Costs of tertiary treatment of municipal wastewater by rapid sand filter with coagulants and UV


* Dept. of Env. Sciences, Univ. of Kuopio, POB 1627, FIN-70211 Kuopio, Finland (E-mail: heinotan@uku.fi)
** Soil and Water Ltd, Itkonniemenk 13, FIN-70500 Kuopio, Finland
*** Tampere Water, POB 487, 33101 Tampere, Finland
**** Plancenter Ltd, POB 68, 00521 Helsinki, Finland

Abstract Municipal treated wastewater has been tertiary treated in a pilot-scale rapid sand filter. The filtration process was improved by using polyaluminium coagulants. The sand-filtered water was further treated with one or two UV reactors. The quality changes of wastewater were measured with transmittance, total phosphorus, soluble phosphorus, and somatic coliphages, FRNA-coliphages, FC, enterococci and fecal clostridia. Sand filtration alone without coagulants improved slightly some physico-chemical parameters and it had almost no effect on content of microorganisms. If coagulants were used, the filtration was more effective. The reductions were 88–98% for microbial groups and 80% for total phosphorus. The wastewater would meet the requirements for bathing waters (2,000 FC/100 ml, EU, 1976). UV further improved the hygiene level; this type of treated wastewater could be used for unrestricted irrigation (2.2 TC/100 ml, US.EPA 1992). The improvement was better if coagulants were used. The price for tertiary treatment (filtration + UV) would have been 0.036 €/m³ according to prices in 2001 in 22 Mm³/a. The investment cost needed for the filtration unit was 0.020 €/m³ (6%/15a). Filtration with coagulants is recommended in spite of its costs, since the low transmittance of unfiltered wastewater impairs the efficiency of the UV treatment.

Keywords Disinfection; indicator microbes; phosphorus; polyaluminium coagulation; rapid SF; treatment costs; UV transmittance

Introduction
Treated wastewater invariable contains high amounts of microorganisms including pathogens and opportunistic pathogens (Koivunen et al., 2001). The spread and survival of these microorganisms can be a problem even in cold climates, where the microorganisms survive better (Rajala and Heinonen-Tanski, 1998). The pathogens in surface waters may be a higher risk for bathing waters or even for irrigation waters. The risks posed today and in the future must be taken seriously in the industrialised countries where an increasing percentage of the population (22.8% in Finland according to Niemi et al., 1998) belong to risk groups called YOPIs (young, old, pregnant, immuno-compromised).

There are enteromicrobiological limitations for bathing waters, thus the imperative values are 10,000 CFU/100 ml (colony forming unit) for TC and 2000 CFU/100 ml for FC, the mandatory values being 500, 100 and 100 for TC, FC and enterococci, respectively (EU, 1976). If surface water receiving wastewaters are used for irrigation, it is essential that the numbers of enteric microorganisms are even less since irrigation water has shown to contaminate different plants, e.g. alfalfa sprouts by Salmonella and enterohaemorrhagic Escherichia coli O157:H7 (Charkowski et al., 2002; Howard and Hutcheson, 2003), cabbage by non-pathogenic E. coli (Wachtal et al., 2002), lettuce by E. coli O157:H7 (Solomon et al., 2002) and zucchini by Cryptosporidium (Arnon et al., 2002). Therefore some legislations such as Italy and California decree that irrigation water used for plants eaten uncooked should contain only 2 or 2.2 TC/100 ml (US.EPA, 1992; Lubello et al.,...
Wastewater has to be tertiary treated with a method including disinfection, if the above values are to be achieved in the treatment or if the treated wastewater is being discharged to surface water with a high value and limited dilution ability such as a small lake or river.

The reduction of enteric microorganisms can be achieved by disinfection chemicals or with UV-irradiation. Since Finnish surface waters are humus-rich, chlorine-containing disinfection compounds are not a feasible alternative even though they are still sometimes used today. Al-Mogrin (1999) was able to produce water meeting the requirements for irrigation water by using slow sand filtration and UV. Slow sand filtration requires a large area, which is a disadvantage nor it also can be optimal for the Nordic climate with its cold winter. We therefore selected a combination of rapid filtration and UV-irradiation as a treatment method for this study.

Material and methods

Wastewater treatment process for pilot plant

Tampere Viinikanlahti wastewater treatment plant is one of the largest Finnish wastewater treatment plants. It serves 190,000 inhabitants and some industry (load corresponding to an extra 10,000 inhabitants) including a cardboard factory, which increases the colour (approximately 100 mgPt/L) and decreases the UV transmittance of wastewater making more difficult to perform UV-irradiation. The treatment plant has a primary physical phase and an activated sludge biological process with simultaneous phosphorus precipitation as its second phase. The biological part has been sized to a wastewater flow rate of 70,000 m³/d. The maximal flow rate was 4,870 m³/h and the total annual flow rate was 22 Mm³ in 2000 (Tampere Water, 2001). Some of the phosphorus was precipitated during activated sludge phase with ferrisulphate (175 mg/L). The environmental court allows the effluent to contain $P < 0.8$ mg/L (reduction $> 90\%$), $BOD_{7\text{ATU}} < 15.0$ mg/L (reduction $> 90\%$). The $P$-content of effluent was 0.13–0.48 mg/L. It also contained 3–4 log units/100 ml of all of the studied enteric indicator microbes.

The pilot plant runs were carried out from 7 December 2000 to 3 March 2001, during the wintertime so that the wastewater flow is balanced because precipitation falls as snow and spring melting had not yet started. The plant was operated normally during the runs and it surpassed the purification requirements. The pilot plant was established in a hall so that frost would not cause any problems for the instruments. The pilot plant comprised a continuously washing sand filter (DynaSand DST07, Waterlink, 1998) and one or two vertical UV reactors set in series (ProMinent Dulcodes).

The sand particle size was 0.9–1.2 mm, sand bed height about 3.5 m, and filter area 0.7 m². The secondary treated effluent was running from the bottom up and the sand on the surface was washed. The hydraulic load was 7.7 or 6.0 m/h. The runs were carried out mechanically or as contact-filtering using two commercial polyaluminium chloride coagulants, (PAX 18 and PAX XL60, Kemira Chemicals). The amounts of coagulants were 15, 20 or 27 g/m³ (as aluminium between 1.1–2 g Al/m³).

Physico-chemical parameters during the pilot plant run. The total and soluble phosphorus, suspended solids, colour, turbidity, chemical oxygen demand and transmittance-% were measured with standard methods. These measurements were carried out on wastewater samples taken before and after the filtration usually twice a week.

Microbiological parameters. The numbers of coliphages, FC, enterococci and sulphite reducing clostridia, somatic coliphages (host *Escherichia coli* ATCC 13706) and FRNA-coliphages (host *E. coli* ATCC 15597) were determined before and after the filtrations and
after the both UV-treatments also twice a week. The bacterial determinations were done with standard membrane filtration methods and the coliphages with the method of Grabow and Coubrough (1986).

UV-irradiation doses and their calculation

The filtered wastewater was lead to UV-reactors with irradiation efficiencies 16 or 32 W. Theoretically the irradiation doses on the surface of lamps would have been 900 J/m² and 1,800 J/m². The irradiation doses (D) used in pilot plant experiments and those that would be needed for sizing UV-irradiation apparatus of full scale plant were calculated from irradiation intensity (I), which was calculated from the absorption constant $\alpha$ by using Eq. (1):

$$Tr = 100\% e^{-\alpha}$$

(1)

where,

Tr: transmittance, which can be measured with UV spectrophotometer at 254 nm.

The intensity ($I$) was calculated by Eq. (2).

$$I = P \left(1 - e^{-\alpha(r-r_o)} \right) / \left[ \pi l \alpha (r^2 - r_o^2) \right]$$

(2)

where,

$P$: UV efficiency of lamp (W)

$\alpha$: absorption constant (1/cm)

$l$: length of lamp (cm)

$r$: radius of the reactor (cm)

$r_o$: radius of lamp (cm)

To attain a safety factor, we estimated that the efficiency of lamp would be reduced, when the lamps became old or fouled. We therefore estimated that only 90% of UV efficiency would serve for irradiation doses. The final UV-doses ($D$) were calculated:

$$D = I \cdot t$$

(3)

where, $I$: intensity; $t$: retention time (s)

By using the above formulas and the measured $Tr$ values, the irradiation doses calculated were 190–340 J/m² or 390–670 J/m² according to transmittance values of wastewater and the UV lamp system (one or two lamps). These values of UV doses are less than those calculated from the formula presented by Sommer et al. (2001), but their formula could not be used for an unknown lamp system, where initial intensity was not known.

The plan for sizing a full scale process has been made according to the results obtained from the pilot plant experiment. The costs have been checked from manufactors or importers. The salaries and their side costs have been estimated from the salary statistics.

Results

When the rapid sand filtration was performed mechanically without any coagulants, the transmittance changed from 37.8% to 45.5%. In these runs the reductions for microorganisms were low (11–35%, Table 1). The reduction of total phosphorus was 30–40%, being 0.12–0.26 mg/L after the filtrations were carried out mechanically without any coagulants, and the soluble phosphorus remained the same (0.01–0.04 mg/L) as before filtration.
When coagulants were used in filtration, the transmittance improved up to 60% (mean 57.8%). The reductions for microorganisms were 88–98%. The reductions were so similar with using both coagulants at the different concentrations that the results in Table 2 are presented together. The microbiological quality of this treated effluent would have fulfilled the imperative limits of FC in bathing water (76/160/EC). The amount of total phosphorus in filtered water was 0.03–0.08 mg/L (reduction >80%). The parameters correlating to transmittance, phosphorus, or microorganisms (SS, NTU, COD, colour) showed also clear reductions in filtration and the reductions were higher if coagulants were used (typically reduction-% of 70–90) than if the coagulants were not used (typically 25–40% reductions)

UV-irradiation improved still further the reductions in microbial numbers (Tables 1 and 2). The reduction was clearly better if coagulants were used, because the coagulants increased the transmittance and allowed a higher UV-dose even though the same UV-lamp treatment was in use. If coagulants and two UV-lamps were used, the geometric means for FC would fulfil the Californian or Italian limits for unrestricted irrigation water (US.EPA, 1992; Lubello et al., 2002). The inactivation rates K from the formula $N = N_0 e^{-KD}$ would be 0.0061 m²/J for FC, 0.044 m²/J for enterococci, 0.0008 m²/J for clostridia, 0.0072 m²/J, for somatic coliphages, and 0.0054 m²/J for FRNA-coliphages.

### Sizing calculations of tertiary treatment in a full scale process

The sizing calculations were made in order to reduce the number of FC to 200 CFU/100 ml, which would comply with North-American limit value for wastewater being discharged into lakes (Trojan Technologies, 1999). The flow rate of Viinikanlahti can be 70,000 m³/d with high flow rates of 3,500 m³/h. Thus, if the hydraulic load of filter would be 8 m/h, the filter surface needed would be 440 m². The filter could treat also the washing water (5–10%). During the temporary peak flow rates (4,780 m³/h), the hydraulic load could temporarily be 11 m/h, which should still be tolerated according to Waterlink, (1998). The filter

### Table 1

The geometric means of microorganisms in effluent before sand filtration and after filtration and UV-irradiation with one or two lamps, when no coagulants were used. The bacterial numbers are CFU/ml and the viral numbers are PFU/100 ml. The reduction percentages from the effluent before filtration in parenthesis

<table>
<thead>
<tr>
<th>Microbial groups</th>
<th>Before filtration (n = 6)</th>
<th>After filtration, no coagulants (n = 6)</th>
<th>UV with one lamp (n = 4)</th>
<th>UV with two lamps (n = 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FC</td>
<td>64,000</td>
<td>41,000 (35.9%)</td>
<td>440 (99.3%)</td>
<td>3 (99.995%)</td>
</tr>
<tr>
<td>Enterococci</td>
<td>23,000</td>
<td>11,000 (52.2%)</td>
<td>170 (99.3%)</td>
<td>3 (99.987%)</td>
</tr>
<tr>
<td>Sulphite reducing clostridia</td>
<td>420</td>
<td>140 (66.7%)</td>
<td>240 (42.9%)</td>
<td>49 (88.3%)</td>
</tr>
<tr>
<td>Somatic coliphages</td>
<td>19,000</td>
<td>13,000 (31.6%)</td>
<td>27 (99.9%)</td>
<td>1 (99.995%)</td>
</tr>
<tr>
<td>FRNA-coliphages</td>
<td>3400</td>
<td>3000 (11.8%)</td>
<td>53 (98.4%)</td>
<td>5 (99.85%)</td>
</tr>
</tbody>
</table>

### Table 2

The geometric means of microorganisms in effluent before sand filtration and after filtration and UV-irradiation with one or two lamps, when polyaluminium coagulants (all concentrations) were used. The bacterial numbers are CFU/ml and the viral numbers are PFU/100 ml. The reduction percentages from the effluent before filtration in parenthesis, $n = 19$. $<1 = \text{less than detection limit}$

<table>
<thead>
<tr>
<th>Microbial groups</th>
<th>Before filtration</th>
<th>After filtration with coagulants</th>
<th>UV with one lamp</th>
<th>UV with two lamps</th>
</tr>
</thead>
<tbody>
<tr>
<td>FC</td>
<td>58,000</td>
<td>870 (98.5%)</td>
<td>6 (99.99%)</td>
<td>2 (99.997%)</td>
</tr>
<tr>
<td>Enterococci</td>
<td>12,000</td>
<td>200 (98.3%)</td>
<td>7 (99.3%)</td>
<td>2 (99.98%)</td>
</tr>
<tr>
<td>Sulphite reducing clostridia</td>
<td>600</td>
<td>13 (97.8%)</td>
<td>10 (98.3%)</td>
<td>3 (99.5%)</td>
</tr>
<tr>
<td>Somatic coliphages</td>
<td>29,000</td>
<td>2,700 (90.7%)</td>
<td>5 (99.98%)</td>
<td>$&lt;1 (&gt;99.997%)$</td>
</tr>
<tr>
<td>FRNA-coliphages</td>
<td>12,000</td>
<td>180 (98.5%)</td>
<td>$&lt;1 (&gt;99.99%)$</td>
<td>$&lt;1 (&gt;99.99%)$</td>
</tr>
</tbody>
</table>
is designed to contain 80 basic filtration units of 5.5 m². Ten basic filtration units could be arranged into eight concrete basins. The basins could be set partly underground, to reduce the power needed for pumping and thus the pumping height would be only 4 m. The filter could be situated outdoors because the temperature of wastewater is at least 6°C, but the washing unit and the chemical pumps and pipes needed for coagulant must be protected against freezing. The chemical selected for coagulation would be 15 g/m³ PAX XL60, although both coagulants were equally good in the present work (data not shown), but PAX XL60 appeared to be somewhat superior to PAX 18 in a study conducted in four different treatment plants (Rajala et al., 2002).

The UV-dose needed in full scale was estimated to be 250 J/m², as calculated with formulas 1, 2 and 3, which would have been sufficient in the present experiment. Due to changes in hydraulic load, the flow rate selected here was 4,500 m³/h and the transmittance (Tr) only as 50%, which is less than that achieved in the present work with used coagulants and it is less than that recommended by ProMinent (2002).

The UV-power needed could be satisfied by 220 high intensity UV-lamps with UV-irradiation efficiency of 100 W (electrical energy efficiency 300 W). These lamps have thus more efficiency than those used in the pilot work. The radius of one such lamp (rₒ) is 1.27 cm and its length 100 cm. The lamps could be set in two parallel water channels as two 10 × 11 matrices with lamp middle point distances separated 7.5 cm from each other. The total cross section of water surface would be 1.1 m² and water should run along the lamps with a maximal flow rate of 1.1 m/s so the retention time in the vicinity of the lamps would be at least 0.9 s. The use of electrical power by each lamp could be controlled automatically, even by a mobile telephone and so that a broken lamp could be rapidly changed.

**Price estimation according to prices in autumn 2001**

The costs presented include only those extra costs emanating from the tertiary treatment. The capital costs for investments have been assumed to be paid in 15 years with interest of 6%.

**Investment costs of filter.** The investment costs of the filter comprise the filter units with sand (1.5 Me), basins (1.0 Me), compressors and pumps (0.5 Me), water pipes and channels leading and dividing water to the filter and between filter units and in addition a building for pumping (0.4 Me), geotechnical work (0.2 Me), electrical work with automation (0.3 Me), planning work (0.4 Me) and a chemical pump and tubes for coagulant dosage and ground (together 0.06 Me). The total price would be 4.36 Me. In a climate, where there is no frost, it would not be necessary to construct a building to protect the small tubes and pumps from being frozen.

**Maintenance costs of the filter.** The annual maintenance costs of filter are presented in Table 3.

**Table 3** The annual maintenance costs of filter

<table>
<thead>
<tr>
<th>Cost factor</th>
<th>Clearance</th>
<th>Price (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maintenance work</td>
<td>Salary of 3 h in working days with side costs</td>
<td>15,000</td>
</tr>
<tr>
<td>Coagulant</td>
<td>330 t PAX XL60</td>
<td>72,000</td>
</tr>
<tr>
<td>Energy</td>
<td>Pumping 22 Mm³/a to 4 m and washing utility percentage 75%</td>
<td>28,700</td>
</tr>
<tr>
<td>Renewal costs</td>
<td>Mammut-pump renewal each 5 years, annual amortisation</td>
<td>7,600</td>
</tr>
<tr>
<td>Other costs</td>
<td>Extra administration etc.</td>
<td>1,700</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>125,000</strong></td>
</tr>
</tbody>
</table>
Investment costs of UV reactors. The investment costs of UV reactors comprise the lamps and their control units and a cleaning units (0.38 Me), channel building with electrical work (0.38 Me) and the planning work (0.06 Me). The total price would be 0.84 Me.

Maintenance costs of UV-reactors. The annual maintenance costs are presented in Table 4.

The total costs. The annual costs of the tertiary treatment have been calculated from investment costs and from maintenance costs as calculated above in the text and in Tables 3 and 4. The total costs for the whole 22 Mm³ and the cost per wastewater m³ are presented in Table 5.

Discussion
The pilot plant experiments suggest that the planned tertiary treatment could well be converted into a full scale wastewater treatment plant. The inactivation rates achieved from the UV reactor were at similar levels as those presented by Niewstad et al. (1991) and Al-Mogrin (1999), so the upsizing appears to be feasible.

The greatest cost of the tertiary treatment originates from the investment and coagulant chemical costs of filtration. However, filtration with coagulants had such a beneficial effect on the reduction of both microorganisms and phosphorus, that it may be possible to use them alone, if the hygiene quality of wastewater would be sufficient. One cannot recommend that a UV reactor would be alone sufficient since earlier studies (Savolainen, 1991 and Al-Mogrin, 1999) were not able to improve the wastewater hygiene with mere UV treatment. This is attributable to the low transmittance of the non-filtered wastewater effluent. The filtration with coagulants as pre-treatment led to major reductions in the impurities and thus it may reduce the fouling of the UV lamps and the maintenance costs of the UV reactor.

The major reduction in the phosphorus content achieved by filtration may well be very important for surface water quality, since phosphorus is the limiting factor for quality of many lakes and seas. It is highly likely that the limit values of phosphorus content in effluent will be reduced in the future by environmental legislation. Filtration with coagulants may be one economical possibility to achieve the necessary reductions in phosphorus.

Table 4 The annual maintenance cost of UV-reactors

<table>
<thead>
<tr>
<th>Cost factor</th>
<th>Clearance</th>
<th>Price (£)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maintenance work</td>
<td>Salary of 2 h in working days with side costs</td>
<td>10,000</td>
</tr>
<tr>
<td>Lamps</td>
<td>Use time 10,000 h, need for changing 0.876/a × 220 × 400 e</td>
<td>77,000</td>
</tr>
<tr>
<td>Energy</td>
<td>Electricity efficiency 300 W → 578, 160 kWh/a × 0.07 e/kWh</td>
<td>40,500</td>
</tr>
<tr>
<td>Other costs</td>
<td>Testing, repair costs, waste treatment fee for lamps containing mercury</td>
<td>10,000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>137,500</strong></td>
</tr>
</tbody>
</table>

Table 5 Annual total for the tertiary treatment of 22 Mm³ wastewater and for 1 m³ of wastewater

<table>
<thead>
<tr>
<th>Annual total costs (£)</th>
<th>Costs/ wastewater m³ (£)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment of the filter</td>
<td>450,000</td>
</tr>
<tr>
<td>Maintenance for the filter</td>
<td>125,000</td>
</tr>
<tr>
<td>Investment of the UV reactor</td>
<td>86,000</td>
</tr>
<tr>
<td>Maintenance for the UV reactor</td>
<td>137,500</td>
</tr>
<tr>
<td><strong>Grand total</strong></td>
<td><strong>798,500</strong></td>
</tr>
</tbody>
</table>
levels. This reduction of phosphorus may be still useful even the water is to be used for irrigation despite the fact that phosphorus is one of the main nutrients. It must be seen, however, that a crop may need irrigation water during its long growing period but no more phosphorus due to its maturation phase or if the previous P-fertilisation has been high. The high levels of phosphorus in irrigation water basins would also allow excess growth of cyanobacteria, algae and weeds, especially if irrigation water has to be preserved before use. Still extra phosphorus in water can lead to problems of excess biofilm formation, which could protect pathogenic microorganisms. Therefore it is advisable to control the levels of phosphorus during treatment.

If there would have been even higher requirements for microbiological hygiene of the effluent, those could be achieved by using more UV-lamps and perhaps also a longer water channel. The extra cost in this would have been mainly extra investment costs of UV reactor which are rather low (Table 5).

Conclusions

Based on the results of this study, the following conclusions can be drawn.

(a) A tertiary treatment of wastewater effluents can be done successfully with rapid sand contact filtration using polyaluminium chloride coagulation and a subsequent UV disinfection, if needed.

(b) The filtration with coagulants improved the microbiological quality and the physicochemical parameters, which improved the UV irradiation penetration. The filtration also highly reduced the phosphorus content of effluent.

(c) The treatment can produce water, which could be used for even unrestricted irrigation in agriculture.

(d) Comparing the costs to other wastewater treatment costs, the extra expense at a level of 0.04 €/m³ would not be considered as excessively high.

Acknowledgements

This study was funded by the National Technology Agency of Finland (Tekes) in the years 2000–2001 as a part of the technology programme “Water Services and Technologies 2001”. Petri Juntunen has received a grant from Foundation of Soil and Water Technology (Maa- ja Vesitekniikan Tuki). We thank the process personnel of Tampere Water for maintaining the pilot and all the companies (especially Kemira Chemicals, ProMinent and Voda Pro) for giving the support during the pilot plant runs and the providing detailed prices. We thank Dr. Ewen Macdonald for correcting the English language.

References


