Computing Hydrological Balance in the Medard Mining Pit With the Help of the Water Balance Conceptual Model (WBCM)

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Abstract

A positive water balance is the main prerequisite for successful hydro-reclamation of residual mining pits. Under the current conditions of climate change, long dry periods occur more frequently, which may have a negative impact on the water supply to fill the pit lakes. This study deals with the hydrological balance of the Medard mining pit, which has been computed with the help of the Water Balance Conceptual Model (WBCM). The purpose of this study is to test the feasibility of the WBCM model for water balance estimation in endorheic catchments. The water contribution of the Medard mining pit's own catchment was quantified, in order to determine if an external supply of water is necessary to fill the pit within several years. The outcomes of the study have shown that the internal water sources of the Medard catchment can hardly provide sufficient water supply, either during a normal, or during a dry hydrological year. Thus, an external water supply from the Ohre River is needed in addition to the water from the mining pits (the quality of the water from the mining pits must of course be carefully monitored). The WBCM-6 model can serve as a useful tool in hydro-reclamation of residual mining pits. However, the final performance regulations of pit lakes must be based on water management balance, including human-induced activities.

Introduction

The landscape of the Ore Mountains foothills (North Bohemian Brown Coal District, and Sokolov District) has been strongly modified by the excavation of brown coal. In the first half of the 20th century, the coal was mined mostly underground, whereas in the post WW2 period the share of opencast mining has dominated significantly. The extraction of brown coal through opencast mines has to a large extent modified the landscape in this part of the Czech Republic [1]. The practice of open-pit mining created residual pits, overburden or waste rock piles, and sometimes left tailings impoundments in the landscape [2]. The excavated pits are of various depths and sizes, but all require environmental reclamation. Pit lakes are formed by water which fills the open pit upon the completion of mining activities [3]. Such pits can be filled artificially, by flooding or by allowing the pit to fill naturally through hydrological processes, such as precipitation or ground water infiltration [4]. First mining pits hydro-reclamation projects in North Bohemian and Sokolov Brown Coal Districts were elaborated in the beginning of the 1990's. Some artificial lakes have been successfully created in this way (Lezaky near Most, Michal near Sokolov, etc.), while others are under construction at present (Medard near Sokolov), and still others are planned to appear on the territories where brown coal is still being mined [5,6]. The pit lakes can serve as water reservoirs for industrial or municipal use, for recreation, sports, landscape-planning end ecological purposes. However, both the quantity and quality of the water meant for filling the pit must be assessed, in order to determine if the water available from the own catchment is sufficient and of good quality, or if external water supply is necessary. Hydrological modelling provides a useful tool for assessing the character of water balance in a catchment. In order to compute water balance rainfall-runoff, various models are applied e.g. HBV [7] WBCM [8,9], SWAT [10,11] etc. Simulated components of water balance are used as basic data, when deciding if water from the pit catchment, including deep mine waters, usually acid, should be supplemented by external deliveries, usually surface water from neighbouring catchments. In other words, the hydrological balance computation provides essential data for water management balance, which includes human-induced activities. Water balance models can also be used to calculate the time to fill the lake.

In this study, the WBCM (Water Balance Conceptual Model, Kulhavy and Kovar [8]; Kovar et al. [10]) was used to test its suitability for a simulation of rainfall-runoff processes in an endorheic (closed) catchment of the Medard mining pit. The main purpose was to evaluate the water balance, firstly in a normal hydrological year 2001. Next, the water balance was computed also for a dry hydrological year 2003, as water supply problems resulting from annual and seasonal low-flow regimes tended to occur more frequently in the past years [12-14]. This may have a crucial impact on the time period necessary for filling the pit, as well as on water quality. The study attempted to quantify the contribution of the Medard pit's own catchment, and subsequently to determine if an external supply of water from the Ohre River flowing nearby (along the southern border of the catchment) is necessary.

Materials and Methods

Description of the site

The catchment of the Medard pit is situated in the Sokolov region of Western Bohemia (Czech Republic), between the towns of Sokolov, Svatava and Habartov (Figure 1). Most of the area has been impacted by open-cast mining of brown coal. The characteristics of the studied catchment in an individual continuous ident section, such as: total catchment area = 14.6 km², lake area (after filling) = 4.9 km², lake length = 4.0 km, lake width = 1.5 km, lake maximum depth = 50 m, lake total volume = 120 milli. m³, bank line length = 12.4 km, planned water level elevation = 400.0 m a. s. l. The water divide was identified by land surveying and the area of the catchment was read from the ZABAGED map system at scale 1:10 000. Hydrological and climate data of the catchment were provided by the Czech Hydrometeorological Institute: annual average precipitation amount = 610 mm, annual

discharge at the gauging station of Citice on the Ohre River (flowing south to the catchment) = 74 l. s^{-1}, minimum M-day discharge = 8.51 l. s^{-1}. The land use characteristics and corresponding runoff curve numbers CN are provided in Table 1. The CN-values for individual land use categories were obtained from standard tables [15,16], which describe the prevailing hydrological soil group as belonging to category "C" [17]. Climate data (in daily step) of precipitation (mm), average air temperature (°C), sunshine duration (h), average relative air humidity (%), global radiation (J.m^{-2}) and average wind speed (m.s^{-1}) were used as input data for the WBCM-6 model in order to estimate daily potential evapotranspiration and subsequently determine actual evapotranspiration, with reference to the available soil moisture content.

The hydrological balance of a particular area in a given time period (in mm) is described by Eq. 1 to Eq. 3:

$$SP = SAE + STF + \Delta W \tag{1}$$

$$\Delta W = ASM + GWR - SBF \tag{2}$$

$$STF = SOF + SBF \tag{3}$$

where SP is rainfall, SAE is actual evapotranspiration, STF is total runoff, ASM is the change of soil moisture content, and GWR is the groundwater recharge. ASM and GWR create together the total change in subsurface water storage ΔW. SBF is base flow and SOF is a direct runoff. SP and SAE are the driving factors influencing the other components of the hydrological balance. The direct runoff SOF depends on CN values. Baseflow from the saturated zone SBF, ASM and GWR counting together ΔW which is the difference between the beginning and the end of hydrological balance period. These three components are determined by the hydrological processes which are simulated by the WBCM-6 model. The parameters of the model are based on soil characteristics and catchment parameters, determined during field tests. A survey of the geomorphology of the residual pit provided the bathygraphic curves relating the lake water volume V, water surface area A and water level elevation H (Figure 2).

The WBCM-6 model

The WBCM-6 model [6] was used in order to quantify the water balance in the Medard catchment. The WBCM-6 is a conceptual model, and it is based on an integrated storage approach. Each storage element represents natural storages of interception, soil surface runoff, root zone, the entire unsaturated zone, and the ground water zone in its active part. The model takes the storage of individual zones in to account, assesses their daily values, including input and output rates, in line with physical regularities, as reflected by the system of recursive finite deference and algebraic equations balancing the following processes: potential evapotranspiration, interception and through fall, surface runoff recharge, active soil moisture zone dynamics, groundwater dynamics, base flow and total runoff. The individual parameters of the WBCM-6 model provides Table 2 and they have the following physical meaning [6]. The WBCM-6 model has 11 parameters and only three of them are to be optimised. Here are SMAX and GWM parameters that represent the maximum capacity of unsaturated (SMAX) and saturated (GWM) zones, resp., and BK is the transformation parameter of the baseflow process. Concerning soil parameters for the area, the average value of the Field capacity from six measurement was assessed 0.35 (-) and the Total porosity from 5 measurement was assessed 0.43 (-). Parameters P2 and P7 are based on particular soil retention
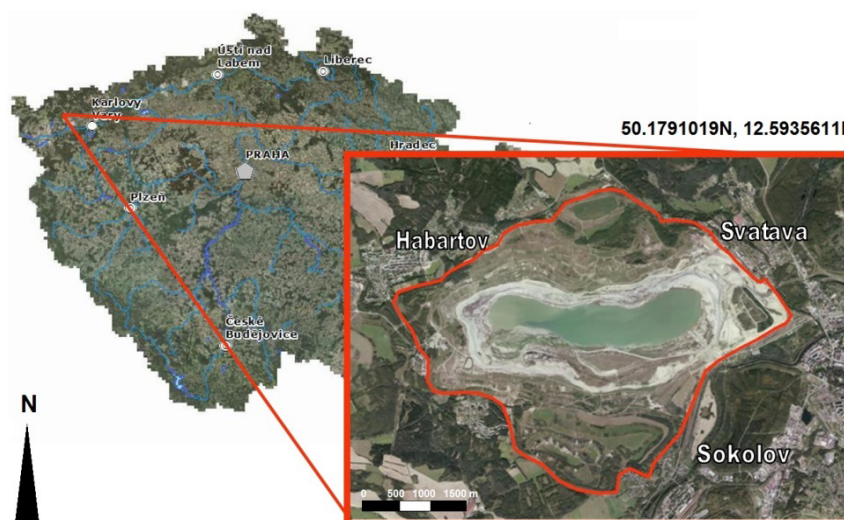

Figure 1: The catchment of the mining pit Medard.

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	84.9
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	52.0	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

Table 1: Curve Number (CN) values in the Medard catchment corresponding to land use at different stages of filling.
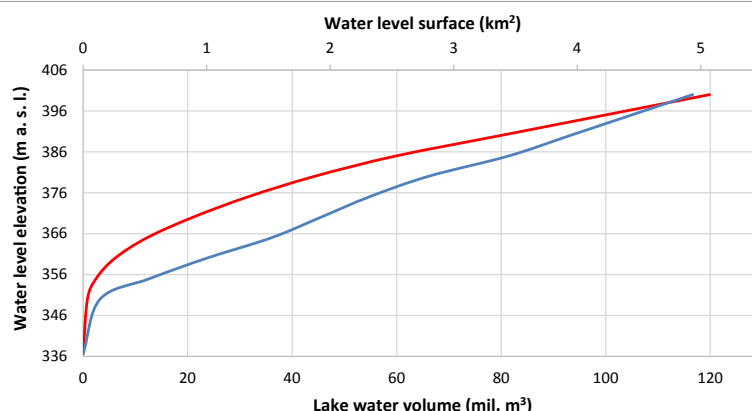
Figure 2: Lake Medard bathygraphic curves.

AREA	Catchment area (km²)
FC	Parameter characterising the average value of the field capacity of the active zone (–)
POR	Parameter characterising the average value of the soil porosity of the active zone
DROT	Depth of the active zone (mm)
WIC	Upper limit of interception capacity (mm)
SMAX	Parameter representing the maximum capacity of unsaturated zone (mm)
ALPHA	Parameter expressing non-linear filling procedure of the unsaturated zone (–)
CN	Runoff curve number (–)
P1, P2, P7	Parameters affecting unsaturated zone dynamics (filling and exhausting processes) (–)
GWM	Parameter expressing capacity of the active part of the ground water zone (mm)
BK	Linear transformation parameter of the base flow process (days)

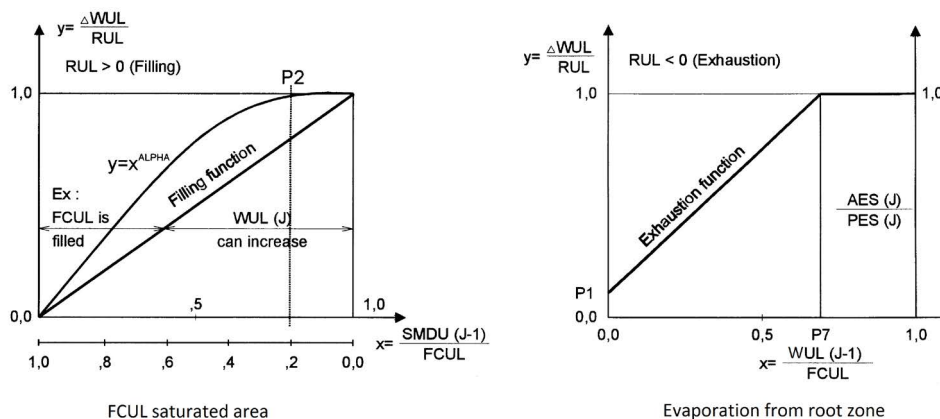**Table 2**: List of the WBCM-6 parameters and their physical meanings.

Figure 3: Filling and exhausting function in the WBCM-6 model.

curves: $P2 \cong 0.2$, $P7 \cong 0.7$ (loamy soils), 0.6 (for clayey soils) and 0.8 (for sandy soils). Parameter $P1 \cong 0.1$ describes very dry conditions through stomata transpiration. The model computations were implemented 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. The WBCM-6 model was used for assessing free water evaporation from (SAE_W), and actual evapotranspiration from the dryland part of the catchment SAE_T. The total actual terrestrial evapotranspiration SAE thus equals to the sum of these two components (Eq. 4).

$$SAE = SAE_W + SAE_T \qquad (4)$$

The hydrological balance of the lake volume DW is then expressed by Eq. 5:

$$DW = SP(L) + STF - SAE_W \qquad (5)$$

Where SP(L) refers to the part of the precipitation reaching the area of water level in the lake.

The modified Penman-Montheith method [18,19] and the Prisley-Taylor method [20] were used for computing daily potential evapotranspiration values. The model routine that computes the actual interception and through-fall is based on simulation of the irregular distribution of local interception capacities around their upper limit, WIC.

The USDA SCS [17] based on Curve Number (CN) assessment was used for quantifying direct runoff. The standard procedure for determining the initial CN value was accepted, and 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 to a large extent on previous soil moisture content and is verified by the field capacity (FC) parameters. Figure 3 provides a description of the filling function

principle, wherein rainfall input recharges the balance with a positive water surplus. The exhaustion function with negative input represents prevailing evapotranspiration in a daily step. This is applied for the root zone and also for the lower layer of unsaturated soil. There is also a possibility to substitute linear soil retention curves by a non-linear curve, introducing the parameter alpha (Figure 3). Figure 4 shows deep infiltration (i.e. percolation) and its dynamics through base flow and upward capillary flux for evaporation. The exhaustion of this zone by evapotranspiration is computed simultaneously. In order to simulate this procedure, the proportions between the actual evapotranspiration and the potential evapotranspiration, according to the soil moisture content and according to the particular physical properties of soil, were used. The saturated zone is filled with groundwater recharge and is depleted through base flow. Automatic optimization of the three significant parameters is applied where the efficiency of the model can be controlled through the water balance regime components.

The resulting equations are included in Appendix 1. The parameters SMAX, GWM and BK are optimized by minimizing the sum of the least squared differences between the computed decade and the observed decade (10 days) in the control profile.

Results and Discussion

The overall annual hydrological balance of the Medard mining pit computed by the WBCM-6 model for normal (2001) and dry (2003) characteristic hydrological years is described in Table 2. The main hydrological balance components, according to Equation 1, are highlighted in bold letters.

The decadal (10 days) water balance is shown graphically in Figures 5 and 6. The figures are arranged as graphs sequentially, step by step, subtracting the water balance components on the right side of the Equation 1, i.e. (1): SP, (2): SP – SAE, (3): SP – SAE – STF, (4): SP –
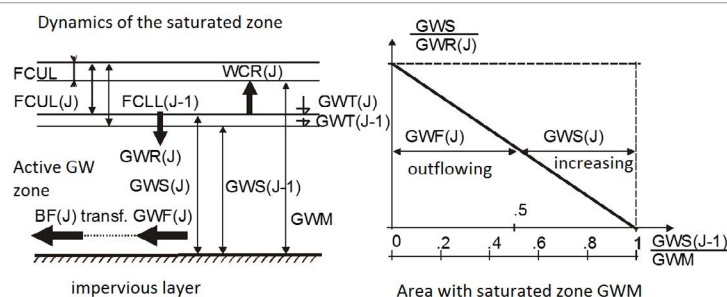

Figure 4: Dynamics of the saturated (groundwater) zone in the WBCM-6 model.

Figure 5: Hydrological balance of the Medard catchment for normal hydrological year (2001) computed by the WBCM model; (SP – precipitation, SAE – actual evapotranspiration, STF – total runoff, ΔW – subsurface water).
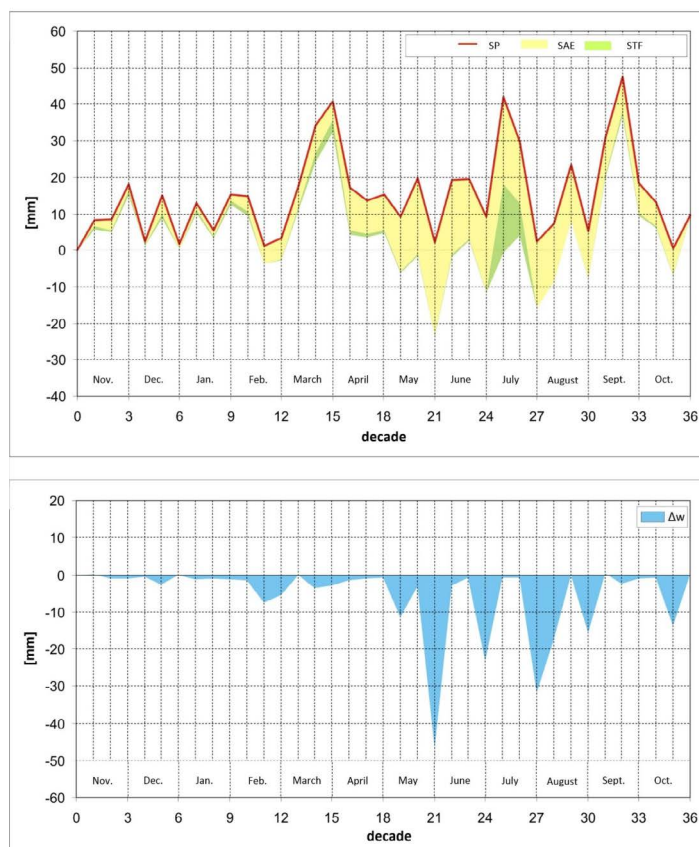
Figure 6: Hydrological balance of the Medard catchment for dry hydrological year (2003) computed by the WBCM model; (SP – precipitation, SAE – actual evapotranspiration, STF – total runoff, ΔW – subsurface water).
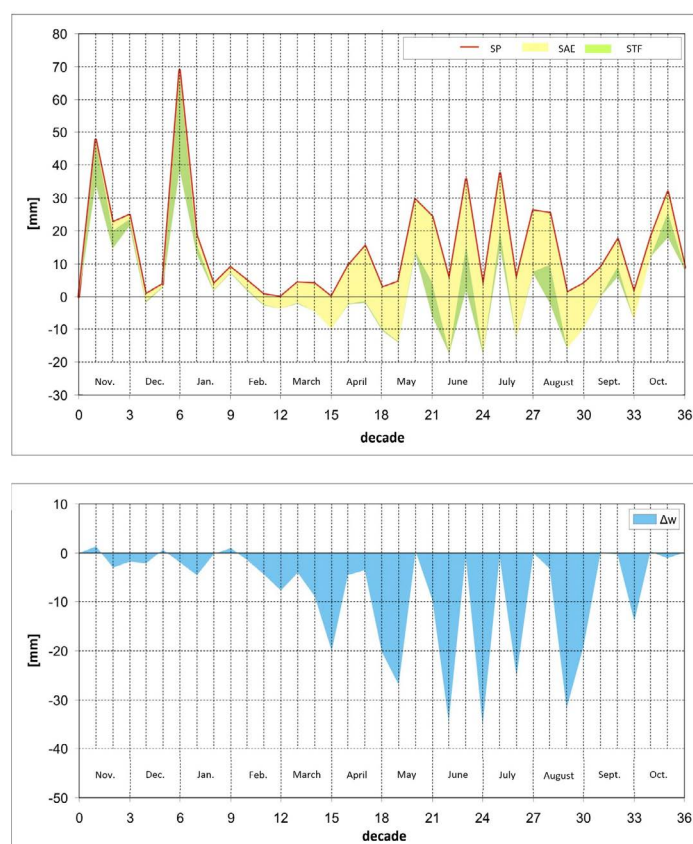
SAE – STF – ΔW. The symbol "–" means minus. The total change of subsurface water ΔW was drawn separately. Various components are shown in different colours. Precipitation is a broken line between vertical ordinates, while other components occupy areas in the graph and are subtracted in downward direction. If the actual evapotranspiration in a certain decade is less than the precipitation, it is placed in a negative area, below the horizontal zero axis. In Table 2, Figures 5 and 6 it can be seen, that the hydrological balance is positive for both normal (2001) and dry (2003) years, as the sum of losses (actual evapotranspiration SAE and total runoff STF) is less than the precipitation SP. Therefore, the elementary prerequisite for sustainable hydro-reclamation of the Medard mining pit has been confirmed.

Next, the question was set; whether external water supply is needed in order to fill the lake within several years. Table 3 compares bathygraphic lake volumes (Figure 2) with the volumes of water provided by the own Medard catchment and calculated by the WBCM-6 model for the normal year (2001). Evidently, the Medard catchment can hardly provide significant water source to fill the lake within a few years, even in a normal hydrological year. The situation in a dry hydrological year would be far more serious. A detail computation of the water management balance of the Medard catchment is provided by Kovar et al. [6]. In their study, authors estimated the time necessary to fill the lake (without any external water sources) to be 27 years. Thus, external water supply is necessary, if we want to accelerate the filling process. Since 2008 the filling has been supplemented by water from the local mining drainage system, when the pumping of mining water out of the Medard pit was stopped. In 2009, additional water from two neighbouring pumping stations (Lomnice and Rafanda) has been

redirected in to the Medard pit. Since 2010, external water supply from the Ohre River is available through a hydraulic intake. Both these water sources (mining and river water) may accelerate the filling process. However, their impact on water quality must be considered. The mining waters in this area are typical for their high acidity and metal contents concentration (i.e. Fe and Mn), making the lake resistant to eutrophication, but less suitable for common biota. The water pH value may be increased by mixing with the river water [21]. The intake of river water strongly depends on the minimimum M-day discharge values and the water quality, which can be by deteriorated by high concentration of sediments after heavy rainfalls or during dry periods. This fact must be taken into consideration, especially due to the endorheic character of the Medard mining pit. Once the water enters the lake, the only possibility of removing the highly eutrophicated water would be by pumping. This is hardly feasible in terms of cost and technology. To propose an optimum mixing rate between the surface water and the acid mining water in order to control the quality of the water mixture is an issue that must be dealt with through relevant hydrobiological expertise. A corresponding inflow/outflow mechanism should thus be a part of the Medard lake performance regulations [6] (Table 4).

The results of this study show that the WBCM-6 water balance model is suitable for the simulation of the hydrological balance of residual mining pits. However, human-induced acitivities must be included in order to calculate the water management balance, according to which the final pit lake catchment management should be run. Its hydrological balance shows, that the Medard Lake would be filled from its own water sources within more than 25 years. This horizon may even be longer due to climate change, which could bring

Component of the Hydrological Balance	2001 (mm)	2003 (mm)
Precipitation (SP)	565.6	529.1
Total runoff (STF)	53.1	110.6
Surface runoff (SOF)	26.4	88.6
Potential evapotranspiration (SPE)	390.3	430.6
Actual evapotranspiration (SAE)	349.3	344.3
Total change in subsurface water (ΔW)	166.7	74.5
Balance erros (ER) in mm	-3.58	-0.27
Balance erros (ER) in %	-0.63%	-0.05%

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

Water Level Elevation	Water Surface Area	Water Volume According To The Bathygraphy	Annual Water Volume Provided By The Catchment Dw*
(m a. s. l.)	(km^2)	(10^3, m^3)	(10^3, m^3)
336.56	0	0	0
350	0.13	827	793
360	1	6, 101	897
370	1.9	20, 985	1, 007
380	2.8	44, 229	1, 118
390	3.9	79, 858	1, 252
400	4.9	119, 851	1, 374
*Equation 4			

Table 4: Comparison of the Medard mining pit bathygraphic volume and the annual water volume increase due to the local inflow.

dry periods [12,13]. Therefore, an external water supply, the quality of which would be carefully monitored, is necessary to accelerate the filling process. Faster filling would contribute to faster reclamation of the disturbed landscape of the Medard catchment. This would increase the value of the surrounding landscape in terms of its productivity, ecological stability and sustainability.

The analysis of the water balance equation leads to a mass conservation equation, which can be derived from equations (1) and (2):

$$(ASM + GWR) = SP – STF – SAE – BF \qquad (6)$$

According to the Kirchner analysis [22], (Eq. (6) should take into consideration the question of how its individual components can be measured in order to determine the degree of uncertainty of their values. Precipitations SP are local, and therefore loaded with the highest bias, due to their heterogeneous distribution in the catchment area. The SAE data depend on the applied evapotranspiration method. Potential evapotranspiration is often presented through an empirical method, described by the Hargreaves formula (e.g. Gunkel et al. [23]) in the Penman-Monteith method (e.g. Smiatek et al. [24]). These two methods do not provide the same results. The global radiation data and unsaturated soil moisture content parameters ensure reliability only in a small catchment area. The total runoff STF and base flow BF components cannot be calculated directly. This problem was mentioned by Banks et al. [25], in their description of spatial and temporal connectivity between surface water and groundwater in a regional catchment. Currently (2016), the water surface is approximately 7 meters below the final elevation of 400 m a. s. l. This information was provided by Sokolov Coal a. s. – the company which is in charge of mining and reclamation activities. The intake of river water through the hydraulic inlet had to be slowed down because of the quality of water in the Ohre River, which has been influenced by long dry periods followed by heavy rainfalls. Therefore, the end of the filling process has again been delayed. Fortunately, the landscape already started to fulfil its recreational and partly productive (agricultural) function, which allows us to assume that the main goal of reclamation is about to be reached in the near future.

Acknowledgements

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