Sludge removal from primary wastewater stabilization ponds with excessive accumulation: a sustainable method for developing regions

Stewart M. Oakley, Luciana Coêlho Mendonça and Sérgio Rolim Mendonça

ABSTRACT

Wastewater stabilization ponds have long been considered a sustainable treatment option for developing regions. Sludge buildup in primary ponds is also a sustainability issue since ponds must be desludged every 2–15 years depending on their design and solids loading. Pond systems in developing regions are often designed without a desludging plan and operated without the amortized desludging cost included in the operation and maintenance budget. This paper presents a method where sludge drying within a pond is effected by rooted plants; after drying, the sludge is removed with a mid-sized excavator. The method was tested in the desludging of a primary pond in Tela, Honduras, where sludge 4 m deep was dried to a solid (TS ≈ 18%) to a depth >1 m using the wetland plant *Ludwigia octovalvis*. The data suggest that both evapotranspiration and drainage through the root system contributed to dewatering. The total cost in 2011 US dollars was $13,716 or $4.47 m³ removed, which was paid from the municipality’s general fund without external aid. The method presented is sustainable, and serves as a model for desludging operations where excessive sludge accumulation has occurred—a likely scenario in many primary ponds in developing regions.

Key words: desludging stabilization ponds, sludge drying, sludge removal, sustainable sludge management, wastewater stabilization ponds

INTRODUCTION

Wastewater stabilization ponds have long been considered an appropriate wastewater treatment option for developing regions. In addition, pond effluents can be valorized for use in agriculture and aquaculture. This effluent valorization can be a critical component of long-term operational sustainability for poor municipalities with scarce resources.

Sludge buildup in primary ponds is also a critical issue for long-term sustainability since anaerobic ponds must be desludged every 2–5 years and facultative ponds every 5–15 years. The detailed requirements of primary pond desludging as an integral part of the overall treatment process, however, with the exception of works such as those of Gonçalves (1999) and von Spelling (2007), is usually given cursory attention in the pond literature (e.g., Yánez 1992; Mendonça 2000; Mara 2004; Shilton 2005; Arceivala & Asolekar 2007; US EPA 2011). Unfortunately, numerous pond systems in developing regions, most of which were constructed with international aid, operate without a desludging plan, without the amortized desludging cost included in the operation and maintenance budget, and without knowledge of how to proceed with desludging when it becomes necessary. Many of these ponds, such as those in Central America, have operated for years and have sludge accumulation depths >1 m that will be difficult and costly to desludge (Oakley et al. 2000; Oakley & Salguero 2011). If pond systems are to be sustainable in the long-term, it is imperative that simple desludging methods be developed and fully integrated into their design and operation.

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Gonçalves (1999) divided the methods of pond desludging into two general categories: (i) wet removal where the pond remains in operation and the sludge is pumped or dredged to trucks or drying beds; and (ii) dry removal where the pond is taken out of service, drained, and the dried sludge removed manually or with heavy equipment. Carré et al. (1990) and Picot et al. (2005), in two case studies of pond desludging in France, presented detailed results of wet removal of sludge. The technology used in these case studies, (e.g., sludge pumps, vacuum trucks, centrifuges for dewatering), however is generally not available in developing regions, and the final cost of removal at 10% total solids ranged from US$ 29 to US$ 156 m³ in 2011 dollars (Picot et al. 2005), a high cost for poor cities that have never planned for pond desludging (e.g., assuming sludge accumulation of 0.04 m³/person-y (Mara 2004), a population of 2,500 would produce 1,000 m³ (at 10% TS) after 10 years, which would cost from US$ 29,000 to US$ 156,000 to remove). There are very few removal and cost data published in the literature on dry sludge removal from ponds in developing regions; while Gonçalves (1999) addresses dry sludge removal in detail, no cost data are presented.

The objective of this paper is to (i) present an innovative and sustainable method for dry removal of deep sludge (>1 m) from primary stabilization ponds, where drying is effected through evapotranspiration by plants rooted in the sludge and desludging is performed with a hydraulic excavator that enters the pond; and (ii) present a case study of sludge removal using this method for a pond system at Tela, Honduras. (It should be noted that one disadvantage of this method is that the pond must be taken out of service for one or two months.)

**METHODOLOGY**

**Theoretical considerations**

Sludge normally forms a surface crust approximately 0.15–0.2 m deep during drying that restricts further evaporative water losses (US EPA 1987). Deep sludge within a pond will therefore not dry unless it is mechanically turned, which is difficult if sludge depth is >1 m since heavy equipment cannot easily maneuver within the pond. This problem can be minimized if plants are allowed to root within the sludge before the crust forms; in this case, evaporative water losses will occur up to the depth of the roots, which are normally >1 m (Canadell et al. 1996).

After a primary pond has been drained for desludging, the time required for drying before removal with equipment can be estimated from the following equation modified from US EPA (1987) and Arceivala & Asolekar (2007):

\[
t_d = \frac{h_0 \cdot (1 - (TS_0/TS_f)) \cdot (1 - D_S)}{(K_C ET_0 - I)_{\text{n}}}
\]

where \(t_d\) is the drying time (days), \(h_0\) the initial depth of sludge (m), \(TS_0\) the initial percentage of total solids in sludge, \(TS_f\) the final percentage of total solids in sludge, \(D_S\) the decimal fraction of water draining from the sludge, \(K_C\) the evapotranspiration coefficient for the type of sludge surface (e.g., with vegetation or bare), \(ET_0\), the reference evapotranspiration for the given climatic conditions, and \(I\) the infiltration of rainwater into the sludge. The term \((K_C ET_0 - I)_{\text{n}}\) is the net evapotranspiration for contiguous dry days, \(n\), used in design (mm/day or m/day).

The infiltration, \(I\), is defined by

\[
I = (P - RO)(1 - D_I)
\]

where \(I\) is the infiltration, \(P\) the precipitation, \(RO\) the runoff from the sludge surface (all in mm/day or m/day), and \(D_I\) the decimal fraction of infiltrating water that is not absorbed and drains through the sludge.

Equations 1 and 2 differ from the assumptions and design equations used for sludge drying in both sand beds (US EPA 1987; Arceivala & Asolekar 2007) and drained primary ponds (Gonçalves 1999). As a result of sludge mounding at the entrance and in areas where hydraulic dead zones exist (Gonalves 1999; Nelson et al. 2004), runoff from the sludge surface, which does not occur in sand beds, will occur within a drained primary pond. Because of mounding, the top layers of the wet sludge will also drain for several days \((D_S)\) after the pond is emptied. Finally, once the sludge has dried beyond the plastic limit and becomes a solid, it will not rehydrate to a semi-solid when wetted (Dillard 1981). Thus dried sludge layers will
not absorb all infiltrated water and will drain a fraction of it (\(D_1\)), a phenomenon that commonly occurs in sand beds (Arceivala & Asolekar 2007). Rooted plants within the sludge also form pathways for water to drain, which includes water from the sludge (\(D_3\)) and infiltration (\(D_1\)) (US EPA 1987; Metcalf & Eddy 2005).

Daily and monthly values of ET_0 and \(P\) can be obtained from published values of evapotranspiration and precipitation at a given site such as those available in CLIMWAT 2.0 (FAO 2006). The evapotranspiration coefficient, \(K_C\), which can range from 0.1 for a dry soil or sludge surface to 1.2 for some wetland plants, can also be found in published materials (Allen et al. 1998). RO from the sludge surface once a pond has been drained can be estimated using the Soil Conservation Service (SCS) method, which takes into consideration antecedent moisture conditions, rainfall intensity, and vegetative cover for each rainfall event (SCS 1972).

As an example, Table 1 shows evapotranspiration, precipitation and runoff data for a hypothetical sludge surface in the drained primary pond at Tela, Honduras. In this table it is assumed the sludge is covered with a grass vegetation (\(K_C = 1\)), and the fraction of RO is calculated for each month using the SCS method (SCS 1972). As seen in the table, the months of March, April, May and June have significant net evapotranspiration, and this should be the design period used for drying; February would be used for pond draining and initial site preparation such as planting a vegetative cover.

Because \((K_C \cdot ET_0 - I)_n\) varies from month to month, it is convenient to rearrange Equation 1 on a monthly basis to the following form

\[
h_{m_i} = \frac{t_d \cdot (K_C \cdot ET_0 - I)}{(1 - (TS_0/TS_f))(1 - D_3)}
\]

where \(h_{m_i}\) is the total depth that the sludge is dried from \(TS_0\) to \(TS_f\) during month \(i\), \(t_d\) the number of days in month \(i\), and \((K_C \cdot ET_0 - I)_{m_i}\) the net daily evapotranspiration for contiguous days during month \(i\). The total depth, \(h_T\), that is dried from \(TS_0\) to \(TS_f\) during the drying period is then the sum of each individual month in which drying occurs:

\[
h_T = \sum h_{m_i}
\]

After drying through evapotranspiration, the final depth of sludge (equivalent to the root depth) and the final volume as a fraction of the initial volume can be estimated with the

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*Table 1* | Net evapotranspiration data for Tela, Honduras (\(K_C = 1.0\))

<table>
<thead>
<tr>
<th>Month</th>
<th>(ET_0) (mm/day)</th>
<th>(P) (mm/day)</th>
<th>(RO) (mm/day)</th>
<th>(I = P-RO) (mm/day)</th>
<th>(K_C \cdot ET_0 - I) (mm/day)</th>
<th>(K_C \cdot ET_0 - I) (m/day)</th>
</tr>
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<tbody>
<tr>
<td>January</td>
<td>2.90</td>
<td>8.35</td>
<td>3.76</td>
<td>4.60</td>
<td>-1.70</td>
<td>-0.00170</td>
</tr>
<tr>
<td>February</td>
<td>3.49</td>
<td>7.39</td>
<td>3.33</td>
<td>4.07</td>
<td>-0.58</td>
<td>-0.00058</td>
</tr>
<tr>
<td>March</td>
<td>4.08</td>
<td>3.74</td>
<td>1.68</td>
<td>2.06</td>
<td>2.02</td>
<td>0.00202</td>
</tr>
<tr>
<td>April</td>
<td>4.19</td>
<td>2.77</td>
<td>1.25</td>
<td>1.52</td>
<td>2.67</td>
<td>0.00267</td>
</tr>
<tr>
<td>May</td>
<td>4.08</td>
<td>2.61</td>
<td>1.18</td>
<td>1.44</td>
<td>2.64</td>
<td>0.00264</td>
</tr>
<tr>
<td>June</td>
<td>3.71</td>
<td>4.90</td>
<td>2.21</td>
<td>2.70</td>
<td>1.02</td>
<td>0.00102</td>
</tr>
<tr>
<td>July</td>
<td>3.81</td>
<td>6.55</td>
<td>2.95</td>
<td>3.60</td>
<td>0.21</td>
<td>0.00021</td>
</tr>
<tr>
<td>August</td>
<td>3.72</td>
<td>7.42</td>
<td>3.34</td>
<td>4.08</td>
<td>-0.36</td>
<td>-0.00036</td>
</tr>
<tr>
<td>September</td>
<td>3.63</td>
<td>7.73</td>
<td>3.48</td>
<td>4.25</td>
<td>-0.62</td>
<td>-0.00062</td>
</tr>
<tr>
<td>October</td>
<td>3.29</td>
<td>13.16</td>
<td>5.92</td>
<td>7.24</td>
<td>-3.95</td>
<td>-0.00395</td>
</tr>
<tr>
<td>November</td>
<td>3.29</td>
<td>12.93</td>
<td>5.82</td>
<td>7.11</td>
<td>-3.82</td>
<td>-0.00382</td>
</tr>
<tr>
<td>December</td>
<td>2.98</td>
<td>13.29</td>
<td>5.98</td>
<td>7.31</td>
<td>-4.33</td>
<td>-0.00433</td>
</tr>
</tbody>
</table>

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*Data from meteorological station at Tela, Honduras, published in CLIMWAT 2.0 (FAO 2006).*

*Runoff calculated using the Soil Conservation Service methodology (SCS 1972). It is assumed that runoff originates from a rainfall event of 25 mm; greater quantities of rainfall produce a greater fraction of runoff (SCS 1972). The majority of rainfall events at Tela throughout the year are less than 25 mm as reported in the global summary of daily precipitation for the Tela station (National Climate Data Center: www7.ncdc.noaa.gov/CDO/cdoselect.cmd?datasetabbv=GSOD&countryabbv=)&Georegionabbv=).*
following equations (US EPA 1987):

\[ h_f = h_0 \cdot \left( \frac{TS_0}{TS_f} \right) \] (5)

\[ \frac{V_f}{V_0} = \frac{TS_0}{TS_f} \] (6)

where \( h_f \) is the final sludge depth (m) and \( V_f \) and \( V_0 \) the final and initial sludge volumes (m\(^3\)). Equations 5 and 6 assume the change in depth and volume is primarily due to water loss, which is true as long as the sludge is a liquid or semi-solid.

Figure 1 is a plot of Equations 3 and 4 using the Tela data presented in Table 1 for drying from \( TS_0 = 12\% \) to \( TS_f = 18\% \). (Earlier studies had shown that the initial \( TS_0 \) within the pond sludge was 12\%, and that the sludge would change to a solid that could be removed with excavators at \( TS_f = 18\% \) (ECOMAC 2004)). In this figure, it is assumed rooted wetland plants such as *Ludwigia* species grow on the surface of the sludge and dewater it through evapotranspiration with \( K_C = 1.10 \), a value typical of wetland plants (Allen et al. 1998); the depth of drying is thus equivalent to the root depth of the plants. It is also assumed the top layers of sludge would drain for the first 7 days with \( D_S = 0.5 \), and that there is drainage of infiltrating water \( (D_I = 0.43) \), values which have been reported for well-digested anaerobic sludges in drying beds (Arceivala & Asolekar 2007). The effects of drying on a bare sludge surface are also shown for comparison; here it is assumed the value of \( K_C = 1.0 \) for the first 7 days and then decreases to 0.3–0.5 as the surface dries (US EPA 1987; Allen et al. 1998).

Figure 1 shows it is theoretically possible to dewater the pond sludge to a solid (\( TS_f \approx 18\% \)) to a depth of approximately 1.3 m using plant evapotranspiration and drainage. A bare sludge, however, would only dry to 0.15–0.2 m, and would remain a liquid or semi-solid sludge beneath this depth, making it extremely difficult to remove mechanically,
especially if the sludge were >1 m. (Gonçalves (1999) has noted cases where heavy machinery has become stuck in ponds in Brazil attempting to maneuver in deep sludge that was not dried to a solid.) Using Equations 5 and 6, a change from 12 to 18% TS as shown in Figure 1 would yield a volume reduction of 33% with a final depth equal to 0.67h0.

Sludge removal plan for Tela, Honduras

The evapotranspiration methodology was used to plan the desludging of the primary pond at Tela, Honduras. The Tela system consists of three ponds in series: a 4 m deep anaerobic pond, a secondary facultative pond, and a maturation pond (Figure 2). Monitoring studies showed the primary pond always operated as a facultative pond because of low organic loading rates (Oakley & Salguero 2011). In 2003, a bathymetric study of the primary pond showed the depth of sludge to be 1.5 m at the entrance, tapering down to 0.5 m at the midpoint of the pond; it was estimated the sludge occupied a volume of 2,336 m³ (TS0 = 12%) out of a total volume of 7,026 m³, or 33.2% of the pond’s volume at this time (ECOMAC 2004).

By early 2007, the pond had been in continuous operation for 15 years, and sludge began to surface at the entrance. At this time, the municipality, in an effort to avoid losing the system, decided to desludge the pond by hiring a private contractor; the municipality did not have the equipment or personnel to perform this work on its own, a common situation in many small municipalities in developing regions. Technical assistance for the desludging plan was provided by California State University, Chico. The desludging plan consisted of (i) construction of a bypass canal to divert influent to the secondary pond; (ii) drainage of the primary pond during the month of February; (iii) sludge drying during the months of March–June as previously presented; (iv) sludge removal with an excavator; and (v) filling and renewed operation of the pond.

RESULTS AND DISCUSSION

Sludge removal

As a result of delays in funding to the Department of Public Works, the entity in charge of the operation of the pond system, the project did not start until March 2007; at this time it was decided to continue with the desludging plan in spite of the onset of the rainy season in order to avoid another year’s accumulation of sludge. After the bypass canal was constructed, the primary pond was drained by pumping from 11 to 23 July 2007, one month later than the last optimum month for sludge drying (Table 1).

After draining the pond, the wetland plant Ludwigia octovalvis immediately began to grow and was allowed to spread over the entire sludge surface within the first half of pond (Figures 3 and 4). (Ludwigia grows naturally in areas adjacent to the pond and seeds were likely deposited in the sludge by the wind or birds; in other circumstances the sludge would have to be seeded.) By the end of August, the depth of sludge at the entrance had decreased ≥1.0 m due to water loss by net evapotranspiration, \((Kc\cdot ET_0 - I)\), and drainage \((D_s)\) from the sludge into the second half of the pond (Figures 3 and 4).

By September, the sludge at the entrance was sufficiently dry (i.e., a solid) at depths >1.0 m that an excavator was able to enter the pond to begin removal (Figure 5). The solid layers of sludge had concentrations of TSf ≥18% based on sludge drying experiments at this site (ECOMAC 2004; Oakley & Salguero 2011). Once the top 1.0–2.0 m of sludge was removed, the excavator removed the remaining layers with the help of a bulldozer that pushed the semi-solid material to the excavator, which then loaded it into a dump truck for disposal onsite on the pond’s embankment.
The contractor removed 1,967 m$^3$ of sludge in 48 h of machine time in the first half of the pond, which contained all of the deep sludge (>1.0 m) and roughly 2/3 of the total sludge, by September 30. Thus in 6 days the contractor was able to remove an average of 328 m$^3$/day of solid and semi-solid sludge that varied in depth from 1 to 3 m. After September, a conflict with the municipality over payments caused the contractor to abandon the site. Due to political problems within the municipality and the onset of the wet season, the pond remained empty until the following July when a second contractor was finally hired to complete the desludging. The second contractor used the same methodology as the first and removed 1,100 m$^3$ in 24 h of machine time for an average removal of 367 m$^3$/day; the sludge in the second half of the pond, however, was less than 1 m deep (Figure 4b) and much easier to remove.
The pond was refilled and returned to operation in August 2008.

The total cost for the removal of 3,067 m³ as shown in Table 2 was US$ 13,716 or US$ 4.47 per m³ (at TSf = 18%), and was paid from the general fund of the Municipality of Tela.

Role of evapotranspiration and drainage

In spite of the worst possible timing to initiate desludging activities at the start of the wet season, the deep sludge at the pond’s entrance dried to a solid to a depth ≥1 m, allowing the contractor to remove all of the sludge occupying the first half of the pond within two months. The data presented in Table 1, however, suggest that sludge drying would not be possible from July–September. While the precipitation data presented in Table 1 are based on long-term averages over decades, precipitation for any given month can vary widely from year to year (evapotranspiration is not likely to change significantly). Daily precipitation data for worldwide meteorological stations are available for any year from the National Climatic Data Center of the US government (http://www.ncdc.noaa.gov/oa/ncdc.html). Table 3 shows the summary for the daily precipitation data in Tela for the months of July–September 2007.

The precipitation data for 2007 show the monthly totals for July, August and September (70.9; 89.9; 101.1 mm) are only 34.9, 39.1, and 43.6%, respectively, of the long-term averages (Table 1). As a result, the net evapotranspiration ($K_C ET_0 - I$)

### Table 2 | Final cost of desludging with TSf = 18%

<table>
<thead>
<tr>
<th>Sludge removal</th>
<th>Volume (m³)</th>
<th>Equipment hours</th>
<th>Cost US$ (2011)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase I</td>
<td>1,967</td>
<td>48</td>
<td>$9,200</td>
</tr>
<tr>
<td>Phase II</td>
<td>1,100</td>
<td>24</td>
<td>$4,516</td>
</tr>
<tr>
<td>Total</td>
<td>3,067</td>
<td>72</td>
<td>$13,716</td>
</tr>
</tbody>
</table>

### Table 3 | Net evapotranspiration as calculated from measured precipitation, July–September 2007 ($K_C = 1.0$)

<table>
<thead>
<tr>
<th>Month</th>
<th>ET₀ (mm/day)</th>
<th>Pᵇ</th>
<th>mm</th>
<th>mm/day</th>
<th>ROᵇ (mm/day)</th>
<th>I − P−RO (mm/day)</th>
<th>$K_C ET₀ I$ (mm/day)</th>
<th>$K_C ET₀ I$ (m/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>July</td>
<td></td>
<td></td>
<td>70.9</td>
<td>2.28</td>
<td></td>
<td></td>
<td>0.66</td>
<td>0.00066</td>
</tr>
<tr>
<td>(23–31)ᵇ</td>
<td>3.81</td>
<td>24.1</td>
<td>3.45</td>
<td>0.30</td>
<td>3.15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>August</td>
<td>3.72</td>
<td>89.9</td>
<td>2.90</td>
<td>0.48</td>
<td>2.42</td>
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<td>September</td>
<td>3.63</td>
<td>101.1</td>
<td>3.37</td>
<td>1.17</td>
<td>2.20</td>
<td></td>
<td>1.43</td>
<td>0.00143</td>
</tr>
</tbody>
</table>

ᵇData from Table 1.
ᵇ譬如precipitation data for July, August, and September, 2007 as reported by the daily global summary for the meteorological station at Tela, Honduras (National Climatic Data Center; www7.ncdc.noaa.gov/CDO/cdoselect.cmd?datasetabbv=GSOO&countryabbv=HG&regionabbv=--).
ᵇRunoff calculated for each rainfall event using the Soil Conservation Service Method (SCS 1972).
ᵇSince sludge drying began when the pond was empty on July 23, only the precipitation data for July 23–31 are included in the calculations.
is positive for all three months and is much greater, ranging from 3.1 times greater for July to 5.6 times for August, than that calculated from the long-term averages. These values, however, are still only about 50% of those calculated for the optimum months for sludge drying (March–May) as seen in Table 1.

The values in Table 3 do not include the fraction of water draining from the sludge, $D_S$, and the fraction of infiltration that drains and is not absorbed, $D_I$. A plot of Equation 3 for the 2007 data with several combinations of $D_S$ and $D_I$ is shown in Figure 6. In three combinations, it is assumed that $D_S = 0.5$ for the first 7 days of drying after the pond is emptied, values typical of anaerobically digested sludges on sand beds (Arceivala & Asolekar 2007). In one graph in Figure 6, it is assumed $D_S = 0.5$ for 30 days, which could be possible for lower layers of sludges that drain more gradually as standing water recedes (Figure 4).

Figure 6 assumes there is drainage of infiltrating water ($D_I$) in three of the graphs. A value of $D_I = 0.43$ has been reported by Arceivala & Asolekar (2007) as an average value for anaerobically digested sludges in sand drying beds; this is likely a minimum value for pond sludges with plant growth since plant stems and root systems form permanent pathways for continuous drainage of infiltrating water as has been demonstrated with the use of reed beds for sludge drying (US EPA 1987; Metcalf & Eddy 2003). A value approaching $D_I = 1.0$ (100% drainage of infiltrating water) may be possible for dried, solid layers of sludges with rooting systems since they do not rehydrate when wetted and remain a solid (Dillard 1981).

The experience at Tela demonstrates that drainage ($D_I$) played a role in drying, since plant evapotranspiration alone could not have dried the sludge to the depths encountered in the field; in this case the maximum depth to form a solid (TSf = 18%) would have been only 0.3 m or less as seen in the bottom graph in Figure 6 ($D_I = 0$). The net evapotranspiration was thus higher than the values shown in Table 3 because of $D_I$. In conclusion, the significant growth of Ludwigia with the concomitant evapotranspiration, and the drainage of water, including RO, $D_S$, and $D_I$ towards the discharge side of the pond all played roles in sludge drying.

### Heavy equipment selection and use

The selection and use of heavy equipment for removal of sludge from primary ponds is a critical component of
sustainable desludging. Bulldozers cannot work in deep, semi-solid sludges because the tracks slip and they are only adequate for shallow (<0.5 m), solid sludges (Gonçalves 1999). As demonstrated in this case study of Tela, an excavator is capable of maneuvering in deep, semi-solid sludge without getting stuck. If the tracks should slip in deep wet sludge, an excavator can still move using its boom and bucket. Once the deep sludge is removed, a ramp can be built so a bulldozer and dump truck can enter the pond. An excavator is most efficient when it is stationary, and the bulldozer then plays an important role in pushing the sludge to the excavator. At the least a mid-size excavator (≈150 hp) with a 1.0 m³ bucket should be used in sludge with a depth >0.5 m. An excavator this size typically rents for <US$ 100/h (including the operator) in Latin America.

Onsite disposal

Pond sludges will contain viable helminth eggs and all primary pond designs should include a location where excavated sludge can be stored for at least one year to meet the WHO guidelines for inactivation of helminth eggs (WHO 2006). In the case of Tela, the only available option was to dispose of the sludge on the pond’s embankment. When sludge removal first began five samples were collected at various locations and analyzed for helminth eggs using a previously developed methodology (Nelson et al. 2004). The viable egg concentrations ranged from 0.4 to 25.0 eggs/gram dry weight. After 1 year at temperatures >20 °C, the sludge should be essentially free of viable eggs and can be used offsite in agriculture (WHO 2006).

Financing

There are very few reported examples of small cities in developing regions financing the sludge removal from their own wastewater stabilization pond systems. Two studies have been reported for Nicaragua, but these were financed by international organizations: The European Union funded the sludge removal of a pond system in Nicaragua (Oakley & Salguero 2011), and the Inter-American Development Bank funded sludge removal for 17 pond systems in Nicaragua at a cost of approximately US$ 58,000 per system in 1995 (Oakley et al. 2000).

This study is one of the few to be reported where the municipality itself paid for the desludging operation out of its general fund. The wastewater stabilization pond system in Tela serves a population of approximately 10,000 persons, and there are 2,500 sewer connections that discharge to the pond system. The monthly tariff for connections is shown in Table 4. The monthly rate varies depending on the location and the amount of pumping needed to reach the pond system.

Compared to the annual income from sewer fees, the total cost of desludging of US$ 13,716 (Table 2) over a 15 year period is a very small percentage of the total income generated. As is common in small Latin American municipalities, however, administrators in Tela do not necessarily return funds to the departments where they were generated and instead may use them for other purposes. The first contractor abandoned the site because they had not been paid by the municipality, and it is likely the funds that were promised to the Department of Public Works were spent on other, more visible projects during an election year. Nevertheless, the following year funds were made available to finish the project and it is one of the most successful desludging projects to date in Central America where the entire project was funded by the municipality.

Table 4 | Sewer fees and municipal income for population served by Tela pond system<sup>a</sup>

<table>
<thead>
<tr>
<th>Number of connections</th>
<th>Monthly rate/ connection US$</th>
<th>Monthly income US$</th>
<th>Yearly income US$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,000</td>
<td>2.89</td>
<td>5,789</td>
<td>69,474</td>
</tr>
<tr>
<td>500</td>
<td>3.68</td>
<td>1,842</td>
<td>22,105</td>
</tr>
<tr>
<td>Total:</td>
<td></td>
<td>7,632</td>
<td>91,575</td>
</tr>
</tbody>
</table>

<sup>a</sup>Values in 2011 US$.

CONCLUSIONS

Desludging of primary wastewater stabilization ponds is an urgent issue for the sustainability of many existing systems in developing regions with excessive sludge accumulation. Unfortunately, there are very few examples in the literature showing methods and costs appropriate to the resources of...
small, poor cities. This paper presents a method that is sustainable and low-cost, that was performed and paid for by the municipality without external aid, and serves as a model for low-cost desludging operations.

The ramifications for primary pond design and desludging process design include the following:

- The bottom of primary ponds should be designed with a slope towards the discharge side so water draining from the sludge deposits on the intake side, whether RO, D$_S$, or D$_I$, will drain away from the sludge (Figure 4).
- Detailed design of the sludge drying process using evapotranspiration data and the equations presented in this paper should be included in the design of all primary pond systems.
- Wetland plants with rapid growth, such as *Ludwigia* species, should be planted immediately after draining the pond. Plants foster dewatering through both evapotranspiration and drainage, and without plant growth deep sludges will not dry to solids at depths >0.15–0.2 m.
- Excavators are the best heavy equipment to remove deep sludges that have been dried to a solid or semi-solid.

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**REFERENCES**


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