Impact of UV radiation dose, suspended solids and organic matter on its efficiency to remove pathogens from greywater

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Abstract
Onsite greywater (GW) reuse is receiving growing interest as a measure to alleviate water scarcity. In spite its advantages, GW even after treatment often contains pathogens that have to be inactivated. An increasingly popular disinfection method for onsite installations is the use of low-pressure UV irradiation. Yet, inadequate water quality might reduce UV efficiency, specifically the presence of elevated particulate matter and organic substance. In this study, we tested low-pressure UV disinfection of GW under a range of TSS and BOD_5 concentrations in a controlled collimated beam laboratory setup, and in a flow through UV reactor commonly used in full scale onsite GW treatment systems. In the laboratory, treated GW were used as is or subjected to increase concentration of either TSS or dissolved organic matter (measured as BOD_5) or a combination of both. These samples were exposed to three UV doses applied by a collimated beam setup, and the inactivation efficiency of fecal coliforms (FC) was recorded. The results indicate that TSS reduced the UV disinfection efficiency more than the presence of BOD_5. Further, the reduction in UV efficiency was more pronounced at the lower UV doses, in which FC removal was reduced as TSS concentration was higher than 50 mg/L. However, as UV dose increased, the negative influence of TSS reduced. Based on the laboratory results a multiple linear regression model was developed, that correlated between the removal of FC with applied UV dose, TSS and BOD_5 concentrations, and FC concentrations in the GW (before irradiation). The model was validated against results from the flow-through reactor. Finally, the model was used to suggest a conversion factor between the laboratory and flow-through reactor experiments.

Keywords
Greywater; disinfection; UV; suspended solids; BOD; flow through UV reactor

INTRODUCTION

Onsite reuse of greywater (GW), which consists of domestic wastewater excluding the stream generated by the toilet, has been recognized as an important facet in addressing water supply shortage. For example, Beck *et al.* (2013) estimated that greywater consumption in a US household average 114 L/person/day. Friedler (2004) claimed that using GW may reduce domestic water use by up to 50%, while using graywater for household toilet flushing alone can reduce urban water consumption by 10–20%, which consequently can result in various environmental and economic benefits. Moreover, using GW in dry, water-stressed areas might be the only way to sustain public and private gardens year-round (Gross *et al.*, 2015) as well as onsite agriculture. Local, decentralized systems used for treatment and reuse of GW from individual and clusters of homes, are an attractive option as they minimize the need for additional distribution infrastructure (Winward *et al.*, 2008). Greywater reuse standards often require to lower indicator bacteria concentrations (e.g. fecal coliforms) to levels ranging between 3-1000 cfu/100 mL which in practice means that disinfection is needed (WHO, 2006; Franke *et al.*, 2013).

The most common ways for onsite GW disinfection is chlorination and low-pressure UV irradiation which is the focus of this study (Fenner and Komvuschara, 2005; Benami *et al.*, 2015; Ekeren *et al.*, 2016). UV disinfection inactivates microorganisms by a photochemical reaction that damages their nucleic acids (in the DNA or RNA), thereby preventing them from replicating (USEPA, 2006). Disinfection by low-pressure (254 nm) UV irradiation is popular since: a) it does not require addition of chemicals; b) it was found effective on a wide range of pathogens including some chlorine-resistant viruses and protozoans; c) it is a feasible solution in terms of capital and operating costs; d) operation and maintenance of the apparatus are simple, and hence it is safe for operators in general and in comparison to chlorination (Fenner and Komvuschara, 2005). However, varying disinfection efficiencies were reported in full-scale installations (Benami, *et al*., 2015). Some studies demonstrated that insufficient water quality might reduce UV efficiency. Specifically, particulate matter and organic substances present in the water may negatively influence the performance of UV disinfection by reducing the exposure of the target organism to the UV irradiation (Crittenden *et al*., 2005; Mamane, 2008; Christensen and Linden, 2003; Cantwell and Hofmann, 2011). In general, particles affect UV disinfection by shielding microorganisms from the irradiation, and by absorbing or scattering the light, which reduce the UV dose absorbed by the bacteria. The presence of particulate matter and organics in GW was observed in many studies, and found to have a deleterious impact on UV disinfection efficiency. For example: Fenner and Komvuschara (2005) who studied disinfection of artificial GW estimated that 60 mg/L suspended solids of and turbidity of 125 NTU are practical limits beyond which greywater cannot be disinfected to achieve four log reduction of fecal coliforms (FC), irrespective of UV reactor dimensions. Beck *et al.* (2013) recommended filtration to remove particles to obtain turbidity of 2 NTU for allowing a more efficient UV disinfection. Other studies focused on the sizes at which particles protects microorganisms from UV light (Winward *et al*., 2008), or the particle associated with bacteria in treated GW causing bacterial shielding from UV disinfection (Madge and Jensen, 2006). In contrast, to the best of our knowledge no study focused on the combined effect of particulate matter and organic matter, measured as total suspended solids (TSS) and 5-d biochemical oxygen demand (BOD_5), on low-pressure UV disinfection efficiency. More so, as UV disinfection efficiency is studied in the laboratory by collimated beam or by flow through units in full-sale onsite installations, there is a need to compare these two in general and GW in particular.

The objectives of this study were to test the efficiency of low-pressure UV disinfection of GW under a range of UV doses and TSS and dissolved BOD_5 concentrations in a controlled laboratory setup and in a flow-through UV reactor. In addition, the study aimed to develop a statistical model for the prediction of the impact of TSS and BOD_5 on disinfection efficiency in a collimated beam that is mostly used in the laboratory, and for flow-through reactors which are mostly used in the field, and to correlate between the two.

MATERIALS AND METHODS

The current research was executed in two phases. Initially modified GW of varying quality was irradiated using collimated beam after which results were used for developing a multiple linear regression model. In the second phase GW treated in full-scale onsite treatment systems (described below) were irradiated using commercial low pressure flow-through UV reactor. The applicability and verification of the model were tested and compared with results of the second phase.

Collimated beam experiment

GW samples. Treated domestic GW (1 L) from six single-family full-scale recirculating vertical flow constructed wetland (RVFCW) systems located in the central Negev desert, Israel were collected at least 4 times and immediately brought to the laboratory where subsamples were analyzed as described below. The RVFCW system consists of two 500 L plastic containers (1.0 m×1.0 m×0.5 m) placed one on top of the other. The upper container holds a planted three-layered bed, while the lower one functions as a reservoir. The bed consists of a 5 cm upper layer of woodchips followed by a 35 cm middle layer of tuff gravel and a 10 cm lower layer of limestone pebbles. GW is pumped from a 200 L primary equalization-sedimentation tank and applied to the top of the bed, from there it drips through the bed and into the reservoir through the perforated bottom of the upper container (Figure 1). GW is recirculated from the reservoir to the top of the upper bed at a rate of about 300 L/hr for 8 hours following filtration through 130 μm filter. Further details about the system can be found in Gross *et al.* (2007) and Alfiya *et al.* (2013)

Treated GW samples were used as is or subjected to increase concentration of either TSS (final TSS concentration ranging from 1–130 mg/L) or organic matter measured as BOD_5 (final BOD_5 concentration ranging from 3-100 mg/L) or a combination of both suspended particles and organic matter concentrations at different ratios. Overall, 432 combinations were tested.

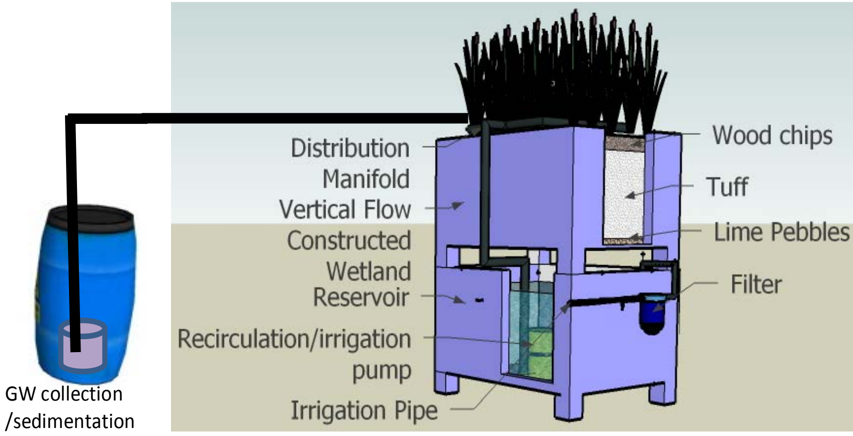

Figure 1. Schematic of the onsite Recirculating Vertical Flow Constructed Wetlands (RVFCW) greywater treatment system (After Alfiya *et al.*, 2013).

TSS was increased by adding different amounts of powdered dried suspended matter to the treated GW. The suspended matter was obtained from centrifuging (6000 rpm for 5 min.) raw GW and drying the pellet at 60 °C for to 48 hrs. The increase in organic matter was accomplished by adding different quantities of filtered (0.2 μm) raw GW, with known concentration of BOD_5, to the treated-GW. In cases where both concentrations of suspended solids and organic matter were increased known concentrations of BOD_5 (dissolved) and amounts of TSS were added to the treated GW. The required components were mixed in a beaker with a stirrer for 15 min to allow a uniform mixture. Additionally, FC were introduced by adding <0.5 mL per L GW sample of kitchen effluent to confirm FC concentration between 10^4 and 10^5 CFU/ 100 mL.

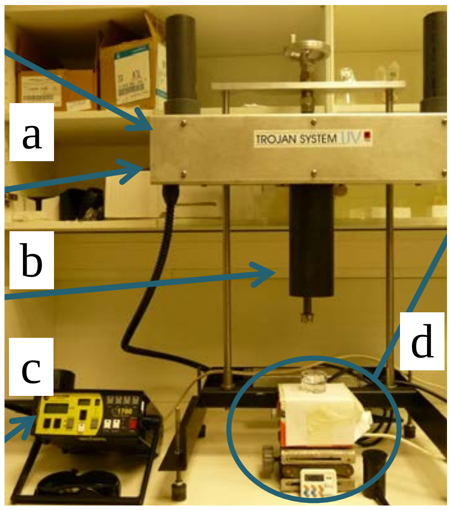

Figure 2. Trojan UV collimated beam system excluding the shutter. a) UV lamp, b) collimated beam, c) Radiometer, d) water sample with magnetic bar on the stirrer.

Collimated beam setup. The efficiency of UV disinfection was tested with a quasi-parallel beam bench-scale UV apparatus (Trojan Technologies Inc., Ontario, Canada). The system consisted of a solid steel base, which supports a horizontal aluminum housing holding an 11 W low-pressure mercury vapor germicidal UV lamp emitting monochromatic UV radiation at 254 nm. The UV lamp was centered in the housing directly over a non-reflective inner 25 cm long collimator beam of 40 mm diameter; the collimation tube directs UV light to provide incident radiation normal to the surface of the test suspension. The exposure time was controlled manually by a shutter. Peripherals consisted of a magnetic stirrer (placed on a laboratory jiffy jack) to hold the sample vessel, and an ILT 1700 radiometer (International Light, Peabody, Massachusetts, USA) with a sensitive detector at 254 nm (IL photonic SED240). The intensity of the incident UV light was measured by placing the radiometer detector at the same height as the surface of the water sample. The sample, to be exposed, was placed under the collimating tube in a 50 x 35 mm crystallization dish and mixed with a 1-cm stir-ring bar at a rate of approximately 110 rpm, providing uniformity of the UV dose to the entire sample (Figure 2).

Sample aliquots of 25 mL were exposed to three UV irradiation doses of 7.5, 15 and 30 mJ/cm^2, applied by controlling the exposure time of the well-stirred sample to the UV light. The exposure times for each of the UV doses depended on several factors such as: incident intensity, reflection, petri factor, divergence, and water factors. The latter, specific to each sample, was determined by the spectral UV absorbance. The methods for the factors determination were as described in Mamane and Linden (2004). The divergence and reflection factors were constant in all experiments and their values were 0.960 and 0.975, respectively. The petri factor was calculated every week and averaged 0.88 ± 0.05. The water factor varied from values of 0.40 to 0.89 and the incident intensity measured at the water surface varied from 0.30 to 0.32 mW/cm^2. Subsamples were analyzed before and after irradiation and characterized for TSS by the gravimetric method, BOD by the standard 300 mL bottles, and FC by membrane-filtration methods and mTEC agar (Acumedia). All methods followed standard procedures (APHA, 2005).

Multiple linear regression (MLR) model. The laboratory results were used for developing the MLR model. The model correlated between the observed log removal of FC in the laboratory examinations with applied UV dose and TSS, BOD_5 and log FC concentrations in the GW before irradiation. The model was then validated against the results from the onsite greywater samples from the flow-through reactor experiment (see below). Finally, the model was used to suggest a conversion factor between the laboratory collimated beam and flow-through reactor experiments.

Flow-through reactor

Treated GW samples (10 L each) from 11 operating onsite systems were collected and brought to the laboratory for further analysis. The systems were constructed and maintained by the residents.
Low-pressure continuous flow UV reactor (UV6A, WaterTec Inc.) was used for irradiating the samples. The reactor (43 mL in volume) contained a low-pressure mercury lamp (4 W, 1.6 cm diameter and 13.5 cm long) with startup time from turn-on to maximum intensity of 100 s (Reactor manual). Further details about the UV reactor can be found in Friedler and Gilboa (2010).

The treated water samples were conveyed through the reactor with a peristaltic pump (Masterlex, Cole-Parmer Instrument Co.) at a flow rate of 24 L/h. The actual UV intensity and dose in the reactor as measured by the iodide–iodate chemical actinometery was 44 mJ/cm^2 (calculated lamp intensity 2.8 mW/cm^2, mean residence time 14 s; Friedler and Gilboa, 2010). Sub-samples were analyzed for FC, BOD_5 and TSS before and after disinfection, in three replicates as described above.

RESULTS AND DISCUSSION

Collimated beam

The efficiency of UV disinfection to reduce FC under a range of TSS and dissolved organic matter concentrations as tested in the collimated beam experiment using three doses 7.5, 15 and 30 mJ/cm^2 is plotted in Figure 3. As expected, disinfection efficiency increased with increasing UV dose and was negatively affected by the presence of TSS and BOD.

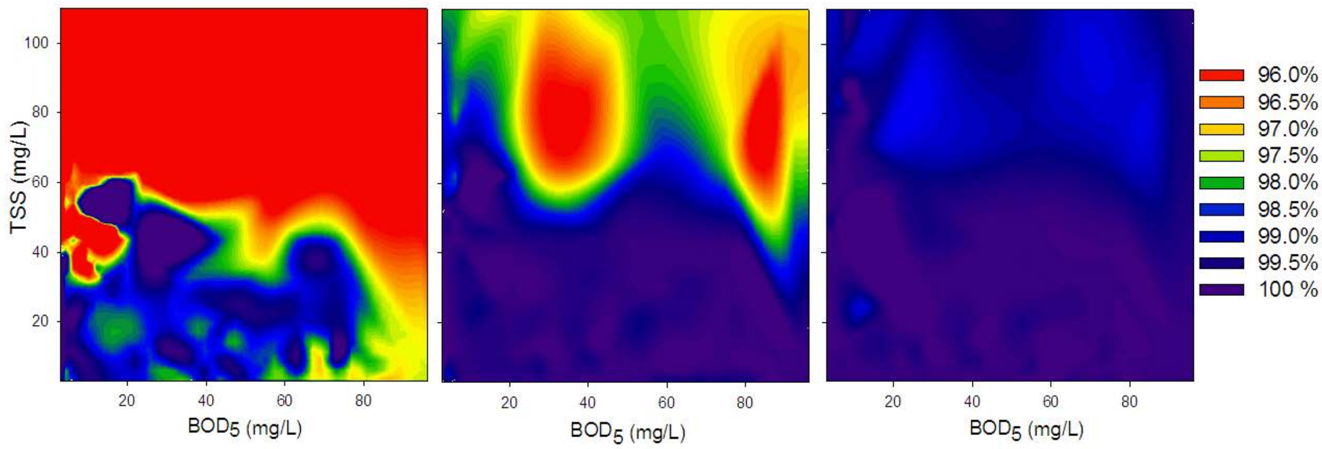

Figure 3. Effects of TSS and dissolved BOD_5 on the removal of fecal coliforms from greywater at 3 UV doses: (a) 7.5 mJ/cm^2 , (b) 15 mJ/cm^2 and (c) 30 mJ/cm^2. Different colors represent percent removal between 96 – 100 % with line interval of 0.5%.

In order to distinguish between the effect of each parameter (TSS or dissolved BOD) on FC reduction, results were divided to two scenarios: changing concentration of TSS while keeping BOD concentration below 20 mg/L (20% of the maximum BOD concentration examined), and changing concentration of BOD while keeping TSS concentration below 30 mg/L (23% of the maximum TSS concentration examined). TSS reduced the UV disinfection efficiency more than BOD_5 (Figure 4). Reduction in UV efficiency was more pronounced at the lower examined UV doses (7.5 and 15 mJ/cm^2), in which FC removal was reduced when TSS concentrations increased beyond 50 mg/L. These results are in line with previous findings by Fenner and Komvuschara (2005) who stated that a 4 log reduction of FC may be achieved by low-pressure UV irradiation when suspended solids concentration is kept below 60 mg/L. In contrast, at the highest examined dose of 30 mJ/cm^2 virtually 100% inactivation of FC was achieved for the entire range of TSS and BOD_5 and increasing UV dose from 7.5 to 15 and 30 mJ/cm^2 resulted in additional 1 and 1.5 log FC removal, respectively.

BOD_5 (dissolved) scenarios exhibited a different trend than the TSS and FC removal was hardly changed when UV dose increased from 15 to 30 mJ/cm^2. At UV dose of 15 mJ/ cm^2 and higher almost 100% inactivation of FC was achieved for the entire range of BOD (while keeping TSS<30 mg/l). Meaning that dissolved organic substances do not affect UV disinfection efficiency as much as TSS. These results are in line with Scott *et al.* (2005) who suggested that adjusting UV absorption through the composition of organic matter (estimated by organic extracellular polymeric substance) did not have significant effect on UV disinfection. Furthermore, Cantwell and Hofmann (2011), who compared UV absorption of various materials, indicated that wastewater and surface water solids have higher UV absorption than organic matters (estimated by organic extracellular polymeric substances).

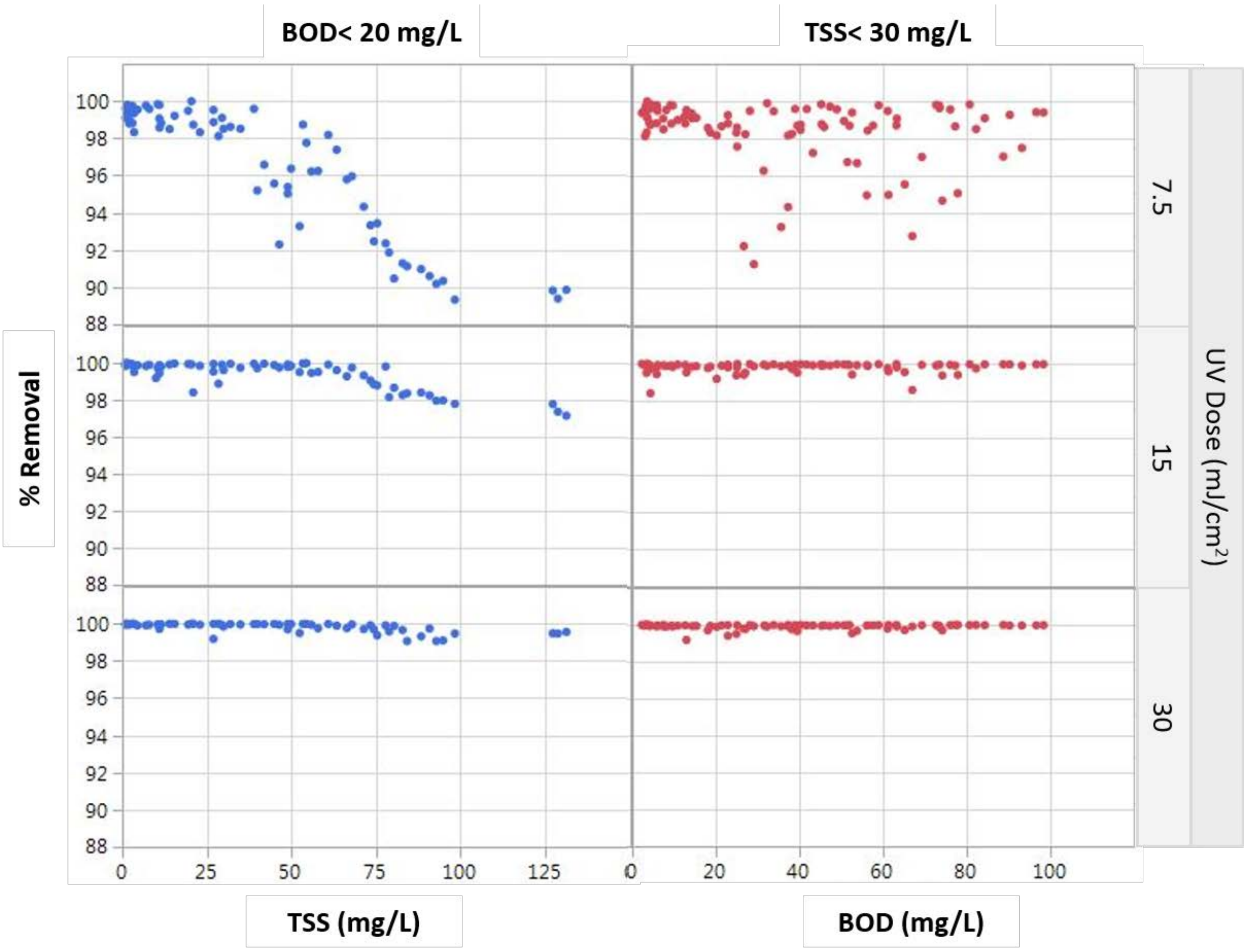

Figure 4. Effects of TSS and dissolved BOD on FC removal under 3 UV doses: 7, 15 and 30 mJ/cm^2. a) at low BOD concentration (<20 mg/L) and b) at low TSS concentration (<30 mg/L).

Multiple linear regression (MLR) model

The relationship between log FC removal and TSS, BOD, , log FC concentration of the treated GW (before application of UV) and the applied UV dose were described by an MLR model (Eq. 1).

(1) log FC removal= $\beta_1 \cdot$[BOD]+ $\beta_2 \cdot$[TSS]+ $\beta_3 \cdot$[log FC raw]+ $\beta_4 \cdot$[UV dose]

Where:

β_1, β_2, β_3 and β_4 are the coefficients estimates of the explanatory variables (Table 1). All coefficients were established based on the laboratory analysis and the model was found to be statistically significant ($p<0.0001$ and R^2= 0.6; Figure 5a). Moreover, all explanatory variables were statistically significant except of the dissolved BOD. That is to say, that the dissolved BOD has only moderate influence if at all, on the efficiency of UV disinfection (at the concentrations tested <20 mg/L to 100 mg/L).

Table 1. Calculated model variables

Explanatory Variable	Coefficient	Estimate	p-value
Dissolved BOD (mg/l)	β_1	0.001	**0.2211***
TSS(mg/l)	β_2	-0.012	<0.0001
Log FC raw (log(CFU/100ml))	β_3	0.495	<0.0001
UV dose (mJ/cm^2)	β_4	0.059	<0.0001

* not statistically significant

It should be noted that we tried to fit other combinations of these variables (including interactions between them), and could not increase the model fitting, hence the simplest model is presented. The model indicates that high initial microbial concentration and UV dose will result in higher FC removal while increase in the TSS concentration reduces FC removal. These results are line with the theory and demonstrate the negative effect of TSS on UV disinfection likely due to the shielding and shadowing effect of the particles (Mamane, 2008).

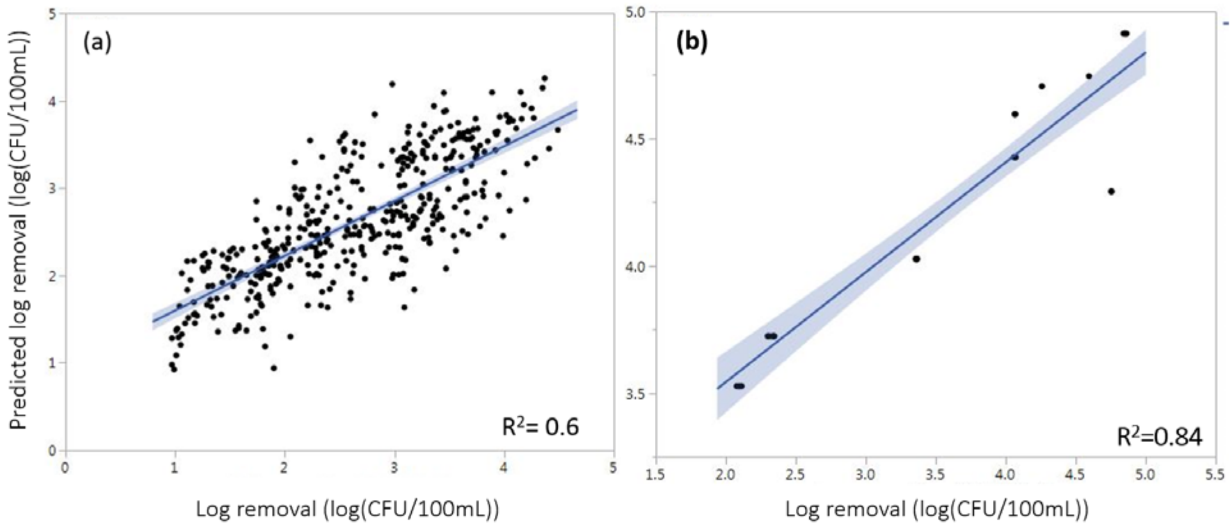

Figure 5. Predicted log FC removal vs. measured log removal. (a) collimated beam results. (b) Flow through reactor and model verification.
Note: different scales of the X and Y axes

Flow through reactor and model verification

The quality of pre-disinfected treated GW from the 11 onsite systems is given in Table 2. FC, TSS and BOD_5 and the concentrations ranged from 0-10^6 CFU/100 mL, 3.9-233 mg/L and 0-107 mg/L respectively. Fecal coliform counts after UV irradiation were as also analyzed and were compared with the model predictions.

Table 2. Quality of pre-disinfected treated GW from 11 onsite treatment systems that was used in the flow through experiment. Each site was sampled 4 times (n = 44 samples).

	Range	Average	Median
TSS (mg/l)	3.9-233	38	15
Dissolved BOD (mg/l)	0- 107	41	37
% $Transmission_{254\ nm}$	39-85	64	67
Turbidity (NTU)	1.47-512	87	18
FC (CFU/100ml)	0-10^6	10^5	10^5

Model verification was found to be statistically significant with p-value<0.0001 and R^2= 0.84 (Figure 5 b). It should be noted, that although the quality of treated GW samples from the 11 systems was quite different from those used for the collimated beam experiment, and so were the means of UV application (collimated vs. continuous flow reactor) and UV doses, the model fitted well and explained most of the variability in the measured FC removal. Interestingly, a shift between the model (based on the batch collimated beam experiments) and the flow-through results was found. The difference in FC removal efficiencies was probably due to the difference in the UV application. In the collimated beam, the sample was small, well mixed and directly irradiated, while in the flow-through UV reactor the flow regime was more complex (being partially well-mixed and partially plug-flow; Friedler and Gilboa, 2010) and thus not all the GW passing through the reactor received the same dose. For the same log removal dividing the measured UV dose in the flow-through reactor (44 mJ/cm^2 in this study) by the model-predicted UV dose (based on the batch collimated beam results), resulted in a correction factor (CF) of 7.47 (STD = 1.25). This factor transforms the value of the UV dose from the collimated beam experiment to the dose required by the UV flow through reactor, for the same FC removal.

In other words, to achieve the same log FC removal, the UV dose required from the flow through reactor is 7.47 times higher than the dose required in the collimated beam, for similar water quality (TSS, BOD and pre-disinfection FC concentrations). Similar differences between collimated beam results and flow-through reactors were reported by Cabaj et al. (1998). Using the model and the calculated CF, the required UV dose in flow-through reactors can be determined based on laboratory examination. This approach is valuable not only from an operational point of view but also for research.

CONCLUSIONS

This study indicated that UV disinfection efficiency of treated GW reduces as a result of increasing TSS concentration beyond a threshold value of 50 mg/L. However, as UV dose is increasing the influence of TSS is reduced. The batch collimated beam examination indicated that dissolved organic substances affect UV disinfection efficiency significantly less in comparison to TSS. A multiple linear regression model was developed and was verified against results of treated GW from 11 sites that were disinfected by a flow-through UV reactor achieving high $R>0.8$ in the verification. The model demonstrated that for the same TSS, BOD, pre-irradiation FC concentrations and UV dose, log removal obtained in the collimated beam, was higher than the removal achieved in the flow-through reactor. Using the model and the correction factor calculated, can assess the UV dose required in flow-through reactors based on batch collimated beam results.

ACKNOWLEDGMENTS

This study was partly supported by the Rosenzweig-Coopersmith Foundation and the Zuck Maccabi Fund. The authors greatly thank Dr. Hadas Mamane for assisting with the of the collimated beam apparatus.

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