

AN ALTERNATIVE APPROACH TO NITROGEN MANAGEMENT WITHIN SEWAGE TREATMENT WORKS

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ABSTRACT

Nitrogen and phosphorus management within sewage treatment works is problematic since all releases are subject to increasing regulation and hence cost escalation. Any action to improve quality within one part of the treatment system invariably impacts on releases or quality standards elsewhere in the process. A new approach needs to be taken to managing nitrogen within treatment plant to ensure that all elements of the water treatment process are optimised while maintaining costs at sustainable levels.

Short rotation woody crops of willow and poplar have been tested to determine their capacity to renovate raw and partially treated wastewater. The principal benefits of the employing land based treatment include reduced or zero sludge production, low capital and operational costs, reduced energy use within the treatment works, and low management requirement.

This paper discusses how these intensive tree based systems may be employed and provides illustrations of systems currently in operation.

KEY WORDS

Tertiary treatment, biosolids reduction, land treatment, willow, poplar,

INTRODUCTION

Sewage treatment works are designed primarily to achieve a prescribed quality in the treated, discharged effluent. This is largely the consequence of the regulatory focus on easily monitored point discharges. However, in addition to treated effluent, sewage treatment works (STW) produce sludge which is also discharged to the environment. This product has not had to meet quality standards but has been regulated indirectly through long term soil limit values for persistent, potentially toxic metals. The Safe Sludge Matrix demands that advanced sludge treatment achieves defined levels of pathogen kill, but this does not impact on decisions concerning effluent quality. Consequently, on a day to day basis, all effort is directed towards delivering one quality product from the treatment works, the effluent, usually regardless of the impact on the ease and cost of managing that second product, the biosolids. The result is ever increasing quantities of biosolids with ever increasing concentrations of nitrogen (N) and phosphorus (P). At the same time, the limits on the timing and amount of nitrogen application to land are becoming more stringent, while concerns over P induced eutrophication may bring about limits on P application.

Sewage treatment works should be designed and operated such that all products are given equal consideration in order that costs are minimised and standards optimised. This rethink in works design and operation needs to consider the mass balance for N and P and the energy use throughout the works, including biosolids transport costs in order to answer the question, how can effluent quality be maintained or increased while avoiding additional biosolids production or excessive energy costs?

Biosolids are produced during biological processes to remove N and P. These processes also tend to be energy expensive due to aeration requirements and may involve the cost of chemical addition. An alternative means of removing N and P is to employ a plant based approach whereby the N and P are taken up and used for plant growth. Irrigation to a biologically active medium such as soil employs the same processes, both aerobic and anaerobic, as are taking place within the contained system of treatment works without the energy input or microbial biomass production. Employing a plant based treatment stage enables actions to be taken to reduce sludge production at the early treatment stages within a works since the resultant increased loadings of soluble pollutants in the effluent, will subsequently be managed within the tree plantation. Hence, additional treatment in the form of phosphate removal and denitrification stages with their associated energy cost, are not required.

TREE-BASED WASTEWATER MANAGEMENT

There has been considerable interest in the last 15 years in the beneficial use of wastewater nutrients in the production of woody biomass for use as a renewable fuel. In more recent years the focus has been on wastewater treatment, with the wood production element taking back stage except for its role in achieving high effluent quality.

WRc is leading an EU funded project, the objective of which is to bring to commercial adoption the use of short rotation energy forestry of willow and poplar for the management of wastewater. Research has been conducted on this subject in Europe, the USA, Australia and New Zealand and commercial adoption has taken place in New Zealand, the US and Sweden. However, there has been no commercial adoption in the UK and both regulators and potential users are uncertain as to its relevance to, and effectiveness under, UK conditions.

The Water Renew project is endeavouring to overcome this information gap by putting in place a series of demonstration sites. These sites will also be used to collect data for use in the development of a computer based model to assist in the design of sites in the future.

The Water Renew approach to wastewater management employs the water and nutrient take up capacity of fast growing intensively planted trees and the filtration and microbial action of soil to remove potential pollutants from wastewater. It may be used as a final polishing of a partially treated effluent or as the sole treatment system employed, depending on the strength and volume of the wastewater to be managed. They may also be used to treat a portion of a wastewater stream to reduce the load on conventional treatment facilities.

Liquors which have been treated in this way include dairy shed effluent, sewage effluent, wastewater from log yards and landfill leachate. The most common trees species employed are willow, poplar and eucalyptus, because they have high nutrient and water uptake capacity, are tolerant of a wide range of conditions, including high salinity and can be used to produce significant amounts of wood fibre in short rotation.

Wastewater may be applied at rates which match the tree water use such that there is no effluent drainage from the site. Alternatively, it may be applied at rates which permit drainage of renovated water. Irrigation rates may vary through the year according to which approach is to be employed. Irrigation is applied to the soil surface by a range of techniques, according to the conditions at specific sites. The technology is very flexible and can be adapted to a wide range of situations. The approach also offers secondary benefits in terms of corporate responsibility and environmental impact. These include a reduced carbon cost of wastewater treatment, sites are aesthetically attractive and bring about wildlife enhancement within the vicinity of treatment works, and production of wood fibre, a tradable commodity for energy or wood chip markets.

NITROGEN MANAGEMENT

Nitrogen is managed by plant uptake, soil absorption and denitrification. Root exudates, and plant material including leaf litter, decaying roots and fallen stem material provide a ready and continuous carbon supply to facilitate nitrogen processes. The soil provides a highly nitrifying environment. Soil biology is considerably more active and diverse under trees than grassland, or any agricultural production system and as a site matures, these processes will become more effective such that loading rates should be able to be increased.

Matching loading rates with system assimilation capacity will minimise the risk of nitrate leaching. The optimum proportion by weight of nutrients for short rotation willow coppice where N = 100 is N = 100, P = 14 and K = 72 [1]. Typical nutrient concentrations in municipal wastewater are present in a similar proportional balance of N = 100, P = 18 and K = 64 [2]. This means that there is a very good match between plant requirement and what will be supplied in sewage wastewater.

SRC wastewater systems achieve good nitrogen removal after an initial stabilisation period. In a three year lysimeter trial using willow, leaching from clay and sand soils was found to drop from over 300 and 140 kg N ha⁻¹ respectively in the first year, to 3 and 1 kg N ha⁻¹ in the third [3]. Since the highest nitrogen application was only 244 kg N ha⁻¹, it seems likely that a significant proportion of the initial N leaching was associated with soil nitrogen released as a consequence of the disturbance of the soil during the filling of the lysimeters, particularly since nitrate leaching was occurring before the trees had

been planted and wastewater applied. This is somewhat surprising since the lysimeters had been filled nine years previously and left undisturbed. Similarly, in another lysimeter study, [4] noted that lysimeters irrigated with deionised water released as much nitrate-N as did those irrigated with final effluent over a 6 month period, suggesting that soil N reserves were contributing a major portion of the nitrate leaching losses.

A field trial in Hertfordshire using willow to manage landfill leachate found that, over a three year period, the proportion of applied N leached from the site decreased from 35% in the first year to 17% in the third year, despite the rate of N application increasing from 40 kg N ha⁻¹ in the first year to 215 kg N ha⁻¹ in the third year [5]. Danish and Swedish studies of SRC willow cultivation without wastewater irrigation but with fertiliser inputs have found nitrate leaching to fall to virtually zero three years after planting [6, 7]. Poplar used in riparian buffer zones have achieved 80% N and P removal [8].

Nitrate leaching is not related to the volume of irrigation but to plant uptake and the mass of nitrogen applied suggesting that nitrogen is the land limiting component of sewage effluent application rather than hydraulic loading [9]. Hasselgren [10] found that N leaching was about 10% of the applied N for irrigation rates of both 2mm and 12 mm. A very wide range of nitrogen applications have been made to SRC plantations under different circumstances with leaching losses from them all being low.

The level of treatment performance achieved by tree based systems compares favourably with conventional wastewater treatment systems [11] (Table 1), and with constructed wetlands which achieve N removal of between 35 and 60% [12]. Losses of pollutants to groundwater in uncontained systems is a key concern directed at SRC wastewater treatment units. However, the evidence is that with appropriate design and management, nitrogen losses from these systems are small (Table 2).

There is a tendency to assume that SRC wastewater management systems duplicate the functions and performance of constructed wetlands. However, this type of treatment system is not designed to substitute for existing land based systems such as reed beds, but rather to add to the matrix of treatment options available to wastewater managers.

The hydraulic loading of constructed wetlands is much higher than short rotation coppice (SRC) based systems and the footprint much smaller. However, the treatment performance of the two systems also differ. The SRC systems will tend to operate predominantly aerobically, while constructed wetlands will have both aerobic and anaerobic zones. Both have similar anticipated lifetimes. Green [12] suggests that constructed wetlands will operate satisfactorily for 20 years before the gravel substrate will need replacement. Willow SRC plantations managed for wood fibre production are anticipated to last between 20 and 30 years before requiring replanting due to declining yields. However, there are no plantations of that age to test that estimate, other than those grown for basket willow. Since breeding programmes are developing varieties of willow that yield 20-40% more biomass than those which were planted in the early phases of SRC energy forestry development, and these improvements can be expected to continue for some time, it is probable that plantations will be replaced more frequently than every 20 years where biomass production is the primary aim.

No data are available for BOD removal by SRC plantations but [5] found COD and TOC to be reduced by 92 and 98% respectively in landfill leachate with a mean COD concentration of 517mg l⁻¹ and a mean TOC concentration of 198 mg C l⁻¹. This compares favourably with removal of COD and BOD in constructed wetlands which typically ranges between 65 and 85% for COD, and 80-95% for BOD [12].

OPERATIONAL OPTIONS AND COSTS

Tree based wastewater management systems are highly flexible in the manner in which they can be implemented. They are a non-sensitive system capable of coping with variable flow and loading without failing. Any design should always incorporate a high buffering capacity to enhance this characteristic. A series of situations where they may be adopted are outline below.

The costs of operating small treatment works are disproportionate to the amount of effluent they treat and biosolids they produce. Often the impact of a system failure is also disproportionate since the receiving waters for small works are typically small streams. Achieving improved effluent quality at such works can be challenging since many of the technologies do not necessarily bolt easily onto the existing equipment or need more management input than can be given to an unmanned works. Land-

based treatment systems offer an alternative at small or rural works serving around 5000 pe or less, where the cost of conventional secondary or tertiary treatment would be disproportionately high.

The impact of effluent on receiving water bodies, in terms of water quality can be significant in periods of low flow. It is possible to combine summer removal of nutrients using land treatment with the use of conventional methods in winter to eliminate the negative impact of the effluent and reduce sludge production and treatment costs. The Kågeröd treatment works described below is one such system.

A significant proportion of the nitrogen within a treatment works can be recirculated back through the process in activated sludge such that it is 'treated' multiple times. Also, certain stages within a works such as sludge dewatering, will produce strong liquors which need to be put back in at the head of the works. Diversion of sludge dewatering liquors and other concentrated flows within a treatment works to a SRC based treatment stage will significantly reduce the load on other parts of the treatment facility. The Swedish STW at Enköping adopts this approach, as is described below.

Tree based treatment systems may be operated year round, may use summer application only, reverting to conventional treatment in the winter or use lagoons to store winter effluent production for application during the summer. The landfill site at Riverbend in Oregon State, USA employs this latter storage approach, as is described below. A further variation is to irrigate all the wastewater during the summer and store only the dewatering supernatant in the winter which will require substantially less storage capacity.

Diversion of particular, possibly troublesome, wastewater flows entering treatment works to a tree based component of the treatment works can reduce the loading on existing treatment facilities and possibly reduce the incidence of process failure. Similarly, SRC plantation may be used to accommodate storm overflow in the same way as constructed wetlands are, to minimise impact on, or the chance of failure of the STW.

The Water Framework Directive is bringing about the review of all sources of nutrients into surface waters within a catchment, both point and diffuse, with a aim of delivering plans to reduce those inputs. There are many small treatment works which require investment to improve the quality of the effluent they produce. In addition to requiring investment at these works, more sludge will need to be tankered to regional sludge treatment centres, increasing the load on these facilities and potentially requiring capacity building for sludge treatment. Using tree based effluent polishing at these sites will require substantially less investment than conventional approaches to treatment. Even where nitrogen removal is already satisfactory, there may be a requirement to install phosphorus removal, a function that a short rotation coppice based treatment facility could very satisfactorily fulfil.

A system which employs a combination of summer SRC irrigation and winter conventional treatment will not reduce capital costs since the technology for both systems needs to be installed, but it will have lower operational costs. All secondary and tertiary treatment process technology can be avoided if a pond for storage of winter production of wastewater can be built, but this is practical only for smaller works. The treatment of landfill leachate using SRC is potentially cheaper per unit of nitrogen since leachate can be pumped direct from within the landfill with no need for additional storage ponds.

Several studies have looked at the cost operating a system to irrigate SRC with wastewater, both in terms of the benefits to the economics of wood energy production and making comparison with more conventional costs of wastewater treatment. Costs may be quoted in cubic metres of wastewater treated, in kg N managed, or by hectare of plantation used. Since nitrogen loading is the primary land limiting component of sewage, costs are greatly influenced by the N concentration of the wastewater. A low concentration wastewater will require a smaller area of plantation to accommodate it but will incur higher pumping and storage costs. A higher N level lowers the cost per kg N given a constant application rate. The total treatment cost and cost per cubic metre increase with high nitrogen concentrations. Costs per hectare and costs per kg N decrease with a high nitrogen concentrations [16].

The nitrogen loading rate per unit area will also influence the cost of the system. Assuming a typical raw sewage N load of 13 g per day per capita, 500 pe would require 4 ha willow at 600 kg N ha⁻¹ yr⁻¹ loading rate where no other treatment stage is employed. Alternatively, following primary treatment and using a loading of 150 kg N ha⁻¹ yr⁻¹, one hectare will be sufficient for 120 people. [2].

The capital costs of trees based wastewater treatment are low in comparison with more highly engineered techniques. Intensive willow plantations cost in the region of £2000- £2500 ha⁻¹ to establish. The cost of the effluent application equipment depends on the type used, and economies of scale can be obtained with larger systems, but £800 - £1,200 ha⁻¹ would be fairly typical. The use of pond storage would probably double that figure. Table 3 gives indicative costs for three treatment systems and where data is available makes comparison with conventional treatment costs. Costs of conventional N and P removal typically range between £5.83 and 14.80 kg N⁻¹ [2] and saving £5-12.80 kg N⁻¹ can be achieved by using a tree based facility over conventional treatment [17].

ENKÖPING, SWEDEN

Enköping STW treats wastewater from 20,000 people. The effluent from the sludge dewatering centrifuge is applied, after dilution, to 75 hectares of short rotation willow between May and September and stored in an open lagoon through the winter. The willow plantation manages 25% of the STW nitrogen load, some 16,000 kg, but only 1% of its water. Approximately 200,000 m³ are applied, equivalent of 254mm supplying 160 kg N ha⁻¹ and 3 kg P ha⁻¹ [14]. Nitrate leaching losses remain below 10 mg l⁻¹ through the year. The site has been in full operation since 2000 and is managed by sewage treatment works staff with a local farmer contracted to managed the crop. One third of the site is harvested each year to provide a continuous supply of wood to the district heating plant which is located immediately adjacent to the STW and willow plantation.

KÅGERÖD, SWEDEN

This 11 ha willow plantation was established in 1995 and irrigation commenced in 1997. The site manages effluent from 1500 people and a milk powder processing plant giving a total pe of 5000. Wastewater passes through screens, sand filtration and a surface aerated activated sludge unit. The resulting secondary effluent with a mean total-N concentration of 10mg l⁻¹ is irrigated to the willows from May to end October. Chemical precipitation of P using AlSO₄ is also avoided during this irrigation period. Key benefits are reduced chemical sludge production and reduced electricity costs through less stirring in the flocculation stage and less aeration & pumping of sludge. This system discharges to watercourse which has seen 80% reduction in N content of the effluent and 55% reduction in the BOD, compared with previous discharge quality.

CULMORE, NORTHERN IRELAND

Culmore sewage treatment works in Northern Ireland has a treatment capacity of 120,000 pe and undertakes primary treatment only – aeration and sedimentation - prior to discharge to the neighbouring river. Four hectares of experimental short rotation willow plots were planted in 1998 immediately adjacent to the treatment works, as part of an EU project. A range of hydraulic loadings were tested the highest of which was 1750mm applied through the growing season. Average N concentration in the effluent was 20 mg l⁻¹, 14 mg l⁻¹ P and 104 mg l⁻¹ BOD. The maximum nitrogen application was 250 kg ha⁻¹yr⁻¹. Soil nitrate levels did not exceed 5 mg l⁻¹ and were not elevated about background concentrations. The willow vegetation filter removed 80% of the applied nitrogen 98% of the P and of the 74% BOD [18]. This particular plantation has been removed to allow for the expansion and upgrading of the treatment works, but a new plantation was planted in spring 2005 as part of the Water Renew project.

RIVERBEND LANDFILL SITE, OREGON STATE

Planted in 1992, this 6 ha plantation of poplar is irrigated during the growing season between May and October with 460mm of landfill leachate, equivalent to 4600m³ ha⁻¹ per year. This applies 335 kg N ha⁻¹ annually. The leachate is collected from closed and active cells and stored in a 26,000 m³ open lagoon. The lagoon is empty by the end of the irrigation period. Irrigation commenced one year after tree planting and uses fixed spray heads mounted on one metre tall poles. The site was installed as an alternative to discharge to foul sewer or installation of an onsite treatment facility. Groundwater nitrate levels do not exceed 10 mg l⁻¹ during the growing season and peak at 30 mg l⁻¹ in the early autumn [8]. The local regulator and site operator are sufficiently satisfied with the operation of the facility that was extended by a further 30 ha in 2003 to accommodate more leachate from the expanded landfill site.

CONCLUSIONS

Tree based systems of wastewater treatment achieve high levels of N, P and suspended solids removal. They may be employed in a wide range of situations, are robust and can be managed by any competent agricultural contractor. Establishment and management is highly mechanised but operational demands are low. Irrigation systems may be fully automated with appropriate safeguards put in place in the

event of failure in any of the components. Capital and operating costs are lower than for conventional processes to achieve the same outcome and performance is as good or better.

Wastewater managed should review their facilities to identify those which may benefit from adoption of a tree based treatment stage. The Water Renew project will provide information which will aid in the design of these facilities.

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TABLES

TABLE 1 - TYPICAL NITROGEN REMOVAL EFFICIENCY OF A RANGE OF WASTEWATER TREATMENT PROCESSES

Technology	Total-N removal efficiency
Aerobic units with pulse aeration	25-61
Sequencing batch reactor	60
Single-Pass Sand Filters (SPSF)	8-50
Recirculating Sand/Gravel Filters (RSF)	15-84
Multi-Pass Textile Filters	14-38
RSF with anoxic Filter	40-90
RSF with anoxic Filter & external carbon source	74-80

Source: Washington State Department of Health 2005, Nitrogen Reducing Technologies for Onsite Wastewater Treatment Systems, Report to the Puget Sound Action Team, June 2005

TABLE 2 - NITROGEN LEACHING FROM FERTILISED WILLOW AND POPLAR

Species	Poplar	Willow	Willow	Willow	Willow
Material applied	Sludge and final effluent	Diluted sludge dewatering supernatant	Landfill leachate	Nutrient solution	Secondary effluent
Period of application (years)	2	3	3	3	1
Tree age at end of trial	3	4	4	3	3
Wastewater conc. (mg l ⁻¹)	19.3	64	70	74	8
Total N applied (kg ha ⁻¹)	800	460	351	710	56
Mean NO ₃ -N conc. in soil water (mg l ⁻¹)	19.5	>10	11.9	<25	2
Reference	13	14	5	3	15

TABLE 3 - INDICATIVE COSTS OF WASTEWATER TREATMENT USING TREE BASED SYSTEMS

System	Capacity (m ³ yr ⁻¹)	Wastewater concentration (g m ⁻³)	Capex		Opex		Ref	
			WWTW	SRC	WWTW	SRC		
			(£'000)		(£ m ⁻³)			
Landfill leachate ¹	15,000	70	180	30	4	0.8	11.42	5
Landfill leachate	195,000	24		430	0.41	0.22	9.19	16
Primary effluent	43,000	35		66.3		0.21	6.51	2

¹ Equivalent Capex and Opex costs using methane stripping and discharge to foul sewer are £180,000 and £4/ m³ respectively