Assessment of the reliability of an on-site MBR system for greywater treatment and the associated aesthetic and health risks

E. Friedler, Z. Shwartzman and A. Ostfeld

ABSTRACT

This study analyses the reliability of an on-site MBR system for greywater treatment and reuse. To achieve this goal simulation was performed based on the IWA ASM1 model which was adapted to describe biological and physical mechanisms for MBR greywater treatment based systems. Model results were found to agree well with experimental data from an on site pilot greywater treatment plant, after which the calibrated model was used in a Monte Carlo mode for generating statistical data on the MBR system performance under different scenarios of failures and inflow loads variations. Effluents quality and their associated risks were successfully estimated.

Key words | greywater reuse, MBR, on-site treatment, risk assessment, simulation, stochastic modeling

INTRODUCTION

On-site reclamation of greywater is believed to decrease urban water demand and thus to enhance its sustainability. Nevertheless, greywater may be polluted, with COD values of up to several hundred mg L\(^{-1}\), turbidity up to 70–100 NTU, faecal coliforms about \(10^4–10^6\) cfu (100 ml)\(^{-1}\), and significant concentration of detergents. Thus, if not treated to high standard, greywater may cause health risk and negative aesthetic and environmental effects (Dixon et al. 1999; Diaper et al. 2001; Friedler 2004). In order to minimise these adverse effects, current greywater treatment units combine biological and physicochemical treatment stages (Jefferson et al. 2001; Gardner 2003; Lazarova et al. 2003). MBR systems are especially attractive for on-site greywater treatment and reuse in densely populated urban areas due to incorporation of a biological treatment stage, efficient separation and small footprint. To date, not that many full scale systems were installed and even less were monitored for a long period of time in order to analyze their long-term performance. This is the objective of this paper: to analyze the reliability of an on-site MBR system for treatment and reuse of greywater. As a first step to achieve this goal, a simulation model was developed based on the IWA Activated Sludge Model 1 (ASM1, Henze et al. 2000). The equations of the ASM1 model were adapted to describe the biological and physical mechanisms occurring in an MBR based system. Model results were compared with experimental results of an on site pilot greywater treatment plant. Once validated, the model was further developed to be run in a stochastic mode, providing statistical data on the MBR system performance working under different scenarios of potential failures and assessing the associated risks.
Light greywater of seven flats (originating from baths, showers and washbasins) were separately conveyed to the treatment system situated in the building’s basement. The treatment plant comprised of a pretreatment step, which included fine screen followed by an equalisation basin, followed by an MBR system. Raw greywater was pumped from the equalisation basin to the MBR unit. The pilot MBR unit is a downscaled model of a commercial full scale system (Triqua B.V., Netherlands), with the following components (Figure 1).

- Aeration basin of 0.1 m$^3$, with hydraulic residence time of 5–8 h (in correspondence with the flux through the membranes). Mixed liquor was removed daily to set sludge age to 15–20 d.
- Centrifugal pump withdraw 1.67·10$^{-3}$ m$^3$ s$^{-1}$ of mixed liquor from the aeration basin into a side membranes module at a total head of 3 atm, creating cross-flow velocity of 4.0 m s$^{-1}$ through the membranes. Pressure drop along the membranes was adjusted to 1 atm. Retainate was recirculated back to the aeration basin, while permeate was discharged to a small holding tank.
- Two side modules of 4 tubular cross-flow UF membranes in series, MWCO 100,000 Dalton, total surface area 0.34 m$^2$ (8 membranes). Permeate flux varied from 0.0588 m$^3$ m$^{-2}$ h$^{-1}$ (clean membranes) to 0.0382 m$^3$ m$^{-2}$ h$^{-1}$ just before cleaning.
- Treated effluent holding tank. Fraction of the treated effluent was returned to the aeration basin in order to maintain its volume constant (return flow was adjusted to compensate the difference between raw greywater inflow, $Q_{in}$, and permeate discharge, $Q_{m}$), while the rest was discharged.

The pilot plant was operated for eight months. Raw greywater, treated effluent, and mixed liquor were sampled twice a week and analysed for various quality parameters. These data served as input (raw greywater) and validation data (mixed liquor, effluent) for the model. A more detailed description of the pilot plant can be found in Friedler et al. (2006)

The simulation model

The simulation model comprises three main components: a kinetic module which simulates the reactions occurring in the system, a transport module which represents all flows and the resultant mass balances within the physical system modeled, and a failure and stochastic framework which introduces random failures of various components into the model and accounts for the variable nature of raw greywater quality. The first to modules are deterministic, while the third one is a stochastic Monte-Carlo simulation framework. The model was written in MATLAB using the ode15s numeric algorithm for solving the differential equations.

Kinetic module

The kinetic module is based on the ASM1 model, the governing equations of which can be found in Henze et al. (2000). The model has 19 stoichiometric and kinetic parameters, the values for which were taken from Henze et al. (2000) and from Sotomayor et al. (2001). Oxygen transfer coefficient ($K_{La}$), needed for the calculation of oxygen dynamics, was determined experimentally in the pilot system ad was found to be 25 h$^{-1}$.

Fractionation of raw greywater COD to its components, as required by the kinetic module, was performed based on the findings of Dixon et al. (2000): soluble biodegradable COD 45%, particulate biodegradable COD 31%, soluble non-biodegradable COD 15%, particulate non-biodegradable COD 9%, heterotrophs COD 0.2%, and autotrophs COD 0.01% (negligible). In order to compare model results and experimental data, state variables of the model were

![Figure 1](https://iwaponline.com/wst/article-pdf/57/7/1103/438868/1103.pdf)
converted to familiar quality parameters (TSS, COD, BOD, TKN, NO₂ + NO₃) using the mechanistic and empirical relationships suggested by Sotomayor et al. (2001). Biomass concentration in VSS term was calculated by summing heterotrophic and autotrophic biomasses (in COD terms) and inert particulate COD arising from biomass decay, and dividing this sum by 1.42 (cell COD/VSS ratio).

**Transport module**

The transport module was constructed in order to represent all internal and external flows in the system under normal operation and under failure events. Under failure conditions two flows were added: \( Q_h \) - flow that leaks through a possible membrane texture failure, and \( Q_{of} \) - overflow from the aeration basin that occurs when inflow is higher than the membranes’ permeate flux. The known flows are: \( Q_{in} \) (inflow), \( Q_p \) (discharge of the recirculation pump), \( Q_m \) (permeate flux through the membranes) and \( Q_w \) (discharge of excess sludge). Under normal operation conditions (\( Q_{in} < Q_m \)), thus \( Q_e \) (effluent discharge) and \( Q_{of} \) can be calculated as follows:

\[
\begin{align*}
Q_e &= Q_{in} - Q_w \\
Q_{of} &= 0
\end{align*}
\]

When \( Q_{in} > Q_m \), \( Q_e \) and \( Q_{of} \) are calculated as follows:

\[
\begin{align*}
Q_e &= Q_m + Q_h \\
Q_{of} &= Q_{in} - Q_e - Q_w
\end{align*}
\]

Having calculated all flows in the system, mass balance of each quality state variables was computed. These were calculated under the assumption (based on the experimental data) that all soluble components pass the membranes and 99% of all suspended components are retained by the membranes. Thus, if \( Z \) is the vector of all quality state variables, then for soluble components \( Z_{ei} = Z \) (Z and \( Z_{ei} \) being concentrations of soluble components in the aeration basin and in the membrane permeate respectively), and for suspended components \( Z_{ei} = 0.01 \cdot Z \) (Z and \( Z_{ei} \) being concentrations of suspended components in the aeration basin and in the membrane permeate respectively). The vector \( Z \) in the concentrate return flow from the membrane to the aeration tank (\( Z' \)) is given by:

\[
Z' = \frac{(Q_p - Q_b) \cdot Z - Q_m \cdot Z_{ei}}{Q_p - Q_m - Q_h}
\]

The vector \( Z \) in the effluent (\( Z_e \)) is given by:

\[
Z_e = \frac{Q_h \cdot Z + Q_m \cdot Z_{ei}}{Q_m + Q_h}
\]

The differential form of \( Z \) within the aeration basin is expressed by:

\[
\frac{dZ}{dt} = ((Q_{in} \cdot Z_0 + (Q_p - Q_m - Q_h) \cdot Z' + (Q_m + Q_{of} \cdot Z_0)/V) + r_Z
\]

where \( r_z \) is the transformation rate of each of the variables that compose the vector \( Z \), as described in the kinetic module of the model.

**Failure module and stochastic framework**

The treatment system comprises of pipes, tanks, membranes, and electric / electronic equipment. Each of these components has a reliability function and a failure rate. The failure rate of electric and electronic equipment it is generally accepted to be constant and memory-less during the main portion of its serviceable life. Thus its reliability can be represented by an exponential distribution, as follows:

\[
f(t) = \lambda \cdot e^{(-\lambda \cdot t)}
\]

where: \( f(t) \) - probability to have a definite time between failures; \( \lambda \) – failure rate (T⁻¹); \( t \) – time since the last failure.

Five types of possible failures were studied, the first four are failures in hardware components of the MBR system, while the fifth simulated external extreme event:

1. Failure in aeration system, which results from mechanical failure of one of the air-blower components, or clogging of air-diffusers, or electrical failure of one of the blower components. When this failure occurs, oxygen is not supplied to the biomass in aeration tank (\( K_L A = 0 \)).
2. Breakdown of the circulation pump. The result of this failure is that no effluent flows through the membranes
(Q_p = 0) and consequently overflow occurs from the aeration basin (Q_{of} > 0).

3. General power failure. When this failure occurs, all electrical equipment halts. Thus, oxygen is not supplied to the biomass (K_{L,a} = 0), no effluent flows through the membranes (Q_p = 0), and overflow occurs from the aeration basin (Q_{of} > 0).

4. Membrane texture failure, i.e. formation of a hole in the membrane surface. The flow through this hole is represented by an equation of flow through an orifice. When this failure occurs, a proportion of the flow (Q_h) bypasses the membranes untreated (mixed liquor) and mixes with the treated effluent.

5. Excess addition of cleaning agents. Cleaning agents can be toxic to biomass in the system (e.g. sodium hypochlorite solution). These are applied regularly to the source of raw greywater as part of cleaning the greywater generating appliances. Usually, the dilution of cleaning agent applied is high. However, every now and then excess amounts of cleaning agents may reach the system jeopardising biomass activity. It was assumed that when this event occurs, biomass decay rates (b_A and b_H for autotrophic and heterotrophic biomass respectively) become one order of magnitude higher than their normal rates.

Failure rates of the aeration system, circulation pump, and membrane texture were set to 5 y^{-1} (Daniel & Louvar 2001). The duration of these failures was set to six hours (i.e. when a failure occurs six hours pass until it is fixed). Based on informal data from Israel Electric Corporation, power failure in urban areas occurs twice a year and lasts up to 2 h. Transient excess addition of toxic material was set to a rate of 5 y^{-1}.

In addition to failures, the MBR system performance was studied both under steady-state conditions and under real operational conditions where influent quality is not constant. Based on the experimental data, probability functions were derived for concentrations of each quality variable in the raw greywater entering the treatment system (for example, probability functions of soluble and particulate biodegradable COD in the raw greywater are depicted in Figure 2). These concentrations ranged from 18 to 649 mg L^{-1} for TSS, 53–948 mg L^{-1} COD and 3–29 mg L^{-1} TKN.

In order to incorporate the failure module into the model and to account for the variability of raw greywater quality a stochastic modelling framework was constructed based on Monte-Carlo method. The kinetic and transport modules were run in a deterministic mode for one year repeatedly, where in each run failures of each of the five components were set stochastically (based on their failure probability function, eq. 6), while the quality of the raw greywater was kept constant. In the second stage, the quality of the inflow was set stochastically with no failures.
RESULTS AND DISCUSSION

Model predictions and experimental data – Steady-state conditions

Comparison between the simulated model results and the experimental data from the greywater treatment pilot plant under steady state conditions generally exhibit good agreement (Table 1). It can be seen that despite the fact that BOD, TSS and COD, did not serve as state variables in the model and were derived from literature conversion equations (see kinetic module above), the model predictions agreed well with the experimental data. Nevertheless, simulated COD removal efficiency was higher than the actual one, implying that the proportion of soluble non-biodegradable COD in the raw greywater was larger than the fraction suggested in the literature (Dixon et al. 2000). Partial denitrification occurred in the aeration basin although oxygen concentration was kept at 1.8–2.0 mg L$^{-1}$. This probably occurred within the flocs of the biosolids where anoxic conditions may prevail.

Effects of failures

The effects of failures on the treatment system performance will be discussed in two ways, first the effect of a single failure will be analyzed and then the consequence of a year-long stochastic failure events will be examined statistically. Each type of failure has distinct cumulative effects of the MBR system performance, as described herewith.

1. When the aeration system fails, oxygen concentration in the aeration basin immediately drops to zero (Table 2), and anoxic conditions develop. Biomass concentration decreases by 12% (after 6 h) due to inhibition (or increased decay rate) of aerobic microorganisms. As a result of lower biomass activity, effluent COD and BOD increase. Due to oxygen deficiency, nitrification does not occur and thus ammonia and TKN concentrations in the effluent increase.

2. When the circulation pump malfunctions, mixed liquor is not pumped to the membranes and thus no effluent is produced. This results in overflow from the aeration basin and significant washout of biomass (~45% is lost during 6 h long failure), and it takes about 15 days for the biomass to reach 90% of its “normal” concentration. Oxygen concentration increases, as a result of lower overall oxygen demand by the biomass.

3. General power failure halts the operation of the aeration equipment and the circulation pump. Therefore, under this failure no effluent is produced. On the onset of the power cutoff oxygen immediately drops to zero, however when power returns, oxygen concentration rises above its normal operation value since its consumption rate is lower due to biomass washout that occurs during the failure (~35% of the biomass is lost during 2h of power failure. The recovery time of the biomass is about 8d (to reach 90% of its pre-failure value).

4. Failure of the membrane texture has the most significant effect on effluent quality since mixed liquor which leaks through the membrane mixes with the permeate as indicated by the very high effluent COD, BOD and TSS values (Table 2). Another effect is significant washout of the biomass from the aeration basin and resultant higher oxygen concentrations.

Table 1 | Comparison between model predictions and experimental results – steady-state conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Raw greywater</th>
<th>Effluent removal [%]</th>
<th>Biomass in the reactor</th>
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<tbody>
<tr>
<td>COD$_{t}$</td>
<td>mg L$^{-1}$</td>
<td>270</td>
<td>12</td>
<td>3,330</td>
</tr>
<tr>
<td>BOD$_{5}$</td>
<td>mg L$^{-1}$</td>
<td>95</td>
<td>2.4</td>
<td>5,530</td>
</tr>
<tr>
<td>TSS</td>
<td>mg L$^{-1}$</td>
<td>147</td>
<td>8.3</td>
<td>–</td>
</tr>
<tr>
<td>Ammonia</td>
<td>mg-N L$^{-1}$</td>
<td>3.4</td>
<td>0.73</td>
<td>–</td>
</tr>
<tr>
<td>Nitrate + Nitrite</td>
<td>mg-N L$^{-1}$</td>
<td>0.024</td>
<td>0.65</td>
<td>–</td>
</tr>
<tr>
<td>TKN</td>
<td>mg-N L$^{-1}$</td>
<td>11</td>
<td>0.98</td>
<td>5,330</td>
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<tr>
<td>Removal eff. [%]</td>
<td>Model</td>
<td>96</td>
<td>94</td>
<td>3,530</td>
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<tr>
<td>Pilot plant</td>
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<td>86</td>
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5. Excess application of cleaning has the second most severe effect on effluent quality. Significant proportion of the biomass is lost due to enhanced decay, and thus effluent quality degrades considerably.

The number of hours per year where effluent quality deviates from normal (or required) values gives a measure of the risk associated with each type of failure. These are a function of the failure rate and of the effect that a failure has on effluent quality. Failure in the aeration equipment at a stochastic rate of 5 times \( y^{-1} \) results in 100% probability that 20 h \( y^{-1} \) effluent BOD concentration will be higher than 5 mg L\(^{-1} \) and 50% probability that it will be higher than 5 mg L\(^{-1} \) for 58 h \( y^{-1} \) (Figure 3-A). For a failure in the membrane texture (at a rate of 5 times \( y^{-1} \)) there is 100% probability that effluent BOD will exceed 5 mg L\(^{-1} \) for 28 h \( y^{-1} \) and 50% probability that it will exceed 5 mg L\(^{-1} \) for 50 h \( y^{-1} \) (Figure 3-B). Excess application of cleaning agent (5 times \( y^{-1} \)) results in 50% probability for effluent COD to exceed 20 mg L\(^{-1} \) for 36 h \( y^{-1} \) (Figure 3-C).

![Figure 3](https://iwaponline.com/wst/article-pdf/57/7/1103/438868/1103.pdf)
Stochastic inflow

Running the model with stochastic inflow quality demonstrated that although effluent quality parameters exhibited some fluctuations, these were much smaller than the fluctuations in the raw greywater indicating ability of the system to overcome these significant perturbations (Figure 4). Effluent TSS, COD and BOD concentrations were found to be quite insensitive to influent quality with average concentrations of 11, 15 and 2.5 mg L\(^{-1}\) and CVs (coefficient of variation) of 0.02, 0.046 and 0.08 respectively. Effluent nitrogen species (TKN, NO\(_3^-\) + NO\(_2^-\) and ammonia) were found to be more sensitive to fluctuations of their inflow concentrations with average concentrations of 2.0, 0.6 and 0.7 mg L\(^{-1}\) and CVs of 0.50, 0.83 and 0.86 respectively. Oxygen in the aeration basin under these conditions was found to have medium sensitivity to these fluctuations (CV 0.37) averaging 1.9 mg L\(^{-1}\) and ranging from 0.0 to 3.3 mg L\(^{-1}\).

CONCLUSIONS

This study presented the development and application of a computer model for reliability analysis of an on-site MBR system treating domestic greywater. The IWA Activated Sludge System Model No. 1 served as the basis for simulating the MBR processes, where failures were expressed via the uncertainty of the input variables, the system components, and the model parameters. An estimation of the output uncertainty was assessed using Monte-Carlo simulations.

The reliability analysis considered four major types of hardware failures: aeration system circulation pump, power and membrane texture. The effect of excess application of cleaning agents was studied too. Membrane texture failure was found to have the most significant negative effect on effluent quality since mixed liquor which leaks through the membrane is mixed with the permeate resulting in very high effluent COD, BOD and TSS values. This failure also resulted in significant washout of biomass from the aeration basin. Excess application of cleaning agent had the second most severe effect on effluent quality. Here, significant proportion of the biomass was lost due to enhanced decay, and thus effluent quality degrades considerably. When a failure in the circulation pump and a power cut off occurred, no effluent was produced and biomass was washed out from the aeration basin. It took the biomass up to two weeks for to reach its normal value, during this period effluent quality was compromised.

Running the model with stochastic inflow quality demonstrated that the MBR system was very effective at stabilizing...
load variations. Effluent TSS, COD and BOD concentrations were found to be quite insensitive to influent quality while effluent nitrogen species (TKN, NO₃⁻ + NO₂ and ammonia) were found to be more sensitive as indicated by higher CV values. Oxygen concentration in the aeration basin was found to have medium sensitivity to these fluctuations (CV 0.37) averaging 1.9 mg L⁻¹ and ranging from 0.0 to 3.3 mg L⁻¹.

As a result of this study the following is recommended for onsite MBR systems: (1) to set up on-line warning for a failure of the electro–mechanical equipment, (2) to add water level controls in order to minimise biomass washout form the aeration basin, (3) to monitor dissolved oxygen on-line, (4) to monitor effluent turbidity on-line in order to reveal membrane failure, and (5) to add regular maintenance procedures for the mechanical equipment. Applying the above recommendations will enhance the system reliability very significantly without a need to have redundance to all electro-mechanical equipment.

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REFERENCES


