Water balance of coal mines and its determination under the conditions of humid climate of Central Europe

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Abstract: Water balance of the mine is the basis of general assessment of deposit saturation. The problem of solving of the equation of water balance of a mine is a complicated series of unknowns or directly immeasurable values. Each value of the equation is considerably weighed with different determination error. In this paper there are some case studies of coal basins in the Czech Republic showing the methods of determination of mine water balance equation and methods of determination of some directly immeasurable parameters of this equation.

1 WATER BALANCE EQUATION OF A MINE

Water balance of mine is the basis of general assessment of deposit saturation. Hitherto hydrogeological assessment of mines is based on observation of discharges pumped to the surface. These values are mistakenly considered as "*mine inflows*".

The problems connected with the solution of the water balance equation of a mine are complicated by a variety of unknown or directly immeasurable values. The water balance equation has substantially more components than those obtained by geologists during assessment of hydrogeological conditions of a mine. Generally, the equation can be formulated in the following form /$m^{3}\cdot$ period^{-1}/:

$$\mathbf{Q_p = Q_{op} + Q_{en} - Q_v - Q_t \pm Q_l \pm Q_r}$$

where Q_p......amount of water pumped to the surface
Q_{op}.....amount of operational water put into a mine
Q_{en}.....amount of water recharged from rock environment $Q_{en}=Q_{in}+Q_{aq}$
where Q_{in}....amount of infiltrated water from precipitation
Q_{aq}....amount of water recharged from aquifers

Q_v........amount of water led off the mine by mine air
Q_t........amount of water transported out of the mine with coal production
Q_l........amount of water of unspecified losses and gains
Q_r........amount of water accumulated in or released from reserves (gob water)

Of the aforementioned components of the balance equation, only values of Q_p are observed in most cases and they are frequently presented as an equivalent of Q_{en}. To solve the equation - or, better to say, to approximate its values - we start from analogy of values obtained by a measurement of the balance equation components on selected localities of respective mining districts. In many cases, due to non-acquaintance or complete absence of data, it is necessary to accept certain simplifications. In particular, the equation parameters of Q_l and Q_r are unascertainable in a given time section and, therefore, it is necessary to eliminate them from the balance equation in most cases, or to consider them as time constants, i.e.:

$$\frac{\partial \mathbf{Q_l}}{\partial \mathbf{t}} = \mathbf{0} \qquad \text{or} \qquad \frac{\partial \mathbf{Q_r}}{\partial \mathbf{t}} = \mathbf{0}$$

The balance equation will then be in the following form:

$$\mathbf{Q_p = Q_{op} + Q_{en} - Q_v - Q_t}$$

The value of $\mathbf{Q_p}$ is usually the most common value determined by a hydrogeologist and often incorrectly serves as a value of "mine saturation". It is monitored either by flow meters installed on an outlet piping, or only by an orientation calculation based on pumped discharges.

To determine $\mathbf{Q_v}$, it is necessary to measure humidity of downcast and upcast air of a mine field. It has been established that the amount of mine water led off by mine air (i.e. the evaporation in mine workings) amounts to a substantial percentage of the total water balance of mine. It was proved in the mines of the Upper Silesian Coal Basin (Upper Carboniferous in paralic development of Variscides of the Bohemian massif) and, similarly, in the Lower Silesian Coal Basin. This is the most frequently neglected component of water balance of a mine and, consequently, causes its biggest error charge.

To determine the increment of humidity in mine air, it is necessary to measure the air humidity with a psychrometer by means of measuring the dry and wet air temperature (usually three times a day - at 7 a.m., 2 p.m. and 9 p.m.) and calculating the relative air humidity from the measured values. In the course of the year, the values of relative air humidity in humid climate of central Europe were as follows:

Table 1 Determination of water led off the mine by mine air.

Interval	average air temperature min. / aver. / max.			relative air humidity input			output	Q_v
	7 a.m.	2 p.m.	9 p.m.	7 a.m.	2 p.m.	9 p.m.	2 p.m.	m^3
I. - III.	-14 / -5 / 0,2	-8 / -1,6 / 4	-8 / -2,4 / 4	91%	90%	88%	95,1 %	19900
IV.- VI.	3 /13 /24	6 /18 / 28	2 /13 / 18	74 %	51 %	76 %	95,1%	18800
VII.- IX.	7 /10 / 14	13 /19 / 23	8 /14 / 17	86 %	55 %	83 %	95,6 %	17730
X.- XII.	-9 /2 / 4	-9 /6 / 11	-17 /2 / 9	84 %	70 %	71 %	95,4 %	21490

Note: air flow rate of mine is approx. 325 $m^3 \cdot s^{-1}$

The value of $\mathbf{Q_t}$ is to be calculated. Water content in mine run represents the amount of the so-called "*gross water*". Gross water is considered to be water contained in mine run as a result of technological processes (soaking, drilling etc.). This parameter can be determined in laboratory by weighing. The parameters of the so-called "*crude production*" (substance extracted to the surface) and "*sorted waste*" (part of production separated manually in sorting plant) were monitored on an experimental locality (Paskov Mine in the Upper Silesian Basin) in the course of the year; the percentual parameter of "*gross water*" was determined in laboratory. An example of an annual measurement is presented in the following table 2.

All those values depend, above all, on mine run grain size, and are, statistically, not significantly proportional to or directly dependent on secondary addition of operational water. The monthly values measured at the abovementioned monitored locality were relatively constant and ranged between 2.7 and 3.3%.

Table 2 Determination of water transported out of the mine with coal production

month	crude production	sorted waste rock	gross production	gross water		Q_t	Q_{op}	Q_p
	Tons / month			%	m^3/month			
I	1185525	16329	102203	3,2	3271	3066	23400	29700
II	111232	13196	98036	3,0	2941	2941	24800	31900
III	92094	10356	81738	3,2	2616	2452	22900	33400
IV	100314	11860	88454	3,7	3273	2654	25300	31900
V	84288	11610	72678	3,6	2616	2180	24800	33700
VI	90836	12296	78540	3,1	2435	2356	20100	34500
VII	83310	10323	72987	2,9	2117	2190	23800	35900
VIII	77367	9166	68201	3,3	2251	2048	22200	36700
IX	98014	10850	87164	3,4	2965	2615	20200	31400
X	126301	12534	113767	3,9	4437	3413	19900	30270
XI	106177	12654	93523	3,4	3180	2806	18400	30000
XII	82084	10505	71579	2,6	1861	2147	17900	27000

Determination of $\mathbf{Q_{op}}$ is, however, substantially more complicated. Unless flow meters are installed on piping, the exact value of Q_{prov} is usually quite unknown. To determine an orientational value, we used the method of hydrograph separation for pumped mine water. It was presupposed that during long periods without precipitation ($Q_{en} = 0$), mine water was dotted only by operational water put into mine and by inflows from aquifers (Q_{aq}). With respect to the fact that, under the conditions of the coal mines of both the Upper and Lower Silesian Basin, it was possible to select mine sections with negligible saturation of Carboniferous massif in exploitation depths, we could, in those experimental sections, take the simplification for determining Q_{aq} as zero. In the other parts of mine, the value of Q_{aq} was considered constant.

Under the conditions of the mines of the Upper Silesian Basin, we used hydrogeochemical methods to determine the value of $\mathbf{Q_{aq}}$. The methods are based on the processing of mixed samples of mine water by means of multiparametric analyses (agglomeration analysis, method of principal components, and fuzzy agglomeration). This objective method is very advanced and allows to determine the values of Q_{aq} with the accuracy of approximately 7% (Grmela, 1987, Grmela & Machek, 1990).

To separate the hydrograph it is suitable to use the Kille´s method (Fendekova et al., 1998). The calculation proceeds with minimum monthly values of pumped amounts in a long-term time series (10 to 20 years). The use of this method e.g. in Šverma Mine in Žacléř (Lower Silesian Basin) is shown in Figure 1.

To determine the average value of pumped amount without extremes of maximum inflow caused by the infiltration of precipitation into the mine, it is possible to proceed with the same method. As in the case of determination of the value of Q_{op}, we used the method hydrograph separation in such a way that mean monthly discharges in respective years were used in the calculation (Figure 2).

Having determined the values of Q_p, Q_{op}, Q_t and Q_v and a representative value of Q_{aq} by the methods described above, it is possible to determine the last unknown value of the water balance equation, i.e. $\mathbf{Q_{en}}$. It can be regressively inserted into the equation and calculated as:

$$\mathbf{Q_{en} = Q_p - Q_{op} + Q_v + Q_t}$$

It is represented mainly by water infiltrated from the surface into mine workings through secondary fissures. In most cases, the proportion of such water considerably decreases with exploitation depth. A dominant role is played mainly by rheological properties of rocks overlaying mine workings (including their thickness and sequence), structural-tectonic position of a developed part of deposit, character and thickness of covering formations, deposition depth and depth of mining activity. The table below (Table 3) shows examples of equation values ratio in the Heřmanice Mine in Ostrava (Upper Silesian Basin).

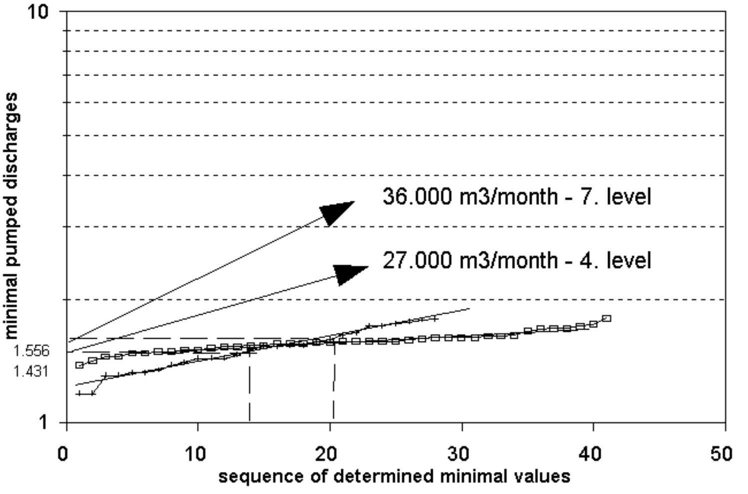

Figure 1 Mine Jan Sverma-Zaclér. Graph oh pumped discharges

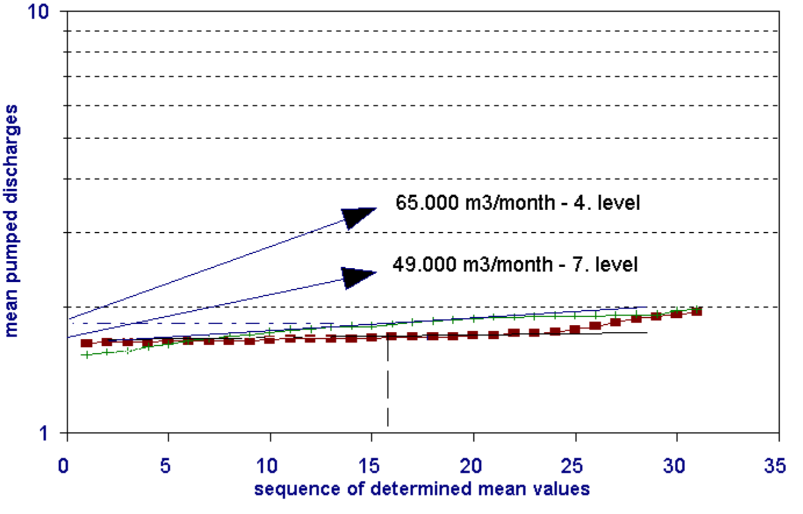

Figure 2 Mine Jan Sverma-Zaclér. Graph oh pumped discharges

Table 3 Determination of the main parameters of water balance equation - Heřmanice Mine

Depth level	Q_v	Q_{in}	Q_{aq}			Q_{op}	Q_p
	$l.s^{-1}$		Miocene base	Carboniferous mantle	Carboniferous		$l.s^{-1}$
Surface [2] (+211 m)	12,9						53,7
2.level (-54 m)		65 % [1]	---	35 %	---	---	
3.level (-180 m)		2 %	7 %	21 %	1 %	69 %	
4.level (-300 m)		---	10 %	32 %	6 %	52 %	
5.level (-450 m)		---	17 %	43 %	9 %	31 %	

Note: [1] strong correlation with precipitation course (retardation approx. 17 days) - infiltration in places of shallow stopes and in places of minimum Miocene cover.
[2] surface = total discharge led from all levels to the surface by ventilation.
Characteristics: total mine production: 0,7 – 0,9 mil. Tons/year, area: 20,72 km^2, average seam thickness: 1.05 m, aver. Annual worked-out space: 0,50 – 0,68 mil. m^3,production since 1940, precipitation approx. 740 mm / year

2 OVERVIEW OF SOME RESULTS FROM MINES OF THE UPPER AND LOWER SILESIAN BASIN IN THE CZECH REPUBLIC

Paskov Mine near Ostrava

The mine is situated in the Upper Silesian Basin on the Carboniferous crest. Quaternary sediments with intercalations of glacial gravel reach the thickness of approx. 3 to 15 m. Miocene cover is formed by weakly consolidated quasi-plastic clay representing an impervious rock (hydraulic conductivity $K< n*10^{-8}$ $m.s^{-1}$) overlaying the productive Carboniferous massif. Basal clastics (gravely sands) are preserved on the base of Miocene, which is deposited subhorizontally. The basal clastics (thickness ranging from 0 to 50 m) contain connate water (salinity about 40 g/l) with considerable proportion of dissolved CH_4. The water pressure in this aquifer reaches up to 4 MPa. The hydraulic conductivity ranges between $n*10^{-4}$ and 10^{-6} $m.s^{-1}$.

A strongly fractured and tectonically deformed debris of a Mesozoic sheet (psammits and aleuropelits of the Graz phase of Alpine orogenesis) is preserved between the Quaternary and Miocene covers. The thickness of this complex is approx. 50 - 125 m.

Seams of the thickness of 50 - 140 cm (with dip of strata between 5 and 20° - subhorizontal position is predominant) are developed in the Upper Carboniferous in cyclical paralic development. The number of completely extracted seams in profitable development (exploited downward in planarly strongly irregular geological bocks and sections) totalled 45. Carboniferous strata are not considerably folded, but they are frequently affected by normal and reverse faulting. Tectonic faults (with vertical throw being very frequent in the orders of $n*10^{-1}$ to $n*10^{1}$ m) are hydraulically insignificant. Nor do regional tectonic faults (with vertical throw ranging between 160 and 240 m) show increased saturation. The primary tectonic faulting is, with regard to the problem in question, important for the range and development velocity of secondary cut joints situated above exploited seams (directional longwall caving). They are - at higher height levels, contact places with saturated basal clastics of Miocene, and together with primary fissure systems - the cause of higher Q_{en} inflows into mine workings.

The mining area of this mine does not border with any other mine and, therefore, is not hydraulically influenced. It creates a separate hydrodynamic system with an artificial hydraulic depression 660 m below the surface (the surface = +251 m, 1st level = -150 m, the bottom 3rd level = -490 m below sea level).

Šverma Mine in Žacléř

The mine is situated in the Bohemian part of the Lower Silesian Basin of the Bohemian Massif (Upper Carboniferous in paralic development). Direct cover of Carboniferous is formed by Quaternary with thickness of the order of few ones to few tens of metres. Structural-tectonic conditions, seam thickness and petrographic types of rocks are similar to those at the Paskov Mine locality.

Mining activity has, in primarily impermeable Carboniferous rocks, created a hydraulically and hydrogeologically separate hydrodynamic system, which does not practically communicate with other systems in the area. It is a semi-confined hydrogeological structure, with presently closed water circulation caused by hydraulic gradient induced by secondary joints, fissures, mine workings and other priority ways. The depth range of the primary circulation is approx. 80 m below the surface.

The deposit lies under the level of a local drainage base, which lies on the +560 m level (1st level +481 m, 9th level -160 m). It is surrounded by rocks that are impermeable in their primary state. The values of the hydraulic conductivity are as follows:

discontinuous Quaternary cover	$n*10^{-3}$ to $n*10^{-5}$
Carboniferous rock mantle	$n*10^{-5}$ to $n*10^{-10}$ (according to petrographic rock types)
undisturbed Carboniferous rocks	$n*10^{-6}$ to $n*10^{-12}$
tectonically disturbed - hydraulically active	$n*10^{-6}$ to $n*10^{-7}$

The atmospheric precipitation (= 860 mm/year) infiltrates into the Carboniferous rocks as a consequence of secondary rock fracturing caused by mining activity. The intensity of the fracturing is spatially non-uniform. It reaches the maximum distance of approx. 40 - 60 m above the working faces, so the surface infiltration area is mainly developed in the sections above the mine workings that were the closest to the surface. Priority circulation pathways of groundwater are, in turn, formed by old adits and surface-reaching mine workings.

Only little amount of water infiltrates into the mine through tectonic faults. There is no danger of water breakout from those saturated zones. The inflows from zones of tectonic faults, that are being crushed, are quickly weakening. The hydraulic function of the faults is, due to their low number and good exploration, well recognised.

The deposit was exploited by underground mining (directional longwall caving). The dewatering is realized by pumping to the surface. Principal pump stations are located on the 4th (+338 m a.s.l.) and 7th (+50 m a.s.l.) levels. Mine inflows are irregularly distributed in the mining area. They are mostly fixed to tectonic zones opened by mine workings. The total average inflow from rock environment into the mine amounts to approx. 21.5 $l \cdot s^{-1}$. The mean specific inflow into the mine per mining area is approx. 2.32 $l \cdot s^{-1} \cdot km^{-2}$.

The average value of mine ventilation abundance is about 108 $m^3 \cdot s^{-1}$. The average production is approx. 220.000 tons/year. The total infiltration from the mining area (approx. 9.25 km^2) amounts to 73.5 mm / year.

Table 4 Resultant parameters of the balance equation
(example of years selected from long-term observations).

equation parameter	Mine Paskov 1992		Mine Šverma 1998	
	m^3/month	$l.s^{-1}$	m^3/month	$l.s^{-1}$
Q_p	36 700	14,1	112 000	43,0
Q_{op}	25 300	9,7	60 180	23,1
Q_{en}	20 460	7,9	56 630	21,7
Q_v	6 490	2,5	3 250	1,2
Q_t	2 570	1,0	1 560	0,6

3 CONCLUSION

The parameters of water balance equation of the mine are determined by different methods and procedures. The solution of water balance equation is complicated by a number of unknown or directly immeasurable values. Particular components of the equation are, therefore, charged by very different determination errors. Each mining enterprise, or its part, shows a different development of mine saturation in the course of its existence. Therefore, the results are different in particular years of observation, mainly as a consequence of total intensity of atmospheric precipitation in respective years, rate of infiltration, planar and spatial concentration of exploitation activities, exploitation depth etc. The least variable values of Q_v and Q_t will be measured in a fully developed mine with stabilized production. Then, their determination is sufficiently accurate.

The crucial factor for the total accuracy of the mine water balance equation is the length of period of parameter measurements. It is optimal to monitor for approx. 10 years in a mine with stabilized exploitation and planar and vertical development.

4 REFERENCES

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Bilans wodny kopalń węgla kamiennego i jego określanie w warunkach wilgotnego klimatu Europy Centralnej

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Streszczenie: Bilans wodny jest podstawą dla ogólnej oceny zawodnienia złoża. Problem rozwiązania równania bilansu wodnego kopalni jest skomplikowany, gdyż zawiera elementy bilansu trudne do bezpośredniego pomiaru. Wartość elementów bilansowego równania jest obciążona błędem jej oceny. W artykule opisano niektóre przykłady badań hydrogeologicznych basenów węglowych na terenie Republiki Czeskiej i przedstawiono metody określania bilansu wodnego kopalń jak również metody określania składowych bilansu niemożliwych do bezpośredniego pomiaru.