runoff data are available. However, they were not calibrated in our case and their values were set up according to maps, field measurements and authors' experience from similar terrotories. The reason was that no runoff measurement was available (no stream network has developed around the pit. Therefore, the CN method (USDA SCS, 1986; Janeček et al., 2002) was implemented to identify direct runoff. The saturated hydraulic conductivity K_s and the sorptivity *So* were measured along two characteristic transects. Their values were then used for the assessment of CN values and *SMAX* and *GWM*. The modified Penman–Monteith method (Penman, 1948; Monteith, 1965) was used for computing free water evaporation from the lake as well as the potential evapotranspiration from the terrestrial part of the catchment. In winter, when the daily values of air temperature were negative and the daily precipitation was positive, the precipitation was regarded as snowfall. A simple degree-day snowmelt method was used (Maidment, 1993). A linear distribution of local interception capacities over the catchment area was assumed, which resulted in a catchment-wide estimate of the actual interception and throughfall. The WBCM model uses the US Soil Conservation Service method, based on the runoff curve number (*CN*) assessment, to quantify the surface runoff (USDA SCS, 1986; Hjelmfelt, 1991) The model also assumes that both the recharge of the active zone and its depletion depend, in addition to the atmospheric boundary condition, on the soil parameters (field capacity, porosity, hydraulic conductivity) and on the previous soil moisture content, being principally controlled by the field capacity parameter. The finite-difference form of the one-dimensional Richards equation is used to model these processes (Kulhavý, Kovář, 2000). The depletion of the root zone storage by actual evapotranspiration is modelled as the appropriate fraction of the potential evapotranspiration, depending on the soil moisture content related to physical properties of the particular soil (Greenwood et al., 2009). The saturated zone is assumed to fill via the groundwater recharge and to get depleted via the base flow (groundwater runoff) only. The water balance equation (1) for the catchment is used as a check of the model.

RESULTS AND DISCUSSION

WBCM model computations were made for six major lake water levels and their corresponding lake volumes starting from 359 m a.s.l. at 10 m steps up to 400 m a.s.l.

Hydrological balance

The WBCM model was used for assessing evaporation from free water surface, SAE_W, and actual evapotranspiration from the dryland part of the catchment, SAE_T. The total actual territorial evapotranspiration *SAE* thus amounted to:

$$SAE = SAE_W + SAE_T \tag{3}$$

The runoff section of the model estimates the total runoff *STF* from the dryland part of the catchment as a sum of the direct runoff *SOF* and the base flow from the saturated zone, *SBF*:

$$STF = SOF + SBF \tag{4}$$

The hydrological balance of the lake volume *DW* is then:

$$DW = SP(L) + STF - SAE_W \tag{5}$$

where *SP*(*L*) is the part of precipitation reaching water level in the lake. The overall annual hydrological balance of the catchment for characteristic hydrological years is provided in Table 3, with major hydrological balance components printed in bold. This table provides evidence that in all tested years the hydrological balance is positive, whereas even in the dry year the sum of losses (the actual evapotranspiration plus the total runoff) is less than the precipitation. This fact is a prerequisite for sustainable hydro-restoration of old mining pits. On the other hand, it is difficult to distinguish between the unsaturated and the saturated subsurface zones of the catchment because groundwater table measurements are either missing or highly non-representative (because of disturbed soil layers due to huge earth transportation during coal mining).

Water management balance

In addition to the hydrological balance discussed above, the water management balance also includes com-

Table 3. Annual hydrological balance of the Medard lake catchment for characteristic hydrological years 2001 (normal), 2002 (wet) and 2003 (dry)

Component of hydrological balance	2001 (mm)	2002 (mm)	2003 (mm)
Precipitation (SP)	**565.6**	**692.0**	**529.1**
Surface runoff (SOF)	26.4	62.4	88.6
Subsurface runoff (BF)	26.7	32.7	22.0
Total runoff (STF)	**53.1**	**95.1**	**110.6**
Potential evapotranspiration (SPE)	390.3	408.0	430.6
Actual evapotranspiration (SAE)	**349.3**	**365.8**	**344.3**
Total change in subsurface water (ΔW)	**166.7**	**231.7**	**74.5**
Balance error (ER) in mm	–3.58	–0.59	–0.27
Balance error (ER) in % precipitation	–0.63%	–0.08%	–0.05%

Table 4. Annual water management balance of the Medard lake under normal year (2001) conditions at different stages of filling

Lake water level	Lake water surface area	Dryland catchment area	Annual inflow from the local catchment		Annual losses	Annual volume increment due to local inflow	Annual volume increment due to external inflow			Other indicators	
			$SP(L)$	STF	SAE_W	DW	$I_M - O_M$	O_S	O_I	$DW+I_M-O_M+O_S$	V
			precipitation	total runoff	[1] water evaporation	equation (5)	mining water	[2] seepage water	direct surface inflow from the Ohře	local and spontaneous inflow	lake water volume
m a.s.l.	km^2	km^2	10^3 m^3	10^3 m^3	10^3 m^3	10^3 m^3	10^3 m^3	10^3 m^3	10^3 m^3	10^3 m^3	10^3 m^3
350.00	0.13	14.50	73.5	770.0	50.7	792.8	[3] 142.1	1 800.0	[5] –	2 734.9	827.0
360.00	1.00	13.60	565.6	722.0	390.3	897.3	[3]+[4] 3 440.3	1 545.1	[5] –	5 882.7	6 101.0
370.00	1.90	12.70	1 074.6	674.4	741.6	1 007.4	[3] 52.0	1 030.1	12 717.6	2 089.5	20 985.0
380.00	2.80	11.80	1 583.7	626.6	1 092.8	1 117.5	[3] 101.6	515.1	21 394.0	17 34.2	44 229.0
390.00	3.90	10.70	2 205.8	568.2	1 522.2	1 251.8	[3] 160.1	257.5	33 800.7	1 669.4	79 858.0
400.00	4.90	9.70	2 771.4	515.1	1 912.5	1 374	[3] 181.1	128.0	38 109.0	1 683.1	119 851.0

Explanations:
[1] water evaporation is taken equal to potential evapotranspiration
[2] seepage amounts were derived from 2010 measurements and are assumed to depend linearly on the river-lake water level difference
[3] expected mining water pumping from the Josef station
[4] deep mining water volume from the pumping stations Lomnice and Rafanda in 2009 and 2010 taken together (pumping ended in 7/2010)
[5] no direct inflow via the intake because of bank improvement works, as in 2009–2010

ponents brought about by human activities, i.e. the deep mine water outflow O_M (stopped on 1 July 2008) or inflow I_M, the subsurface inflow of seepage water from the Ohře river, O_S, and the planned direct surface inflow from the same river, O_I, via the hydraulic intake. All these external inflows can be added to the hydrological balance of the lake (5), giving the total increase in the lake volume INW as:

$$INW = DW - O_M + I_M + O_S + O_I \qquad (6)$$

Eq. 6 was used for calculation of the lake filling process. Table 4 shows the annual water management balance for a hydrologically normal year when, like in 2001, the annual precipitation was 565.6 mm, the annual evaporation was 349.3 mm and the total runoff was 53.1 mm. Individual rows show the balance for different stages of the filling. The actual lake volume in June 2010 was about 15 000 · 10^3 m^3 (with water level at 366 m a.s.l.). It is evident that the Medard's lake local catchment can hardly provide significant sources of water to fill the lake within a few years.

Therefore, external water supply is needed to speed up the filling. The direct inflow from the Ohře river through the operated hydraulic intake is the most substantial external source. The small inflow I_M regulates pH of lake water and thereby controls the phytoplankton growth. The seepage inflow O_S from the Ohře river is of minor importance and is assumed to diminish, due to the decrease of water level difference between the river and the lake. At present, the spontaneous seepage from the Ohře river channel (flowing along nearby) is continuously measured at monthly intervals. In July 2010 it was about 1 030 · 10^3 $m^3 \cdot year^{-1}$. When this value, reduced to one half (assuming a linearly decreasing process), is added, the time needed to fill the lake will be about 27 years. Altogether, about 13.7% (16.4 mil. m^3) of the future lake volume can be provided by the local and spontaneous sources (including the mining water and the seepage water), while the rest, i.e. 86.3% (103.5 mil. m^3) must be supplied by the direct inflow from the Ohře river.

It is matter of hydrobiological expertise to propose an optimum mixing rate between the surface Ohře river water and the acid mining water in order to control the quality of the water mixture. A corresponding inflow/outflow control mechanism should then be a part of the Medard lake performance regulations.

CONCLUSION

From the results, it is apparent that the WBCM model can be applied for hydrological balance simulation of mining pits catchments. Nevertheless, the water management balance evaluation in these catchments is necessary for assessment of components caused by human activities which can heavily influence the time of mining pits filling.

It is evident from the hydrological balance, that the Medard lake would be filled from its own sources of water within 20 to 40 years. Possible climate change effects that cause less water available may even worsen this situation. Filling the lake within about three years would require about 1.0 $m^3 \cdot s^{-1}$ of surface intake rate from the Ohře river (about 31.5 mil. m^3 annually). Even though the water quality tests would have to be made regularly to keep an eye on the mixing process, the shortening of the time of filling could be recommended in order to improve the landscape value and to open new opportunities for recreation. This shortening could be expected with the inflow of waters from the Ohře river, although this can surely cause many landscape as well as ecological problems.

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Received for publication on July 13, 2010
Accepted for publication on October 11, 2010

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Využití modelu hydrologické bilance pro vodohospodářskou rekultivaci zbytkových jam.

Scientia Agric. Bohem., *41*, 2010: 206–212.

Příspěvek uvádí výsledky modelování hydrologické bilance povrchovou těžbou devastovaných území zbytkových jam. Účelem příspěvku je metodika určení hlavních komponent této bilance včetně bilance terestrické části povodí a možného využití hlubokých důlních vod. Výsledky bilance simulované modelem WBCM slouží jako podklad pro rozhodnutí o vhodném scénáři plnění jámy a o míchání vlastní srážkové vody z povodí s důlní vodou a vodou z externích dotací. Příspěvek je zaměřen na lom Medard na Sokolovsku. Modelové výpočty hydrologické bilance jsou provedeny pro tři experimentální roky 2001 (normální rok), 2002 (mokrý rok) a 2003 (suchý rok). Po výpočtech hydrologické bilance bylo zjištěno, že voda z vlastního povodí nestačí pro naplnění zbytkové jámy Medard v přijatelném čase. Využití modelu WBCM bylo dále směrováno k řešení vodohospodářské bilance se započtením interních důlních vod, převodu externí důlní vody, průsaků z řeky Ohře a hlavně řízených odběrů z této řeky jako hlavního přítoku pro naplnění jezera Medard. Z vodohospodářské bilance pro rok 2001 je evidentní, že z vlastních zdrojů by se jezero plnilo asi 20 až 40 let, zatímco dotací z Ohře je možno tuto dobu podstatně zkrátit.

hydrologická a vodohospodářská bilance; doba napouštění zbytkových jam; extrémní hydrologické roky

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