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THE USE OF FREE SURFACE CONSTRUCTED WETLAND AS AN ALTERNATIVE PROCESS TREATMENT TRAIN TO MEET UNRESTRICTED WATER RECLAMATION STANDARDS

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ABSTRACT

The purpose of this study was to assess the capability of constructed wetland and a UV disinfection unit to meet Title 22 California Reuse Standards for public use irrigation. This study examines fecal coliform reduction in domestic waste water after receiving treatment through: a constructed open water wetland, a slow sand filter, and a portable ultraviolet disinfection unit. The results of the one year pilot project utilized oxidation pond effluent as the influent to the test system. Effectiveness of removal of key constiuents (BOD, TSS, turbidity, fecal coliform, and nitrate nitrogen) along with the cost of the system is compared to the results and costs of other water reuse treatment systems. Long term (12 years) monitoring of the City of Arcata's (California, USA) free surface constructed wetlands has demonstrated high efficiency and reliability in removing suspended solids. The performance data for the proposed pond/wetland/UV system has been incorporated into a decision support model, WAWTTAR (Water and Wastewater Treatment Technologies Appropriate for Reuse).

KEYWORDS

Water reuse; wetlands; ultraviolet disinfection; marshes; tertiary treatment; slow sand filtration.

PROBLEM STATEMENT

Reclaimed water is a proven and reliable source of water in many regions of the world. The technologies available for treating domestic wastewater, to levels sufficient for unrestricted uses of reclaimed water have proven to be expensive to both construct and to operate (USEPA, 1992). In the United States, for example, technology standards have been used to specify reclamation treatment system. In California, specifically, secondary treatment (oxidation), coagulation/flocculation, filtration, and disinfection is required to meet the highest reuse standard. While this treatment train has proven to be highly effective it has by its technical specification eliminated many small to medium size communities from utilizing reclaimed water for unrestricted water uses. The cost of these required technologies both in terms of construction and operation is prohibited to all but the larger and more affluent communities. Many of the reuse schemes developed to date are centralized systems where economies of scale for treatment can be realized but are located considerable distance from reuse sites.

The data presented in this paper is from both a pilot and full scale level treatment systems (Gearheart, 1983, 1992). The pilot and full scale work was done at the City of Arcata's wetland treatment facility which is comprised of the following; 1) pilot cells comprised of ten six and 60 meter pilot wetland cells, 2) treatment wetland comprised of three one hectare treatment wetlands in parallel (4500 m^3/day), enhancement wetlands (polishing) comprised three four cells in series, and demonstration level UV and slow sand filter operations. This study was used to design a wetland reclamation system in Hawaii (Halewai, Oahu).

Water reuse guidelines/standards are established for the type of reuse. A minimum of secondary treatment (oxidation) combined with disinfectant (usually chlorination) is normally required (Asano, 1990, USEPA, 1992). Some reuse guidelines give significant disinfection credit to longer detention treatment systems such as oxidation ponds. Since equalization and storage is a necessary function of a reclamation system oxidation ponds can be considered as a sufficient but not a necessary component in a reclamation system. This paper will present both treatment effectiveness and cost effectiveness for several types of water reclamation trains. The two trains chosen represent a passive minimum technology options (oxidation ponds, wetlands, slow sand filters, and UV disinfection and an active intensive technology options (head works, activated sludge, coagulation, high rate filtration, and UV disinfection).

FREE SURFACE CONSTRUCTED WETLAND

A free surface constructed wetland is a shallow (emergent aquatic macrophyte natural treatment process which acts as a sequence of unit processes. The dominant process is autoflocculation and flocculation settling. These organic solids are then anaerobically broken down to dissolved by-products, gases and non-degradable organic compounds. More complex reactions occur in the water column where the dissolved organic carbon, nitrogen forms, and phosphorus forms are cycled through a series of interconnected biological compartments.

Numerous studies have investigated the use of wetland marshes for the treatment of wastewater. These studies have demonstrated that wetlands can reliably and effectively treat domestic wastewater to advanced secondary and tertiary levels in terms of BOD and suspended solids (Figure 1). Wetland BOD and TSS were found to be less than 5 mg/l on average and less than 10 mg/l 95% of the time. Fecal coliform removal mirrored the removal of TSS in pilot cell which had 8 subcompartments (Figure 2). This strongly suggests adsorption and settling as the principal removal processes. However, wetland treatment systems have not shown the ability to produce effluents with coliform levels low enough to meet California's strict shellfish or wastewater reuse standards.

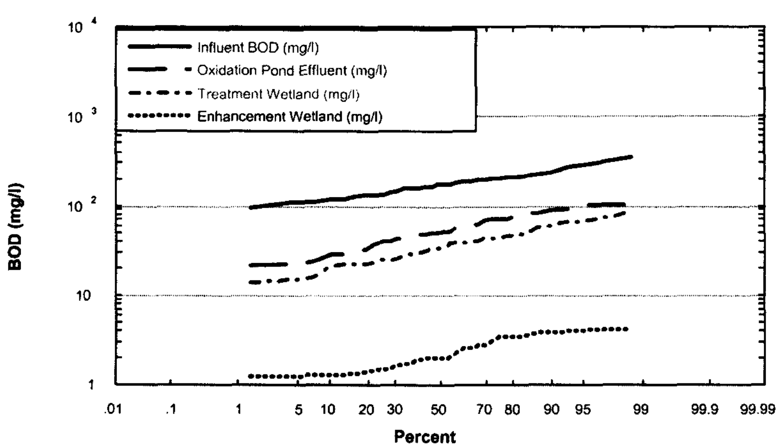

Figure 1. BOD distribution through all treatment unit operations 1991-1998.

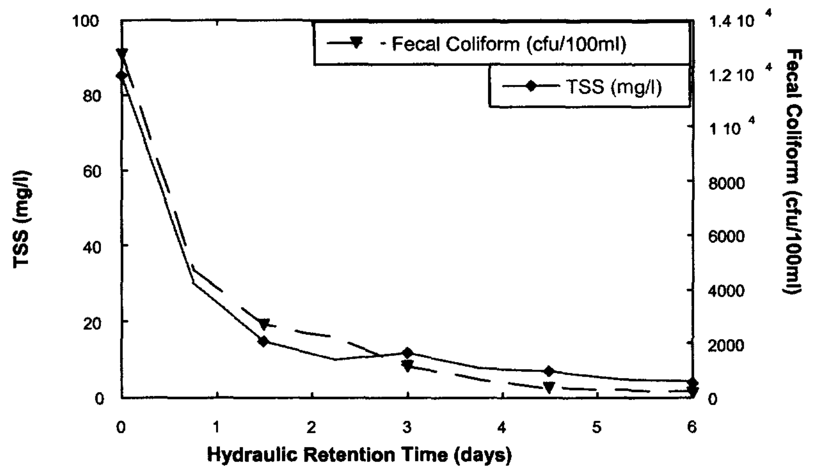

Figure 2. Fecal coliform and TSS removal in pilot project cell with 8 subcompartments.

PUBLIC HEALTH SIGNIFICANT ORGANISMS

The most common indicator of the level of microbial contamination and potential human pathogens is the amount of coliform measured in a sample of the effluent. Fecal coliforms were used both as an indicator of potential pathogen levels and the measurement of effectiveness of the UV pilot unit. Due to mariculture oyster farming in Humboldt Bay (sixty percent of the oyster production in California) the receiving water for the final effluent must meet the strict shellfish standard of a 14 fecal coliforms/100 ml. A study of enhancement marsh effluent by Gearheart (1992) found low effluent fecal coliform (<20 CFU/100 ml), BOD (<30 mg/l) and suspended solids (<30 mg/l) concentrations 90% of the time (Figure 3). These coliform levels are far below those typically used in other UV disinfection studies, but is characteristic of constructed wetland effluents.

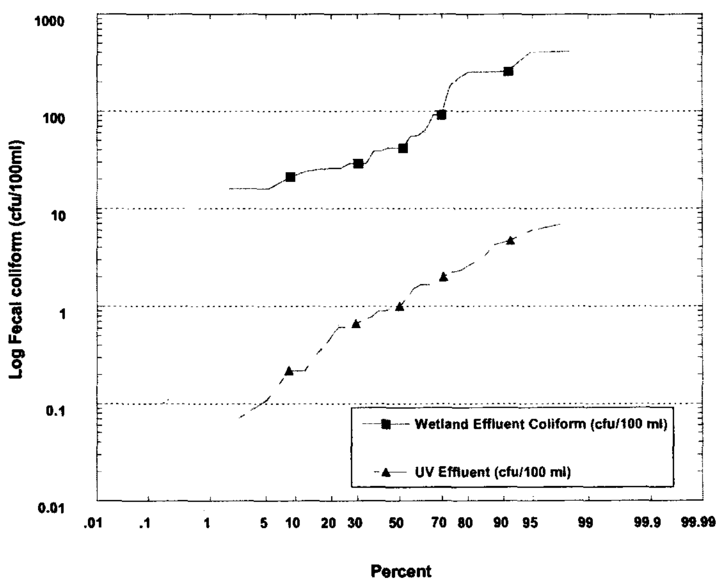

Figure 3. Enhancement wetland effluent fecal coliform levels before and after UV disinfection.

The UV system consists of a 7.5 cm diameter PVC UV reactor, a 1/10 hp pump, 2.5 cm and 1.25 cm PVC piping and is assembled using the appropriate valves and fixtures . The UV disinfection reactor itself is a modified QL-40 by Lifeguard Aquatics. The system consists of two inlets, two outlets, and three defuses (two before the contact chamber, and one after). To control flowrate there is a split in the flow after the pump. A portion of the effluent is directed through the reactor and the rest is diverted back into the chlorination basin and samples can be collected easily from the flexible Tygon tubing outlet pipes. The system was in almost continual operation from August of 1994 to May of 1995 and was out of service for only short periods of time for general maintenance. The pilot unit built for this project was designed to exhibit exposure rates similar to larger more conventional rectangular trough style reactors. The three diffusers and the upward vertical direction of flow increased the plug flow characteristics and eliminated the potential for the settling of solids in the reactor.

The UV disinfection unit was in constant operations from September 1994 to May 1995. Inlet and outlet samples were taken once a week for the first five months of the study. Five months into the the study the inlet fecal coliform counts dropped below 20 CFU/100 mL the sampling was scaled to bi-weekly. During each sample event three separate inlet and three seperate outlet samples were collected with outlet samples collected at one detention time later. Only one sample was collected for each of these extra samples. All the samples were filtered for fecal coliforms within an hour of sampling and all other water quality parameters are measured in accordance with Standard Methods (APHA, 1989). All of the water quality analysis was conducted on influent samples with the exception of effluent fecal coliform counts. Fecal coliforms were enumerated using the membrane filter technique as described by Standard Methods (APHA, 1989), procedure 9222 A. Total Suspended Solids can be seen that 95% of the inlet samples had FC counts below 300 CFU/100 ml and 90% of the outlet samples were below 3 CFU/100 ml.

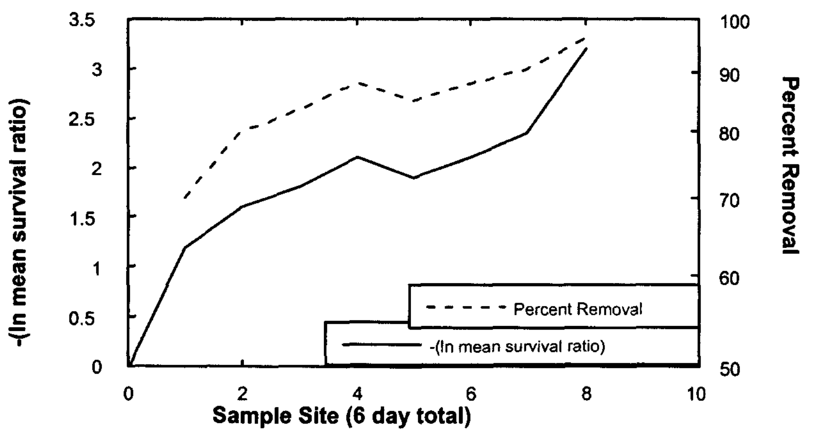

Figure 4. Coliphage MS-2 percent removal and natural log survival ratio through a wetland cell.

TSS (non-filterable residue) and BOD were determined as outlined in Standard Methods (APHA, 1989 procedure 2540 D and 5210 D respectively. Figure 3 shows the frequency distribution of all of the fecal coliform results for unexposed (IN) and the full range of UV exposed (OUT) polishing marsh effluent. It shows that 50% of the inlet samples had FC counts below 30 CFU/100 ml and 50% of the outlet samples were below 0.7 CFU/100 ml. Typically the performance of a UV reactor is measured by the dose applied vs. log survival of the indicator (Figures 4 and 6). This relationship usually exhibits a curve, but the limit of the range of the log survival and the high number of data points have given this relationship a linear appearance. It was impossible to measure log survival rates larger than -3.2 due to the fact that the maximum population of coliform only reached 412 CFU/100 ml and disinfected effluents could only be measured to the detection level of 0.1 CFU/100 ml. It is expected that with larger numbers of FC in the unexposed inffl, a larger survival ratio would occur even at the same exposure levels. Due to the small range of log survival it is difficult to evaluate the results of this UV unit against other UV units and varying qualities of effluents experienced by related studies. In any case the disinfection rate, expressed as the log survival of the outlet FC, decreased as detention time or dose increased. With the wetlandwater quality parameters being as good as they are and fecal coliform counts being so low, it is difficult to find a statistically relevant correlation between these parameters and the performance of the UV reactor at this time. The very low coliform counts also increase the margin of error and the effects random spikes may have on the data.

Figure 4 shows the removal of MS-2 bacteriophage through a constructed wetland (Ives, 1986). This test cell had a treatment retention time of 6 days with 8 subcompartments. Eighty percent of coliphage were removed in the first subcompartment (0.75 days HRT). This finding strongly suggested that adsorption and settling are the principal processes in a wetland. This is similar to the fecal coliform/TSS settling removal trace through this cell (Figure 3).

ULTRAVIOLET DISINFECTION

Disinfection technologies should also be evaluated for their potential in wastewater reuse. Chlorinated effluents discharged into the environment are associated with toxicological effects from chlorine residuals and by-products such as trihalomethanes (THMs). UV technology can be a preferable alternative to chlorination due to its effective disinfection without the production of residuals and by-products. UV disinfection has been shown to enhance water quality by eliminating toxicity and by significantly reducing the health and safety concerns associated with chlorination (Darby *et al.*, 1995).

Ultraviolet (UV) disinfection was observed to provide an additional 89 percent reduction in total coliform, if an average contact time of approximately 4 to 6 seconds was utilized. Total coliforms were reduced from an influent average of 1349 cfu/ml before filtration to 79 cfu/ml. after UV disinfection cumulatively representing a 94 percent reduction in total coliform content within the water treated. Thus initial UV contact was found to be proportionately more effective in reducing total coliform content in tertiary effluent. This study seems to indicate that quite possibly UV intensity may be more critical to coliform reduction than the length of UV contact with the treated effluent (Wilson, 1996).

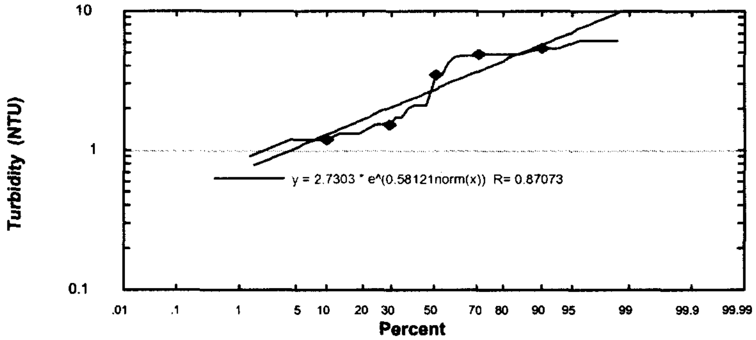

Figure 5. Annual distibution of weekly turbidity levels from the enhancement wetland effluent.

The standard of 14 CFU/100 ml was met in 100% of the outlet samples at all of the different doses and levels of water quality and was even met in 19% of the inlet samples (Figure 3). Fifty percent of the outlet samples were below 2.0 CFU/100 ml in samples exposed to a dose of less than 100 mW s/cm^2 and greater than 48 mW x/cm^2 (~10 sec) approximately 10% of the outlet samples exposed to doses larger than 100 mW s/cm^2 (~20 sec) were above 2.0 CFU/100 ml. The highest of these was 2.7 CFU/100 ml. Exposure to UV doses greater than 200 mW s/cm^2 (~35 sec.) produced only one sample with a FC count higher than 2.0 CFU/100 ml at 2.3 CFU/100 ml>. This peak sample value is believed to have been caused by a fouled UV reactor influent line this was corrected and the fouling never reoccurred during the duration of the study. Outlet FC counts decreased with an increased exposure to UV light (Figure 5). All outlet samples exposed to doses greater than 130 mW s/cm^2 (~25 sec) resulted in FC measurements less than 2.5 CFU/100 ml.

Fecal coliform counts in 50% of the outlet samples exposed to less than 130 mW s/cm^2 were also below 2.5 CFU/100 ml. Figure 5 shows the turbidity levels from the enhancement wetlands over the period of the study (weekly samples for one year). The median value is 2.7 NTU with 90 per cent of the weekly samples being less than 5 NTU. Since turbidity relates directly to UV efficacy these results directly supports fecal coliform reductions and virus reductions.

The Total Inorganic Nitrogen (TIN) removal through the AWTP is shown in Figure 6. The TIN is composed of ammonia, nitrate, and nitrite species of nitrogen. The effluent TIN from the wetland averaged 5 mg/l over a 10 year period. The TIN at the ninety five percent level or less was 10 mg/l. This level of TIN (less than 10 mg/l) would allow the effluent to be used to recharge a groundwater drinking water supply. Discharge guideline for nitrate nitrogen to groundwater is 10mg/l as nitrogen. Filtering the wetland effluent through granular activated sludge increased the UV transmittance of the sample 41 percent. This suggests that a majority of the UV transmittance interference is most likely due to polar molecules such as humic acids and other dissolved organic compounds. These types of compounds are common in marsh effluents and other natural systems where the decomposition of leafy vegetation is present. They are known to inhibit UV transmittance in the water column and can have an adverse effect on the efficiency of the UV disinfection process. This lowered transmittance poses the largest obstacle in the UV disinfection of wastewater marsh effluents.

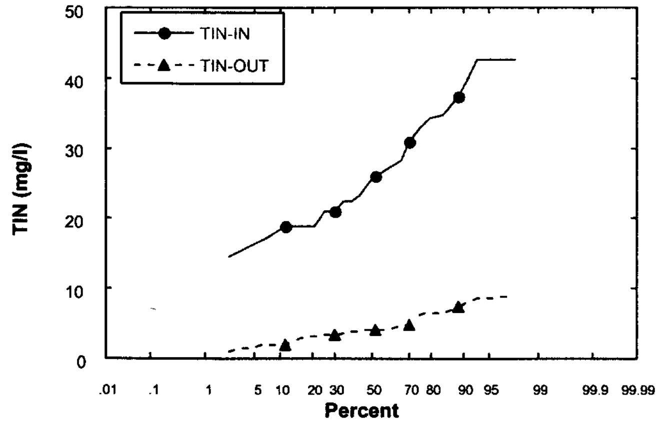

Figure 6. Total Inorganic Nitrogen (TIN) removal full scale enhancement wetland.

RESULTS

The fecal coliform permit standard for the AWTP of 14 CFU/100 ml was met constantly during the duration of this study at every UV dose applied to the polishing marsh effluent. Water quality parameters of polishing marsh effluent has no significant measurable effect on the efficacy of the UV disinfection process except at low retention times. With fecal coliform counts in the unexposed effluent also being low, it is difficult to find a statistically relevant correlation between these parameters and the performance of the UV reactor at this time. Low % UV transmittance in wetland effluents may be an important factor when considering UV disinfection and appears to be the most significant water quality parameter that may retard disinfection by UV irradiation. Humic acids in the wetland effluent absorb UV light reducing. However, this effect may be somewhat offset by the low levels of coliform, TSS, and turbidity typical of marsh effluents. The results of this study demonstrate that UV irradiation is an effective technology alternative for the disinfection of wastewater marsh effluent, similar to that found in the AMWS enhancement wetlands. Due to the consistently low influent fecal coliform counts of polishing marsh effluent and the normal dose required to meet CWRC standards it can be concluded that UV light may be an effective method for disinfecting marsh effluent.

Table 1 shows a comparison of data contained in the WAWTTAR program (Finney and Gearheart, 1998) for two water reclamation treatment trains. The high technological train represents the technology standard required by the State of California to meet its Title 22 water reclamation guidelines for high value users (groundwater injection, landscape irrigation, etc.). Performance standard for unrestricted water reclamation is less than 5 mg/l BOD and TSS, less than 5 NTU turbidity, and less than 2 CFU/100 ml. The low technological train includes natural processes plus UV disinfection. UV disfection is considered an appropriate technology based upon its lack of need for a continuous chemical supply, its ability to be operated with photovoltiac cells (w/wo batteries), and its relative ease of operations. The compared land requirements for a 4,000 cubic/meter/day flow is 0.7 ha for the high tech system versus 10 ha for the low tech system. The total cost for the two systems are seventeen million dollars for the high tech system and seven million dollars for the low tech system. The unit cost for cubic meter of reclaimed water is $17.00/month for the high tech system versus $7.00/month for the low tech system. Ancillary benefits favor the low tech system with approximately 20 days of available storage.

Table 1. Comparison of a high tech and low tech water reclamation train

	Technological Intensive Treatment Train			Low Technological/Sustainable Treatment Train		
Constiuents	Process/es	Removal Efficiency	Retention (days)	Process/es	Removal Efficiency	Retention (days)
Settleable Solids	Grit /Primary Clarification	100 % SS	0.08	Primary Cell Oxidation Pond	100% SS	10
Flocculant Solids	Primary Clarification	70 % TSS	(0.08)	Primary and Secondary Ox Pond Cell Wetland Cell 1	90% TSS	(10)
Oxidizable Organics	Activated Sludge	90% BOD 90% FC	0.25	Secondary and Tertiary Ox Pond Cell Wetland cell 1	80% BOD 75 % TSS 99.9% FC	20
Oxidizable Nitrogen	Activated Sludge	80% TN 95% FC	0.15	Minimum in Tertiary Ox Pond Cell Wetland 2&3	80% TIN Denitrification	10
Small Particles DOCs	Chemical Addition Filtration	98% BOD 99% TSS 99.9% FC	0.025	Wetland Cell 3 Slow Sand Filters	98 % BOD 98 % TSS 99.99 % FC	
Disinfection	Ultra Violet/ Chlorination	99.99999 % FC		Wetland Cells UV Disinfection	(99.9999%) FC 99.99999 FC	(10)
HRT (days)			0.5			40
Total Cost O&M and Capital	$17,106,000			$6,736,000		
Dollars per Cubic Meter/Mo.	$17.50			$7.00		

Cost based on ENR 5,800, land cost $10,000, 20 yr. interest 7%, inflation 5%. Total cost included capital plus O/M for project period-monthly cost total cost/240.

CONCLUSIONS

Emerging combinations of natural treatment systems have been studied in an attempt to demonstrate comparable efficacy and reliability. This paper presented technical arguments for using performance standards rather than technology standards for meeting these reclaimed water requirements. Specifically the paper presented data demonstrating the efficacy of using oxidation ponds, free surface constructed wetlands, and UV disinfection in meeting these standards. An important finding is that the water quality from the pond/wetland component of the system produces an effluent that can be used for a wide variety of irrigation and groundwater recharge reuses without the UV disinfection.

Wetland system do produce an effluent which has significant amounts of dissolved organic carbon (DOC) which contribute to the color of the effluent, supply carbon for denitrification processes, add acidity to the water tending to buffer the effluent, and affords multiple targets for disinfection by-products where chlorine is used as a disinfectant.

Research to-date has demonstrated that an oxidation pond effluent followed by a free surface constructed wetland and UV disinfection can produce a reclaimed effluent which meets the Title 22 unrestricted water resue standards. An effluent of less than 5 mg/l BOD and SS, less than 5 NTU turbidity, and less than 2 CFU/100 ml fecal coliform of a weekly basis and less than 5 mg/l of TIN 95% of the time on an annual basis.

A free surface constructed wetland with a 10-12 days HRT has been shown to perform equivalent level of fecal coliform and virus removal as the coagulation/filtration step in California's Title 22 reclamation technology standard. This level of removal efficiency coupled with pathogen removal capability of an oxidation pond (helminths, oocyst, pathogenic bacteria, and viruses) combined with the storage/equalization capability of pond/wetland systems make these processes of choice in those locations where capital and recurrent costs are limiting. A comparison between a low technological treatment/reuse system (oxidation pond, wetland, and UV) and technological intensive treatment/reuse system shows that the technology intensive systems costs US$17.00/month compared to US7.00/month for the passive treatement system (oxidation ponds,wetland, and UV disinfection) at a 4,000 CM/day flow rate.

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