Water quality dependence on the depth of the vadose zone in SAT-simulated soil columns

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Abstract Three soil aquifer treatment (SAT) columns were operated for five months to investigate the dependence of the treated water quality upon the depth of unsaturated vadose zone in terms of its organics, nitrogen and phosphorus contents. It was found that DOC removal was independent of the unsaturated vadose zone depth except during the initial flooding period when the effluent was injected into each column. From tests to study the nitrate profile, it was found that the pattern of nitrification was dependent on the depth of the unsaturated zone during the initial periods of SAT flooding. However, no further nitrification occurred at the end of the flooding since the injection of the effluent continued to provide a high loading concentration to the SAT columns. The lack of phosphate removal in this study indicates that its removal is more dependent upon the soils and aquifer characteristics than on the depth of unsaturated zone.

Keywords Nitrogen; organics; phosphorus; soil aquifer treatment; unsaturated vadose zone; wastewater effluent; water reuse

Introduction
Soil aquifer treatment (SAT) has been applied to reuse wastewater effluents in arid regions where there is a significant lack of water resources (Idelovitch and Michail, 1984). Dry regions usually have deep unsaturated vadose aquifer zones, ranging 15 to 30 meters or more from the soil surface (Amy et al., 1993; Drewes and Fox, 1999; Viswanathan et al., 1999; Wilson et al., 1995), which are known to provide an appropriate environment for microbial degradation as well as a larger capacity of underground storage for a SAT system treating wastewater effluents (Drewes and Jekel, 1998; Drewes and Fox, 1999). This is related to the fact that organics are significantly degraded by microbial activity at the early stage of SAT treatment (Quanrud et al., 1996b).

Unsaturated vadose is important in the removal of nitrogen as well since it is known that a substantial amount of nitrification occurs in the uppermost layer of the unsaturated zone (Reemtsma et al., 2000). A great amount of ammonia is transformed to nitrate in the vadose zone, resulting in the high nitrate concentrations within groundwater aquifers (Wilson et al., 1995). Fryar et al. (2000) and Siemens et al. (2003) have shown that the denitrification is restricted within a certain depth (tens of meters) within the deep vadose zone. It was also found that the extent of denitrification depended upon the length and intensity of the drying and wetting cycles, which may alter the height of the unsaturated vadose zones by the infiltration of wastewater effluent (Bouwer, 1985).

Since most SAT systems have been implemented in deep unsaturated vadose zones (Amy et al., 1993; Drewes and Jekel, 1998; Quanrud et al., 1996a,b), little research has been done dealing with the effects of a shallow vadose zone upon the performance of such systems. Considering that, in the most regions of Korea, the aquifers are shallow, it is questioned if the depth of unsaturated vadose zone significantly influences the water quality of SAT-treated effluents in terms of the dissolved organics and major nutrient components. Therefore, this study looks at the effects the depth of the unsaturated vadose zone have on
the water quality of SAT-treated effluents when the SAT system is to be applied in shallow unsaturated aquifer zones. To accomplish this, laboratory experiments were conducted using SAT-simulated soil columns with different unsaturated zone depths.

**Materials and methods**

**Wastewater effluent**

Effluent from the Gwangju wastewater treatment plant (GWWTP) in Gwangju, South Korea, was determined, in a previous study by Cha et al. (2004), to be an appropriate effluent for possible SAT application in South Korea. Thus the secondary effluent from the GWWTP, where wastewater is treated by an activated sludge process and subsequently with a secondary clarifier, was used in this study as a feed solution for the SAT-simulated soil columns. The GWWTP effluent contained, on average, 4.5 mg/L of DOC, 24.9 mg/L of total nitrogen, and 3.7 mg/L of phosphate. The effluent was kept at 4°C after being collected from the GWWTP and, after passing through a water bath to heat it up to about 20°C, was injected into columns during the flooding cycle of the SAT operation.

**Unsaturated SAT simulation**

Three 10-L acrylic columns, with an inner diameter of 11 cm and a height of 1.3 m, including the headspace (30 cm), were constructed for SAT simulation by modifying the soil columns used by Quanrud et al. (1996a). Each column had four Rhizon soil moisture samplers (Eijkelkamp, The Netherlands) along the depth of the column (8, 18, 38, 78 cm from the top surface) to obtain a one dimensional water quality profile (Figure 1). The depth of the unsaturated zone was set to 0, 0.5, and 1 m for columns I, II and III, respectively, adopting a different height of discharge for each column. As depicted in Figure 1, the discharge point of column I was placed at the same height as the top soil (1 m from the bottom of the column), the discharge point of column II in the middle of the soil column (0.5 m from the bottom), and column III’s outflow was discharged from the bottom of the column, i.e., at a height of 0 m. Thus this will provide the columns with different unsaturated zones during the drying period since the infiltrated effluent stays below the discharge point of each column. Since the volumetric discharge through columns I, II and III was set to 1, 2, 3 ml/min, respectively, the hydraulic properties of these unsaturated SAT columns varied accordingly as summarized in Table 1. Hydraulic parameters were calculated assuming a saturated condition in all three columns during the flooding (wetting) period of SAT. The

![Figure 1 Schematic diagram of the soil columns with different depth of unsaturated zone (depth of the unsaturated zone, I: 0 m, II: 0.5 m, III: 1 m)](image-url)
soil was collected from the bottom of Youngsan River, South Korea, and sieved so that it was less than 2 mm in diameter. This soil originally contained 5% (w/w) of water and 0.5% (w/w) total organics. The characteristics of the column soil are summarized in Table 2. The columns were used to simulate a SAT system by employing a cyclic operation of 4-days flooding and 3-days drying along with artificial lighting for 6 hours per day.

Analytical methods
The major concerns in this study were placed on the organic, nitrogen, and phosphorous content changes for the different unsaturated zones. All samples were filtered with a 0.45 µm membrane prior to analysis. Ultra-violet absorbance (UVA) was measured at a wavelength of 254 nm with a 1-cm path length using a Shimadzu UV mini 1240 UV-VIS Spectrophotometer (Shimadzu, Japan) to determine the aromatic characteristics of the organics. Dissolved organic carbon (DOC) was analyzed with a PPM LabTOC (Pollution & Process Monitoring, U.K.) with an ultraviolet lamp and a 5% sodium persulfate solution. Ionic nitrogen and phosphorus compounds, ammonium, nitrite, nitrate, and phosphate, were analyzed with a Dionex DX-500 Ion Chromatograph (Dionex, USA).

Results and discussion
Removal of dissolved organics
To avoid minor fluctuations in the water quality, the columns were operated for a long period of time. Figure 2 shows the variations in the DOC and specific UV Absorbance (SUVA) over five months for each column. SAT-treated samples (column outflows) were collected at the end of each flooding period, i.e. the fourth day of flooding, to measure the DOC and SUVA. For all three columns, each operated with a different unsaturated vadose zone depth, the average DOC removals were similar, i.e., 22.7, 21.7, and 24.8% for columns I, II and III, respectively, although the DOC concentrations were fluctuated during the operation (Figure 2a). Similar results were also observed for the SUVA values, which increased an average of 26.7% for all three columns (Figure 2b). It is known that SUVA, defined as a

Table 1 Hydraulic properties of SAT-simulating soil columns having different vadose zone depths (assuming saturation of the columns during the wetting period).

<table>
<thead>
<tr>
<th>Columns</th>
<th>Volumetric discharge, Q (cm³/d)</th>
<th>Effective porosity, n_e (1)</th>
<th>Hydraulic gradient, dh/dl</th>
<th>Cross-sectional area, A (cm²)</th>
<th>Hydraulic conductivity, K (cm/d) (2)</th>
<th>Average linear velocity, v (cm/d) (3)</th>
<th>Retention time (day) (4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1,440</td>
<td>0.34</td>
<td>0.3</td>
<td>95.0</td>
<td>50.5</td>
<td>44.6</td>
<td>2.9</td>
</tr>
<tr>
<td>II</td>
<td>2,880</td>
<td>0.8</td>
<td></td>
<td>37.9</td>
<td>89.2</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>4,320</td>
<td>1.3</td>
<td></td>
<td>35.0</td>
<td>133.8</td>
<td>1.0</td>
<td></td>
</tr>
</tbody>
</table>

1) assumed n_e ≅ n; 2) calculated using Darcy’s law: Q = -KAdh/dl; 3) calculated from advection flow equation: v = (K/n_e)(dh/dl); 4) calculated from linear velocity and column height (including headspace): 130/v

Table 2 Characteristics of the column soil

<table>
<thead>
<tr>
<th>Variables</th>
<th>Soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source</td>
<td>Youngsan River, Korea</td>
</tr>
<tr>
<td>Soil type</td>
<td>Sand</td>
</tr>
<tr>
<td>Soil classificationa</td>
<td>SP (poorly graded sand)</td>
</tr>
<tr>
<td>Dry bulk density</td>
<td>1.51 g/cm³</td>
</tr>
<tr>
<td>Porosity</td>
<td>0.34</td>
</tr>
<tr>
<td>Total organic content</td>
<td>0.49% (w/w)</td>
</tr>
</tbody>
</table>

aUnified soil classification (ASTM-D2487)
ratio of UVA at 254 nm (UVA254) to DOC concentration, indirectly describes the degree of biodegradation as the aliphatic portion of DOC is degraded by biomass and the aromatic part (UVA254) remains refractory to microbial activity (Quanrud et al., 1996b). Considering the column retention time, 1–3 days, it was found that the DOC removal was comparable to the biodegradable dissolved organic carbon (BDOC) fraction (40.7% in 7 days) obtained in a previous study (Cha et al., 2004) for the same effluent. This implies a significant contribution of biological activity to DOC degradation in the SAT system and may be related to the rapid removal of easily biodegradable organics during the initial stage of SAT (Fox et al., 2001; Quanrud et al., 1996b; Schuh, 1991). However, the use of different unsaturated zone depths had only a minor effect on the removal of organics in the system, although a somewhat more significant difference was observed when operated for five months.

The DOC profile along the depth of column is plotted in Figure 3. Samples were collected two times during each cycle, on the first day (1F) and the fourth day (4F) after effluent injection. During the initial stages of flooding (1F), a significant decrease in the DOC was seen at a depth of 80 cm in column III, 40 cm in column II, and 10 cm in column I, clearly showing the different DOC profiles along the depth of each column (Figure 3a). Consequently, one day after flooding, the point of highest removal was related to the depth of the unsaturated zone in each column. However, towards the end of the flooding stage (4F), the DOC concentrations decreased gradually along the depth of columns and the entire DOC profile was similar between the columns (Figure 3b). Therefore, it may be concluded that the DOC profile initially differed with the depth of the unsaturated zone but became coincident as the flooding time increased. The average DOC concentrations in the treated effluent for the two sampling times (1F and 4F) were 3.2 and 3.4 mg/L, respectively. Combining the DOC profile (Figure 3) with the overall DOC removal characteristics through the columns (Figure 2) it was found that there was little dependence on the depth of unsaturated vadose zone in the soil columns, except for a somewhat aberrant behaviour during the initial period of flooding (1F).

**Nitrogen transformation**

Nitrogen was measured in the forms of ammonium, nitrite, and nitrate. Table 3 shows how each form of nitrogen changed after passing through the three columns using the different unsaturated conditions. One day after injection (1F), a significant reduction in ammonium was observed in all the columns, with the highest removal in column I, while the nitrate concentration increased most notably in column III. It is well established that ammonium nitrogen is ultimately converted to nitrate through an autotrophic nitrification process and is also assimilated into the cells through biomass synthesis (Atlas and Bartha, 1998). Thus a significant decrease in ammonium could be caused by both its conversion and assimilation,
especially with the help of air being able to penetrate into the column during the drying period, which would promote nitrification during the initial periods of the injection. A concurrent decrease in the dissolved oxygen (DO) concentration and pH also supports the active nitrification of ammonium (data not shown). Such a drop in the DO and pH is probably caused by the biological oxidation of organics and ammonia (Bouwer et al., 1974; Reemtsma et al., 2000). As well, the higher nitrate concentration seen in column III demonstrates that a greater degree of nitrification may take place in columns having larger unsaturated zones.

After injection for four days (4F), the ammonium concentrations within the treated effluent increased significantly in columns I and II, when compared with the initial injection (1F) results, while column III still showed a continued removal. As the wastewater effluent was injected into the columns continuously over 4 days, the hydraulic loading of ammonium per the limited surface area of soil might increase as the effluent injection continued, which would result in the build-up of ammonium in the system (Bouwer et al., 1974). Since column III had a greater capacity within the unsaturated zone to hold the influent, this would allow it to continue to eliminate the ammonium at a relatively high level until the end of the flooding period, although this rate tended to decrease. Based upon these results, the nitrification rate decreased in all columns throughout the flooding period but due to its larger unsaturated zone column III showed relatively high removal efficiency over the extent of the experiment. Defining the nitrate ratio (NR) as the ratio of nitrate nitrogen to the total nitrogen (the sum of ammonium, nitrite and nitrate), the NR of the wastewater effluent was 0.307 but increased to 0.769, 0.695, and 0.777 for columns I, II and III, respectively, after an injection time of one day (1F). However, they decreased to 0.338, 0.543, and 0.598 for each respective column by the end of the flooding period (4F). This clearly demonstrates that the nitrification rate gradually lessened as the effluent injection time elapsed.

For total nitrogen, the average removal for the three columns was 57.5% for 1 day (1F) but decreased to 291% by the fourth day, showing that the nitrogen removal rate gradually decreased with longer injection times, as was seen with nitrification. However, the results of column III, in contrast with those of columns I and II, showed similar a total nitrogen removal for both 1F and 4F. Although the total nitrogen removal efficiency for each column changed as the injection time increased, the average values from 1F and 4F showed that the total nitrogen removal was similar, with values ranging from 35.8 to 44.1% for the three columns.

Figure 4 shows a plot of the nitrate profiles according to the depth for the three columns and times of 1F and 4F. During the initial injection period (1F), quite distinct behaviour was
observed for each column (Figure 4a). The highest nitrate concentrations were seen at the bottom of the unsaturated zone in column III and in the middle of column II, while column I showed nitrate reduction at the top of the column. This is presumably due to the assimilation of nitrate because it is unlikely that dissimilatory nitrate reduction (nitrite ammonification or denitrification) would occur in the presence of oxygen (greater than 1 mg/L) (Atlas and Bartha, 1998). However, as shown in Figure 4b, no nitrate peak was observed after four days, regardless of the depth of the columns. From these profiles, it was found that the nitrification pattern differs according to the depth of unsaturated zone during the initial periods of SAT flooding (1F), but that no further nitrification occurs after 4F, as the effluent injection continues to provide a high loading rate into the SAT columns.

Phosphate removal

The phosphate concentration within the effluent from the GWWTP was 3.7 mg PO₄-P/L on average. Furthermore, it did not decrease in any of the columns, though there was a slight fluctuation according to the depth of the columns (depth profile data not shown). It is known that phosphate is removed either through its adsorption by phosphate-fixing materials, such as iron oxide and aluminium oxide, or through a precipitating reaction with the calcium and magnesium ions presented in soil (Bouwer et al., 1974). Therefore, the lack of phosphate removal in this study indicates that phosphate removal is more dependent upon the characteristics of the soil column than on the depth of unsaturated zone and that the composition of the column soil used in this study is not conducive to its removal.

![Figure 4](https://iwaponline.com/ws/article-pdf/5/1/17/417427/17.pdf)

**Figure 4** Nitrate profile according to the depth in the soil columns (a) after one day of flooding and (b) after four days of flooding during the period from May 2 to August 8, 2003 (depth of unsaturated zone – column I: 0 m; column II: 0.5 m; column III: 1 m)
Conclusions

The following conclusions are supported by the experimental results obtained in this study regarding the water quality dependence of a SAT-treated effluent upon the depth of the unsaturated vadose zone in the soil columns:

1. The presence of different unsaturated zone depths had little or no influence on removal of organics within the SAT-simulated soil columns.
2. The DOC profile differed according to the depth during the initial periods of flooding, showing a relationship between the point of the highest DOC removal and the depth of the unsaturated zone. However, the total removal was similar for all three of the columns as the flooding time was extended.
3. The nitrification rate decreased in all three columns as the time of flooding continued but column III, having a larger unsaturated zone, continued to show relatively high removal efficiencies until the end of the flooding period.
4. Nitrification differed according to the depth of unsaturated zone for the initial SAT flooding period. Additionally, no further nitrification occurred after a flooding period of four days.
5. Phosphate removal was found to be dependent upon soil column characteristics, but not on the depth of the unsaturated zone.

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References


