ANNEX 4: GENERAL DESCRIPTION OF SLUDGE TREATMENT ON REED BEDS

Sludge drying reed beds (RBs) enable sludge dewatering, stabilization, mineralization, and hygenization. They are an alternative to mechanical treatment (e.g., belt presses, centrifuges). In the process, digested sludge slurry is spread on an open bed of sand or gravel, after which drying takes place by a combination of evaporation and gravity drainage through the filter layer.[1]

Planted RBs enable effective dewatering of sewage sludge and produce a mineralized product that can be used as a soil amendment in agriculture and other uses. RBs are used for more than two decades in different countries; consequently, several technological options are available. In the summer of 1988, the first two sludge dewatering and mineralization systems were inaugurated in Denmark. The systems comprise 2 (Allerslev) and 4 (Regstrup) reed beds, respectively.[2]

Figure 1: Regstrup sludge dewatering system in 1989[3]

RBs are constructed and operate similarly to drying beds; however, more physical, chemical, and biological processes take place in sludge dewatering and stabilization. Usually, they are planted with common reeds (Phragmites australis), but other wetland ones can also be used.

Sludge drying reed beds can treat primary and secondary sludge, septage as well as their mixtures. In sludge drying reed beds, the vegetation, filter media, sun, and gravity, separate solids and liquids in the sludge. The solid fraction of the sludge remains on the surface, while some of the water percolates through the filter media. Sludge is applied sequentially and between the series of sludge application, a resting period is allowed, when sludge is dewatered and partly mineralized. This procedure is carried out along time until the bed is filled with stabilized dewatered sludge, and the bed has to be emptied. The beds are dimensioned to be filled up in approximately ten years. The water drained from the

1 https://books.google.si/books?id=drobBQAAQBAJ&pg=PA245&lpg=PA245&dq=Regstrup+reed+beds&source=bl&ots=Ocuwf7ugkc&sig=ACfU3U1CT73BhTqDPz7K5O5WYxCpARWCJg&hl=sl&sa=X&ved=2ahUKEwiS3KzzytDlAhUls4sKHXXADs8Q6AEwAHoECAgQAQ#v=onepage&q=Regstrup%20reed%20beds&f=false

2 Carlos A. Arias.

3 https://books.google.si/books?id=drobBQAAQBAJ&pg=PA245&lpg=PA245&dq=Regstrup+reed+beds&source=bl&ots=Ocuwf7ugkc&sig=ACfU3U1CT73BhTqDPz7K5O5WYxCpARWCJg&hl=sl&sa=X&ved=2ahUKEwiS3KzzytDlAhUls4sKHXXADs8Q6AEwAHoECAgQAQ#v=onepage&q=Regstrup%20reed%20beds&f=false

sludge percolates through the filter layer of the unsaturated filter bed with prevailing aerobic conditions where treatment processes reduce pollutant concentrations of the drained water. The latter is then pumped back to the wastewater treatment plant for further treatment.

Sludge dewatering in reed beds run by gravity, water percolation, release of capillary water, evapotranspiration, and an additional contribution of the reeds. The continuous growth of the reeds and the combined mechanical effect of the wind on the stems of the plants create new pathways for water drainage and thus increase the drainage of water and prevent clogging. Simultaneously to dewatering, also mineralization of organic matter in the sludge takes place. Both processes reduce the sludge volume and make it a stable, homogenous end-product suitable for further use.

Sludge drying reed beds are widely and successfully used in temperate climates, while there is little data on their application and performance in subtropical and tropical climates. Despite this, they are expected to perform even better in warmer climates due to the more convenient and stable temperatures, which would accelerate the biological activity and thus mineralization and dewatering of the sludge.

Compared to other techniques, the main advantages of sludge drying reed beds are lower initial investment cost, lower operation and maintenance costs, and low power consumption. Experience has shown that the quality of the final product concerning pathogen removal and mineralization of hazardous organic compounds after treatment makes it possible to recycle the biosolids to agriculture as an enhanced treated product.[4]

1.1 Principle of operation

Reed beds are constructed in rectangular concrete basins or soil excavated basins. The bottom of basins is impermeabilized with a waterproof membrane to protect groundwater and to prevent water gains. The drained water from the sludge is collected through perforated pipes, placed on the bottom of beds, and returned to a wastewater treatment plant. The bed hosts a filter with layers of gravel and sand. In the top layer of sand, reeds (Phragmites australis) are planted.

The number of beds and the surface area varies and depends on the amount of sludge to be treated and the local climate. The minimum recommended number of beds for big WWTPs is at least 8. Sludge is distributed homogeneously on the surface of the bed in loading calculated batches. Each feeding period is followed by a resting period that can last for several weeks. During this time, sludge dewatering and mineralization occurs. Sludge feeding of beds rotates within the system, which is why several beds are needed. The duration of resting periods depends on the system's treatment capacity, local weather conditions, age of the system, dry matter content, and characteristics of the sludge.

Sludge dewatering occurs mainly due to the percolation of water through the sludge residue and filter layer, while solids remain on the surface. Residual water content is further reduced by plant evapotranspiration and evaporation from the surface. Final product can be dewatered to up to a maximum 40% of dry matter content, while the volume of all loaded sludge is reduced to 5% of the initial volume.

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[4] S. Nielsen. Helsinge sludge reed bed system: reduction of pathogenic microorganisms. Water Science and Technology, 56 (2005), pp. 175-182;
E. Uggetti, I. Ferrer, S. Nielsen, C. Arias, H. Brix, J. Garcia. Characteristics of biosolids from sludge treatment wetlands for agricultural reuse- Ecological Engineering, 40 (2012), pp. 210-216

Figure 2: Example of excellent performances of sludge treatment reed beds – Skövde (2003, 1.200 tonnes of dry solids per year; left), Rudkøbing (1992, 250 tonnes of dry solids per year; middle), Kolding (1998, 2.000 tonnes of dry solids per year; right)[5]

Sludge mineralization occurs from top to bottom of filter layers due to aeration by plants, cracks in the sludge residue, granular filter layer, and aeration pipes, placed on the bottom of beds. The passive aeration creates aerobic conditions that promote the presence of aerobic microorganisms that accelerates sludge mineralization.

It is expected that a reed beds system can be in operation for more than 30 years. After approximately 8 to 10 years of operation, individual beds are emptied sequentially. Before harvesting the biosolids, the bed to be emptied will not be loaded for about 3 to 4 months to stabilize the top layer further. Once the bed is emptied, a resting period is recommended to allow the regrowth of the plants and the microbial community before a new cycle of loading. The final harvested product from the reed bed system is a dewatered, mineralized, and stabilized sludge. It is an earthy material, which can be reused.

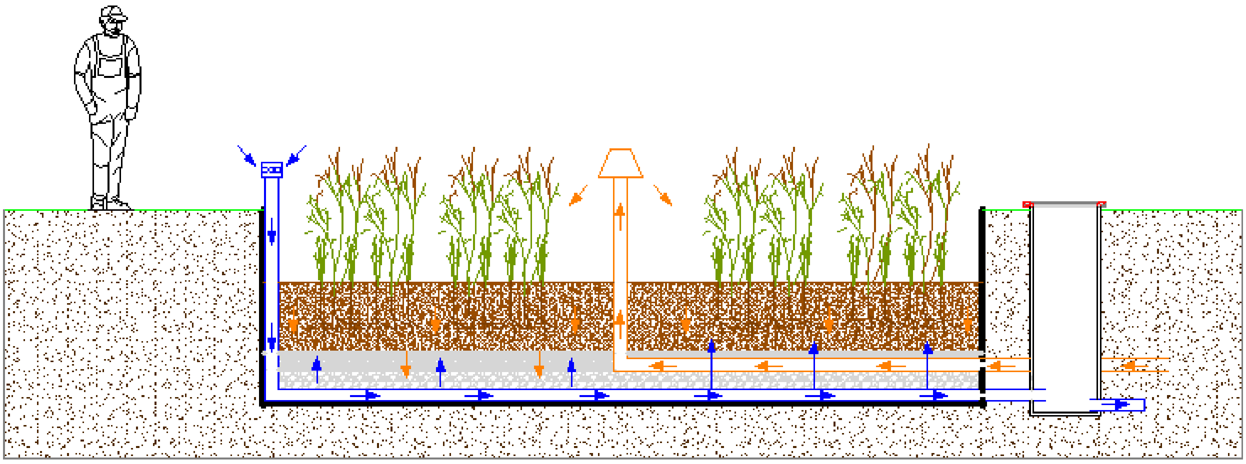

Figure 3: Scheme of reed beds

1.2 Role of plants

Sludge drying reed bed without plant is just a filter layer, also known as (unplanted) drying beds. In a sludge drying reed bed, plants, along with the sun, soil, and wind, create and enhance the biological activity needed to transform sludge into biosolids. The added benefit is transpiration and improved sludge treatment due to the plants. The critical improvement of the planted bed over the unplanted bed is that the filters do not need to be de-sludged after each feeding/drying cycle. Fresh sludge can be directly applied to the previous layer; the plants and their root systems maintain the filter's porosity.

[5,40] Arias, A., C., 2013. Sludge dewatering and mineralization in reed beds. Design and operation consideration. Pictures borrowed from S. Nielsen.

Besides, the roots of the plants create pathways through the thickening sludge that allow water to escape easily.[6] Higher solids content (>30-40 %) may be achieved, but this usually requires sacrificing the plants to drought stress (Nielsen, 1990)[7]. Freezing conditions enhance performance since ice crystals lyse the cell walls of the bacteria in the biosolids (Reed et al., 1995)[8]. It is believed that freezing during the winter aids in dewatering (Kadlec and Wallace, 2009).[9] The filter layer is planted with emergent wetland plants (typically Phragmites australis), and fed throughout the year in intervals. Wetland plants are an essential component of reed beds, and the plants have several roles in relation to the sludge treatment processes.

Figure 4: Rhizomes of common reed[10]*:*

Plants execute the following influences on treatment[11]:

- Photosynthesis;
- Nutrient uptake;
- Contaminant uptake;
- Water uptake (evapotranspiration);
- Insulation;
- Preferential flow;
- Microbial attachment sites;
- Release of organic compounds;
- Release of oxygen.

[6] https://akvopedia.org/wiki/Planted_Drying_Beds

[7] Nielsen S.M. (1990) Sludge dewatering and mineralization in reed bed systems. In: *Constructed Wetlands in Water Pollution Control*, Cooper P.F., Findlater B.C. (eds.) Pergamon Press: Oxford, United Kingdom, pp. 245–256.

[8] Reed S.C., Crites R., Middlebrooks E.J. (1995) *Natural Systems for Waste Management and Treatment.* Second Edition, McGraw-Hill: New York.

[9] https://sswm.info/sites/default/files/reference_attachments/KADLEC%20WALLACE%202009%20Treatment%20Wetlands%202nd%20Edition_0.pdf

[10] Constructed Wetlands for pollution control. Training-course 18-24 October, 2015. Aarhus University, Denmark. Presentation: Plant Functions and Species Selection Strategies in Treatment Wetlands Carlos A. Arias, Pedro N. Carvalho, Otto R. Stein.

[11] Constructed Wetlands for pollution control. Training-course 18-24 October, 2015. Aarhus University, Denmark. Presentation: Plant Functions and Species Selection Strategies in Treatment Wetlands Carlos A. Arias, Pedro N. Carvalho, Otto R. Stein.

Root oxygenation occurs during the daylight and depends on photosynthetic activity[12,13]. Oxygenation by roots has been shown to have a significant impact on important mechanisms of wastewater treatment in constructed wetlands, including influence on redox potential[14], which is critical in determining nitrogen fate, oxidation of some phytotoxins[15], and enhancement of microbial activity.[16]

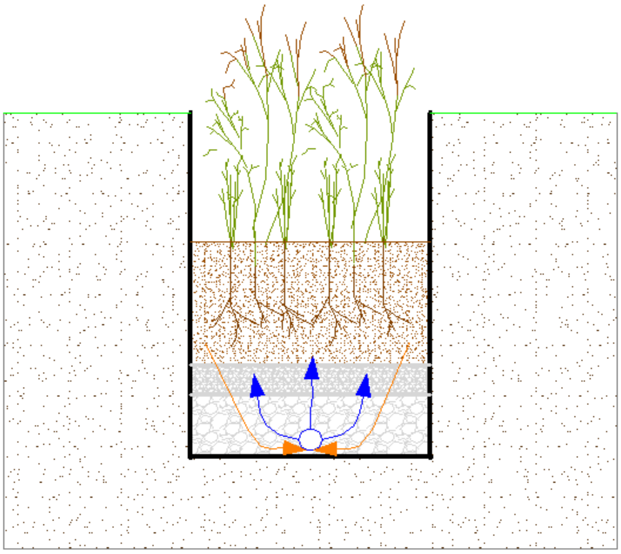

Figure 5: Water and oxygen paths in RBs

The evapotranspiration has a significant role in the process of sludge drying in reed beds. Wetland plants increase the rate of evapotranspiration and hence the loss of water.[17] Plants remove capillary-bound water in the sludge by plant uptake and transpiration. The evapotranspiration rate of reeds is very high and can be even higher than the potential evaporation from an open water surface[18,19]. The movement

The movement of the stems in the wind and the reeds' complex root system maintain the porosity of the sludge residue[20] and create a crack, which is very important as these allow smooth transfer of air (and hence oxygen) into the sludge that stimulate mineralization and further dewatering.[21]

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[12] Williams, H.G.; Bialowiec, A.; Slater, F.; Randerson, P.F. Diurnal cycling of dissolved gas concentrations in a willow vegetation filter treating landfill leachate. Ecol. Eng. 2010, 36, 1680–1685.

[13] Stein, O.R.; Hook, P.B. Temperature, plants, and oxygen: How does season affect constructed wetland performance? J. Environ. Sci. Heal. A 2005, 40, 1331–1342.

[14] Bialowiec, A.; Davies, L.; Albuquerque, A.; Randerson, P.F. The influence of plants on nitrogen removal from landfill leachate in discontinuous batch shallow constructed wetland with recirculating subsurface horizontal flow. Ecol. Eng. 2012, 40, 44–52.

[15] Armstrong, W.; Cousins, D.; Armstrong, J.; Turner, D.W.; Beckett, P.M. Oxygen distribution in wetland plant roots and permeability barriers to gas-exchange with the rhizosphere: A microelectrode and modelling study with Phragmites australis. Ann. Bot. 2000, 86, 687–703.

[16] https://www.researchgate.net/publication/236201259_Role_of_Plants_in_a_Constructed_Wetland_Current_and_New_Perspectives

[17] Constructed Wetlands for pollution control. Training-course 18-24 October, 2015. Aarhus University, Denmark. Presentation: Plant Functions and Species Selection Strategies in Treatment Wetlands Carlos A. Arias, Pedro N. Carvalho, Otto R. Stein.

[18] Stefanakis, A.I.; Tsihrintzis, V.A. Dewatering mechanisms in pilot-scale sludge drying reed beds: Effect of design and operational parameters. Chem. Eng. J. 2011, 172, 430–443.

[19] Chen, Z.B.; Hu, S.S.; Hu, C.X.; Huang, L.L.; Liu, H.B.; Vymazal, J. Preliminary investigation on the effect of earthworm and vegetation for sludge treatment in sludge treatment reed beds system. Environ. Sci. Pollut. Res. 2016, 23, 11957–11963.

[2020] Nielsen, S. (2003). Sludge drying reed beds S. Nielsen. Water Science and Technology **Vol**, 48 **No** (5 **pp**), 101–109 © IWA Publishing 2003. https://doi.org/10.2166/wst.2003.0292

[21] ReviewBrix, H. (2017). Sludge Dewateringdewatering and Mineralizationmineralization in Sludge Treatment Reed Beds Hans Brix sludge treatment reed beds. Water 2017,(Switzerland), 9, 160(3). https://doi.org/10.3390/w9030160

The created microclimate conditions by plants enhance system resilience to all kinds of extreme weather, such as freezing in winter and dry periods in summer. The aboveground biomass of reed during winter (dried plant cover on the surface) has an insulating effect and ensures better winter efficiency of the reed beds.

A dense vegetation of reeds keeps a high hydraulic capacity in sludge treatment reed beds.[22] Root growth is well known to affect some soil hydraulic qualities[23,24]. Physical effects of roots include filtering, flow velocity reduction, improved sedimentation, decreased resuspension, and even the distribution of water and prevention of clogging[25,26]. The root growth and the physical presence of the stems that moves by the action of wind keep the bed substrate permeable to water (Figure 9).[27]

Reed roots are also a base for microorganisms. They provide surface area for attached microbial growth. Plants stimulate microbial activities in the sludge[28], and transfer oxygen to the sludge through root release[29], but these functions are less documented and are probably of less importance. Oxygen diffusion from the roots into the sludge residue might enable aerobic microorganisms to exist close to the roots and in the sludge residue.[30]

The ability to transport O2 and aerate below-ground tissues is the most crucial factor in emergent plant survival in treatment wetlands.[31] Thomas et al.[32] mentioned that aerenchyma tissue plays a role in the emission of methane into the atmosphere through emergent wetland plants (Figure 6), supporting Reddy et al.[33] who revealed the role of aerenchyma in releasing, to the atmosphere, N_2 and N_2O produced by anaerobic denitrification of NO_3 in the wastewater.[34]

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[22] Constructed Wetlands for pollution control. Training-course 18-24 October, 2015. Aarhus University, Denmark. Presentation: Plant Functions and Species Selection Strategies in Treatment Wetlands Carlos A. Arias, Pedro N. Carvalho, Otto R. Stein.

[23] Stottmeister, U.; Wiessner, A.; Kuschk, P.; Kappelmeyer, U.; Kastner, M.; Bederski, O.; Muller, R.A.; Moormann, H. Effects of plants and microorganisms in constructed wetlands for wastewater treatment. Biotechnol. Adv. 2003, 22, 93–117.

[24] Cooper, P.; Boon, A. The Use of Phragmites for Wastewater Treatment by the Root Zone Method: The UK Approach. In Aquatic Plants for Water Treatment and Resource Recovery; Reddy, S.W., Ed.; Magnolia Publishing: Orlando, FL, USA, 1987; pp. 153–174.

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[26] Vymazal, J. Plants used in constructed wetlands with horizontal subsurface flow: A review. Hydrobiologia 2011, 674, 133–156.

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[28] Faulwetter, J.L.; Gagnon, V.; Sundberg, C.; Chazarenc, F.; Burr, M.D.; Brisson, J.; Camper, A.K.; Stein, O.R. Microbial processes influencing performance of treatment wetlands: A review. Ecol. Eng. 2009, 35, 987–1004.

[29] Gersberg, R.M.; Elkins, B.V.; Lyon, S.R.; Goldman, C.R. Role of aquatic plants in waste-water treatment by artificial wetlands. Water Res. 1986, 20, 363–368.

[30] Review Sludge Dewatering and Mineralization in Sludge Treatment Reed Beds Hans Brix[30] Brix, H. (2017). Sludge dewatering and mineralization in sludge treatment reed beds. Water (Switzerland), 9(3). https://doi.org/10.3390/w9030160

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[32] Thomas, K.L.; Benstead, J.; Davies, K.L.; Lloyd, D. Role of wetland plants in the diurnal control of CH4 and CO2 fluxes in peat. Soil Biol. Biochem. 1996, 28, 17–23.

[33] Reddy, K.R.; Patrick, W.H.; Lindau, C.W. Nitrification-denitrification at the plant root-sediment interface in wetlands. Limnol. Oceanogr. 1989, 34, 1004–1013.

[34] https://www.researchgate.net/publication/236201259_Role_of_Plants_in_a_Constructed_Wetland_Current_and_New_Perspectives

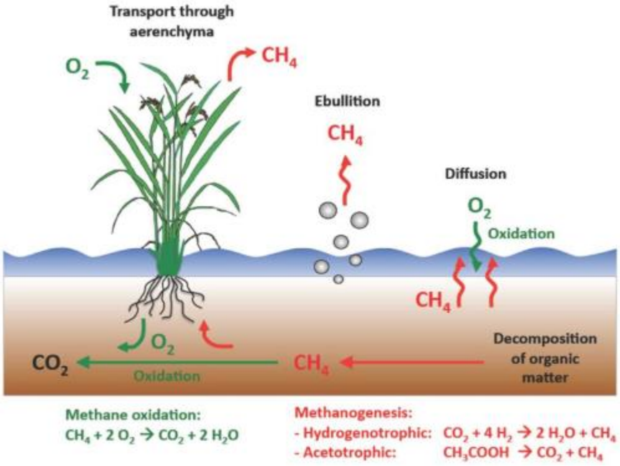

Figure 6: Generation and emission of methane from wet soils. (Courtesy of Josef Zeyer, ETH Zurich, Switzerland.)[35]

Phragmites australis has a root porosity of 58 % of air.[36] Reeds enable transport by internal molecular diffusion of gases in air-space tissue (Figure 7). Transport by internal convective flow of gases in air-space tissue is important for aeration of roots and ability to grow in deep water. [37]

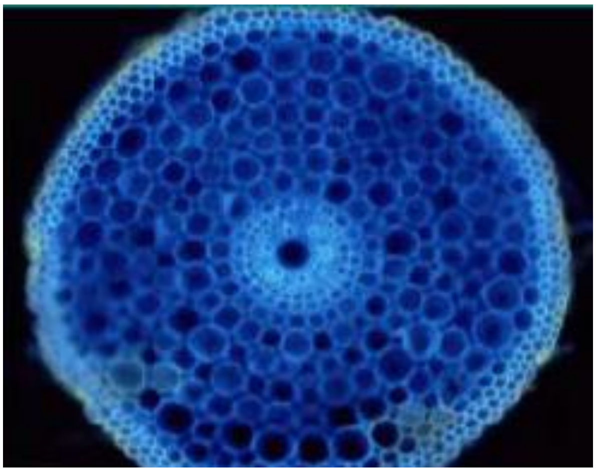

Figure 7: *Phragmites*, schizogenous spaces near root tip[38]

The presence of plants has shown to be essential for limiting the discharge of pollutants by RBs. The influence of plants on pollutant removal varies with time, with generally higher differences between species in mid-summer, which is possibly related to plant establishment and maturity.[39] Planting plants on reed bed performance is not more significant in a cold climate than in a warm environment.

[35] https://dl.sciencesocieties.org/publications/sh/articles/53/4/12

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[38] Constructed Wetlands for pollution control. Training-course 18-24 October, 2015. Aarhus University, Denmark. Presentation: Plant Functions and Species Selection Strategies in Treatment Wetlands Carlos A. Arias, Pedro N. Carvalho, Otto R. Stein.

[39] Effect of plant species on water quality at the outlet of a sludge treatment wetland Vincent Gagnon a, Florent Chazarenc b, Margit Ko˜iv a, Jacques Brisson a, a Institut de Recherche en Biologie Ve´ge´tale, De´partement de Sciences Biologiques,

1.3 Filtration and interception

The reed beds are built as planted vertical filters with an efficient drainage system to dewater the sludge effectively.[40] Physical filtration and deposition of organic matter on the surface of beds separate solids from a liquid where suspended solids concentrations, bed loading, and composition of the filter layer play a key role. Inappropriate bed material and operation without adequate rest interval can cause clogging of the bed. High loading of suspended solids can lead to excessive biological growth, which may also clog the filter layer and failure of the RBs. When the filter layer clogs, water stays on the surface and results in poor sludge treatment, odor, and proliferation of vectors.

Variable sizes of filter media can be used. Coarse media (e.g., gravel) has more pore spaces and allows the passage of more solids, whereas finer media provides a greater frictional resistance to the liquid flow and removes more solids. RBs are usually designed with layers of increasing size media, from sand at the top to gravel at the bottom. The depth of the filter determines the hydraulic retention time, and the head loss of the liquid, or the energy each unit volume needs to flow through the filter.[41] Media for filter layer has to be pre-washed, so that fine particles do not clog the media. RBs filtration is driven by gravity. Solid materials are removed from the liquid through filtration/interception and other settling mechanisms (straining, sedimentation on media, adhesion, and flocculation).

Filtration, enhanced by the presence of plants, plays a vital role in pollutant removal, resulting in the retention of solids by the granular matrix.[42]

1.4 Evapotranspiration (ET)

Water loss to the atmosphere occurs from open or subsurface water (evaporation), and through the evapotranspiration of the emergent plants.[43] Sludge stabilization happens through dewatering and evapotranspiration. The majority of sludge water content flows vertically through the sludge residue and the filter layer. The sludge residue water content is further reduced through evapotranspiration along the years that the sludge is in the beds.[44] The evapotranspiration is particularly important during the final resting period (usually several months during summer) before the beds have to be emptied. Because of the high evapotranspiration rates of the reeds, which exploit the capillary-bound water in the sludge, the dry matter content of the sludge may be as high as 40 % when the beds are emptied.[45] Regarding RB design, water volume lost through ET is of main concern, and the attendant energy flows associated with ET can be ignored. However, there are a variety of methods to estimate ET. Some estimation methods rely on energy balance calculations, while others rely on surrogate measurements.[46]

Universite´ de Montre´al, 4101 Sherbrooke Est, Montre´al, Que´bec, H1X 2B2 Canada b Ecole des Mines de Nantes, GEPEA UMR CNRS 6144, 4, rue Alfred Kastler, B.P. 20722, F-44307 Nantes Cedex 3, France

[40] Sludge Dewatering and Mineralization in Sludge Treatment Reed Beds. Hans Brix

[41] https://www.un-ihe.org/sites/default/files/fsm_book_lr.pdf

[42] Effect of plant species on water quality at the outlet of a sludge treatment wetland
Vincent Gagnon a, Florent Chazarenc b, Margit Ko˜iv a, Jacques Brisson a,*

[43] https://sswm.info/sites/default/files/reference_attachments/KADLEC%20WALLACE%202009%20Treatment%20Wetlands%202nd%20Edition_0.pdf

[44] Sludge drying reed beds S. Nielsen. Water Science and Technology **Vol 48 No 5 pp 101–109** © IWA Publishing 2003

[45] Review Sludge Dewatering and Mineralization in Sludge Treatment Reed Beds Hans Brix Water 2017, 9, 160

[46] https://sswm.info/sites/default/files/reference_attachments/KADLEC%20WALLACE%202009%20Treatment%20Wetlands%202nd%20Edition_0.pdf

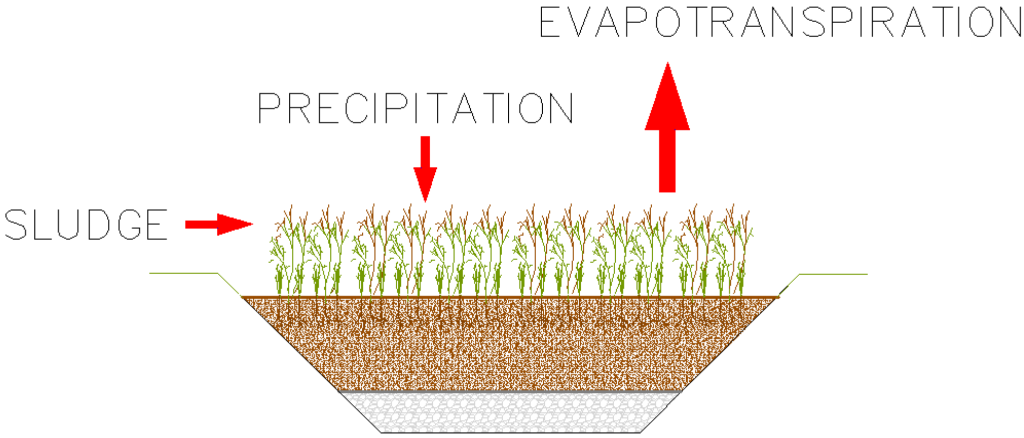

Figure 8: Water balance in RB system

Commonly used reed *(Phragmites australis)* is exceptionally tolerant of variable environmental conditions and has a high evapotranspiration rate[47]. Evapotranspiration rates in the Czech Republic from wetland dominated by *Phragmites australis* was reported to be between 6,9–11,4 mm·d^{-1} (Květ 1973)[48]. Loading rate and precipitation data impact the biomass production of plants, thus water balance under extreme seasonal conditions should be taken into the account when operating the system. The plant health depends on water availability in the system. During dry periods, measures for water retention within the system may also be applied.

Because evapotranspiration is a mayor dewatering force, climate has a significant effect on reed beds operation. Climate most significantly influences the ET of water from the bed. Precipitation and humidity increase drying time while high temperatures and wind reduce it.

1.5 Mineralization and stabilization

Mineralization of organic matter in the sludge is a treatment mechanism minimizing sludge volume over time. Mineralization is the process by which biologically available inorganic nutrients are released during the degradation of organic material (e.g., the degradation of amino acids results in the release of ammonia).[49] Aerobic conditions accelerate mineralization. The organics in the sludge oxidize, resulting in the mineralization of organic-bound substances. Oxygen from the atmosphere to the filter layer enters through the ventilation and drainage piping system, cracks in the sludge (Figure 9), and plant root release. The sludge volume reduction relies on natural processes (biological and physical) without the use of chemicals. The degree of mineralization achieves rates from 20 to 40 %, mainly depending on the climate and maximum loading rate (kg TSS/m^2 y).

[47] https://apps.dtic.mil/dtic/tr/fulltext/u2/a273500.pdf
[48] Květ J (1973) Transpiration of South Moravian Phragmites communis littoral of the Nesyt Fishpond. Studies Cz Acad Sci 15:143–146
[49] https://www.un-ihe.org/sites/default/files/fsm_book_lr.pdf


Figure 9: Cracks in the sludge[50]

Stabilization is a process aiming to reduce and transform the biodegradable fraction of the organic matter, thus decreasing the risk of anaerobic degradation and reducing the concentration of pathogens. Stabilization also brings a reduction in the solids mass in the sludge.[51] Solids in sludge can be either volatile or fixed. The ratio of volatile to total solids (VSS/TSS) indicates the organic fraction in the sludge solids, as well as its level of digestion. A decrease in the load of total solids is expressed in a reduction of volatile suspended solids. Total volatile solids (TVS) content indicates the change in readily degradable material[52]. A performance of reed bed treatment is indicated in the reduction of TVS content. The decomposition (mineralization) processes in reed beds are mainly temperate (climate) dependent. The mineralization in a warmer climate can reduce more than 50 % of organic matter resulting in TVS values under 40 %.

RBs stabilize the sludge and produce biosolids for potential reuse. The stabilized biosolids have nor odor and reduce pathogens. Further stabilization of sludge after sufficient residence time of several months is not needed.

1.6 Pathogen removal

Sludge microbial quality is a significant issue to be assessed for the sustainable reuse of sludge in agriculture.[53] Final sludge disposal might present a health risk issue because of the risk of spreading pathogens.[54] The contents of pathogenic bacteria must be reduced before sludge can be spread on agricultural land as a fertilizer.[55] The degree of pathogen reduction in the sludge varies with the climate.[56] Reduction of the concentration of pathogens is achieved with the application of a resting period of a few months to one year after the last dosing of sludge. During this period, natural air-drying on the open air of reed beds continues to accelerate pathogen die-off. The resting period usually occurs during spring and summer because warm and dry weather is better for pathogen reduction, but also because of potential sludge reuse in autumn. The reduction of pathogenic bacteria must be high enough to produce high-quality biosolids. Process depends very much on the local climate, temperature, storage time, water content, solar/UV radiation, and pH.

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[50] Arias, A., C., 2013. Sludge dewatering and mineralization in reed beds. Design and operation consideration.
[51] http://site.iugaza.edu.ps/rkhatib/files/2015/02/Sludge-Managemant-Chapters-1-and-2.pdf
[52] https://www.un-ihe.org/sites/default/files/fsm_book_lr.pdf
[53] https://www.researchgate.net/publication/260852165_Hygienization_by_innovative_sludge_treatment_processes_to_assure_safe_land_spreading
[54] Biological Wastewater Treatment Principles, Modelling and Design. Mogens Henze Mark C. M. van Loosdrecht George A. Ekama Damir Brdjanovic
[55] Review Sludge Dewatering and Mineralization in Sludge Treatment Reed Beds Hans Brix Water 2017, 9, 160
[56] http://www.dwm-acc-jordan.net/fileadmin/Library/How_Treatment_Impacts_the_Climate/Module5_L15-17_offline.pdf

Most pathogens are inactivated above temperatures of 60˚C when cell proteins and nucleic acids are denatured. As the temperature increases, less time is needed for pathogen inactivation. Another important parameter that plays a role in the process of pathogen reduction is the long storage time (sludge storage time). Most of pathogens bacteria can only survive between 1 week and two months. Helminth eggs, however, are very persistent and can maintain viability for several months to years. [57] Sludge on reed beds accumulates for 8 and more years, thus content of pathogens is lower in the old sludge layers (close to filter media) and higher in the fresh sludge layers (close to surface). Sludge on reed beds accumulates for eight and more years, thus the content of pathogens is lower in the old sludge layers (close to filter media) and higher in the fresh sludge layers (close to surface).

All dewatering technologies are contributing to pathogen die-off because microorganisms require water for their survival. Solar/UV radiation in the range of 300-400 nm effectively inactivates pathogens by denaturing DNA molecules via photochemical reactions[58]. Pathogen reduction due to solar/UV radiation occurs only in the surface layer of accumulated sludge, because it cannot penetrate the lower layers. Ph of biosolids on reed beds does not affect the pathogen reduction (pH values are not below three or above ten where most pathogens cannot survive).

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[57] https://www.un-ihe.org/sites/default/files/fsm_book_lr.pdf

[58] Borrely, S.I., Cruz, A.C., Del Mastro, N.L., Sampa, M.H.O., Somessari, E.S. (1998). Radiation processing of sewage and sludge. A review. Progress in Nuclear Energy 33(1–2), p.3-21.