Reed beds: constructed wetlands for municipal wastewater treatment plant sludge dewatering

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Abstract Reed beds are an alternative technology wastewater treatment system that mimic the biogeochemical processes inherent in natural wetlands. The purpose of this project was to determine the effectiveness of a reed bed sludge treatment system (RBSTS) in southern New England after a six-year period of operation by examining the concentrations of selected metals in the reed bed sludge biomass and by determining the fate of solids and selected nutrients. Parameters assessed in both the reed bed influent and effluent: total suspended solids, biochemical oxygen demand, nitrate-nitrogen and total phosphorus. In addition, the following metals were studied in the reed bed influent, effluent and Phragmites plant tissue and the sludge core biomass: boron, cadmium, chromium, copper, iron, lead, manganese, molybdenum, nickel, and zinc. The removal efficiencies for sludge dewatering, total suspended solids and biochemical oxygen demand were all over 90%. Nitrate and total phosphorus removal rates were 90% and 80% respectively. Overall metals removal efficient was 87%. Copper was the only metal in the sludge biomass that exceeded the standards set by the Massachusetts Department of Environmental Protection for land disposal of sludge. The highest metal concentrations, for the most part, tended to be in the lower tier of the sludge profile. The exception was boron, which was more concentrated in the middle tier of the sludge profile. The data and results presented in this paper support the notion that reed bed sludge treatment systems and the use of reed beds provide an efficient and cost effective alternative for municipal sludge treatment.

Keywords Constructed wetlands; reed beds; sludge dewatering

Introduction

Constructed wetlands for wastewater treatment are complex biological systems that mimic self cleansing processes inherent in natural wetlands. The Reed Bed Sludge Treatment System (RBSTS) is one type of constructed wetland. The RBSTS is a vegetated submerged bed that can be used to dewater. The RBSTS is planted with wetland plants such as Phragmites australis Cav. (common reed). Drying and mineralization reduce the liquid sludge volume by as much as 90%, and physical filtration removes almost 100% of the total suspended solids from the RBSTS effluent (Seidel, 1976). The final product is a well decomposed, stabilized compost suitable for land application (Krueger, 1991).

The general hypothesis of this research was that RBSTSs serve as an effective sludge dewatering system producing underdrain effluent quality that meets National Point Discharge Environmental Standards (NPDES) for direct discharge into waterways. The project examines the fate of metals in the sludge biomass and the possible accumulation of metals in Phragmites plants. Concentrations of metals in the sludge are a major concern for final disposal, affecting issues such as town economics, public safety, and state and federal compliance.

The reed bed at the Shelburne/Buckland wastewater treatment plant located in Buckland, MA served as the project site. The data series began in the fall of 1992 and continues until the spring of 1999. The specific objectives of this project were: i) quantitatively show that RBSTSs effectively dewater sludge; ii) measure total suspended solids, biochemical oxygen demand, nitrate-nitrogen, and total phosphorus in the underdrain effluent, and compare, where relevant, to DEP discharge standards; and iii) to determine the concentrations of boron, cadmium, chromium, copper, iron, manganese, molybdenum, nickel,
lead and zinc in RBSTS sludge biomass and in Phragmites plant tissue to determine the fate of these metals.

**Materials and methods**

**Background**

The Shelburne/Buckland wastewater treatment plant services the business districts and densely populated residential areas of two towns. During dry weather, flows to the plant typically average about 570 m$^3$/d, but during storm events flow rates can exceed 2000 m$^3$/d. After initial screening and settling processes, an extended aeration system treats the raw wastewater followed by aerobic digestion of the sludge in an aerated 200 m$^3$ above-ground tank with a residence time of 25 to 30 days. During that time the volatile solids are reduced to between 60% and 70%. The results reported herein only pertain to the first reed bed planted in 1992.

**Bed Design.** The reed bed is 16.5 m wide by 30 m long with an overall depth of 2.4 m. Each reed bed is lined with an impervious material and has a 20–30 cm layer of pea stone (3–6 mm) or gravel (>2 mm) around the 100 mm perforated underdrain pipes. On top of the pea stone is 30 cm of coarse sand (0.5–1 mm). The pea stone and sand are the initial growing medium for the Phragmites plants and the primary physical filtration medium for the sludge. The rhizomes and root system of Phragmites penetrate the growing medium and help channel wastewater flow. The effective depth of sludge storage is 1.2 m and the expected length of time between reed bed cleanings, limited by the effective depth of sludge storage, is 8–10 years. The underdrain pipes surrounded by pea stone and underlain by the impervious liner direct the effluent to a concrete cistern where a sump pump forces the effluent from the cistern back to the headworks for chlorinating prior to discharge.

**Analyses**

**Dewatering efficiency and total suspended solids.** Measurements of biomass volume were taken in March of 1995 and 1999 from ten random locations. Biomass volume was compared to sludge volume data. A mass balance determination relates the applied liquid sludge volume to residential biomass for a six-year period. Fifteen samples were collected to determine the bulk density of the sludge. Samples were dried at 103–105°C until they reached a constant weight and the bulk density was calculated. Solids content was determined by gravimetric procedures in the laboratory for the sludge influent and the underdrain effluent following Standard Methods 2540 A-G (Standard Methods for the Examination of Water and Wastewater, 1995).

**Biochemical Oxygen Demand (BOD$_5$).** For each loading of the reed bed BOD$_5$ samples were collected. The samples were analyzed following Standard methods 5210 B (Standard Methods for the Examination of Water and Wastewater, 1995).

**Nitrate-nitrogen and total phosphorus.** Nitrate and total phosphorus concentrations were determined with a modified colorimetric analysis utilizing a spectrophotometer (Hach model DR-2000). Nitrate analysis followed cadmium reduction (Standard Method 4500-NO$_3$-E). Samples for phosphorus analysis were digested with persulfate (Standard Method 4500 P B 5) prior to colorimetric analysis (Standard Methods for the Examination of Water and Wastewater, 1995).

**Metals.** Sludge biomass samples (1998) were taken at five points in the reed bed. Phragmites plants were harvested at random in December of 1994, 1995, and 1998 to be ana-
lyzed for metal content. The plants were severed at the sludge surface. Thirty plants formed a composite sample. Both sludge and tissue samples were dried at 100°C until constant weight was reached. The dried plant material was milled and washed in a muffle furnace at 500°C. Both dry sludge and washed tissue samples were then digested in nitric acid (Standard Method 3030 and 3030 E, respectively), and analyzed by ICP plasma emission spectrometry following Standard Method 3120 B (Standard Methods for the Examination of Water and Wastewater, 1995) to determine the concentrations of selected elements, including boron, cadmium, chromium, copper, iron, manganese, molybdenum, nickel, lead and zinc.

Results and discussion

Sludge dewatering efficiency

The sludge volume applied from 1992–1995 was 2637 m³ (Lavigne, 1996), the volume of sludge applied from 1996–1999 was 2704 m³ for a total of 5341 m³. In an earlier study of the Shelburne/Buckland reedbed system during the period of October 1992 to October 1995 dewatering efficiency was 96.9% (Lavigne, 1996). After a total of six years of operation the dewatering efficiency is 92.6% (Table 1).

In addition to the influent applied to the reed bed, precipitation, averaging 1.2 m/y over the last six years, added approximately 3569 m³ of water to the reed bed. The total (8909 m³) was either evaporated through the *Phragmites* plants or pumped back to the headworks. While sludge application and dewatering are year-round processes there is approximately 189 m³ more treated effluent per winter month returned to the headworks via the underdrain than during the growing season months. This amount likely represents the evapotranspiration taking place during the summer (see Figure 1). This indicates an average evapotranspiration rate during the summer months of 39 cm³ per month.

A water balance for the reed bed (Table 2) shows that 85% of the water is accounted for. If the volume unaccounted for (1375 m³ over a six-year period) is averaged for the seven months of winter usage per year it would equal 32.7 m³/month (4.7 cm/month). During those winter months evaporation still takes place; it is reasonable to conclude that the 4.7 cm/month remainder are evaporated during the winter months. The measured water loss at the Shelburne/Buckland reed bed was 39 cm/month during the growing season and 4.7 cm/month during the winter.

Monthly underdrain records were compared to inflow data (Figure 1) showing that 80%
of the total volume of effluent returned to the headworks was returned during the non-growing season when little transpiration is happening.

The bed was designed with a 1.2 m effective biomass storage depth anticipating a storage life of 8–10 years. The application of 1,411,100 gallons of sludge over a 6-year period resulted in 0.75 m of reed bed residual biomass, 62% of its storage capacity.

**Total suspended solids**

The Shelburne/Buckland wastewater treatment plant has a DEP discharge limit for total suspended solids of 30 mg/l, a limit they must meet daily in order to avoid fines and revocation of their permit. The average reed bed influent TSS concentration is 12,352 mg/l with the average effluent TSS concentration 14.2 mg/l, which is well below discharge standards. Removal rates for total suspended solids average over 98%.

**Biochemical oxygen demand (BOD<sub>5</sub>)**

The state DEP discharge permit for the SBWWTP sets the BOD<sub>5</sub> limit at 30 mg/l. Results from the Shelburne/Buckland BOD<sub>5</sub> data set, covering a 3-year period with 43 samplings of the reed bed’s influent and effluent, show that the reed bed effluent BOD<sub>5</sub> quality consistently passed regulatory standards. The average reed bed influent BOD<sub>5</sub> concentration was 1,342 mg/l and the average reed bed effluent BOD<sub>5</sub> concentration was 6 mg/l, resulting in a BOD<sub>5</sub> treatment efficiency of 99%.

**Nitrate-nitrogen and total phosphorus**

RBSTs show positive removal capacities for nitrogen and phosphorus with the removal mechanisms ascribed to plant adsorption, plant uptake, or chemical transformation and precipitation (Revitt *et al.*, 1997). Removal efficiencies for nutrients vary considerable and have been reported ranging from 10 to 93% for total nitrogen and from 9 to 94% for total phosphorus (Reed, 1990; Yang *et al.*, 1995). At the Shelburne/Buckland reed bed nitrate and total phosphorus were not monitored on a regular basis. For purposes of this study, 11 samples were taken over a six-month period (March through October 1998) from the reed bed influent and effluent. The results show a 90% reduction in nitrate-nitrogen and an 80% reduction in total phosphorus (data not included).
Metals

It is reasonable to assume that metals associated with a wastewater/sludge stream may concentrate in the biosolids. This may be specially true for reed beds because of the reduction in sludge over time. Sludge core analyses of the RBSTS were used to assess to what extent this happens. Pollutants concentrated in the reduced biosolids mass could complicate final disposal because the material may exceed regulatory standards.

The results from the Shelburne/Buckland RBSTS show an average metal concentration removal rate of 87% (influent to effluent) (Table 3). By analyzing influent and effluent in addition to analyzing sludge and plant tissue an attempt was made to determine the fate of metals in the reed bed. The concentrations of metals in the sludge biomass and in the Phragmites tissue are indicative of the wastewater quality of the treatment plant influent. In this case the metals concentrations are relatively innocuous as there is little industry in either Shelburne or Buckland. Of the ten elements studied iron consistently had the highest concentration, followed by copper, zinc, nickel, manganese, lead, boron, chromium, cadmium and molybdenum.

At the Shelburne/Buckland treatment plant the roots and rhizomes were not harvested nor analyzed. During regular operation only the above ground portion of the Phragmites plants are harvested, thus the contribution of the root biomass to metal attenuation is ignored. Metal attenuation in the above ground portion of the plants can also be ignored as the standard operating procedure at the Shelburne/Buckland treatment plant for disposal of the upper portion of the Phragmites plants is to burn them right in the reed bed with the residual ash incorporated into the reed bed sludge.

Conclusions

The dewatering efficiency of the Shelburne/Buckland reed bed system after a 6-year period is 93%. Of the 7535 m³ of sludge and rain received over a six-year period, 5678 m³ were lost due to evapotranspiration during the growing season, 1486 m³ were returned to the headworks, approximately 372 m³ of water was held in the sludge biomass. While the Phragmites plants do not transpire significant amounts of water during the winter months there is still water loss from the reed bed due to evaporation. To account for the remaining 1375 m³ we estimate that winter evaporation would have to equal approximately 32.7 m³/month (6 cm/month).

TSS and BOD₅ effluent concentrations are well under the regulatory standards, showing that reed beds can produce an effluent of high quality that needs no further treatment and

<table>
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<th>Parameter</th>
<th>Sludge</th>
<th>Phragmites</th>
<th>Method detection limit</th>
<th>Influent</th>
<th>Effluent</th>
<th>Average removal efficiency</th>
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<tr>
<td>Boron</td>
<td>60</td>
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<td>Chromium</td>
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<tr>
<td>Copper</td>
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<tr>
<td>Iron</td>
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<tr>
<td>Lead</td>
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<tr>
<td>Manganese</td>
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<td>Molybdenum</td>
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<td>mg/l</td>
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</table>

Mean removal rate of all elements combined: 86.7
could be discharged directly to our waterways. The Shelburne/Buckland reed bed average BOD$_5$ effluent concentration was 6 mg/l, well below the regulatory discharge limit of 30 mg/l. With less transpiration taking place in the winter months there was a greater amount of effluent returned to the headworks, however there was no significant difference in TSS and BOD$_5$ treatment results for winter or summer months. This clearly shows that, even when located in northern climates, reed bed technology is a viable alternative to conventional sludge treatment.

Nitrate-nitrogen reduction was 90% and total phosphorus reduction was 80%, these results are encouraging and seem to follow reports in the literature.

The overall average metal removal efficiency was 87%. Metals tend to concentrate in the reed bed sludge and not in the *Phragmites* plant tissue. All metal concentrations in the sludge except for copper meet DEP standards for Type 1 sludge, suitable for land application. The metal concentrations in the *Phragmites* plants are below the disposal standards set by the DEP and do not pose a problem if disposal of separately from the sludge.

The data presented in this paper confirm the reported success of RBSTS in cold climates and show that while RBSTS are not a panacea for all parameters of wastewater treatment, they are certainly a viable alternative to current technology.

**References**


Reed, S.C. (1990). *Natural Systems for Wastewater Treatment*. Water Pollution Control Federation, Alexandria, VA.


