JEE Journal of Ecological Engineering

Journal of Ecological Engineering 2021, 22(2), 63–69
https://doi.org/10.12911/22998993/130879
ISSN 2299-8993, License CC-BY 4.0

Received: 2020.11.16
Accepted: 2020.12.14
Published: 2021.01.01

Assessment of the Influence of Evaporation and Evapotranspiration on the Volume of Sludge Accumulation in the Sludge Drying Beds

Svitlana Velychko[1*], Olena Dupliak[1]

[1] Department of Water Supply and Sewage, Fuculty of Engineering System and Ecology, Kyiv National University of Construction and Architecture, 31, Povitroflotsky Avenue, Kyiv, 03037, Ukraine

[*] Corresponding author's e-mail: velychko.sv@knuba.edu.ua

ABSTRACT

At present, the sludge drying beds of the Kyiv wastewater treatment plants are operated as a sludge accumulator in an emergency mode, practically without free volume. The purpose of the work was to determine the equation for the evaporation losses calculation from sludge drying beds and the required free volume for sludge accumulation for the next 7 years. The required free volume was calculated using the water budget method which takes into account evaporation from the water surface and evapotranspiration during the vegetation. The total losses from sludge drying beds is 1076 mm/year in normal year and is 920 mm/year in a cold year. The required free volume was calculated considering the trend of increasing average temperature over the last decade and considering the significant environmental risk. A correction was made for one unfavourable year with cold summer and warm winter and an additional rain rate of 1% probability. The additional free volume required is 3.24 million m^3 for 7 years if all three sludge drying beds are operated.

Keywords: sludge drying beds, evaporation, evapotranspiration, sludge, sewage

INTRODUCTION

The wastewater treatment facilities of the Bortnychi Aeration Station (BSA) were put into operation in 1965 (the II part in 1976). According to the design fermented sludge from anaerobic digestion tanks, the sludge from primary clarifier and the sludge from aerobic digester are pumped into the sludge drying beds, where they are dewatered under natural conditions, and the dried sludge is transported to a waste landfill once a year. In 1985, the removal of dried sludge from drying beds was forbidden due to the high content of heavy metals. Thus, for the last 30 years, sludge has been accumulating in sludge drying beds. The dewatering process is as follows: the sludge is pumped into one of the sludge drying beds number 1, 2 or 3, where it is settled for 12 days, the clarified water is transported to the aerobic digester or to the head of the treatment plant. Periodically, due to the lack of the necessary free volume for the sludge accumulation, the time of necessary settling is not maintained, so the clarified water that is being collected contains a significant amount of sludge, which creates an additional problem for the wastewater treatment station (BSA). Therefore, in order to maintain the technology of sludge dewatering in sludge drying beds and to continue their operation, it is necessary to provide additional free volume, which can be done by raising the existing dykes.

The total surface area of the drying beds is 219.23 ha. According to a survey performed during the vegetation season, there are two main types of surface: open water and surface covered with vegetation (reed, reedmace, sedge). The area with open water occupies 14.2%, 4.7% and 2.9% of the total area of drying beds No. 1, 2 and 3, respectively. The current states of the sludge drying beds are shown in Figures 1 and 2.

The development of the existing methods of calculating the necessary volume of sludge drying beds is based mainly on the use of empirical research materials, as well as an approximate

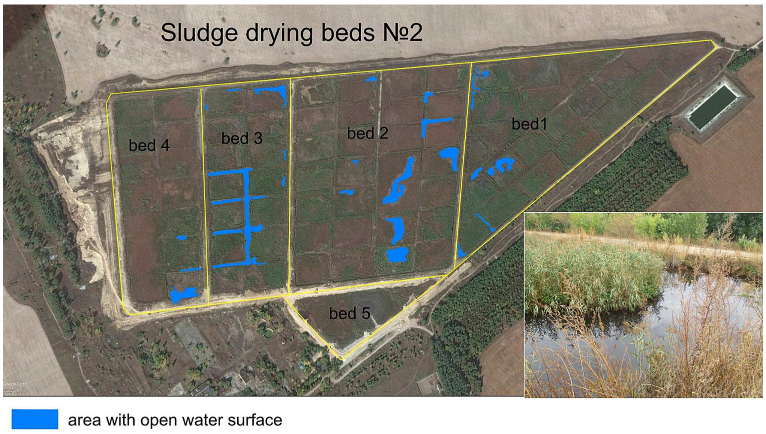

Figure 1. Current state of sludge drying beds No. 2

method of calculation using the basic output parameter – the permissible load on the sludge beds, which is dependent upon the climate and provides for the periodic removal of dried sludge from the beds. The most thorough theoretical studies of sludge beds are given in the works in which were developed some design schemes and dewatering technologies for drying beds with single or periodical loading [Brix et al. 2017, Uggetti et al. 2012]. Today, there is a great experience related to the sludge drying beds covered with vegetation, accumulated in many countries around the world, but most of the design recommendations relate to sludge load, number of beds, and the period of operation up to 10 years with periodical sludge removal [Kolecka et al. 2018]. For 10 years operation period and climatic condition of Denmark the height required to accumulate sediment is suggested to be approximately 1.2–1.5 m [Nielsen 2007].

The works [Uggetti and al. 2012, Nielsen 2007] emphasize the significant role of evaporation in the process of sludge dewatering in reed drying beds, but the quantitative assessment of evaporation is purely empirical and significantly different for different climatic zones: it is 58–84% for Greece [Stefanakis et al. 2011], from 2.7 mm/day in autumn to 50.4 mm/day in summer for southern Italy [Milani et al. 2013], 876.8 ± 54.58 mm/year for central Europe [Anda A. et al. 2015]. During the growing season, plants can evaporate large amounts of water. According to [Herbst et al. 1999] (Germany) the average monthly evapotranspiration of reed exceeds the evaporation from the free surface of the water by 1.5–2.0 times, depending on the climatic conditions. In another work [Tokuo Yano et al. 2017] mentioned that if there is a favourable salt composition, the sludge evapotranspiration in 3 times higher than the reference evapotranspiration. The studies on different plant species show a significant difference in evaporation for different plant species [Milani et al. 2019]. Therefore, to determine the additional volume for the accumulation of sludge over the next 7 years, it is necessary to use the method of water balance, for which it is

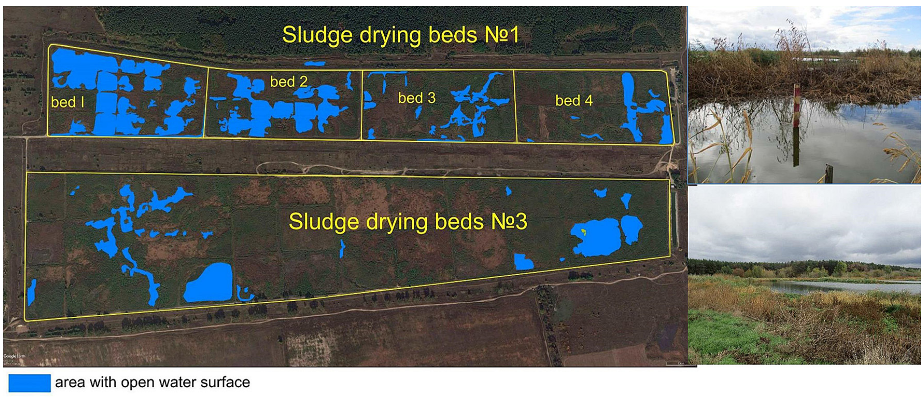

Figure 2. Current state of sludge drying beds No. 2 and No. 3

necessary to determine the losses of evaporation and evapotranspiration.

The purpose of the work is the development of the equations to determine the losses of evaporation and evapotranspiration from sludge drying beds for further simulation of sludge during beds operation over the next 7 years and determine the required free volume created by raising the existing dykes.

MATERIALS AND METHODS

The water budget method was used to determine the required volume for sludge accumulation over 7 years. The process of sludge dewatering on sludge drying beds can be divided into three stages: the settlement of solids on the bottom of sludge drying beds, formation of a top zone of clarified sludge water, as well as removal of sludge water and natural drying by evaporation of moisture from the surface of water and sludge. The moisture condensation process over the surface of the drying beds does not affect the water budget, so it was not taken into account in the calculations. The volume of accumulated sludge during the calculation period is determined by the formula:

$$\Delta \mathrm{W} = \sum_{1}^{n} (\mathrm{W}_{sl} + P - E - W_f - E\mathrm{T} - \Delta V) \quad (1)$$

where: ΔW – volume of accumulated sludge, m^3
W_{sl} – volume of sludge coming into the sludge fields, m^3
W_f – seepage through bottom and dykes, m^3
P – volume of precipitation, m^3
E – evaporation from water surface, m^3
ET – evapotranspiration, m^3
ΔV – volume of clarified sludge water, m^3
n – number of years.

Some assumptions were made to determine the required reserve volume in the sludge drying beds for a period of 7 years according to formula (1):

- the larger evaporation area, the more efficient the sludge drying process will be, so in the calculations it was assumed that during the year all fields 1, 2 and 3 work;
- the existing reserve volume is 418665 m^3;
- annual supply of sludge in the sludge drying beds is 4 140 712 m^3/year;
- the amount of clarified water pumped out is 2 635 624 m^3/year (63.7%);
- the mean long-term precipitation value according the Boryspil meteorological station is 560 mm/year;
- hydrogeological surveys of the dykes did not reveal any seepage across the sides and bottom of dykes, so the seepage losses from the sludge drying beds were not taken into account;
- additional volume for accumulation of 1% probability rain, which is 104 mm/m^2, is included in the calculation.

Evaporation from the water surface

Evaporation from the water surface during the year is divided into evaporation in the ice-free period (May-October) and evaporation from the non-freezing water (November-April).

The equation for calculating evaporation from the water surface in the ice-free period, which corresponds to the modern climatic conditions of Ukraine [Shereshevsky and al. 2000] is:

$$\mathrm{E}_0 = 0.37\mathrm{n}(1 + 0.14u_{200}) \cdot (e_0 - e_{200}) \quad (2)$$

The mean wind speed over the drying beds at the height of 200 cm (u_{200}) was determined as a result of observations at the Boryspil meteorological station, taking into account the degree of protection of the metrological station, the nature of the relief, the mean length of the air flow acceleration above the drying beds, as well as the protection of the drying beds and vegetation.

The maximum elasticity of water vapour (e_0) is determined by the temperature of the water surface, which was taken as a result of observations on sludge drying beds during the year.

The mean value of water vapour elasticity on the height of 200 cm up the water surface (e_{200}) was determined using the equation:

$$e_{200} = \mathrm{e}^*_{200}(0{,}8e_0 - e_{200}) \quad (3)$$

where: e^*_{200} – mean humidity which was measured at the climate station, mbar.

Evaporation from non-freezing water surface or its parts, as well as when the surface temperature of water at 5°C is higher than the air temperature, is calculated by the equation:

$$\mathrm{E}_{0w} = 0{,}104n(e_0 - e_{200}) \cdot (K_0 + u_{200}) \quad (4)$$

where: E_{0w} – evaporation from non-freezing water surface in the period from November to March, mm
K_0– a coefficient that depends on the difference in water surface temperature and air
n – time period, month.

Evapotranspiration

The sludge drying beds are almost completely covered with plants: on the drying beds No. 1 vegetation occupies 85.8% of the area; on the beds No. 2 is 95,2%; on the beds No. 3 is 97,2%. Reed, reedmace, and sedge mainly grow in sludge drying beds.

The FAO-56 technique developed on the basis of the updated Penman-Monteith equation was used to estimate the total evaporation. Crop evapotranspiration is calculated by the equation:

$$\mathrm{ET}_c = K_c ET_0 \tag{5}$$

where: ET_c – crop evapotranspiration, mm
K_c – crop coefficient
ET_0 – reference evapotranspiration, mm.

Reference evapotranspiration (ET_0) is evapotranspiration rate from a reference surface without water shortage is calculated by the equation:

$$\mathrm{ET}_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_{200}(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{6}$$

where: R_n – net radiation at the crop surface, MJ/(m^{2}day)
G – soil heat flux density, MJ/(m^{2}day)
T – mean daily air temperature at 2 m height, °C
u_{200} – wind speed at 2 m height, m/s
e_s – saturation vapour pressure, kPa
e_a – actual vapour pressure, kPa
Δ – slope vapour pressure curve, kPa/°C;
γ – psychrometric constant, kPa/°C.

Crop coefficient and its distribution during a year was taken according observations carried out in the work [Anda et al. 2014]. The evapotranspiration calculations were carried out on the CROPWAT 8.0 software package.

Since evaporation from the water surface does not differ significantly from the mean annual value (the coefficient of variation for the Boryspil meteorological station is 0.09), so the mean annual evaporation from water surface for free accumulation volume of sludge was calculated. However, evapotranspiration significantly depends on the temperature during the growing season; therefore, the calculations were carried out for the year with the average temperature during the growing season (16°C) and for the cold year, with the temperature during the growing season 15°C. The initial data for the calculations is shown in Table 1.

The sludge drying beds No. 1, No. 2, and No. 3 have both an open water surface and a significant part of the vegetation. The total evaporation from the surface of the sludge drying beds consists of evaporation from the open surface (A_w) and evapotranspiration (A_{ET}):

$$E_{sb} = A_w E_0 + A_{ET} ET_c \tag{7}$$

where: E_{sb} – evaporation from sludge drying beds
A_w – area of beds with open water surface
A_{ET} – area of beds is covered with vegetation.

RESULTS AND DISCUSSION

In the period from April to October, the evaporation from sludge drying beds consists of evaporation from the water surface (E_0) and evapotranspiration (ET_c); in winter (from November to March), losses occur due to evaporation from the non-freezing reservoir (E_{0w}). The results of the calculations of evaporation from sludge drying beds for the mean and cold years are shown in Table 2.

Table 1. The initial climate data for the calculation of evaporation

Indicator	Months											
	01	02	03	04	05	06	07	08	09	10	11	12
Mean year												
Mean month temperature, °C	-5	-3	1	9.5	15	19	20	19	14	9	2	-2
Mean humidity, mb	3.9	4	4.9	7.2	10.2	13.7	15.5	15.1	11.6	8.2	6.4	4.6
Wind velocity, m/s	4.9	4.9	4.8	4.6	3.83	3.57	3.57	3.32	3.70	4.21	4.85	4.9
Crop coefficient				0.8	1.24	1.4	1.41	0.99	0.77			
Cold year												
Mean month temperature, °C	-6	-6	-1	6.8	14.6	17.4	19.5	18.3	13.4	7.3	0.9	-4
Mean humidity, mb	3.9	3.9	5.1	7.2	10.7	13.6	15.3	14.3	11.2	8.5	6	4.5
Wind velocity, m/s	4.97	4.97	4.85	4.59	3.83	3.57	3.57	3.32	3.70	4.21	4.85	4.97
Crop coefficient				0.6	0.62	0.72	0.77	0.8	0.6			

The average evaporation from the surface of the sludge drying beds was determined as 1076 mm/year for the mean year and amounts to 920 mm/year for the cold year

The distribution of the evaporation components on the example of the field No. 1 is shown in Figure 3. The figure shows that in the growing season evapotranspiration (green line) exceeds the evaporation from the open surface (blue line) by a maximum of 35%. Evaporation increases during the vegetation season along with average monthly temperature and begins to decrease along with temperature and inhibition of plant development until September.

Figure 3 shows that with decreasing temperature in the winter evaporation increases significantly, so the relationship between evaporation from the sludge drying beds (E) and the average monthly temperature (t) has the form of a parabola, which is determined by the equations:

- for the mean and warm years:

$$E = 0.48 \cdot t^2 - 5 \cdot t + 58 \tag{8}$$

- for cold years:

$$E = 0.40 \cdot t^2 - 5 \cdot t + 58 \tag{9}$$

In order to verify equation (8), the evaporation and evapotranspiration losses that occurred in the sludge drying beds were calculated for the periods of observations from 2008 to 2016.The years from 2008 to 2016 were all warm with the average temperature during the vegetation season above 16°C and the average annual temperature above 8.3°C. Figure 4 shows a comparison of the evaporation losses from sludge drying beds, obtained by using the method of water balance using the observations, and the evaporation losses calculated by equation (8).

In 2012–2013 accidents and sludge spills occurred on sludge drying beds during the dykes breaking, so these years were excluded from the analysis because it was not possible to separate the losses due to sludge spills and evaporation. The average evaporation loss from sludge drying beds for 2008–2011 and 2014–2016 is 1142±57 mm/year, which corresponds to calculating evaporation by empirical equation (8), which is 1152 mm/year for the mean year. Therefore, it is possible to use the empirical formulas for calculating evaporation from sludge drying beds.

The analysis of the temperature regime showed that the average annual air temperature for the last 50 years is 8.3°C, and for the last 20 years the average annual temperature has increased to 9.22 °C, a similar trend is observed with the average temperature during the growing season, which for 50 years is 16.2°C, and over the past 20 years has increased to 17.3°C. Increasing

Table 2. The evaporation losses from the sludge drying beds for the mean and cold years

Months												Year, mm
01	02	03	04	05	06	07	08	09	10	11	12	
Mean year												
93	80	67	71	124	150	152	129	67	32	34	77	1076
Cold year												
103	98	70	55	78	100	112	102	47	20	46	89	920

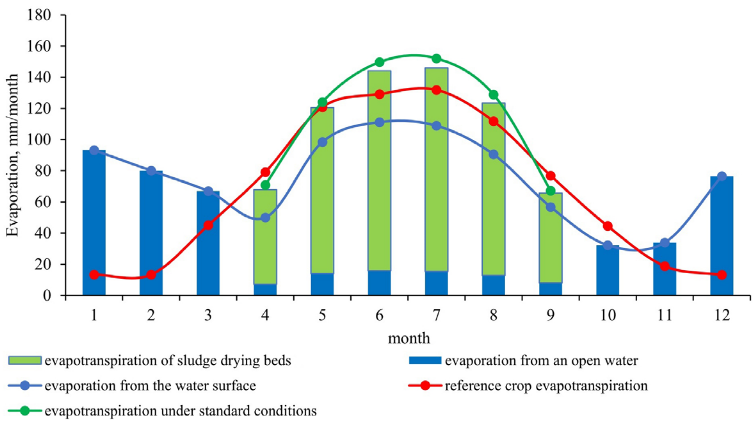

Figure 3. Estimated evaporation of sludge drying beds No. 1 and its components

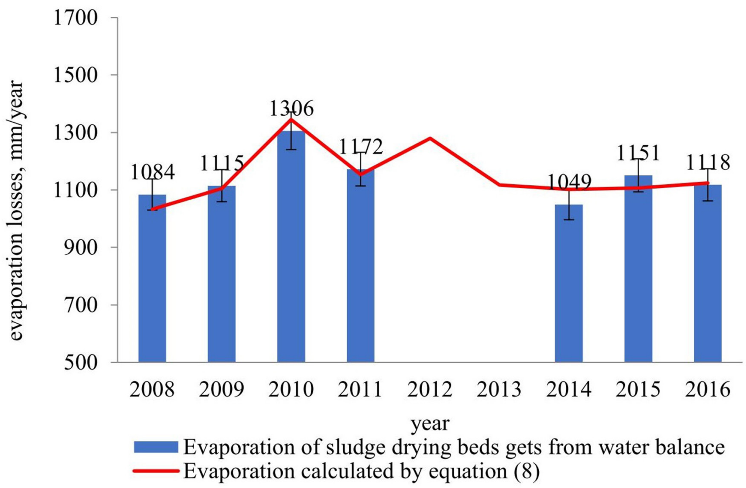

Figure 4. Evaporation losses calculated using the water budget method (blue bars) and calculated using equation (8) (red line)

the temperature during the vegetation season with 100% water supply will have a positive effect on the water loss due to evaporation. At the same time, the winter temperature has become higher, so the evaporation from water surface reduces during the winter period. The warm winters of 2008, 2009, 2014–2016 explain the decrease of evaporation compared to 2010–2011, despite the high summer temperature. The greatest evaporation losses occur in the years of cold winter and hot summer, which occurred twice in 2010 and 2012, in recent years. The combination of cold summer (average temperature during the vegetation season less than 15°C) and warm winter (above 1°C), which gives the lowest evaporation losses, occurred once in the last 20 years.

Due to their large area and location near settlements, sludge drying beds are an ecologically dangerous object, so despite the tendency to increase the temperature in recent decades, one cold year was taken into calculation and six years were chosen with a temperature above average to simulate the operation of sludge drying beds in the next 7 years.

Taking into account the accepted assumptions and the additional volume for short-term extreme rainfall, the required volume is 3.24 million m^3 to continue the operation of sludge drying beds for 7 years.

CONCLUSIONS

Evaporation of sludge drying beds depends on the climatic conditions and at full saturation condition mostly depends on the temperature during the vegetation season and in winter. The greatest evaporation losses occur in cold winters with average temperatures below 0°C and hot summers with average temperatures above 16°C during the vegetation season.

The temperature regime of central Ukraine has changed significantly over the last 20 years: hot summer months prevail with average temperatures during the vegetation season above 17°C and moderately warm winters, which is favourable for plant development and leads to increased evaporation by 100 mm/(m^2·year). At the same time, a combination of unfavourable conditions for evaporation: cold summers and warm winters do not occur often, such a year was observed once in 2004 during the last 20 years.

The evapotranspiration during the vegetation period (April-September) is 693 mm/year for the mean year and 494mm/year for the cold year for climatic conditions of the central part of Ukraine. The evaporation losses per unit area of sludge drying beds located in the central part of Ukraine is 1076 mm/(m^2·year) for the mean year and 920 mm/(m^2·year) for the cold year and 870 mm/(m^2·year) for the year with a combination of unfavourable conditions.

Taking into account the precipitation on the surface of sludge drying beds, the evaporation losses amount to 27% of the sludge inflow in the mean year and 19% in the cold year.

The volume required to accumulate sludge for 7 years, one of which is cold, with three drying beds operating is 3.24 million m^3.

REFERENCES

1. Allen R. G. 2000. Using the FAO – 56 dual crop coefficient method over an irrigated region as part of an evapotranspiration inter comparison study. Journal of Hydrology, 229(1–2), 27–41.
2. Anda A., Teixeira da Silva J. A., Soos G. 2014. Evapotranspiration and crop coefficient of common reed at the surroundings of Lake Balaton Hungary. Aquatic Botany, 116, 53–59.
3. Anda A., Soos G., Teixeira da Silva J. A., Kozma-Bognár V. 2015. Regional evapotranspiration from a wetland in Central Europe, in a 16-year period without human intervention. Agricultural and forest meteorology. 205, 60–72.
4. Brix H. and Arias C.A. 2017. Sludge Dewatering and Mineralization in Sludge Treatment Reed Beds. Water. Special Issue Constructed Wetlands for Water Treatment: New Developments, 9(3), 160, 17–24.
5. Herbst M., Kappen L. 1999. The ratio of transpiration versus evaporation in reed belt as influenced by weather conditions. Aquatic Botany, 63(2), 113–125.
6. Kolecka K., Obarska-Pempkowiak H., Gajewska M. 2018. Polish experience in operation of sludge treatment reed beds. Ecological Engineering, 120, 405–410.
7. Milani M., Toscano A. 2013. Evapotranspiration from pilot-scale constructed wetlands planted with Phragmites australis in a Mediterranean environment. Journal of Environmental Science and Health, Part A, 48 (5), 568–580.
8. Milani M., Marzo A., Toscano A., Consoli S., Cirelli G.L, Ventura D. and Barbagallo S. 2019. Evapotranspiration from Horizontal Subsurface Flow Constructed Wetlands Planted with Different Perennial Plant Species. Water, 11, 2159.
9. Nielsen, S. 2007. Sludge treatment and drying reed bed systems. Ecohydrology & Hydrobiology, 7 (3–4), 223–234.
10. Shereshevsky A.I., Sinitskaya L.K. 2000. Assessment of changes in evaporation from the water surface in Ukraine. Trudy UkrNDGMI, 248, 67–76.
11. Stefanakis A. I., Tsihrintzis V. A. 2011. Dewatering mechanisms in pilot-scale Sludge Drying Reed Beds: Effect of design and operational parameters. Chemical Engineering Journal, 172 (1), 430–443.
12. Tokuo Yano, Masatomo Nakayama, Kazuhiro Yamada, Akiko Inoue-Kohama, Shinya Sato, Keijiro Enari 2017. Influence of Growth of Reeds on Evapotranspiration in Horizontal Subsurface Flow Constructed Wetlands. Environment and Ecology Research, 5(6), 427–435.
13. Uggetti E., Argilaga A., Ferrer I., García J. 2012. Dewatering model for optimal operation of sludge treatment wetlands. Water Research, 46(2), 335–344.