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Willow-based evapotranspiration systems for on-site wastewater effluent in areas of low permeability subsoils

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ABSTRACT

Six different full-scale willow evapotranspiration systems receiving both septic tank and secondary treated domestic effluent from single houses in Ireland have been investigated as a potential solution to the problem of on-site effluent disposal in areas with very low permeability subsoils. Continuous monitoring of rainfall, reference evapotranspiration, effluent flows and water level in the sealed systems revealed varying evapotranspiration rates across the different seasons with annual rates ranging from 576 to 929 mm/yr. The results showed that no system managed to achieve zero discharge in any year remaining at maximum levels for much of the winter months, indicating some loss of water by lateral exfiltration at the surface. This was attributed partly to the fact that the in-situ low permeability soil that had been excavated to form the lined basin was shown to have a much lower effective (useful) porosity when used to backfill the systems than had been assumed in the original designs. In addition, the Irish maritime climate, with its typical high relative humidity levels throughout the year (>85% on average), resulted in muted evapotranspiration performance of the systems. However, chemical and microbiological sampling of the water in the sumps and ponded water over the winter periods demonstrated that the systems were acting as excellent passive pollutant attenuation processes.

1. Introduction

The potential impacts of domestic on-site wastewater effluent are the pollution of either groundwater and/or surface waters. In particular, areas with inadequate percolation due to low-permeability subsoils and/or insufficient attenuation due to high water tables and shallow subsoils present the greatest challenge to find appropriate solutions. If there is insufficient permeability in the subsoil to take the effluent load, ponding and breakout of untreated or partially treated effluent at the surface may occur. This is associated with serious health risks, and there will be a risk of effluent discharge/runoff of pollutants to surface water and also wells which lack proper headworks or sanitary grout seals (Hynds et al., 2012). A potential solution for the treatment of on-site effluent in such regions of low subsoil permeability could be evapotranspiration (ET) systems using willows trees, particularly if they could operate effectively as zero discharge systems across the year and thus remove any risk of pollution to either groundwater or surface waters. Furthermore, domestic wastewater from single houses has high concentrations of both nitrogen and phosphorus (Gill et al., 2009) which should promote the rapid growth (and corresponding evapotranspiration) of willows.

The use of willows in sealed basins as zero discharge systems as a technology has been introduced into Denmark with some success (Gregersen and Brix 2001; Arias 2012) with national guidelines produced (Miljøstyrelsen, 2003). Willow has numerous physiological traits which make it highly suitable for such phytoremediation purposes in temperate climates: high transpiration rates throughout the growing season (Persson and Lindroth, 1994; Rosenqvist et al., 1997; Hall et al., 1998; Guidi et al., 2008); efficient uptake of nutrients (Elowson, 1999; Dimitriou and Aronsson, 2010, 2011) and ability to facilitate denitrification in the root zone (Aronsson and Perttu, 2001); tolerance of flooded or saturated soils and oxygen shortage in the root zone (Jackson and Attwood, 1996; Kuzovkina et al., 2004); ease of vegetative propagation due to preformed root primordial on the stems and vigorous re-establishment from coppiced stumps (Ceulemans et al., 1996; Philippot, 1996); and an extensive fibrous root system, with approximately 80% of the fine root hairs found at depths of less than 40 cm (Rytter and Hansson, 1996; Crow and Houston, 2004). Willow has also been shown to be resilient to high polluting substances (Bialowiec et al., 2007; Białowiec and Randerson, 2010) and so has the necessary rigour to cope with the wide ranging pollutants in wastewater.

The only reported ET values for full-scale zero discharge willow systems treating on-site wastewater effluent come from trials

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carried out in Denmark from 1997 to 1999 (Gregersen and Brix, 2001 Brix and Arias, 2011) ranging from 980 to 1270 mm for the first year and 1470–2090 mm in the second year. These figures are comparable to ET rates determined by Guidi et al. (2008) in lysimeter experiments for willows receiving fertilisation, but somewhat lower than other lysimeter experiments by Martin and Stephens (2006) under higher levels of fertilisation. Indeed, ET rates have been strongly correlated to plant development (Guidi et al., 2008; Pistocchi et al., 2009) and mainly dependent on its nutritional availability rather than on the differences between the varieties. This was recently confirmed under Irish meteorological conditions in mesocosm trials comparing four different willow varieties receiving three different effluent types: primary effluent, secondary effluent and rainwater (Curneen and Gill, 2014). The results showed no statistical difference between the ET performances of the different species, but a statistically significant difference in relation to the effluent loading, with the highest ET rates for those cultivars receiving primary effluent, compared to secondary treated effluent which were in turn much higher than those receiving just rainfall. In addition, the willows were also found to uptake a high proportion of the nitrogen and phosphorus from the primary and secondary treated effluents added every year, with comparable uptake rates to those reported by Sugiura et al. (2008), Aronsson and Bergström (2001) and Dimitriou and Aronsson (2011).

The domestic wastewater of approximately one third of the population in Ireland, ~500 000 dwellings, is treated by on-site domestic wastewater treatment systems (DWTSs) of which more than 87% are septic tanks (CSO, 2011). It has been estimated that 39% of the country has inadequate percolation (due to heavy clay soils), which can arise all year round or intermittently during wet weather conditions (EPA 2013). The direct discharge of treated on-site effluent to surface water is not allowed in Ireland without a licence which no Local Authorities are prepared to grant. Hence, a series of full-scale trials were set up in regions of low subsoil permeability in Ireland. The research objectives were to assess the overall performance and the applicability of the system in such a maritime temperate climate to provide an alternative on-site wastewater disposal option for areas with low permeability soils.

2. Materials and methods

2.1. System design

Six full scale willow systems were constructed to treat domestic wastewater effluent from single house dwellings in County Wexford, located in south-east Ireland. The sites were located in areas with considerable deposits of lacustrine clay ("marl") subsoils with low permeability, in which effluent percolation would not be a feasible disposal method for the on-site effluent.

The systems were designed (plan area and depth) on the basis of a modelled water balance between the typical wastewater effluent rates expected from the dwelling, the precipitation onto the area and the estimated evapotranspiration from the basin over a four year period. The numerical model was built using realistic time-varying fluctuations in flows on the basis of previous research carried out by Gill et al. (2009), local meteorological conditions as measured in the locality over the previous four years and estimated crop coefficients to provide an accurate temporal simulation of willow evapotranspiration (and associated volume storage) across a four year period (see Fig. S.1 for an example design model simulation). The crop coefficients were assumed to be 1 throughout the winter months increasing up to maximum values of 2.65 across the summer months (using willow crop coefficients from current design guidelines for zero discharge willow systems exist in Denmark (Miljøstyrelsen, 2003). Once the required volumes were determined, they were then divided by the porosity of the soil expected within each willow system (estimated at 30%). The final dimensions of the willow systems were compared using different combinations of area and depth (see Table S.1 for design loading rates and estimated storage volumes). A soil depth of 1.8 m was chosen for the design with an extra 0.2 m lined bund around the perimeter of the willow system to contain any potential flooding.

The systems were designed to specifications that would allow for the long-term study and comparison of their evapotranspiration rates against key design parameters (effluent type, willow species, plan area, aspect ratio and effluent distribution) as seen on Table 1.

In addition, two of the systems were designed and constructed to receive primary treated (septic tank) effluent (STE), three to receive secondary treated effluent (SE)—i.e. microbiological treatment in aerated conditions. Site VI never received any effluent during the trials and so acted as an interesting control site.

2.2. Construction

The basins were excavated to a depth of 1.8 m with the slopes of the sides of the basin kept as straight as possible in order to maximise the storage volume in the system (Fig. 1). A geosynthetic barrier was laid along the bottom and sides of the excavated basin, and then an impermeable membrane (minimum 0.5 mm thickness butyl rubber or sealed LDPE) was laid on top of the geosynthetic barrier. A second geosynthetic barrier was then laid on top of the impermeable membrane. The excavated soil was then back-filled into the basin up to ground level, in addition to installing a distribution layer. A 2.2 m long, 300 mm diameter inspection well was located in the middle at the opposite end of the system from where the effluent was discharged, sitting in a slight sump, as shown in Fig. S.2.

2.2.1. Effluent distribution (non-pressurised)

The effluent was distributed by gravity throughout the willow systems from the base in a high porosity layer situated in the soil medium. Wavin® 110 mm percolation pipes were placed in a layer of 8–32 mm washed gravel either in 300 mm × 300 mm trenches (Sites II and VI) or in a 300 mm deep layer across the whole base (Sites III–V) to improve storage volume within the system.

2.2.2. Effluent distribution (pressurised)

Site I was constructed according to the Danish design guidelines. The soil was backfilled to a depth of 1 m. A 0.1 m layer of washed sand (1–4 mm) was placed on top of the soil. The distribution layer which consisted of EXPO-NET BIO-BLOK® 200 trickling filter media (0.275 × 0.275 × 0.55 m) were placed end to end along the centre line of the system on top of the sand layer and surrounded in a geosynthetic barrier. A semi-rigid 40 mm diameter distribution pipe with drilled percolation holes was laid on top (at a depth in the system of approximately 0.4 m) into which effluent was pumped on a volume-dosed basis.

2.2.3. Willow establishment and maintenance

Three different varieties of willow (from a selection of 8 willow varieties—all cultivars of *Salix viminalis*), as shown in Table 1, were planted on each site in order to resist disease and parasites. 300 mm long willow cuttings (see Table 1 for varieties) were planted at a density of 3 per m^2 by mapping out the surface of the system into 1 m^2 grids. The planting density was chosen according to previous Danish experience (Miljøstyrelsen, 2003), which is twice the density recommended by the short rotation coppicing (SRC) industry in the UK and Ireland (DEFRA, 2002). After the first year of growth the willows generally had 1–3 shoots with a maximum height of 2–3 m. Coppicing of all the willows was then carried out, in accordance with standard SRC guidelines (DEFRA, 2002; Caslin et al.,