Case Study of an Advanced On-Site Wastewater Treatment System Connected to a Single-Family Residence

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ABSTRACT

Limited test data on typical wastewater characteristics from a single-family household are currently available in the literature. Most verifications, certifications, and field studies are either done using municipal wastewater or done without measuring the influent characteristics. Since flow rates and mass loading rates to a residential wastewater treatment unit are highly variable, this may result in incorrectly sized units or reduced performance, especially during upset conditions.

A study has been performed by the University of California at Riverside on an advanced wastewater treatment system installed by MicroSepTec, Inc. The purpose of the study was to assess influent and effluent characteristics during treatment of wastewater from a single-family owned residence to provide additional insight regarding the mechanisms for enhanced nutrient removal. Special provisions were made to characterize the influent. A sample well equipped with a mixer to homogenize incoming raw wastewater was installed on the influent line and equipped with an automatic sampler. The influent and effluent were characterized as 24-hour average concentrations over a two-month period and as hourly concentrations for four 24-hour periods.

The advanced on-site wastewater treatment unit, called the EnviroServer, can be described as a hybrid fixed-film-suspended growth extended aeration system with a two-stage biological process to optimize denitrification. The treatment process is unique in that excess biomass is periodically decomposed to carbon and inert ash in a thermal processor as opposed to periodic wasting and subsequent disposal in conventional biological treatment processes.

The influent and effluent quality were measured in terms of TDS, TSS, TOC, $CBOD_5$, TKN, Ammonia-N, Nitrate-N, Total Phosphorous, Reactive Phosphorous, Total and Fecal Coliform. The study showed that despite large variations in mass loading rates, there was little effect on effluent water quality. For instance, less than one fifth of all 24-hour composite samples exceeded 10 mg/l for both $CBOD_5$ and TSS. Examination of hourly track study results show a strong correlation between high water flow rates and high phosphorous mass loading rates, which suggest that the source of phosphorous was washing detergents. Unexpectedly, the system removed almost 90% of the total phosphorous.

INTRODUCTION

Approximately 25 million housing units, or more than 25% of all housing units in the United States, are served by onsite wastewater treatment units. These systems include a variety of components and configurations, the most common being the septic tank/soil absorption system. The number of onsite systems is increasing each year. The limitation of the septic tank is that it relies on the soil to do more than 50% of the wastewater treatment. This may create a problem in areas with shallow groundwater or areas with poor soil conditions. The soil absorption field is also very sensitive to upset conditions, such as high solids loading which may be caused by failure to have the septic tank pumped, lack of an outlet filter, or overloading of the tank. High solids loading together with biomat formation are the two main causes of septic tanks/soil absorption field failure resulting in wastewater backing up into the house and/or septic tank effluent surfacing or ponding.

A high efficiency onsite residential treatment unit, wherein the entire treatment of the wastewater takes place inside the unit and not in the soil, takes care of this problem. Such a unit can also be used in areas with shallow ground water tables, in nitrogen sensitive areas or areas with poor soil conditions. In areas subject to periodic drought there is a need for a reliable source of water. The benefits with high efficiency treatment units also include a reduced demand for potable water by substitution, which would lessen overall water consumption. High efficiency treatment of household wastewater may encompass in-house recycle of treated wastewater either as a separate source of non-potable water for washing and flushing and/or as a source of irrigation water.

Studies were conducted at the UCR campus where an Enviroserver 600 gpd treatment unit, complete with sampling and monitoring equipment, was connected to a University owned single-family residence occupied by a family of four. The primary objectives of the study were to assess the effluent quality that can be achieved using the Enviroserver treatment system connected to a single household and to develop data that would provide additional insight regarding the mechanisms for enhanced nutrient removal and treatment efficiency under varying loading conditions (Wistrom and Matsumoto, 1999).

METHODS AND PROCEDURES

System Design and Operation

The test unit was a full-scale residential treatment unit, Enviroserver 600, equipped with an above ground thermal processor and computer control system for local and off-site control and process monitoring (Figure 1). In the latest design of the EnviroServer, the thermal processor is installed below ground in the first riser and the effluent storage tank has been incorporated into the main tank (Figure 2). The EnviroServer 600 is designed to treat 600 gallon of household waste per day. Depending on regulatory sizing requirement, this typically corresponds to a 4- to 6-bedroom house. The EnviroServer 600 consists of a single fiberglass tank with five compartments located below ground level and two small fiberglass cabinets typically installed on the outside wall of the house. The first cabinet contains the custom designed controller, and the second cabinet holds the air compressor.

The Enviroserver unit operates continuously and on demand. The influent feed from the residence is by gravity flow similar to an activated sludge plant. Residential wastewater enters the first compartment where primary clarification takes place. Because the contents of the first compartment is anoxic, it also serves as a pre-react zone where soluble $CBOD_5$ (Carbonaceous Biochemical Oxygen Demand) removal is enhanced by adsorption onto existing microbial flocs. The primary clarified wastewater along with the floatables including grease then overflows to the first aerated compartment where it undergoes aerobic digestion. Biological $CBOD_5$ removal and nitrification takes place in this and the subsequent aerated compartment. To promote $CBOD_5$ removal and nitrification both compartments contain moving media for attached biofilm growth. Biologically treated wastewater underflows into the fourth compartment reactor where final clarification takes place.

Excess biomass including biomass sloughed off the fixed film support is wasted using a thermal process that converts biological solids to a small residual consisting of carbon and inert ash. Periodically, a small submersible pump is activated to return settled biomass from the secondary clarifier to the primary clarifier (pre-react zone). Settled biomass from the primary clarifier is periodically pumped from the bottom of the compartment to the thermal processor where the solids are retained by a stainless steel sieve and the water is drained back to the primary clarifier. After a set number of pump cycles the control system initiates the thermal decomposition of the retained solids, which includes drying, gasification, and oxidation at controlled temperatures. The exhaust gas is forced back into the water in the first compartment, which further scrubs the gases to remove any remaining particulates, gas products, and potential odor before it is vented together with the air in the tank through the normal vent at the roof of the house. The controlled temperatures in combination with forced air results in minimum emissions. The end product is an inert residual of carbon and ash that is flushed back into the tank the next time the primary clarifier sludge pump is turned on. Recirculation of settled biomass from the secondary clarifier to the primary clarifier in combination with periodic thermal processing also help maintain low effluent TSS (Total Suspended Solids) concentrations.

Enhanced nitrogen removal also becomes possible when the aerobically treated and nitrified wastewater from compartment two and three is recycled from compartment four to compartment one if a carbon source is readily available and the first compartment is free of dissolved oxygen, e.g. anoxic. The NO_3-N in the aerobically treated wastewater serves as the terminal electron acceptor and the raw wastewater influent entering the first compartment serves as the necessary carbon source for the denitrification reactions. Anoxic conditions are normally maintained throughout the day because the pre-react zone in compartment one is not aerated and because incoming raw wastewater quickly depletes any available oxygen despite the periodic influx of dissolved oxygen that is introduced into the pre-react zone during recycle pumping, assuming the recycle ratio is in balance with the incoming wastewater.

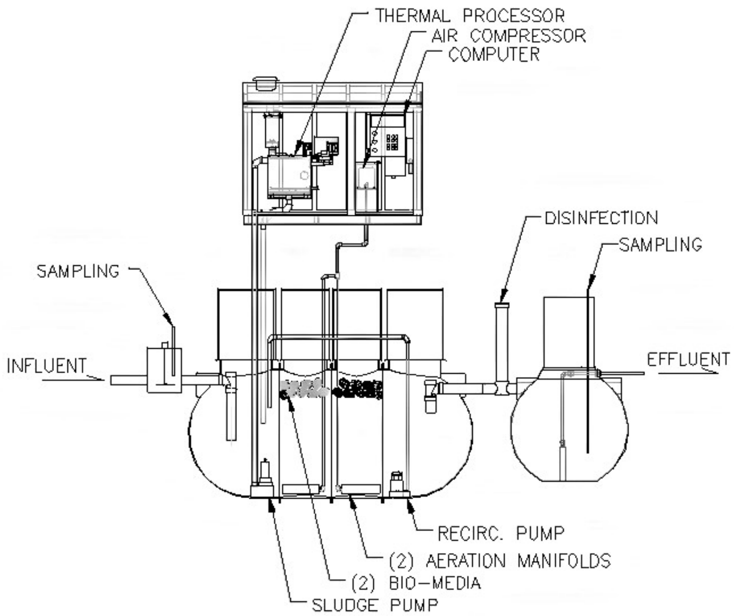

Figure 1. **Schematic rendering of the UCR test facility, an Enviroserver 600 residential treatment unit with an above ground thermal processor and a separate chlorination tank.**

The clarified and treated wastewater next flows from the fourth compartment through a chlorination unit, which comprises a flow-through cell with a receptacle containing calcium hypochlorite ($CaCl_2O_2$) tablets, into the chlorination contact and effluent storage tank. The chlorination contact tank is designed for a hydraulic residence time of 90 minutes for complete coliform destruction.

The EnviroServer System is controlled by a custom computer control system. The computer is capable of detecting failures of electrical and mechanical components critical to the treatment processes and delivering signals both remotely via a telephone connection and locally with a visible and audible alarm. The most important alarms are high tank level, pump failures, air compressor failure, incomplete thermal decomposition cycle, and disinfection failure.

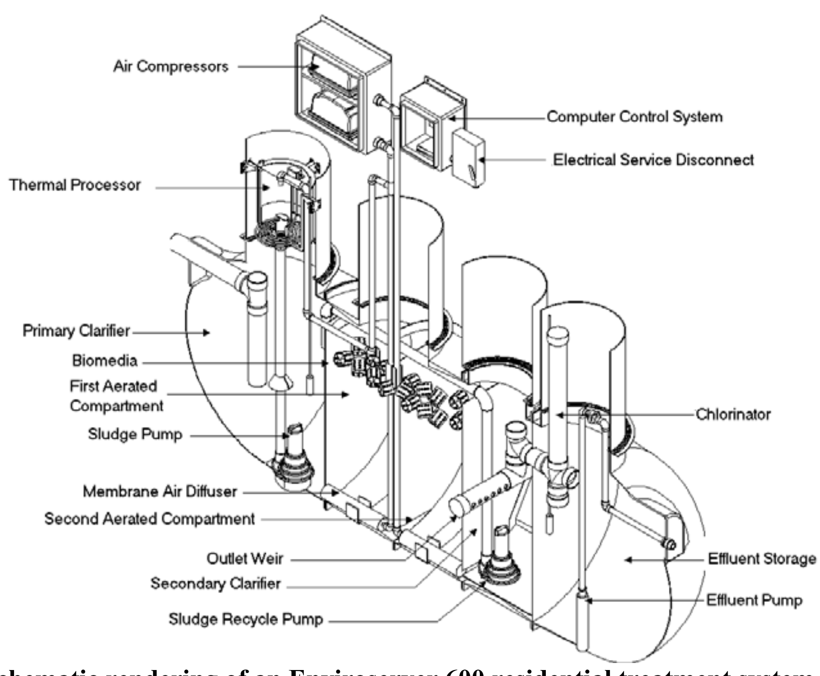

Figure 2. **Schematic rendering of an Enviroserver 600 residential treatment system.**

Sample Collection and Analysis

Evaluation of the EnviroServer treatment unit was carried out from January 1999 to July 1999. Since flow rates and mass loading rates to a residential wastewater treatment unit are highly variable, special provisions were necessary to characterize influent and effluent water quality. A sample well equipped with a mixer to homogenize incoming raw wastewater was installed on the influent line. A flow meter complete with data logger was installed on the residential water line to measure the potable water consumption on a continuous basis. Because all water consumed by the residents was discharged to the test facility a representative estimate of wastewater flow rates were obtained assuming that the time delay between usage and discharge did not adversely affect the analysis.

Wastewater samples were automatically collected on an hourly basis and a 24-hour composite sample was obtained in the laboratory by manually blending hourly samples in proportion to actual water usage. Samples for water quality analysis were collected from the influent sample port, and the chlorination contact tank. The location of sample points is shown in Figure 1. For the long-term evaluation of treatment efficiency of the EnviroServer treatment unit samples were collected during the period May 21, 1999 to July 30, 1999. Four track studies were also conducted during this period where influent and effluent samples were analyzed on an hourly basis to provide a measure of short-term variability of flow and mass loading rates.

RESULTS AND DISCUSSION

During the long-term performance of the EnviroServer treatment unit, the influent wastewater flow was characterized both in terms of quality and quantity. In a single household little or no "averaging" of wastewater composition and flow rates take place over time, as activities in a single residence are sequential. In addition, there is no infiltration of other water, such as rainwater, which typically dilutes and “averages” the composition of wastewater in municipal plants. Consequently, the large variations in wastewater composition, constituent concentrations, and flow rates observed during the testing, which reflect the diverse activities and varying schedules in a single household, are to be expected.

Measured concentrations of influent and effluent wastewater constituents are found in Table 1. Examination of the chemical analysis data of wastewater constituents in the 24-hour composite samples also revealed large day-to-day concentration variations. The influent wastewater was characterized by a typical $CBOD_5$ concentration averaging 212 mg/L and ranging from 75 mg/L up to 431 mg/L, which testifies to the large variations of wastewater strength and composition originating from single households. Nutrients such as nitrogen and phosphorus follow a similar pattern.

The importance of flow averaging is shown in Figure 3 where the average and standard deviation of hourly flow rates are plotted. Over a 24-hour period average water usage follows the classical diurnal pattern with a morning and an evening peak but variations from hour to hour and from day to day were considerable. In this study the average daily flow per capita was 39 gpcd, which is similar to what have been reported for households residing in apartments and mobile home parks that include little or no water for irrigation (Metcalf and Eddy, 1991).

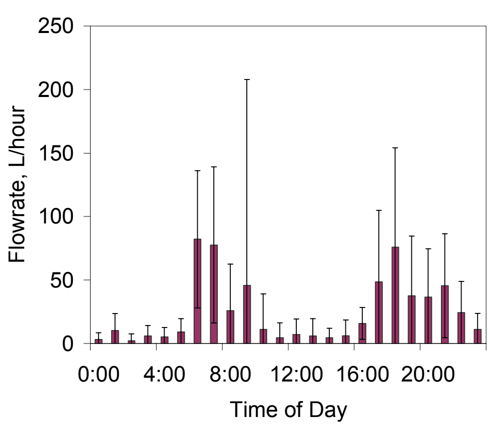

Figure 3. Average hourly flow rates with error bars showing one standard deviation.

The large variations in flow rate coupled with large variations in wastewater composition and strength offer no alternative testing methodology other than composite, flow averaged, sampling for evaluating removal efficiency of on-site residential wastewater treatment systems.

Average removal for $CBOD_5$ was 97.3 percent and for TSS 97.8 percent with an average effluent concentration of 5.7 and 5.9 mg/L, respectively. Maximum recorded effluent $CBOD_5$ and TSS concentrations were 14.0 mg/L for both constituents. Average influent and effluent TOC, $CBOD_5$, and TSS are also plotted in Figure 4 where the error bars indicate one standard deviation. The low TSS concentrations in the effluent is in part due to excellent solids settling characteristics with an average sludge volume index (SVI) in the secondary clarifier being 75 mL/mg and never exceeding 150 mL/mg. (Samples for TSS determinations were collected while the reactor contents were well mixed). The effectiveness of the sludge recycle pumping from the secondary clarifier to the primary clarifier and periodic decomposition in the thermal processor was evidenced by the average TSS concentrations tapering from a high 5,600 mg/L in the first compartment to a low of 450 mg/L in the fourth compartment.

Table 1. Measured concentrations of influent and effluent wastewater constituents and average removal rates in percent from the EnviroServer 600 study for a 10 week period.

Constituent[1]	Units	Influent Average	Concentration Std Dev (N=31)	Effluent Average	Concentration Std Dev (N=31)	Removal %
$CBOD_5$	mg/l	212	101	5.7	3.1	97.3
COD	mg/l	727	481	54	21	92.6
TOC	mg/l	121	153	18	7.6	85.1
TSS	mg/l	267	185	5.9	4.1	97.8
TDS	mg/l	653	348	543	143	-
TKN	mg/l	43	24	7.0[2]	4.6	83.7
Ammonia-N	mg/l	20	17	0.1	0.1	-
Nitrate-N	mg/l	1.1	0.9	2.1	1.5	-
Total Nitrogen	mg/l	44.1	24.9	9.1	6.1	79.4
Reactive Phosphorous	mg/l	12	6	1.3	0.6	89.2
Total Phosphorous	mg/l	19	8	2.0	0.7	89.5
Fecal Coliform[3]	CFU/100ml	490,000	180,000	<2	0	-
Total Coliform	CFU/100ml	860,000	230,000	<2	0	-
Total Chlorine	mg/l	-	-	12	20	-
Free Chlorine	mg/l	-	-	9	18	-
Turbidity	NTU	80	102	5.1	4.6	-
Conductivity	µmho/cm	525	77	599	120	-
pH	-	7.5	0.6	8.0	0.3	-

[1] $CBOD_5$=Carbonaceous Biochemical Oxygen Demand; COD=Chemical Oxygen Demand; TOC=Total Organic Carbon; TSS=Total Suspended Solids; TDS=Total Dissolved Solids; TKN=Total Kjeldahl Nitrogen

[2] N (number of samples) = 24

[3] Results reflect disinfection after modifications were carried out on the through-flow chlorinator.

Some nitrogen and phosphorus are removed by assimilation into new cell mass and subsequently removed from the reactor by thermal conversion to ash. Phosphorus removal was nearly 90 percent with an average effluent concentration for the Enviroserver of 2.0 mg/L with a standard deviation of 0.7 mg/l. Such high removal rates were not expected because no operational provisions were made for a "feast-and-famine" strategy to develop and maintain a phosphorus accumulating biomass. Average influent and effluent reactive and total phosphorous are plotted in Figure 5 where the error bars indicate one standard deviation.

Maintaining both aerobic and anoxic zones in the reactor allows for additional amounts of nitrogen to be removed. Nitrogen is biologically removed by nitrification followed by denitrification. In both instances, an organic carbon and energy source are required. The absence of ammonia in the effluent indicates that complete nitrification was achieved during the study period. The average daily ammonia concentration in the effluent was 0.1 mg/L with a standard deviation of 0.1 mg/L and a maximum of 0.2 mg/L. Ammonia oxidation results in nitrate formation but the average nitrate concentration in the effluent was only 2.1 mg/L with a standard deviation of 1.5 mg/L and a maximum of 8.7 mg/l. To achieve removal of both ammonia nitrogen and oxidized nitrogen both aerobic and anoxic microenvironments must exist within the reactor. The pre-react zone is kept anoxic which would permit oxidized nitrogen removal to take place as readily available carbon is continuously being added to the reactor. Influent and effluent TKN, NH_3-N, and NO_3-N concentrations are plotted in Figure 6.

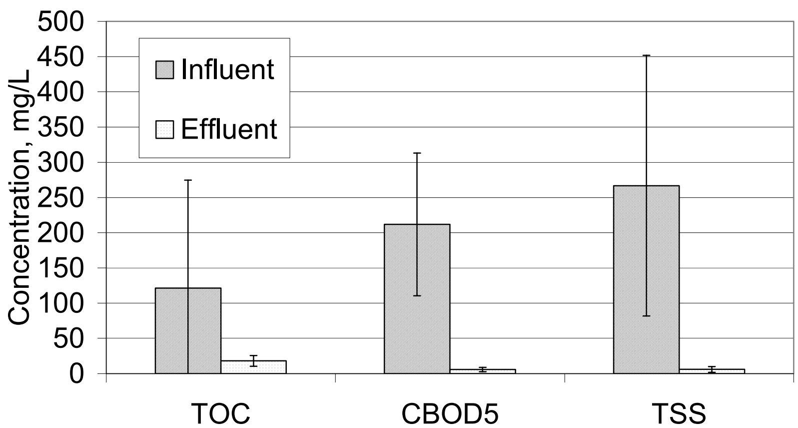

Figure 4. **Average influent and effluent Total Organic Carbon, CBOD5, and Total Suspended Solids. Error bars show one standard deviation (N=31).**

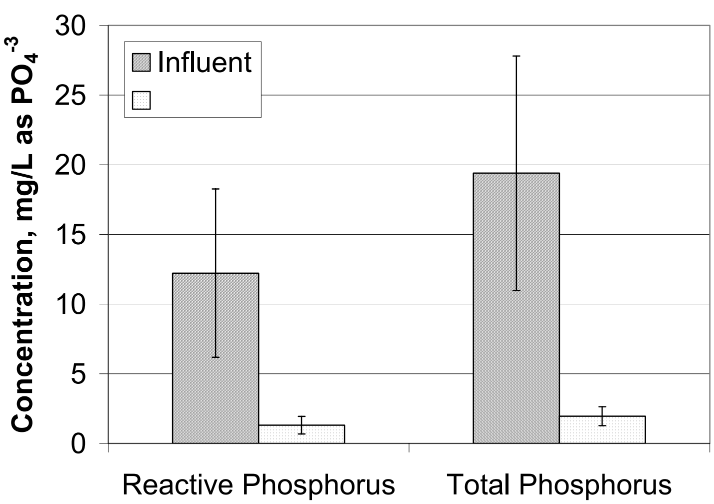

Figure 5. **Average influent and effluent Reactive and Total Phosphorous concentrations. Error bars show one standard deviation (N=31).**

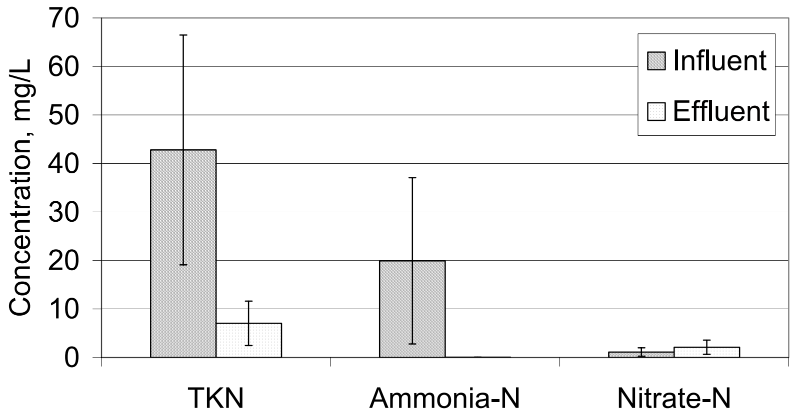

Figure 6. **Average influent and effluent TKN, Ammonia-N, and Nitrate-N concentrations. Error bars show one standard deviation (N=24 for TKN, and N=31 for Ammonia and Nitrate).**

To gain a better understanding of the effect of the inherent variability of influent flow rates and wastewater composition on removal efficiency over the short-term, 24-hour track studies were performed on four weekdays during the study period. A track study typically included influent and effluent samples automatically collected every hour. Samples were analyzed for TDS, TSS, TOC, COD, TKN, NH_3-N, NO_3-N, TOT-P, and PO_4-P concentrations.

In Figures 7 and 8 influent and effluent concentrations of COD and TKN are plotted as a function of time of the day. When high concentrations were found in the influent then effluent concentrations are also somewhat elevated for the same time interval. This observation is consistent with the hydraulic performance of a treatment process with recycle. The recycle stream dilutes incoming wastewater and at the same time disperses the contents of the four compartments to modify effluent water quality in the chlorinator tank and discharge. Even so, average COD concentration in the effluent was 50 mg/L, which corresponds to approximately a $CBOD_5$ concentration of 10 mg/L or less, based on linear correlation of the COD and $CBOD_5$ influent data. Similarly, TSS and TKN concentrations in the effluent were consistently low despite large fluctuations of both influent concentrations and flow rates. The correlation between influent and effluent concentrations is relative weak for the same time interval and does not appear to affect effluent water quality.

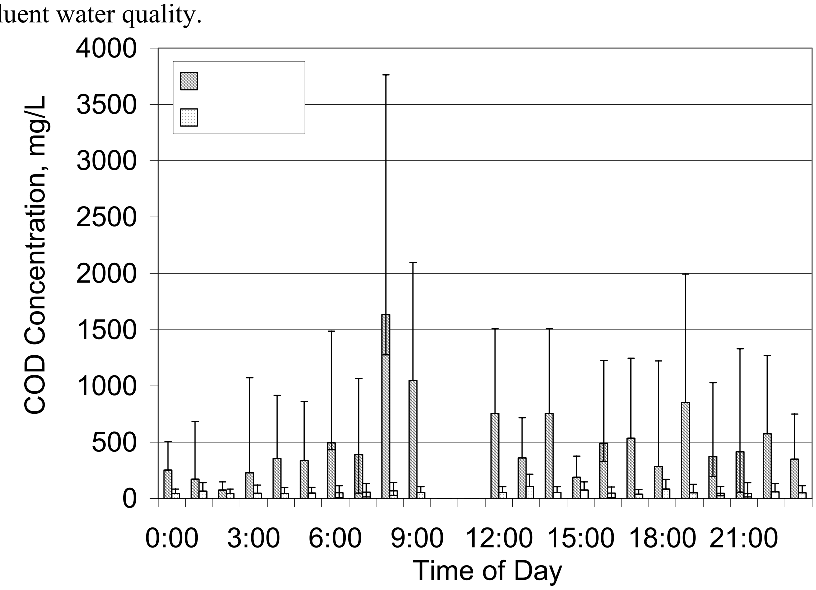

Figure 7. **Hourly influent and effluent COD concentrations for weekday track study. Error bars show maximum and minimum values. (N=4)**

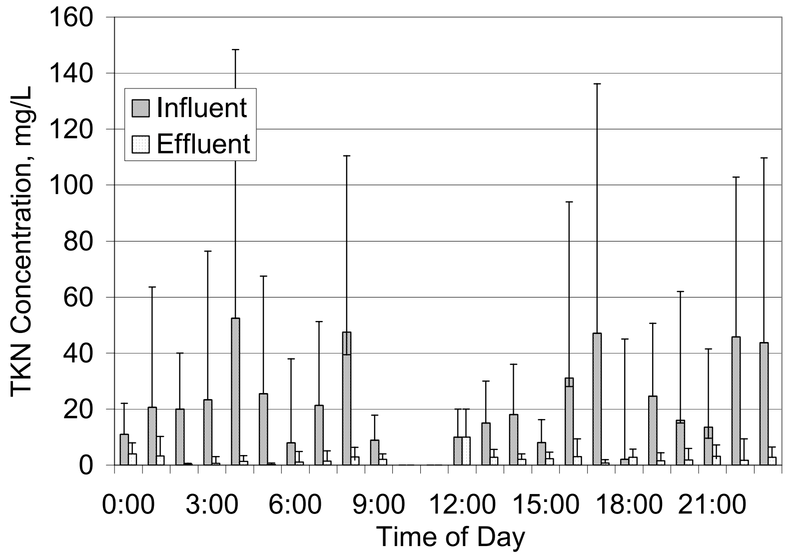

Figure 8. **Hourly influent and effluent TKN concentrations for weekday track study. Error bars show maximum and minimum values. (N=4)**

CONCLUSION

The principal conclusions resulting from the evaluation of the Enviroserver 600 residential wastewater treatment unit are as follows:

1. Average carbon, as $CBOD_5$, and solids, as TSS, removal rates were 97.3 percent and 97.8 percent, respectively.
2. Despite large variations in hydraulic and mass loading rates less than one fifth of all 24-hour composite samples exceeded 10 mg/L for both $CBOD_5$ and TSS.
3. Nearly complete nitrification and denitrification was obtained. Average removal rates for TKN and inorganic nitrogen was 83.7 percent and 89.7 percent, respectively. The nitrification and denitrification removal yielded a total inorganic nitrogen concentration rarely greater than 5 mg/L.
4. The thermal processor combined with recycle pumping of settled solids from the secondary clarifier to the pre-react zone produced a tapered solids concentration from approximately 5,600 mg/L in the first compartment to about 450 mg/L in the fourth compartment with subsequent low TSS concentrations in the effluent.
5. An effluent free of detectable total and fecal coliform, <2 CFU/100 mL, was consistently achieved using a bypass contact chlorinator using calcium hypochlorite in tablet form.
6. Hourly and daily variations of influent flowrates and mass-loading rates had little or no effect on effluent water quality.

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