The Improvement of the Lake Most Evaporation Estimates

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http://doi.org/10.29227/IM-2019-02-28

Submission date: *01-12-2019* | Review date: *21-12-2019*

Abstract

The Lake Most represents extensive hydric reclamation of the former surface mine of Most–Ležáky, which is unique in the sense that it does not have a natural inflow and runoff. The main goal of the ongoing research is to costruct a mathematical model predicting the water balance of Lake Most. Therefore, it is important to separate amount of water that is lost by the evaporation and amount of water that is lost into the subsoil. In this article, we focus on the possibilities of evaporation estimates and their improvements.

Keywords: evaporation, Penman equation, hydric reclamation, Lake Most

1. Introduction

The city of Most is located in northwest of Czech Republic, approximately 80 km from Prague, near Bílina river, at the foothills of The Ore mountains. Firstly it was mentioned in the Chronica Boemorum in 10th century and then under name of „Brux" in German books in early 11th century. Its name likely comes from the system of wooden bridges over the swamps, since that „the bridge" is the meaning of german word – „die Brucke" – and czech word „most".

The history of the city, or at least its modern history, is closely connected with the coal, since Most lies in te center of the northern Bohemian coalfield. But not only prosperity came with the coal mining, it also lead to the end of the old royal town of Most. In 1960s it was decided to build whole new city of Most, while the old city had to be pulled down in order to get access to the coal reserves underneath. Only the gothic Church of the Assumption of the Virgin Mary was spectacularly moved for the distance about 840 m.

On August 31, 1999 the coal mining in the strip mining area of the Most–Ležáky was definitively closed and the natural question of its recultivation arose. As the best solution it was choosen the extensive hydritorial recultivation, thus it was decided to flood the area and so build up new lake – The lake Most.

Whole region affected by mining activities in the Most–Ležáky has the total area of 1264 ha. The planned lake surface area is 310 ha and its level is set to 199 m above the sea level. This level, which is about 30 m below the surrounding terrain, was choosen with regard to the foundations of the Virgin Mary Church and it also allows future usage of the whole reclamated territory for the suburban recreation.

The process of recultivation is managed by the state enterprise Palivový kombinát Ústí (PKU). By its original plans from 2002 the was to be filled from the Bílina River, but the sanitary service banned this option because of the high level of water pollution. Thus the Nechranice water dam on the Ohře river was chosen as a better water source and new water supply lines were built for this purpose.

Before the flooding of the area of the residual pit a whole lot of sanitation works had to be done, such as building sewerage of the future lake, construction of the underground sealing wall, construction of the banks, according to the law in the Czech Republic. All these landscape interventions were done with respect to the future usage of the lake.

The uniqueness of the newly created waterworks lies not only in the final parameters of Lake Most after the completion of the filling, but also in the way and speed of filling the residual pit with water. The flooding itself started in october 2008 and the designated water level 199 m above sea level was reach in september 2014. Filling speed is one of many crucial factors influencing the resulting water quality in the lake. Adhering to adequate water quality is the primary objective to be achieved in order to allow the future water surface to be fully exploited for recreational purposes. Therefore, the water quality of the feeder, the inlets and the water accumulated in the lake are regularly monitored.

2. Studies concerning the Lake Most

Hydric recultivation of the residual coal pit is often associated with huge intervention into the landscape which involves changes in microclimate, ecosystem and air quality in the surrounding areas. All these effects were studied within the project no. TA01020592 called "Impacts on microclimate, air quality, water and soil ecosystems within the frame of the hydrologic reclamation of brown coal open cast mines" which was supported by Technologic Agency of the Czech Republic as a part of the programme ALFA TA ČR. The project was solved together by Brown Coal Research Institute, Inc., University of J. E. Purkyně and by Institute of Atmospheric Physics, Academy of Sciences CR.

The project started 1.1.2011 and ended 31.12.2014, thus it took place during the Lake Most filling up. This enabled make use of unique opportunity tu monitor and evaluate the process of the formation of new ecosystem and its influences. Project resulted in certificated complex methodology, that

Fig. 1. View of the lake from the hill Hněvín
Rys. 1. Widok na jezioro ze wzgórza Hněvín

quantificates environmental impacts of hydric recultivations of coal pits, ALAKE software and set of specialised maps. All these results should be used in the preparation, planning and realization of future hydric recultivations of the residual mine pits.

3. Problem statement

Generally it could be said that in water tanks, water loss is due to the seepage caused by water pressure. This seepage depends on the filter coefficient corresponding to the type of soil and to its saturation with water. These losses are gradually reduced after the first filling of each water tank because of the sedimentation of the suspended substances into the surface sealing layers and thus limiting the water penetration into the preferential paths. Closing of these preferential pathways is sequentially done by the swelling processes of clay soils after their saturation.

Similar behavior was also observed in the case of Lake Most, where everything is happening on a larger scale with respect to the given area of the lake. However during the summer months of the year 2015 unexpected lake surface level drop was observed.

Due to this fact the PKU company requested a study concerning a mathematical model predicting water balance of the Lake Most. Also the geological model of the area, the digital model of the terrain, the analysis of water quality, monitoring and assessment of the water pollution risk. All these activities are important parts of accurate prediction of the future development of the water balance of the Lake Most in relation to the climatic, hydrological and hydrogeological factors. As an example of the so far obtained results let us mention analysis of land and soil moisture changes in the Lake most surroundings using SENTINEL-1 and COSMO images, (Land and soil moisture change analysis in the Lake Most surroundigs from the Sentinel-1 and Cosmo images, 2017).

For the purpose of model verification it is necessary to keep the fluctuations around the constant horizon dimension as small as possible.

The goal of the ongoing project is to separate amount of seepage and evaporation. In this paper we describe the ways to estimate the amount of water loss caused by evaporation, i.e. during the vaporization process in which the water is transformed from its liquid or solid state into water vapor which is transfered to the atmosphere.

Generally, the water losses in the lake system are composed by outflow to river downstream, seepage vertically through the lake bottom and evaporation from the lake surface. Since the Lake Most is closed, i.e. it has no natural outflow, we may consider only losses caused by seepage and evaporation.

The seepage water loss is influenced by the water pressure, the filtering coefficient of soil, in non-saturated and saturated state, and rock samples under the lake bottom. The amount of these losses should decrease as the suspended solids are sedimenting and closing water seepage paths. The paths of water seepage paths are also closed by expanding of the clays after their saturation by water.

Evaporation plays key role in the evolution of void lakes and thus in this context the distinguishing between the water loss caused by subsoil seepage and those caused by evaporation aquire great importance.

4. Approaches of Evaporation determination

Basically there are five method of determining evaporation: water budget method, mass transfer method, energy budget method, pan evaporation method and combined method, see (Brutsaert, 2005), (Maidment, 1993). Each of these methods could yield different equations, although the basic ideas are the same. This is could be caused by different approaches to determination of involved empirical constants and coefficients.

4.1 Water budget method

Water budget method deals with change of storage capacity ΔS which is equal to

$$\Delta S = I + P - O - GW - E \tag{1}$$

where I resp. O is surface inflow resp. outflow, P precipitation, GW subsurface seepage to groud and finally E stands for evaporation. The main idea is quite simple, however espicially determining the term GW might be difficult.

4.2 Mass transfer method

Mass transfer method, as its name indicates, is based on idea of water vapor transfer to the atmosphere which is depends on vapor pressure difference and wind speed of the water surface. Going back to the Dalton´s theories, as cited in (Bedient, a další, 2013) we have

Tab. 1. Parameters of the Lake Most
Tab. 1. Parametry jeziora Most

Parameter	Value
Surface area	309.4 ha
Water volume	70 500 000 m
Coastal line of peripheral communications	9380 m
Operating level quota (constant horizon)	199 m above sea level
Maximum depth	75 m

Tab. 2. Water budget method
Tab. 2. Metoda bilansu wodnego

Year	In	Out	Total	Measured change
2015	80	-54	26	1
2016	75	-47	28	-5
2017	87	-52	35	4

$$E=(e_s-e_a)(a+bu) \quad (2)$$

with e_s being saturation vapor pressure at temperature T_s of water surface, e_a vapor pressure at some fixed level above the water surface, which could be computed as a product of relative humidity and saturation vapor pressure at air temperature T_a, u is wind speed and finally a, b empirical constants.

4.3 Energy budget method

Energy budget method could be wieved as the most accurate one although its idea, comparing, suming and substracting incoming and outcoming energy, is once again quite simple. We have

$$Q_s-Q_r-Q_b-Q_h-Q_e=Q\theta-Q_v$$
$$Q_s-Q_r-Q_b=Q_N \quad (3)$$

with Q_N net radiation absorbed by water computed from Q_s shortwave solar radiation, Q_r reflected shortwave radiation and longwave radiation back to the atmosphere. And Q_h sensible heat transfer, Q_e energy used for evaporation, $Q\theta$ increase of energy stored in water and Q_v advected energy of outflow and inflow. All of Q_* considered here are in langleys $1\ Ly = 1\ cal\ cm^{-2}$.

Using the relationship $Qe=E\rho L_e$, E evaporation in centimetres per day, cm d^{-1}, ρ water density in g cm^{-3}, L_e latent heat of vaporayation in cal g^{-1} and writing the ratio $Q_h/Q_e = R$ we obtain following equation

$$E=(Q_N+Q_v-Q\theta)/(\rho L_e\ (1+R)) \quad (4)$$

As mentioned above the energy budget method is accurate, but it requires a lot of complicated measurements of incoming or net radiation, also precise determination of ratio R could be hard, because Q_h could not be computed directly. This leads to the usage of the Bowen ratio which is computed from atmospheric pressure, air and water surface temperature, vapor pressure and psychrometric constant γ.

4.4 Pan evaporation method

The pan evaporation method measures evaporation directly in standartized iron tank which is filled with water and change of water level is monitored. Daily evaporation is then given by difference between measured water levels from which we substract daily precipitation. For example, the standard US Wheather Bureau class A pan has diameter 4 feet, its depth is 10 inches and is placed 12 inches above the ground, see (Maidment, 1993), the pan is filled to the level 8 inches and refill to this depth whenever its level fall under 7 inches. Pan evaporation rates are certainly higher then actual lake evaporation, hence it must be adjust by multiplying them by so-called pan coefficient. For US class A pan this coefficient ranges between 0.64 and 0.81 and the average for USA is 0.70.

4.5 Combined method

Combined methods use properties and relation from both mass transfer and energy budget method in order to get evaporation equation which is easy to compute and does not require any special measurements. As in mass transfer method we use vapor pressures, temperature and wind speed and usage of net radiation, Q_N, is adopted from energy budget method. As a representatives name here Penman and Penman-Monteith equation.

5. Colecting and sorting data

From previous section it is apparent that the first obvious step in order to estimate the evaporation is collect and sort all available data. Set of data provided by PKU company consists of daily measured water level (meters above sea level), water and air temperature (°C), volume of water inflow (m^3), precipitation (mm) and evaporation estimate in mm.

Since there is no natural surface inflow I and outflow O we could easily use water budget equation (1) to estimate water loss, which is given by E evaporation and GW subsurface seepage. This is summarized in the table 2, where In column consist of precipitation and water supply inflow and Out is given by provided evaporation estimate. Since the water level is measured with 1 cm accuracy the inflow volume is convert to cm using the area of 310 ha and also all values are rounded to whole numbers for sake of simplicity.

In the table 2 we see big differences between predicted and measured water level change. For example in 2016 the level should have been rising by 28 cm, but its 5 cm fall was measured. The difference of 33 cm is equivalent to one million m^3 water loss and the natural questions is whether such huge loss could be explained by the seepage or the data

Tab. 3. Evaporation sum during the period 18.8.2017-24.9.2018
Tab. 3. Wielkość parowania w okresie 18.8.2017–24.9.2018

Method	**Sum**
PKU estimate	55.8 mm
Evaporation pan	138.7 mm
Penman PKU meteostation	135.3 mm
Penman UFA meteostation	113.3 mm
Penman micrometeostations	109.7 mm

provided by PKU highly underestimates water loss caused by evaparotion.

As the reaction to this discrepancy PKU requested detail description of lake behaviour. It was mentioned above that this study consists of several parts, concerning geological and hydrogeological aspects and climatic aspects causing evaporation. The latter is starting point of mathematical determination of water evaporation.

The PKU company also decided to buy and operate its own meteostation with evaporation pan. This meteostation was installed on water surface in july 2017 and since then all result could be compare with local measurements.

6. Building the network

Although climatic data set provided PKU are quite poor, it contains only one air temperature value a day, one could try to estimate potentional evaporation using so-called temperature based equations. For example we could name Thornthwaite method (1948), Blancly-Criddle equation (1950), Hargreaves-Samani (1985) or Kharuffa equation (1985). But only the Thornthwaite equation works with air temperature alone, the other ones takes also daily sunlight percentage in account.

For the Thornthwaite estimate it is enough to determine mean monthly temperature t_m (the index m corresponds to month), from which we compute monthly heat index i_m, then the annual heat I and finally annual potential evaporation E_T.

$$i_m = (\frac{t_m}{5})^{1.514}, I = \Sigma_{m=1}^{12} i_m,$$

$$E_{T,m} = 16\left(\frac{10t}{I}\right)^{\alpha}, \alpha = 675\times10^{-9} I^3 - 771\times10^{-7} I^2 + 1792\times10^{-5} I + 0.49239, \quad (5)$$

$$E_T = \Sigma_{m=1}^{12} P_{T,m}.$$

From the temperatures in the year 2016 we get E_T=566.7 mm year^{-1}, whereas the PKU table estimates annual evaporation E_{PKU}=525.2 mm year^{-1}. The difference may not seem to be so big, but this four centimetres could correspond to124 000 m³ of water, i.e. more then 10% of which had to bought in order to have water level stabilized at 199 m above the sea level.

Moreover obtained Thornwaithe estimate could be corrected by the term taking the theoretical sunshine hours N and length of the month d in account, i.e. multiplying $E_{T,m}$ by $N/12\ d/30$. For the year 2016 this means E_T=649.9 mm year^{-1}, i.e. another 8 cm or 248 000 m³ of water.

Of course such wide range of estimates need to be make more accurate, but this could be done only using more precise and detailed climatic data together with more complex evaporation equations, that is method mentioned and lightly described in section 4.5. Now let us show and describe the Penman equation in more details,

$$E_P = \frac{\Delta}{\Delta+\gamma} \times \frac{R_n - G}{\lambda} + \frac{\gamma}{\Delta+\gamma} \times \frac{6.43 f(u)(e_s - e_a)}{\lambda} \quad (6)$$

The term Δ stands for the slope of vapour pressure curve (*kPa* °*C*$^{-1}$), R_n net radiation at the surface (*MJ m*$^{-2}$ *d*$^{-1}$), G heat storage change (*MJ m*$^{-2}$ *d*$^{-1}$), which is set to be $G=0$ for water surface, γ is psychrometric constant (*kPa* °*C*$^{-1}$), λ=2.45 *MJ kg*$^{-1}$ is latent heat of vaporization, *f(u)* is so-called wind function with u itself being wind speed (*m s*$^{-1}$) and finally e_s-e_a is saturation vapour pressure deficit (*kPa*).

Althoug the equation (6) and the provided description seems to be complicated, its form shown here is still in quite compressed form and all terms appearing in it are to be computed from its own equations. As the Penman-Monteith method is recommended by the FAO (Food and Agriculture Organization of the united Nations) we refer to FAO Irrigation and drainage paper No. 56, (Allen, a další, 1998), where it could be found all necessary relations.

Here we mention just that Δ depends on air temperature, γ on atmospheric pressure, *f(u)* on wind speed and e_s-e on relative humidity and temperature. Obtaining the term R_n is the most complicated, since it is computed only from climatic data air temperature, relative humidity and theoretical and measured daily sunshine hours, but the observed site latitude, day number and solar declination, solar hour angle and relative solar distance for the day and also several constant (σ Stefan-Boltzmann,G_{sc} solar constant) is taken in account.

From this point of view climatic data provided by PKU are insufficient, this lead us to contact Ústav fyziky atmosféry Akademie věd ČR (Institute of atmospheric physics of Czech Academy of Sciences (UFA)) and request all relevant data, i.e. air temperature, relative humidity, atmospheric pressure, wind speed and sunshine day duration and also daily precipitation. The UFA operates from Kopisty meteostation which is located about 1 km from the Lake Most, all measurements are automatically recorded and we obtained them monthly sorted in excel file with ten minutes frequency. Thanks the UFA data we could go as back as to the year 2014, the year of reaching the level 199 meters above the sea.

The meteostation operated by PKU on the lake surface produce the same set of climatic data, i.e. air temperature, atmospheric pressure, wind speed, relative humidity and precipitation, together with water temperature and evaporation pan, only the sunshine duration is missing. But whereas on the one hand PKU meteostation is located exactly at the lake and it also reduce dependence on UFA, on the other hand it runs in kind of testing mode with malfunctions and moreover it is still one point measurement.

The latter reason leads us to the idea of building the network of micrometeostations around the Lake Most. With its support we could use Thiessen polygons to divide the lake according to obtained measurements and them adjust evapo-

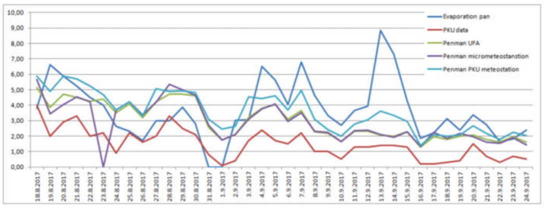

Fig. 2. Excel output – daily evaporation rates

Rys. 2. Dane wyjściowe Excel – dzienne szybkości parowania

ration estimates. Another one advantage of the network lies in number of stations, since in the case of failure of one station the measurement could be save by the rest.

7. Results and conclusions

During the testing period, from 18.8.2017 to 24.9.2017, the perfomance of Penman evaporation equation was checked and compared with the estimates obtained from PKU dataset and from PKU floating evaporation pan. We computed potential evaporation with data that came from UFA Kopisty station, PKU floating meteostation and testing micrometeostation. The result are summarized in the figure 2. The red line of the PKU estimates is the lowest one, the blue line of evaporation pan measurement is the highest one, values computed by Penman equation are in between. The sums of all daily values are in the table 3.

There is the description of the US class A evaporation pan in the section 2.4, the PKU floating evaporation pan has diameter slightly bigger then half of the US pan, its area is 3000 cm² and depth is 60 cm in total and it is filled up to 48 cm. The measurement is based on the change of hydrostatic pressure at the bottom of the pan. As was mentioned in the section 2.4 pan measurements eed to be adjust by pan coefficient, but there is no recommended coeficient for the PKU floating pan. If we use lowest and highes US recommendation we get values 88.8 mm and 112.3 mm, both still bigger then estimates from PKU data set.

Thus in order to use the floating evaporation pan and its measurements more properly the pan coefficient should be set and that is another one aim designated micrometeostation network.

Nowadays there are five micrometeostations placed on the banks of the Lake Most and another one is fastened to the PKU station on the lake surface. With this network we could divide the lake using Thiessen polygon, use its data directly in these subregions, compute and specify evaporation rates and also determine the pan coefficient.

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Poprawa szacunków parowania jeziora Most

Jezioro Most stanowi rozległy teren rekultywacji wodnej byłej kopalni odkrywkowej Most – Ležáky. Jezioro jest wyjątkowe w tym sensie, że nie ma naturalnego dopływu i odpływu. Głównym celem trwających badań jest opracowanie modelu matematycznego przewidującego bilans wodny jeziora Most. Dlatego ważne jest oddzielenie ilości wody utraconej w wyniku parowania i ilości wody utraconej w podłożu. W artykule skupiono się na możliwościach oszacowania parowania i ich ulepszeniach.

Słowa kluczowe: parowanie, równanie Penmana, rekultywacja hydrologiczna, Jezioro Most