  Journal of Water Supply: Research and Technology—AQUA | 57.1 | 2008

Practical paper

Pilot plan protocol for optimization of UV dose required to obtain an appropriate municipal wastewater disinfection

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ABSTRACT

In this work a simple but comprehensive protocol for ultraviolet (UV) pilot plant studies was developed in order to meet the microbiological guidelines established by the Andalusian Regional Government (ARG) and Aguas de Jerez, Empresa Municipal, S.A. (AJEMSA). For this purpose, two pilot UV disinfection systems were tested at the municipal wastewater treatment plant in Jerez de la Frontera (Spain) over a period of thirteen months. Both pilot units were operated using unfiltered secondary wastewater. The results obtained from the pilot plant experiments suggest that an average UV dose of 50 mW s/cm^2 is sufficient to meet required microbiological quality standards. The quality of the unfiltered wastewater shows that turbidity and total suspended solids could serve as good indicators for UV transmittance variations. The key parameters for an optimum protocol definition are temporal wastewater characterization, the planning and executing of UV disinfection experiments, determining the hydraulic behaviour of the UV channel, calculating the UV dose applied and, finally, evaluating experimental data.

Key words | bacterial indicators, municipal wastewater, pilot plant, wastewater quality, water reuse, UV disinfection

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INTRODUCTION

Ultraviolet (UV) light has grown in popularity over the last 20 years as an important alternative to conventional chlorination for the disinfection of municipal wastewaters. The number of facilities using UV disinfection has increased considerably in the last few years and is expected to augment significantly over the next few years (Schmelling 2003).

The effectiveness of UV light in the inactivation of pathogenic microorganisms in wastewater has been well documented (Darby *et al.* 1993; Ho *et al.* 1998; Bourrouet *et al.* 2001). The germicidal effects of UV light include photochemical damage to DNA and RNA within the cells. Because DNA and RNA carry vital genetic information, damage to these molecules can effectively render cells unviable and prevent their division (USEPA 1986).

Municipal wastewater generally requires disinfection in order to meet regulatory microbial limits when the effluent is to be reused. At present, coliform bacteria are the most-commonly used indicators of the presence of faecal pathogenic organisms, and it is generally assumed that the inactivation of these bacteria correlates with the inactivation of other pathogenic organisms present in wastewater. In Spain, there are currently no specific regulations on the reuse of municipal wastewater. In order to establish effluent quality standards for reuse applications, this research followed the wastewater reuse criteria proposed by the Andalusian Regional Government (ARG) (Consejería de Salud 1996). For irrigation of golf courses and green spaces with public access, the effluents are considered to be adequately disinfected if the number of faecal coliforms does not exceed 200 CFU/100 mL in the 95th percentile. This study also takes into account the criteria set out by the municipal water company AJEMSA, which considers that

doi: 10.2166/aqua.2008.072

the effluents are adequately disinfected if in 95% of samples the numbers of total coliforms and faecal streptococci are lower than 1000 and 200 CFU/100 mL, respectively.

The effectiveness of UV disinfection devices is dependent on the quality of the wastewater that is to be treated. UV transmittance at 254 nm is the water quality parameter which has most often been used to predict UV disinfection effectiveness. Many chemical substances, turbidity, suspended solids, particle size distribution, total organic carbon and chemical oxygen demand affect UV transmittance (Braunstein *et al.* 1996; Linden & Darby 1998; Emerick *et al.* 2000).

Due to the great variability of the characteristics of municipal wastewater according to its origin and subsequent treatment, it is advisable to carry out pilot studies before implementing a full-scale UV system. The research presented here was designed to develop a simple but comprehensive protocol for pilot plant studies aimed at assessing the viability of UV light in meeting the municipal and tourist/recreational disinfection criteria specified by ARG and AJEMSA. The protocol includes temporal wastewater characterization, the planning and executing of UV disinfection experiments, determining the hydraulic behaviour of the UV channel, calculating the UV dose applied and evaluating experimental data.

MATERIALS AND METHODS

Two studies with two different UV pilot units were carried out from February to July 2000 and from July 2002 to March 2003 at the municipal wastewater treatment plant (WWTP) in Jerez de la Frontera (Spain), using unfiltered secondary effluent.

Ultraviolet pilot units

Two UV pilot units (called A and B) consisting of low-pressure high-intensity mercury UV lamps were tested.

Unit A

It was a 12.0 m^3/h horizontal-lamp open-channel UV disinfection system. The unit consisted of a 3.4 m × 21.0 cm × 75.5 cm single stainless steel channel with a single UV lamp bank. The bank contained 4 lamps, each with an arc length of 1.43 m and a production of 125 W UV-C at 254 nm. Lamps were positioned parallel to the fluid flow direction and encased in a 60 mm diameter quartz sleeve.

Unit B

The other unit was a 5.0 m^3/h horizontal-lamp open-channel UV disinfection system. It consisted of a 2.4 m × 23.2 cm × 38.1 cm single stainless steel channel with a single bank of lamps. The UV bank contained three modules in parallel, each with 2 lamps. The lamps, positioned parallel to the fluid flow direction, had an arc length of 1.47 m and produced 30 W UV-C at 254 nm. The lamps were encased in a 23 mm diameter quartz sleeve.

Disinfection experiments

In each experimental period several different flow rates were tested within the manufacturer's recommendation for the different UV units. Flow regulation was determined according to the previously measured UV transmittance of the water in order to obtain a target UV dose (between 50 and 200 mW s/cm^2).

Before each experiment the quartz sleeves were cleaned in order to ensure maximum UV intensity and to avoid biological fouling of the UV lamps. Unit A was cleaned for 15 minutes using the *in situ* air scrubbing system. The quartz sleeves of Unit B were hand cleaned with a commercial scale-removing solution.

Analytical procedures

Samples were collected twice a week for at least 6 months in each period to characterize temporal variability. The water quality was characterized by measuring UV transmittance (UVT), turbidity, total suspended solids (TSS), total coliforms (TC), faecal coliforms (FC) and faecal streptococci (FS). Electrical conductivity was used to characterize the salt concentration from pulses applied in order to obtain the residence time distribution (RTD) curves.

All parameters were analyzed according to *Standard Methods* (APHA/AWWA/WEF 1995). The membrane filter technique was used to determine total coliforms, faecal coliforms and faecal streptococci concentrations. At least three appropriate dilutions were employed for each sample.

Determination of UV dose

UV dose (mW s/cm^2) is defined as the product of average UV light intensity (mW/cm^2) and average exposure time(s).

The most common mathematical method used to determine average UV intensity in a UV disinfection system is the point source summation (PSS) method (USEPA 1986; Qualls *et al.* 1989; Braunstein *et al.* 1996; Ho *et al.* 1998). In this study, the average UV intensity of each unit was calculated by the PSS method using a Microsoft Excel® application developed by the authors and according to the UV transmittance of the water and the lamp configuration. UV intensity was corrected for lamp ageing and soiling and loss through the quartz sleeve based on data provided by the manufacturer.

The exposure time was calculated from the influent flow rate and channel volume, once it had been experimentally demonstrated (by calculating the RTD) that the channel had near perfect plug-flow conditions.

Hydraulic behaviour of the UV channel

Pilot and full-scale UV disinfection systems must be designed to ensure that plug-flow conditions exist in the contact channels (USEPA 1986, 1996). In order to obtain the RTD curves, a set of instantaneous impulses (50 mL saturated NaCl solution injections) were passed into the influent flow whilst a conductivity probe, positioned immediately downstream in the effluent, recorded the response to the pulse over time (with time intervals of one second).

Five flows, ranging from 8 to 50 m^3/h, were used for RTD studies. From each experimental curve the mean residence time (θ), variance (σ), coefficient of dispersion (D) and dimensionless dispersion number (d) were calculated (USEPA 1996; Levenspiel 1999).

When theoretical and mean residence time are similar and the dispersion number is low ($d < 0.05$), it is reasonable to assume that the channel behaves like a plug-flow reactor.

The hydraulic study was only carried out for Unit B, but the similarities between the design and configuration of Unit B and Unit A suggest that Unit A also behaves like a near perfect plug-flow reactor. Table 1 shows the mean experimental residence time (from RTD curves) versus theoretical residence time. The results clearly show a similar trend between experimental and theoretical data. The dispersion number was very low (<0.03) for the entire flow range studied (Table 1). This observation confirms that the channel had a near perfect plug-flow behaviour.

Disinfection data evaluation and modelization

As a first approximation, inactivation kinetics can be modelled as a first-order photobiochemical reaction (Water Environment Federation 1996):

$$-\frac{dN}{dt} = k \cdot I_{avg} \cdot N$$

where N, viable microorganisms concentration (UFC/100 mL); k, first order kinetics rate (cm^2/mW s); t, time of UV exposure (s); I_{avg}, average UV radiation intensity (mW/cm^2).

Table 1 | Characterization of hydraulic behaviour of the UV channel (Unit B)

	Channel flow (m^3/h)				
Parameter	**8.40**	**22.20**	**29.70**	**44.10**	**51.80**
Theoretical residence time (s)	35.73	13.52	10.10	6.81	5.82
Experimental residence time (s)	33.02	12.55	9.71	7.34	6.93
Number of dispersion	0.03	0.02	0.03	0.03	0.02
Confidence interval (s)	3.03	0.95	0.65	0.89	0.26

Table 2 | Wastewater quality characteristics during both studied periods

	Period 1		Period 2	
Parameter	**Range**	**Average**	**Range**	**Average**
UV transmittance (%)	34 to 60	48	36 to 61	48
Turbidity (NTU)	2.8 to 12.2	6.8	2.3 to 13.3	8.3
Total suspended solid (mg/L)	6 to22	13	4 to 23	16
Total coliforms (CFU/100 mL)	2.1×10^5 to 1.1×10^7	2.9×10^6	1.3×10^6 to 16×10^7	5.0×10^6
Faecal coliforms (CFU/100 mL)	9.7×10^3 to 1.6×10^6	2.0×10^5	1.7×10^5 to 1.1×10^6	4.9×10^5
Faecal streptococci (CFU/100 mL)	3.0×10^3 to 1.3×10^6	1.1×10^5	8.5×10^4 to 1.0×10^6	3.1×10^5

By mathematical integration of the previous equation, a typical exponential model is obtained:

$$\frac{N}{N_0} = e^{-k \cdot I \cdot t}$$

where N_0, concentration of viable microorganisms before exposure (UFC/100 mL); $I.t$, UV dose (mW s/cm^2).

Although, more complex models are being developed (Emerick *et al.* 2000), the exponential model is valid for

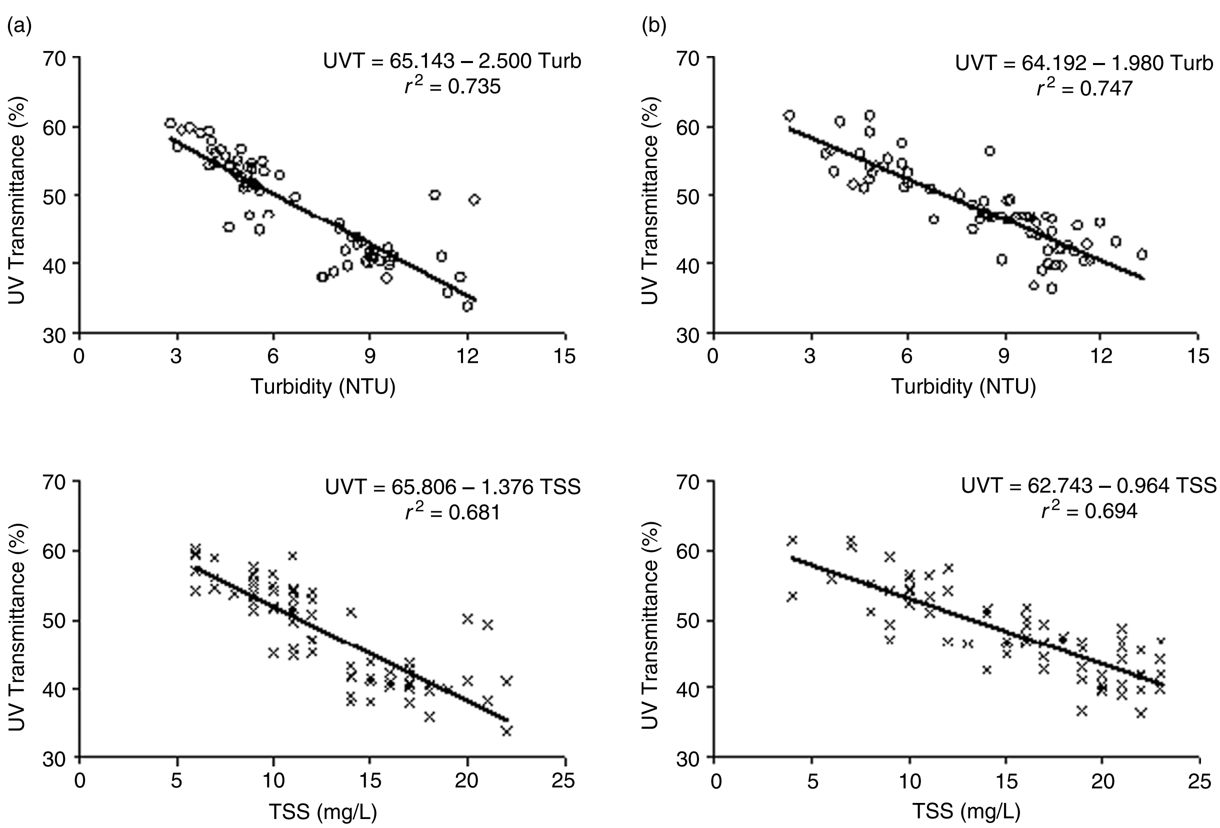

Figure 1 | UV transmittance versus turbidity and total suspended solids: (a) Period 1 and (b) Period 2.

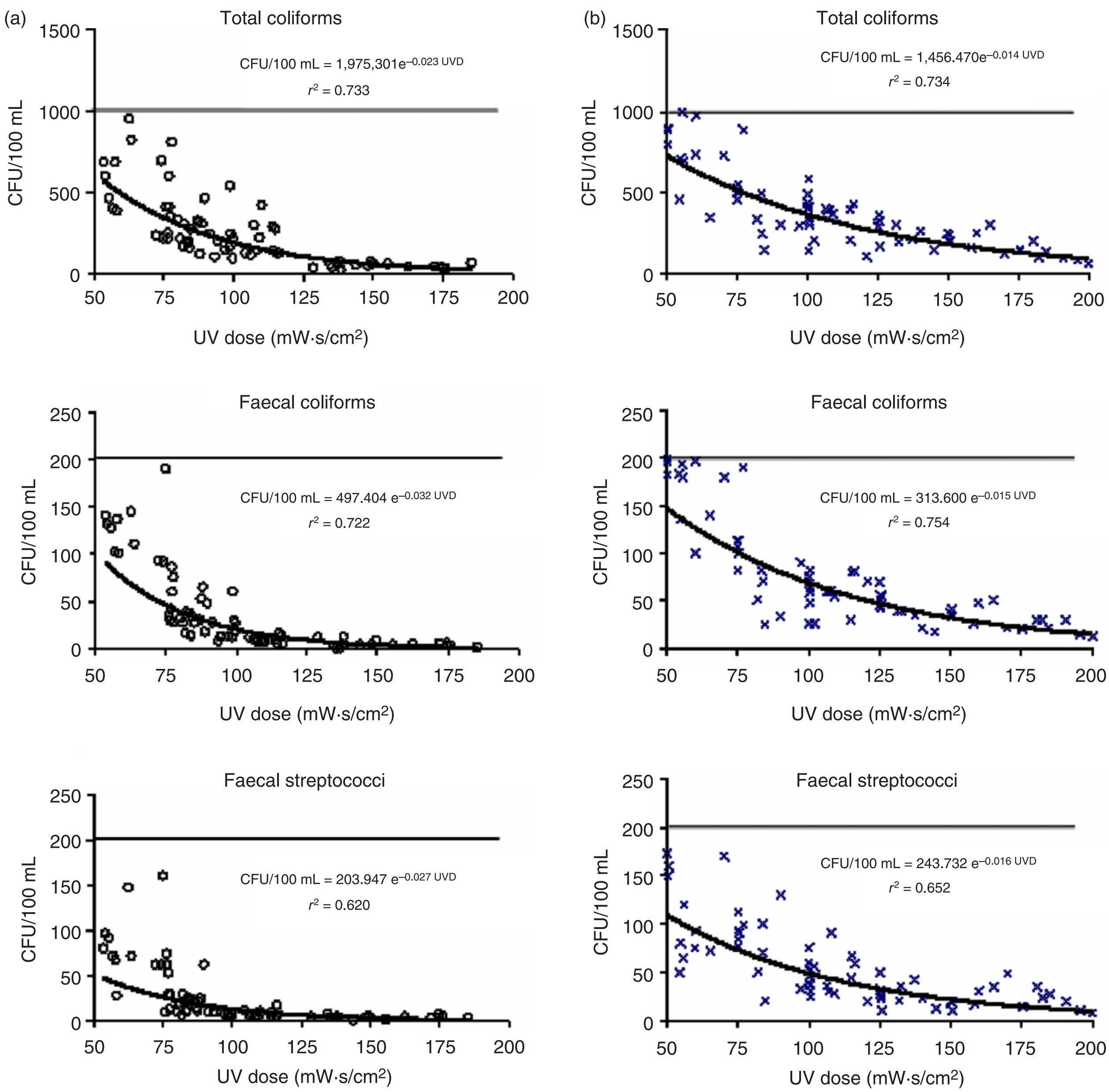

Figure 2 | Effluent total coliforms, faecal coliforms and faecal streptococci concentration as a function of UV dose: (a) Period 1 and (b) Period 2.

estimating the tendency of microorganisms abatement versus UV dose applied.

RESULTS AND DISCUSSION

Influent characteristics

The unfiltered secondary effluent characteristics for each period are summarized in Table 2. The results from both periods indicated that the worst unfiltered secondary effluent quality is mainly observed during the summer, including June and October. In any case, the unfiltered secondary effluent was low-quality for all parameters monitored.

In both periods, evaluation of the relationship between transmittance and the other water quality parameters revealed that turbidity and TSS gave the strongest correlation (Figure 1). A linear regression of UV transmittance showed a decrease coincident with increasing turbidity and TSS, so we can conclude that the behaviour of the transmittance is strongly affected by variations in turbidity and TSS. This means that the variability of turbidity and TSS could account for the variability in UV transmittance in case this WWTP lacks on-line photometers to continuously monitor UV transmittance.

These results are in good agreement with similar findings in the literature (Ho *et al.* 1998; Sakamoto *et al.* 2001), which report that both turbidity and TSS could serve as good indicators of UV transmittance variations.

Disinfection performance

UV disinfection effectiveness was evaluated for a range of UV doses from 50 to 200 mW s/cm^2 during two periods. The results are discussed in terms of their compliance with the guidelines set out by the ARG and AJEMSA. Microbial effluent concentrations as a function of UV doses are presented in Figure 2. A horizontal line representing the standard of 1000 CFU/100 mL for total coliform and 200 CFU/100 mL for faecal coliforms and faecal streptococci is shown for illustration purposes.

In general, the analyzed microorganisms decreased with increasing UV doses according to an exponential model. The ARG guidelines were successfully met for all effluents in both periods. For FC, the criterion of a maximum of 200 CFU/100 mL was consistently met in samples exposed to a UV dose of 50 mW s/cm^2 or greater. For TC and FS, the AJEMSA criterion of a maximum of 1000 and 200 CFU/100 mL in the 95th percentile of effluent samples, respectively, was met with UV doses of 50 mW s/cm^2 or greater in both periods. These effectiveness values agree with those already published, Savoye *et al.* (2001), Ho *et al.* (1998) and Darby *et al.* (1993).

In short, the results show that with the *low-quality wastewater* from this study, it is possible to meet the less stringent criteria of ARG, AJEMSA but that in order to comply with stricter regulations it would be necessary to implement a further treatment stage (i.e. coagulation–flocculation–filtration) before UV disinfection.

For a more quantitative and illustrative evaluation, the effectiveness of UV disinfection was determined through logarithmic reduction for each microorganism during the two periods (Table 3). The results show that at a high UV dose (greater than 100 mW s/cm^2) TC are significantly more susceptible (average 4.1 log-units reduction) to UV inactivation than the other two microorganisms. FC with an average of 3.8 log-units reduction were only slightly more sensitive to UV inactivation than FS, with an average of 3.7 log-units reduction. These results agree with previous studies which indicate that FS are generally more resistant to UV disinfection than the other two bacteria (Bourrouet *et al.* 2001).

Table 3 | Summary of applied UV doses and log-units reduction during both periods

		Period 1, Unit A	Period 2, Unit B
UV dose	Range	54–185	50–200
	Average	103	116
Total coliforms log-units	Range	3.1–5.1	3.5–5.1
	Average	4.0	4.2
Faecal coliforms log-units	Range	2.3–4.9	3.2–4.7
	Average	3.7	3.9
Faecal streptococci log-units	Range	2.0–5.0	3.1–4.8
	Average	3.6	3.8

CONCLUSIONS

The following conclusions were obtained from two pilot investigations on the use of UV light for the disinfection of a municipal effluent:

- Wastewater quality parameters such as turbidity and TSS solids were found to have a relatively good correlation with UV transmittance and may be used as good indicators of variations in UV transmittance.
- Hydraulic experiments demonstrated that the pilot UV disinfection systems behaved almost like a perfect plug-flow reactor.
- Two pilot plants operating with the same protocol but with lamps of different output arranged in different ways provided similar results for wastewater disinfection.
- In both periods, it was demonstrated that UV light with a UV dose of 50 mW s/cm^2 or greater can be used to disinfect the unfiltered secondary effluent to meet the 1000 CFU/100 mL TC, 200 CFU/100 mL FC and 200 CFU/100 mL FS standards in the 95th percentile of effluent samples.
- The exponential model predicts adequately the micro-organism inactivation versus the UV dose. Total coliforms appear to be more susceptible (4.1 log-units reduction) to UV inactivation than faecal coliforms (3.8 log-units reduction) and faecal streptococci (3.7 log-units reduction).

ACKNOWLEDGEMENTS

The authors are grateful to AJEMSA, Trojan Technologies Spain, Wedeco Water Technology, for supporting this work.

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First received 5 September 2006; accepted in revised form 25 June 2007