The Treatment of On-site Wastewater using Willow Bed Evapotranspiration Systems in Ireland

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Abstract
Willow bed evapotranspiration systems can treat on-site wastewater effluent with the advantage that, if sized correctly, they produce no discharge either to ground or to surface water. Willow beds are a viable alternative to conventional treatment methods, when for example, in situ soil is of too low a permeability to allow for treatment / disposal via percolation or when a discharge of treated/untreated effluent to a watercourse is not permitted. 11 willow bed systems have been constructed as pilot trials at houses around County Wexford to treat the domestic wastewater produced. The systems have been built with the idea of evaluating different parameters with respect to overall performance including effluent type (septic tank or secondary treated effluent), willow varieties and aspect ratios of the basins. The effluent flow into the basins, water level, rainfall and evapotranspiration have all been monitored on each site to assess the effectiveness of the system. The overall aim is to produce guidelines for the design of such on-site treatment systems. In parallel to the full scale systems, mesocosm experiments have been set up in Dublin. These experiments have investigated the evapotranspiration rate of four different willow varieties against reference evapotranspiration while also monitoring the effects of the application of three different effluent types onto each variety. Results have indicated that the application of both primary and secondary effluent has significantly increased the evapotranspiration rates for all the varieties of willow, although there has been no noticeable difference in evapotranspiration between varieties.

Keywords: on-site wastewater, willow beds, zero discharge, evapotranspiration, crop coefficient

Introduction
Ireland has over one third of its population using on-site wastewater treatment systems (CSO, 2007), mostly consisting of septic tanks discharging effluent into a subsoil percolation area. However, in some regions the subsoil is of too low a permeability to allow for treatment by percolation, so an alternative is required. County Wexford, which is located in the south east of Ireland is one such region where there are extensive areas of such clayey subsoil. In the last decade, during the construction boom, the local authority in Co. Wexford granted hundreds of planning permissions for single houses, for which on-site treatment consisted of a septic tank followed effectively by the discharge of effluent to a nearby stream. Many of these streams and rivers throughout the county are being shown to suffer from poor water quality. Hence, in order to improve this situation and find a more appropriate solution to the treatment and disposal of on-site effluent in such areas the council implemented a pilot trial to investigate the use of zero discharge willow bed systems at a number of different sites.

The design and monitoring of the willow beds was carried out by a research team from Trinity College Dublin. The four year trial is being carried out on eleven different full-scale systems at eight different sites throughout the county. The willow bed design is similar to the systems outlined by Gregersen and Brix (2001), which have proved successful in Denmark, but have
been based upon realistic Irish rainfall, evaporation and on-site effluent production statistics. The system consists of a lined basin refilled with excavated soil and then planted with willow cuttings. The primary objective of the project is to determine the optimum size required to treat a known volume of effluent and corresponding volume of rainfall at any given location. Other parameters including aspect ratio, effluent types and willow variety are also being compared. The latter two parameters have also been investigated in more detail in a series of mesocosm experiments that compare four different willow varieties against the application of three different effluent qualities.

**Methods**

**Full Scale Systems**

**Background**

Eleven full scale systems have been constructed in Co. Wexford to treat wastewater effluent from single house dwellings. The sites are distributed throughout the county in areas which are known to have marl (i.e. pure clay) subsoils. The systems were designed with deliberate variations between key parameters (effluent type, willow species, plan area, aspect ratio and effluent distribution) as seen on Table 1, in order to provide comparisons and determine sensitivity to these in terms of overall performance.

**Construction**

On each site the basin was dug out to a depth of 1.8 m. The slopes of the sides of the basin were kept as straight as possible in order to maximize the volume of the system. The layer of top soil was kept separate from the subsoil. Any sharp stones were then removed from the basin to help aid against punctures. Following this, a 1.5 mm, 180 g per m² non-woven geotextile was installed. A 0.5 mm Low Density Polyethylene (LDPE) impermeable membrane was then laid on top of the geotextile layer, with the joins being welded together to ensure a watertight seal. An excess of 0.38 m along the top edge of the basin was required, in order to maintain water-tightness along the berm. A second geotextile layer was then laid on top of the LDPE to aid against punctures from willow tree roots and stones. An inspection/pump well was installed at one end of each willow bed. The 300 mm diameter plastic pipe was placed, standing vertically upon a concrete tile such that it protruded over the top surface of the willow bed. Slots were cut in the side of the pipe, which was then wrapped in geotextile to allow for ingress of water while preventing clay blocking the slots.

The effluent is distributed throughout the systems via a number of rigid 110 mm dia. percolation pipes, which are laid in a 0.3 m layer of 20 mm washed gravel at the bottom of the basin. The pipes are laid at 3.0 m centres as shown in Fig. 1. The effluent from the septic tanks or package treatment systems is either gravity fed or is pumped into the head of the pipe network from where it flows by gravity.

![Figure 1 Willow bed schematic](image)

The soil that had been excavated for the basin was then backfilled into the lined hole, starting with the subsoil and finished with the layer of topsoil. A 0.3 m high berm was constructed around the edge at the top of the bed incorporating the geotextile and impermeable membrane to act as an overflow protection in the instance of flooding, due to heavy rainfall in the first year for example, or in winter time.

**Willow Planting**

The Danish EPA Guidelines (Miljøstyrelsen, 2003) stated that the planting of multiple different varieties is imperative in order to resist...
disease and parasites. Hence, from a pool of 8 willow varieties, each treatment system was planted with 3 different varieties of willow (see Table 1) in a predetermined pattern. The cuttings were planted at a density of 3 per metre square.

**Monitoring**

The flow into each willow bed was monitored continuously using either tipping bucket flow recorders for the gravity fed systems or via a level meter situated in the sump for the pumped sites (Thalimedes, OTT Hydrometry). The water level in each basin was monitored continuously using a pressure gauge sensor (Orpheus, OTT Hydrometry) situated in the inspection sump. Chemical and microbiological analysis was carried out on the effluent and water in the inspection sump on a monthly basis for each treatment system. Weather stations (Casella) were erected at each site to continuously monitor and collect rainfall data as well as other meteorological parameters (wind speed, air temperature, humidity, solar radiation) from which the reference evapotranspiration ($ET_o$) could be determined.

**Table 1** Summary of design parameters being compared between 10 full-scale systems

<table>
<thead>
<tr>
<th>Constructed</th>
<th>Effluent Type</th>
<th>Area (m$^2$)</th>
<th>Aspect ratio (length:width)</th>
<th>Distribution</th>
<th>Willow species</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 May 2009</td>
<td>SE</td>
<td>570</td>
<td>1.6:1</td>
<td>pumped</td>
<td>Bjorn, Tora, Jorr</td>
</tr>
<tr>
<td>2 May 2009</td>
<td>SE</td>
<td>296</td>
<td>4.6:1</td>
<td>pumped</td>
<td>Bjorn, Tora, Jorr</td>
</tr>
<tr>
<td>3 April 2010</td>
<td>STE</td>
<td>420</td>
<td>2.9:1</td>
<td>pumped</td>
<td>Tora, Thorhild, Olof</td>
</tr>
<tr>
<td>4 May 2010</td>
<td>STE</td>
<td>464</td>
<td>1.8:1</td>
<td>gravity</td>
<td>Tora, Thorhild, Olof</td>
</tr>
<tr>
<td>5 April 2010</td>
<td>STE</td>
<td>24</td>
<td>2.7:1</td>
<td>gravity</td>
<td>Native Irish species</td>
</tr>
<tr>
<td>6 July 2010</td>
<td>SE</td>
<td>900</td>
<td>1.4:1</td>
<td>gravity</td>
<td>Tora, Tordis, Olof</td>
</tr>
<tr>
<td>7 July 2010</td>
<td>SE</td>
<td>900</td>
<td>9.0:1</td>
<td>gravity</td>
<td>Tora, Tordis, Olof</td>
</tr>
<tr>
<td>8 Sept. 2010</td>
<td>SE</td>
<td>340</td>
<td>3.4:1</td>
<td>gravity</td>
<td>Tora, Tordis, Olof</td>
</tr>
<tr>
<td>9 April 2011</td>
<td>STE</td>
<td>520</td>
<td>5.2:1</td>
<td>pumped</td>
<td>Tordis, Sven, Inger</td>
</tr>
</tbody>
</table>

**Water Balance**

The water budget for each system was carried out throughout the monitoring period on the basis of influent flows combined with rainfall and evapotranspiration rates. $ET_o$ was calculated from the meteorological parameters using the Penman-Monteith equation (FAO, 1998). The product of the water level in the sump and the void ratio of the soil in the basin provided the volume of water in the system. The actual evapotranspiration ($ET_{willow}$) from the willow bed for a given time period was then calculated using a water balance equation. A crop factor can then be determined by comparing $ET_{willow}$ to $ET_o$.

**Mesocosm Experiments**

Cylindrical containers of height 1000 mm and diameter 540 mm were placed at an open site at the Trinity College Botanic Gardens in Dublin, and filled with layers of gravel (75 mm), sand (440 mm) and topsoil (460 mm). A 30 mm inspection plastic inspection pipe was also inserted into each container to allow for measurement of the water level. Each pipe had 10 mm diameter holes drilled at the bottom to allow for the ingress of water from the gravel layer (see Fig. 2).

**Table 2** Classification of willow varieties

<table>
<thead>
<tr>
<th>Willow Variety</th>
<th>Clone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tordis</td>
<td>((Salix schwerinii x S. viminalis) x S. viminalis,)</td>
</tr>
<tr>
<td>Sven</td>
<td>(Salix viminalis x S. schwerinii)</td>
</tr>
<tr>
<td>Inger</td>
<td>(Salix triandra x S. viminalis)</td>
</tr>
<tr>
<td>Torhild</td>
<td>((Salix schwerinii x S. viminalis) x S. viminalis)</td>
</tr>
</tbody>
</table>

Four willow varieties were then planted: Tordis, Sven, Inger and Torhild, which are all subspecies of *Salix viminalis* (see Table 2), one plant per container.
A plant from each variety was then given an application of primary (septic tank) effluent, secondary treated effluent or rain water (as a control). The dosage was 2.2 litres per week which equated to the approximate areal hydraulic loading rate that one willow tree would receive in a full-scale willow bed. The recipes for the synthetic effluent were based upon recipes by Peeples and Mancl (1998) but then adjusted so the effluent reflected the concentrations more usually found in Irish septic tank (i.e. primary treated) and secondary treated on-site effluent (see Curneen and Gill, 2012). A water balance of the systems was carried out, in a similar manner to the full scale systems. However, for the mesocosm experiments, the level was recorded manually at regular intervals instead of automatically (as with the full scale systems). The actual evapotranspiration for that time interval was then determined using the water balance equation, and respective crop factors calculated.

Results

Full Scale Systems

Climate variation

The climatic variation between 5 of the total 8 sites has been compared over a 12 month period. System 5 was omitted due to some data missing during the monitoring period and Systems 9, 10 and 11 omitted as data was only started to be collected in Spring 2012. The reference evapotranspiration varied between 420 and 480 mm annually over the 5 sites (see Fig.3) and there was no obvious pattern between the evapotranspiration rate and geographical location within the county. The same applies to the wind speed measurements on the 5 sites, with the mean wind speeds between sites varying from 1.37 m/s to 2.68 m/s. However, for the rainfall there does appear to be a noticeable difference between north Wexford (WB 3, 6/7) and south Wexford (WB 1/2, 4, 8), see as shown on Fig.3, with higher rainfall recorded in the north of the county.

System performance

Monitoring of the full scale systems is currently ongoing. The willow systems which have been established for 2 or more growing seasons have so far performed as intended, operating with zero discharge whilst receiving all the household effluent in addition to rainfall. For example, Fig. 4 shows the monitoring results of daily water level within System 1 and the daily rainfall. It is interesting to note the effect that large rain events have on the water level within the basin which can be clearly seen. These jumps are being analysed as one technique to determine the relevant net void ratio within the systems. The difference in plan area with respect to performance can also be seen when comparing System 1 against System 2. Both systems are...
situated on the same site; however, it is evident from Figs. 4 and 5 that the larger willow bed system (System 1) could cope more effectively with the hydraulic loading, showing much lower levels for longer towards the end of the growing season. It was also better able to assimilate the larger rainfall events in winter.

Figure 4 Levels and Rainfall data for System 1, Rathmakee, Co. Wexford

System 4, which was located in the north of the county and built a year later, has also performed as intended. Although the water levels inside the system did not fully drop to zero in the first summer due to the willow trees being in the first growing season and hence relatively small (see Fig. 6), the system was able to contain all the receiving rainfall and effluent over the winter, hence maintaining zero discharge. As with Systems 1 and 2 the effect of large rain events on the water level can again be seen.

Figure 5 Levels and Rainfall data for Willow System 2, Rathmakee, Co. Wexford

Soil core samples from the willow systems are being analysed as an alternative method to determine the relevant net void ratio of the backfilled soil in each basin. Once this is determined for each system, the volume of water at any instant can be calculated from the continuous level monitoring at the inspection well. From this, a water balance can be applied to the system to determine the actual evapotranspiration across any given time period.

Daily effluent quantities discharged by the single houses into the three most mature operational systems can be seen in Table 3. It should be noted that these quantities, although significantly lower than the EPA Code of Practice design value of 150 litres per capita per day (Lcd), compare favourably with other recent research on on-site wastewater production in Ireland as, determined by Gill et al., 2009.

Table 3 Selected effluent quantities

<table>
<thead>
<tr>
<th>System</th>
<th>Flow (L/d)</th>
<th>Person Equivalent (Lcd)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>281</td>
<td>70.3</td>
</tr>
<tr>
<td>3</td>
<td>230</td>
<td>115.0</td>
</tr>
<tr>
<td>4</td>
<td>452</td>
<td>113.0</td>
</tr>
</tbody>
</table>

Table 4 shows some examples of the effluent quality being discharged into the systems as well as the water quality at the inspection wells. This shows that significant reductions in organics, nutrients (nitrogen and phosphorus) and
indicator bacteria (*E. coli*) had occurred by the water quality taken from the inspection sumps with respect to the STE being discharged into each system. Some of this reduction will be due to rainfall dilution but a significant amount is also due to natural attenuation as well as uptake by the trees for growth. However, it is noticeable that there was a much more limited change in chloride concentrations between the influent and inspection sump and on some sites a slight increase occurred. It is expected that the background chloride concentrations will increase over the years as chloride should not be significantly picked up by the willows nor naturally attenuated and so these levels will need to be monitored in order to determine what levels might start to inhibit tree growth.

Table 4 On-site effluent (STE) and willow bed inspection well (WB) water quality parameters

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>COD (mg/l)</th>
<th>Total N (mg/l)</th>
<th>Ortho-P (mg/l)</th>
<th>Chloride (mg/l)</th>
<th>E. coli (MPN/100ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>STE</td>
<td>498</td>
<td>76.7</td>
<td>6.24</td>
<td>67.0</td>
<td>4.61x10^6</td>
</tr>
<tr>
<td>WB</td>
<td>11</td>
<td>4.7</td>
<td>0.16</td>
<td>38.4</td>
<td>6.49x10^2</td>
</tr>
<tr>
<td>STE</td>
<td>477</td>
<td>78.0</td>
<td>5.99</td>
<td>37.8</td>
<td>6.49x10^5</td>
</tr>
<tr>
<td>WB</td>
<td>29</td>
<td>3.7</td>
<td>0.22</td>
<td>25.5</td>
<td>9.8x10^5</td>
</tr>
<tr>
<td>STE</td>
<td>383</td>
<td>58.1</td>
<td>4.15</td>
<td>37.7</td>
<td>6.5x10^5</td>
</tr>
<tr>
<td>WB</td>
<td>55</td>
<td>6.3</td>
<td>0.64</td>
<td>58.7</td>
<td>1.19x10^6</td>
</tr>
<tr>
<td>STE</td>
<td>396</td>
<td>54.5</td>
<td>6.47</td>
<td>27.6</td>
<td>2.9x10^6</td>
</tr>
<tr>
<td>WB</td>
<td>30</td>
<td>3.7</td>
<td>0.06</td>
<td>34.7</td>
<td>4.23x10^5</td>
</tr>
</tbody>
</table>

Finally, some early lessons have been learned at this stage of the trials with respect to the construction of these systems. It seems that weeding is imperative in the first growing season in order to remove the competition for light, space and nutrients. In fact, even more effective was the laying of a weed proof barrier on top of the backfilled soil. It is also important to plant the willow cuttings as early as possible in the growing season (ideally in March), in order to give them the benefit of a full first season’s growth before effluent is introduced to the system as this will enhance their chances of surviving the initial winter period. This was particularly apparent at one site (System 4) whereby the immediate inflow of effluent had a detrimental effect on the willow cuttings resulting in the majority dying off, which effectively set the performance of the system back 2 years.

**Mesocosm Experiments**

**Climate**

The average monthly weather data along with the monthly ET$_0$ at the site location for the 2010 and 2011 growing seasons are shown in Fig. 7. As can be seen, the climatic data for the two growing seasons were quite similar with a few notable exceptions. The average temperature during June and July was noticeably higher for 2010 and the evapotranspiration rate for August 2011 was comparatively low due to unseasonable weather. During the 2011 growing season time frame (June to Sept) the total rainfall was 372 mm. The average temperature for the period was 13.4°C and the reference evapotranspiration at the site was 313 mm. It can be seen from Fig. 7 that the air temperature had an almost direct correlation with the reference evapotranspiration with the exception of August as a result of unseasonal weather. For comparison, the total rainfall for the 2010 growing season was 302 mm with an average temperature of 15.6°C and a reference evapotranspiration of 331 mm.

![Figure 7 Monthly meteorological data for 2010 and 2011 growing seasons](image-url)
Evapotranspiration and crop coefficient values for the two growing seasons can be seen in Figs. 8 and 9. The pattern for the 2010 and 2011 seasons is quite similar, although the actual evapotranspiration values are lower for the 2011 season. There was no discernible difference in the evapotranspiration between the four willow varieties, with the exception of the Torhild being applied with secondary treated effluent. This was due to poor growth and development issues which persisted from the start with the plant.

The benefit to evapotranspiration by adding synthetic effluent (both primary and secondary) is apparent for the 2010 and 2011 seasons (Figs. 8 and 9). Over the 2010 growing season it was observed that the trees applied with primary treated effluent had slightly higher evapotranspiration (1165, 1129, 1030 and 1087 mm) compared to the trees receiving secondary treatment (1064, 995, 962 and 410 mm), and both of these well outperformed the trees receiving neither primary nor secondary effluent (544, 867, 579 and 656 mm). The crop coefficients followed the same pattern. The 2011 growing season resulted in much lower evapotranspiration values but a slight increase in crop coefficient values. Again, the trees under primary treatment (734, 667, 590 and 800 mm) had slightly higher ET$_{willow}$ values compared to the trees under secondary treatment (665, 602, 517 and 286 mm) and both these outperformed the trees receiving no treatment (445, 476, 362 and 453 mm), with the exception of the Torhild variety receiving secondary treated effluent.

At the time of writing (August 2012) the trees during the current season appear to have produced improved evapotranspiration rates with some of the trees having already surpassed 2011 results, with 8 weeks (approx.) of the growing season still remaining.

**Figure 8** Evapotranspiration rates and crop coefficients for 2010 season

**Figure 9** Evapotranspiration rates and crop coefficients for 2011 season

**Discussion and Conclusions**

**Full Scale Systems**

The full scale systems are all now constructed and are being monitored. The sites in which the willows have been growing for two or more seasons are showing good potential in terms of operating as sustainable solutions for the treatment and disposal of on-site effluent in areas of low permeability subsoils as shown in Figs. 4, 5, 6. Systems 1 and 2 in particular have produced positive results, with all effluent and rainwater being disposed of via evapotranspiration in the 2011 season.
Several lessons have been learnt during the trials on full-scale system to date. There is evidence that the initial growth of willows was hampered by weed growth, primarily on Systems 6 and 7 and it has been noted that willows need to be growing for a full season before effluent is added to the system. In addition, the background chloride levels in the willow basins will need to be monitored for several years to assess whether it eventually reaches a level to inhibit tree growth.

Mesocosm trials
The mesocosm trials have proved very interesting to compare directly the evapotranspiration from different willow varieties against strength of effluent applied. The increase on evapotranspiration brought about by the addition of effluent matches the findings from other studies, e.g. Guidi et al. (2008), Gregersen and Brix (2001) and Martin (2007). The results for the 2010 growing season also compare favourably with results obtained in Italy by Guidi et al. (2008) for willows in their first growing season, especially in the case of the willows treated with effluent or fertilisation. However, the total evapotranspiration across the second season for the willows in Ireland was more muted than the Italian based study which reported a 50% increase on the first season. The crop factors for the second season’s growth are more comparable with 3.18 being reported in the Italian study compared to 2.9 here in Ireland. The crop coefficients in these mesocosm trials also compare favourably to the crop coefficients determined by Bialowiec et al. (2007) used to treat landfill leachate in Poland.

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Acknowledgments
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