Impact of Long-Term Application of Wastewater

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Summary:
Environmental regulatory agencies are applying more stringent guidelines to the discharge of wastewater effluents while also promoting the reuse of treated wastewater. Therefore, we can expect slow-rate land application to become an integral part of more treatment systems in the future, especially for the arid and semiarid southwest region of the United States. Yet, as common as land application systems are in the United States, design of these systems is still less than optimum. Much of the problem is the lack of communication between the design engineers and the agriculturalists involved with the systems. Often the agriculturalists forget that the purpose of the land application site is treating wastewater and not maximizing profits from the crop being produced. On the other hand, engineers forget that "good agricultural practices" are necessary for a long-term, effective land treatment system. When a land application system for secondary treated municipal wastewater is properly designed, both from the standpoint of good engineering principles and good agricultural practices, the system can be operated successfully for many years without posing a threat to the environment.

Keywords:
Municipal wastewater, secondary effluent, nutrient management, nitrate, groundwater

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Impact of Long-Term Application of Wastewater

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Historical Background

The Lubbock, Texas Land Application Site (LAS) is one of the oldest, continuously operating, slow-rate land application systems in the United States. Throughout its life, the LAS has provided an efficient method for disposal of secondary treated municipal effluent. Yet, over the years some changes were required in order to implement new regulations required by the state’s environmental regulatory agency. Some parts of the LAS (Figure 1) have been in operation since 1925 when an average daily flow (1 mgd) of secondary treated effluent was applied to 200 acres of land. This application provided an annual average of 5.6 ft of water for this irrigated area. By 1955, the LAS had grown to applying nearly 8 mgd on 1800 acres of land for an average annual application of 5 ft of effluent. Since the inception of the LAS until the 1960's, estimating crop water requirements was a relatively new science. Therefore, the application rates were based primarily on land availability and simply the appearance of the crop. Due to this approach in determining the application rate and the fact that irrigation was accomplished with furrows (one of the least efficient methods of irrigation currently available), a mound of groundwater developed beneath a portion of the LAS.

In order to reduce the groundwater mound, a pumping program was developed in the early 1970s that utilized 27 wells to pump the groundwater to a lake system in the Yellowhouse Canyon. This program was developed to improve the aesthetics of a city park within the canyon while providing a convenient way to utilize the groundwater for recreational purposes. However, this water only maintained the water level in the system of six small lakes.

With the onset of new environmental regulations surrounding the operation of land application sites and the development of new technology, the City of Lubbock decided, in 1986, to purchase the LAS with additional land to allow for growth. By that time, the wastewater flow rate was approximately 12 mgd. The City immediately upgraded the irrigation application method to a center pivot system which has a much higher application efficiency than the furrow irrigation method. The LAS consisted of 5,200 acres of which 2,950 acres are under 31 center pivots where the average wastewater application rate was reduced to 4.6 ft. In 1999, the City purchased another 4,000 acres of land that included approximately 2,400 acres under center pivot irrigation. This site, previously under different management receiving approximately 4.5 mgd, now receives 5.5 mgd of secondary treated effluent for an average annual application rate of 2.6 ft/ac.

By the time the City of Lubbock took over the operations of the LAS, not only was a groundwater mound present, but the groundwater contained elevated levels of nitrate-nitrogen (\(\text{NO}_3^-\)) (higher than the drinking water standard of 10 mg/L \(\text{NO}_3^-\)). With this new information, the City modified the comprehensive pumping program to recycle the groundwater onto park land, a golf course, and farm land in order to effectively utilize the groundwater nutrients.

Since the new design approach was implemented to optimize the application of treated effluent to
the LAS where minimal storage is provided, significant progress has been made to correct the elevated nitrate levels in the groundwater beneath the LAS. The new operational design has been followed with only minor modifications needed to account for differing crops required by weather conditions or other externalities.

**Design Approach**

Figure 1. Layout of the Lubbock Land Application Site detailing the location of center pivot and row irrigation plots. The numbers within highlighted areas represent plot numbers for management purposes.

The objective of this research was to examine the principles and procedures used to design effective land treatment systems for arid and semi-arid regions and to provide an analysis of one of the oldest land application sites in the U.S. based on 8 years of in-depth groundwater samples and 3 years of soil and plant nitrogen data. The groundwater analysis is provided for the entire 5,200-acre LAS where 2,950 acres of center pivot irrigation exist. Three plots from the LAS, consisting of land that had been irrigated with effluent for as little as six years and up to 65 years,
were chosen for the detailed nitrogen analysis. Total nitrogen in the effluent applied to the soil varied from 10 to 25 ppm. The nitrate nitrogen in the top 2 ft of soil varied from 0 to 15 ppm with an average of about 3 ppm resulting in readily available nitrogen for plant uptake averaging about 38 lb NO$_3$-N/acre.

The first step in removing nitrate from the groundwater was to remove the source without shutting down the land application system. The initial factors considered in the design were size of the effluent storage reservoirs along with determining the land area and type of crops required to remove the applied nitrogen. The first goal was to minimize the size of the effluent storage due to the associated cost ($2,500-$3,000/ac-ft). Investing in storage reservoirs in order to utilize winter flows in the summer is not a cost effective approach to an optimum land application system. In addition, since the soil has the capacity to store water, that storage volume should be integrated into the design approach.

**Water Balance**

The water balance that includes soil storage of water for a land treatment system is not a standard calculation; yet, it is the main component of the design of any land application system. Its use results in significant economic consequences for the overall system. Before the water balance can be completed, the designer must develop a design philosophy, select the crop or crops, determine the most appropriate method to calculate evapotranspiration (ET) (Jensen et al., 1990; Doorenbos and Pruitt, 1977), and quantify leaching requirements for the selected crops. With the water balance complete, the quantity of effluent storage can be determined. Other considerations include the determination of the operational mode with respect to scheduling the irrigation, the determination of the type of irrigation system to be used (Keller and Bliesner, 1990) with a realistic assessment of its water application efficiency (Karmeli et al., 1978), and the determination of the procedure that will be used to calculate the water balance.

Incorporating the basic approach of land limiting constituents (Overcash and Pal, 1979) with an irrigation schedule, an effluent application plan can be developed that strictly controls the fate of nitrogen or any other wastewater constituent applied. The basic equation used to develop the schedule of effluent application is

$$SM_i = SM_{i-1} + P_i + I_i - ET_i - L_i \pm S_i$$  

where $SM_i$ is the soil moisture in month $i$, $SM_{i-1}$ is the soil moisture in the previous month, $P_i$ is the precipitation in month $i$, $I_i$ is the irrigation in month $i$, $ET_i$ is the evapotranspiration in month $i$, $L_i$ is the leaching that occurs in month $i$, and $S_i$ is the water going into or out of the storage reservoir in month $i$. To simplify the calculations, all the variables in Equation 1 have units of depth per month. Note that the soil moisture cannot be less than zero nor more than the available water holding capacity of the soil throughout the depth of the crops’ root zone. Any water applied in excess of the water holding capacity is deep percolation, also called leaching water.
Leaching Requirements

Leaching of salts from the root zone is an important aspect of good irrigation practices. Leaching is especially important for land application systems because municipal effluents particularly are often high in total dissolved solids (TDS) and sodium. The necessity of leaching is recognized by the environmental regulatory agencies (TNRCC, 1990) in their recommendation of the traditional procedure for determining the depth of leaching as proposed by Richards (1954).

Blindly following the recommendations described in some guidelines used for land application system designs can lead to some costly recommendations. One problem is the recommendation of providing leaching during the summer months. For most locations in the Southwest, leaching during the summer months is extremely difficult because the ET rates are high, precipitation rates are relatively low, and the hydraulic capacities of irrigation systems are generally limited.

A general misconception regarding land application systems is that constant seasonal leaching is required to maintain a favorable salt balance in the soil. A field can tolerate some increase in salinity for one or two years without causing major damage to crops. Systems can be designed to permit leaching during periods of high precipitation with minimal leaching occurring during low precipitation periods. This will minimize storage and allow the land area to be sized using the land-limiting-constituent concept rather than being sized by the amount of agronomic crops that can be irrigated during the summer months.

To determine the potential crop yield reduction due to TDS in the effluent, the procedures recommended by Ayers and Westcot (1976) could be used. The procedures allow the designer to calculate the minimum leaching requirement for various tolerable degrees of yield reduction caused by the TDS in the effluent. The yield reduction that the designer will allow for a given depth of leaching can also be back-calculated using Equation 2.

\[
LR = \frac{EC_w}{(5EC_e - EC_w)}
\]  

(2)

where LR is the minimum leaching requirement needed to control salt accumulation in the soil, EC\(_w\) is the electrical conductivity of the effluent (micromhos/cm), and EC\(_e\) is the electrical conductivity of the saturation extract of the soil for a given crop appropriate to the tolerable degree of yield reduction—usually 10% or less (micromhos/cm). The relationship between EC\(_e\) and the yield reduction of a crop is given by Ayers and Westcot (1976) or other irrigation and drainage reference texts.

To design the optimum land application system, water application should occur year round with little consideration given to carryover storage from season to season. With a year-round irrigation schedule, the effluent storage is needed primarily for wet and cold weather periods, and leaching requirements can occur during the winter months when crop ET rates are low. For most arid and semi-arid regions, little storage is needed for normal operation taking into consideration
crop water requirements, leaching, and the fact that precipitation rates are less than ET rates.

**Design Philosophy**

The procedure used to calculate the water balance uses long-term (30 year or more preferred, but a 20 year minimum is desired for best results) average data for precipitation and ET and the scheduled irrigation as prescribed by the designer. In performing the overall water balance using Equation 1, the quantity of effluent provided each month remains constant. Allocation of this effluent application depth is a judgment based on the land limiting constituent, ET, precipitation, timing of cropping cultural practices, water holding capacity of the soil, leaching requirements, and the effect on storage volume. As a result of this water balance approach, the actual amount of leaching that occurs from one year to another varies with the change in actual precipitation. This design approach produces a system with a fixed amount of wastewater application and a variable amount of leaching—unlike that of TNRCC (2000), which operates with a fixed leaching quantity and a fixed application of wastewater.

To account for the fact that any wastewater treatment system design cannot be based solely on average wastewater flows, the designer must conduct a simulation of the water balance using long-term (50 years or more is best) precipitation data. Using the water balance equation and obtaining the limits for soil water holding capacity in the root zone, the actual quantity of leaching is determined along with the associated volume of storage required. Monthly precipitation data can be obtained from historical records or can be synthetically generated based on historical records available. Note that the synthetically generated precipitation data will have the same statistical parameters as the base historical data. The principal difference in using synthetic data is that more years of simulation are allowed and, thus, a greater probability of generating extreme conditions exists. Most climatic stations have approximately 80 years of historical data. This period is of sufficient length to provide reasonable results regardless of the method of obtaining precipitation data.

**Site Evaluations**

**Groundwater Nitrogen**

Nitrate-nitrogen data from the individual monitoring wells collected quarterly from mid-1991 through 1999 were used to determine the progress of the groundwater remediation plan that was implemented. To examine the data, the area of each NO$_3$-N concentration plume (contour) greater than 10 ppm was used to determine the mass of nitrogen beneath the LAS. The mass of nitrogen was determined by taking a unit depth for those contour areas, multiplying by the respective nitrate concentration, which resulted in a unit mass basis for comparison between each set of quarterly data. Since any single quarterly data only represented a snapshot in time, the quarterly data were averaged to produce an average annual mass of nitrogen. The total of these products provides the total mass of NO$_3$-N that exists for a unit depth beneath the entire LAS and the surrounding and consecutively joined areas. This procedure was completed for each quarter
during the 8-year period from 1992 through 1999. The resulting eight annual data points were then plotted against time (Figure 2).

From this plot, it can be seen that the total mass of NO$_3$-N beneath the LAS is decreasing. When a linear function is determined for the data, it indicates that the mass of NO$_3$-N would be reduced to allowable levels (10 mg/L NO$_3$-N) in 12 to 16 years after 1999. A linear decline in the nitrate concentration is not expected due to the natural processes of water movement. The true relationship will follow an exponential decay-type function with time. This type function appears to be occurring. Based on this more representative function, the nitrate decay rate was determined to be 13% per year. With this rate of decay, nitrate removal from the site will take nearly 30 years since initiation if no changes in the current operation of the LAS pumping scheme are made. The principle reason a status quo operation will take longer than initially predicted is that many of the active pumping wells are not located centrally within the actual nitrate plumes.

**Depth to Groundwater**
When the groundwater remediation plan was implemented, the area found to be the peak of the groundwater mound was on the north side of Plot 13 where the water elevation contour was 3150 ft with an actual recorded maximum value of 3152.8 ft. In 1999, the groundwater elevation in that same region was 3114 ft, which is a reduction of 36 ft. Considering only the change in elevation between 1991 and 1999, the total reduction in the groundwater mound was 22 ft. This region of the main groundwater mound has been reduced to the point that no “mound” of groundwater exists. The groundwater elevation contours from the northwest region of the site to the southeast region show a continuous decline, which is the natural flow of the water in this region.

Moving across the Land Application Site from the northwest to the southeast region, the reduction in the groundwater elevation decreased by 2 ft. In the region of the boundary corner southeast of Plot 17, the total reduction in groundwater elevation is 10 ft. Moving to the corner of 50th Street and FM 835, the reduction in the groundwater elevation is 8 ft. From the northwest corner of Plot 25 to the southeast corner of Plot 27, the groundwater elevation reduction is from 5 ft to 2 ft. Since 1991 in this same region, the groundwater elevation has remained nearly unchanged. In the region where a groundwater mounding problem did exist, it has been proven that adequate reductions can be achieved. The newer land of the LAS has been operated under the optimum design approach based on the water balance and there is no impact on the groundwater.

**Soil Nitrogen**

For the analysis of nitrogen in the soil, three plots were chosen to represent land irrigated from as little as 8 years to as much as 67 years. Plots 6, 9, and 13 were selected where Plot 6 has been irrigated since 1991, Plot 9 since 1987, and Plot 13 since 1932. Total Kjeldahl nitrogen (TKN) and nitrate-nitrogen analyses were performed on soil samples collected monthly since May 1997 at two depths, 0 to 6 inches and 18 to 24 inches. A summary of the nitrogen data is provided in Table 1. The only plot with a difference in the TKN is Plot 13, which is the longest operated plot in the study. Plot 13 began with a cotton and wheat rotation for the first year of the study period and was then changed to alfalfa. Plots 6 and 9 have had alfalfa growing until recently when they were changed to a tall wheat grass. Each plot was grazed with cattle as the mechanism for harvesting the crops, and thus the nitrogen.

During this test period, the total nitrogen (TN) concentration in the treated effluent averaged 20 mg/L, the NO₃-N concentration averaged 13 mg/L, and the ammonia concentration averaged 4.4 mg/L. During this period, the average wastewater application depth was 4.8 ft annually, which is equivalent to a total of 260 lb. N/acre applied annually. There is no significant difference (p<0.05) in the soil nitrogen concentration for either TKN or NO₃-N at either depth among all the plots tested. This illustrates the fact that, with a properly operated scheduling of the wastewater applications, large quantities of nitrogen will not accumulate in the soil. Nitrogen removal from a land application system results from more than just plant harvesting. Mineralization of the organic nitrogen to inorganic forms allows for plant uptake, volatilization, and leaching of the more
soluble forms (Feigin, 1991; Broadbent ad Resisenauer, 1985; Brockway et al., 1972). In addition, active microbial growth will immobilize inorganic nitrogen in the form of nucleic acids and proteins (Loehr et al., 1979). Overall, the wetting and drying that occur with each successive irrigation event allow both the nitrification and denitrification processes to proceed. These two processes are critical, and significant, to good nitrogen removal in a land application system (Suzuki, 1992; Monnett et al., 1995; Russell et al., 1993; Korom and Jeppson, 1994).

A small study was completed to examine the concentration of TKN in the soil following a period of wastewater application. It was determined that a constant background concentration of TKN in the soil could be reached within 4 to 6 days following the application. The background concentration at the 0 to 6 inch layer was found to be 280 mg/kg. In the 18 to 24 inch layer the TKN concentration was 370 mg/kg. This is most likely contributable to the fact that more conversion of the organic fraction is occurring in the upper layer due to nitrification. The decay rate for TKN at the 0 to 6 inch depth following application was found to be 0.77 units per day (p<0.05) compared to 0.54 units per day (p<0.05) at the 18 to 24 inch depth.

TABLE 1. Summary of nitrogen concentration in the soil of Plots 6, 9, and 13 at depths of 0 to 6 inches and 18 to 24 inches.

<table>
<thead>
<tr>
<th>TKN, mg/kg</th>
<th>0 to 6&quot;</th>
<th>18 to 24&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plot</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>560</td>
<td>750</td>
</tr>
<tr>
<td>9</td>
<td>600</td>
<td>770</td>
</tr>
<tr>
<td>13</td>
<td>990</td>
<td>862</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>N0₃-N, mg/L</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>3.7</td>
<td>1.1</td>
</tr>
<tr>
<td>9</td>
<td>7.2</td>
<td>2.4</td>
</tr>
<tr>
<td>13</td>
<td>4.7</td>
<td>2.8</td>
</tr>
</tbody>
</table>

**Conclusion**

Design of land application systems is a complicated process that must incorporate the principles of land limiting constituents, irrigation and the respective inefficiencies, water balance, evapotranspiration, and crop selection which include nutrient assimilation and leaching requirements. Each of the principles must be carefully analyzed, both independently and collectively, to provide the optimum design. From the standpoint of nitrogen, long-term application of secondary treated wastewater on land where crops are harvested can be successful when designed and operated from the philosophy of a water balance and scheduling of the wastewater irrigation. The Lubbock, Texas Land Application Site has been in operation since the
mid-1920’s operating under typical agricultural practices. In the beginning, an area farmer operated the LAS by applying an average of 5.6 ft of effluent to 200 acres of land, growing mostly cotton and some grasses. As the wastewater flows increased to nearly 8 mgd in the mid-1950’s, the land area where effluent was applied increased to about 1800 acres. This increase in operation size decreased the average effluent application to 5 ft annually on mostly cotton with a double crop of wheat and on small amounts of alfalfa or grasses.

Unfortunately, the best available technology in the early years was insufficient, especially with regard to understanding the crop water and nutrient requirements. Currently, this understanding of the crop-water-soil system is far greater, which has contributed to the correction of some problems created by their predecessors. When a land application system for secondary treated municipal wastewater is properly designed, both from the standpoint of good engineering principles and good agricultural practices, the system can be operated successfully for many years without posing a threat to the environment.

Total nitrogen in the effluent applied to the soil varied from 10 to 25 ppm. The nitrate nitrogen in the top 2 ft of soil varied from 0 to 15 ppm with an average of about 3 ppm resulting in readily available nitrogen for plant uptake averaging about 38 lb/acre. These low values of available nitrogen illustrate that when the operators follow the schedule of irrigation as prescribe by the optimized design approach, plants are efficiently removing nitrogen, thus preventing the potential for groundwater contamination.

References


