Pond treatment and effluent reuse of sewage from an oil production site in an arid coastal environment

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Abstract A pond system consisting of two lines each of an anaerobic followed by facultative and maturation ponds is used to treat site sewage from oil and gas production operations in an arid coastal environment. The performance of the pond system was evaluated together with the suitability of treated effluent for reuse in local irrigation. Effluent from the pond system by-and-large satisfies criteria for irrigation of non-food crop plants with respect to chemical parameters. The primary problem is coliform bacteria levels which are an order of magnitude higher than preferred values. First-order decay rate constants for each pond were calculated from a mass balance model that assumes complete mixing and incorporates the considerable evaporation that occurs in this setting. While the anaerobic ponds of both lines exhibit suitable performance, rate calculations indicate that the facultative and maturation ponds of the East Line are performing better than the West. A tracer study of the facultative and maturation ponds indicates that some short-circuiting is occurring in the West Line. A field experiment of coliform transport in irrigated soil gives indications of short- and long-term risks associated with reuse of the effluent.

Keywords Arid environment; coliform bacteria; tracer study; waste stabilization ponds; water reuse

Introduction
A pond system consisting of two lines each of an anaerobic followed by facultative and maturation ponds is used to treat site sewage from oil and gas production operations along Egypt’s Red Sea Coast. Effluent from the system was formerly discharged to the sea, but is now reused for irrigation on non-food crop trees, garden plants, and grass. The site represents the unique natural elements of an arid, coastal climate and landscape, with oft-high temperatures and winds producing high evaporation rates. The objectives of this study were to: (1) evaluate the performance of the pond system in this setting, and (2) evaluate the suitability of treated effluent for reuse in local irrigation.

Numerous national and international guidelines exist regarding the use of reclaimed wastewater for irrigation, with the aim of preventing transmission of communicable diseases while optimizing resource use (USEPA, 1992; WHO, 2000a). There is considerable emphasis on control of microbiological contamination, especially for the case of municipal wastewater, where industrial pollutants have been segregated from the sewage stream. Current World Health Organization (WHO) guidelines are more lenient than in the past, reflecting an effort to apply more realistic approaches to the use of treated wastewater and consideration of the most recent epidemiological evidence (WHO, 2000b). Total and/or fecal coliforms are most often used as indicators for regulating purposes, with guidelines qualified according to reuse and exposure group restrictions, types of crops or lands to be irrigated, or even the irrigation technique to be applied. Most guidelines also assume or require a certain level of treatment prior to reuse.

Experience demonstrates that acceptable levels of biological and other pollutants can be reliably achieved in well designed waste stabilization ponds (Brissaud et al., 2000; WHO, 2000b). In the case of hot climates, studies indicate that the WHO guidelines are appropriate, particularly in the instance of dry (arid or semi-arid) environments (WHO, 1989; Blumenthal et al., 2000).
Methods
Site description
The study site is an oil and gas production community, 370 km southeast of Cairo. The isolated industrial community, with a population of about 1,000, generates approximately 650 m³/day of sewage which is treated by two matching lines of waste stabilization ponds (referred to from hereon as East and West lines). Each consists of a square-shaped anaerobic pond with total volume \( \sim 2,000 \) m³, rectangular facultative basin of volume \( \sim 7,200 \) m³, and rectangular maturation pond with volume \( \sim 1,400 \) m³. The corresponding full depths are 2.8 m, 1.8 m, and 1.1 m, respectively. Flow is equally distributed to the two lines by a header weir station. Flow through the ponds is regulated by exit weirs in each pond, thereby maintaining a nearly constant liquid volume, and the effluent from the two maturation ponds is combined and piped through a single line for discharge. The discharge is pumped through a network of pipes feeding furrows that workers use to flood irrigate non-food crop plantations near the treated ponds and throughout the community. A dedicated tank truck is used to transport irrigation water to distant plantations not accessed by the pipe network.

Effluent monitoring
The pond system was monitored for conventional wastewater parameters over a one-year period (August 2000–August 2001). For each sampling event, samples were collected at the influent header, the effluent weirs from each of six ponds, and a discharge valve downstream of the combined effluent from the maturation ponds. At each sampling point, grab samples were collected according to the following: (1) 1 L in sterilized glass bottle for organics (BOD₅ and COD) and NH₃-N analysis; (2) 100 mL in sterilized polyethylene bottle for biological (coliform) analysis; and, (3) 1 L cleaned polypropylene bottle for other inorganic analyses (TSS, alkalinity, hardness, chloride, nitrate, phosphorus, iron, manganese). Samples were stored in an ice chest immediately after collection and transported to the laboratory for immediate analysis in the case of biological and organic parameters. Initial events also analyzed for the heavy metals Pb, Cu, Cr, and Cd by atomic absorption spectroscopy. In every instance, analytical procedures were conducted according to Standard Methods (1992). Temperature, pH, total dissolved solids, and dissolved oxygen were measured directly on site using field probes.

Tracer studies
Sulforhodamine B was selected as the tracer for experimental investigation of residence time distribution in the ponds. The experiments began in early October 2001 (maturation ponds) and early November (facultative ponds). The average daily ambient temperatures during these months were about 29.0 and 26.0°C, respectively, representing the range of average annual temperature at the location. The dye was dissolved in 10 L of water the day before initiation of the test. The solution was poured rapidly into the small sump beyond the outlet weir of the preceeding pond, which feeds immediately to the inlet pipe of the pond to be tested. Pond outlet samples were collected manually at regular time intervals from the weir and filtered using a glass-fiber filter to remove any residual solids. Dye concentration was measured by a fluorescence method using a spectrofluorimeter with excitation and emission wavelength settings of 565 and 590 nm, respectively (Smart and Laidlaw, 1977; Torres et al., 1997).

Field sampling of effluent used in irrigation
A sampling device was constructed to collect irrigation water as it percolates through the upper soil layer in order to observe the fate of coliforms as a result of flood irrigation as practiced at the site. The device has 15 sampling ports at 2 cm intervals from the surface.
Each port is a 5 cm polyurethane funnel covered with stainless steel mesh (US standard 100 size – 150 µm openings). Each collector is connected to 0.6 mm clear polyethylene tubing that drains into a side assembly housing individual polypropylene sampling tubes. The device was fixed in a permanent location in the field and packed with site soil to the same bulk density as determined through laboratory measurements. The hydraulic loading rate was that typically used in flood irrigation at the site, corresponding to 72 cm/hr for 10 minutes of watering over the designated area. Fifteen minutes after cessation of watering, the sample tubes were removed, sealed, transported to the laboratory in an ice cooler, and analyzed for fecal coliforms within 6 hours.

Results and discussion

Flow balance
Due to the arid climatic conditions characterized by high temperatures and winds, evaporation was incorporated in rate calculations associated with treatment. To estimate evaporation from the ponds, a flow meter was installed in the effluent line in addition to the existing meter prior to the influent header of the plant. Because reliable flow analysis is critical to a mass balance assessment, and as a check on the calibration of the meters, an evaporation pan was also installed on site as an estimate of evaporation rates. Monthly average influent flow to the plant during the study period ranged from 538 to 800 m³/day with an average of 648 m³/day. Outlet flow averaged 468 m³/day during this period, a difference of 180 m³/day or an estimated 28% of the inflow evaporated during retention (all of the ponds are lined with a synthetic liner to prevent seepage). Measurements from the evaporation pan yielded monthly averages ranging from 11 mm up to 26 mm, an average monthly rate of 17 mm, and a corresponding monthly average evaporation rate of 206 m³/day using water surface areas calculated for the ponds. Added to the measured outlet rate this gives a value of 674 m³/day which is just 4% higher than the metered value at the inlet. This flow balance was considered sufficiently accurate to use the metered values to represent the flows through the system, and a proportional scaling of measured evaporation rates was used to calculate inlet and outlet flows for individual ponds to estimate hydraulic retention and pollutant removal rates.

It is interesting to note that the evaporation peak in July or August may amount to nearly 40% of the inlet flow. This drops to less than 15% during the winter months. While this considerable evaporation concentrates water quality parameter values, it also serves to proportionally increase the (theoretical) residence time for the ponds, lending an advantage to decay processes higher than zero order as, for example, coliform reduction.

Pond performance – pollutant removals
Average effluent values and percent removals based on inlet concentrations are given for five water quality parameters in Table 1. These data represent eleven sampling events over a one-year period. Effluent from the pond system by-and-large satisfies criteria for irrigation of non-food crop plants with respect to chemical parameters. Measured COD values are on the high side, but BOD values are within an acceptable range. Chloride is also high, but this is expected given the coastal environment (i.e., impact of sea water/air). Metals, including iron, manganese, and four heavy metals, were all well below published criteria for irrigation reuse. The primary problem is coliform bacteria levels which are at least an order of magnitude higher than preferred values.

In order to quantify the performance of the ponds with respect to kinetic rate constants, a material balance analysis was conducted for each pond, assuming they function as completely mixed reactors and that all rate processes are first order. If evaporation losses are considered, the general form of the mass balance is:
where \( V \) is the liquid volume of the pond (L\(^3\)), \( Q_{in} \) and \( Q_{out} \) represent the inlet and exit flows (L\(^3\)/t), \( C_{in} \) is the inlet concentration (M/ L\(^3\)), \( C \) is the (uniform) concentration in the pond (M/ L\(^3\)), and \( k \) is the first-order rate constant (t\(^{-1}\)). The steady state solution for \( k \) can be written as a function of the hydraulic residence time, \( \theta_h = \frac{V}{Q_{out}} \).

First-order decay rate constants for each pond calculated from Eq. (2) and field monitoring data are presented in Table 2 for 24°C, the average water temperature. The results demonstrate that the anaerobic ponds exhibit suitable and similar performance for the sewage on both east and west lines, with BOD\(_5\) removal at about 60% for average loads in the range of 350–400 kg BOD\(_5\)/ha⋅day. The only notable difference is that the ammonia conversion rate in the east anaerobic pond is an order of magnitude higher than in the west. Furthermore, dissolved oxygen measurements at various depths suggest that these are indeed functioning as anaerobic stabilization ponds.

The rate calculations indicate that the facultative and maturation ponds of the east line are performing considerably better than the corresponding ponds of the west line. In fact, average effluent values for total coliforms (240 per 100 mL) and BOD\(_5\) (12.7 mg/L) in the east maturation pond are in line with published criteria for irrigation water used in green areas and landscaping in limited human access areas, as in the study area. Such is not the case for the West Line effluent, with values of 6,050 per 100 mL and 28.7 mg/L for total coliforms and BOD\(_5\), respectively.

Based on these results, a tracer study was conducted on both the facultative and maturation ponds in order to ascertain whether short-circuiting is occurring in the west line. Examples of tracer concentrations at the outlet versus time are presented in Figures 1 and 2 for the East Maturation and West Facultative Ponds, respectively. The curves exhibit a general pattern typical of completely mixed reactors, namely an almost immediate rise to a high peak, followed by a first-order-like decay, and culminating in an extended tail. In every instance, a significant breakthrough of tracer occurred within the first 2–4 hours of the test. In the case of the East Maturation Pond, the mean hydraulic residence calculated from the tracer data is 6.6 days, which corresponds closely to the theoretical value, \( \theta_h \), for the maturation ponds of ~7 days. The experimental mean residence time for the West Maturation Pond was just slightly less, about 6.0 days. As seen in Figure 1, however, there is considerably more vertical scatter (“noise”) in the data from the maturation versus the facultative ponds. As a result, the statistical uncertainty in terms of 95% confidence limits of \( \theta_h \) (experimental) is in the order of 25%. This may be due to the fact that discharge from the pond system is not even over a 24-hour period, since pumping is normally done 12–16 hours per day.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Effluent</th>
<th>% Removal in pond system</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOD(_5)</td>
<td>mg/L</td>
<td>22</td>
<td>75</td>
</tr>
<tr>
<td>TSS</td>
<td>mg/L</td>
<td>23</td>
<td>81</td>
</tr>
<tr>
<td>NH(_3)-N</td>
<td>mg/L</td>
<td>10.3</td>
<td>70</td>
</tr>
<tr>
<td>Total coliforms</td>
<td>/100 mL</td>
<td>6,260</td>
<td>&gt; 99.9</td>
</tr>
<tr>
<td>Fecal coliforms</td>
<td>/100 mL</td>
<td>4,780</td>
<td>&gt; 99.9</td>
</tr>
</tbody>
</table>

\[
V \frac{dC}{dt} = Q_{in} C_{in} - Q_{out} C - V k C
\]

\[
k = \frac{\left( \frac{C_0}{C} - \frac{Q_{out}}{Q_{in}} \right)}{\theta_h}
\]
For the West Facultative Pond (WFP), the actual mean residence time is \( \sim 12.5 \) days, well below the theoretical value of \( \sim 27 \) days for November 2001 conditions. This result together with the shape of the tracer curve suggests considerable short circuiting in the WFP (Torres et al., 1997; Shilton et al., 2000). The dimensionless dispersion number is about 0.6, also indicating a hydrodynamic regime that is approaching complete mixing rather than plug flow. While there is an indication of short circuiting in the East Facultative Pond (EFP) as well, it is substantially less, with actual residence time of more than 20 days. This difference could account for a measure of the variation in pollutant removals in the respective lines. The reason(s) for the difference in retention between the two facultative ponds, however, is not obvious. There is visually more algal growth and a few water plants in the EFP, and this could be promoting more dispersion/mixing within the volume. The additional algal growth could in itself contribute to enhanced removal of certain pollutants (e.g., N and P compounds) and enhance the oxygen condition for biodegradation of organics. The motivation for indifferent algal growth, however, is not evident. The desludging schedule of the ponds is staggered; however, sludge accumulation in the facultative ponds is minimal.

Although the exit weirs are in the same relative location in both ponds, the inlet pipes are positioned differently. Together with this positioning, the prevailing wind originating primarily from the NW would appear to work to reduce the “dead” or inactive volume of the EFP, while increasing it in the WFP. Since these latter issues are speculative, further work is being organized to implement a dynamic flow model to better understand the existing flow pattern in the ponds, and to hopefully design system modifications (e.g., insertion of baffles) to reduce the inactive volume and improve the performance of the ponds (Shilton, 2000; Salter et al., 2000).

### Use of effluent in flood irrigation

Based on WHO microbiological guidelines for treated wastewater (WHO, 1989, revised 2000a), irrigation practices at the study site are Category B2; i.e., flood irrigation with

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**Table 2** First-order removal rates for four pollutants in individual ponds

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Anaerobic East</th>
<th>Anaerobic West</th>
<th>Facultative East</th>
<th>Facultative West</th>
<th>Maturation East</th>
<th>Maturation West</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOD$_5$ (d$^{-1}$)</td>
<td>0.23</td>
<td>0.22</td>
<td>0.059</td>
<td>0.024</td>
<td>0.033</td>
<td>0.0086</td>
</tr>
<tr>
<td>TSS (m/d) *</td>
<td>0.29</td>
<td>0.35</td>
<td>0.15</td>
<td>0.1</td>
<td>0.049</td>
<td>0.0051</td>
</tr>
<tr>
<td>NH$_3$-N (d$^{-1}$)</td>
<td>0.031</td>
<td>0.0056</td>
<td>0.030</td>
<td>0.028</td>
<td>0.173</td>
<td>0.042</td>
</tr>
<tr>
<td>Total coli. (d$^{-1}$)</td>
<td>0.263</td>
<td>0.186</td>
<td>4.44</td>
<td>0.644</td>
<td>20.4</td>
<td>6.56</td>
</tr>
</tbody>
</table>

* Given as a first-order settling rate

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### Figure 1
Tracer curve for East Maturation Pond
restricted application to non-edible crops and exposure to adult workers only. Under these conditions, fecal coliform counts should be less than 1,000/100 mL. U.S. Environmental Protection Agency guidelines for conditions of restricted irrigation are at 200/100 mL (USEPA, 1992). As given in Table 1, fecal coliform levels in the treated effluent do not meet these conditions. To better understand the potential extent of exposure, a controlled field irrigation experiment was conducted. An indication of the fate of bacteria after treated effluent is applied by flood irrigation is presented in Figure 3 for the first of six such events conducted from April to September 2001 (Figure 4 is the summary data for soil bacteria for all six events). The plot shows concentration of fecal coliforms in soil water relative to the number in the treated effluent versus depth of soil. Values of $C_o$ ranged from $10^3$–$10^4$ per 100 mL. The symbols and error bars represent the mean and standard deviation of three separate samples (plate counts) at each depth. In selected experiments, extracted soil samples were also analyzed after the irrigation water had drained, to determine whether substantial numbers of viable organisms were associated with the soil. These data also appear in Figure 3 as the amount extracted from 10 g of soil. Although some soil-phase bacteria were detected in the first 1–2 cm of soil, the results indicate that the bacteria are mostly associated with the soil water under ponded irrigation. This suggests that the primary human exposure to bacteria is in the handling of the treated effluent via the piping network and while the water is ponded in the furrows. It is important to note that exposure is enhanced in this latter instance as a result of the high winds at the site that produce bacterial aerosols. Once

![Figure 2](https://iwaponline.com/wst/article-pdf/48/2/45/423198/45.pdf)

**Figure 2** Tracer curve for West Facultative Pond

![Figure 3](https://iwaponline.com/wst/article-pdf/48/2/45/423198/45.pdf)

**Figure 3** Soil water bacteria versus depth for Field Sampling Event #1. Ponded irrigation of previously dry soil at HLR of 72 cm/hr for 10 minutes
water drains from the upper layers of the soil, the human threat is reduced. The enhanced bacterial transport motivated by the flood irrigation technique, however, will tend to promote ground water contamination.

**Conclusions**

Using a mass balance calculation incorporating evaporation losses, first order rate constants were evaluated for pollutant removals in an anaerobic-facultative-maturation pond system in an arid coastal environment. While these parameter estimates were based on the assumption of ideal complete mixing, they provided a basis for quantifying and distinguishing the performance of the two treatment lines in the system. Tracer studies revealed considerable short circuiting in the more poorly performing WFP, with measured $\theta_h$ less than half of the theoretical value. Flow modeling should be explored to elucidate the existing flow pattern and identify inactive zones and other phenomena which may be contributing to the disparity in effluent quality from the relative lines. Associated corrective actions can then be implemented and monitored to determine whether more acceptable effluent levels can be achieved for the intended reuse function. Finally, the practice of flood irrigation at the site results in a primary risk to field workers deriving from exposure to bacterial aerosols and ponded water prior to its drainage into the soil.

**References**


