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EVALUATION OF TREATMENT SCHEMES APPROPRIATE FOR WASTEWATER REUSE IN GREECE

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ABSTRACT

The scope of this paper is the evaluation of wastewater reuse quality criteria and treatment specifications, appropriate to Greek conditions. The parameters that affect wastewater reuse criteria were taken into consideration, concerning among others reuse priorities, available treatment plants and effluent characteristics. The proposed wastewater reclamation criteria were verified by a series of lab-scale experiments, designed to study the feasibility and effectiveness of the following treatment schemes to produce treated wastewater suitable for reuse: a) disinfection of secondary effluent with UV radiation and chlorination and b) tertiary treatment and disinfection of wastewater with UV radiation and chlorination. The experimental data were analyzed using a stochastic statistical model that employs Monte Carlo simulation. The main scope of the stochastic approach was the regeneration of a greater set of data, based on the defined by the experimental information mathematical distribution of each parameter involved and the determination of relative probability distributions. Following this approach the standards proposed are realistic and feasible and in the case of restricted reuse can be readily achieved by the existing wastewater treatment plants in Greece. Even in the case of unrestricted reuse the additional treatment required can be achieved at a moderate cost, through upgrading of the existing plants with tertiary treatment.

KEYWORDS: Wastewater reuse, criteria, wastewater treatment, ultraviolet disinfection, chlorination, Monte Carlo simulation

INTRODUCTION

The sustainable management of water resources often requires the identification of wastewater as a valued source of water. The benefits of wastewater reuse and reclamation have increased significantly in Europe because of the advances in effectiveness of wastewater treatment and disinfection technologies. In Greece due to the existing EU legislation concerning effluent discharge limitations, secondary biological treatment is the minimum treatment employed, usually with full or partial nitrogen removal in about 80% of the cases. Therefore, although there are no wastewater reuse quality criteria currently in effect in Greece, restricted wastewater reclamation is an already feasible possibility. Additionally the quality needed for unrestricted reuse can be achieved at a moderate cost, through upgrading of existing plants.

In view of the current situation in Greece the Sanitary Engineering Laboratory (SEL) of NTUA, proposed a set of wastewater reuse recommendations in order to enhance wastewater reclamation and to form a basis for further consultation, involving all interested parties (Andreadakis *et al.*, 2001). In order to evaluate the ability of secondary and tertiary treatment processes to produce effluents that meet the proposed wastewater reclamation criteria and to develop treatment specifications for wastewater reuse in Greece, SEL conducted series of lab scale experiments using non disinfected effluent samples from various wastewater treatment plants. The experiments were designed to study the feasibility of the following treatment schemes to produce treated wastewater suitable for reuse:

- disinfection of secondary effluent with UV radiation and chlorination
- tertiary treatment and disinfection of wastewater with UV radiation and chlorination.

The efficiency of each method to disinfect secondary and tertiary effluent was evaluated by determining the percent reduction of both total and fecal coliforms. The experimental data were analyzed using a stochastic statistical model that employs Monte Carlo simulation. The main scope of the stochastic approach was the regeneration of a greater set of data, based on the defined by the experimental information mathematical distribution of each parameter involved and the determination of relative probability distributions. The stochastic approach applied fulfils the statistical aspect of most guidelines that have been developed for wastewater reuse, enabling the estimation of the removal efficiency of each treatment scheme at a certain level of certainty.

This paper presents the results of the evaluation of the alternative wastewater treatment schemes and it summarizes the revised proposal on wastewater reused guidelines and treatment specifications.

EXPERIMENTAL MATERIAL AND METHODS

Non disinfected secondary effluent samples from fifteen of the largest WWTPs in Greece were subjected to: a) disinfection with UV radiation or chlorination and b) tertiary treatment and disinfection with UV radiation or chlorination. Tertiary treatment consisted of addition of coagulants, rapid mixing and filtration through a cylindrical sand filter with an inside diameter of 10 cm and a total bed depth of 70 cm. Rapid mixing, performed in a jar test apparatus, took place for 2 minutes at 200 rpm. The coagulants employed in the on line filtration experiments were alum ($Al_2(SO_4)_3 \cdot 18\ H_20$) and a low charge density, medium molecular weight, cationic polymer at doses that ranged from 0 - 90 mg l^{-1} and 0-0.75 mg l^{-1}, respectively.

A collimated UV source, consisting of one low pressure mercury lamp, was employed to derive dose response curves for a variety of secondary and tertiary effluents. The intensity of UV radiation was measured using an International Light IL 1700 radiometer with an SED 240 detector. The average UV intensity was calculated using Beer's Law taking into account the reduction of UV light through the depth of the sample. UV dose was calculated as the product of the UV intensity and the exposure time.

Chlorination of secondary or tertiary treated effluent was carried out in a 1 - L batch reactor, where chlorine was added in the form of sodium hypochlorite. In order to test different Cxt products samples were collected after 5, 10, 20, 30, 60 and 90 min contact time. Immediately after sampling and before microbiological analyses, residual chlorine was inactivated by sodium bisulphite addition.

For each secondary or tertiary treated effluent sample, coliform inactivation was determined as a function of combined chlorine dose (mg l^{-1} Cl_2 x min) or UV dose (mW sec cm^{-2}). Samples were analysed for a variety of water quality characteristics that included total suspended solids (TSS), turbidity, ultraviolet transmittance of filtered and unfiltered samples, pH and total and fecal coliforms. All methods were according to the Standards Methods (APHA, 1994).

RESULTS AND DISCUSSION

Secondary and tertiary effluent characteristics

In order to obtain an accurate representation of the WWTPs in Greece, secondary effluent samples from fifteen of the largest treatment plants were taken. The WWTPs included in the survey were selected in order to cover the greater part of Greece and their total capacity was approximately 60% of the treatment capacity of all the biological WWTPs in Greece. According to the results of the survey most of the WWTPs appeared to provide satisfactory secondary treatment complying with the EC Directive 91/271 for wastewater disposal. Secondary effluent BOD_5 and TSS concentrations were in the range from 5-36 mg l^{-1} and 2-57 mg l^{-1}, respectively with approximately 90% of the samples having a BOD_5 and a TSS of less than 25 mg l^{-1} and 23 mg l^{-1}, respectively.

Water quality characteristics of the tertiary treated effluent for the various doses of coagulants and polymer employed, are shown in Table 1. Average turbidity removal ranged from 55 - 75 %. For all alum doses greater or equal to 10 mg l^{-1}, average tertiary effluent turbidity was below 2 NTU.

UV disinfection performance

Ultraviolet light disinfection of secondary and tertiary effluent was evaluated for a range of UV doses from 10-150 mW sec cm^{-2}. The first step in order to estimate treatment performance was to determine fecal and total coliform removal achieved by UV radiation. UV inactivation of bacteria in the ideal case of plug flow conditions and uniform UV exposure, can be described by the following expression (Andreadakis *et al.*, 1999):

$$N_t = N_0\, exp(-kIt) + N_p \qquad (1)$$

where: N_t = bacterial density after exposure to UV (FC/100 ml), N_0 = initial bacterial density (FC/100 ml), k = inactivation rate constant (cm^2 mW^{-1} sec^{-1}), I = the intensity of UV radiation ($mW\ cm^{-2}$), t = exposure time (sec), N_p = bacterial density associated with particulate matter (FC/100 ml) = c f(TSS), TSS = suspended solids concentration, mg l^{-1}.

According to previous studies (Scheible, 1987), the experimental disinfection results obtained using the UV collimated beam unit appear to follow the general trend described by the above equation. To estimate process performance, probability distributions for each of the parameters included in the above equation were identified based on the experimental results. The identified probability distributions were then used in a Monte Carlo simulation to estimate the distribution of fecal and total coliform density and associated variability, in the disinfected effluent. According to this stochastic approach coliform density in the disinfected effluent was calculated by the following equation:

$$N = f(N_0)^{-f(k)D} + f(c)f(TSS) \qquad (2)$$

where the above functions correspond to the propability distributions of the various parameters included in the equation describing bacteria inactivation by UV radiation.

The total and fecal coliform density in the disinfected secondary effluent were determined for a variety of UV doses and suspended solids concentration. The cumulative distribution of fecal coliform density in UV disinfected secondary effluent is presented in Figure 1 for UV doses in the 10 - 120 mW sec cm^{-2} range and effluent suspended solids concentration equal to 35 mg l^{-1}. Table 2 illustrates the required UV doses to comply with WHO guidelines and California regulations (Andreadakis *et al.*, 2001). According to the

Table 1. Physicochemical characteristics of tertiary effluents from lab scale unit

Tertiary effluent from lab scale on line filtration unit								
	Alum=0 mg l^{-1} polymer=0 mg l^{-1}		Alum=10 mg l^{-1} polymer=0.75 mg l^{-1}		Alum=50 mg l^{-1} polymer=0.75 mg l^{-1}		Alum=90 mg l^{-1} polymer=0.75 mg l^{-1}	
	T_{UV} * %	Turb. NTU	T_{UV} * %	Turb. NTU	T_{UV} * %	Turb. NTU	T_{UV} * %	Turb. NTU
Average	83.2	2.3	81.7	2.0	82	1.2	85.6	1.1
Median	86.7	2	78.5	1.6	83	1.1	87	1
Min	58	1.5	60.7	1	62.7	0.7	67.7	0.8
Max	95.1	5.9	95.2	6.0	96.3	2	97	1.7
90th perc.	92	3.4	92.9	2.4	93.8	1.7	95.2	1.5

* Transmittance at 253.7 nm

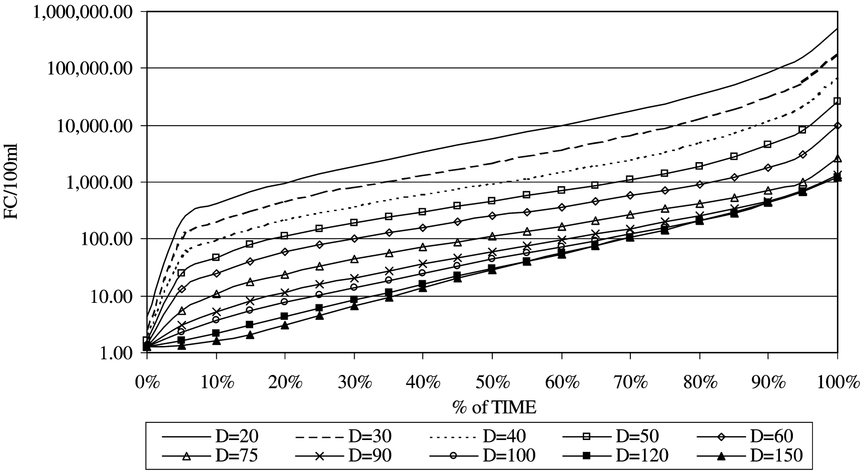

Figure 1. Cumulative distribution of fecal coliform density in UV disinfected secondary effluent for TSS = 35 mg l^{-1} (UV doses in mW sec cm^{-2}).

results of the Monte Carlo simulation compliance with WHO microbiological guidelines requires a UV dose in the 30-75 mW sec cm^{-2} range. On the other hand California regulations for restricted reuse cannot be met at the range of UV doses studied, using secondary effluent.

The total and fecal coliform density in the disinfected tertiary effluent were determined for the various alum and polymer doses employed. The cumulative distribution of fecal coliform density in UV disinfected tertiary effluent is presented in Figure 2 for UV doses in the 10 - 120 mW sec cm^{-2} range, alum and polymer doses of 10 mg l^{-1} and 0.75 mg l^{-1}, respectively. According to the results of the

Table 2. Required UV doses to comply with WHO wastewater reclamation guidelines and California regulations, using secondary and tertiary effluent.

Secondary Effluent				
	WHO guideline for unrestricted irrigation		**California Regulation**	
			Restricted Irrigation	**Unrestricted Irrigation**
	FC<1000 FC/100 ml [1]	FC<200 FC/100 ml [1]	TC<23 TC/100	TC<2.2 TC/100 ml [1] and TC<23 TC/100 ml [2]
TSS = 20 mg l^{-1}	40 mW sec cm^{-2}	60 mW sec cm^{-2}	–	–
TSS = 35 mg l^{-1}	40 mW sec cm^{-2}	60 mW sec cm^{-2}	–	–
TSS = 60 mg l^{-1}	50 mW sec cm^{-2}	75 mW sec cm^{-2}	–	–
		Tertiary Effluent		
Alum=0 mg l^{-1}	20 mW sec cm^{-2}	20 mW sec cm^{-2}	45 mW sec cm^{-2}	75 mW sec cm^{-2}
Alum=10 mg l^{-1}	10 mW sec cm^{-2}	20 mW sec cm^{-2}	45 mW sec cm^{-2}	75 mW sec cm^{-2}
Alum=90 mg l^{-1}	5 mW sec cm^{-2}	10 mW sec cm^{-2}	30 mW sec cm^{-2}	30 mW sec cm^{-2}

[1] median value, [2] 95th % of samples

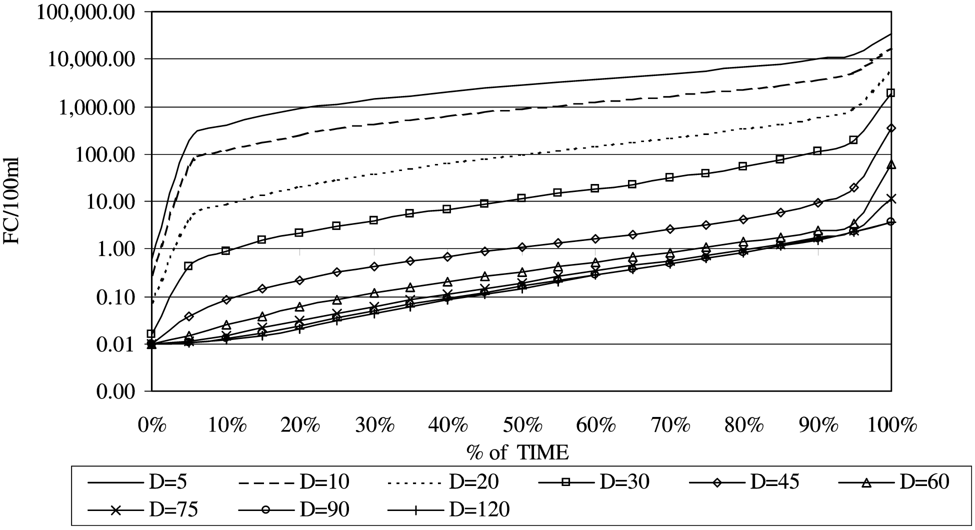

Figure 2. Cumulative distribution of FC density in UV disinfected tertiary effluent, for various UV doses in mWseccm^{-2} (TSS=5 mg l^{-1}, alum dose=10 mg l^{-1}, polymer dose=0.75 mg l^{-1}).

Monte Carlo simulation (Table 2), compliance with WHO microbiological guidelines requires a UV dose in the 5 - 30 mW sec cm^{-2} range. California regulations for restricted and unrestricted irrigation can be met at a range of UV doses 30 - 45 mW sec cm^{-2} and 30 - 75 mW sec cm^{-2}, respectively.

Chlorination Disinfection Performance

Chlorination of treated wastewater was evaluated for a range of chlorine doses from 25 - 600 mg l^{-1} combined chlorine x min. Chlorination performance was evaluated in terms of total and fecal coliform removal. Collins equation was used to describe coliform inactivation by chlorination (Darby *et al.*, 1995):

$$N_t = N_0 \left(\frac{Cxt}{b} \right)^{-n} \tag{3}$$

where: N_t = coliform density after chlorination, N_0= initial coliform density, Cxt= chlorine dose mg l^{-1} combined chlorine x min, b,n = constants.

The values of the above constants were determined according to the experimental results. To estimate chlorination performance, probability distributions for each of the parameters included in the above equation were identified. Chlorination performance was evaluated using a two step stochastic process. Initially all the probability distributions for each of the parameters included in the above equation were identified and then the identified probability distributions were used in a Monte Carlo simulation to estimate the distribution of fecal and total coliform density, in the disinfected effluent. According to this stochastic approach coliform density in the disinfected effluent was calculated by the following equation:

$$N = f(N_0) \left(\frac{Ct}{f(b)} \right)^{-f(n)} \tag{4}$$

where the above functions correspond to the propability distributions of the various parameters included in the equation describing bacteria inactivation by chlorination.

The cumulative distribution of fecal coliform density in UV disinfected secondary effluent was determined for chlorine doses in the 25 - 600 mg l^{-1} Cl_2 x min range. According to the results of the Monte Carlo simulation compliance with WHO microbiological guidelines requires a chlorine dose of less than 25 mg l^{-1} Cl_2 x min. California regulations for restricted reuse can be met at a chlorine dose of 25 mg l^{-1} Cl_2 x min where as regulations for unrestricted reuse cannot be met at the range of chlorine doses studied.

The total and fecal coliform density in the chlorinated tertiary effluent were determined for the various alum and polymer doses employed. The cumulative distribution of fecal coliform density

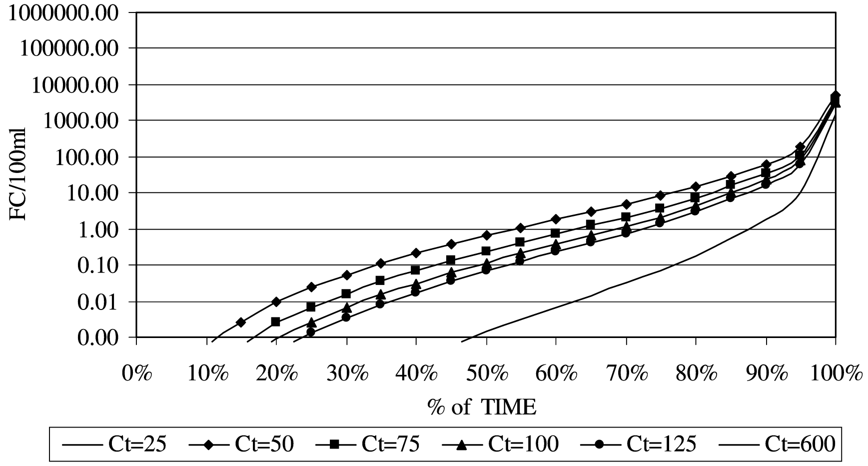

Figure 3: Cumulative distribution of FC density in chlorinated tertiary effluent, for chlorine doses in the 25 - 600 mg l^{-1} Cl_2 x min range (alum = 10 mg l^{-1}, polymer = 0.75 mg l^{-1}).

in chlorinated tertiary effluent is presented in Figure 3 for chlorine doses in the 25 - 600 mg l^{-1} Cl_2 x min range, alum and polymer doses of 10 mg l^{-1} and 0.75 mg l^{-1}, respectively. According to the results of the Monte Carlo simulation compliance with California microbiological regulations for restricted reuse requires a chlorine dose of approximately 25 mg l^{-1} Cl_2 x min. California regulations for unrestricted reuse were met only at high alum doses and superchlorination.

Recommended Wastewater Reuse Criteria and Treatment Specifications for Greece

The analysis of the previously presented experimental results as well as the evaluation of the existing situation in Greece, concerning among others reuse priorities, available treatment plants and effluent characteristics, has led to the recommendations presented in this paper, for developing future wastewater reuse guidelines appropriate to Greek conditions. The recommendations are presented in relation to the different types of reuse, with appropriate specific standards and recommended treatment systems wherever applicable. The identified various types of wastewater reuse are as follows:

- Restricted agricultural reuse (Forests and areas where access to the public is not expected, fodder, industrial crops, pastures, trees (including fruit bearing trees on the condition that during collection the fruits do not come into contact with the ground), seed crops, crops that produce products which are processed before consumption)
- Unrestricted agricultural reuse (All crops such as vegetables, vineyards, crops with products, which are consumed raw, greenhouses. Unrestricted irrigation allows for different irrigation methods including spray irrigation)
- Urban non potable reuse - Habitat restoration - Recreation (Landscape areas (cemeteries, freeway landscaping, golf courses, parks), landscape and recreational impoundments, fire fighting, soil compaction, dust control, cleaning roads, sidewalks, toilet and urinal flushing, decorative fountains)
- Industrial reuse
- Groundwater recharge for non potable reuse
- Direct and planned indirect potable reuse

The recommended guidelines for microbiological and conventional parameters for wastewater reuse are presented in Table 3. It is recommended that potable reuse of any kind should not be allowed and therefore no specifications are included for this type of reuse.

The major points regarding treatment specifications required to achieve the proposed wastewater guidelines are the following:

- Recommended methods for secondary treatment include various types of activated sludge process, biological filters and rotating biological contactors. Other systems producing efflu-

Table 3. Recommended Guidelines for microbiological and conventional parameters for agricultural wastewater reuse in Greece

	Fecal coliforms/ 100 ml	**BOD_5 (mg l^{-1})**	**SS (mg l^{-1})**	**Turbidity (NTU)**	**Recommended treatment**
Restricted Irrigation **Industrial Reuse** *Once through cooling waters*	*200 as median value*	*25 for 80% of samples*	*35 for 80% of samples*	–	• secondary biological treatment • disinfection
Unrestricted Irrigation **Urban ReuseIndustrial Reuse**[1] **Groundwater recharge** *Not used for drinking purposes*	*5 for 80% of samples*	*10 for 80% of samples*	*10 for 80% of samples*	*2 median value*	• secondary biological treatment • tertiary treatment • disinfection

[1] Recirculated cooling systems, boiler and process waters

ents of equivalent quality (BOD_5/SS = 25/35 for 80% of samples) can be accepted on the basis of adequate documentation. Nitrogen concentrations in the effluent these must be lower than 35 mg l^{-1} except in cases of long term surface storage or irrigation of nitrogen vulnerable zones, where an average concentration of 15 mg l^{-1} for nitrogen must be adopted. In cases of small agglomerations with population equivalent less than 2000, it is possible to apply treatment systems that cannot achieve the BOD_5/SS standard, under the condition that there is no direct contact of the public or the farmers with the treated wastewater. In these cases a median value of 1000 FC/100 ml for fecal coliforms can be adopted.

- Chlorination, ozonation, UV radiation or other methods for reduction of pathogens may be used to disinfect secondary effluent as long as they can ensure the required median concentration of fecal coliforms at the effluent. In all cases during chlorination the product of residual chlorine and contact time (C·t) must be greater or equal to 30 mg·min/l. When disinfection is practiced with UV, a minimum dose of 70 mW sec cm^{-2} at the end of the life of the lamps should be ensured and the design of the UV system must be based at a maximum value of transparency equal to 50%.
- Appropriate tertiary treatment schemes that ensure the limit values of Table 3 with respect to BOD_5 and turbidity should be based on the following minimum requirements: a) alum addition at doses greater than 10 mg l^{-1} and b) direct filtration at sand filters with the following characteristics: depth of sand filter (L) $\geq$ 1.40 m, effective diameter of sand (De) ~ 1 mm, uniformity coefficient of sand (u) 1.45-1.6 and hydraulic surface load $\leq 8\ m^3\ m^{-2}\ h^{-1}$ for normal operation.
- Chlorination, ozonation, UV radiation or other disinfection methods may be used to disinfect tertiary effluent as long as they can ensure the required concentration of fecal coliforms at the effluent, for 80% of the samples. In all cases during chlorination a minimum residual chlorine concentration of 2 mg l^{-1} and a minimum contact time of 60 min, must be ensured, while the necessity of dechlorination prior to wastewater reuse must be examined on a case-by-case basis. When disinfection is practiced with UV, a minimum dose of 50 mW sec cm^{-2} at the end of the life of the lamps should be ensured and the design of the UV system must be based at a maximum value of transparency equal to 70%.

CONCLUSIONS

Monte Carlo simulation was used to assess secondary and tertiary treatment processes for wastewater reclamation. This paper presents recommendations for developing guidelines and treatment specifications for wastewater reuse in Greece, considering the results of the stochastic analysis of the experimental data, the effluent characteristics of WWTPs, the available water resources, the socio-economic conditions and the guidelines applied in different countries that have a wide experience in wastewater reclamation and reuse. Following this approach the standards proposed are realistic and feasible and in the case of restricted reuse can be readily achieved by the existing wastewater treatment plants in Greece. Even in the case of unrestricted reuse the additional treatment required can be achieved at a moderate cost, through upgrading of the existing plants with tertiary treatment.

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