Sustainable Urban Renewal and Wastewater Treatment

No. 37 2003

Short-rotation Willow Biomass Plantations Irrigated and Fertilised with Wastewaters

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Results from a 4-year multidisciplinary field project in Sweden, France, Northern Ireland and Greece

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Content

Foreword

This report summarises findings from a 4-year European research project "Biomass Short-Rotation Willow Coppice Irrigated and Fertilised with Municipal Wastewater" partly financed by the EU FAIR Programme (Project No CT97-3947). The participating partners were as follows:

- Svalöf Weibull AB, Sweden, represented by Dr. Stig Larsson (Project Co-ordinator)
- Association pour le Développement des Culture Energétiques, France, represented by Mr. Christian Cuingnet/Mr. Pierre Clause
- Swedish University of Agricultural Sciences, Sweden, represented by Mr. Ingvar Jakobsson
- Queens University, UK (Northern Ireland), represented by Dr. Malcolm Dawson
- A & B Backlund ApS, Denmark, represented by Mr. Arne Backlund
- Agricultural University of Athens, Greece, represented by Prof. George Mavrogianopoulus

Besides the mentioned participants and representatives above, the project group included:

Dr. Inger Åhman (Svalöf Weibull AB, Sweden), Prof. Kurth Perttu, Dr. Pär Aronsson and Dr. Håkan Rosenqvist (Swedish University of Agricultural Sciences, Sweden), Dr. Fiona Wilson (Queens University, UK), PhD student Drusilla Riddel-Black (Water Research Centre, UK), Prof. Thor Axel Stenström and PhD student Anneli Carlander (Institute of Infectious Disease Control, Sweden), and Mr. Kenth Hasselgren (SWECO VIAK AB, Sweden).

The information and results given in this report are based primarily on annual and final reports on the various activities within the project. To this, all the members of the project group have contributed. Kenth Hasselgren has been responsible for the compilation of the final text.

I am deeply grateful for all the efforts and contributions delivered and would like to thank all members of the group for a fruitful work and a wonderful time together.

Svalöv, Sweden
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Summary

This report summarises results and experiences gathered from field trials with recycling of pre-treated wastewater, diverted human urine mixed with water, and municipal sludge, within plantations of willow species specifically selected for biomass production. Experimental sites were established in Sweden (Roma), France (Orchies), Northern Ireland (Culmore) and Greece (Larissa). The project was carried out during a 4-year period with financial support from the EU FAIR Programme.

The experimental sites were supplied with primary effluent from municipal treatment plants (Culmore and Larissa), stored industrial effluent from a chicory processing plant (Orchies), biologically treated and stored municipal wastewater (Roma) and human urine mixture from diverting low-flush toilets mixed with water (Roma). Application rates of the wastewaters or the urine mixture were equivalent to the calculated evapotranspiration rate at each site. Wastewaters were also applied up to three times this value to evaluate any possible negative effects.

Estimations and evaluations were carried out mainly concerning: biomass growth, potential biological attacks of the plantations, plant water requirements, fertilisation effects of the wastewater, plant uptake of nutrients and heavy metals from applied wastewater, possible soil or groundwater impact, sanitary aspects, and potentials for removal in the soil-plant filter of nutrients and biodegradable organic material from applied wastewater.

The results clearly indicated that biomass production in young willow plantations could be enhanced substantially after recycling of wastewater resources. The impact on soil and groundwater of nutrients (nitrogen and phosphorus) and heavy metals (copper, zinc, lead and cadmium) was limited, even when the application of water and nutrients exceeded the plant requirements. Also, the soil-plant system seemed to function as a natural treatment filter for pre-treated (primary settled) wastewater, with a treatment rate fully comparable to a tertiary effluent quality with regard to biodegradable organic material and eutrophying nutrients (nitrogen and phosphorus).

Introductory analyses of the costs of a wastewater irrigated willow plantation for bio-fuel production indicate that the benefits of the wastewater treatment per se appear to be greater than the benefits from the increased production of wood chips. The risks of contamination via faecal micro-organisms of animals and humans seem possible to reduce or eliminate if proper precautions are taken. The awareness of the hygienic aspects is among the most important issues to deal with concerning the public acceptance.

The gathered opinion from the members of the multidisciplinary project team is that the concept of recycling wastewater or fractions of wastewater within willow plantations for combined energy production and wastewater treatment would be worth developing on a wider scale. Experiences from a few full-scale facilities in Sweden are well in accordance with the findings outlined here. The fact that wastewater could be treated at reasonable costs might encourage the municipal sector as well as the energy and agricultural industry in Europe

to further expand the concept with increased willow plantation areas as a consequence. This would increase the opportunities for an over all better environment for generations to come.

Conclusions and recommendations

The project has resulted in a quantity of information on wastewater use and treatment in willow biomass plantations. The following conclusions and recommendations have been extracted from our findings.

- Wastewater, urine mixture or sludge could stimulate wood ***biomass production*** (willow stem growth) substantially and could replace conventional fertilisers to a large extent. In general, growth levels after a first 3-year rotation were higher compared with non-irrigated and pure water irrigated plants, as well as those reported from commercial willow plantations in Sweden.

  The biomass production increased to some extent with increased waste-water application rates, especially at Larissa. This was likely a result of increased fertilisation rather than increased water supply. Plants supplied with the human urine mixture developed best and showed the highest growth. Although attacks from leaf beetles and rust were observed on some of the plantations, the effects on the biomass production seemed relatively limited.

- The ***water requirement*** of willow plantations was assessed as being close to the theoretical potential evapotranspiration (PE) rate, independent of site location. Wastewater application up to three times the PE was proven to increase biomass growth to some extent, especially at Larissa, where the climate normally supports high evapotranspiration. However, with regard to economising with water and nutrient resources as well as minimisation of the operational costs, the total water application rates should not exceed the expected evapotranspiration rate to a considerable extent.

- The ***nutrient content of the wastewaters*** (N, P and K) varied due to their origin and pre-treatment level. The primary municipal effluent at Larissa and the stored industrial effluent at Orchies were fairly well balanced but resulted in higher applications of nutrients than the total requirement. The primary municipal effluent at Culmore contained N and K amounts similar to the plant requirement but almost 10 times the level of P required. At Roma the biologically treated and stored municipal effluent had N and P contents similar to the stem uptake, while K was in excess. The urine mixture contained a fairly balanced nutrient solution although the P content was low compared with the long-term plant requirement.

- The annual ***uptake of nutrients in willow stems*** at the different sites varied within 18-73 kg N/ha, 3-9 kg P/ha and 6-27 kg K/ha. Average P/N- and K/N-ratios of analysed stems were low at Larissa indicating that some disturbances in plant nutrition may have occurred. At Roma, N concentrations of stems were low, probably as a consequence of the markedly low N content in the applied wastewater. At Culmore, the plants seemed fairly well supplied with nutrients.

- Application of ***heavy metals*** (Cu, Zn, Cd and Pb) with the wastewaters exceeded, in general, plant uptake rates except for Zn at the sites at Roma and Culmore. No obvious correlations were found between plant uptake of metals and soil or wastewater content of metals. In a long-term perspective, added metals should balance with metals removed by the crop (harvested stem wood after defoliation) in purpose to avoid accumulation of metals in the soil. Source control of applied wastewater and selection of willow clones with abilities to assimilate specific metals are possible methods of meeting the “balance criteria”.

- A general pattern was that the ***groundwater quality*** was not specifically affected by the various treatments compared with the controls. At Larissa and Culmore, the concentrations of total N and NO_3 in superficial groundwater appeared higher after low than high application rates. This was likely caused by better prerequisites for denitrification in treatments with higher hydraulic loads resulting in temporary anoxic conditions.

  Metal concentrations in groundwater beneath the urine treatment were lower compared to other treatments at Roma including the control treatment. This could probably be explained by the relatively low concentrations in the applied urine mixture.

- Calculations of ***wastewater treatment effects*** using a mass balance technique over the willow-soil systems at Culmore resulted in removal rates of BOD, total N and total P within 67-74 %, 52-75 % and 90-98 %, respectively. In general, the highest removal rates were found in the most loaded systems. The results clearly indicate that wastewater purification of primary effluent in willow plantations could be substantial and fully comparable to tertiary effluent qualities.

  A hydraulic load up to three times the evapotranspiration rate from the system did not influence wastewater treatment capacities as exemplified with data from Culmore. Thus, managing a system with wastewater irrigation according to water and nutrient requirements of a willow biomass plantation seems possible without negative environmental impacts with regard to oxygen demanding substances and eutrophying components.

- The potential transmission routes for ***pathogens*** to animals and humans after wastewater irrigation are via aerosols (depending on the type of irrigation equipment installed), transportation via the groundwater zone to production wells or transportation via surface run off to surface waters. A general recommendation concerning elimination of the aerosol problem is to install equipment based on solid-set sprinklers operating at low pressures with a short throwing distance or pipes laid on the ground and equipped with drip emitters. The risk of contamination of surface waters increases with high hydraulic loads and low soil permeability in combination with the actual slope of the terrain.

  The risk of groundwater contamination primarily depends on the soil permeability and/or the distance to the saturated groundwater zone or actual production wells. In this study was found that the number of indicator microorganisms in superficial groundwater indicated a contamination risk to the groundwater at the Culmore site. Probable explanations could be that the unsaturated zone was shallow (varied between 0.5 m and 2.5 m) and that the soil profile was relatively permeable (sandy loam). The concentration of indicators increased with the wastewater application rates.

- ***Economic calculations*** regarding willow growing in Northern Ireland show that 9 tonnes of biomass (dry matter basis) per hectare is required to achieve a positive income from the land. The outcome from a willow plantation could be competitive with grassland-based enterprises. In connection with wastewater treatment, the possibilities of reducing costs, compared to conventional nutrient removal from wastewater, is more important than the reduced costs for the farmer in savings from purchasing fertiliser. Factors for keeping costs low in a willow bio-filter system are high concentrations and applications rates of nutrients, an extended irrigation season (since fixed costs are much higher than running costs), short pumping distances and large areas of willow plantations to be irrigated.

- Recycling of resources and production of environmentally sound biofuels are integral parts of sustainable development and thus are promoted by the political society. Nevertheless, the ***public acceptance*** of the use of wastewater, urine or sludge in willow biomass systems, as in other projects with possible environmental impact, is most important and must be treated with the same consideration as anything else in the realisation phase of a project. Any fear the public may feel has to be met with openness and confidence.

  In most European countries the environmental laws include obligatory parts where any plaintiff or citizen with appropriate authority has the right of objecting before any permission or licence can be accepted and approved. In Sweden, some facilities with wastewater irrigation of willow plantations have been in operation since 1997. Before approval, the Swedish environmental authorities required the municipalities to carry out risk assessments on the possibility of infectious diseases spread, to inform the public via posters at the site, and to use ground based irrigation equipment for elimination of aerosols. No complaints from the citizens or others have been reported from the Swedish sites.

An irrigation pipe lateral placed in a double-row of a willow plantation.
(Photo: Stig Larsson)

1 Introduction

1.1 Background

Human wastes have been used on land since ancient times. One of the first land treatment facilities documented in the literature was situated at Bunslaw, Germany (Reed and Crites, 1984). A sewage irrigation system commenced here in 1531 and was in operation for over 300 years. Many “sewage farms” existed in the latter half of the 19th century and during the first few decades of the last century. They were replaced gradually by in-plant alternatives starting round 1920 when the activated sludge process and other biological treatment methods were introduced.

In the United States, land treatment methods in general, especially irrigation applications, have regained respect in recent years as cost-effective and competitive alternatives to conventional wastewater treatment processes in combination with recycling of wastewater nutrients. This result is mainly due to the pioneering and extension work carried out at the Penn State University in the 1960s and the early 1970s (Sopper and Kardos, 1973). In many countries throughout the world where water resources are scarce, reclaimed wastewater is used in agriculture as a replacement for natural water supplies.

Cultivation of selected species of willows (*Salix* spp.) for energy purposes has rapidly increased in Sweden. About 15 000 hectares of short-rotation energy forestry have been established (Larsson, 2002). The total cost of chip production from willow biomass plantations by known technique amounts to 12-13 Euro/MWh (Melin, 2001), which figure is comparable to the price of chipped residuals from conventional forestry. Further development within the area of plant breeding and cultivation technology would most likely reduce the cost of biofuels from *Salix* plantations.

Fertiliser costs are of great importance and corresponds to 15-20 % of the total chip production cost (Rosenqvist, 1997). As a complement or alternative to manufactured fertilisers recycling of waste products rich in nutrients, *e.g.* municipal or industrial wastewater, sewage sludge, leachate from sanitary landfills, and ashes from various combustion processes, have been discussed (Hasselgren, 1992; Aronsson and Perttu, 1994). In Sweden there are a few full-scale facilities where willow plantations are irrigated with pre-treated wastewater (Carlander *et al.*, 2002). The first one began operation in 1997.

The project background has bearing on both energy and agricultural policies within the EU member states. The stated need for replacement of fossil fuels by sustainable energy sources is well documented and bio-fuels take a central position in this respect. The development of alternative crops in European agriculture is being promoted partly due to a general over-production of cereals. Energy crops are on the agenda. A third aspect is that wastewater treatment in soil-plant systems combined with reuse of wastewater resources (water, organic material and nutrients) for crop production has potentials for saving finite resources in terms of manufactured fertilisers and less use of chemicals and energy compared with traditional wastewater treatment.

1.2 Objectives

The project group consisted of scientists and professionals with backgrounds in wastewater and/or willow applications that saw synergetic benefits in coupling together the two disciplines. The basic expected benefits were:

- Willow plantations - as an alternative energy source - do not contribute to the increase of carbon dioxide (green house gas) in the atmosphere, as the plantations assimilate the same amount of carbon dioxide as is discharged by combustion.

- Wastewater can supply a major part of the nutrition for the willow crop. Divrted urine from domestic wastewater can supply nutrients in an even more balanced way.

- The willow crop provides an active bio-filtration system for the wastewater's content of oxygen demanding organic material and eutrophying nutrients such as nitrogen and phosphorus.

The aims of the 4-year project, based primarily on small-scale field experiments in four countries, were evaluations of:

- The growth and biomass production of willow coppice irrigated with pre-treated wastewater and a urine mixture.

- The effectiveness in removal, from the wastewater, of biodegradable organic material and eutrophying nutrients by the soil-plant system

- The contribution of wastewater application to the overall nutrient and water requirements of the willow crop.

- Some economic, environmental, social and legal aspects of wastewater recycling in a willow-to-energy system.

2 Field experiments

2.1 Experimental procedures

2.1.1 Experimental sites and climatic conditions

Experimental fields were established in Sweden, France, Northern Ireland (UK) and Greece. The experimental sites were located in the vicinity of wastewater treatment plants at Roma on the isle of Gotland (Sweden), at Orchies near to Lille (France), at Culmore near to Londonderry (UK), and at Larissa 300 km north of Athens (Greece), see Fig. 1.

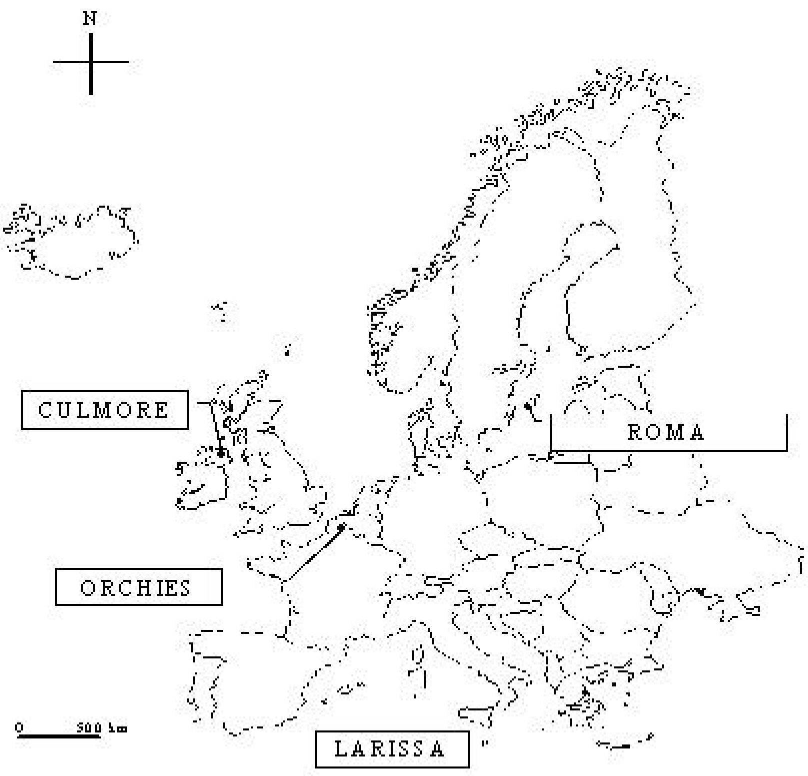

Figure 1. Location of the experimental fields.

Climatic conditions varied between the four experimental sites (Table 1) and could be characterised as:

- Northern European local-maritime climate with relatively low, evenly distributed precipitation, and a high amount of sunshine hours (Roma)

- Central European local-continental climate with evenly distributed precipitation (Orchies)

- Typical western European maritime climate with mild, wet winters and relatively cool summers (Culmore)

- Typical Mediterranean climate with dry, hot summers and rainy winters (Larissa)

Table 1. Normal values (averages 1961-1990) of air temperatures, precipitation, and sunshine hours at the four experimental sites. The values on the two last lines indicate the Penman evaporation in mm and the sunshine hours in % of the annual maximum possible (i.e. from sunrise to sunset without any clouds), respectively.

	France			**Greece**			**Sweden**			**United Kingdom**		
	Orchies			**Larissa**			**Roma**			**Culmore**		
	Temp ºC	Prec mm	Sunsh H	Temp ºC	Prec mm	Sunsh H	Temp ºC	Prec mm	Sunsh h	Temp ºC	Prec mm	Sunsh h
January	2.5	67	49	5.1	30	105	-0.5	48	34	4.2	94	38
February	3.2	54	78	6.8	35	118	-1.2	28	60	3.1	70	64
March	5.7	73	106	9.5	6	158	0.7	32	132	5.6	77	94
April	8.7	57	147	14.0	29	214	4.1	29	194	7.4	55	149
May	12.7	70	190	19.6	37	266	9.5	29	287	10.0	60	175
June	15.5	78	185	24.9	24	307	14.0	31	308	12.6	62	154
July	17.2	75	186	27.1	20	337	16.4	50	283	14.0	68	127
August	17.0	63	182	26.0	16	320	16.0	50	241	13.9	82	130
September	14.4	59	144	22.0	29	248	12.4	59	161	12.2	87	102
October	10.4	71	114	16.1	47	172	8.5	50	105	9.9	103	78
November	6.0	78	65	10.8	58	126	4.3	57	48	6.2	94	51
December	3.4	76	44	6.3	52	101	1.2	51	29	5.0	91	29
Average	**9.7**	**821**	**1490**	**15.7**	**413**	**2471**	**7.1**	**514**	**1882**	**8.7**	**943**	**1191**
ET, mm		**669**			**912**			**585**			**467**	
Sunsh, %			**34**			**56**			**43**			**27**

Due to the different needs of water supply during the growing season wastewater irrigation regimes were adapted for the specific sites. The water requirement to fill the gap up to a theoretical potential evaporation was calculated by using available normal climate variables from the sites. The irrigation requirement figures are given as daily average values for the actual months of growth (Table 2). The range of irrigation in mm/day during the growing season varies considerably between the sites showing an interesting range of extremes. Similarly, plant requirements of macronutrients (N, P, and K) were calculated from empirical data from the Swedish willow projects (Table 3). The average annual production level was estimated from practical and experimental cultivation.

Table 2. Comparison of requirement for irrigation given as daily mean values per month at the four experimental sites.

	Required irrigation (mm/day)			
	Orchies	Larissa	Roma	Culmore
April	-	0.8	0.1	-
May	0.4	2.5	1.3	0.4
June	0.9	5.3	2.6	0.7
July	1.7	7.7	2.8	0.2
August	1.8	8.1	2.3	-
September	2.7	5.6	0.4	-
October	0.7	2.3	-	-

Table 3.Wastewater irrigation requirement (1 PE level) and corresponding estimated nutrient application (assuming the nitrogen content of wastewater is 27 mg/l and the proportion between N/P/K is 100/13/65) compared with optimal removal of N with stem wood harvest.

	Estimated stem growth, optimal conditions (t DM/ha/year)	**Irrigation requirement (mm)**	**Application of N, P, K via irrigation (kg/ha)**	**Removal of N by stem harvest (kg/ha)**
Orchies	12	248	68, 9, 44	72
Larissa	18	965	260, 34, 169	108
Roma	9	285	77, 12, 59	54
Culmore	12	40	11, 1.5, 7	72

The information from Tables 1-3 was used during the starting period of the project in order to be able to design proper levels of irrigation and nutrient supply to the willow stands.

2.1.2 Plot design

Willows were planted on an area of up to 5 hectares at each experimental site. Within the experimental field, sub-plots were placed with different treatments randomised in each of three replicates. The sub-plots were planted with the Svalöf Weibull AB variety “Jorr” (*Salix viminalis*). Guard rows, to give at least a 20 m buffer zone between each plot, were planted at the same density with the same clone (Sweden and France) or a mixture of *S. viminalis* clones (Culmore). Guard areas in Greece were left in grass.

Three replicates resulted in 12 to 18 plots in total per site. The plot size was 16 m x 25 m = 400 m^2 resulting in plot width of 7 double-rows (7 x 2.25 m = 15.75 m) and the length equivalent to a row of some 40 plants. The total number of plants was approximately 600 per plot. The treatment set-up for each site based on a randomised block design is shown in Table 4.

The experimental fields at Roma, Culmore and Larissa were all irrigated with municipal wastewater. The wastewater used at Roma was biologically treated in oxidation ponds after primary settling and then stored. At Culmore and Larissa the wastewater was primary effluent taken from the outflow of primary clarifiers. The wastewater at Orchies was a stored industrial effluent from a chicory processing plant. The willow plantations were supplied with wastewater via drip irrigation systems at Larissa, Roma and Orchies and with a low-level sprinkler system at Culmore. The human urine mixture (urine + flush water), used at Roma, was mixed with water before application to the crop.

The soil type can be described as follows:

Roma: loam / clay-loam / sandy-clay-loam
Culmore: sandy loam
Larissa: loam / clay-loam / sandy-clay-loam
Orchies: silt / silt-clay

Table 4. Treatment set-up for each site.

Site	1 PE WW	2 PE WW	3 PE WW	1 PE PW	1 PE Urine/PW	Sludge	Control
Roma	X	X	X	X	X		X
Orchies	X	X	X				X
Culmore	X	X	X	X		X	X
Larissa	X	X	X	X			

Explanations:
PE = Potential evapotranspiration, i.e. site-specific rate applied according to historical data on monthly basis. Thus, monthly irrigation rates are equivalent to a multiple (1, 2 or 3 times) of the corresponding calculated potential evapotranspiration rate.
WW = Wastewater used at each site.
PW = Pure water refers to potable water from the public water supply system, ”clean” river water, groundwater outside the field, or other proper non-polluted water source.
Urine = Human urine was collected from a school close to Roma with low-flush diverting toilets collecting urine and faeces separately, and a water flushing urinal. The urine solution was mixed with pure water to a rate of 1 PE before application. Information from studies on different types of diverting toilets and waterless urinals and contents of material in collected urine/urine mixture can be found in Backlund (2002), Backlund *et al.* (2002) and Holtze and Backlund (2002a, 2002b and 2002c).
Sludge = Sludge from the primary clarifier of the wastewater treatment plant at Culmore was applied at approximately 100 t/ha as a ‘once-off’ treated to sludge plots at the start of the experiment.
Control = Non-irrigated and non-fertilised treatment. Control treatment was assessed not meaningful in Larissa since drought was expected to cause plant die-off.

2.1.3 Sampling and analyses

2.1.3.1 Water

Samples of wastewater and human urine for chemical analyses were taken once a month during the irrigation period for chemical analyses, *i.e.* 5-9 analyses per year depending on local conditions. Analyses were carried out concerning pH, COD, BOD, Total N, NH_4-N, NO_3-N, Total P, PO_4-P, K, Cu, Zn, Pb, Cd and Cl^-. Chemical analyses of pure water and rainwater were performed where applicable.

A plastic groundwater pipe with slits was installed centrally in each plot with the bottom end placed below the known or assumed lowest groundwater table. The upper 0.5 m around the pipes was sealed with bentonite (impermeable volcanic clay) or common clay to prevent short-circuit flow of wastewater or rainwater along the pipes. Sampling of superficial groundwater from these pipes was carried out year round bimonthly (BOD, NH_4-N, NO_3-N, PO_4-P and Cl^-) or three times per year (pH, COD, Total N, Total P, K, Cu, Zn, Pb, and Cd). Groundwater levels were measured with a plumb bob twice a month during the irrigation periods and once a month rest of the year.

2.1.3.2 Soil

Soil sampling, primarily for analyses of nutrients and heavy metals, was carried out at the start (in winter 1998/99) and at the end of the experiment (in winter 2001/02). The objective of this sampling was twofold. First it enabled description and characterisation of soil properties at the four locations and secondly it allowed detection of changes in soil properties due to the various treatments.

In each plot 10 soil cores were taken from topsoil (0-30 cm) and subsoil (30-90 cm), respectively. The soil samples were mixed to form pooled samples from each plot and level. The soil was classified according to the FAO-system.

Test pit for soil characterisation at the experimental site at Roma.
(Photo: Stig Larsson)

2.1.3.3 Vegetation

Biomass estimations were based on non-destructive measurements each year during 1999-2001 and a destructive weighing after a final harvest during the final winter, 2001/2002.

For non-destructive biomass measurements, the mean weight of 10 randomly selected living stools (plants) in each net plot was estimated. The net plot was allocated as the centre of each plot and had a width of 3 double-rows (6.75 m) and a length of 10 m (15-17 plants), or in total about 100 plants. On each randomly selected stool, the diameter of all living shoots was measured to the nearest tenth of a millimetre using a calliper. The diameter was measured at the 55 cm height of the shoot, i.e. 55 cm along a straight line from the ground at the point where the shoot is attached to the stump, distance "A" in Fig. 2. Dead shoots and shoots shorter than 55 cm were not included. If the shoot was branching below 55 cm, the main shoot that showed apical dominance was measured. Plant shoots shorter than 55 cm were not measured, but still regarded as living.

For calculation of the relation between shoot diameter and shoot dry weight an exponential function describing the relationship was established for each location and each year. For this purpose 20-25 shoots were destructively sampled. The diameter was measured at the 55 cm point and the stem cut at 10 cm above the ground surface, corresponding to the cutting height of mechanised harvesters, distance ”B” in Fig. 2.

The fresh weight of each shoot was determined separately to the nearest tenth of a gram (0.1 g), dried at 85 °C until constant weight occurred (48 to 72 hours), and the dry weight measured. The best data for calculation of the relationship between dry weight and diameter were obtained by (selectively) collecting shoots of all diameter sizes represented in the stand.

During the final winter (2001/2002), a final harvest was performed in each plot. All stools in the net plots were included in the harvest and weighed in the field. A representative sample of 20-30 shoots was also weighed separately, oven dried to a constant weight (105 °C, 48 h), and weighed again. The dry matter percentage was calculated and used for calculating the dry matter content of the total harvested biomass.

Stems were also sampled for chemical analyses at the final harvest. Chemical analyses of stem biomass were carried out concerning N, P, K, Cu, Zn, Pb, Cd and chloride. Samples were weighed fresh, air-dried a day or two, milled/finely divided, dried in the oven at 85 °C for 3 days. After decomposition with acid solution, the sample solutions were analysed.

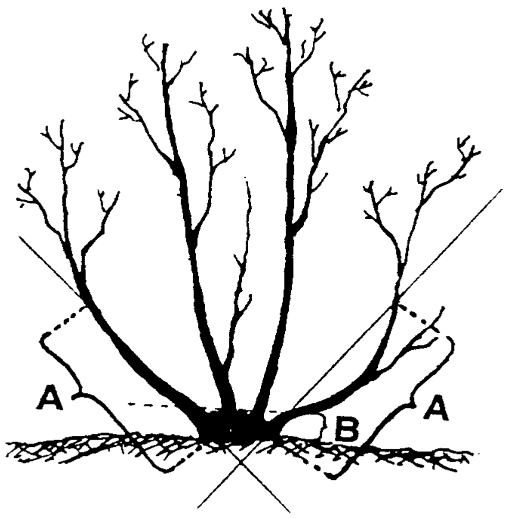

Figure 2. Location of diameter measurement (A) and shoot for weight measurement (A-B).

2.2 Results and discussion

2.2.1 Operational and technical aspects

Some problems with weeds in the plantations were apparent. Weeds were controlled with herbicides, mechanically or by hand before plantation and during the establishing year. After the first year it was assessed that all field trials were well established.

At the start of the second irrigation season at Culmore some difficulty was experienced with problems caused by solid particles in the irrigation system. The amount of suspended solids in the wastewater led on some occasions to clogging of the sprinkler heads. To help overcome this, a filter was installed in line after the pump in the irrigation system. The problems decreased but the spray units still needed to be checked frequently. The following season, a finer steel mesh cylinder was placed around the outside of the filter cylinder. With this system it was only necessary to clean the filter once a week. A water meter was installed in order to monitor the actual irrigation rates.

At Larissa no significant difficulties were experienced during the project. However, from December 2000 onwards, an unexpectedly deep water table (below the well bottom) prohibited sampling of the ground water.

At Roma problems arose with clogged filters due to sediments and growth of algae. As a result of this, it was decided to invest in a sand filter. Water gauges were installed in order to measure more precisely the water flow. The injection of human urine worked properly during the irrigation season except for some minor problems of mechanical nature.

At Orchies parts of the willow plantations suffered from drought and leaf beetle attacks.
Occasionally there were also problems with heavy precipitation incidents making the ground in the lower parts of the plantation wet and flooded. The soil was very compact, which decreased the transportation of air and water into the soil horizon.

Most of the problems that occurred were normal disturbances for these kind of studies and acceptable within the frame of project. However, the rather poor trial conditions at Orchies, which were not obvious before the project started, limited the delivery of test results from this site.

2.2.2 Application of wastewater and water requirement

The amount of water used for irrigation was initially calculated using the normal climate values from adequate nearby meteorological stations. In order to control the irrigation regimes the evapotranspiration data was continuously updated during the trial period using most recent measured data. Irrigation rates and precipitation at the four sites are shown in Table 5. The plots were only irrigated during the growing season and when the weather was appropriate, *i.e.* the irrigation was stopped on major rain occasions. The application of wastewater at Orchies was reduced due to limited supply of wastewater and also sometimes due to clogged emitters. For instance, irrigation during 2001 amounted to approximately half the calculated values.

Table 5. Wastewater application and precipitation at the four sites.

	Year	Irrigation (mm/year)			Precipitation (mm/year)	Irrigation+Precipitation (mm/year)		
		1 PE WW	2 PE WW	3 PE WW		1 PE WW	2 PE WW	3 PE WW
Larissa								
	1999	718	1354	2214	314	1032	1668	2528
	2000	736	1524	2278	257	993	1781	2535
	2001	1072	1797	1797	274	1346	2071	2071
Roma								
	1999	352	704	1056	482	834	1186	1538
	2000	480	960	1440	565	1045	1525	2005
	2001	533	1066	1599	473	1006	1539	2072
Orchies								
	1999	186	372	558	752	938	1124	1310
	2000	226	452	678	1023	1249	1475	1701
	2001	183	366	549	719	902	1085	1268
Culmore								
	1999	308	615	923	731	1039	1347	1655
	2000	451	901	1352	766	1216	1667	2118
	2001	581	1162	1742	618	1199	1779	2360

The water requirement in *Salix* plantations has been studied *e.g.* by Lindroth and Halldin (1988). They simulated evapotranspiration within a 15-year period from hypothesised stands under optimum access to water and nutrients in south Sweden. The evapotranspiration rate was estimated to be ca 700 mm during the growth period, corresponding to an average rate of about 4 mm/d. Lindroth and Båth (1999) measured maximum evapotranspiration rates of 7 mm/d in southern parts of Sweden.

Some studies have indicated that the total water loss to the atmosphere (evaporation, interception and transpiration) from a willow biomass plantation could exceed the potential evapotranspiration according to the Penman formula, which refers to a water saturated and mowed grass area

(Penman, 1956). For instance, Persson and Lindroth (1994) compared actual water losses from irrigated and well-established willow stands with Penman evapotranspiration. They reported ratios of 0.7-1.0 in the beginning, 1.2-1.6 in the middle and ca 2.0 at the end of the growing season, indicating the importance of water access when the leaf canopy is fully developed.

Lindroth and Båth (1999) estimated the difference between actual and potential evapotranspiration to be ca 1 mm/d, resulting in 200 mm per season in southern Sweden. Calculated differences between precipitation and potential evapotranspiration according to Penman gave water surpluses in the western part of south Sweden of ca 200 mm and deficits of about 50 mm for the southeastern part of Sweden. A conclusion was that for optimum biomass growth it could be assumed that a general water deficit, by and large, prevails in normal years in the southern parts of Sweden. Hence, irrigation of plantations would most likely enhance biomass production in that area.

It is obvious that the plant water requirement was reached at the sites already after 1 PE wastewater application (except, possibly, for Orchies during 2001) indicating that water availability was probably not a growth limiting factor.

2.2.3 Biomass production

By the non-destructive method, dry weight of biomass in tonnes per hectare was calculated each year (Fig. 3). According to these estimations the urine treatment (Roma) gave the highest biomass production. At Culmore and Larissa the productivity increased with increased load of wastewater. However, this was not the case at Roma and Orchies where the highest productivity after wastewater irrigation occurred when the load was 2 PE WW.

In December 2001 net plot areas were harvested. According to the results from the final harvest at Culmore (Fig. 4), there were fewer differences between treatments compared with the non-destructive estimations (Fig. 3). The 3 PE WW treatment and the sludge treatment produced the largest amounts of biomass, ca 9 t DM/ha/year. These values were similar to those calculated for the estimated biomass production for these treatments. The 1 PE WW treatment and the control treatment resulted in higher values in harvested biomass than estimated by the non-destructive method, while the 2 PE WW treatment and the 1 PE PW treatment showed lower values. In general, however, the number of stools measured becomes much larger at harvest, and these results are likely to be more robust than those derived from the non-destructive method.

Similar to the non-destructive estimates, the differences between treatments in biomass were not statistically significant. In general, however, the results indicated that the wastewater and sludge treatments did not confer any significant production advantage to the coppice. The high rainfall values at this field trial indicate that irrigation treatments were unlikely to give plants any advantage in terms of water availability. Any advantage in terms of nutrient availability might not be apparent yet because of the fertile soil at this site. Another harvest cycle with irrigation treatments would help ascertain if treatment differences due to nutrient availability would emerge. On the other hand, it is possible to conclude that the wastewater and sludge treatments have not been detrimental to coppice growth.

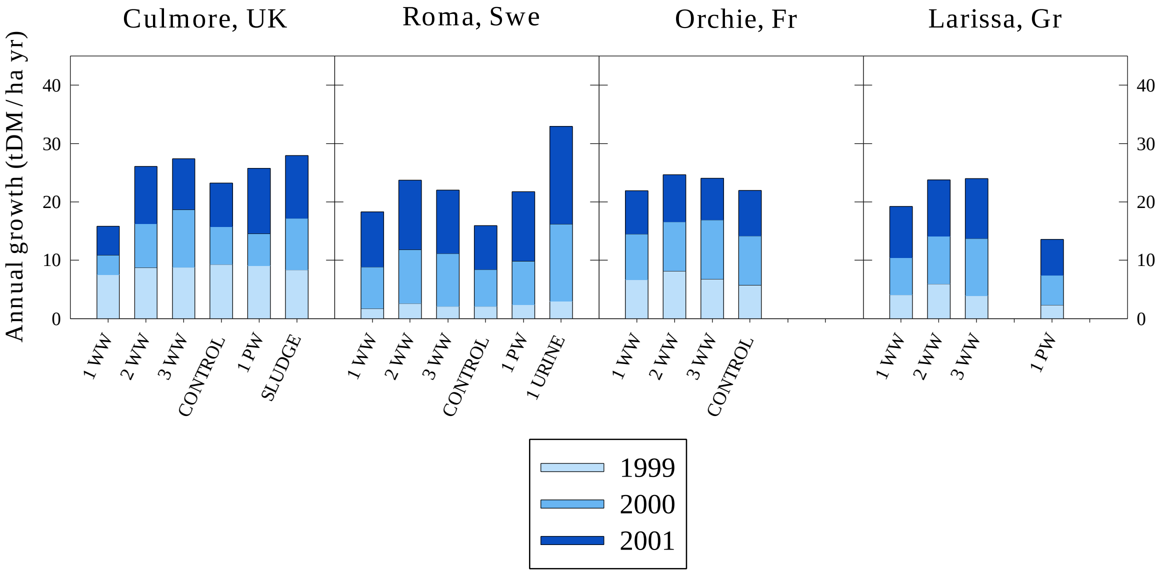

Figure 3. Estimated annual shoot growth as means of three replicates during years one to three.

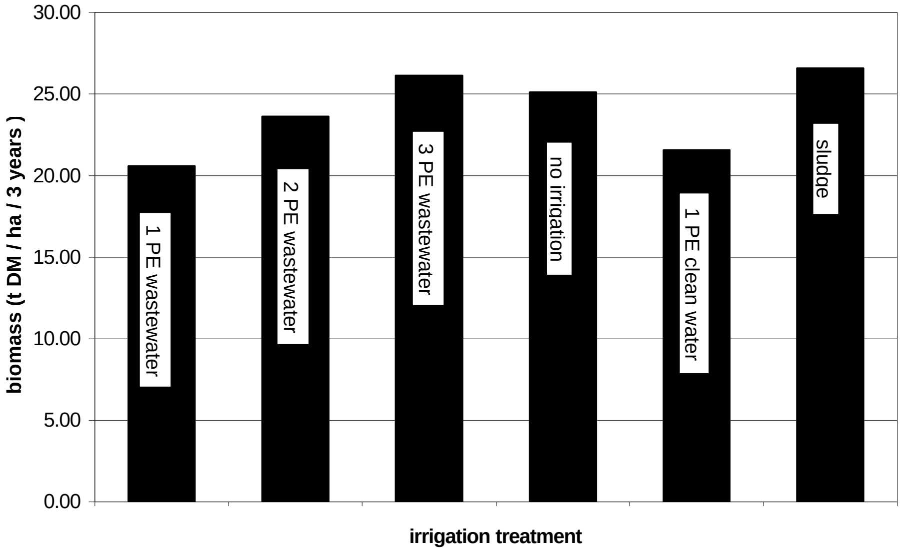

Figure 4. Culmore field trial: harvest 2001 - tonnes dry matter per hectare after 3 years of growth.

After the first year of growth in Larissa, all the treatments using wastewater for irrigation resulted in significantly higher biomass production than the treatment using pure water for irrigation (Fig. 3). The 2 PE WW treatment was the most productive one and there were statistically significant differences between this treatment and the 1 PE WW and 3 PE WW, respectively. There was no significant difference between the 1 PE WW and the 3 PE WW treatments.

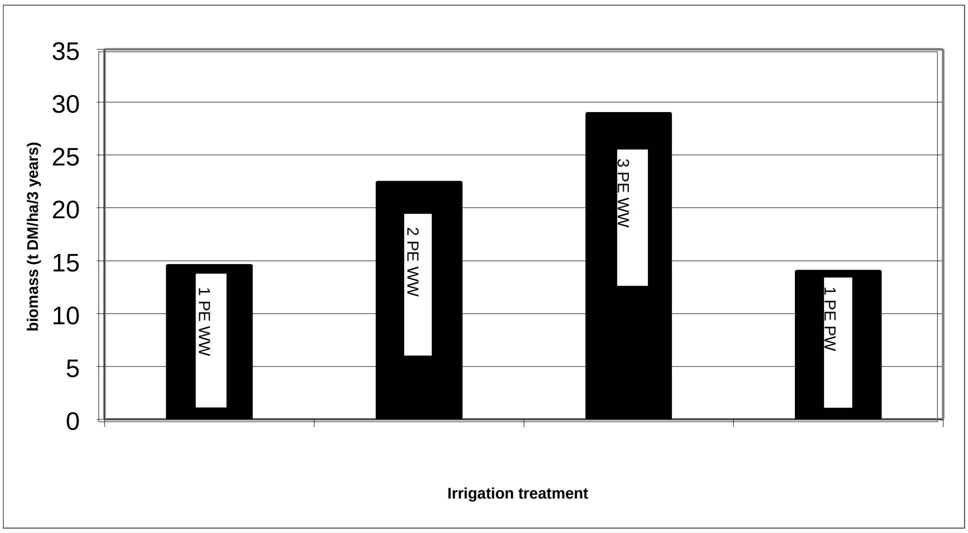

Figure 5. Larissa field trial: harvest 2001 - tonnes dry matter per hectare after 3 years growth

Also after the second year it was found that all wastewater treatments gave biomass production significantly higher than the treatment using pure water for irrigation. The 2 PE WW and 3 PE WW treatments were the most productive ones with statistically significant differences between these treatments and the 1 PE WW. There was no significant difference between the 2 PE WW and 3 PE WW treatments. Also during the third growth period, all wastewater treatments produced significantly higher biomass than the 1 PE PW treatment. The 2 PE WW and 3 PE WW treatments were the most productive ones. There was no significant difference between these treatments.

The yield per hectare, based on harvested three-year-old stools, showed that the estimation of dry matter per hectare based on the diameter measurements, slightly overestimated the production of 1 PE WW but underestimated the production of 3 PE WW (Fig. 5). Statistical analysis on the yield the final year, demonstrates that 3 PE WW yielded most (almost 10 t DM/ha/y as annual mean) and 1 PE WW yielded least (ca 5 t DM/ha/y as annual average). No significant difference was found between 1 PE WW and 1 PE PW.

The estimated biomass production the first year at Orchies averaged 3.5 t DM/ha. The survival rate was 91.2 %. Due to different factors the biomass production was limited to a rather modest level in spite of the contributions made by irrigation: 7.7 t DM/ha/y was the annual average of all treatments, see Fig. 3. The low biomass production could be the result of poor soil conditions or the documented leaf beetle attacks. The final harvest of the willow plantation was not completed due to difficulties caused by very wet soil conditions. Two different machines were tested but the bearing capacity of the wet soil was unfortunately not sufficient.

At Roma the estimated shoot growth during the growing season 2001 was high and exceeded the growth in 2000. On average during 2001, the growth was 11.4 t DM/ha with the lowest growth, 7.5 t DM/ha, in the control treatment and the highest growth, 16.7 t DM/ha, found after the urine treatment, see Fig. 3. The destructive measurement during the final harvest gave similar results to the non-destructive estimations. The urine treatment resulted in an annual production of almost 10 t DM/ha, where as growth after wastewater irrigation gave ca 7 t DM/ha as annual averages (Fig. 6). Control and PW plots produced ca 6 t DM/ha/y.

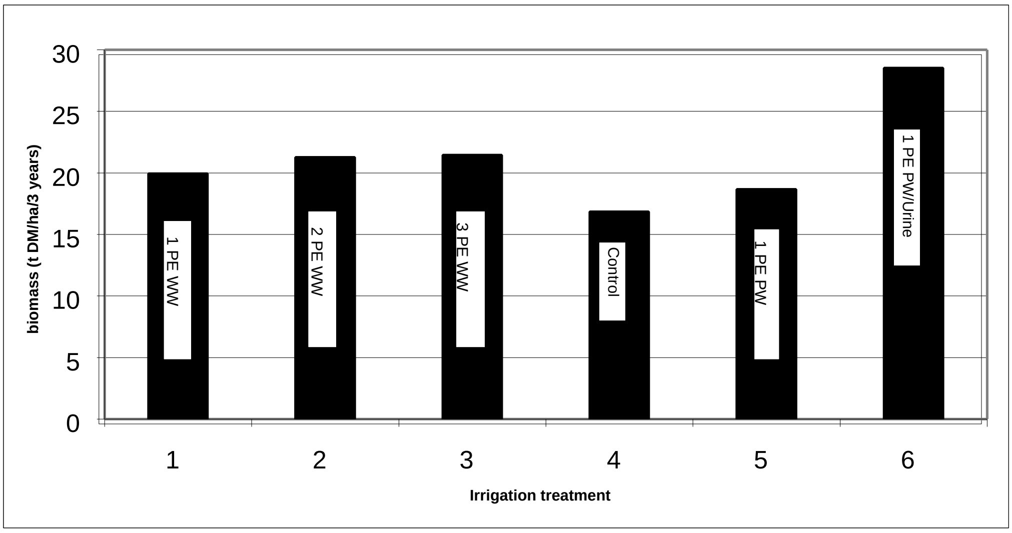

Figure 6. Roma field trial: harvest 2001 - tonnes dry matter per hectare after 3 years growth

Combined harvesting and chipping of a willow plantation in Sweden.
(Photo: Stig Larsson)

The results from the experimental sites clearly indicate that wastewater, human urine and sewage sludge can stimulate willow production substantially.

Application of human urine mixture mixed with water to reach expected plant water requirement resulted in the highest willow growth when non-destructive estimation and weighing after harvest are evaluated together. In general, growth results recorded in this study were at higher levels than those of other production results from commercial plantations in Sweden. During the winters 1995/96 and 1996/97, some 1600 hectares of willow plantations in southern Sweden were harvested. The stem growth of the 4-year stands varied between 2 and 15 t DM/ha/y with an average of 4.8 t DM/ha/y (Larsson, 1998). Jonsson (1997) reported an average growth amounting to 6.8 and 7.2 t DM/ha/y during the first rotation period (5 years) and the second rotation period (3 years), respectively, based on data collected from about hundred commercial plantations in the southern parts of Sweden. Jonsson (1997) concluded that the greatest restrictions on growth potential were 1/ frost damage, 2/ water shortage, and 3/ insufficient fertilisation and/or weed control.

2.2.4 Biological attacks in vegetation

Leaf damage estimations were carried out in 1999, 2000 and 2001, in the same way and by the same observers, on leaf samples from all four sites. In addition, aphids on stems were scored during year 2000 at the Culmore site. At this site bird activity and flora in the plantations were investigated as well.

There were differences between the trials in the four countries in terms of leaf damages and which organisms/conditions causing the damage. Larissa differed from the other sites in that symptoms due to the leaf roll gall midge (*Dasineura marginemtorquens*) were never observed there. On the other hand, the Larissa plantation had symptoms of abiotic stress, which were not observed in the other trials. The willow leaves at the Larissa site were curling, particularly in 1999, and starting from the margins, the leaves first became chlorotic, then necrotic. Furthermore, leaf size was just half of that at the other sites in 2001. Yet the stem wood production at Larissa was quite high. However, it is unclear if the stress, presumably due to the hot climate/high solar irradiation, might threaten the sustainability of the plantation. The trial at Orchies had extremely high levels of attack by leaf beetles (chrysomelids). At Culmore populations of these beetles also increased to high levels over the three years of study. Rust (*Melampsora epitea* var. *epitea*) disease levels were fairly low at all sites. The variety Jorr used in the plantations is partially resistant to leaf rust. The plantations at Larissa and Roma had very low levels of rust. The trial at Roma also had very little of mechanical damage to leaf blades caused by insects and wind.

Curled willow leaves from the experimental site at Larissa.
(Photo: Inger Åhman)

Very few effects of the wastewater/urine/sludge treatments on leaf damages were found. The urine treatment was more attacked by leafhoppers in 2000 and by rust in 2001 than the other treatments at the Roma site. Also, damages to leaf edges were more frequent in the urine treatment in 2001. It is likely that the fertilisation effect of urine is favourable for organisms like herbivorous insects and for a biotrophic fungus, such as leaf rust, since nitrogen often is a limiting factor for their growth. However, since the urine fertilisation is encouraging willow growth as well, there is no reason to avoid urine treatment in commercial applications. For unknown reasons willows on the lowest dose of wastewater had more galling on leaf margins at Orchies in 1999 and more lost leaf area at Culmore in 1999 and 2000. There is no clear explanation why the rust was most frequent on the middle dose of wastewater at Orchies in 2001, compared to other treatments at the site. The result was probably due to the influence of other environmental factors at the site, such as high humidity caused by wet soil conditions.

Stress symptoms occurred on all treatments at Larissa, but the symptoms were less severe in the PW treatment. Mites were also less frequent on those leaves.

In an additional study at Culmore in 2000, where stem dwelling aphids (*Pterocomma salicis*) were quantified, it was found that irrigated plots had fewer aphids. In this case it is likely that the sprinklers used at this site had a disturbing effect on the aphids.

2.2.5 Application and plant uptake of nutrients and metals

2.2.5.1 Nutrient and metal application with wastewater and urine

Concentrations in applied wastewater and urine of main nutrients (nitrogen (N), phosphorus (P) and potassium (K)) and easy biodegradable organic substances, measured as BOD, were calculated from mean concentrations during each irrigation season (Table 6). The values fluctuated to some extent from one year to another.

The wastewater quality at Larissa was fairly normal considering a primary effluent with low impact of storm water. The wastewater at Culmore was also a primary effluent but probably more diluted by rainwater from the existing combined sewer system. The relatively high P content is more difficult to explain. It may be due to a specific industrial effluent connected to the municipal sewer system. The industrial wastewater at Orchies showed high concentrations compared to municipal wastewater quality in general, especially considering K and BOD. The high BOD content probably explains the clogging problems with the irrigation equipment.

Table 6. Annual average concentrations of N, P, K and BOD in wastewater and urine (before diluting with pure water) used for irrigation.

	Concentration of N, P, K and BOD (mg/l)			
	N	**P**	**K**	**BOD**
Larissa				
1999	46	8	19	161
2000	55	9	19	153
2001	47	9	15	122
Culmore				
1999	24	21	15	140
2000	21	15	8	91
2001	14	6	9	84
Orchies				
1999	50	12	153	1200
2000	56	17	ND	2125
2001	41	15	99	3300
Roma				
1999	3	1	9	18
2000	5	2	10	9
2001	3	1	9	ND
Roma, urine				
1999	1400	51	450	400
2000	1500	49	520	450
2001	1900	63	580	360

ND=No data

High-strength effluent from the chicory processing plant at Orchies. *(Photo: Stig Larsson)*

The extended biologically treated wastewater at Roma showed a low content of measured wastewater components. A willow plantation filter in this case will serve more as a general polishing step rather than specific wastewater treatment.

The chemical composition of urine differed from the other wastewaters to a large extent, particularly with regard to the nutrient content. In order to reach the water requirement, the urine mixture was mixed with pure water and applied in practice at a ratio of about 1:100 – 3:100 (1 – 3 % urine mixture).

Due to the different chemical composition of the wastewaters with respect to their origin and/or pre-treatment level and the various water requirements of the willow depending primarily on the climate, the applied amounts of nutrients varied greatly between the experimental sites (Fig. 7 and Table 7). At Larissa the nutrient application with wastewater was higher than the need of the willow stems even at a level of 1 PE WW (*cf.* the following chapter). At Roma the application of N and P was close to the stem uptake while the K supplied was 2-3 times above the need. The urine treatment resulted in a fairly balanced nutrient application, with the exception of the P amount, which was low. At Culmore, the P application was almost 10 times above the plant requirement while N and K fertilisation were at suitable levels. At Orchies all measured nutrients were above the stem uptake levels.

The main part of applied nitrogen was in plant available forms (NO_3^- an NH_4^+). A small proportion of the nitrogen was bound to organic material (especially at Larissa). Most of the organic nitrogen should be released and available through mineralisation in coming years (if accumulation in the soil has occurred). In the primary effluent at Culmore only a small part of the phosphorus was in the plant available phosphate form (15-20 %). Potassium exists almost always in dissolved forms in wastewater and thus is readily available to plants. At Orchies and Roma the measured macronutrients in the wastewater and the urine were in readily plant absorbable forms.

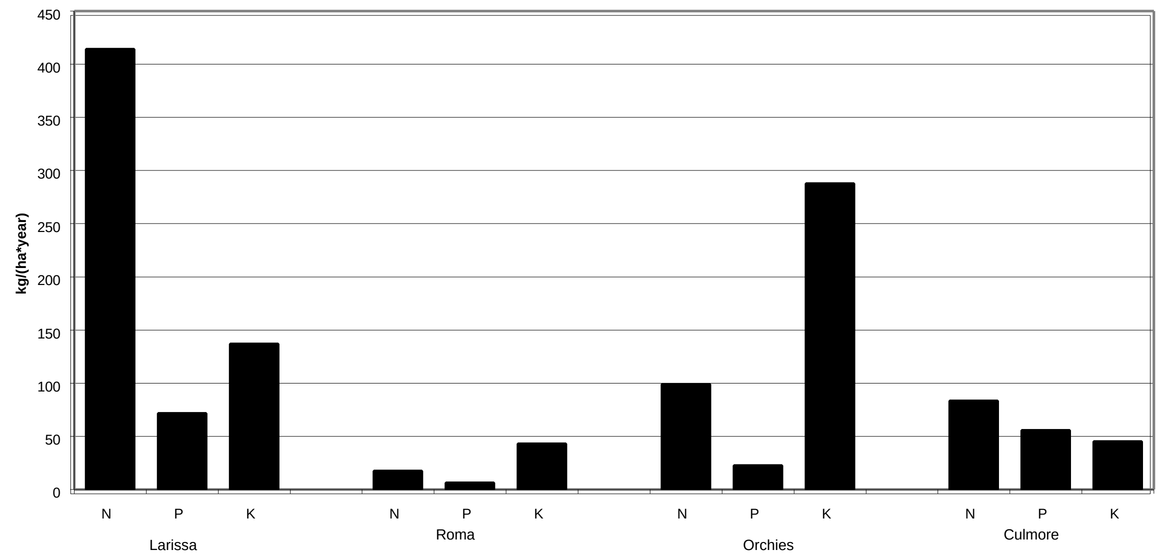

Figure 7. Application of N, P and K with wastewater at normal irrigation rates (1 PE) as means over 3 years.

Table 7. Annual average application of macronutrients and metals.

	Application of macronutrients and metals (kg/ha/year)						
	N	**P**	**K**	**Cu**	**Zn**	**Pb**	**Cd**
Larissa							
1 PE WW	414	72	137	0.3	0.6	ND	ND
2 PE WW	771	164	252	0.8	1.1	ND	ND
3 PE WW	1176	201	387	1.3	1.8	ND	ND
Roma							
1 PE WW	18	6	43	0.07	0.41	0.02	0.01
2 PE WW	35	12	86	0.14	0.83	0.03	0.02
3 PE WW	53	19	129	0.21	1.24	0.05	0.03
1 PE PW+URINE	85	2.4	26	0.31	0.28	0.01	0.003
Orchies							
1 PE WW	99	23	288	0.14	1.20	0.06	0.84
2 PE WW	198	45	575	0.27	2.39	0.11	2.25
3 PE WW	237	68	863	0.41	3.59	0.17	3.37
Culmore							
1 PE WW	83	56	45	0.05	0.52	0.78	0.08
2 PE WW	167	111	90	0.09	1.04	1.57	0.17
3 PE WW	250	167	135	0.14	1.55	2.35	0.25

ND=No data

Other required macronutrients, i.e. calcium (Ca), magnesium (Mg) and sulphur (S), exist in municipal wastewater and were in some cases analysed. However, these nutrients are rarely limiting in normal soils and, hence, are not applied as conventional fertilisers.

In Table 7 results are shown of all treatments with wastewater and urine regarding measured macronutrients and heavy metals. The wastewaters contained sufficient amounts of nutrients at 1 PE and in most cases the amounts were above the plant requirement. At Roma, however, application of nitrogen with wastewater and phosphorus with the urine mixture seemed lower than the plant requirement (*cf.* Table 7 and Table 8).

Due to a fairly high content of metals, the application rate of 1 PE WW is recommended for long-term use in a plantation. In a sustainable crop system, the nutrient and metal load should not exceed the need and uptake in harvested crop parts. Although willows in general have the ability to extract metals to a large extent, the metal load in these field trials was high, in general higher than the stem uptake (see the following chapter).

2.2.5.2 Nutrient and metal uptake in stem wood

Assimilation of N in willow stems varied largely between the sites, from 18 to 73 kg N/ha as annual averages (Table 8).

Table 8. Uptake of nutrients and metals in stem biomass. Since no final harvest could be executed at Orchies, data from this site cannot be presented.

	Uptake of nutrients and metals in stem biomass (kg/ha/year)						
	N	**P**	**K**	**Cu**	**Zn**	**Pb**	**Cd**
Larissa							
1 PE WW	37.1	2.9	6.3	0.051	0.19	0.007	0.004
2 PE WW	72.9	4.9	8.9	0.099	0.57	0.010	0.008
3 PE WW	73.3	6.3	10.9	0.110	0.38	0.014	0.012
1 PE PW	27.0	3.3	5.9	0.020	0.32	0.010	0.007
Roma							
1 PE WW	24.4	4.9	15.7	0.036	0.31	*	0.010
2 PE WW	25.5	5.9	17.7	0.042	0.33	*	0.014
3 PE WW	25.2	5.0	15.7	0.037	0.29	*	0.012
Control	18.0	3.9	13.5	0.025	0.24	*	0.007
1 PE PW	20.5	5.0	16.0	0.029	0.31	*	0.010
1 PE PW/Urine	35.2	6.7	27.2	0.040	0.32	*	0.009
Culmore							
1 PE WW	45.6	6.5	16.2	0.036	0.92	0.52	0.043
2 PE WW	49.7	7.7	20.0	0.040	0.83	0.62	0.054
3 PE WW	57.6	8.2	18.8	0.043	0.76	0.71	0.060
Control	46.1	7.0	18.7	0.051	0.86	0.61	0.063
1 PE PW	40.5	6.3	15.0	0.042	0.73	0.50	0.051

*Below detection level, 4 mg/kgTS (uptake < ~0.040 kg/ha/y)

For Roma the N content in stems were relatively low and for Larissa both low and high. For Culmore more typical N levels were found, *i.e.* ca 50 kg N/ha/y.

N concentrations in stem wood were higher after wastewater application than for other treatments at Culmore. At Larissa the 2 PE WW treatment resulted in the highest and 1 PE PW treatment in the lowest N concentrations in stems compared with the other treatments at this site. The low N uptake in harvested willow stems at Roma (ca 25 kg N/ha/y) could possibly be a result of the low content of nitrogen in applied wastewater. Plants supplied with the urine mixture grew best and contained higher amounts of nitrogen (ca 35 kg N/ha/y) than plants from the wastewater irrigation treatments, which could be a result of the high nitrogen content in the urine mixture compared with the biologically pre-treated wastewater.

Large variations in the nitrogen content in the *Salix* crop has been reported earlier. Alriksson (1997), for instance, reported that the distribution of nitrogen varies throughout the plant; of the whole N pool in the plant, 9-57 % was found in the foliage and 13-47 % was found in the root system. This indicates that nitrogen fertilisation should to some extent exceed the stem uptake even when account is taken of part of the N in leaf litter being recycled within the stand.

Mean uptake of phosphorus and potassium was in the range of 3-9 kg P/ha/y and 6-27 kg K/ha/y, respectively. Ericsson (1981) reported ratios of P/N = 0.13 and K/N = 0.65 for optimum cell growth for various *Salix* clones. Average P/N- and K/N-ratios for wastewater-irrigated willows found here amounted to 0.08 and 0.15 (Larissa), 0.14 and 0.36 (Culmore), and 0.21 and 0.65 (Roma), respectively. These results may indicate some imbalances in terms of nutrition. At Larissa, for instance, both the P and the K content in stem biomass appeared low, even though the nitrogen uptake for some treatments was high (*cf.* Table 8). Even after irrigation at the lowest rate (1 PE WW), application of P and K appeared to be sufficient, indicating that nutrients should have been available in the soil.

The rates of uptake of heavy metals in stem biomass differed substantially between the sites. For lead, the uptake rates were about 50 times higher at Culmore (500-700 g Pb/ha/y) than at Larissa (7-14 g Pb/ha/y), irrespective of treatment. The mobility of Pb in soil is generally low and normal extraction of Pb in willows found elsewhere amounts to 1-30 g/ha/y (Aronsson and Perttu, 1994; Hasselgren, 1999a; Hasselgren, 1999b). There seems to be no rational explanation to this difference other than a possible error in the chemical analysis. With regard to zinc, the Larissa and Roma sites showed values within 200-600 g Zn/ha/y, being below those in Culmore (700-900 g Zn/ha/y). In other investigations were reported uptake ranges in willow plantations of various ages of 300-1700 g Zn/ha/y (Aronsson and Perttu, 1994; Hasselgren, 1999a; Hasselgren, 1999b). For the other metals analysed, the levels were similar at the different sites. The content of Cu and Cd in stems varied within 35-110 g Cu/ha/y and 4-60 g Cd/ha/y, respectively, with values increasing with higher rates of wastewater application. Plants irrigated with PW and control plants averaged 20-50 g Cu/ha/y and 7-63 g Cd/ha/y, indicating that uptake of Cd takes place quite readily from the Cd supply in the soil irrespective of treatment. In other studies, assimilation rates of 4-77 g Cd/ha/y from willows of various shoot age have been reported (Aronsson and Perttu, 1994; Hasselgren, 1999a; Hasselgren, 1999b).

Willow plants irrigated with the urine mixture at the Roma site.
(Photo: Ingvar Jakobsson)

No obvious correlations were found between plant uptake of metals and soil or wastewater content of metals. Application of metals with the wastewater to the system exceeded in general the metal uptake of plants after 1 PE WW treatment. For Cu the application was 6 times and twice the withdrawal by plants at Larissa and Roma, respectively, while at Culmore approximately the same amounts were taken up as applied. The application of Zn was 3 times higher than found in harvested stems at Larissa, while the plants took up twice the amount applied at Culmore. At Roma the application of Zn with the wastewater and the urine mixture was fairly well balanced with the plant assimilation of Zn. At Culmore the plants extracted about half of the Cd applied with wastewater.

In a sustainable perspective, added nutrients and metals to willow biomass plantations should balance with nutrients and metals removed from the field by the crop, *i.e.* harvested stem wood after defoliation. Phosphorus, a finite resource necessary for all biological life, is probably the most important parameter to consider in a sustainable wastewater irrigation system. Irrigation with 1 PE WW resulted in P application rates of ca 10 times the plant requirement, according to the results obtained at Larissa and Culmore. At Roma the water need was balanced quite well with the P requirement. Thus, if the system design were to be based on a balanced phosphorus concept, *i.e.* input of P equivalent to stem biomass extraction of P, the conditions for sustainable metal balances over the soil-plant system would improve.

2.2.5.3 Impact on soil and groundwater

2.2.5.3.1 Soil

The final soil analysis at Larissa showed that the NO_3-concentration in the surface and deeper soil layers from the 3 PE WW treatment was lower than from the 1 PE WW and 2 PE WW treatments, possibly because anoxic conditions due to high irrigation rates prohibit the transformation of NH_4 to NO_3. The potassium concentration was slightly higher at the end of the experiment both in surface and deep soil. There was a slight decrease of the pH levels at the end of the experiment in comparison to the beginning.

The soil at Orchies consisted predominantly of clay with an acid tendency and a low $CaCO_3$ reserve. Throughout the experiment the content of NH_4 increased, while the content of NO_3 decreased. This evolution was probably due to the high organic load from the wastewater resulting in temporary oxygen deficiency in the soil. The stock of nitrogen decreased sharply with the depth, which means that nitrogen could have leached to the saturated zone. The total N content was stable throughout the trial period but the NO_3 content was low in some cases (less than 1 mg/kg). This could have contributed to the relatively poor willow growth at Orchies. Over the period, the values of other major elements were rather homogeneous. The organic material content increased, but was low compared to the desirable value for this kind of soil.

At Roma interesting observations were noted for some of the metals. Wastewater irrigation had little or no effect on the Cu content of the soil. However, control treatment and 1 PE PW treatment resulted in a decrease of the Cu content. A similar result was seen for the Zn content. The decrease of Zn was approximately 10-30 %. Pb generally decreased for all treatments. Still, the major decrease occurred for the non-irrigated plots. However, Cd increased up to twice the initial value in all treatments, which indicates that the Cd analyses were less reliable in this case. The pH level increased by around 0.5 units in the upper 30 cm soil layer and 0.8 units in the lower 30-90 cm layer. After treatment both nitrogen and potassium decreased. This was true for all treatments and both depths. For the upper soil layer an increase in organic matter was observed after wastewater irrigation.

The result of the preliminary soil analysis from Culmore showed an acid soil with a high content of organic matter and, probably related to this, a high level of total N, particularly in the upper 0-30 cm layer. This could be expected since the site was previously used as grass-land. Organic matter decreased, in general, according to the final soil analysis, regardless of irrigation treatment, while total N values increased, except under the 3 PE wastewater treatment. The levels of several of the metals (Cu, Mn, Fe and Co) measured rose over the course of the experiment and these increases did not appear to be influenced by the irrigation treatment. Zn values rose in the 3 PE WW treatment, but did not change much under the other treatments. Levels of ammonium lactate extractable K generally increased under wastewater treatments and decreased under the control and pure water irrigation treatments. Total P levels rose in the 0-30 cm soil horizon and decreased further down the soil profile, regardless of treatment. Ammonium lactate extractable P decreased, throughout the soil profile, in all treatments over the course of the experiment.

The soil impact in general was low and more or less independent of applied wastewater rates. However, changes in soil chemistry could take place in a long-term perspective. The decrease of metals (Cu, Zn and Pb) at the test site at Roma shows that willow has a capacity to remove certain metals from the soil. Other investigations have clearly shown that willow plantations are effective for soil remediation and are also commercially used for this purpose (*e.g.* Bertholdsson, 2001, and Greger and Landberg, 1999).

2.2.5.3.2 Groundwater

Sampling of superficial groundwater was, in general, carried out according to the description in the 'Experimental procedure' section. At Larissa, however, sampling was possible only during the first half of the 3-year test period due to extremely low groundwater levels (> 7 m below the ground surface and below the sampling well bottom) during the rest of the period.

At Culmore, generally lower concentrations of BOD and COD in superficial groundwater samples were recorded during the wintertime, probably due to dilution with rainwater. A general pattern was that the groundwater quality was not specifically affected by the different treatments compared with the control (Table 9).

However, the Cl^--concentration increased with wastewater application. Throughout the experiment concentrations of metals were low. Also nutrient concentrations were low in treated plots and comparable to concentrations in control plots, even though a relatively high content of N, especially as nitrate N, was detected in the 1 PE WW treatment. This may have been a result of the lower N uptake (relatively low biomass yield) after this treatment. Also, the lower wastewater application may have facilitated favourable conditions for nitrification and less favourable conditions for denitrification. Further, in most soils nitrate ions in general have a higher mobility than ammonia ions (*e.g.* USEPA, 1981). Generally, the 1 PE PW treatment resulted in the lowest impact on groundwater and was comparable to the control. However, the groundwater concentrations after pure water irrigation were in general higher than the concentrations of applied pure water, indicating downwards transport of constituents remaining in the soil from previous activities.

Table 9. Concentration of constituents in superficial groundwater at Culmore (mg/l). Mean values during the sampling period July 1999-April 2002. Mean values of wastewater (WW) and pure water (PW) are included for comparisons.

Parameter	WW	1 PE WW	2 PE WW	3 PE WW	PW	1 PE PW	Sludge	Control
pH	6.9	6.4	6.3	6.4	7.1	6.3	6.4	6.4
BOD	106	32	35	30	3.6	31	31	31
COD	245	171	149	196	13	126	119	177
N-tot	19	6.5	4.5	3.6	2.7	4	4.8	3.3
NH_4-N	18	1.6	1.6	1.6	1.8	1.6	1.7	1.5
NO_3-N	0.53	4.9	2.9	2	0.92	2.4	3.1	1.7
P-tot	12	1.3	1.3	0.89	0.02	1	1.3	1.25
PO_4-P	2.0	0.57	0.5	0.65	-	0.48	0.49	0.57
K	11	3.8	4.4	4.3	1.9	3.3	5.2	2.3
Cl^-	215	91	99	149	24	56	122	58
Cd (g/l)	0.018	0.018	0.017	0.016	0	0.016	0.017	0.014
Pb (g/l)	0.15	0.16	0.28	0.18	0.22	0.18	0.19	0.16
Zn (g/l)	120	70	69	110	25	67	58	70
Cu (g/l)	15	40	39	51	7	40	52	30

Table10. Concentration of constituents in superficial groundwater at Larissa (mg/l). Mean values during the sampling period April 1999-December 2000. Mean values of wastewater (WW) and pure water (PW) are included for comparisons.

Parameter	WW	1 PE WW	2 PE WW	3 PE WW	PW	1 PE PW
pH	7.5	7.6	7.6	7.6	7.8	7.6
BOD-7	156	<3	<3	<3	<3	<3
COD	272	1.7	2.7	2	ND	0.6
N-tot	55	36	27	18	ND	14
NH_4-N	35	0.36	0.35	0.60	ND	0.26
NO_3-N	0	26	24	16	2	12
P-tot	8.1	0.59	0.67	1.2	ND	0.61
PO_4-P	7.5	0.47	0.41	0.38	0.07	0.34
K	19	1.9	1.8	1.6	1.6	1.6
Cl^-	50	60	54	68	7.9	64
Zn (µg/l)	124	58	32	18	ND	16
Cu (µg/l)	73	19	18	14	ND	11

ND=No data

At Larissa, the groundwater quality appeared to be unaffected by wastewater irrigation in terms of BOD and K (Table 10). The nitrogen and phosphorus fractions, as well as the content of COD, Zn and Cu, increased to a certain extent compared with the pure water treatment. The groundwater table fluctuated between 3 and 7 m below the soil surface, resulting in a fairly deep unsaturated zone with good prerequisites for removal of various wastewater constituents. Similar to the results at Culmore, the concentration of Total N decreased with increased wastewater irrigation, probably as a result of more favourable conditions for nitrification/denitrification. The relatively low chloride content in applied wastewater resulted in similar concentrations in superficial groundwater independent of treatment.

The wastewater used for irrigation at Roma was well pre-treated and resulted in very low concentrations of all measured parameters in the groundwater zone (Table 11). However, the Cl-concentration increased to some extent with wastewater application rates. Despite the relatively high N application with urine, this treatment did not affect the groundwater quality. Metal concentrations in superficial groundwater beneath the urine treatment plots were lower compared to the wastewater treatments as well as control and pure water treatments. This is likely to be a result of low content of metals in applied urine mixture (*cf.* Table 8).

2.2.5.4 Calculation of wastewater treatment effects

Eutrophying components (N and P) and oxygen demanding organic material (BOD) are problematic constituents if untreated wastewater is discharged to surface waters or ground water aquifers. Traditional wastewater treatment processes could to some extent be replaced by a soil-plant system exemplified in this study by wastewater irrigation of biomass willow plantations. A soil-plant system may be defined as a "natural" physical-biological-chemical reactor including the following main active parts and processes (Hasselgren, 1992):

Table11. Concentration of constituents in superficial groundwater at Roma (mg/l). Mean values during the sampling period September 1999-December 2001. Mean values of applied wastewater (WW), pure water (PW) and urine are included for comparisons.

Parameter	WW	1 PE WW	2 PE WW	3 PE WW	PW	1 PE PW	Urine	1 PE PW/Urine	Control
pH	8.0	7.4	7.5	7.4	7.8	7.4	9.0	7.4	7.4
BOD	3	6	<3	<3	<3	<3	370	<3	<3
COD	36	68	28	36	<30	17	691	29	48
N-tot	2.9	0.33	0.40	0.49	2.0	1.1	1440	0.80	1.09
NH_4-N	1.3	0.13	0.11	0.12	0.03	0.12	1580	0.17	0.09
NO_3-N	0.82	0.08	0.10	0.03	1.76	1.1	0.16	0.67	0.69
P-tot	1.4	0.41	0.18	0.25	0.005	0.25	91	0.19	0.16
PO_4-P	1.2	0.28	0.09	0.22	0.003	0.18	44	0.03	0.10
K	9.4	16	7.3	10	4.5	11	484	7	9.1
Cl^-	81	42	47	51	37	25	72	29	20
Cd (µg/l)	0.05	0.40	0.12	0.27	0.05	0.76	0.05	0.11	0.15
Pb (µg/l)	1.9	27	14	16	3.3	14	4.0	7.1	16
Zn (µg/l)	110	60	18	35	89	22	69	12	25
Cu (µg/l)	16	21	8.9	18	72	13	92	6.8	11

- *Soil particles*, which filter suspended solids and chemically fix dissolved components in the wastewater by adsorption, ion exchange or precipitation,

- *Macro- and microorganisms*, which transform and stabilize organic substances and transform nitrogen in applied wastewater, and

- *Vegetation*, which utilizes macro- and micronutrients in the wastewater for growth, maintains or increases the infiltration capacity of the soil and reduces applied wastewater volumes by transpiration

As indicated in the previous chapter, willow plantations have the potentials to treat pre-treated wastewater to a high quality. For a conventional “closed” wastewater treatment process or system, it is easy to analyse and evaluate the treatment or purification efficiency, since a well defined outlet, normally in terms of a pipe from the unit, collects and discharges the same wastewater volume as was put in. In an “open” wastewater irrigation system with a diffuse outlet following natural drainage it is necessary to measure and/or calculate the terms of the water budget in order to evaluate the treatment efficiency.

Precipitation could be explicitly collected and measured according to normal procedures, but for evapotranspiration and percolation indirect measures are needed as a base for calculation of the treatment effects. Since chloride is not adsorbed or released by most soils and is taken up by plants only to a small extent, it is often used as a tracer for calculation of the leaching fraction of water in irrigation design (*e.g.* Salameh Al-Jamal *et al.*, 1997; Pratt *et al.*, 1978).

Sampling of superficial groundwater for chemical analysis.
(Photo: Stig Larsson)

Consequently, the chloride ion was used in an attempt to compensate for the dilution effect of rainwater and possible influence of surrounding groundwater with regard to analysed superficial groundwater.

Mass balance calculations over the soil-plant system concerning N, P and BOD were exemplified with data from the experiment at Culmore (Table 12). With knowledge of the total amounts applied to the plots (wastewater + precipitation) calculated evapotranspiration, calculated amounts of percolated wastewater in superficial groundwater beneath the plots, and assimilated amounts in Salix stems, rest terms in the mass balances are given concerning uptake in plant foliage and roots (N and P), accumulation or degradation in the soil (N, P and BOD), and denitrification of nitrogen from the plots (N losses in terms of N_2 and N_20).

Correction was made for percolated amounts from control plots (non-irrigated and non-fertilised plots) to better reflect the impact of wastewater, as indicated with "corr" in the table. Thus, calculated percolated amounts in superficial groundwater from the control treatment were subtracted from the calculated amounts found in superficial groundwater samples from waste-water-irrigated treatments.

Removal of BOD from wastewater in soil is generally a result of filtration and microbiological activity in the soil profile. In well-aerated and well-drained systems, the degradation is easily sustained via aerobic microbes. Irrigation activities give altered saturated and drained conditions creating possibilities for anaerobic and anoxic (denitrification) degradation of the organic material as well. However, at some of the sites irrigation with 2 and 3 PE seemed to cause more or less constant anaerobic conditions which limited the degradation of organic matter and transformation of NH_4 to NO_3. This can also be a result of a high soil content of silt and clay, which decreases the supply of oxygen. The organic matter in the upper soil horizon increased generally.

Table 12. Wastewater treatment effects for Culmore in terms of nitrogen (Total N), phosphorus (Total P) and BOD. Corrections (corr) were made for percolation from rainwater control plots.

Parameter			1 PE	2 PE	3 PE
Nitrogen	Applied amount,	kg/ha/y	83	167	250
	Uptake in stems,	kg/ha/y	46	50	58
	Uptake of applied amount,	%	55	30	23
	Percolation,	kg/ha/y	81	76	77
	Removal rate,	%	2	55	69
	Percolation (corr),	kg/ha/y	54	49	50
	Removal rate (corr),	**%**	**35**	**71**	**80**
Phosphorus	Applied amount,	kg/ha/y	56	111	167
	Uptake in stems,	kg/ha/y	7	8	8
	Uptake of applied amount,	%	13	7	5
	Percolation,	kg/ha/y	8	7	6
	Removal rate,	%	86	94	96
	Percolation (corr),	kg/ha/y	6	4	3
	Removal rate (corr),	**%**	**89**	**96**	**98**
BOD	Applied amount,	kg/ha/y	558	1032	1506
	Percolation,	kg/ha/y	400	594	644
	Removal rate,	%	28	42	57
	Percolation (corr),	kg/ha/y	150	344	394
	Removal rate (corr),	**%**	**73**	**67**	**74**

It is suggested that a major part of the applied nitrogen not accounted for, *i.e.* amounts not percolating or amounts not found in willow stems, was probably due to N losses via denitrification in the soil. Other possible routes of nitrogen retention in soil systems could be temporary immobilisation (biologically or chemically) and volatilization of ammoniacal nitrogen to the atmosphere (*e.g.* Wittgren and Hasselgren, 1992). It is well documented that net accumulation of nitrate or ammonia ions in soil in general is rarely substantial and may be neglected in practice with regard to the contribution to sustainable N removal effects (*e.g.* Reed and Crites, 1984).

Volatilization of NH_3-N of up to 20 % of applied N amounts, from spray irrigation with alkaline (pH 7.5-8.5) wastewater, was reported by Pettygrove and Asano (1984). In another American investigation 10 % ammonia volatilization at pH 7.8 was reported (USEPA, 1981). Ammoniacal nitrogen evaporation is promoted from soils with low cation exchange capacities (CEC:s), mainly sandy or organic soils (USEPA, 1981). The soil profiles in this study were mainly silty/clayey so it could be assumed that the NH_3 volatilization rate was limited from the experimental plots.

Phosphate ions not taken up by plants could be sorbed to oxides or hydroxides of iron and aluminium in clay soils or precipitated with iron, aluminium and calcium in the soil to crystalline mineral forms. In soils unsaturated with P normally small percentages will leach from the system (Wittgren and Hasselgren, 1992).

The results clearly indicate that purification of primary effluent in willow plantations could be substantial. A hydraulic load up to three times the evapotranspiration rate from the system did not influence wastewater treatment capacities, as exemplified with data from Culmore. Thus, managing a system with wastewater irrigation according to the water and nutrient requirements of a willow biomass plantation seems possible without negative environmental impacts with regard to oxygen demanding substances and eutrophying components.

2.2.5.5 Sanitary aspects – micro-organism analyses

Conventional sewage system reduces the concentration of human enteric pathogens in the treated wastewater reaching a water course but does not exclude later risks. It functions as the first barrier in disease prevention, but does not safeguard populations exposed through direct contact, recreational activities or the one using the recipient as a source for drinking water production.

Within this project some questions to be solved in relation to sanitary aspects and potential secondary transmission to humans were related to the site-specific characteristics. These in turn may function as a base for generalised guidelines to be applied when irrigation with wastewater or use of sludge as fertiliser is practised in willow plantations. These questions further apply to a) the optimal supply of wastewater under the prevailing local conditions, b) potential sanitary problems arising in relations to humans, c) environmental problems due to the presence of wildlife.

For these assessments a number of faecal indicator organisms were used including the traditional coliforms indicators, supplemented with faecal enterococci, anaerobic sulphite reducing *Clostridium perfringens,* and the somatic coliphages (bacteria virus). Coliphages are often used as a model virus to indicate transport of human viruses down to the groundwater zone. In addition, analyses were made concerning the bacterial pathogens *Salmonella* and *Campylobacter* and the protozoan parasites *Giardia* and *Cryptosporidium*. All of these represent organisms that can infect both humans and animals.

The potential transmission routes from wastewater for disease causing organisms are through groundwater, surface drainage and aerosols, via animals and direct contact. These possibilities were compared at Roma, Larissa and Culmore.

2.2.5.5.1 Removal in pre-treatment plants

At Roma all selected indicator microorganisms and pathogens were analysed in inflow water to the pre-treatment plant. In the untreated wastewater the faecal coliforms and *E. coli* varied between $4*10^2$ - $3*10^3$ cfu/ml and were reduced, over the pond system, to below the detection limit, between <1 to <0.01 cfu/ml, giving a total reduction of >99.8 to >99.99 % of faecal coliforms and *E. coli*.

The faecal enterococci likewise gave a reduction of >3 $\log_{10}$ (>99.9 %) while the spore forming bacteria (*Clostridium perfringens*) initially occurred in low values but were still detectable, 0.1-0.5 cfu/ml after treatment. The coliphages had influent concentrations of $1\text{-}4*10^2$ cfu/ml and a reduction of 99.8-99.98 % (from below detection limit <0.1 pfu/ml to 0.3 pfu/ml).

Salmonella and *Campylobacter* (analysed semi-quantitatively) were detected just on one occasion between the first and the second pond but never in the effluent used for irrigation. No *Giardia* or *Cryptosporidium* were detected in the untreated wastewater (detection limit <2.5/L) or in the treated wastewater used for irrigation (detection limit <0.3/L).

In general the treated water used for irrigation had low or undetectable values of both indicator and pathogenic organisms although the wastewater is treated in open ponds, which are also a habitat for birds that could give an input of the organisms to the water. The presence of *Salmonella* and *Campylobacter* in the wastewater can be due to either their presence in the wastewater or as a result of the presence of birds.

Analyses of untreated and treated wastewater were also carried out at Larissa and Culmore (Figure 8). At Larissa the treated wastewater used for irrigation contained concentrations of *E. coli* and faecal streptococci (60 to 80 cfu/ml and 10 to 20 cfu/ml, respectively). For coliphages the corresponding values were 150-160 pfu/ml with a treatment reduction efficiency of 99.2-99.8 %. The concentrations of *E. coli* in the wastewater used for irrigation in Culmore were $4*10^4$ cfu/ml (average of four samplings) and the reduction capacity varied between 12 and 99.8 % over the treatment plant. Also the reduction capacity varied for the *Clostridium perfringens*, 44–99.1 %, and the coliphages, 75-98.6 %. For coliphages the concentrations varied dramatically between the different sampling occasions, from 30 pfu/ml to $1.9*10^4$ pfu/ml in the pre-treated wastewater used for irrigation.

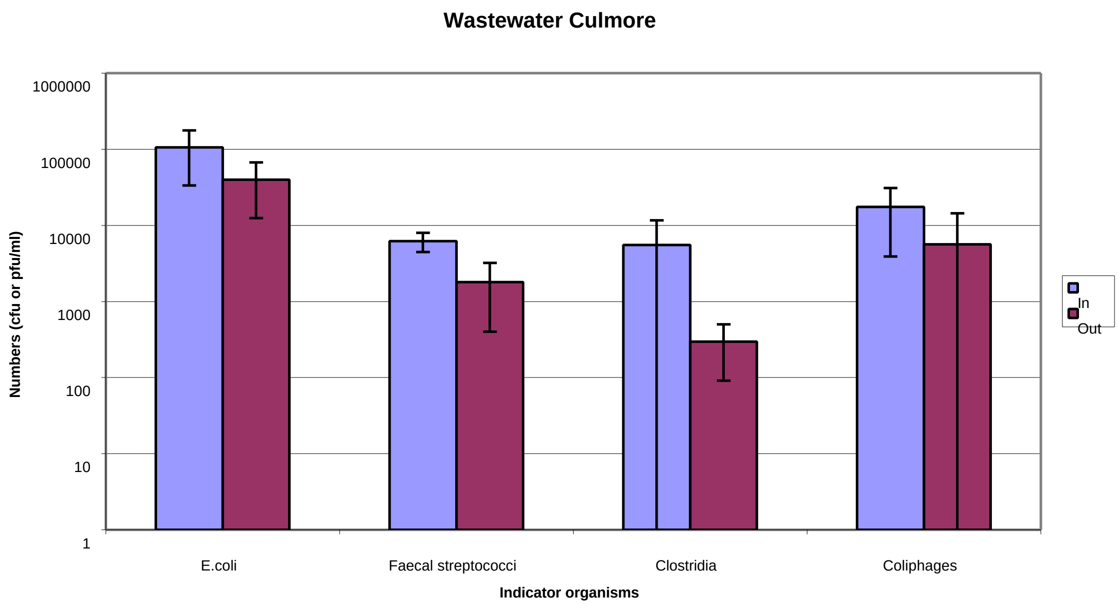

Figure 8. Occurrence and reduction of indicator organisms in the treatment plant at Culmore, n=4.

Salmonella was detected in both the untreated and treated wastewater used for irrigation at both Culmore and Larissa. *Campylobacter* were not detected at any time. For *Giardia* and *Cryptosporidium* the concentrations varied between the different sampling occasions. At Larissa the incoming numbers of *Giardia* varied between 100/L (100 % DAPI+) to 6326/L (of these 1217/L were DAPI+) and with a reduction of 99.5-99.97 % giving concentrations of 0.5 to 1.7 cysts/L in the water used for irrigation. For *Cryptosporidium* the numbers were low: in the untreated wastewater <2 to 4.3/L and in the treated wastewater the concentrations were in the same range, indicating no significant reduction over the treatment plant. The corresponding concentrations for these pathogens at Culmore were for *Giardia* the highest of all treatment plants included in this study. In the untreated wastewater the cysts varied between 24 cysts/L (100 % DAPI+) to 15 000 cysts/L, while in treated wastewater the concentrations varied between <0.7-2805 (39 % DAPI+)/L. The reduction varied from a very low 7 % to 99.5 %. For *Cryptosporidium* the concentrations in the untreated wastewater were 4 oocysts/L to 104 oocysts/L while the pre-treated wastewater had concentrations of <0.7-42 oocysts/L, giving a reduction capacity of 50-60 %.

At Roma, the urine mixture collected from the toilets and the urinal were sampled and analysed for indicator organisms on one occasion, soon after filling up the tank. In the urine mixture, *E. coli*, faecal streptococci, *Clostridium perfringens* and the coliphages, were detected in numbers of 90 cfu/ml, 655 cfu/ml, 1400 cfu/ml and 140 pfu/ml, respectively. *Salmonella*, *Campylobacter*, *Giardia* and *Cryptosporidium* (detection limit <10/L) were not detected in human urine.

2.2.5.5.2 Leakage to groundwater

The results from the sampling of superficial groundwater at Roma showed that most of the organisms were below the detection limit, <0.1 cfu/ml (Table 13). The exception was total coliforms which were detected in concentrations of 3-25 cfu/ml.

Total coliforms in low numbers can be found naturally in the environment. The low numbers were anticipated at Roma since the pre-treated wastewater was stored prior to irrigation. Due to the low number of organisms no differences could be seen between the different irrigation regimes.

The numbers of indicator organisms found in the superficial groundwater at Culmore were consistently much higher than values found at Roma (Fig. 9). The total coliforms showed very high concentrations, indicating a clear groundwater contamination. No clear differences could be seen between the different treatments even though increased numbers of organisms were noticed in the 3 PE WW treatment compared with the 1 PE WW and 2 PE WW treatments. Coliphages are the smallest organisms and more likely to be transported than bacteria, helminth or protozoan parasites.

Table 13. Concentrations of indicator organisms in superficial groundwater in the wastewater irrigated field at Roma. Numbers presented as cfu or pfu/ml.

Treatment	**Total coliforms**	***E. coli***	**Faecal streptococci**	***Clostridium perfringens***	**Coliphages**
1 PE WW	4	0.2	<0.1	<0.1	<0.1
2 PE WW	11	0.1	<0.1	<0.1	<0.1
3 PE WW	25	2	0.1	<0.1	<0.1
1 PE PW	3	<0.1	0.1	<0.1	<0.1
1 PE Urine/PW	8	<0.1	<0.1	<0.1	<0.1

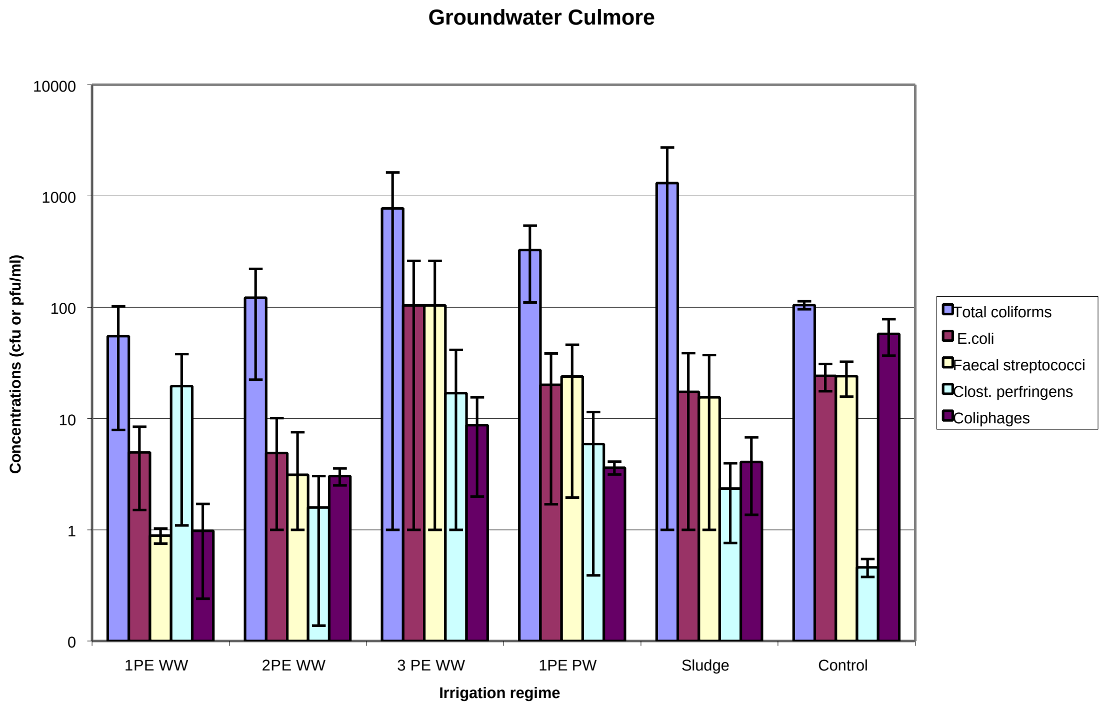

Figure 9. Concentrations of indicator organisms in the groundwater in the irrigated field at Culmore.

The rate of leakage to the groundwater depends on the soil texture and the distance to the saturated zone. The infiltration capacity is normally higher in a sandy soil compared with clayey soil, which could be an explanation of the relatively low reduction rates at the Culmore site. Further, the unsaturated zone at Culmore was shallow and varied between 0.5 and 2.5 m during the course of the project. In a soil type with larger parts of clay particles cracks can occur in which the water can be transported rapidly. However, the risk of contamination varies with the occurrence of nearby wells.

At Culmore sprinklers were used for irrigation whereby creation of aerosols could occur. Transport of aerosols is dependent on the prevailing wind conditions and direction. At the sites, the irrigated field was placed in an open area with no natural barriers against the transport of aerosols. However, the willow vegetation itself could create a barrier if the outer parts are not irrigated.

When the plantation is irrigated with wastewater, the animals living in the willow coppice area are exposed to pathogens occurring in the wastewater, with a potential risk of direct infection and/or as carrier of infection to house pets, humans or water reservoirs. Results from analysis of faecal samples from wildlife did not indicate that this would be the case. Still, the observations were few and no final conclusions regarding this aspect could be drawn.

In order to reduce or minimise the risk for direct contact with the wastewater or the crop irrigated with the wastewater, the irrigated area can be fenced to keep the public or larger animals out of the field. Another way of reducing the risk is to inform the public that the irrigated field is part of the wastewater treatment system. No public recreational areas should be located near the irrigated field, which also reduces the risk for humans and especially children to come into contact with the wastewater. The distance from the different fields to houses or farms in this study varied between 30 m to 800-1000 m. One way of reducing direct contact, and also aerosols, is to restrict the irrigation and exclude the outer parts of the plantation.

A mature willow stand at the Roma site in mid-summer the third year.
(Photo: Ingvar Jakobsson)

3 Economical, legal and social aspects

3.1 Economical aspects

Two different economical studies were carried out relating to conditions in Northern Ireland. Sweden has been studied in this respect before (Rosenqvist, 1997; Rosenqvist *et al.*, 1997). One of the studies concerned economical conditions for willow growing and business development of willow coppice production in general. The other study investigated the economy on willow irrigation with wastewater from a treatment plant. Where possible, comparisons were made with Swedish conditions.

The willow biomass industry in Northern Ireland is in a very early stage of development, imposing cost penalties on the pioneer growers. This situation could be compared with the situation in Sweden with an established industry based on at present 15 000 ha of willow plantations and where production costs are significantly lower.

To provide a positive return, according to the study, the price of willow chips must be at least £ 35/tonnes of dry matter (t DM). This figure does not include any opportunity cost for the land or any subsidy payment. From the model, it was estimated that a yield of 9.2 t DM/ha/y (from the second harvest cycle) was required to obtain a positive income from the land. Thus if the expected yield level was lower than 9.2 t DM/ha/y the land should be used for other purposes or be left fallow. For each increase in the number of harvesting cycles taken, the calculated gross margins will increase and production costs per t DM will decrease. A minimum of five rotations (16 years) would be required to attain a positive income from the land.

In Northern Ireland the average annual costs of growing willow biomass over a 22 year rotation were calculated to £ 349/ha or £ 35/t DM. Grain production and willow show a similar gross margin result. Willow was competitive when the grain prices were lower than £ 70– £ 80/t. This study also shows that with gross margins, without the present subsidies for suckler cows of £ 200/ha and for lowland sheep of £ 234/ha, willow coppice can be competitive with other grassland-based enterprises, depending on the individual circumstances on each farm.

When the situation and costs for planting and harvesting willow in countries with different acreages of willow are compared, the connection between the established area of willow plantations and production costs is clearly seen. The cost for plantation decreases both through new technology and through the increasing numbers of hectares planted with willows.

The possibility of reducing the costs for conventional N and P treatment, £ 5 – £ 14/kg N (Rosenqvist. *et al.*, 1997), is by far the most important economic factor when considering wastewater irrigation of willow coppice as an alternative treatment technique. The increased biomass production and the reduced costs for the farmer (corresponding to £ 0.60/kg N), have a limited impact on the total economic result. Increased biomass production by growing even more vigorous plants would allow an increased N application without increased risks of N leaching. The increased rate of wastewater application that these enhanced yield potentials allows would reduce the cost for each kg N treated.

If there are no existing willow plantations or no immediately available areas for new plantations in the vicinity of treatment plants, it may be appropriate to invest in pipelines to reach suitable areas. An alternative is to offer farmers with suitable land in the vicinity of the treatment works the opportunity to handle the wastewater by giving them appropriate support. If a farmer accepted wastewater irrigation corresponding to 150 kg N/ha/y, he could theoretically be paid up to the alternative cost for conventional treatment, *i.e.* £ 5 – £ 14/kg N (amounting to about £ 700 – £ 1800/ha/y for the wastewater production during the irrigation season). In practice, however, society is likely to try to profit from a new treatment system by demanding a lower price for wastewater treatment. This, together with the value of the increased biomass production, would give the farmer maximally £ 800 – £ 1900/ha/y. This implies that the farmer has to cover all the costs for pumping and distribution.

Some of the project participants in the middle of the willow forest.
(Photo: Stig Larsson)

The costs for handling and distribution of wastewater containing 150 kg N/ha are £ 800 and £ 1600 for the summer and all year options respectively. Using these figures the financial advantage of using willow coppice as a bio-remediation system, when compared with conventional wastewater treatment, ranges between £ -5 and £ 1100/ha for the summer option and between £ -500 and £ 1100/ha for the whole year option, including wastewater storage in ponds. These figures take into account:

- The range of costs for the conventional treatment of nitrogen/phosphorus
- The efficiency of willow coppice as a bio-remediation system.
- The handling and distribution of wastewater with an irrigation system
- The value of the additional biomass produced
- The reduction in nitrogen levels during storage in the case of the whole year option

A more expensive but environmentally sound solution, would be to take treated water from a treatment work, which would normally be discharged to the sea or a river, and irrigate a willow plantation with this conventionally treated water. This could be beneficial in districts with problems concerning eutrophication of surface waters. If 10 ha were irrigated with wastewater containing 10 mg N/l and given 430 mm/ha/y, the cost would be £ 16 /kg N or £ 600/ha without storage ponds.

Different treatment works have different costs for using vegetation filters depending on the planning situation and the strategy. When costs are low in the vegetation filter system, it is easier for the treatment works to accept higher costs, for pumping the wastewater longer distances. It can be of interest for large treatment works to take only the “excess water” and pump it a longer distance.

Some of the most important conclusions are:

- Saved costs in treatment works are much more important than saved costs and higher yield in the willow plantation.
- It is important to find treatment works with high costs for traditional treatment and low costs for vegetation filter systems.
- Pumps, ponds and pipes to reach the field are more costly than the irrigation equipment in the field.
- Fixed costs are much higher than variable costs.

Factors to keep costs at a low level are:

- High applications of N and P.
- High concentrations of N and P in the wastewater.
- Extended irrigation season.
- Short distances between treatment works and vegetation filters.
- Large area of willow plantations.

3.2 Legal aspects

Normally when using willow plantations for treating wastewater, the two parties involved are a municipality (or an industry) and the owner or farmer of the plantation. The basis for wanting to enter into a contractual relationship of this kind is primarily mutual economical gain. The municipality is responsible for the handling of the wastewater from the connected citizens.

From the municipality's point of view, the use of vegetation filters will allow decreased investments and operational costs of the required wastewater pre-treatment facility. Less use of chemicals and electric energy, a reduced sludge production and a decreased need of working staff primarily sustain reduction of operational costs. The owner or farmer of the willow plantation will profit from the increase in growth that may lead to greater and more secure harvests.

A contract has to be set up to define the rights and duties of the parties. These rights and duties need to take into account the financial positions of the parties as well as their respective ability to take part in, oversee and verify the object of the contractual relationship. This can be seen as the splitting of risk-taking appropriate for each party. The amount of risk a party is willing to accept depends on the gain he is likely to make.

Today it is usually felt that there is a greater gain for the municipality to have access to a vegetation filter than for the willow farmer to acquire extra water and nutrients. It is also the municipality that can influence the quality of the wastewater and can better handle unpredicted extra costs. Therefore the farmer should be able to demand that the municipality take the major economic responsibility. It is also fair that the municipality should have the responsibility for the risks with the wastewater, even after it is delivered to the willow farmer. The municipality should be liable to pay compensation to the farmer for costs incurred by variation in the amount and quality of the wastewater.

The municipality should demand from the farmer that application of wastewater would be made in accordance with recommendations from authorities. The farmer should have the responsibility to take care of the plantation so it can be used for the whole contract period. A contract about buying of wastewater would last over a long period of time and the different parties would probably adjust their operations with the assumption that the contract will last the predetermined time. Therefore it would be necessary to have a mutual period of notice.

Usually in this kind of contract the deliverers of the product pay the receiver. This can lead to problems if bills are not paid. The farmer should have the right to cut off the supply if payment is absent. The municipality, in turn, should have the right to have access to the plantation even if the plantation area change owners.

If there are many willow farmers receiving wastewater they can create a union or co-operative. An association of farmers or landowners can then carry out the negotiations or even be a contract party with the municipality. In the latter case the association could have the form of a trading company.

3.3 Social aspects

Projects involving the use of reclaimed water for irrigation usually face problems with public acceptance. Public perceptions are constantly changing because they are influenced by many different factors (age, gender, economic status, level of education and political persuasions) and current events. It is important to treat the public acceptance with the same consideration as anything else in the realisation phase of project.

Reuse of water and nutrients replaces natural water supplies and manufactured fertilisers. The willow biomass system itself could very well be characterised as an ecologically and socio-economically sustainable and alternative farm crop, by providing rural development and reducing dependence on imported energy. Therefore, it is an integrated part of society that concerns everyone in the local community. The system has more societal impact than many other wastewater systems due to the fact that it requires large land areas.

It is important that the citizens feel that they are part of the system, since it depends on their co-operation. The citizens can "destroy" the system performance by "polluting" the resource on purpose or by carelessness. If the system is working properly it serves the citizens and one must not forget that the citizens pay for it (as for any wastewater treatment).

"Dubletten", a commercial Swedish toilet for diverting urine and faeces.
(Photo: Arne Backlund)

To implement an initial acceptance from the public the following strategy (or parts of it) is suggested:

1. Allow a budget for information/communication/awareness-raising/education/training. This should be done at the same time as the rest of the project is budgeted.
2. Choose one message-bearer and educate and train him/her. This person can be a management staff member, a professional or an ordinary citizen in favour of the idea.

3. Identify the target audience. This can be citizens, farming communities, decision-makers (political/environmental authorities), environmental groups etc.
4. Begin informing with, for example, meetings, media communication, information brochures and questionnaires.
5. Reach consensus.

The citizens should be aware of potential problems with the systems before the project starts. If something goes wrong with the system, the citizens have to be informed so that they understand the magnitude of the problem and how they should act upon it. They should also be informed about how the problem will be solved.

A strategy, such as that described above, could possibly be useful in case a full-scale application of the system is undertaken at Larissa, as has been discussed there.

The aspects of reducing the pressure on energy and water resources were analyzed for the region of Larissa, an area with rapid economic growth. The possibility of using an integrated solution for municipal wastewater management and agricultural land use around big cities like Larissa, in such a way as to preserve natural beauty and enhance animal and plant life, was also investigated.

Larissa is located in central Greece within an agricultural area. One of the most important problems of this area is the demand on water resources which has become even more severe in the last couple of years. The main income of the town is based on agricultural production, and, therefore, the lack of water recently has created serious problems. It is obvious that in the wider area of Larissa there is need for efficient use of every possible water resource. Thus reuse of properly pre-treated municipal wastewater is foreseen as an important complementary water resource for crop production.

Also, the need for replacement of fossil fuels with renewable and environmentally friendly biofuels has become increasingly pronounced. Further, alternative agricultural crop production, to balance the general over-production of cereals and cotton on the market, is generally promoted. The municipality of the town has already expressed interest in the extension of the activities on willow growing for energy production on a larger scale. Thus, the use of municipal wastewater for irrigation of willow coppice, as a crop system for producing bioenergy in the area of Larissa, is a possible solution to the existing economical and environmental problems, possibly also improving the social life of the people.

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