Sludge reed bed facilities: operation and problems

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Abstract Short operating periods and problems with dewatering efficiency, vegetation, mineralisation and odour are primarily caused by incorrect construction of the filter, poor capillary connections, an inadequate number of basins, insufficient basin area and overloading during commissioning and during subsequent operation. Dimensioning should be based on the sludge quality including the dewatering qualities and not solely on calculations of the sludge production. Loading after planting depends on the development level of the vegetation. The loading program should ensure that reed establishment is not impeded and should prevent the sludge residue from growing so quickly horizontally and vertically that the reeds cannot colonise the sludge residue. Overloading results in an anaerobic sludge residue with ensuing methane production. Typically, a sludge reed bed facility with a loading period of maximum 5 days, must be built with 10 basins to permit a rest phase of about 40 days. Facilities with 8 basins, where it is possible to load 1 basin for 7 days, will be able to have a 7-week rest phase before the first basin is loaded again. Facilities with for example 8–13 basins and loading period of between 4 and 10 days are able to achieve rest periods of up to 2 to 2½ months, which results in the optimal evapotranspiration and mineralization. The conditions and thus the possibilities vary depending upon the type of sludge.

Keywords Dimensioning; capillary function; loading; methane; problems; reed bed; sludge dewatering

Introduction

Sludge treatment in reed beds facilities has been practised in Denmark for the last 15 years. Experience shows (Nielsen 2002, 2003) that correct dimensioning, construction and operation of the basins ensures a 10-year operational period, effective dewatering in the form of draining and evapotranspiration of water from the sludge as well as a good decomposition of organic matter. In general, short operational periods and operational problems with loading and dewatering capacity, vegetation, mineralisation, odours, as well as poor sludge residual quality are predominately associated with improper construction of the filter, too few basins and/or insufficient basin area. Overloading during the run-in period and in the subsequent operational period are other typical operational errors. Dimensioning and construction of a sludge reed bed facility must be based on an analysis of the sludge quality, in particular the dewatering characteristics of the sludge. Furthermore, knowledge about the composition of the sludge, for example the fat content, the ratio between organic and inorganic material, etc. As well the climatic conditions must be considered when dimensioning sludge reed bed facilities. The construction of the filter, and not least the upper growth layer composition, has an important effect on the efficiency of the sludge dewatering process. In addition to determining the type of sludge, dimensioning of a reed bed facility must be based on knowledge of the annual excess sludge production from the wastewater treatment plant in units of tons of dry matter. Will the sludge production increase or decrease in the future? How reliable is the production accounting? What type of sludge will the facilities be treating? It is recommended that a sludge reed bed facility be dimensioned with a capacity that is 10–20% larger than the estimated sludge production. Dimensioning starts with an areal loading (kg dry matter/m²/year) on the filter surface. In terms of operation, the following requirements constitute the basis for dimensioning a sludge reed bed facility (Nielsen 2002, 2003):
An operational period of at least 8 years (including the run-in period) before the first basin must be emptied.

• A cycle of, for example, 4 years for emptying of all the basins.

• Treatment capacity for the facilities as a whole must be maintained during the emptying phase during which the basins are emptied in turn and subsequently re-established.

• Re-establishment of the vegetation after emptying without requiring re-planting.

Operation
In Denmark, the areal loading (kg dm/m²/yr) has been extremely variable, especially for the first 30–50 sludge reed bed facilities, where loading at some of the facilities was up to 100 kg dm/m²/yr. It quickly became apparent that the reed beds facilities were being overloaded. Thereafter, the loading was stabilised to about 50–60 kg dm/m²/yr (Nielsen 2002, 2003). Generally, the sludge reed beds facilities treat activated sludge. A few facilities treat a blend of activated sludge and digested sludge. With regard to the sludge quality the following maximal loadings to a facility running at full capacity are recommended: 60 kg dm/m²/yr for activated sludge and 50 kg dm/m²/yr for digested sludge (Nielsen 2002, 2003). About 60–70 of the Danish sludge reed bed facilities have between 1 and 7 basins. In terms of an operational period of 10 years, the effectiveness of the dewatering, as well as the mineralisation process, it is crucial that a sludge reed bed facility is run so that operation of individual basins alternates between loading and resting periods. A minimum of 8 basins is required to achieve the necessary balance between loading and resting periods (Nielsen 2002, 2003). Facilities with a treatment capacity greater than 500 tons of dry matter generally have 8 or more basins. The largest facilities have up to 10–18 basins. At a properly functioning reed bed facility, the dewatering of the activated sludge will have curves with a clear peak with a maximal drainage of the order of 0.01–0.015 l/s/m² (Nielsen 2002, 2003).

Operational problems
Sludge reed bed facilities with operational problems often have a rapidly growing layer of residual sludge and thus a short period of operation. Based on experience from the last 15 years operation of sludge reed bed systems, the most common operational problems are the following: insufficient dewatering, poor vegetation growth and coverage, odour problems and poor mineralisation (Table 1). The symptoms clearly signal whether a facility is properly constructed and properly operated without overloading. Often symptoms of a poorly run facility are observed in the vegetation, the degree of dewatering and the growth in the residual sludge layer. Vegetation becomes stressed, fails, and holes in the vegetation coverage result. In the basins, conditions develop which result in less than 100% vegetation coverage, and in some cases the vegetation completely disappears from the basins. Dewatering is incomplete and proceeds slowly (<0.002 l/s/m²). In a facility with operational problems, the dewatering is more or less constant without a drainage profile with a maximum related to the loading. The thickness of the residual sludge layer in the basins increases rapidly as a consequence of poor sludge dewatering. At some overloaded facilities a situation has arisen where the vegetation is satisfactory, but the dewatering of the residual sludge is so poor that the sludge residue is very wet or there may even be a permanent layer of water on the surface of the residual sludge layer. Causes of operational problems are typically the following: 1, improper construction of the facility, in particular the filter; 2, excessive areal loading during the commissioning phase and in the subsequent operation relative to the type of sludge; 3, improper balance between loading and resting phases due to an inadequate number of basins.
Insufficient dewatering is most often due to the quality of the sludge and the sludge residual, poor permeability in the residual sludge layer and in the growth layer, and a lack of capillary connection between the layers in the filter including the sludge layer, poor vegetation or poor coverage and overloading. Typically, in well-drained sludge reed bed facilities, the drainage will continue until the sludge residue attains a dry matter content of about 20% (Nielsen 2002, 2003). At some Danish facilities with evapotranspiration it has been possible to achieve a dry matter content of 40% in the sludge residue prior to the emptying phase. The capacity of the reed bed facility is limited if evapotranspiration takes place from the water surface or from a half-wet sludge residue (<20% dry matter). Improperly exploited evapotranspiration may lead to reduced dewatering, which in turn may result in sludge residue experiencing permanent anaerobic conditions and an increase in the thickness of the layer which shortens the operational period before emptying is required.

Overloading, sludge quality and sludge residue

Overloading causes obvious operational problems (Table 1). There are examples of facilities treating activated sludge, where an excessive areal loading and/or too few basins, results in operational problems. A Danish reed bed facility (Personal communication, 1), which is dimensioned to treat activated sludge (420 tons of dry matter), is constructed with 8 basins with a total filter area of 4800 m² giving an areal loading rate of 88 kg dry matter/m²/yr. The basins were planted with reeds in April 2002, and brought into operation in June 2002. The reed bed facility was loaded with 327 tons of dry matter in the first year, which resulted in an average areal loading of 68 kg dm/m²/yr. While the facility had the correct number of basins, the total area was not adequate. During some periods the loading occurred daily rather than with alternating rest phases. During some periods the rest phases ranged from 2–3 days, during other periods there were no pauses between loading periods. After 1 year of operation, the vegetation had died in 3 basins, and was

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Table 1 Reasons for operating problems in sludge reed beds facilities

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<th>Insufficient dewatering</th>
<th>• Sludge and sludge residue quality</th>
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<td>• Overloading during commissioning in general, and in each loading period</td>
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<td>• Uneven loading (kg dm/m²/yr)</td>
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<td>• Lack of accurate registration of areal loading rate (kg dm/m²/yr)</td>
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<td>• Lack of operation and data collection modules</td>
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<td>• Insufficient operating instructions and training</td>
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<td>• Insufficient area and number of basins</td>
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<td>• Loading periods on each basin are too long and rests phases are too short</td>
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<td>• Filter composition (growth medium) and poor capillary connection</td>
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<td>• Incomplete vegetation coverage or stressed vegetation</td>
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<td>• Evapotranspiration from open water surface instead of from sludge residue</td>
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<td>Poor vegetation growth and inadequate cover</td>
<td>• Planting of too few and immature plants per m²</td>
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<td>• Planting out directly on filter and problems with weeds and insects</td>
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<td>• Lack of additional planting during commissioning phase</td>
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<td>• Overloading during commissioning phase and in newly re-planted basins</td>
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<td>• General overloading and anaerobic conditions (methane generation)</td>
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<td>• Insufficient dewatering efficiency and no regrowth after emptying</td>
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stressed in the remaining 5 basins. A sludge residue with a dry matter content of about 10–15% had accumulated. Loading stopped at the beginning of July 2003. The thickness of the sludge residue and the yearly growth in the thickness of the sludge residue was a minimum average of about 0.45 m in January 2004. Normally, during the first year of commissioning a new facility, a sludge residue thickness of 0.10–0.14 m would accumulate (Nielsen 2002, 2003). In addition to overloading, the facility had problems due to poor capillary connection between filter layers and the sludge layer. The combination of poor capillary function, high areal loading and short rest periods resulted in a slow dewatering and a permanently high water content in the residual sludge.

Another Danish sludge reed bed facility was brought into operation in the spring of 1996 with loading at full capacity (Personal communication, 2). The facility is composed of 4 basins each with a filter area of 644 m². The facility is dimensioned to treat 160 tons of dry matter per year for a period of 10 years, representing an areal loading of 62 kg dm/m²/yr. The yearly sludge production is estimated to be about 135 tons of dry matter. During the 6-year period, between 1997–2002, the annual loading ranged between 45 and 63 kg dm/m²/yr. The basins have, on average, been loaded with about 54 kg dm/m²/yr. The activated sludge distributed to the basins has a dry matter content of 0.5–4.0%. In the period from when the facility was established until April 2002, the loading pattern was loading 1 day of loading per basin, giving each basin a rest period of 3 days. Since April 2002 the loading pattern has been loading 1 basin per week followed by a 3-week loading pause in that basin. The thickness of the sludge residue was on average about 1.1 m in January 2004, representing an average annual growth rate of about 0.16 m/yr (Figure 1). One basin was emptied in July/August 2003. If another basin is removed from operation to be emptied, then the loading in 2004 will cause the thickness of the sludge residue in the remaining basins to reach the maximum allowable level in the basins. Based on prognoses, at the end of 2005, the facility will have treated approximately 1,200 tons of the total of 1,600 tons dry matter it was dimensioned to handle (Figure 1). A similar sized facility, correctly constructed and established with 8 basins, could have treated a maximum annual sludge load of approximately 55 kg dry matter/m² in about 10 years (Nielsen 2002, 2003) in total about 1,850 tons of dry matter (Figure 1).

A third Danish sludge reed bed facility was dimensioned to treat activated sludge (220 tons dm/yr). The facilities have 6 basins and a total filter area of 3800 m². The basins were planted with reeds in October 2000 and brought into operation in 2001. The facility had the following loadings: about 20 kg dm/m²/yr (2001); about 46 kg dm/m²/yr (2002); about 66 kg dm/m²/yr (2003) (Personal communication, 3). Until December 2002, the loadings were approximately daily and the rest periods in the basins were about 5–10 days between loadings. From December 2002, the basins were loaded for about 6 days and then left for about 30 days until the next loading. After 3 years of operation the vegetation is now stressed and there are holes in the vegetation cover in all basins. The thickness of the residual sludge layer was about 0.60–0.70 m in April 2004, which represents an increase of about 0.20–0.25 m/yr with a dry matter content of <20%. The increase has been so rapid that the vegetation could not adapt to the constantly changing elevation of the sludge residue layer. Today the reeds are limited to the original filter area. There has been no spreading of vegetation in the residual sludge on the sloping sides of the basin (Figure 3). Normally, during a period of operation of 3 years a sludge thickness of about 0.25–0.30 m (Nielsen 2002, 2003) would develop. Although the areal loading has been more or less suitable considering the basin areas and age of the facility, the short rest periods resulted in a slow constant dewatering (about 0.0009 l/s/m²) and a permanent high water content in the residual sludge. The moist residual sludge acts as a wet seal, which prevents aeration. Residual sludge, which is constantly anaerobic, with significant
gas development (Figure 2B), deteriorates the environmental conditions for reeds and various animals, particularly earthworms, which normally live in the residual sludge.

Investigations of methane gas production from the Helsinge Sludge Reed Bed Facility (Danmarks Tekniske Universitet, 1998) demonstrate that there was production of methane from the wet sludge residue in the first days after a loading phase until the residual layer became suitably dewatered. The Helsinge facility has 10 basins. It was operated with about 7 days loading followed by 50–70 days rest phase before the next loading. It is important that the individual basins receive a rapid loading of short duration followed by an aeration of the sludge residue. A condition for aeration of the sludge is that the upper layer, in particular, becomes cracked and broken during the rest phase. When the first basins in Rudkøbing were emptied after 10 years of operation, visible channels with dimensions of 1–2 cm were observed. In addition, there were openings and cracks in the residual sludge in the various layers due to desiccation during pause periods (Nielsen 2002, 2003). If this cracking does not take place either due to ineffective dewatering or due to the sludge residue forming a tight layer, then there is a risk of anaerobic sludge residue with methane formation, which can inhibit vegetative growth. If vegetation is missing, or poor quality, the dewatering efficiency is reduced, and the mechanical reed activity, which can break up the sludge residue is also reduced. This leads to a situation where anaerobic conditions are maintained. Experience with distribution of pre-aerated

Figure 1 Growth in the thickness of the sludge residue layer for sludge reed bed facilities with 8 and 4 basins brought into operation in 1992 and 1996, respectively. (Nielsen 2002, 2003; Personal communication, 2)

Figure 2 Structure and quality of the residual sludge layer. Danish sludge reed bed systems: A. Rudkøbing, B. (Personal communications, 3), C. Nakskov, D. Tidaholm (Sweden)

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primary sludge with a sludge age of 2–6 days has demonstrated that a similar type of anaerobic conditions develop due to the sludge type which forms a very tight and relatively dry sludge residue which has been observed in the facilities in Nakskov (10 basins) and Tidaholm (8 basins, 20 kg dm/m²/yr in 1998 to about 40–45 kg dm/m²/yr in 2002), respectively. After distribution the residual sludge formed a continuous layer like a membrane, which was both thin and tough. The layer was stable for long periods and only partially split during rest phases. Aeration via the surface of the residual sludge was reduced and this contributed to anaerobic conditions throughout the entire sludge residue layer. The anaerobic conditions probably resulted in methane production and the vegetation growth was inhibited. The membrane-like residual sludge was furthermore physically inhibiting for new plant growth, as new plants had difficulty sprouting through the tough layer (Figure 2C, D). This condition requires a very long pause phase to break the sludge surface. Such a tight and dry residual layer is normally not observed during treatment of activated sludge where the alternating operation creates a very open and cracked sludge layer.

Filter construction
Correct filter construction is a critical factor in the effectivity of a sludge reed bed facility. Both the composition of the individual layers as well as the capillary connection between the individual layers, especially between the uppermost layer of the filter and the residual sludge layer must be considered. If the capillary connection between two layers is broken a situation may arise which is referred to as ‘hanging water’. The downward pressure of the water in a saturated uppermost layer is exceeded by the resistance imposed by the lack of capillary connection between the upper and lower layers. Thus, the water ‘hangs’ above the underlying layers, rather than infiltrating. The lack of capillary function is due to an inappropriately large increase in the pore size of the filter material used in adjacent layers.

A sludge reed bed facility in Norway has a filter composed of 2 sand layers. The uppermost sand layer is composed of about 90% coarse sand (0.25–2.0 mm) and about 10% fine sand (<0.25 mm). This layer represents the growth layer where the vegetation was planted. Drainage measurements from the reed bed facility indicated a rapid drainage (maximum about 0.01–0.02 l/s/m²), immediately after loading of the basins and then a rapid decrease in the drainage rate. The permeability was estimated to be between 30 and 63 m/day, giving a flow rate in the 15-cm thick sand layer of about 7–4 minutes, respectively. This demonstrates that there is appropriate flow through the sand layer. Measurements of the dry matter content in the residual sludge have been maximum 12–15% (Personal communication, 4). These measurements support the above-mentioned theory regarding ‘hanging water’. Initially, during a loading, the height of the loaded sludge exceeds the resistance imposed by the lack of capillary connection and the sludge drains. Drainage proceeds until an equilibrium is again reached. The residual sludge is only partially dewatered. When hanging water is observed the explanation may thus be a lack of capillary connection between the sand and the residual sludge layer. Hanging water is an operational problem which has been seen in Danish sludge reed bed facility (Personal communication, 1). The growth media was spread directly on a stone layer (16–32 mm) and drainage was very slow because there was no connection between the growth medium and the stone layer. At the Skive Sludge reed bed facility the problem was the construction of the filter. The growth media had a high content (>10%) of fine particles (clay, silt and organic matter), which resulted in a slow drainage (0.002 l/s/m²). In addition to the poor drainage, growth conditions in the residual sludge worsened and resulted in stressed and dying vegetation partly because the run-in loading rate was too
high (Nielsen 2002, 2003). Improvement of the drainage problems arising from errors in the construction of the filter is a difficult and expensive process. Generally, the residual sludge layer and the uppermost filter layers must be excavated. The filter must be rebuilt, and a new growth medium layer added and new reeds must be planted.

**Poor vegetation growth and inadequate cover**

It is important that the vegetation receives suitable conditions to establish itself and grow. Furthermore, the number of reed facilities must be sufficient to provide a rapid coverage over the entire basin within 1–2 growing seasons (Nielsen, 2002). The reeds contribute to improved drainage of the sludge (Figure 4A). When the residual sludge has drained to about 20% dry matter, the dewatering process continues via evapotranspiration until a dry matter content of about 40% is obtained. The dewatering capacity of a reed bed is maintained or improved by the mechanical activity of the reeds in the residual sludge layer and the filter. The mechanical activity includes shoots and rhizomes, which move through the layers, as well as the above ground movement of the plants due to wind. This movement prevents clogging, and maintains the porosity in the residual sludge and the filter, which in turn maintains the dewatering efficiency (Nielsen, 2002). Overloading and insufficient draining of the residual sludge may result in poor vegetation growth and insufficient root and rhizome development in the residual sludge layer (Figures 3B and 4B), because the thickness of the residual layer is increasing too rapidly. In some facilities almost no root or rhizome development in the residual sludge layer has been observed. Vegetation establishes itself in the filter and sends only underground shoots through the un-dewatered residual sludge and the basins may appear to be well established with reeds and have a good degree of coverage.

**Discussion**

The dimensions of a reed bed facilities must consider the particular dewatering characteristics of a particular type of sludge, as this determines the ratio between loading and rest phases. Experience has shown that sludge reed bed facilities with too few basins (less than 8) often have operational problems and short periods of operation before an emptying phase is necessary. Often the residual is poorly drained and anaerobic. Two sludge reed bed facilities with the same filter area, but with, for example 4 and 8 basins, respectively, will produce different residual sludge volumes (Figure 1) and thus have different operational periods. A common characteristic for the majority of the Danish sludge reed bed facilities is that they have a loading period of 2–8 days. Facilities with a maximal possible loading period of 5 days must typically have 10 basins and thus achieve about 40 days rest phase. A facilities with 8 basins where it is possible to load one basin for

**Figure 3** Reeds (A) Well developed vegetation with slope vegetation in the residual sludge layer on the sides of the basin (B) Missing slope vegetation
7 days will thus result in a 7-week pause before the next loading (Nielsen 2002, 2003). The conditions and possibilities are thus different from facility to facility. A facility with for example 8–13 basins and a loading period of for example 4–10 days has a rest phase of 2–2½ months which gives the desired evapotranspiration, degree of mineralisation and residual sludge quality. Individual facilities with a loading of about 30–40 kg dm/m²/yr and a number of basins ranging between 6–10, have achieved long periods of operation. The Nakskov sludge reed bed system is the oldest such facility and is now in its 14th year of operation, with a prognosis of 3 more years of operation before an emptying phase will be required. The Rudkøbing reed bed facilities (8 basins and 55–58 kg m²/yr began an emptying phase in its 10th year of operation, and is expected to be finished with the emptying in 2005, 13 years after operation began. A number of facilities with a maximum loading of between 45–60 kg m²/yr have had operational problems due to an insufficient number of basins, typically 4–6. Too few basins make it impossible to maintain the correct balance between loading and rest periods resulting in overloading. Low areal loading is thus not necessarily sufficient to ensure proper dewatering and mineralisation of the sludge if the reed bed facilities do not have an adequate number of basins. Facilities with too few basins will be unable to obtain long rest periods (min. 30 days) by increasing the number of loading days because the total loading will exceed the volume that is suitable for the particular sludge type (Nielsen 2002, 2003).

Conclusions
Generally, sludge reed bed facilities that have had operating problems or that do not meet expectations are incorrectly dimensioned and built with too few basins. These problems are typically associated with overloading during the run-in phase, and in the subsequent operation. The effectivity of a facility is dependent upon whether the filter is properly constructed both in terms of the composition of the individual layers, and also of the capillary connection between the individual layers, particularly between the uppermost filter layer and the residual sludge layer. Reduction in the volume of sludge over a 10-year period depends upon whether there is a suitable balance between alternating loading and rest periods in each individual basin. Furthermore, the number of loading days must be adjusted to the type of sludge and to the dewatering efficiency. Loading, after
vegetation has been planted in a basin, depends upon the development of the vegetation and the degree of vegetative cover. Loading must be planned so that it does not inhibit establishment of the reed facilities, and so that the thickness of the residual sludge layer does not increase more rapidly than the rate at which the reeds can colonise the residual sludge layer horizontally and vertically. Typically, a sludge reed bed facility with a loading period of maximum 5 days, must be built with 10 basins to permit a rest phase of about 40 days. Facilities treating activated sludge with for example 8–13 basins and a loading period of between 4–10 days are able to achieve rest periods of up to 2 to 2½ months, which results in the optimal evapotranspiration and mineralization.

References