Final Report

Edwards Aquifer Recharge Zone Irrigation Pilot Study

Prepared for

San Antonio Water System

CH2MHILL

in association with

Texas A&M University

May 2004

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Executive Summary

The Edwards Aquifer is the primary source of drinking water for the City of San Antonio, the second most populated city in Texas. Because of the high quality of the aquifer water, it requires no pretreatment before distribution to the community. However, current pumping demands from the aquifer have reached the maximum sustainable rate, and future development of the city of San Antonio and the surrounding areas will depend on developing alternate water sources combined with wise and conservative use of the available aquifer water. One alternative water source suitable for irrigation and many industrial activities is recycled water; recycled water is municipal wastewater that has been treated to meet specific health and environmental standards. Therefore, the San Antonio Water System (SAWS) has invested in the design and construction of two main distribution systems from their wastewater treatment facilities, which produce Type 1 recycled water. Type 1 recycled water represents the highest level of tertiary treatment and is intended to allow the safe utilization of recycled water for conservation of surface and ground water, to ensure the protection of public health, to protect ground and surface waters, and to supplement potable water resources with an adequate supply of an alternate water source for present and future needs. Type I water quality requirements were also established for safe incidental human contact. SAWS has built more than 74 miles of pipeline capable of delivering up to 35,000 acre feet of Type 1 recycled water annually to customers throughout the city and nearby areas. Primary purchasers of recycled water have been golf courses, military bases, parks, cooling tower operations, sod farms and other facilities managing large acreage of irrigated turf.

During the initial investigation of the recycled water pipeline construction route, SAWS received requests to provide recycled water for the irrigation of facilities located over the Edwards Aquifer Recharge Zone (EARZ). Great concern was raised that use of recycled water over the EARZ would result in contamination of the aquifer, including contamination due to plant nutrients, other inorganic or organic chemicals that may be present in recycled water, or disease causing biological organisms such as fecal coliforms. To aid in SAWS' decision making process regarding whether or not to provide recycled water service to facilities located over the EARZ, the Edwards Aquifer Recharge Zone Irrigation Pilot Study (EARZIPS) was conducted. One of the major goals during the design and development of the EARZIPS study conditions was to mimic the soil conditions and irrigation practices used at golf courses currently located on the EARZ. The EARZIPS' primary objective was to provide scientific information to SAWS concerning the fate of nutrients and other constituents of Type I recycled water when used for irrigation of turf areas on the recharge zone and the potential for contamination of the underlying aquifer. A second major objective was to compare the amounts of nutrients and other constituents in runoff and leachate from turf-covered areas irrigated with Type 1 recycled water versus Edwards Aquifer water. The third objective was to conduct two literature reviews to summarize the current state of knowledge concerning 1) the fate of plant nutrients, and 2) the fate of biological organisms and biologically active compounds in irrigated soils. The literature reviews were intended to help put the current study into perspective with the larger body of knowledge and possibly aid in the extrapolation of the present field data to other locations and soil conditions.

Therefore, the results of the current study would include:

- Recommendations on proper use of recycled water and fertilizers on turf over the Edwards Aquifer Recharge Zone based on the data collected in this study and the results of the analyses performed.
- Assessment of potential negative environmental impacts associated with the use of recycled water over the recharge zone.
- Comparison of leachate and runoff water quality of recycled and Edwards irrigation plots.

Table ES.1 presents the key issues of the project in a table format.

The pilot study was a collaborative effort between CH2M HILL, Texas A&M University, and SAWS. The study was designed to last two years beginning in March of 2002 and ending in March of 2004. The study site is located on a 5-acre tract of land within the Bladerunner Turf Farms, Inc. (BTF), immediately adjacent to SAWS' Leon Creek Water Recycling Center.

Typically, the Edwards Recharge Zone has a shallow soil profile with a thickness ranging from 0 to 18 inches. Many of these surface soils are characterized as belonging to the Tarrant Series. The Tarrant Series is described as a thin layer of stony soils consisting of clay and silty clay (loam) with large limestone fragments. The limestone fragments range from one-quarter of an inch to in excess of 24 inches in diameter, and comprise approximately 20 percent of the soil layer by volume. These soils occur on the limestone prairies, typically found overlying the Edwards Limestone formation.

Beneath the surface soils lies the Edwards Limestone Group (undivided). This group is divided into two formations, the upper Person Formation, and the lower Kainer formation. The Person Formation is made up of limestone and dolomite with common chert nodules, and ranges from 200 to 260 feet in thickness. Typically brownish gray, near the surface the Person weathers to yellowish orange.

According to the Bexar County Soil Survey, the Bladerunner Turf Farm is located on a deposit of Lewisville silty clay soil series. Soil analyses were performed at the site, and the resulting data illustrated a similarity to fairway soils at a large golf complex. This complex is located on the EARZ and has expressed interest in recycled water service from SAWS.

The Lewisville series is part of the Lewisville-Houston Black, terrace association, which covers approximately 12 percent (roughly 95,846 acres) of the county. The Lewisville soil series is a fertile and productive soil that is desirable for use in urban areas that may be deficient in topsoil. It would not be unusual to see this type of soil mined and sold for use as supplemental topsoil for home lawns, highway medians, parks, golf courses, or other landscaped areas. This is a common practice in areas such as the EARZ where native topsoil is thin or, in some cases, insufficient. Selection of this soil for use in the Turf Study is acceptable because it served as a "typical" soil that exhibits both runoff and macropore flow.

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Primary Objective	The EARZIPS' primary objective was to provide scientific information to SAWS concerning the fate of nutrients and other constituents of Type I recycled water when used for irrigation of turf areas on the recharge zone and the potential for contamination of the underlying aquifer. The results of this study will include recommendations on the use of recycled water and fertilizers on turf over the Edwards Aquifer Recharge Zone based on the data collected in this study and the results of the analyses performed.
Study Site	A five-acre tract of land at the Bladerunner Turf Farms, Inc., adjacent to the San Antonio Water System's Leon Creek Water Recycling Center.
Experimental Design	A total of eighteen study plots were arranged in a random manner. Each plot was 20 feet by 20 feet, with an additional 5 feet of non-irrigated buffer area around the perimeter of each plot. Leachate samples were collected from the center 10 feet by 10 feet inner area to avoid potential edge effects. Plots included three replications each of three irrigation treatments (Edwards Aquifer water applied at the potential evapotranspiration rate, SAWS' recycled water applied at the potential evapotranspiration rate, and SAWS' recycled water applied at the rate of potential evapotranspiration plus a leaching fraction) and two turfgrass species (bermudagrass and zoysiagrass).
Waters Used for Irrigation	Recycled water was obtained from the San Antonio Water System's Leon Creek Water Recycling Center. Edwards Aquifer water was obtained from the SAWS municipal potable water system. Water supplies to the site were constructed to deliver approximately equal water pressure to help ensure equal water application rates.
Irrigation Treatments	All irrigation occurred between 8:00 p.m. and 10:00 a.m. The following three irrigation treatments were employed: 1. Replacement of the potential evapotranspiration (PET) rate using recycled water (1XRW treatment). 2. Replacement of the potential evapotranspiration rate plus a 10% leaching fraction using recycled water (LFRW treatment). 3. Replacement of potential evapotranspiration rate using Edwards aquifer water (EA treatment).
Turf Grasses Tested	Jamur zoysiagrass and Tifway 419 hybrid bermudagrass were the turf grasses employed. These grasses were selected as being representative of turf grass species commonly used on golf course fairways in the San Antonio area.
Duration of Study	The study began in March of 2002 and ended in February of 2004.
Fertilizer Applications	Because the soils already had adequate Phosphorus, Potassium, Magnesium and Iron, the fertilization program centered on applying the required amount of N for good turf growth and quality. During the first year, 2 and 3 pounds nitrogen per 1,000 square feet were applied as ammonium sulfate to the zoysiagrass and bermudagrass plots, respectively (not including nitrogen applied through irrigation water). During the second year, fertilizer applications were made in smaller but more frequent amounts, applying a total of 4 and 6 pounds nitrogen (including nitrogen applied through irrigation water) per 1,000 square feet to the zoysiagrass and bermudagrass plots, respectively. During the second year, granular fertilizer applications were adjusted to account for the N content of the recycled water. This practice is typical good management for users of recycled water.
Soil Textures	Soil textures identified at Bladerunner Turf Farms, Inc. were very similar to those on the fairways of a large golf complex. This complex is located on the Edwards Aquifer Recharge Zone and has expressed interest in recycled water service. Therefore, the San Antonio Water System conducted the study without any modification of the soil types and profiles at the experimental site. The golf course complex had Clay and Clay Loam soils, while the study site had Clay, Clay Loam, and some Silty Clay and Silty Clay Loam soils.
Irrigation System	Each test plot was equipped with four pop up irrigation heads (1.0 gpm Rain Bird T-Bird). Heads were located at each corner of the plots and provided head-to-head coverage for optimum coverage and uniformity. The system was designed to provide complete separation and independent operation of

TABLE ES.1
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	the two water sources: Edwards and recycled water. Three programmable valves and totaling water meters provided control and monitoring of the amount of irrigation provided to each plot.
Sampling	Lysimeters: Water samples were collected monthly from glass block lysimeters buried at three depths. Additional samples were collected immediately following storm events that produced over 1.5 inches of precipitation in a 24 hour period at the field site. Soils: Soil samples were collected quarterly from all plots. Runoff: Runoff water samples were collected from the six plots equipped with runoff collection systems any time there was sufficient volume in the collection bottles. Tissues: Plant tissue samples were collected monthly from each plot during the growing season. Rainwater: Several rainwater samples were collected during 2003.
Endpoints Evaluated	Constituents of concern that were quantified in the turfgrass tissue, soil, rainfall runoff, and leachate volumes are as follows: Lysimeter water samples: total Salts, calcium, copper, iron, magnesium, manganese, nitrogen (ammonium, nitrate, nitrite, and total Kjeldahl nitrogen), phosphorus, potassium, sodium, zinc and fecal coliform. Soil samples: total salts, calcium, copper, iron, magnesium, manganese, nitrogen (ammonium, nitrate, nitrite, and total Kjeldahl nitrogen), phosphorus, potassium, sodium, and zinc. Runoff water samples: total salts, calcium, copper, iron, magnesium, manganese, nitrogen (ammonium, nitrate, nitrite, and total Kjeldahl nitrogen), phosphorus, potassium, sodium, zinc and fecal coliform. Tissue samples total salts, calcium, copper, iron, magnesium, manganese, total Kjeldahl nitrogen, phosphorus, potassium, sodium, and zinc. Rainwater samples: total salts, calcium, copper, iron, magnesium, manganese, nitrogen (ammonium, nitrate, nitrite, and total Kjeldahl nitrogen), phosphorus, potassium, sodium, zinc and fecal coliform. Aesthetics: Each plot was photographed and evaluated for turf quality on a monthly basis. Turf quality was visually rated on a scale of 1 to 9 with 9 equating to the best quality.
Literature Reviews	The following two literature reviews were conducted to act as supporting documentation for the present study: 1. Potential Groundwater Contamination from Irrigation of Turf with Recycled Water 2. Risk Evaluation of Microbiological and Toxicological Components of the San Antonio Water System's Recycled Water: A Literature Review
Conclusions	**Aesthetics:** Turf quality was very low at the start of the study due to poor maintenance and winter dormancy. By mid-summer of the first year, the quality had increased to a high rating of 8 or above. Turf quality showed a seasonal trend of increased quality in the summer months and decreased quality during the winter. Irrigation treatments had no significant effect on turf quality, indicating that the SAWS Type 1 recycled water may be used to irrigate turf with no adverse effect on turf quality. **Runoff water samples**: The depth of runoff from the six plots that were outfitted with collection devices was highly variable and ranged from 9.4 to 31.5 inches of water. However, 5 of the 6 plots that were monitored for runoff had amounts in the range of 9.4 to 17.9 inches, which is a more typical range. The electrical conductivity of the runoff water was in the range of 0.167 to 0.193 dS/m, or 107 to 124 mg/L TDS, which is well within the safe range and should not have any adverse environmental impacts. Although in the safe range, plots receiving the recycled water generally had higher EC values in the runoff water.

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Sodium concentrations in the runoff water remained less than 40 mg/L and should not have any adverse environmental impacts.

Manganese concentrations in the runoff water remained less than 0.40 mg/L and should not have any adverse environmental impacts.

Magnesium concentrations in the runoff water remained less than 14 mg/L and should not have any adverse environmental impacts.

Iron concentrations in the runoff water remained less than 18 mg/L and should not have any adverse environmental impacts.

Copper and zinc concentrations in the runoff water remained less than 0.2 mg/L and should not have any adverse environmental impacts.

Calcium concentrations in the runoff water remained less than 125 mg/L and should not have any adverse environmental impacts.

Potassium concentrations in the runoff water remained less than 16 mg/L and should not have any adverse environmental impacts.

Total Kjeldahl Nitrogen concentrations in the runoff water remained less than 8 mg/L and should not have any adverse environmental impacts.

Nitrite concentrations in the runoff water remained less than 2 mg/L, with the majority of samples less than 0.5 mg/L, and should not have any adverse environmental impacts.

Ammonia concentrations in the runoff water remained less than 2.25 mg/L. These concentrations were similar to the EA treatment samples and should not have any adverse environmental impacts.

The fecal coliform concentrations were also similar to those of the EA treatment, although the measured values were quite variable.

The data indicate that nitrate concentrations in runoff may reach as high as 45 mg/L; however, nitrate concentrations from treatments receiving SAWS recycled water had nitrate concentrations similar to those from the EA treatments. While nitrate concentrations above 10 mg/L are of some environmental concern, these levels were not reached on a consistent basis. Therefore, nitrates in runoff from irrigated turf areas may have an occasional small adverse environmental impact.

Leachate samples:

Leachate from the lysimeters at the 6-inch depth had a small but significantly greater pH compared to that from the 18 and 30-inch depths. Therefore, the use of recycled water on soils that are at least 18-inches deep should have no effect on the pH of water leaching past the root zone of turf areas.

The mean electrical conductivity of the runoff water ranged from 0.499 to 0.653 dS/m, or 319 to 418 mg/L TDS, which is well within the safe range and should not have any adverse environmental impacts. Although in the safe range, plots receiving the recycled water had significantly higher EC values in the leachate water passing the 30-inch depth and will contribute small amounts of salts to the groundwater.

In 14 out of 15 sampling dates, there were no significant differences between the iron concentrations from the different irrigation water treatments. On the one date when significant differences were present, the EA treatment had the highest iron concentration. Thus, the use of recycled water for irrigation of turf will not significantly affect the iron concentration in the leachate moving below the root zone. Consequently, the use of recycled water for irrigation of turf areas should not impact the iron content of underlying aquifers any more than if Edwards Aquifer water were used for irrigation.

Approximately half of the measured mean iron concentrations in leachate were above the EPA MCL of 0.3 mg/L for drinking water. Thus, leachate from turf areas irrigated with either Edwards Aquifer water or SAWS Recycled water will pose a significant possibility of iron contamination of groundwater reserves.

The leachate from the upper 6-inch samplers had the highest magnesium concentration, followed by that of the 18-inch and 30-inch samplers. There also was a significantly higher magnesium concentration in the leachate from the LFRW plots as compared to that from the EA treatment plots. Leachate from the 1XRW plots contained an intermediate magnesium concentration and did not differ from either of the other treatments. Therefore, water leaching past the 30-inch depth will carry higher amounts of magnesium with it and will contribute small amounts of magnesium to the groundwater.

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In the majority of cases, the use of recycled water for irrigation of turf will not significantly affect the ammonia nitrogen concentration in the leachate moving below the root zone and, therefore, should not impact the ammonia nitrogen content of underlying aquifers any more than if Edwards Aquifer water were used for irrigation.

Through the majority of the study (September 2002 through October 2003), the mean nitrate values all remained below 10.0 mg/L, which is the primary EPA Standard for nitrate concentrations in drinking water. There did appear to be a general trend of greater nitrate concentrations in the leachate from the 1XRW and LFRW plots; however, differences were not always statistically significant.

Mean nitrite values were all at or below 0.71 mg/L, which is low and of little environmental concern. When the data were analyzed by irrigation water treatment, no significant differences between irrigation water treatments were found for any of the dates. Thus, the use of recycled water for irrigation of turf will not significantly affect the nitrite concentration in the leachate moving below the root zone. Consequently, the use of recycled water for irrigation of turf areas should not impact the nitrite content of underlying aquifers any more than if Edwards Aquifer water were used for irrigation.

The leachate from the upper 6-inch samplers had the highest potassium concentration, followed by that of the 18-inch and 30-inch samplers. There also was a significantly higher potassium concentration in the leachate from the 1XRW plots as compared to that from the EA and LFRW treatment plots. Therefore, water leaching past the 30-inch depth will carry similar amounts of potassium with it as if the same area were irrigated with Edwards Aquifer water. Based on this information, turf areas irrigated with SAWS Recycled water will not pose a significant danger of potassium contamination of groundwater reserves.
The data from this study show that, in the majority of cases, the use of recycled water for irrigation of turf will not significantly affect the zinc concentration in the leachate moving below the root zone. Consequently, the use of recycled water for irrigation of turf areas should not impact the zinc content of underlying aquifers any more than if Edwards Aquifer water were used for irrigation.
Based on the results of this study, irrigation of turf areas with SAWS recycled water should not significantly change the manganese concentration of water leaching past the root zone. The data also indicate that manganese concentrations in the leaching water should be independent of soil depth and turfgrass species.

Based on the data from this study, the use of recycled water for irrigation of turf will not significantly affect the copper concentration in the leachate moving below the root zone. Consequently, the use of recycled water for irrigation of turf areas should not impact the copper content of underlying aquifers any more than if Edwards Aquifer water were used for irrigation.

Except for the October 21, 2003, the mean Zn values all ranged at or below 0.2 mg/L, which is well within the EPA Secondary Standard of 5.0 mg/L for Drinking Water. Based on these results, leachate from turf areas irrigated with either Edwards Aquifer water or SAWS Recycled water will not pose a significant danger of zinc contamination of groundwater

In the majority of cases, the use of recycled water for irrigation of turf will not significantly affect the number of Fecal Coliform in the leachate moving below the root zone. Consequently, the use of recycled water for irrigation of turf areas should not impact the Fecal Coliform levels of underlying aquifers any more than if Edwards Aquifer water were used for irrigation.
There also was a significantly higher sodium concentration in the leachate from the LFRW and 1XRW plots as compared to that from the EA treatment plots. Therefore, water leaching past the 30-inch depth will carry significantly greater amounts of sodium with it than if the same area were irrigated with Edwards Aquifer water. Based on this information, turf areas irrigated with SAWS Recycled water will pose a small but significant possibility of sodium contamination of groundwater reserves.

In the majority of cases, the use of recycled water for irrigation of turf will not significantly affect the concentration of phosphorus in the leachate moving below the root zone. Consequently, the use of recycled water for irrigation of turf areas should not impact the phosphorus levels of underlying aquifers any more than if Edwards Aquifer water were used for irrigation.**Soil samples:**

Irrigation with SAWS Type 1 recycled water had little to no effect on soil concentrations of calcium, copper, iron, magnesium, manganese, phosphorus, potassium, total Kjeldahl Nitrogen and zinc. A slight increase in electrical conductivity was observed and a significant increase in sodium was

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	measured in soils which received recycled water. **Tissue samples:** Irrigation with SAWS Type 1 recycled water had little to no effect on concentrations of calcium, copper, iron, manganese and phosphorus in turf tissue. Irrigation with SAWS Type 1 recycled water did, however, show occasional increases in the levels of magnesium, zinc and total Kjeldahl nitrogen in turf tissue samples. Definite increases were observed for potassium and sodium concentrations in turf tissue samples. **Mass balance:** To determine the amount of each constituent that migrates to the groundwater, the actual leachate volumes were multiplied by the constituent concentration found in the leachate. Analysis of the results showed that the use of SAWS Type 1 recycled water will result in significantly greater amounts of ammonia, manganese, phosphorus, potassium and total Kjeldahl Nitrogen migrating below the 30-inch depth and possibly to the groundwater. Note, though, that all constituents that were identified as being statistically significant when compared to the Edwards Aquifer water are not listed as a primary drinking water standard. When one takes into consideration the ever-recharging aquifer system and the dilution factor, it is questionable if any overall adverse impact to the system would occur if recycled water was employed over the EARZ.
Quality Control Measures	Control plots irrigated with Edwards Aquifer water were tested concurrently with plots irrigated with recycled water to determine if any study conditions other than irrigation water type influenced the study. Constituent levels were also used for comparison purposes.

As such, it was a good test case to determine potential pollutant migration via runoff and leaching. This aids in making the results from this study more widely applicable to other soils and locations in and near Bexar County.

A total of 18 test plots, each 20 feet by 20 feet, were established on the study site. Plots were randomly assigned to three irrigation treatments, two grasses, and three replications. Irrigation treatments included replacement of potential evapotranspiration (PET) using Edwards Aquifer water (EA), replacement of PET using SAWS recycled water (1XRW), and replacement of PET plus 10 percent for a leaching fraction using SAWS recycled water (LFRW). Turf grasses used were 'Tifway 419' hybrid bermudagrass and 'Jamur' zoysiagrass. The study site was equipped with a weather station to measure environmental conditions and to calculate PET. Each plot was equipped with three underground glass block lysimeters that allowed collection of leachate water at 6, 18, and 30 inches below the soil surface. One plot of each irrigation treatment and grass combination was equipped with a runoff collection device.

Leachate samples were collected from all lysimeters monthly or more frequently in the event of large rainfall amounts. Soil samples were collected from the upper 6 inches of each plot quarterly. Tissue samples were collected from all plots on a monthly basis during the growing season (April to October). Runoff samples were collected whenever present. A summary of the sample collection and frequency schedule is presented in **Table ES.2**. All samples were sent to the SAWS Dos Rios Laboratory for analysis of approximately 20 chemical constituents and associated soil and water properties. When sufficient sample volumes were available, duplicate samples were sent to the Cooperative Extension Soil, Water and Forage Testing Laboratory at Texas A&M University for duplicate analysis.

TABLE ES.2
Sample Collection and Frequency
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Type of Sample	Frequency of Collection
Tissue	Monthly[1]
Lysimeter	Monthly[2]
Runoff	When runoff occurred
Soil	Quarterly
Rainwater	Five samples taken in 2003 during rain events

1. Tissue samples were only collected between April and October when the grass was actively growing.
2. Lysimeter samples were also collected if a rain event delivered 1.5 inches or more within a 48 hour period to the turf site.

Cumulative runoff depths measured for the study period ranged from 9.4 to 31.5 inches. However, 5 of the 6 plots that were monitored for runoff had amounts in the range of 9.4 to 17.9 inches, which is a more typical range. The electrical conductivity of the runoff water was in the range of 0.167 to 0.193 dS/m, or 107 to 124 mg/L TDS, which is well within the safe range and should not have any adverse environmental impacts. Although in the safe range, plots receiving the recycled water generally had higher EC values in the runoff water.

Cumulative leachate volumes ranged from 22.1 to 38.9 liters. Statistical evaluation of the leachate volumes showed no differences due to irrigation treatment for the 6 and 18 inch deep lysimeters. However, the 30 inch deep lysimeters in the EA treatment produced significantly less leachate than did lysimeters in the 1XRW and LFRW treatments. The average electrical conductivity of the leachate samples over the entire study period ranged from 0.499 to 0.653 dS/m, or 319 to 418 mg/L TDS, which is well within the safe range. Irrigation treatment did result in significant differences in the EC of the leachate water. Leachates from the 1XRW and LFRW plots had significantly greater EC values than that from plots irrigated with EA water.

Due to the higher amount of total salts in the recycled water, the plots receiving recycled water had significantly higher EC readings as compared to the soil from the plots irrigated with EA water. However, the EC values from all plots were within the range considered to be safe for turf growth. Therefore, no irrigation leaching requirement was necessary during this two year study to flush out accumulated salts from the soil. Significant rainfall events were instrumental in maintaining an acceptable salt level in the soil.

Visual ratings of turf quality including turf density, color and uniformity were low in the spring and late fall but were high throughout the majority of the growing season. There were no statistically significant differences in aesthetic ratings due to irrigation treatments.

For most sampling dates, the sodium and potassium contents of the tissue samples from the EA plots were lower than that of plots irrigated with recycled water. In addition, occasional increases in the levels of magnesium, zinc and total Kjeldahl nitrogen were measured in turf tissue samples from treatments irrigated with recycled water

Based on the data from this study and provided that turf areas are irrigated responsibly using PET or a fraction thereof to guide the irrigation rate, and a responsible nutrient management program is employed, Type I recycled water may be used for irrigation with a minimal impact on groundwater quality. In other words, if large scale turf irrigators located on the EARZ use SAWS recycled water, the data from this study indicate that it will result in no statistically significant impact to the Edwards Aquifer water quality as compared to irrigation with potable Edwards Aquifer water. Also, there is minimal impact to receiving waters when using recycled water over the recharge zone.

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SECTION 1.0

Project Definition

Several million people who live and work in south-central Texas share the Edwards Aquifer and its associated recharge zone—Edwards Aquifer Recharge Zone, or EARZ. The Edwards Aquifer is a limestone aquifer that displays a "karst" topography on its recharge zone, meaning that caves, sinkholes, and other surface features are present that allow water to enter and recharge the aquifer. Groundwater within the Edwards moves through the system rapidly, relative to other aquifers. The need to protect surface and groundwater quality is a serious environmental issue. Because of the pristine quality of this very important resource, water from the Edwards Aquifer is not treated prior to distribution for potable use. Therefore, activities on the Edwards Aquifer Recharge Zone that adversely affect the water quality of the recharge water and, eventually, the aquifer cannot be allowed.

In addition to this, the Edwards Aquifer is the primary source of drinking water for the City of San Antonio, the second most populated city in Texas. Presently, the Edwards aquifer has reached a point where demands for pumping and springflows cannot be met from historical recharge. As a result, using existing water resources wisely, enhancing the Edwards Aquifer, and developing new water resources are critical to the continued progress and prosperity of San Antonio and the Edwards region.

The EARZ and the contributing region above the Edwards Aquifer have aesthetically appealing landscapes that draw people to the area to live, work, and play. The landscape also contributes considerably to the economic viability of the San Antonio community. In fact, statewide, the economic impact of landscape installation and maintenance is estimated at more than $10 billion (Lard and Hall, 1996). But these activities increase the potential for contaminants to enter the aquifer. Irrigation of urban landscapes, including home lawns, parks, sports fields, and golf courses, not only depletes this precious resource from within the aquifer, but may introduce pesticides, herbicides, fertilizer, and other potentially harmful chemicals. This potential for contamination is exacerbated by the poor soil conditions above the EARZ. Typically, the Edwards Recharge Zone has a soil profile with a thickness ranging from 0 to 18 inches. Many of these surface soils are characterized as belonging to the Tarrant Series. The Tarrant Series is described as a thin layer of stony soils consisting of clay and silty clay (loam) with large limestone fragments. The limestone fragments range from one-quarter of an inch to in excess of 24 inches in diameter, and comprise approximately 20 percent of the soil layer by volume. Shallow, stony soils of this type provide numerous flow paths for water and pollutant movement below the root zone.

Although, maintaining golf course turf at acceptable levels in the San Antonio area requires inputs of plant nutrients and water, trained and environmentally sensitive golf course superintendents manage most golf courses. However, despite using best management practices (BMPs), golf courses often border lakes, ponds, and streams, so the potential for nutrient contamination of surface water and, eventually, aquifer water is a subject of environmental concern. In contrast, many home and business owners have little to no environmental knowledge, yet they maintain lawns and landscaped areas often resulting in greater potential environmental contamination than that from larger landscaped areas managed by trained professionals.

The San Antonio Water System (SAWS) Water Recycling Program completed construction of more than 74 miles of concrete steel cylinder pipeline to provide 35,000 acre feet annually of tertiary-treated Type I recycled water to commercial and industrial businesses in San Antonio, Texas. The use of recycled water replaces approximately 20 percent of SAWS' water demand on the Edwards Aquifer. Therefore, aquifer water can be preserved for drinking water, thus allowing San Antonio a continued quality of life. Advantages of using SAWS' recycled water include: 1) an unrestricted water source that can be used in times of drought or curtailment of Edwards Aquifer potable water, 2) a reduced purchase price in comparison to SAWS' potable water, and 3) an irrigation water supply that contains nutrients essential for plant growth. Recycled water will help to preserve the economic vitality of the region by providing businesses with a firm supply of water for commercial, industrial and manufacturing purposes. Additionally, reuse of treated municipal wastewater for irrigation is an essential element of the SAWS Conservation and Reuse Plan, which was designed to reduce the use of potable groundwater for non-potable applications. One major goal of this Plan is to virtually eliminate the use of groundwater for irrigation and stream augmentation and to preserve the integrity of the Edwards Aquifer.

The Texas Commission on Environmental Quality (TCEQ) is the governing State agency that regulates the quality criteria, design, and operational requirements of recycled water programs. As defined and specified in the *Use of Reclaimed Water*, Texas Administrative Code (TAC), Chapter 210, the requirements must be met by producers, providers, and/or users of recycled water. The criteria outlined in Chapter 210 are intended to allow safe utilization of recycled water for conservation of surface and groundwater; to ensure the protection of public health; to protect ground and surface waters; and to help ensure an adequate supply of water resources for present and future needs. As stated in Chapter 30 TAC ξ 210.33(l), the minimum recycled water quality for Type I recycled water is:

BOD_5 or $CBOD_5$	5 mg/L[1]
Turbidity	3 NTU[1]
Fecal Coliform	20 CFU/100 ml[2]
Fecal Coliform	75 CFU/100 ml[3]

[1] Thirty day average (not to exceed)
[2] Geometric mean (the nth root, usually the positive nth root, of a product of n factors)
[3] Single grab sample (not to exceed)

For comparison, the following is the typical quality of SAWS' Recycled Water:

BOD_5	<2.0 mg/L[1]
Turbidity	1 NTU
Fecal Coliform	<10 CFU/100 ml

[1] Thirty day average

Seventy-eight potential recycled water customers initially requested from SAWS approximately 47,000 acre feet of recycled water. Presently, TCEQ's Chapter 210 allows for the use of only Type I recycled water on the EARZ. Currently, Type I recycled water is the only level of treated recycled water that is designated as safe for incidental human contact. However, this allowance is tempered by special requirements, including initial holding pond permeability criteria. Despite this allowance, the SAWS Board of Trustees opted not to deliver recycled water due to a lack of review of technical issues and a concern about political issues if such a policy were implemented. As such, EARZ developments that are considering the use of recycled water require the development of a standardized policy for the treatment and use of recycled water on the EARZ.

Most of the requests for recycled water on the EARZ were for golf course operations. Because of the concerns for protecting the environment associated with irrigation using recycled water, listed earlier, proper management practices for golf course operators located over the EARZ must be developed and followed to protect this environment. Golf course operators should consider BMPs to maximize resources while minimizing the risk to the environment. In order to evaluate the possibility of servicing any customers located over the EARZ, there is a need for long-term, detailed studies designed to assist SAWS personnel in recommending whether recycled water service should be provided and if any further water treatment requirements should be implemented prior to use of the recycled water.

SECTION 2.0

Project Goals and Objectives

Having defined the need for studies relating to the use of recycled water over the EARZ, SAWS initiated a study to examine the fate of various biological and chemical constituents that are introduced into the soil-plant-water continuum as part of a responsible turf management program. The fate of the recycled water constituents would be estimated through a mass balance and statistical analysis, presenting data necessary to evaluate the environmental suitability of using recycled water to irrigate golf courses and other large turf areas within the EARZ. Secondary benefits of the study included evaluation of the irrigation demand of two common grasses used on area golf courses, evaluation of runoff water quality, and evaluation of potential salinity problems associated with the use of recycled water.

The EARZIPS' primary objective was to provide scientific information to SAWS concerning the fate of nutrients and other constituents of Type I recycled water when used for irrigation of turf areas on the recharge zone and the potential for contamination of the underlying aquifer. In this evaluation, results of the study would include the following:

- Recommendations on proper use of recycled water and fertilizers on turf over the Edwards Aquifer Recharge Zone based on the data collected in this study and the results of the analyses performed.
- Assessment of potential negative environmental effects associated with the use of recycled water over the recharge zone.
- Comparison of leachate and runoff water quality of recycled and Edwards irrigation plots.

To perform the pilot study, SAWS hired CH2M HILL as well as representatives from the Texas A&M University, Soil and Crop Sciences Department and the Texas Cooperative Extension to support their effort. The Texas A&M representatives were instrumental in the design and operation of the study, while CH2M HILL performed the routine system calibration and sampling efforts. The study was designed to last two years, beginning in March 2002 and ending in March 2004. One of the major objectives during the design and development of the study conditions was to mimic the general conditions or anticipated conditions under which large scale irrigators located on the EARZ are currently working.

The study site is located on a 5-acre tract of land (**Figure 2.1**) within the Bladerunner Turf Farms, Inc. (BTF), immediately adjacent to Leon Creek Water Recycling Center. Soil analyses were performed at the site, and the resulting data illustrated a similarity to fairway soils imported to golf courses located on the EARZ and surrounding areas. This is discussed in more detail in Section 3.3.

SAN ANTONIO
WATER SYSTEM

Figure 2.1

SAWS TURF STUDY SITE

EARZ Irrigation Pilot Study

CH2MHILL

SECTION 3.0

Project Site

3.1 Site Background

The EARZIPS was performed at Bladerunner Turf Farms, Inc. (BTF) property located on Mauermann Road, Bexar County, south of San Antonio, Texas. Bladerunner is presently leasing property from SAWS, and this property is adjacent to SAWS' Leon Creek Water Recycling Center. David Doguet, owner of BTF, agreed to allow five acres of his leased property to be devoted to turf demonstrations, informational fairs, and turf research projects.

The following is a brief chronology of the activities that led to the development and implementation of the EARZIPS.

- A deadline of June 30, 1997 was given to the identified potential recycled water customer base to submit to SAWS a signed request for service document. This non-binding document confirmed the intention by customers to purchase recycled water from the SAWS System when such water becomes available. One of the major identified uses of SAWS' recycled water is irrigation of golf courses and athletic playing fields. Approximately 9% (3,000 acre-feet per year) of recycled water was requested for irrigation use by customers located on the Edwards Aquifer Recharge Zone (EARZ).
- Summer, 1998 – Collection of fairway soil samples from a large golf complex located on the EARZ, one of the irrigators who had submitted a request for service, as well as from the proposed study site at Bladerunner Turf Farms, Inc. Based on the test data, a determination was made by personnel of Texas A&M Soil and Science Department that the soil characteristics at Bladerunner Turf Farms, Inc. site are similar to the fairways of a the large golf complex sampled. Since the soil textures identified at the Bladerunner Turf Farms, Inc. were similar to those of golf course fairways located on the Edwards Aquifer Recharge Zone, the study was conducted using the existing soil at the Bladerunner Turf Farms, Inc.
- Fall, 1998 – SAWS provided authorization to initiate the EARZIPS.
- Fall, 1998 – Early Summer of 1999 - Site preparation and installation of lysimeters, irrigation system, fence, gates, walkways and turf.
- Early 1999 – Re-evaluation of the reliability of both potable and recycled water supplies and the need for more reliable water sources.
- Spring, 2000 - Water sampling event to obtain background water quality analysis. Irrigation of recycled and Edwards aquifer water was initiated.
- June, 2000 – Irrigation of the site was discontinued due to irrigation system damage resulting from an operational mishap on the main SAWS' Recycled Water System.

- September, 2000 – Set up irrigation of entire site with recycled water for one month due to extreme heat.
- Spring, 2001 – Installation of dedicated recycled water and potable water lines to the study site.
- Winter, 2001 - SAWS issues a Request for Proposal for the EARZIPS.
- Spring, 2002 – EARZIPS initiated.

Due to the factors listed above, the EARZIPS was not irrigated or maintained regularly for an approximate time period of 16 months immediately prior to the start of this study in February of 2002.

3.2 Study Design

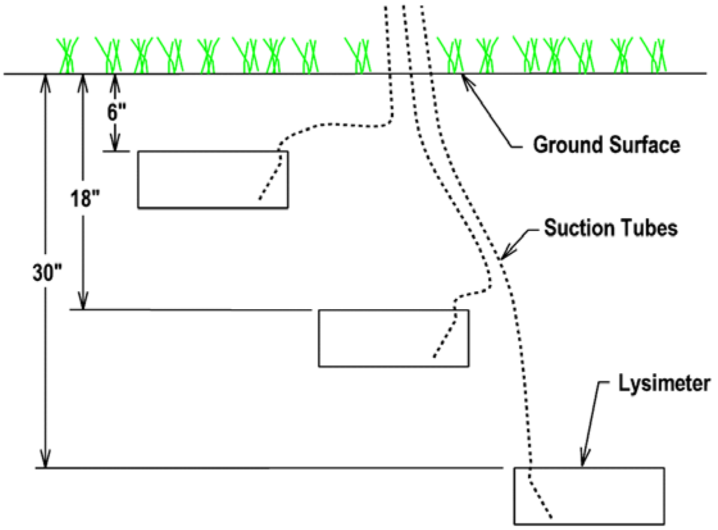
Proper site information and characteristics were considered when designing a study that would meet the objectives listed. The site characteristics and study design were evaluated to ensure that data could be effectively collected from the project site and that these data were reproducible and accurate, as well as applicable to other sites in Bexar County.

Prior to the Study becoming operational, the site had to be prepared. Site preparation was initiated by clearing and removing the indigenous vegetation. Next, the soil was leveled at the existing grade to prepare it for sodding. Once this was completed, the plot borders were marked to guide the installation of the lysimeters and the irrigation system. Following installation of all lysimeters, irrigation equipment, weather station and vacuum lines the plots were sodded, plastic borders were installed around all plots, and the walkways were covered with composted wood chips.

3.3 Data Collection Apparatus

Once site preparation was completed, installation of the project components became necessary. Lysimeters were installed before the irrigation system so that the heavy digging equipment used for lysimeter installation would not damage the irrigation system. **Figure 3-1** illustrates the lysimeter installation; lysimeters were placed at three soil depths (6 inches, 18 inches, and 30 inches below the soil surface) per study plot, resulting in a total of 54 lysimeters. The purpose of the lysimeters is to collect water samples at different soil depths within each test plot without changing the chemical characteristics of the sample.

FIGURE 3-1
A Cross Section of the Below Ground Lysimeter Installation in Each Turf Study Plot
Edwards Aquifer Recharge Zone Irrigation Pilot Study



Representatives from the Texas A&M University System, Department of Soil and Crop Sciences, were responsible for selecting the lysimeter and runoff collection devices to be used in the study. The lysimeter type that was most applicable to this study is known as a "glass block lysimeter" (Brown, 1986; Barbee and Brown, 1986). This device consists of a rectangular glass block, approximately 12 inches x 12 inches x 3 inches in size, with nine holes drilled into the glass top to allow percolated water to enter and accumulate in the lysimeter.

Lysimeter installation was accomplished by excavating a trench approximately 4 feet deep and 8 feet long in the center of each plot. Hand-dug excavations slightly larger than the glass blocks were made into one sidewall of each trench so that the top of the cavities were 18 and 30 inches below the soil surface. Care was taken to try to make the top of the cavities flat and smooth to ensure good contact with the top of the sampling device. The top of each lysimeter was covered with a porous geotextile to prevent soil from falling into the holes in the top of the lysimeter. A 1/8-inch diameter nylon sampling tube was then inserted through one of the holes into the glass blocks and brought to the soil surface, as shown in **Figure 3.2**. These tubes were employed during vacuum system extraction, as described in Section 4.3. The glass block with cover and sampling tube installed was slid into the cavity and pressed up against the soil that formed the top of the cavity. Wooden wedges were used to hold the block in position until soil could be backfilled and packed around and beneath the glass block. Care was taken to pack the soil carefully and firmly to prevent future settlement. Each cavity was completely backfilled until flush with the sidewall of the trench. Each lysimeter was offset at least 2 feet in the horizontal direction from the closest overlying lysimeter to prevent any interference in water movement from overlying lysimeters.

FIGURE 3.2
Sampling Tube Installation into the Glass Block Lysimeter
Edwards Aquifer Recharge Zone Irrigation Pilot Study

A third lysimeter was installed with the top of the lysimeter 6 inches below the soil surface. Due to the shallow depth of this sampler, installation was accomplished by digging an appropriately sized hole from the surface. The lysimeter was placed in the excavation and the sampling tube was laid in a shallow trench that extended to the same location as the sampling tubes associated with the deeper lysimeters. Some of the removed soil was used to carefully backfill around and above the lysimeter up to the original soil surface. After all three lysimeters and sampling tubes were in place, a sheet of clear 4 mil (0.004 inches) polyethylene plastic was placed along the vertical wall containing the lysimeters. Because water may preferentially enter the disturbed soil in the trench, the plastic served as a barrier to prevent this water from immediately running into the lysimeters. The trench was then backfilled with the removed soil.

A 6-inch diameter water meter box was installed near the center of each plot and used for underground storage and easy retrieval of the sampling tubes. The block lysimeters and sampling tubes allow one to convert the volume of water leached into each lysimeter to a depth of water, aiding in the calculation of a water balance and a mass balance for constituents of concern. For purposes of this study, we will assume that nutrients entering the 30 inch lysimeters have passed the root zone and will likely be transported to the aquifer.

The next step was to install separate irrigation piping systems for the delivery of recycled water and Edwards Aquifer water to each plot. Caution was exercised during the construction phase of the system so as to not compact or disrupt the soil profile on the actual plot areas. Each study plot has four pop-up irrigation heads (1.0 gallon per minute, or gpm, Rainbird T-bird), one in each corner of the plot. Each of these heads had a concrete donut installed to surround them for protection. These irrigation heads are similar to typical fairway irrigation spray heads and provide similar patterns. The sprinkler heads provided head-to-head coverage for better coverage and uniformity. Uniformity coefficients are discussed in the Quality Control Section (Section 4.6).

An irrigation controller that commands the solenoid valves in each of the three treatments and compensates for rainfall events was installed. The irrigation controller allows for simplified programming of the irrigation system on a weekly basis, with inputs from information downloaded from the on-site weather station. Irrigation of the turf plots was scheduled after 8:00 p.m. and before 10:00 a.m. This schedule reduced the evaporation rate of the water, minimized the influence of wind, and is similar to the schedule used by San Antonio area golf courses. In addition, this schedule complies with SAWS' irrigation requirements outlined in the Aquifer Management Plan.

The irrigation system was installed to guarantee the complete separation and operation of the two types of water, recycled and Edwards, used for irrigation. The irrigation system was designed and constructed to deliver approximately the same water pressure and rate of application to each plot. Each of the three water irrigation regimes (described in Section 3.2) were metered to verify the total amount of water applied to each plot. Additionally, a rain sensor was installed at each controller to automatically turn off the sprinkler system after the site received ¼ inch or more of rain.

One requirement of the TCEQ Chapter 210, *Use of Reclaimed Water*, is to minimize runoff of the recycled water. However, it is understood that runoff will occur due to natural events, such as large rainstorms. Water quality protection of creeks and streams will diminish the potential for contaminating the Edwards Aquifer as surface water runoff routes itself throughout the recharge zone over sensitive recharge areas. Therefore, runoff collection systems were installed on selected plots. Each runoff collection device consisted of a 24-inch diameter, 6-inch tall steel ring, placed inside the test plot and driven 3 inches deep into the soil. The steel ring has a 0.75-inch diameter outlet located at the downward slope of the plot at ground level. The outlet was connected to a 5-gallon collection jar via a 0.5-inch diameter PVC pipe. The top of the collection jar was below the elevation of the steel ring outlet so the PVC pipe could be installed at a downward slope. Any runoff exceeding the capacity of the collection jar overflowed and was not collected. Runoff collection devices were installed in one plot of each irrigation treatment and turf grass combination, for a total of six collection devices. The plots in which the devices were installed are: 2 (Edwards Aquifer irrigation on zoysiagrass), 17 (Edwards Aquifer irrigation on bermudagrass), 9 (Recycled water irrigation on zoysiagrass), 16 (Recycled water irrigation on bermudagrass), 11 (Recycled water + leaching fraction irrigation on bermudagrass), and 13 (Recycled water + leaching fraction irrigation on zoysiagrass). These treatments will be discussed in greater detail in the following sections.

Additionally, as mentioned earlier, one of the key components of the Turf Study is the calculation of a mass balance. This balance should include all biological and chemical constituent inputs and outputs, including an estimation of the amount of constituents added to the aquifer. The need for a complete mass balance, or the ability to estimate a balance, is of value in scheduling irrigation treatments and in completing a nitrogen balance. The block lysimeters aided in the water balance by collecting most of the water leaving the area above the lysimeters through percolation. The volume of water collected within each block lysimeter was used to estimate the leaching portion of the water balance. To facilitate estimating the remainder of the water balance, a complete weather station is located on-site. The weather station has temperature, humidity, wind speed and direction, and solar radiation sensors, as shown in **Table 3.1**. The weather station was manufactured by Campbell Scientific and configured by Dynamax (Houston, Texas).

TABLE 3.1
Components of the DynaMet Weather Station
Edwards Aquifer Recharge Zone Irrigation Pilot Study

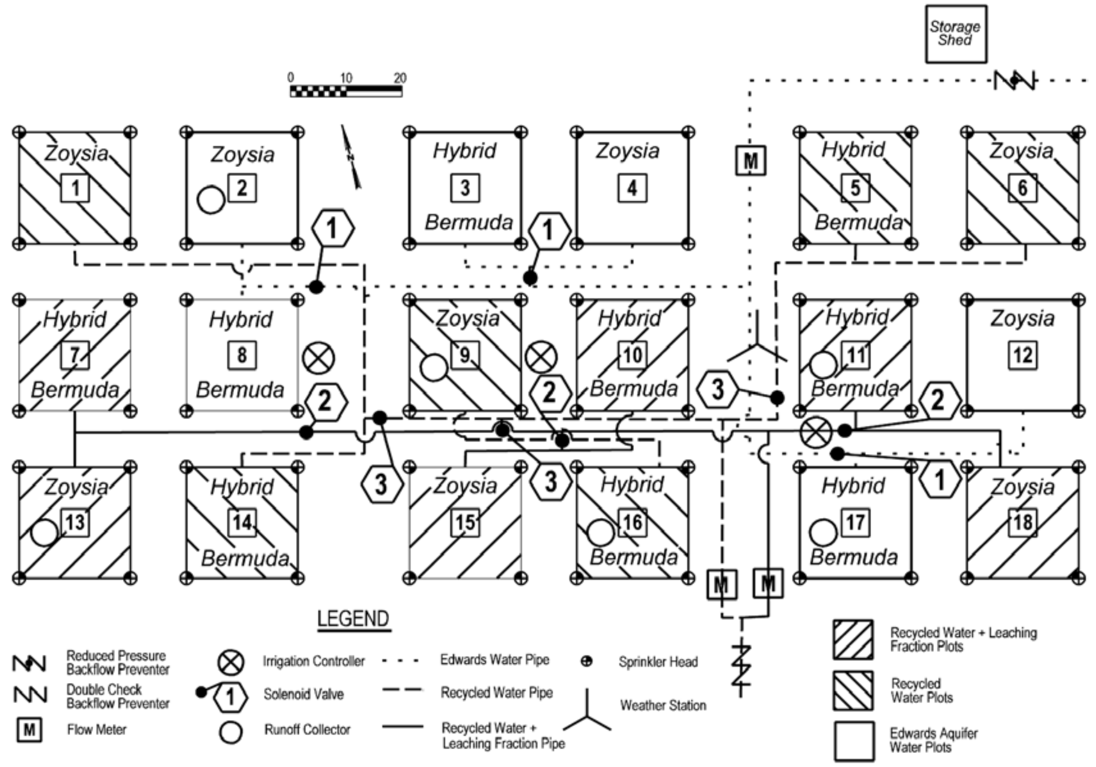
Quantity	Model	Description
1	LI2003S	Pyranometer, measures solar radiation
1	TE525	Tipping bucket rain gauge
1	CS500	Air Temperature
1	107B	Soil Temperature
1	CS500	Relative Humidity (Vaisala)
1	034A-L	Wind Speed and Direction
1	MSX20	20W Solar Panel
1	CR10X	DNX10 Datalogger

Finally, an equipment storage building was placed on the site to ensure the safekeeping of all equipment necessary for day to day operation of the study.

A total of three irrigation treatments were used for the study. Two of the irrigation treatments were established for the recycled water plots. The first treatment is based on replacing the depth of water lost through daily potential evapotranspiration (PET); this is labeled as the 1XRW treatment. PET is the potential amount of water transferred from the earth to the atmosphere due to the combined effects of evaporation and transpiration. The second irrigation treatment is based on the leaching fraction combined with the PET rate; this is labeled as the LFRW treatment. This second treatment is designed to help control any potential salt buildup in the soil caused by the elevated electrical conductivity (EC) levels of the recycled water. This additional water, or leaching fraction (LF), was calculated to be 10 percent of the PET irrigation depth; further details regarding this calculation can be found in Section 5.6, Salinity. The third irrigation treatment is equal to the water lost through daily PET using Edwards Aquifer water; this is labeled as the EA treatment. Generally, turfgrasses are not irrigated at full PET rate, but are irrigated at a level below that. The actual evapotranspiration rate of warm season turf grasses is estimated to be 0.6 of the PET. In addition, many irrigators choose to reduce the irrigation amount below the evapotranspiration rate further for allowable stress. Therefore, it is not uncommon to irrigate warm season turfgrasses at 50% of the PET value. This study was designed to simulate the worse-case condition in which irrigators are applying the PET value in irrigation water.

Each irrigation treatment was tested with two species of turf commonly used on golf courses in the San Antonio area, Jamur zoysiagrass (Zoysia japonica Seud.) and Tifway 419 hybrid bermudagrass (C. dactylon (L.) Pers. X C. transvaalensis Burtt Davy). Each treatment was replicated three times to get a sufficient amount of data for comparisons and statistical analysis. A total of eighteen study plots were arranged in a random manner. Each plot was 20 feet by 20 feet with an additional 5 feet of non-irrigated aisle area around the perimeter of each plot. All aisles were covered with a 1 to 2 inch depth of coarse composted wood chips. **Figure 3.3** is a schematic of the irrigation piping system and study plot layout.

FIGURE 3.3
Plot and irrigation system layout for EARZIPS
Edwards Aquifer Recharge Zone Irrigation Pilot Study



3.4 Soil Characteristics

Much care went into the selection of the experimental site to ensure it was representative of soils presently used on golf course fairways in the San Antonio area. Soil samples were collected from three depths (six, eighteen, and thirty inches) on the fairways at a large golf complex. This complex is located on the EARZ and expressed interest in SAWS' recycled water for irrigation during the initial request for service time period. The soil samples at each depth were composited into four groups for a total of 12 samples, each of which was tested for particle size distribution. The results are summarized in **Table 3.2**.

To make an objective comparison, ten locations were selected and sampled from the proposed study site at the Bladerunner Turf Farm (**Figure 3.4**). Samples were collected at the same depths of six, eighteen, and thirty inches. The results are presented in **Table 3.3**. The data show that the six-inch samples have textures ranging from clay to clay loams, which compares favorably to the clay textures measured on the six-inch samples from the large golf complex fairways. The eighteen and thirty inch samples from the Bladerunner Turf Farm had soil textures ranging from silty clay loam to clay. The golf course samples had textures of clay loam to clay. Overall, this is a very close agreement in soil texture between the two sites, especially considering that much of the soil on the fairways had been imported and, thus, was mixed during transport and placement.

TABLE 3.2
Textural Analysis of the Soil Samples from the Large Golf Complex Fairways
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Sample (Group-Depth)	Location Fairway No.	% Sand	% Silt	% Clay	Texture
A – 6”	1, 2, 3, 17	13	37	50	Clay
A – 18”		31	33	36	Clay Loam
A – 30”		30	30	40	Clay
B – 6”	4, 15, 16, 18	14	32	54	Clay
B – 18”		34	30	36	Clay Loam
B – 30”		32	34	34	Clay Loam
C – 6”	5, 6, 7, 8, 9, 19	18	28	54	Clay
C – 18”		22	32	46	Clay
C – 30”		26	34	40	Clay
D – 6”	10, 11, 12, 13, 14	23	24	48	Clay
D – 18”		23	33	44	Clay
D – 30”		33	24	38	Clay Loam
Range		13-34	24-37	34-54	Clay to Clay

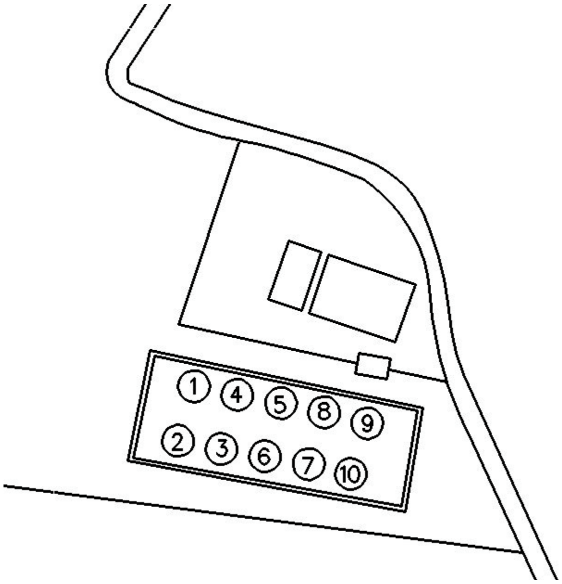
The similarity in particle size analysis between the sites indicates that there should also be similarity in terms of other physical properties. Based on particle size distribution, one may make inferences as to the approximate bulk density, water retention and saturated hydraulic conductivity of a soil in its native state (Rawls, 1983; Rawls and Brakensiek, 1983). Thus, given the similarity in particle size distribution, the experimental site should have a similar amount of water retention and a similar saturated hydraulic conductivity. Because soils plated on golf course fairways are disturbed, they often have less structure; this results in less macropore flow and a lower overall saturated hydraulic conductivity. Therefore, conducting the study on undisturbed soils such as those at the Bladerunner Turf Farm will provide conservative data in that the potential for movement of chemical constituents through soils at an undisturbed site will be slightly greater than for a similar but disturbed soil placed on a golf course fairway.

According to the Bexar County Soil Survey, the Bladerunner Turf Farm is located on a deposit of Lewisville silty clay soil series. The Lewisville series is part of the Lewisville-Houston Black, terrace association which covers approximately 12 percent (roughly 95,846 acres) of the county. The Lewisville series occurs as nearly level, broad terraces along rivers and creeks. The topsoil, or A horizon, is typically about 24 inches deep, has a dark grayish brown to brown color, and has a silty clay or clay texture. The AC horizon extends from 24 to 44 inches below the surface and is typically a brown to dark brown silty clay textured soil. The subsoil, or C horizon, begins at 44 inches below the surface and is a reddish-yellow silty clay textured soil that is highly calcareous and contains common medium and fine, hard, calcium carbonate concretions.

TABLE 3.3
Textural Analysis of the Soil Samples from the Bladerunner Turf Farm
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Sample (Group-Depth)	% Sand	% Silt	% Clay	Texture
1 – 6”	20	40	40	Clay
1 – 18”	16	40	44	Silty Clay
1 – 30”	16	49	35	Silty Clay Loam
2 – 6”	20	38	42	Clay
2 – 18”	16	40	44	Silty Clay
2 – 30”	20	37	43	Clay
3– 6”	22	38	40	Clay
3 – 18”	14	40	46	Silty Clay
3 – 30”	16	37	47	Clay
4 – 6”	22	40	38	Clay Loam
4 – 18”	18	39	43	Clay
4 – 30”	14	41	45	Silty Clay
5 – 6”	26	37	37	Clay Loam
5 – 18”	16	41	43	Clay
5 – 30”	16	49	35	Silty Clay Loam
6 – 6”	26	37	37	Clay Loam
6 – 18”	20	42	38	Clay Loam
6 – 30”	20	39	41	Clay
7 – 6”	22	37	41	Clay
7 – 18”	20	36	44	Clay
7 – 30”	20	39	41	Clay
8 – 6”	29	36	35	Clay Loam
8 – 18”	20	36	44	Clay
8 – 30”	20	35	45	Clay
9 – 6”	25	36	39	Clay Loam
9 – 18”	20	36	44	Clay
9 – 30”	23	34	43	Clay
10 – 6”	25	39	36	Clay Loam
10 – 18”	20	36	44	Clay
10 – 30”	19	34	47	Clay
Range	14-29	34-49	35-47	Clay to Silty Clay Loam

FIGURE 3.4.
Soil Sampling Locations at Bladerunner Turf Farm.
Edwards Aquifer Recharge Zone Irrigation Pilot Study



The Lewisville soil series is a fertile and productive soil that is desirable for use in urban areas that may be deficient in topsoil. It would not be unusual to see this type of soil mined and sold for use as supplemental topsoil for home lawns, highway medians, parks, golf courses, or other landscaped areas.

Selection of this soil for use in the Turf Study was deemed acceptable because it will serve as a "typical" soil that will exhibit both runoff and macropore flow. As such, it will be a good test case to determine potential pollutant migration via runoff and leaching. This will help make the results from this study more widely applicable to other soils and locations in Bexar County and neighboring areas.

SECTION 4.0

Methodology

4.1 Environmental Conditions

As mentioned earlier, an on-site weather station was installed to acquire temperature, humidity, wind speed and direction, and solar radiation data. The weather station data were downloaded twice per month, and the downloaded data were analyzed and used to calculate the potential evapotranspiration rate using the Campbell Scientific Split program and potential evapotranspiration module. Based on this information, the irrigation rates were calculated and the irrigation system was programmed twice per month. This was performed to comply with SAWS recommendations that irrigation scheduling be based on PET data as a means to conserve water.

The EARZIPS Project Team installed a fence around the study site to restrict livestock, wild boars, and other large animals from defecating on and disrupting the site. However, small mammalian, avian, amphibian, and reptilian fauna such as rabbits, squirrels, frogs, mice, birds and snakes can crawl under or go through the holes in the fence and have occasionally been observed on the study site. Rabbit and bird feces have been observed on the study plots from time to time.

4.2 Fertilization and Irrigation

As previously stated, the possibility of nitrate contamination of the Edwards Aquifer from application of recycled water over the EARZ is of primary concern. Pesticides and plant nutrients, such as nitrogen and phosphorus, can be transported in water and sediments. Fortunately, the grasses found in turf areas tend to aid in cleaning the environment by absorbing gaseous pollutants and intercepting pesticides, fertilizers, dust, and soil. Additionally, a healthy stand of turf can help to control erosion and reduce runoff. **Table 4.1** is a comparison of nutrients of concern found in SAWS' recycled water to those found in the Edwards Aquifer water currently being used for irrigation on the EARZ.

Soil samples were collected from the upper four to six inches of soil every three months and tested for major and micro nutrients. The analysis consistently showed a need for nitrogen fertilization. All other plant nutrients were in the adequate to high range. Based on this information, the Project Team decided to apply four pounds of nitrogen per 1,000 square feet per year to the zoysiagrass plots and six pounds of nitrogen per 1,000 square feet per year to the bermudagrass plots. These fertilization rates are typical of what would be applied to a well-managed turf, such as a golf course fairway, and were determined to be sufficient to maintain a dense turf cover and suitable aesthetic quality. To achieve these levels of fertilization, the Project Team decided to apply 1/6th of the total amount to each plot monthly from May through October. Due to several factors beyond our control, only three applications were made during the first year and the total amount of supplemental nitrogen added in 2002 was approximately half of the planned amounts. Thus, the N application rates used in 2002 are significantly less than what would typically be used for these turf species if grown on a golf course fairway or recreational sports field setting. This is more representative of a facility that operates using a very conservative nutrient management plan.

TABLE 4.1
Comparison of SAWS Recycled Water and Edwards Aquifer Water Quality
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Parameter	SAWS Recycled Water[1]	Edwards Aquifer Water	MCL[2]
Electrical Conductivity	1.1 dS/m (704 mg/L TDS)[3]	0.552 dS/m[4] (353 mg/L TDS)[3]	N/A
Nitrate-Nitrogen	12.61 mg/L	1.8 mg/L[5]	10 mg/L
Potassium	11.02 mg/L	0.2 mg/L[5]	N/A
Phosphorus (total)	2.81 mg/L	0.1 mg/L[6]	N/A
Ammonia Nitrogen	0.72 mg/L	N/A	N/A

1. SAWS recycled water constituent values were provided on a daily basis from SAWS, and these values were averaged for the year 2002.
2. Maximum Concentration Limit (MCL) is the Maximum Concentration Limit for potable water.
3. To convert electrical conductivity levels in dS/m to equivalent TDS levels in mg/L, multiply the EC by 640 if the EC value is less than 5. If the EC value is greater than 5, multiply by 800.
3. The value for Electrical Conductivity was taken from the Edwards Composite Analysis, provided by SAWS.
4. The values for potassium and nitrate-nitrogen in EA water were taken from SAWS Potable vs. Recycled Water Comparison.
5. The value for phosphorus in EA water was taken from the high end of the typical range of values presented in the Edwards Aquifer Authority (EAA) annual hydrogeologic report.

Plots that were irrigated with recycled water at either the 1XRW rate or the LFRW rate also received a significant amount of various nutrients from the water. Because the Edwards Aquifer water had much lower nutrient concentrations, plots irrigated with potable water received very few nutrients from the water. The total amount of nutrients added from each treatment between June and December of 2002 is shown in **Table 4.2**. These values include both the fertilizer applications and the nutrients applied via irrigation water.

The elevated amount of nitrogen in the recycled water resulted in almost doubling the N application to the zoysiagrass plots receiving recycled water compared to the same grass receiving Edwards Aquifer water. It also made a significant increase to the N application in the bermudagrass plots that received recycled water.

Total additions of P and Fe were nearly negligible; however, between one and two pounds of Mg and K were added per 1,000 square feet from the recycled water. Because the soils already had adequate P, K, Mg and Fe, the fertilization program for these nutrients is representative of what would be applied on a golf course or other managed turf site. Basically, the only nutrient additions other than nitrogen would be that which is incidental to the irrigation water that is applied.

TABLE 4.2
Total Nutrient Additions to the Test Plots in Pounds per 1,000 Square Feet for the Period June through December 2002, Irrigation Water and Fertilizer Additions
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Turf, Treatment	N	P	K	Mg	Fe
Zoysia, Edwards Aquifer	1.53[1]	0.01	0.02	1.45	0.0004
Zoysia, 1X Recycled Water	2.84	0.29	1.14	1.65	0.0047
Zoysia, LF Recycled Water	3.00	0.32	1.26	1.82	0.0051
Bermuda, Edwards Aquifer	2.23[1]	0.01	0.02	1.45	0.0004
Bermuda, 1X Recycled Water	3.54	0.29	1.14	1.65	0.0047
Bermuda, LF Recycled Water	3.70	0.32	1.26	1.82	0.0051

1. Note that ammonia nitrogen values were not available for the Edwards Aquifer, thus the N applied value given for the Edwards Aquifer plots does not include ammonia nitrogen added through irrigation.

The fertilization program was reviewed at the end of the 2002 growing season and a decision was made to improve the regularity of scheduled nitrogen applications during the 2003 growing season. It was also decided that the N application rates should be adjusted to compensate for the N applied via irrigation water and, thus, make more uniform total N applications across all irrigation treatments. Therefore, the scheduled six fertilizer applications were made during the 2003 growing season using a fine prill form of ammonium sulfate. Total amounts of N added as fertilizer as well as through irrigation water are shown in **Table 4.3**. For the zoysiagrass plots, the total N applied ranged from 4.23 to 4.86 pounds N/1,000 square feet; for the bermudagrass plots, the total N applied ranged from 6.23 to 6.85 pounds N/1,000 square feet. The N application rates used in 2003 are very comparable to what would typically be used for these turf species if grown on a golf course fairway or recreational sports field setting.

The leaching fraction of recycled water required to maintain soil salinity levels was calculated quarterly. The leaching fraction remained at 10% above the irrigation rates applied to replace PET throughout the study; this is further discussed in Section 5.2.

4.3 Sample Collection

Within the two-year study period, numerous samples were taken at varying intervals. Sampling dates were set at predetermined intervals at the onset of the project and were followed to the best of the Project Team's ability. The following table, **Table 4.4**, provides the list of samples collected and the frequency of collection.

TABLE 4.3
Total Nutrient Additions to the Test Plots in Pounds per 1,000 Square Feet for the Period January 2003 through February 2004, Irrigation Water and Fertilizer Additions
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Turf, Treatment	N	P	K	Mg	Fe
Zoysia, Edwards Aquifer	4.23[1]	0.02	0.04	2.56	0.0007
Zoysia, 1X Recycled Water	4.82	0.41	2.67	2.97	0.0055
Zoysia, LF Recycled Water	4.86	0.46	2.98	3.31	0.0062
Bermuda, Edwards Aquifer	6.23[1]	0.02	0.04	2.56	0.0007
Bermuda, 1X Recycled Water	6.82	0.41	2.67	2.97	0.0055
Bermuda, LF Recycled Water	6.85	0.46	2.98	3.31	0.0062

1. Note that ammonia nitrogen values were not available for the Edwards Aquifer, thus the N applied value given for the Edwards Aquifer plots does not include ammonia nitrogen added through irrigation.

TABLE 4.4
Sample Collection and Frequency
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Type of Sample	Frequency of Collection
Tissue	Monthly[1]
Lysimeter	Monthly[2]
Runoff	When runoff occurs
Soil	Quarterly
Rainwater	Five samples taken in 2003 during rain events

1. Tissue samples were only collected between April and October when the grass was actively growing.
2. Lysimeter samples were also collected if a rain event delivered 1.5 inches or more within a 48 hour period to the turf site.

Tissue samples, when scheduled, were obtained by using handheld trimmers as close to the soil as possible and cutting approximately an 8 inch by 8 inch square of grass. This grass was then enclosed in a plastic bag and portions were sent to the Dos Rios Laboratory and the Texas Cooperative Extension Soil, Water and Forage Testing Laboratory. Three samples were taken from each plot and composited prior to submission to the laboratories. The following list provides the dates on which tissue samples were collected:

- May 1, 2002
- May 16, 2002
- June 25, 2002
- July 23, 2003
- August 22, 2002
- September 24, 2002
- November 5, 2002
- April 22, 2003
- May 20, 2003
- June 17, 2003
- July 22, 2003
- August 19, 2003

- September 23, 2003
- October 21, 2003
- February 17, 2004

Lysimeter sampling was the most involved of the sample collection efforts. The water samples were extracted from each lysimeter with the aid of a vacuum system that was accessible throughout the site. At each plot, the sampling tube coming from each underground lysimeter was attached to a 2-liter glass collection jar, which was connected to the vacuum system. As a vacuum was drawn on the collection bottle, any collected liquid in the lysimeter flowed into the collection bottle. Once the rate of water coming from the lysimeters had diminished to near zero, the vacuum system was turned off, and the volumes of each sample were recorded. Samples registering less than 50 milliliters were not harvested for lab analysis. The samples greater than 50 milliliters were transferred to a clean, polyethylene container, labeled, and stored in a cooler with ice until they could be transported to the lab for analysis. The following list provides the dates on which lysimeter samples were collected:

- April 9, 2002
- April 30, 2002
- May 16, 2002
- June 25, 2002
- July 8, 2002
- July 23, 2002
- August 22, 2002
- September 11, 2002
- September 24, 2002
- October 11, 2002
- October 30, 2002
- November 7, 2002
- December 12, 2002
- December 19, 2002
- January 28, 2003
- February 27, 2003
- March 25, 2003
- April 22, 2003
- May 20, 2003
- June 9, 2003
- June 17, 2003
- July 9, 2003
- July 22, 2003
- August 19, 2003
- September 16, 2003
- September 23, 2003
- October 21, 2003
- November 18, 2003
- December 22, 2003
- January 20, 2004
- February 17, 2004

Runoff water samples were collected from the runoff collection containers using the same technique as previously described for lysimeter samples whenever runoff was present. Occasionally, these containers were full to overflowing due to heavy rains in the area. The following list provides the dates on which runoff samples were collected:

- July 8, 2002
- July 23, 2002
- September 3, 2002
- September 11, 2002
- September 24, 2002
- October 11, 2002
- October 25, 2002
- November 5, 2002
- December 12, 2002
- January 15, 2003
- February 18, 2003
- February 27, 2003
- March 4, 2003
- March 25, 2003
- June 9, 2003
- June 17, 2003

- July 9, 2003
- July 22, 2003
- September 16, 2003
- September 23, 2003
- November 18, 2003
- January 20, 2004

Soil samples were taken quarterly from the upper four to six inches of soil for testing levels of major and micro nutrients in the soil. Samples were collected with a 0.75-inch tube sampler to achieve a total of 1,000 grams of consolidated soil samples. Holes in the plots resulting from soil sampling were filled with native soil from adjacent areas outside the plots. This was performed to reduce or eliminate establishing preferential flow pathways in the soil profile in each test plot. The following list provides the dates on which soil samples were collected:

- March 12, 2002
- June 25, 2002
- September 24, 2002
- December 18, 2002
- March 25, 2003
- June 17, 2003
- September 23, 2003
- December 22, 2003
- February 17, 2004

Finally, samples of rainwater were collected for analysis to determine its chemical composition. Collection was achieved by collecting water from the rainfall gauge. When a rainfall event occurred, the water would flow through the gauge and into a plastic holding device. Rainwater was then collected from the bottom drain hole of the rainfall gauge. The following list provides the dates on which rainwater samples were collected:

- February 27, 2003
- March 4, 2003
- March 25, 2003
- June 17, 2003
- July 9, 2003

4.4 Sample Analysis

Once the samples were collected, they were transported to the Dos Rios laboratory and, in some cases, Texas A&M Water and Forage Testing Laboratory, for analysis. Methodologies for sample analyses were recommended by Texas A&M agronomic specialists. **Table 4.5** presents a listing of the constituents that were measured in each type of sample.

If enough sample volume was collected, all relevant parameters were analyzed for each sample type. If this was not the case, however, certain parameters had higher priority than others and these priorities differed between sample type. For instance, when the lysimeter samples were relatively low on volume, the four constituents that took priority were Ammonia Nitrogen, Coliform Bacteria, Nitrate, and Nitrite. However, Ammonia Nitrogen had a much lower priority in the analyses of soil and was not measured in the tissue.

4.5 Sample Analyses Methods

Tables 4.6, **4.7**, and **4.8** provide the methods used in the analysis of each parameter analyzed for the water, soil, and tissue samples, respectively, as well as the reference for each method used.

TABLE 4.5
A Listing of Constituents Measured in Each Sample Type
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Constituent	Tissue	Lysimeter	Runoff	Soil	Rainwater
Ammonia Nitrogen (NH_3-N)		X	X	X	X
Calcium	X	X	X	X	X
Coliform Bacteria, Fecal		X	X		X
Copper	X	X	X	X	X
Iron	X	X	X	X	X
Kjeldahl Nitrogen, Total	X	X	X	X	X
Magnesium	X	X	X	X	X
Manganese	X	X	X	X	X
Nitrate as Nitrogen		X	X	X	X
Nitrate Nitrite Combined		X	X	X	
Nitrite as Nitrogen		X	X	X	X
Phosphorus	X	X	X	X	X
Potassium	X	X	X	X	X
Sodium	X	X	X	X	X
Soluble Salts (1:1 water extract)				X	
Water Electrical Conductivity (EC_w)		X	X		X
Zinc	X	X	X	X	X

TABLE 4.6
Methodology Employed for Water Sample Analysis
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Parameter	Reference	Method Number	Units	Methodology
Sample Digestion	EPA	200.7		Hot Plate/Block Digestion
Ammonia Nitrogen	EPA	350.3	mg/L	Ion Selective Electrode
Calcium	EPA	200.7	mg/L	ICP[1]
Specific Conductance	EPA	120.1	umho/cm	Conductivity Bridge
Copper	EPA	200.7	mg/L	ICP
Coliform Bacteria, Fecal	STD MTD[2] 18	9222 D	Col/100mL	Membrane Filtration
Iron	EPA	200.7	mg/L	ICP
Potassium	EPA	200.7	mg/L	ICP
Magnesium	EPA	200.7	mg/L	ICP
Manganese	EPA	200.7	mg/L	ICP
Sodium	EPA	200.7	mg/L	ICP
Nitrite	EPA	300.1	mg/L	Ion Chromatography
Nitrate	EPA	300.1	mg/L	Ion Chromatography
Phosphorus, Total	EPA	365.2	mg/L	Colorimetric, Single Reagent
Kjeldahl Nitrogen, Total	EPA	351.3	mg/L	Post Digestion Distillation
Zinc	EPA	200.7	mg/L	ICP

1. ICP is the abbreviation for Inductively Coupled Plasma Atomic Emission Spectrography.
2. STD MTD is the abbreviation for the Standard Methods for Examination of Water and Wastewater.

TABLE 4.7
Methodology Employed for Soil Sample Analysis
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Parameter	Reference	Method Number	Units	Methodology
Ammonia Nitrogen (Extractable)	EPA	350.2 Mod	mg/kg	Distillation Procedure
Calcium	SW846	6010	mg/kg	ICP[1]
Copper	SW846	6010	mg/kg	ICP
Iron	SW846	6010	mg/kg	ICP
Potassium	SW846	6010	mg/kg	ICP
Magnesium	SW846	6010	mg/kg	ICP
Manganese	SW846	6010	mg/kg	ICP
Sodium	SW846	6010	mg/kg	ICP
Nitrite as Nitrogen (extractable)	EPA	300.1	mg/kg	Post Extraction Ion Chromatography
Nitrate Nitrite Combined, as Nitrogen (calculation)	EPA	300.1	mg/kg	Post Extraction Ion Chromatography
Nitrate as Nitrogen (extractable)	EPA	300.1	mg/kg	Post Extraction Ion Chromatography
Total Phosphorus	EPA	365.2 Mod	mg/kg	Colorimetric
Soluble Salts 1:1	Methods of Soil Analysis	Part 2, Chapter 10	umho/cm	Conductivity Bridge
Sample Digestion For Total Metals (SW846 3050B)	SW846	6010	mg/kg	Digestion
Total Kjeldahl Nitrogen	EPA	351.3 MOD	mg/kg	Digestion, Distillation, Titrimetric
Zinc	SW846	6010	mg/kg	ICP

1. ICP is the abbreviation for Inductively Coupled Plasma Atomic Emission Spectrography.
2. STD MTD is the abbreviation for the Standard Methods for Examination of Water and Wastewater.
3. SW846 is the abbreviation for the EPA publication entitled “Test Methods for Evaluating Solid Waste, Physical/Chemical Methods”

TABLE 4.8
Methodology Employed for Tissue Sample Analysis
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Parameter	Reference	Method Number	Units	Methodology
Hot Plate/Block Digestion, Biological Tissues (Solids)(by EPA 200.3)	SW846	6010	mg/kg	Nitric Acid & Hydrogen Peroxide Digestion
Calcium	SW846	6010	mg/kg	ICP[1]
Copper	SW846	6010	mg/kg	ICP
Iron	SW846	6010	mg/kg	ICP
Potassium	SW846	6010	mg/kg	ICP
Magnesium	SW846	6010	mg/kg	ICP
Manganese	SW846	6010	mg/kg	ICP
Sodium	SW846	6010	mg/kg	ICP
Phosphorus, Total, Solid Matrix Modification	EPA	365.2 MOD	mg/kg	Colorimetric
Kjeldahl Nitrogen, Total, Solid Matrix Modification	EPA	351.3 MOD	mg/kg	Digestion, Distillation, Titrimetric
Total Solids, Post-Preparatory Drying	STD MTD 18	2540 G	%	Gravimetric
Zinc	SW846	6010	mg/kg	ICP

1. ICP is the abbreviation for Inductively Coupled Plasma Atomic Emission Spectrography.
2. STD MTD is the abbreviation for the Standard Methods for Examination of Water and Wastewater.
3. SW846 is the abbreviation for the EPA publication entitled "Test Methods for Evaluating Solid Waste, Physical/Chemical Methods"

4.6 Aesthetics

Each month, assessments were made of the turf aesthetic quality, and digital photographs were taken of each plot. All plots were visually rated for turf density, color and uniformity by assigning a score of 1 to 3 for each of the three components. The scores for each component were then summed to arrive at an overall score for each plot. A score of 3 was the lowest possible and represented very poor conditions, while a score of 9 was the highest possible quality and represented turf with a high plant density, good color and a very uniform appearance. In general, quality ratings below 5 would not be acceptable for established golf course fairways during the growing season.

Since rating aesthetic quality of turf is subjective and not everyone may rate a given turf exactly the same, **Figures 4.1, 4.2**, and **4.3** provide photographs that provide the reader with some side by side comparisons of turf that received low, medium and high quality ratings. The turf in Figure 4.1 received a low rating of 3, as compared to a medium rating of 6 for the turf in Figure 4.2 and a high rating of 9 in Figure 4.3. Appendix A provides additional photographs; these are further discussed in Section 5.9.

FIGURE 4.1
An Example of a Low Aesthetic Rating (3)
Edwards Aquifer Recharge Zone Irrigation Pilot Study

FIGURE 4.2
An Example of a Medium Aesthetic Rating (6)
Edwards Aquifer Recharge Zone Irrigation Pilot Study

FIGURE 4.3
An Example of a High Aesthetic Rating (9)
Edwards Aquifer Recharge Zone Irrigation Pilot Study

4.7 Quality Control

To ensure the validity of the study, certain control treatments were taken into consideration in the initial phases of the study design. Implementing "control turf plots" that are treated in the exact manner as the test plots, but have a study condition modified, can be one method of measuring the validity of the study. The one changed condition chosen for this study was to irrigate one third of the plots with potable water. If the turf plots irrigated with potable water performed poorly, one could make the assumption that negative factors other than the water type used for irrigation are involved.

Another quality control measure employed included direct comparison of some of the chemical analyses of the samples. The bulk of the analyses were performed by the SAWS Dos Rios Laboratory. When sufficient sample volume was available, part of the sample was evaluated by the Texas Cooperative Extension Soil, Water and Forage Testing Laboratory located on the Texas A&M University campus. More specifically, if over 4,000 milliliters were obtained in the lysimeter and runoff sample collections, samples were sent to Texas A&M. Also, two samples of tissue were sent to Texas A&M monthly and four samples of soil were sent to Texas A&M quarterly. This allowed for a direct comparison of the results from each laboratory.

Additionally, calibration of the weather station was performed at installation and semiannually thereafter to ensure the data generated were accurate. Calibration of the irrigation system, which included calibration of the sprinkler heads and determination of the discharge rate and uniformity of the spray pattern, was also performed at installation and semiannually thereafter. The irrigation rates were recalculated and the system controller reprogrammed twice per month. The irrigation uniformity rates are provided in the following section. Furthermore, the irrigation system was directed by rain sensors to stop irrigation if the site had received more than ¼ inch of rainfall. The switch was released, and irrigation resumed, after the switch dried out. The switch would usually release within a few days, depending on the amount of rain received and the environmental conditions affecting evaporation of moisture from the switch. Finally, water meter readings were recorded bimonthly to verify the irrigation application depth.

4.8 Irrigation System Uniformity

The uniformity of the irrigation spray patterns was determined using the collection cup method. Nine cups were placed in each of the 20 foot by 20 foot study plots. During some of the calibration events, cups were also placed outside the 20 foot by 20 foot plot to determine the amount of irrigation that was being applied to the whole site. This was performed to help in relating the irrigation depth applied to the site versus the meter readings. However, these values will not be presented as part of this report. The calculated application rate for each of the calibration events are listed below in **Table 4.9**. The sprinklers were operated for 12 minutes for each plot, which resulted in approximately 40 milliliters of irrigation water collected in each cup.

TABLE 4.9
Calculated Application Rate in Inches Per Hour for Each Irrigation Calibration Event
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Plot	March 2002	July 2002	March 2003	October 2003
1	0.68	0.8	0.81	0.91
2	0.61	0.76	0.89	0.96
3	0.56	0.67	0.78	0.83
4	0.59	0.73	0.86	1.02
5	0.84	0.69	0.89	0.94
6	0.93	0.77	0.89	0.91
7	0.64	0.86	0.92	1.02
8	0.82	0.86	0.86	0.93
9	0.78	0.72	0.81	0.87
10	0.83	0.75	0.8	0.85
11	0.77	0.87	0.85	0.78
12	0.62	0.82	0.88	0.96
13	0.93	0.66	0.64	0.82
14	0.95	0.64	0.76	0.86
15	0.77	0.72	0.79	0.82
16	0.93	0.8	0.81	0.98
17	0.69	0.93	0.97	1.03
18	0.94	0.78	0.8	0.89

A few of the plots experienced significant changes in application rates between calibration events. This can be explained based on the Standard Operating Procedures (SOP) established for irrigation system calibration. The SOP called for all sprinkler heads to be set the morning of or the day before calibration was to take place. Setting the heads includes setting the spray arc and angle. At the beginning of the study, many of the sprinkler heads had significant overspray onto the aisles between plots. At the time of each calibration, this overspray was decreased until it was almost non-existent by the last calibration event. The angle of spray was also reduced before some of the calibration events. A higher angle also resulted in overspray on the aisles between the plots. However, as time progressed, the angles were decreased so that the spray pattern did not exceed the plot boundary.

Decreasing the arc angle and angle of spray results in more water being applied to the plot in the same period of time, or 12 minutes, as shown in Table 4.9. This increased application rate translates into a shorter time required to apply a certain depth of water to each plot. Following each calibration event, the application rate was adjusted in the calculations used to set the time of application in each irrigation controller.

SECTION 5.0

Results

The results for the entire study period will be presented and discussed in this Section. Statistical evaluation of the entire data set indicated no justification for analyzing any certain time period or events separately, except for phosphorus and zinc concentrations in runoff and leachate samples. For these constituents, some outlier measurements were removed prior to analysis. When reviewing and understanding the data, the following events and conditions should be kept in mind:

1) During the first three months of the study, a programming error of the sprinkler system resulted in excess water being applied to all plots.
2) The site had remained abandoned for an extended period of time prior to the study initiation and required time to acclimatize to the new treatments.
3) Due to conditions beyond the Project Team's control, only about half of the planned amount of N could be applied to the plots during the first year.

5.1 Rainfall

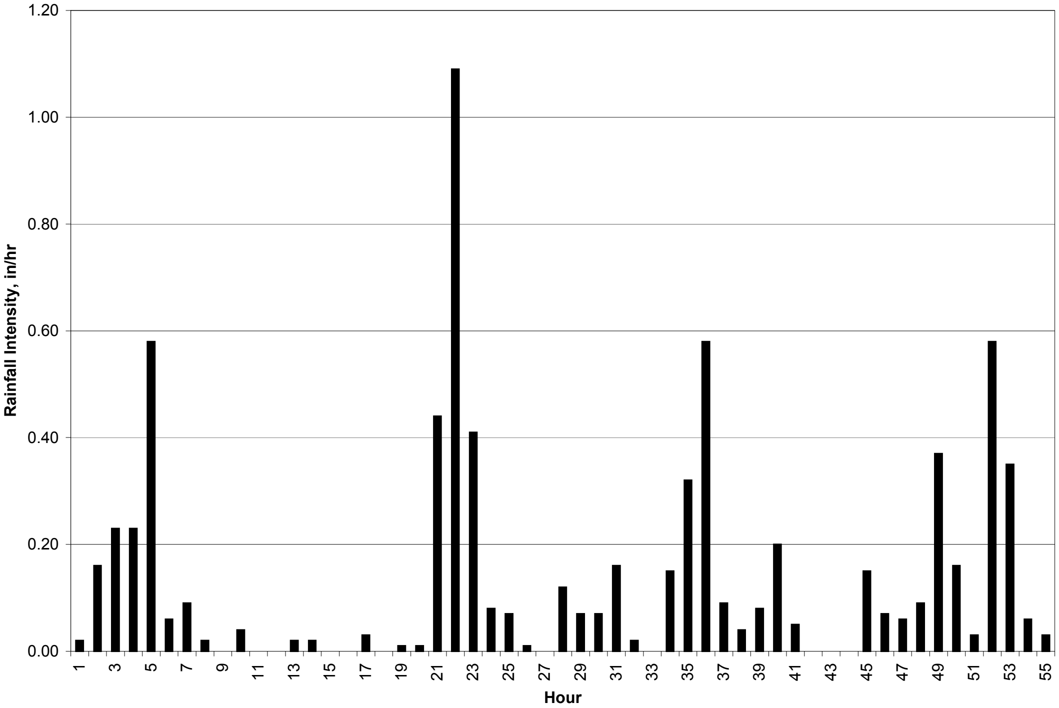
The San Antonio area received several large rainfall events during the first year of the study. **Table 5.1** lists rainfall events exceeding 1 inch per 24 hours received at the study location.

TABLE 5.1
Major Rainfall Events Received at the Study Site
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Date	Total Depth, inches	Maximum Intensity, inches/hour
April 7-8, 2002	2.4	
June 28 – July 6, 2002	8.2	0.9
July 14-15, 2002	1.8	
August 29, 2002	1.4	
September 7-9, 2002	7.5	1.1
October 8-9, 2002	5.1	1.9
October 22-24, 2002	5.6	1.4
December 4, 2002	1.6	
February 19 - 21, 2003	2.0	
June 4 - 6, 2003	2.31	
June 13 - 15, 2003	2.0	
July 15 - 17, 2003	2.94	
September 11 - 12, 2003	1.8	
September 20 - 22, 2003	1.58	

Figure 5.1 shows the rainfall intensity histogram of the September 7-9, 2002 storm. It is important to note that this rain pattern is not atypical of storm events frequently received in the San Antonio area. Storm events, such as those listed in **Table 5.1** are the driving mechanism behind water quality issues related to this Study, such as leaching and runoff water quality. The substantial rain events are what cause deep percolation of water and significant runoff volumes. It was a rare occurrence during the Study that irrigation alone caused deep percolation (to the 30" depth) and for water to runoff from the site. The substantial rains also prevented a significant build up of salts within the soil profile. Therefore, rain patterns in the San Antonio area can be a mixed blessing. They can reduce the overall irrigation requirement and prevent salt buildup, but they can also transport contaminants from the site to receiving surface waters and into the Edwards Aquifer.

FIGURE 5.1.
Rainfall Intensity Histogram for September 7 - 9, 2002 Rainstorm.
Edwards Aquifer Recharge Zone Irrigation Pilot Study



5.2 Irrigation

As previously discussed, six of the recycled water plots and the six Edwards water plots received irrigation based on the PET rate. The other six recycled water plots received additional water to help control any potential salt buildup in the soil caused by the electrical conductivity (EC) levels of the recycled water. This additional water, or leaching fraction (LF), was established at 10 percent of the PET irrigation depth. **Table 5.2** compares potential evapotranspiration, rainfall, and the amount of water applied to the site on a monthly basis.

TABLE 5.2
Monthly Potential Evapotranspiration, Rainfall, and Irrigation Amounts Applied to Turf Plots
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Month	Potential Evapotranspiration (inches)	Rainfall (inches)	Irrigation to EA Plots (inches)	Irrigation to 1XRW Plots (inches)	Irrigation to LFRW Plots (inches)
June 2002[1]	3.98	2.06	2.36	2.36	2.60
July 2002	6.73	8.34	2.88	2.88	3.17
August 2002	6.98	1.80	6.34	6.34	6.97
September 2002	5.42	8.42	3.32	3.32	3.65
October 2002	3.51	10.95	3.78	3.78	4.16
November 2002	2.93	1.59	0.90	0.90	0.99
December 2002	2.23	3.16	0.33	0.33	0.36
January 2003	2.34	1.20	0.66	0.66	0.72
February 2003	1.96	2.74	1.65	1.65	1.83
March 2003	3.35	1.20	2.20	2.20	2.44
April 2003	4.26	0.17	3.70	3.59	3.94
May 2003	6.25	0.08	4.20	4.20	4.68
June 2003	5.81	5.26	3.15	3.15	3.51
July 2003	5.49	4.83	2.80	2.45	3.12
August 2003	4.42	1.70	4.80	4.80	5.40
September 2003	3.40	4.86	3.09	3.09	3.41
October 2003	3.36	1.43	2.70	2.70	2.92
November 2003	2.09	0.33	1.98	1.95	2.14
December 2003	2.13	0.12	2.05	2.00	2.22
January 2004	1.66	1.30	1.40	1.36	1.52
February 2004	2.25	1.31	0.70	0.68	0.76

1. Note the June value only accounts for those values from June 15 through June 30.

The Study design attempted to replace the water lost to potential evapotranspiration with rain water and irrigation. Because the rain events and application depths were unpredictable, it was not unusual for the total water application depth to the plots to exceed the PET depth, as shown in Table 5.2. Turf managers experience wet months where most of the water is supplied by nature in the form of rainfall, but can easily exceed what is required by the turf, and they also experience drought periods, where most or all of the water required by the turf is supplied through irrigation. Excess is what is either stored within the soil profile, lost to deep percolation, or lost to runoff.

5.3 Fertilization

Soil samples were collected at the beginning of the study and quarterly thereafter. All analyses have shown the soil to be low in nitrogen and high in both phosphorus and potassium. The soil samples have contained adequate to high levels of micronutrients, as well. Based on these results, nitrogen was the only nutrient added to the plots during the study period. Given the alkaline pH of the soil, ammonium sulfate was the carrier of choice. **Tables 5.3** through **5.5** show the dates and quantities of nitrogen added to the plots as ammonium sulfate.

TABLE 5.3
Fertilization Additions Made to Plots Irrigated with Edwards Aquifer Water
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Application, lb N/1000 ft^2	
Date	**Zoysia**	**Bermuda**
May 2002	0.65	1.0
August 2002	0.65	1.0
October 2002	0.65	1.0
March 2003	0.67	1.00
April 2003	0.65	0.98
May 2003	0.63	0.97
July 2003	0.60	0.95
August 2003	0.64	0.97
September 2003	0.64	0.96

TABLE 5.4
Fertilization Additions Made to Plots Irrigated with Recycled Water at the Potential Evapotranspiration Rate
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Application, lb N/1000 ft^2	
Date	**Zoysia**	**Bermuda**
May 2002	0.65	1.0
August 2002	0.65	1.0
October 2002	0.65	1.0
March 2003	0.67	1.00
April 2003	0.41	0.74
May 2003	0.32	0.66
July 2003	0.12	0.44
August 2003	0.32	0.68
September 2003	0.27	0.59

TABLE 5.5
Fertilization Additions Made to Plots Irrigated with Recycled Water at the Potential Evapotranspiration Rate Plus a Leaching Fraction
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Application, lb N/1000 ft^2	
Date	**Zoysia**	**Bermuda**
May 2002	0.65	1.0
August 2002	0.65	1.0
October 2002	0.65	1.0
March 2003	0.67	1
April 2003	0.32	0.66
May 2003	0.28	0.61
July 2003	0.05	0.38
August 2003	0.28	0.64
September 2003	0.23	0.54

5.4 Potential Evapotranspiration

The weather station located at the Study Site became operational in May 2002 which resulted in June 2002 being the first full month of PET data. The first four months of PET were estimated using the weather station connected to the Texas Evapotranspiration Network located at the Jones-Maltsberger Turfgrass Management Site in San Antonio. This weather station is maintained by the Texas A&M University System and uses the Penman-Monteith method to calculate PET.

The on-site weather station is programmed to use the Penman-van Bavel method to estimate PET. **Table 5.6** compares the PET values estimated by the Turf Study weather station to those calculated by the TexasET Network weather station located in north San Antonio. The PET values used for calculating irrigation rates came from the Texas PET weather station up through June 2002 and the Texas PET weather station data was used to fill in any missing data from the Turf Study weather station following that date. Approximately 10 days of PET data was used from the TexasET weather station after May 2002.

The PET values for the Turf Study weather station generally ranged within ±0.5 inch of those calculated by the TexasET weather station. Differences in measurements are likely due to the difference in locations of the two weather stations. The TexasET weather station is located approximately 30 miles to the north of the Turf Study site and sits on the edge of the Balcones Escarpment. It is not uncommon for areas separated by this amount of distance to have some differences in climatological data. The average of the daily differences in PET values was 0.11 inches, with a maximum difference of 2.83 inches in July 2002.

TABLE 5.6
Potential Evapotranspiration Rates Measured at the Turf Study Site and Those Reported by the TexasET Program for the Jones-Maltsberger Site in San Antonio
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Date	Depth (inches) - Turf Study	Depth (inches) - ET Network
February 2002	NA	2.53
March 2002	NA	2.30
April 2002	NA	3.27
May 2002	NA	4.77
June 2002	7.53	5.23
July 2002	6.73	3.9
August 2002	6.98	5.03
September 2002	5.42	4.13
October 2002	3.51	2.44
November 2002	2.93	2.65
December 2002	2.23	1.80
January 2003	2.34	1.97
February 2003	1.96	1.56
March 2003	3.35	2.98
April 2003	4.26	3.91
May 2003	6.25	4.94
June 2003	5.81	5.30
July 2003	5.49	4.79
August 2003	4.42	5.74
September 2003	3.40	3.97
October 2003	3.36	3.27
November 2003	2.09	2.54
December 2003	2.13	2.43
January 2004	1.66	2.12
February 2004	2.25	2.43

5.5 Leaching Fraction

As previously discussed, the leaching fraction for the recycled water was set at 10 percent. This value was derived from the following equation:

$$LF\ (\%) = EC_{iw}/EC_{dw} \times 100$$

where LF = leaching fraction

EC_{iw} = electrical conductivity of irrigation water

EC_{dw} = electrical conductivity tolerance of grass

The electrical conductivity of the irrigation water was given as 1.1 dS/m (decisiemens per meter), according to tests conducted on SAWS recycled water. The salt tolerance of both bermudagrass and zoysiagrass was estimated at 1.0 dS/m, although it could be as high as 1.1 dS/m, which would not require any leaching using SAWS recycled water.

The State of Texas also has a leaching fraction component associated with a water balance that must be completed prior to irrigating with recycled water. Following the instructions listed in the *Use of Reclaimed Water*, (TAC) Chapter 210, the leaching fraction is confirmed as 10% for 2002, as shown below:

LF (inches) = Ce/C1 x (E - Ri)

where LF = Leaching requirement, inches
Ce = Electrical Conductivity of irrigation water
C1 = Maximum Allowable Electrical Conductivity of soil
E = Evapotranspiration, inches
Ri = Infiltrated rainfall, inches

Assumptions:

Ce = 1.1 dS/m (see explanation above)
C1 = 7 dS/m (for Turf Grasses)
E = 50.17 inches (total for 2002)
Ri = 28 inches (total rainfall for 2002 was 42.4 inches, but to obtain infiltrated rainfall, 4 inches each was subtracted for the rainfall events in June/July and September, and 3.0 inches each for the two rainfall events in October. These rainfall events all resulted in full runoff collectors, which equates to 2.5 inches of runoff or more.)

Solution:
LF = 1.1/7 x (50.17 - 28)
LF = 3.5 inches
Total irrigation = 38 inches

Therefore:
LF = 3.5"/38" x 100% = 9.2%,
which is close to the 10 percent calculated above.

5.6 Runoff

5.6.1 Runoff Volumes

As described earlier, the runoff water from each plot was collected and measured at each sampling date and shortly after large rainfall events. The volumes collected were then converted to depth of water and summed over the study period. Due to limitations of the equipment size and other factors, the maximum depth of runoff that could be captured for any one storm event was 2.54 inches. Runoff in excess of this amount overflowed the collection container and was lost.

Volumes collected from the runoff collection systems are presented in **Table 5.7**. Heavy rainfall events just prior to the September 11, 2002, October 11, 2002, October 25, 2002, February 27, 2003, and July 22, 2003 sampling events exceeded the capacity of the collection system and an unknown amount of water overflowed the collection containers. Thus, the actual runoff is slightly greater than that which was measured and reported herein. As illustrated in **Table 5.7**, total runoff for the study period was between 9.40 and 31.52 inches of water.

TABLE 5.7
Depth of Runoff Water (inches) Collected from the Experimental Plots
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Date	Plot 2 (EA, Zoysia)	Plot 9 (1XRW, Zoysia)	Plot 11 (LFRW, Bermuda)	Plot 13 (LFRW, Zoysia)	Plot 16 (1XRW, Bermuda)	Plot 17 (EA, Bermuda)
July 8, 2002	1.35	0.00	2.54	2.54	0.40	2.54
July 23, 2002	0.00	0.00	0.00	0.00	0.04	2.48
September 3, 2002	0.03	0.00	0.66	0.07	1.15	2.54
September 11, 2002	2.54	2.54	2.54	2.54	0.00	2.54
September 24, 2002	0.00	0.00	0.05	0.02	0.00	0.06
October 11, 2002	2.54	2.54	0.00	2.54	0.00	2.54
October 25, 2002	2.54	2.54	2.54	2.54	2.54	2.54
November 5, 2002	0.00	0.30	0.00	0.00	0.00	0.13
December 12, 2002	0.00	0.30	0.00	2.54	0.00	2.54
January 15, 2003	0.00	0.00	0.00	0.00	0.00	0.13
February 18, 2003	0.00	0.00	0.04	0.00	0.00	0.12
February 27, 2003	2.54	1.05	2.54	2.54	2.54	2.54
March 4, 2003	0.00	0.55	0.15	0.05	0.12	2.54
March 25, 2003	0.00	0.00	0.00	0.00	0.00	0.04
June 9, 2003	2.54	0.00	0.00	0.00	0.00	2.54
June 17, 2003	0.01	0.05	0.00	0.20	0.05	0.54
July 9, 2003	0.00	0.00	0.15	0.00	0.03	0.03
July 22, 2003	2.54	2.54	2.54	2.54	2.54	2.54
September 16, 2003	0.00	0.00	0.13	0.00	0.00	2.54
September 23, 2003	1.27	0.00	0.00	0.00	0.00	0.00
November 18, 2003	0.00	0.00	0.00	0.00	0.00	0.03
January 20, 2004	0.00	0.00	0.00	0.00	0.00	0.03
Total	17.89	12.42	13.88	18.12	9.40	31.52

Note: The text in parentheses after each plot number is the (irrigation water type, turfgrass type).

5.6.2 Data Analyses

Due to the lack of replicated measurements, a valid statistical comparison of the data cannot be made. Therefore, the concentration data were plotted and evaluated for the presence of general trends and potential differences due to irrigation treatments.

5.6.3 Electrical Conductivity

Electrical Conductivity values of the runoff water samples are shown in **Table 5.8**. There is a slight increasing trend; however, the changes are fairly small and are not of any environmental significance. The data are well within the range commonly observed for runoff from agricultural land and indicate the runoff poses no significant impact to the receiving waters.

TABLE 5.8
Mean EC (dS/m) of Runoff Water for the Entire Study Period
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Irrigation Treatment	EC	TDS
EA	0.167	107
1XRW	0.193	124
LFRW	0.183	117

The total salt content of the runoff water was estimated by measuring the electrical conductivity of the water. The EC of the runoff water samples collected during the study period are shown in Appendix B, **Figures B.1** and **B.2** for the zoysiagrass and bermudagrass treatments, respectively. With the zoysiagrass, there was a clear pattern showing that the EC in runoff from the EA treatment was consistently lowest. The EC from the 1XRW and LFRW treatments were similar, but both remained above the EA at all times. With the bermudagrass treatment, there was no clear trend due to irrigation treatment. All samples from both grasses and all irrigation treatments had EC values well within the acceptable range and should not have any adverse environmental impact.

5.6.4 Sodium

Sodium concentrations in the runoff water samples collected during the study period are shown in **Figures B.3** and **B.4** for the zoysiagrass and bermudagrass treatments, respectively. With the zoysiagrass, there was a clear pattern showing that the sodium in runoff from the EA treatment was consistently lowest. The sodium content of the 1XRW and LFRW treatments were similar, but both remained above the EA at all times. With the bermudagrass treatment, there was no clear trend due to irrigation treatment. All runoff water samples from both grasses and all irrigation treatments had sodium values below 40 mg/L and should not cause any adverse environmental impact.

5.6.5 Manganese

Manganese concentrations in the runoff water samples collected during the study period are shown in **Figures B.5** and **B.6** for the zoysiagrass and bermudagrass treatments, respectively. In the zoysiagrass, the Mn concentrations for EA decreased to the detection limit of 0.02 mg/L by September 8, 2002 and remained below detection for the remainder of the study. The Mn content of the 1XRW and LFRW treatments followed a similar trend, but both remained slightly above the EA at most times. With the bermudagrass treatment, there was no clear trend due to irrigation treatment. All runoff water samples from both grasses and all irrigation treatments had manganese values below 0.40 mg/L and should not cause any adverse environmental impact.

5.6.6 Magnesium

Magnesium concentrations in the runoff water samples collected during the study period are shown in **Figures B.7** and **B.8** for the zoysiagrass and bermudagrass treatments, respectively. With the zoysiagrass, the Mg concentrations for all irrigation treatments decreased to approximately 2 mg/L by September 8, 2002 and remained close to that level for the remainder of the study, save for one spike by the 1XRW treatment in early March of 2003. With the bermudagrass treatment, there was a similar trend with all irrigation treatments containing approximately 2 mg/L, save for a spike by the LFRW treatment in early March of 2003 and a spike by the EA treatment in mid-June of 2003. All runoff water samples from both grasses and all irrigation treatments had magnesium values below 14 mg/L and should not cause any adverse environmental impact. Since the highest Mg concentrations were measured in the EA treatment, it does not appear that the use of SAWS Type I recycled water for irrigation will adversely affect the Mg content of runoff water from turf areas.

5.6.7 Iron

Iron concentrations in the runoff water samples collected during the study period are shown in **Figures B.9** and **B.10** for the zoysiagrass and bermudagrass treatments, respectively. With the zoysiagrass, the Fe concentrations for all irrigation treatments decreased to approximately 0 to 2 mg/L by September 8, 2002 and remained under 4.5 mg/L for the remainder of the study. In the bermudagrass treatment, there was a similar trend with all irrigation treatments containing less than 6 mg/L, save for a spike by the LFRW treatment in early March of 2003. All runoff water samples from both grasses and all irrigation treatments had Fe values below 18 mg/L and should not cause any adverse environmental impact. Since the Fe concentrations were essentially equal between all the irrigation treatments, it does not appear that the use of SAWS Type I recycled water for irrigation will adversely affect the Fe content of runoff water from turf areas.

5.6.8 Copper

Copper concentrations in the runoff water samples collected during the study period are shown in **Figures B.11** and **B.12** for the zoysiagrass and bermudagrass treatments, respectively. With the zoysiagrass, the Cu concentrations for all irrigation treatments decreased to approximately 0.01 to 0.02 mg/L by September 8, 2002 and remained under 0.02 mg/L for the remainder of the study. With the bermudagrass treatment, there was a similar trend with all irrigation treatments containing less than 0.06 mg/L, save for a spike by the 1XRW treatment at the end of the study. All runoff water samples from both grasses and all irrigation treatments had Cu values below 0.2 mg/L and should not cause any adverse environmental impact. Since the Cu concentrations were essentially equal between all the irrigation treatments, it does not appear that the use of SAWS Type I recycled water for irrigation will adversely affect the Cu content of runoff water from turf areas.

5.6.9 Zinc

Zinc concentrations in the runoff water samples collected during the study period are shown in **Figures B.13** and **B.14** for the zoysiagrass and bermudagrass treatments, respectively. With the zoysiagrass, the Zn concentrations for all irrigation treatments decreased to approximately 0.01 to 0.03 mg/L by September 8, 2002 and remained under 0.03 mg/L for the remainder of the study, save for one spike by the 1XRW treatment in early March of 2003. With the bermudagrass treatment, there was a similar trend with all irrigation treatments containing less than 0.10 mg/L, save for a spike by the EA treatment in early October of 2002 and another spike by the LFRW treatment in March of 2003. All runoff water samples from both grasses and all irrigation treatments had Zn values below 0.2 mg/L and should not cause any adverse environmental impact. Since the Zn concentrations were essentially equal between all the irrigation treatments, it does not appear that the use of SAWS Type I recycled water for irrigation will adversely affect the Zn content of runoff water from turf areas .

5.6.10 Calcium

Calcium concentrations in the runoff water samples collected during the study period are shown in **Figures B.15** and **B.16** for the zoysiagrass and bermudagrass treatments, respectively. With the zoysiagrass, there was a clear pattern showing that the calcium in runoff from the EA treatment was consistently lower than that from the LFRW treatment. However, concentrations in the 1XRW treatment varied widely and occasionally were below that of the EA treatment and above that of the LFRW treatment. With the bermudagrass treatment, there was no clear trend due to irrigation treatment. All runoff water samples from both grasses and all irrigation treatments had calcium values below 125 mg/L and should not cause any adverse environmental impact.

5.6.11 Potassium

Potassium concentrations in the runoff water samples collected during the study period are shown in **Figures B.17** and **B.18** for the zoysiagrass and bermudagrass treatments, respectively. With both the zoysiagrass and the bermudagrass treatments, there were no clear trends due to irrigation treatment. All runoff water samples from both grasses and all irrigation treatments had potassium values below 16 mg/L and should not cause any adverse environmental impact.

5.6.12 Phosphorus

Phosphorus concentrations in the runoff water samples collected during the study period, after removal of the outlier data from July of 2002, are shown in **Figures B.19** and **B.20** for the zoysiagrass and bermudagrass treatments, respectively. With both the zoysiagrass and the bermudagrass treatments, there were no clear trends due to irrigation treatment. For all treatments, the initial samples had the highest P concentrations; however, by October of 2002, concentrations had dropped to background levels and remained close to that for the remainder of the study period. All runoff water samples from both grasses and all irrigation treatments had phosphorus values below 10 mg/L, and the majority were below 3 mg/L. These P concentrations should not cause any adverse environmental impact.

5.6.13 Nitrogen

Total Kjeldahl Nitrogen (TKN) concentrations in the runoff water samples collected during the study period are shown in **Figures B.21** and **B.22** for the zoysiagrass and bermudagrass treatments, respectively. With the zoysiagrass, there was no clear pattern and the TKN concentrations in runoff from all treatments were essentially equal. A spike in TKN for the LFRW was measured on the sample collected in early March of 2003. With the bermudagrass treatment, there was also no clear trend due to irrigation treatment. Except for the March of 2003 samples, all runoff water samples from all irrigation treatments had TKN values below 8 mg/L and should not cause any adverse environmental impact.

Nitrite concentrations in the runoff water samples collected during the study period are shown in **Figures B.23** and **B.24** for the zoysiagrass and bermudagrass treatments, respectively. With the zoysiagrass, there was no clear pattern and the nitrite concentrations in runoff from all treatments were essentially equal. A small spike in nitrite for all irrigation treatments was measured on the sample collected in early March of 2003 and then again at the end of the study. With the bermudagrass treatment, there was also no clear trend due to irrigation treatment. Overall, all runoff water samples from all irrigation treatments had TKN values below 2 mg/L, and most were below 0.5 mg/L. These nitrite concentrations should not cause any adverse environmental impact.

Nitrate concentrations in the runoff water samples collected during the study period are shown in **Figures B.25** and **B.26** for the zoysiagrass and bermudagrass treatments, respectively. With the zoysiagrass, there was no clear pattern and the nitrate concentrations in runoff from all treatments were essentially equal. A fairly large spike in nitrate for the 1XRW irrigation treatment was measured on the sample collected in late June of 2003, but values then returned to less than 2 mg/L at the end of the study. With the bermudagrass treatment, there was a trend for the nitrate in the runoff from the 1XRW and LFRW treatments to be higher than that from the EA treatment. It is also notable that very high nitrate concentrations were measured in the runoff water samples from the EA treatment on the last two sampling dates. The data indicate that nitrate concentrations in runoff may reach as high as 45 mg/L; however, nitrate concentrations from treatments receiving SAWS recycled water had nitrate concentrations similar to those from the EA treatments. While nitrate concentrations above 10 mg/L are of some environmental concern, these levels were not reached on a consistent basis. Therefore, nitrates in runoff from irrigated turf areas may have an occasional adverse environmental impact.

Ammonia concentrations in the runoff water samples collected during the study period are shown in **Figures B.27** and **B.28** for the zoysiagrass and bermudagrass treatments, respectively. With the zoysiagrass, there was no clear pattern and the ammonia concentrations in runoff from all treatments were essentially equal. A small spike in ammonia up to 1.2 mg/L for the 1XRW irrigation treatment was measured on the sample collected in early September of 2002, following which there was a gradual decline and values returned to less than 0.5 mg/L. With the bermudagrass treatment, there was a similar trend, with a peak in ammonia concentrations in the runoff from the EA and 1XRW treatments early in the study followed by a gradual decline to under 1 mg/L. It is also notable that a high ammonia concentration was measured in the runoff water samples from the EA treatment on the first three sampling dates. The data indicate that ammonia concentrations in runoff may reach as high as 2.25 mg/L; however, ammonia concentrations from treatments receiving SAWS recycled water were similar to those from the EA treatments. Since the ammonia concentrations in the runoff water stayed below 2.25 mg/L, the runoff will have very little detrimental environmental impact.

5.6.14 Fecal Coliform

The number of colonies formed per 100 mL sample of runoff water in the runoff water samples collected over the study period are shown in B.29 and B.30 for the zoysiagrass and bermudagrass treatments, respectively. The colony counts were fairly uniform and no one treatment consistently had higher or lower numbers of fecal coliforms in the runoff water. However, there were higher counts in the runoff samples from the September 3, 2002 sampling. The fact that the concentrations in the EA treatment are equal to that in treatments receiving recycled water indicate that the coliform counts may be related to biological activity on the site between runoff-generating events. The majority of fecal coliform counts fell in the range of 1.0 to 2,000 col/100 ml. Peak concentrations ranged up to 10,000 col/100 ml. Overall, the fecal coliform content of the runoff water was low and should not pose any significant adverse environmental effects.

5.7 Rainwater

Results of the chemical analysis of the rainwater samples are provided in **Table 5.9**. When possible, all constituents were measured; however, due to limited sample volume, many constituents could only be measured in the February 27, 2003 sample. To get a better understanding of the data, the average chemical concentrations from the Turf Study samples were compared to that reported by Sharpley et al., 1985 for the cities of Riesel, TX and Bushland, TX (**Table 5.10**). When available, preference was given to Riesel data as this city is located closer to San Antonio and has similar climatic conditions.

The rainfall samples collected at the Turf Study site had nitrate concentrations ranging from 0.02 mg/L to 0.87 mg/L, with an average concentration of 0.28 mg/L. This average value is very close to the average of 0.33 mg/L reported by Sharpley et al., 1985 for 236 measurements at Riesel, TX. The rainfall samples collected at the Turf Study site had NH_4 concentrations ranging from 0.10 mg/L to 1.01 mg/L, with an average concentration of 0.52 mg/L. This average value compares favorably with the average of 0.28 mg/L reported by Sharpley et al., 1985 for 229 measurements at Riesel, TX.

Average measured values of phosphorus, potassium and calcium for the Turf Study location were also similar to averages reported by Sharpley. Measured concentrations of nitrite, magnesium, sodium, copper, iron, manganese, and zinc were all below 0.25 mg/L and indicate that the rainfall at the study site is relatively clean with little contamination from urban or other sources of pollution.

TABLE 5.9
Chemical Composition of Five Rainwater Samples Collected at the Turf Study Site
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Parameter (Units)	Feb 27, 2003	Mar 4, 2003	Mar 25, 2003	Jun 17, 2003	Jul 9, 2003	Avg.
NO_3 (mg/L)	0.39	0.87	0.05	0.05	0.02	0.28
NH_4 (mg/L)	0.85	1.01	N/A	0.10	0.10	0.52
NO_2 (mg/L)	0.10	0.03	0.04	0.01	0.01	0.04
TKN (mg/L)	N/A	N/A	N/A	0.95	6.58	3.77
P (mg/L)	0.05	N/A	N/A	N/A	N/A	0.05
K (mg/L)	0.10	N/A	N/A	N/A	N/A	0.10
Ca (mg/L)	2.29	N/A	N/A	N/A	N/A	2.29
Mg (mg/L)	0.10	N/A	N/A	N/A	N/A	0.10
Na (mg/L)	0.14	N/A	N/A	N/A	N/A	0.14
Cu (mg/L)	0.01	N/A	N/A	N/A	N/A	0.01
Fe (mg/L)	0.03	N/A	N/A	N/A	N/A	0.03
Mn (mg/L)	0.02	N/A	N/A	N/A	N/A	0.02
Zn (mg/L)	0.02	N/A	N/A	N/A	N/A	0.02
pH (std. Units)	6.47	N/A	N/A	N/A	N/A	6.47
EC (µmhos/cm)	28.10	N/A	N/A	N/A	N/A	28.10
Fecal Col.(cfu)	20	180	2500	20	20	548
Fecal Strep. (cfu)	10	10	10	220	100	70.0

TABLE 5.10
Average Chemical Concentrations Measured in Rainfall Samples from the Turf Study Location Compared To Average Values Reported by Sharpley et al., 1985 for the Cities Of Riesel And Bushland, Texas
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Turf Study	Sharpley et al., 1985	
Parameter (units)	Average (N)	Average (N)	City
NO_3 (mg/L)	0..28 (5)	0.33 (236)	Riesel, TX
NH_4 (mg/L)	0.52 (4)	0.28 (229)	Riesel, TX
NO_2 (mg/L)	0.04 (5)	N/A	
TKN (mg/L)	6.58 (2)	N/A	
P (mg/L)	0.05 (1)	0.007 (232)	Riesel, TX
K (mg/L)	0.10 (1)	0.28 (42)	Bushland
Ca (mg/L)	2.29 (1)	3.65 (42)	Bushland
Mg (mg/L)	0.10 (1)	N/A	
Na (mg/L)	0.14 (1)	N/A	
Cu (mg/L)	0.01 (1)	N/A	
Fe (mg/L)	0.03 (1)	N/A	
Mn (mg/L)	0.02 (1)	N/A	
Zn (mg/L)	0.02 (1)	N/A	
pH (std. Units)	6.47 (1)	6.5 (31)	Riesel, TX
EC (µmhos/cm)	28.10 (1)	41.0 (29)	Bushland, TX
Fecal Col.(cfu)	548 (5)	N/A	
Fecal Strep. (cfu)	70 (5)	N/A	

Values in parenthesis are the number of samples represented by the average.

5.8 Leachate

5.8.1 Leachate Volumes

As described earlier, the amount of leachate water from each lysimeter was measured at each sampling date and shortly after large rainfall events. The volumes collected were then summed over the entire study period and a statistical comparison was performed on the total for the study period. Due to limitations on the lysimeter volume and other factors, the maximum volume of leachate that could be captured for any one sampling event was 4.9 liters. Leachate in excess of this amount likely flowed around the lysimeter and was lost.

Volumes collected from the individual lysimeters are presented in Appendix C, Tables C.1 through C.3. Volumes were highly variable and ranged from zero during dry periods to 6.2 liters shortly after heavy rainfall events. Occasionally, collected volumes exceeded the storage capacity of the lysimeters due to ponded water in the soil entering the lysimeter during the time of the collection event.

The collected leachate volumes for the period June 15, 2002 to February 17, 2004 were totaled for each lysimeter. The totals were then statistically analyzed using ANOVA, followed by Tukey's procedure for mean separation to establish if there was any significant difference in the volume of leachate due to irrigation treatment. The results of this evaluation are shown in **Table 5.11**.

The analysis showed no difference in total leachate volume due to either grass or irrigation treatment. There was a difference in leachate volume with depth. The samplers at the 6-inch depth collected less water than those at the 30-inch depth. The samplers at the 18-inch depth collected an intermediate amount of leachate and were not separable from the volumes above and below.

One possible explanation for the greater volume in the 30-inch deep lysimeters compared to the 6-inch lysimeters can be related to the storm events and the percolation rate of the soils. There were several substantial rain events in 2002 and leachate samples were collected after each of these events. A pattern arose that highlighted the difference between sample volumes after significant rain events and sample volumes resulting from normal irrigation. Many times the 30 inch-deep lysimeters would have a greater volume of leachate in them compared to the 6 and 18 inch-deep lysimeters after a substantial rain event. However, this trend would be reversed with samples resulting from leachate of irrigation water. Therefore, it is theorized that during substantial rain events, the percolation rate in the soil exceeded the intake rate of the shallow lysimeters. However, by the time the leachate reached the 30 inch-deep lysimeters, the percolation rate had decelerated to a point that it did not exceed the intake rate of the deeper lysimeters.

5.8.2 Data Analyses for Leachate Samples

A preliminary examination of the leachate data suggested the possibility of some outlier data, particularly phosphorus data. To confirm the presence or absence of any outlier data, the entire data set was subjected to a Cluster Analysis. Plots were made of cluster means as a function of date. Outlier data showed up as major deviations from nearly flat lines. An example graph for data with possible outlier data is shown in **Figure 5.2**. Potential outliers were found for nitrate, phosphorus and zinc concentrations in leachate samples.

TABLE 5.11
Mean Total Volume of Leachate Collected from Lysimeters at Three Depths Under Three Irrigation Treatments from June 15, 2002 through February 17, 2004
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Irrigation Treatment	6” Depth Lysimeters	18” Depth Lysimeters	30” Depth Lysimeters
EA	22.1 a	28.1 a	22.1 b
1XRW	25.6 a	36.9 a	37.5 a
LFRW	26.5 a	28.2 a	38.9 a

Values in a given column followed by the same letter do not differ at p=0.05.

FIGURE 5.2
Cluster Analysis for Zinc Concentrations in Leachate Samples. Outlier is the High Value of Cluster 9 (Value of 2.85), which Is Almost 6 Times Greater Than That Of The Other Mean Values
Edwards Aquifer Recharge Zone Irrigation Pilot Study

```
     ,
     ,
2.85 ˆ                                                                                9
     ,
     ,
2.28 ˆ
     ,
     ,
1.71 ˆ
     ,
     ,
1.14 ˆ
     ,
     ,
0.57 ˆ
     ,             3
     ,             3   3      1
0.00 ˆ  8  8 8     33      1  11  1 1 4   4          6   6       7  77  7 5  5   55   9   9    9   2   2
     Šƒƒˆƒƒƒƒƒƒƒƒƒƒƒƒƒˆƒƒƒƒƒƒƒƒƒƒƒƒƒˆƒƒƒƒƒƒƒƒƒƒƒƒƒˆƒƒƒƒƒƒƒƒƒƒƒƒƒˆƒƒƒƒƒƒƒƒƒƒƒƒƒˆƒƒƒƒƒƒƒƒƒƒƒƒƒˆƒƒƒƒƒƒƒƒƒƒƒƒƒˆƒƒ
       100           200           300           400           500           600           700           800

                                                       Date
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The outlier is the high value of cluster 9 (shown in red), which is almost 6 times greater than that of the other mean values.

For all samples without any outliers, an analysis of variance was conducted using the entire data set of measurements made on the leachate samples. Because there were some missing values, the general linear model (GLM) of the Statistical Analysis System (SAS) version 8 software was used (SAS Institute Inc., Cary, NC, USA). The GLM has the capability to estimate values for missing data points and then analyze the completed data set. The analysis model looked for main effects of grass, irrigation treatment, sample depth, and sampling date as well as all possible 2-way, 3-way and 4-way interactions. For those samples with no 3-way or 4-way interaction, no further analysis was needed. For those samples that had significant 3-way or 4-way interactions, the data set was sorted by sampling date and the analysis was repeated for each individual sampling date.

For all samples that had questionable outlier data, the analysis described above was run with and without the outlier data included.

5.8.3 Zinc

Zinc concentrations in the leachate water exhibited some significant 3-way interactions with date. Therefore, the data were sorted by date and an analysis was run on each individual sampling date. The results of these analyses are shown in Tables C.4, C.5, and C.6 of Appendix C. There were a total of 30 sampling events; however, not all lysimeters yielded samples on all dates. Thus, there may be no values shown for certain treatments and dates. When the number of data values were too low to be able to perform a valid statistical evaluation, the means are presented without any indication of statistical difference.

Of the 30 sampling dates, there was only one date on which there was a significant difference in zinc concentration with depth of sampling compared to 14 dates in which there were no differences due to sampling depth. On October 11, 2002, the sample from the 30-inch depth had the highest zinc concentration. It should be noted, however, that even this high concentration of 0.02 ppm was quite low and is of no environmental concern.

On two of the dates, the leachate from plots planted with bermudagrass had greater concentrations of Zn; however, on a third date, the concentration in the zoysiagrass plots was greater. The remaining 9 dates showed no significant difference between grasses. Thus, there is no clear trend and it does not appear that grass type will have a major impact on Zn leaching.

When the data were analyzed by irrigation water treatment, four dates showed a significant difference compared to 11 dates that showed no significant differences between irrigation water treatments. When significant differences were present, the EA treatment always had the lowest Zn concentration while the highest Zn concentration was either in the 1XRW or LFRW treatments. Thus, in the majority of cases, the use of recycled water for irrigation of turf will not significantly affect the Zn concentration in the leachate moving below the root zone. Consequently, the use of recycled water for irrigation of turf areas should not impact the Zn content of underlying aquifers any more than if Edwards Aquifer water were used for irrigation.

Except for the October 21, 2003, the mean Zn values all ranged at or below 0.2 mg/L, which is well within the EPA Secondary Standard of 5.0 mg/L for Drinking Water. Based on these results, leachate from turf areas irrigated with either Edwards Aquifer water or SAWS

Recycled water will not pose a significant danger of zinc contamination of groundwater reserves.

5.8.4 Nitrate

Nitrate is a negatively charged ion (anion) that is not readily adsorbed by soil particles but is taken up in large quantity by plant roots. Therefore, free nitrate, which is not absorbed by the plants, moves through soil very rapidly as a component of the water phase.

Nitrate nitrogen concentrations in the leachate water exhibited some significant 3-way interactions with date. Therefore, the data were sorted by date and an analysis was run on each individual sampling date. The results of these analyses are shown in Tables C.7, C.8, and C.9 of Appendix C. There were a total of 24 sampling events; however, not all lysimeters yielded samples on all dates. Thus, there may be no values shown for certain treatments and dates. When the number of data values were too low to be able to perform a statistical evaluation, the means are presented without any indication of statistical difference.

Of the 24 sampling dates, there were only three dates on which there was a significant difference in NO_3 concentration with depth of sampling compared to 13 dates in which there were no differences due to sampling depth. On March 25, 2003 and January 20, 2004, the sample from the 6-inch depth had the highest NO_3 concentration, while on September 23, 2003, this depth had the lowest NO_3 concentration.

On 5 of the dates, the leachate from plots planted with bermudagrass had greater concentrations of NO_3. The remaining 13 dates showed no significant difference between grasses. While not statistically significant on all dates, there does appear to be a general trend of greater NO_3 concentrations in the leachate from the bermudagrass plots. Some of this increase may be due to the greater nitrogen fertilization requirement of this grass.

When the data were analyzed by irrigation water treatment, six dates showed a significant difference, compared to 13 dates that showed no significant differences between irrigation water treatments. While not statistically significant on all dates, there does appear to be a general trend of greater NO_3 concentrations in the leachate from the 1XRW and LFRW plots. This increase is likely due to the higher concentration of NO_3 in the irrigation water being applied to these plots.

Through the majority of the study (September 2002 through October 2003), the mean NO_3 values all remained below 10.0 mg/L, which is the primary EPA Standard for nitrate concentrations in drinking water. Data for the first sampling date, August 22, 2002, exceeded the drinking water standard and is likely due to a combination of the greater amounts of irrigation applied during the initial startup months, oxidation of other N forms to nitrate, and macropore flow through cracks and fissures in the soil. Nitrate concentrations from November 18, 2003 to the end of the study were also elevated above the drinking water standard.

5.8.5 Fecal Coliform

Fecal coliform counts in the leachate water exhibited some significant 3-way interactions with date. Therefore, the data were sorted by date and an analysis was run on each individual sampling date. The results of these analyses are shown in Tables C.10, C.11, and **C.12** of Appendix C. There were a total of 31 sampling events; however, not all lysimeters yielded samples on all dates. Thus, there may be no values shown for certain treatments and dates. When the number of data values were too low to be able to perform a valid statistical evaluation, the means are presented without any indication of statistical difference.

Of the 31 sampling dates, there were only three dates on which there were significant differences in fecal coliform counts with depth of sampling compared to 25 dates in which there were no differences due to sampling depth. On December 19, 2002 and August 19, 2003, the samples from the 6-inch depth had the highest fecal coliform count, while on April 22, 2003, the 30-inch sample had the highest Fecal coliform count.

On 5 of the dates, the leachate from plots planted with bermudagrass had greater Fecal Coliform counts. In contrast, on two dates the count from the zoysiagrass plots was greater. The remaining 20 dates showed no significant difference between grasses. Thus, there is no clear trend and it does not appear that grass type will have a major impact on fecal coliform leaching.

When the data were analyzed by irrigation water treatment, three dates showed a significant difference, compared to 26 dates that showed no significant differences between irrigation water treatments. When significant differences were present, the EA treatment had the lowest Fecal Coliform count on two dates, compared to one date when it had the highest count. Thus, in the majority of cases, the use of recycled water for irrigation of turf will not significantly affect the number of Fecal Coliform in the leachate moving below the root zone. Consequently, the use of recycled water for irrigation of turf areas should not impact the Fecal Coliform population of underlying aquifers any more than if Edwards Aquifer water were used for irrigation.

5.8.6 Total Salts

Total Salts in the leachate water samples were estimated by measuring the electrical conductivity (EC) of a subsample of the collected water.

The average electrical conductivity of the leachate samples over the entire study period ranged from 0.499 to 0.653 mg/L and had no 3- or 4-way interactions. The analysis showed that there were significant effects due to turfgrass, sampling depth, and irrigation treatments (Tables 5.12, C.13 through C.15). The data show a small but significantly greater EC of leachate from plots planted with bermudagrass (**Figure 5.3**). If the bermudagrass consumes more water than the zoysia, it could result in a concentrating effect on the salts, causing an increase in EC of the leachate water. The leachate from the upper 6-inch samplers had the highest EC, followed by that of the 30-inch samplers and, finally, that from the 18-inch samplers (**Figure 5.4**). Given the higher EC of the recycled water that was surface irrigated, it is reasonable to expect that soil moisture in the upper 6 inches of soil would be elevated. There was a significantly higher EC in the leachate from the 1XRW and LFRW plots as compared to those irrigated with EA water (**Figure 5.5**). Therefore, water leaching past the root zone of turf areas will carry with it about 1.5 times the amount of salts if the same area were irrigated with Edwards Aquifer water.

TABLE 5.12
Mean EC of Leachate Samples Collected Over the Study Period
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Differentiator	Number of Samples	Mean
Turfgrass		
Bermudagrass	238	0.589 a[1]
Zoysiagrass	203	0.552 b
Depth		
6 inches	113	0.654 a
18 inches	161	0.500 c
30 inches	167	0.586 b
Irrigation Treatment		
EA	109	0.425 b
RW	166	0.626 a
LF	166	0.614 a

1. Mean values within a given turfgrass, depth, or irrigation treatment followed by the same letter do not differ significantly at p=0.05.

Based on this information, turf areas irrigated with SAWS Recycled water will pose a small but significant danger of salt contamination of groundwater reserves.

FIGURE 5.3
Mean Electrical Conductivity Measured in Leachate Samples, by Turfgrass
Edwards Aquifer Recharge Zone Irrigation Pilot Study

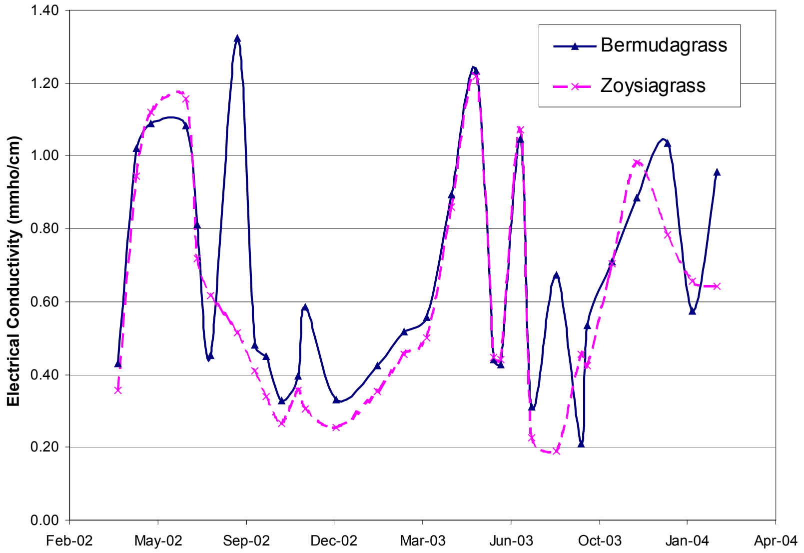


FIGURE 5.4
Mean Electrical Conductivity Measured in Leachate Samples, by Lysimeter Depth
Edwards Aquifer Recharge Zone Irrigation Pilot Study

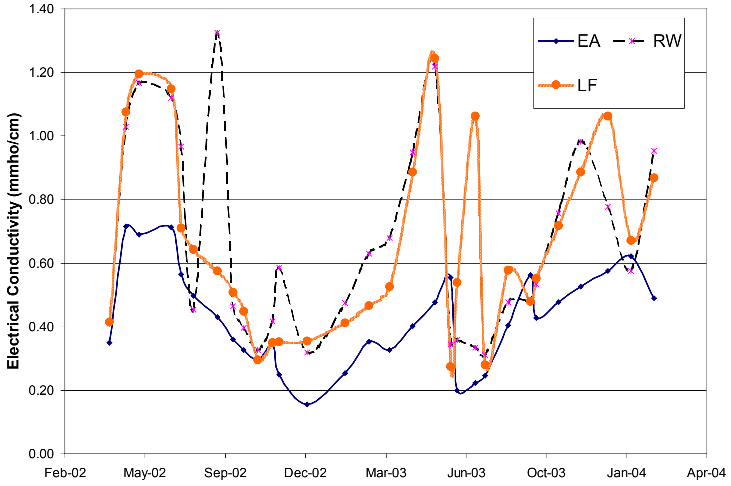
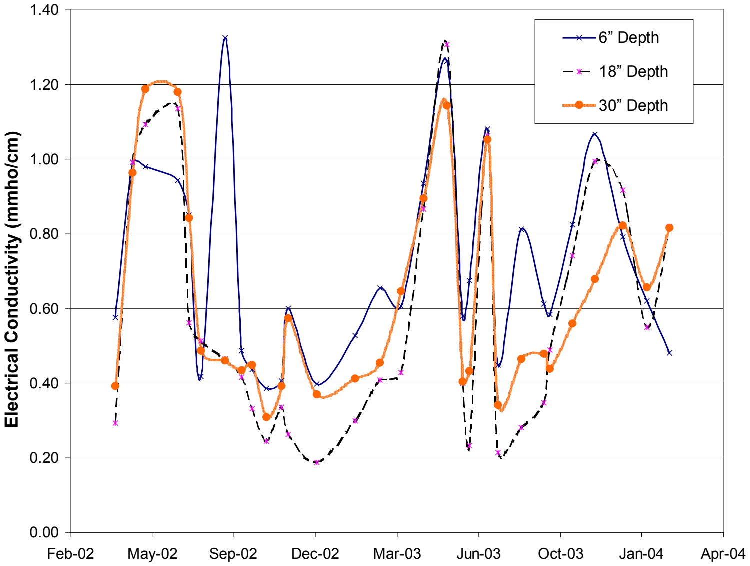


FIGURE 5.5
Mean Electrical Conductivity Measured in Leachate Samples, by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study



5.8.7 pH

The average pH of the leachate samples over the entire study period ranged from 7.07 to 7.34 units and had no 3- or 4-way interactions. The analysis showed that there was a significant effect due to sampling depth, but not turfgrass or irrigation treatments (Tables 5.13, C.16 through C.18). The data show a small but significantly greater pH of leachate from the upper 6-inch samplers. This is likely due to the large buffering capacity of soils. As the water passes through soil, the pH of the water reaches an equilibrium with that of the soil. Based on these results, the use of recycled water on soils that are at least 18-inches deep should have no effect on the pH of water leaching past the root zone of turf areas.

TABLE 5.13
Mean pH of Leachate Samples Collected Over the Study Period
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Differentiator	Number of Samples	Mean
Turfgrass		
Bermudagrass	238	7.16 a[1]
Zoysiagrass	203	7.18 a
Depth		
6 inches	113	7.34 a
18 inches	161	7.07 b
30 inches	167	7.15 b
Irrigation Treatment		
EA	109	7.20 a
RW	166	7.21 a
LF	166	7.11 a

1. Mean values within a given turfgrass, depth, or irrigation treatment followed by the same letter do not differ significantly at p=0.05.

5.8.8 Potassium

The average potassium concentrations measured in the leachate samples over the entire study period ranged from 7.65 to 9.83 mg/L and had no 3- or 4-way interactions. The analysis showed that there were significant effects due to turfgrass, sampling depth, and irrigation treatments (**Tables 5.14,** C.19 through C.21). The data show a small but significantly greater potassium concentration in leachate from plots planted with zoysiagrass. The leachate from the upper 6-inch samplers had the highest potassium concentration, followed by that of the 18-inch and 30-inch samplers. Given the higher potassium content of the recycled water that was surface irrigated, it is reasonable to expect that the potassium concentration in the soil moisture within the upper 6 inches would be elevated. There also was a significantly higher potassium concentration in the leachate from the 1XRW plots, as compared to that from the EA and LFRW treatment plots. Therefore, water leaching past the 30-inch depth will carry similar amounts of potassium with it as if the same area were irrigated with Edwards Aquifer water. Based on this information, turf areas irrigated with SAWS Recycled water will not pose a significant danger of potassium contamination of groundwater reserves.

TABLE 5.14
Mean Potassium Concentrations (mg/L) in Leachate Samples Collected Over the Study Period
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Differentiator	Number of Samples	Mean
Turfgrass		
Bermudagrass	273	8.28 b[1]
Zoysiagrass	236	9.38 a
Depth		
6 inches	142	9.95 a
18 inches	174	8.51 b
30 inches	193	8.18 b
Irrigation Treatment		
EA	141	7.65 b
RW	184	9.83 a
LF	184	8.62 b

1. Mean values within a given turfgrass, depth, or irrigation treatment followed by the same letter do not differ significantly at p=0.05.

5.8.9 Ammonia Nitrogen

Ammonia nitrogen concentrations in the leachate water exhibited some significant 3-way interactions with date. Therefore, the data were sorted by date and an analysis was run on each individual sampling date. The results of these analyses are shown in Tables C.22 through C.24 of Appendix C. There were a total of 30 sampling events; however, not all lysimeters yielded samples on all dates. Thus, there may be no values shown for certain treatments and dates. When the number of data values were too low to be able to perform a valid statistical evaluation, the means are presented without any indication of statistical difference.

Of the 30 sampling dates, there were only two dates on which there was a significant difference in NH_3 concentration with depth of sampling compared to 19 dates in which there were no differences due to sampling depth. On June 25, 2002, the sample from the 6-inch depth had the highest NH_3 concentration, while on March 25, 2003, this depth had the lowest NH_3 concentration.

On 5 of the dates, the leachate from plots planted with bermudagrass had greater concentrations of NH_3; however, on a sixth date the concentration in the zoysiagrass plots was greater. The remaining 14 dates showed no significant difference between grasses. Thus, there is no clear trend and it does not appear that grass type will have a major impact on NH_3 leaching.

When the data were analyzed by irrigation water treatment, only one date showed a significant difference, compared to 22 dates that showed no significant differences between irrigation water treatments. Thus, in the majority of cases, the use of recycled water for irrigation of turf will not significantly affect the NH_3 concentration in the leachate moving below the root zone. Consequently, the use of recycled water for irrigation of turf areas should not impact the NH_3 content of underlying aquifers any more than if Edwards Aquifer water were used for irrigation.

Throughout the study, the mean NH_3 values all ranged at or below 0.26 mg/L, which is very low and of little environmental concern. Although there are no primary or secondary EPA Standards for ammonium-N concentrations in drinking water, concentrations less than 1 mg/L should not be a problem.

5.8.10 Nitrite

Nitrite nitrogen concentrations in the leachate water exhibited some significant 3-way interactions with date. Therefore, the data were sorted by date and an analysis was run on each individual sampling date. The results of these analyses are shown in Tables C.25 through C.27 of Appendix C. There were a total of 24 sampling events; however, not all lysimeters yielded samples on all dates. Thus, there may be no values shown for certain treatments and dates. When the number of data values were too low to be able to perform a valid statistical evaluation, the means are presented without any indication of statistical difference.

Of the 24 sampling dates, there were no significant differences in NO_2 concentration with depth of sampling.

On one of the dates, the leachate from plots planted with zoysiagrass had a greater concentration of NO_2. The remaining 17 dates showed no significant difference between grasses. Thus, it does not appear that grass type will have a major impact on NO_2 leaching.

When the data were analyzed by irrigation water treatment, no significant differences between irrigation water treatments were found for any of the dates. Thus, the use of recycled water for irrigation of turf will not significantly affect the NO_2 concentration in the leachate moving below the root zone. Consequently, the use of recycled water for irrigation of turf areas should not impact the NO_2 content of underlying aquifers any more than if Edwards Aquifer water were used for irrigation.

Throughout the study, the mean NO_2 values all ranged at or below 0.71 mg/L, which is low and of little environmental concern. Although there are no primary or secondary EPA Standards for nitrite concentrations in drinking water, concentrations less than 1 mg/L should not be a problem.

5.8.11 Iron

Iron concentrations in the leachate water exhibited some significant 3-way interactions with date. Therefore, the data were sorted by date and an analysis was run on each individual sampling date. The results of these analyses are shown in Tables C.28 through C.30 of Appendix C. There were a total of 30 sampling events; however, not all lysimeters yielded samples on all dates. Thus, there may be no values shown for certain treatments and dates. When the number of data values were too low to be able to perform a valid statistical evaluation, the means are presented without any indication of statistical difference.

Of the 30 sampling dates, there were four dates on which there was a significant difference in iron concentration with depth of sampling, compared to 11 dates in which there were no differences due to sampling depth. On June 25, 2002, the sample from the 30-inch depth had the highest iron concentration, while on February 27, 2003, June 17, 2003 and September 16, 2003, the samples from the 18-inch depth had the highest iron concentrations. Therefore, there is no consistent pattern of elevated iron concentrations in the leachate.

On one date, the leachate from plots planted with bermudagrass had greater concentrations of iron; however, on a second date, the concentration in the zoysiagrass plots was greater. The remaining 8 dates showed no significant difference between grasses. Thus, there is no clear trend and it does not appear that grass type will have a major impact on iron leaching.

When the data were analyzed by irrigation water treatment, only one date showed a significant difference, compared to 14 dates that showed no significant differences between irrigation water treatments. On the one date when significant differences were present, the EA treatment had the highest iron concentration. Thus, the use of recycled water for irrigation of turf will not significantly affect the iron concentration in the leachate moving below the root zone. Consequently, the use of recycled water for irrigation of turf areas should not impact the iron content of underlying aquifers any more than if Edwards Aquifer water were used for irrigation.

Approximately half of the measured mean Fe concentrations in leachate were above the EPA MCL of 0.3 mg/L for drinking water. Thus, leachate from turf areas irrigated with either Edwards Aquifer water or SAWS Recycled water will pose a significant possibility of iron contamination of groundwater reserves.

5.8.12 Magnesium

The average magnesium concentrations measured in the leachate samples over the study period ranged from 6.23 to 10.05 mg/L and had no 3- or 4-way interactions. The analysis showed that there were significant effects due to sampling depth and irrigation treatments (Tables 5.15, C.31 through C.33). The data show no difference in magnesium concentration in leachate from plots planted with either zoysiagrass or bermudagrass. The leachate from the upper 6-inch samplers had the highest magnesium concentration, followed by that of the 18-inch and 30-inch samplers. Given the higher magnesium content of the recycled water that was surface irrigated, it is reasonable to expect that the magnesium concentration in the soil moisture within the upper 6 inches would be elevated. There also was a significantly higher magnesium concentration in the leachate from the LFRW plots as compared to that from the EA treatment plots. Leachate from the 1XRW plots contained an intermediate magnesium concentration and did not differ from either of the other treatments. Therefore, water leaching past the 30-inch depth will carry similar amounts of magnesium with it as if the same area were irrigated with Edwards Aquifer water. Based on this information, turf areas irrigated with SAWS Recycled water will not pose a significant possibility of magnesium contamination of groundwater reserves.

TABLE 5.15
Mean Magnesium Concentrations (mg/L) in Leachate Samples Collected Over the Study Period
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Differentiator	Number of Samples	Mean
Turfgrass		
Bermudagrass	273	7.32 a[1]
Zoysiagrass	236	7.32 a
Depth		
6 inches	142	10.05 a
18 inches	174	6.23 a
30 inches	193	6.30 a
Irrigation Treatment		
EA	141	7.06 a
RW	184	6.89 a
LF	184	7.96 a

1. Mean values within a given turfgrass, depth, or irrigation treatment followed by the same letter do not differ significantly at p=0.05.

5.8.13 Manganese

The average manganese concentrations measured in the leachate samples over the study period ranged from 0.022 to 0.025 mg/L and showed no significant effects due to turfgrass, sampling depth, or irrigation treatment (Tables 5.16, C.34 through C.36). Thus, irrigation of turf areas with SAWS recycled water should not significantly change the Mn concentration of water leaching past the root zone. The data also indicate that Mn concentrations in the leaching water should be independent of soil depth and turfgrass species.

TABLE 5.16
Mean Manganese Concentrations (mg/L) in Leachate Samples Collected Over the Study Period
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Differentiator	Number of Samples	Mean
Turfgrass		
Bermudagrass	273	0.024 a[1]
Zoysiagrass	236	0.023 a
Depth		
6 inches	142	0.022 a
18 inches	174	0.023 a
30 inches	193	0.025 a
Irrigation Treatment		
EA	141	0.024 a
RW	184	0.023 a
LF	184	0.024 a

1. Mean values within a given turfgrass, depth, or irrigation treatment followed by the same letter do not differ significantly at p=0.05.

5.8.14 Copper

Copper concentrations in the leachate water exhibited some significant 3-way interactions with date. Therefore, the data were sorted by date and an analysis was run on each individual sampling date. The results of these analyses are shown in Tables C.37 through C.39 of Appendix C. There were a total of 30 sampling events; however, not all lysimeters yielded samples on all dates. Thus, there may be no values shown for certain treatments and dates. When the number of data values were too low to be able to perform a valid statistical evaluation, the means are presented without any indication of statistical difference.

Of the 30 sampling dates, there were only four dates on which there was a significant difference in copper concentration with depth of sampling, compared to 11 dates in which there were no differences due to sampling depth. On May 16, 2002 and September 23, 2003, the sample from the 30-inch depth had the highest copper concentration, while on April 30, 2002 and July 8, 2002, the 6-inch samples had the highest copper concentrations.

On one of the dates, the leachate from plots planted with bermudagrass had greater concentrations of copper; however, on two other dates, the concentrations in the zoysiagrass plots were greater. The remaining 8 dates showed no significant difference between grasses. Thus, there is no clear trend and it does not appear that grass type will have a major impact on copper leaching.

When the data were analyzed by irrigation water treatment, two dates showed a significant difference compared to 13 dates that showed no significant differences between irrigation water treatments. When significant differences were present, the EA treatment always had the highest copper concentration. Thus, in the majority of cases, the use of recycled water for irrigation of turf will not significantly affect the copper concentration in the leachate moving below the root zone. Consequently, the use of recycled water for irrigation of turf areas should not impact the copper content of underlying aquifers any more than if Edwards Aquifer water were used for irrigation.

During the study period, the mean concentrations measured in leachate water from all depths remained well below the EPA MCL of 1.0 mg/L for Drinking Water. Because the vast majority of measured Cu concentrations in leachate during the study period were below 0.10 mg/L, leachate from turf areas irrigated with either Edwards Aquifer water or SAWS Recycled water will not pose a significant possibility of copper contamination of groundwater reserves.

5.8.15 Sodium

The average sodium concentrations measured in the leachate samples over the entire study period ranged from 18.33 to 52.91 mg/L and had no 3- or 4-way interactions. The analysis showed that there were significant effects due to sampling depth and irrigation treatments (**Tables 5.17**, C.40 through C.42). The data show no difference in sodium concentration in leachate from plots planted with either zoysiagrass or bermudagrass (**Figure 5.6**). The leachate from the upper 6-inch samplers had the highest sodium concentration, followed by that of the 18-inch and 30-inch samplers (**Figure 5.7**). Given the higher sodium content of the recycled water that was surface irrigated, it is reasonable to expect that the sodium concentration in the soil moisture within the upper 6 inches would be elevated.

TABLE 5.17
Mean Sodium Concentrations (mg/L) in Leachate Samples Collected Over the Study Period
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Differentiator	Number of Samples	Mean
Turfgrass		
Bermudagrass	273	42.78 a[1]
Zoysiagrass	236	41.00 a
Depth		
6 inches	142	50.80 a
18 inches	174	36.64 b
30 inches	193	40.23 b
Irrigation Treatment		
EA	141	18.33 b
RW	184	49.10 a
LF	184	52.91 a

1. Mean values within a given turfgrass, depth, or irrigation treatment followed by the same letter do not differ significantly at p=0.05.

FIGURE 5.6
Mean Sodium Concentrations Measured in Leachate Samples, by Turfgrass
Edwards Aquifer Recharge Zone Irrigation Pilot Study

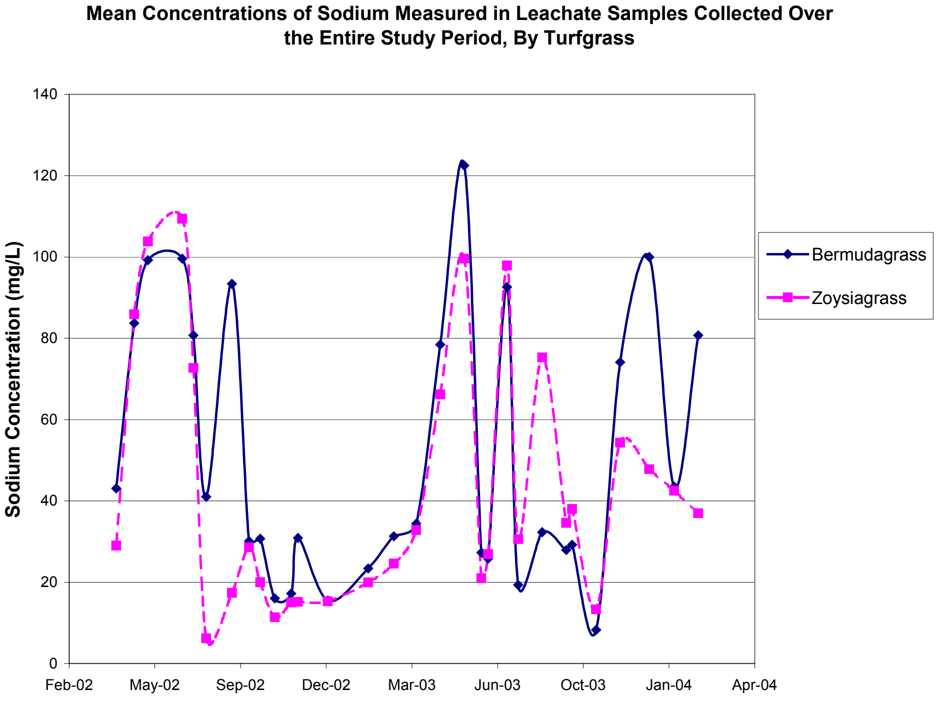


FIGURE 5.7
Mean Sodium Concentrations Measured in Leachate Samples, by Lysimeter Depth
Edwards Aquifer Recharge Zone Irrigation Pilot Study

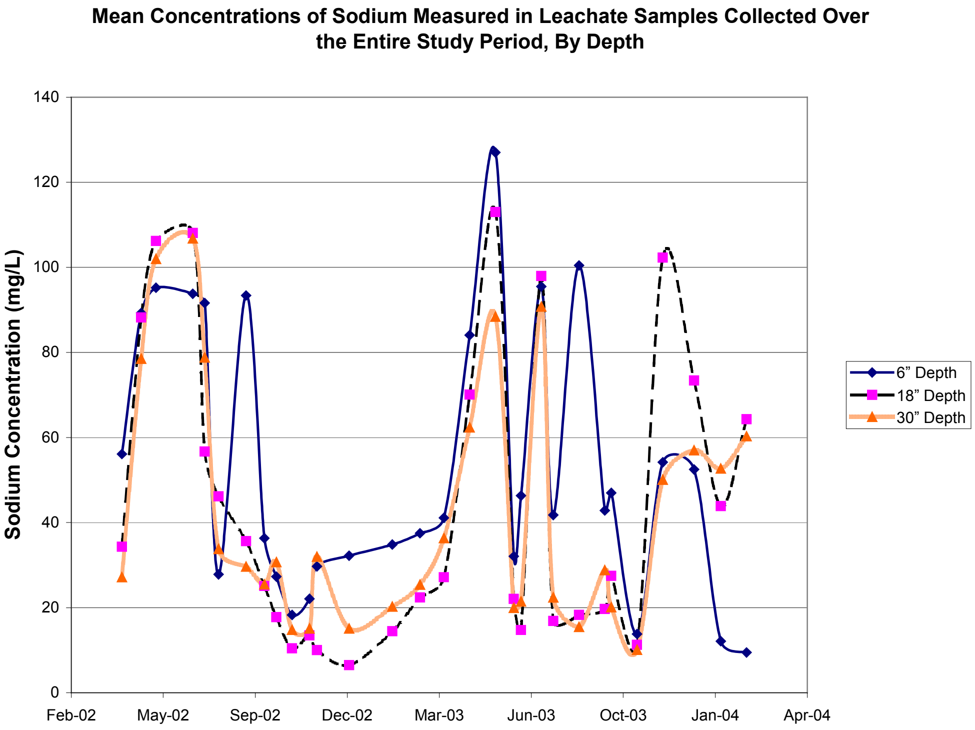
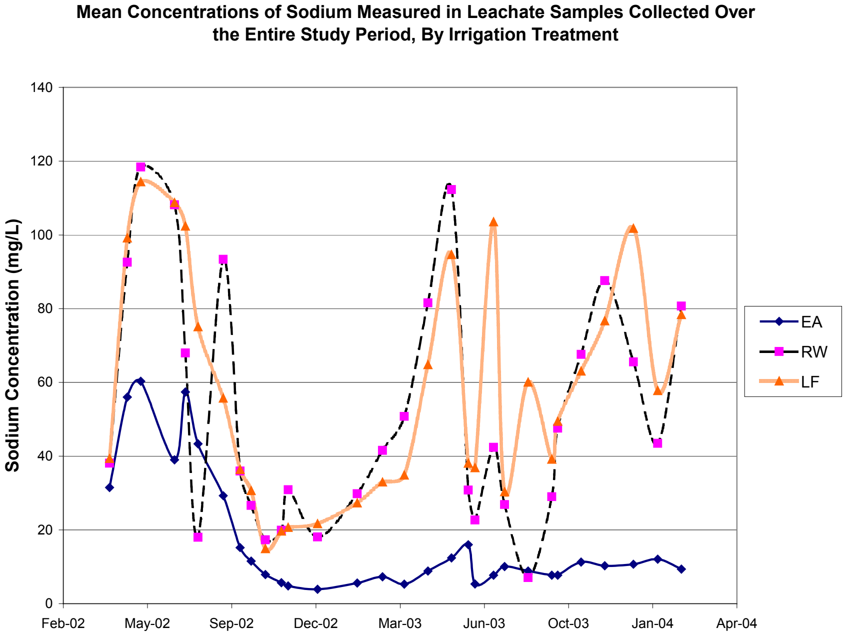


FIGURE 5.8
Mean Sodium Concentrations Measured in Leachate Samples, by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study



There also was a significantly higher sodium concentration in the leachate from the LFRW and 1XRW plots as compared to that from the EA treatment plots (**Figure 5.8**). Therefore, water leaching past the 30-inch depth will carry significantly greater amounts of sodium with it than if the same area were irrigated with Edwards Aquifer water. Based on this information, turf areas irrigated with SAWS Recycled water will pose a small but significant possibility of sodium contamination of groundwater reserves.

5.8.16 Calcium

The average calcium concentrations measured in the leachate samples over the entire study period ranged from 60.7 to 76.9 mg/L and showed no significant effects due to irrigation treatment (**Tables 5.18,** C.43 through C.45). Thus, irrigation of turf areas with SAWS recycled water should not significantly change the Ca concentration of water leaching past the root zone. The data also indicate that Ca concentrations in the leaching water may vary according to soil depth and turfgrass species. The leachate samples from the 18-inch depth had significantly higher Ca concentrations than samples from either the 6-inch or 30-inch depths. This is likely due to spatial variability and the occurrence of macropores in the soil overlying the lysimeters.

TABLE 5.18
Mean Calcium Concentrations (mg/L) in Leachate Samples Collected Over the Study Period
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Differentiator	Number of Samples	Mean
Turfgrass		
Bermudagrass	273	73.2 a[1]
Zoysiagrass	236	66.4 b
Depth		
6 inches	142	76.9 a
18 inches	174	60.7 a
30 inches	193	73.5 a
Irrigation Treatment		
EA	141	71.1 a
RW	184	71.3 a
LF	184	68.0 a

1. Mean values within a given turfgrass, depth, or irrigation treatment followed by the same letter do not differ significantly at p=0.05.

5.8.17 Total Kjeldahl Nitrogen

Total Kjeldahl Nitrogen concentrations in the leachate water exhibited some significant 3-way interactions with date. Therefore, the data were sorted by date and an analysis was run on each individual sampling date. The results of these analyses are shown in Tables C.46 through C.48 of Appendix C. There were a total of 30 sampling events; however, not all lysimeters yielded samples on all dates. Thus, there may be no values shown for certain treatments and dates. When the number of data values were too low to be able to perform a valid statistical evaluation, the means are presented without any indication of statistical difference.

Of the 30 sampling dates, there were seven dates on which there were significant differences in TKN concentration with depth of sampling, compared to 9 dates in which there were no differences due to sampling depth. On all seven dates, the samples from the 6-inch depth had the highest TKN concentration. Because nitrogen was applied to the soil surface and is highly soluble, higher concentrations in the leachate samples from the shallow depths is expected.

On one of the dates, the leachate from plots planted with bermudagrass had a greater concentration of TKN. The remaining 14 dates showed no significant difference between grasses. Thus, it does not appear that grass type will have a major impact on TKN leaching.

When the data were analyzed by irrigation water treatment, six dates showed a significant difference, compared to 10 dates that showed no significant differences between irrigation water treatments. When significant differences were present, the EA treatment always had the lowest TKN concentration. Thus, the data indicate that the use of recycled water for irrigation of turf will increase the TKN concentration in the leachate moving below the root zone. Consequently, the use of recycled water for irrigation of turf areas may result in a small increase in the TKN content of underlying groundwater compared to using Edwards Aquifer water for irrigation.

During the study period, the maximum concentration measured in leachate water from all depths was 2.6 mg/L. There are no primary or secondary EPA Standards for Total Kjeldahl Nitrogen concentrations in drinking water. Based on this information, turf areas irrigated with SAWS Recycled water will contribute a small but increased amount of Total Kjeldahl Nitrogen contamination of groundwater reserves as compared to that which would occur from the use of EA water for irrigation.

5.8.19 Phosphorus

Phosphorus concentrations in the leachate water exhibited some significant 3-way interactions with date. Therefore, the data were sorted by date and an analysis was run on each individual sampling date, except for the July 8, 2002 and July 23, 2002 data, which were shown to be outliers. The results of these analyses are shown in Tables C.49 through C.51 of Appendix C. There were a total of 27 sampling events; however, not all lysimeters yielded samples on all dates. Thus, there may be no values shown for certain treatments and dates. When the number of data values were too low to be able to perform a valid statistical evaluation, the means are presented without any indication of statistical difference.

Of the 27 sampling dates, there were only two dates on which there was a significant difference in phosphorus concentrations with depth of sampling, compared to 12 dates in which there were no differences due to sampling depth. On June 17, 2003 and July 22, 2003, the samples from the 30-inch depth had the highest phosphorus concentrations.

On one of the dates, the leachate from plots planted with bermudagrass had a greater concentration of phosphorus. The remaining 8 dates showed no significant difference between grasses. Thus, there is no clear trend and it does not appear that grass type will have a major impact on phosphorus leaching.

When the data were analyzed by irrigation water treatment, three dates showed a significant difference, compared to seven dates that showed no significant differences between irrigation water treatments. When significant differences were present, the EA treatment always had the lowest phosphorus concentration. Thus, in the majority of cases, the use of recycled water for irrigation of turf will not significantly affect the phosphorus concentration in the leachate moving below the root zone. Consequently, the use of recycled water for irrigation of turf areas should not impact the phosphorus content of underlying aquifers any more than if Edwards Aquifer water were used for irrigation.

The mean phosphorus values all ranged below 5 mg/L. Based on these results, leachate from turf areas irrigated with SAWS Recycled water will not pose a significant possibility of phosphorus contamination of groundwater reserves.

5.9 Tissue

5.9.1 Turf Aesthetic Quality

Photographs of plot 9, taken over the course of the study period, are presented in Appendix A. Visually, the aesthetic rating was very low at the beginning of the study. At the start of this project, the turf plots had been poorly maintained for several years and the turf suffered from low nitrogen fertility, inadequate moisture, and heavy weed infestation. In addition, the plots had not been mowed frequently nor to the proper height for several years and the grass was just beginning to break winter dormancy. These poor conditions are reflected in the low overall turf quality ratings in April and May of 2002 for both the bermudagrass (**Figure 5.9**) and zoysiagrass plots (**Figure 5.10**).

FIGURE 5.9
Bermudagrass Aesthetic Quality Ratings for the Study Period
Edwards Aquifer Recharge Zone Irrigation Pilot Study

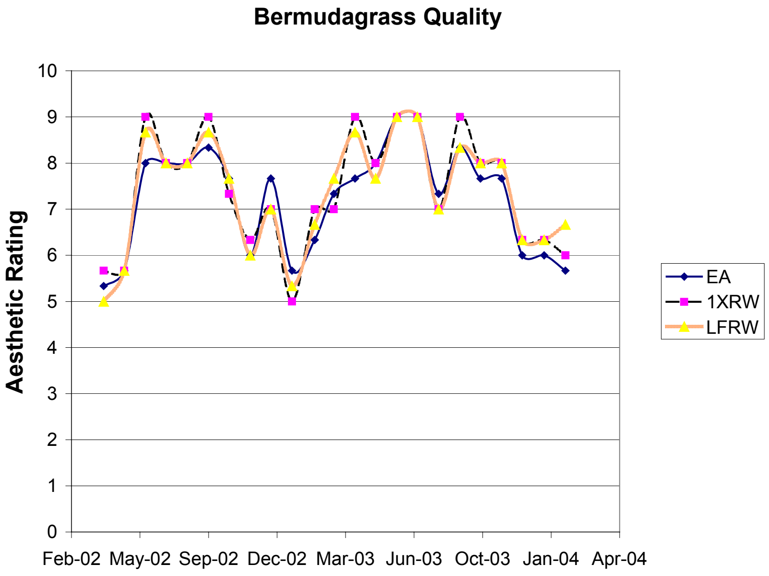
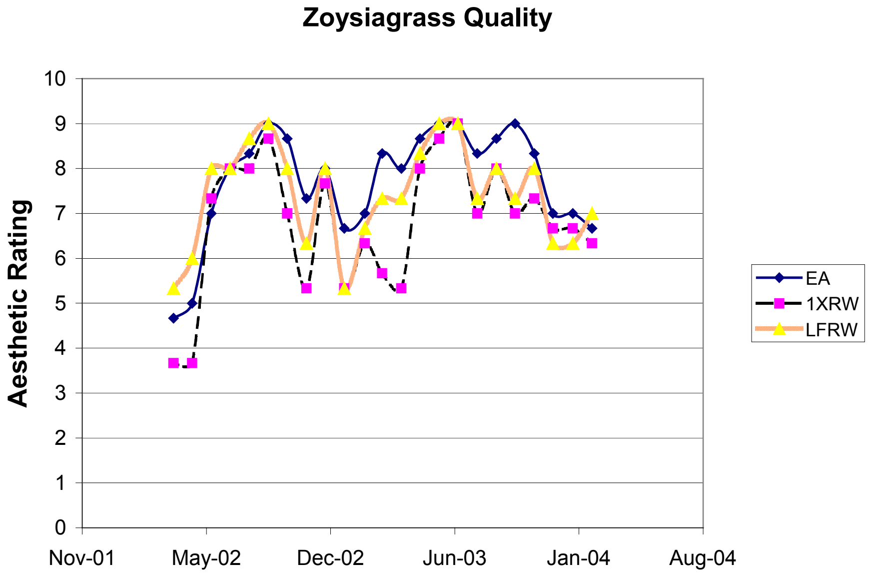


FIGURE 5.10
Zoysiagrass Aesthetic Quality Ratings for the Study Period
Edwards Aquifer Recharge Zone Irrigation Pilot Study



Turf conditions steadily improved throughout the 2002 growing season and, by June of 2002, all plots had risen to an acceptable turf quality of 7 or above. Initially, the plots receiving the leaching fraction recycled water treatment were the slowest to improve in quality; however, by July 2002, all plots were at an acceptable quality of 8. The turf quality remained at 8 or above through August and increased to nearly 9 in September. Following September, turf quality declined as turf growth slowed and color waned. By January 2003, the turf had gone into winter dormancy. Although the color was very poor, the density and uniformity remained high. As green-up was reached in March 2003, the cycle of turf quality repeated itself.

The data show the irrigation treatments had no significant effect on turf quality (**Table 5.19**). Furthermore, the fertility applications in 2002, although less than planned, were sufficient to provide adequate nutrition for a quality turf surface.

5.9.3 Sodium

Sodium concentrations in the plant tissue samples exhibited some significant 3-way interactions with date. Therefore, the data were sorted by date and grass; following that, a separate analysis was run on each of the 15 individual sampling dates.

On 11 of the 15 sampling dates, there were significant differences in sodium concentrations in bermudagrass tissue due to irrigation treatment. In all 11 dates, the tissue from the plots treated with EA water had significantly lower sodium concentrations. On three of the remaining four dates, the trend was the same even though the differences were not sufficient to be statistically significant at p=0.05. In all dates, there were no differences between the 1XRW and LFRW treatments.

TABLE 5.19
Mean Aesthetic Ratings for Plots During the Study Period
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Date	EA Treatment	1XRW Treatment	LFRW Treatment
April 2002	5.0 a	4.7 a	5.2 a
May 2002	5.3 a	4.7 a	5.8 a
June 2002	7.5 a	8.2 a	8.3 a
July 2002	8.0 a	8.0 a	8.0 a
August 2002	8.2 a	8.0 a	8.3 a
September 2002	8.7 a	8.8 a	8.8 a
October 2002	8.2 a	7.2 a	7.8 a
November 2002	6.7 a	5.8 a	6.2 a
December 2002	7.8 a	7.3 a	7.5 a
January 2003	6.2 a	5.2 a	5.3 a
February 2003	6.7 a	6.7 a	6.7 a
March 2003	7.8 a	6.3 b	7.5 a
April 2003	7.8 a	7.2 a	8.0 a
May 2003	8.3 a	8.0 a	8.0 a
June 2003	9.0 a	8.8 a	9.0 a
July 2003	9.0 a	9.0 a	9.0 a
August 2003	7.8 a	7.0 a	7.2 a
September 2003	8.5 a	8.5 a	8.2 a
October 2003	8.3 a	7.5 a	7.7 a
November 2003	8.0 a	7.7 a	8.0 a
December 2003	6.5 a	6.5 a	6.3 a
January 2004	6.5 a	6.5 a	6.3 a
February 2004	6.2 a	6.2 a	6.8 a

Note: Mean values within a given date followed by the same letter do not differ significantly at p=0.05.

On 13 of the 15 sampling dates, there were significant differences in sodium concentrations in zoysiagrass tissue due to irrigation treatment. In all 13 dates, the tissue from the plots treated with EA water had significantly lower sodium concentrations. On both of the remaining two dates, the trend was the same even though the differences were not sufficient to be statistically significant at p=0.05. In all dates, there were no differences between the 1XRW and LFRW treatments.

Sodium concentrations in the bermudagrass turf tissue for samples collected between May 1, 2002 and February 17, 2004 are shown in **Figure 5.11**. Except for the August 22, 2003 sample, all samples from the EA treatment contained lower concentrations of sodium in the tissue. Tissues from the 1XRW and LFRW treatments contained similar but elevated levels of sodium. All tissue levels were within the range considered to be safe for turf grass growth.

Sodium concentrations in the zoysiagrass turf tissue for samples collected between May 1, 2002 and February 17, 2004 are shown in **Figure 5.12**. All samples from the EA treatment contained lower concentrations of sodium in the tissue. Tissues from the 1XRW and LFRW treatments contained similar but elevated levels of sodium. However, all tissue levels were within the range considered to be safe for turf grass growth.

FIGURE 5.11
Concentrations of Sodium Measured in Bermudagrass Tissue
Edwards Aquifer Recharge Zone Irrigation Pilot Study

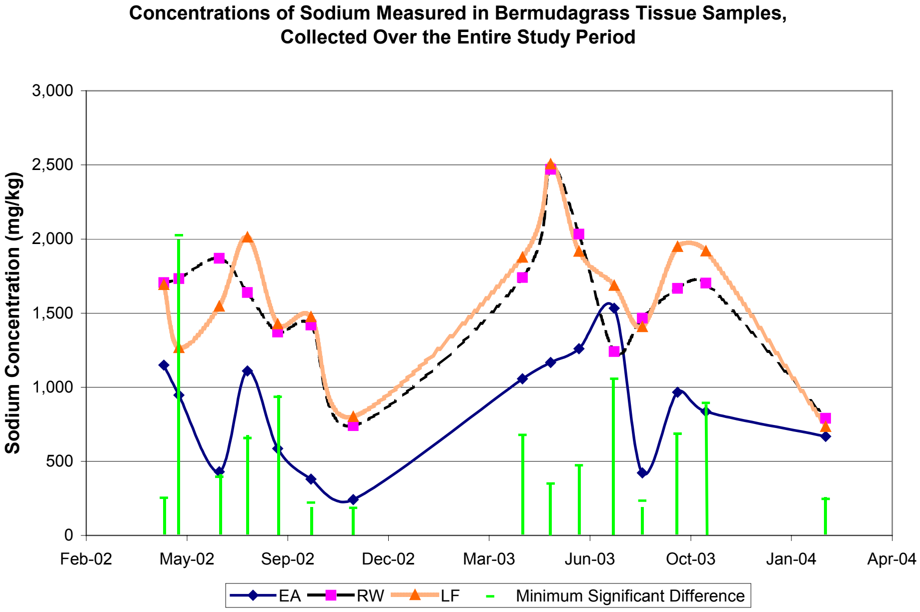
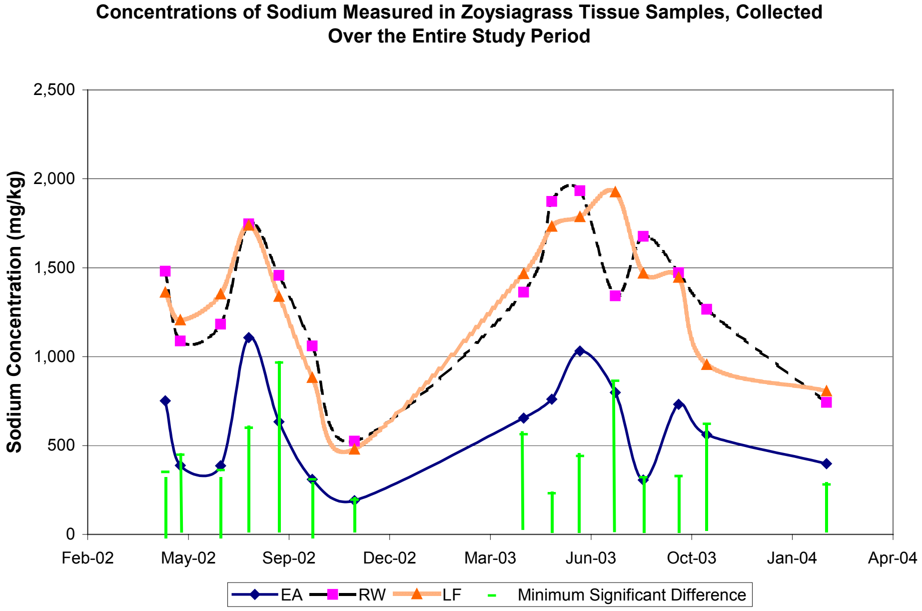


FIGURE 5.12
Concentrations of Sodium Measured in Zoysiagrass Tissue
Edwards Aquifer Recharge Zone Irrigation Pilot Study



5.9.4 Manganese

Manganese concentrations in the plant tissue samples exhibited some significant 3-way interactions with date. Therefore, the data were sorted by date and grass; following that, a separate analysis was run on each of the 15 individual sampling dates.

On 3 of the 15 sampling dates, there were significant differences in manganese concentrations in bermudagrass tissue due to irrigation treatment. In all 3 dates, the tissue from the plots treated with EA water had significantly lower manganese concentrations. On the remaining 12 dates, there was no consistent trend. In all dates, there were no differences between the 1XRW and LFRW treatments.

On 2 of the 15 sampling dates, there were significant differences in manganese concentrations in zoysiagrass tissue due to irrigation treatment. On June 25, 2002, the tissue from the plots treated with EA water had manganese concentrations similar to both the 1XRW and LFRW treatments. On June 17, 2003, however, the tissue from the plots treated with EA water had higher manganese contents than did tissue from the LFRW treatment. In all other dates, there were no significant differences between the irrigation treatments.

Manganese concentrations in the bermudagrass turf tissue for samples collected between May 1, 2002 and February 17, 2004 are shown in **Figure 5.13**. Except for the May 24, 2002 sample, the samples from all the irrigation treatments were very similar and showed no clear trend. All tissue levels were within the range considered to be safe for turf grass growth.

Manganese concentrations in the zoysiagrass turf tissue for samples collected between May 1, 2002 and February 17, 2004 are shown in **Figure 5.14**. Except for the May 24, 2002 sample, the samples from all the irrigation treatments were very similar and showed no clear trend. All tissue levels were within the range considered to be safe for turf grass growth.

FIGURE 5.13
Concentrations of Manganese Measured in Bermudagrass Tissue
Edwards Aquifer Recharge Zone Irrigation Pilot Study

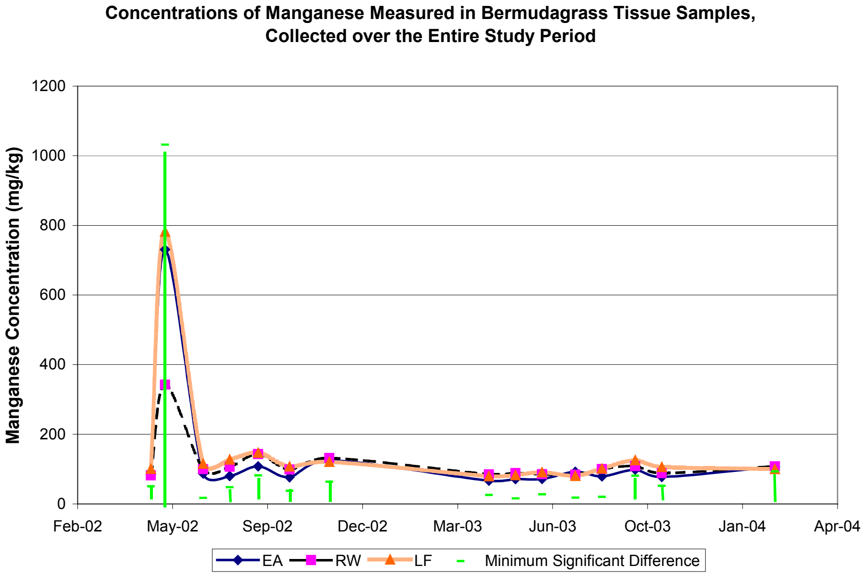
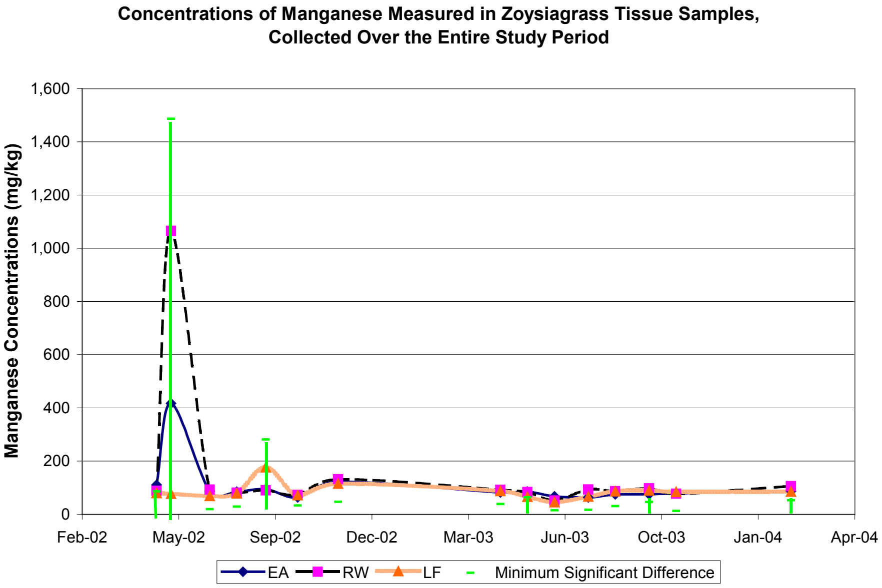


FIGURE 5.14
Concentrations of Manganese Measured in Zoysiagrass Tissue
Edwards Aquifer Recharge Zone Irrigation Pilot Study



5.9.5 Magnesium

Magnesium concentrations in the plant tissue samples did not exhibit any significant 3-way interactions. Therefore, the data were pooled and sorted by date; following that, a separate analysis was run on each of the 15 individual sampling dates to determine if there were any major effects of irrigation treatment or grass species.

On 3 of the 15 sampling dates, there were significant differences in magnesium concentrations in turf tissue due to irrigation treatment. On all three of the dates where differences did occur, the tissue from the plots treated with EA water had significantly lower magnesium concentrations. On the 12 remaining dates, there were no differences in magnesium concentrations between the EA, 1XRW and LFRW treatments; however, the trend of lower magnesium concentrations in the EA treatment continued through most of these samples.

On 6 of the 15 sampling dates, there were significant differences in magnesium concentrations in the turf tissue due to grass species. In all 6 dates, the tissue from the bermudagrass plots had significantly lower magnesium concentrations. For the 6 of the 9 remaining dates, there was evidence of higher magnesium concentrations in the bermudagrass plots.

5.9.6 Iron

Iron concentrations in the plant tissue samples did not exhibit any significant 3-way interactions. Therefore, the data were pooled and sorted by date; following that, a separate analysis was run on each of the 15 individual sampling dates to determine if there were any major effects of irrigation treatment or grass species.

On all 15 sampling dates there were no significant differences in iron concentrations in turf tissue due to irrigation treatment.

On 3 of the 15 sampling dates, there were significant differences in iron concentrations in the turf tissue due to grass species. In 2 dates, August 22, 2002 and June 17, 2003, the tissue from the bermudagrass plots had significantly greater iron concentrations. For the samples collected on May 22, 2002, there was evidence of lower iron concentrations in the bermudagrass plots. For the remaining 12 sampling dates, there were no differences in iron concentration due to irrigation treatment.

The majority of iron concentrations fell above the range of 50-300 mg/kg, which is ideal. Overall, turf tissue concentrations of Fe were more than adequate to maintain good quality turf under moderate to high traffic conditions with no supplemental applications.

5.9.7 Copper

Copper concentrations in the plant tissue samples did not exhibit any significant 3-way interactions. Therefore, the data were pooled and sorted by date; following that, a separate analysis was run on each of the 15 individual sampling dates to determine if there were any major effects of irrigation treatment or grass species.

On only one of the 15 sampling dates were there significant differences in copper concentrations in turf tissue due to irrigation treatment. This difference occurred on August 22, 2002, at which time the tissue from the EA treatment had a significantly higher amount of copper. On the 14 remaining dates, there were no differences in copper concentrations between the EA, 1XRW and LFRW treatments.

On 9 of the 15 sampling dates, there were significant differences in copper concentrations in the turf tissue due to grass species. In all 9 dates, the tissue from the bermudagrass plots had significantly greater copper concentrations. For the 4 of the 6 remaining dates, there was evidence of higher copper concentrations in the bermudagrass tissue, although it did not meet the 95% criteria.

All mean copper concentrations fell in the range of 5-30 mg/kg, which is ideal. Overall, turf tissue concentrations of copper were adequate to maintain good quality turf under moderate to high traffic conditions with no supplemental applications.

5.9.8 Zinc

Zinc concentrations in the plant tissue samples did not exhibit any significant 3-way interactions. Therefore, the data were pooled and sorted by date; following that, a separate analysis was run on each of the 15 individual sampling dates to determine if there were any major effects of irrigation treatment or grass species.

On 6 of the 15 sampling dates, there were significant differences in zinc concentrations in turf tissue due to irrigation treatment. On five of the six dates where differences did occur, the tissue from the plots treated with EA water had significantly lower zinc concentrations. On the 9 remaining dates, there were no differences in zinc concentrations between the EA, 1XRW and LFRW treatments.

On 11 of the 15 sampling dates, there were significant differences in zinc concentrations in the turf tissue due to grass species. In all 11 dates, the tissue from the bermudagrass plots had significantly greater zinc concentrations. For the 3 of the 4 remaining dates, there was evidence of higher zinc concentrations in the bermudagrass plots.

Overall, turf tissue concentrations of Zn were adequate to maintain good quality turf under moderate to high traffic conditions with no supplemental applications.

5.9.9 Calcium

Calcium concentrations in the plant tissue samples did not exhibit any significant 3-way interactions. Therefore, the data were pooled and sorted by date; following that, a separate analysis was run on each of the 15 individual sampling dates to determine if there were any major effects of irrigation treatment or grass species.

On one of the 15 sampling dates, there were significant differences in calcium concentrations in bermudagrass tissue due to irrigation treatment. On this date, June 17, 2003, the tissue from the plots treated with EA water had significantly lower calcium concentrations. On the 14 remaining dates, there were no differences in calcium concentrations between the EA, 1XRW and LFRW treatments.

On 5 of the 15 sampling dates, there were significant differences in calcium concentrations in the turf tissue due to grass species. In 4 of the 5 dates, the tissue from the bermudagrass plots had significantly greater calcium concentrations. For the 10 remaining dates, there were no differences in calcium concentrations between the turf species.

Calcium concentrations in the turf tissue for samples collected between May 1, 2002 and February 17, 2004 are shown in **Figure 5.15**. There is no clear trend of either grass having consistently higher or lower calcium concentrations in the tissue. Calcium concentrations in tissues from the EA, 1XRW and LFRW treatments were similar (**Figure 5.16**) and showed no consistent trend. All tissue levels were within the range considered to be safe for turf grass growth.

5.9.10 Potassium

Potassium concentrations in the plant tissue samples did not exhibit any significant 3-way interactions. Therefore, the data were pooled and sorted by date; following that, a separate analysis was run on each of the 15 individual sampling dates to determine if there were any major effects of irrigation treatment or grass species.

On 2 of the 15 sampling dates, there were significant differences in potassium concentrations in turf tissue due to irrigation treatment; however, there were no trends as to which treatment had the greatest concentration. On the 9 remaining dates, there were no differences in potassium concentrations between the EA, 1XRW and LFRW treatments.

On 10 of the 15 sampling dates, there were significant differences in potassium concentrations in the turf tissue due to grass species. In all 10 dates, the tissue from the zoysiagrass plots had significantly greater potassium concentrations. For all but one of the remaining dates, there was evidence of higher potassium concentrations in the zoysiagrass plots as well.

The majority of potassium concentrations fell in the range of 7,000-12,000 mg/kg, which is less than ideal. Overall, turf tissue concentrations of potassium were adequate to maintain good quality turf under low to moderate traffic conditions. The low concentrations indicate the plants may benefit from additional potassium applications.

FIGURE 5.15

Concentrations of Calcium Measured in Tissue, by Turfgrass

Edwards Aquifer Recharge Zone Irrigation Pilot Study

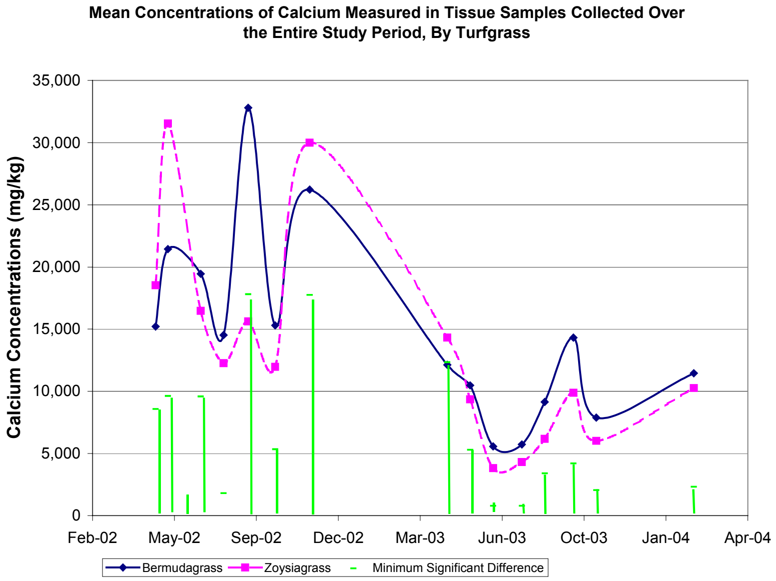
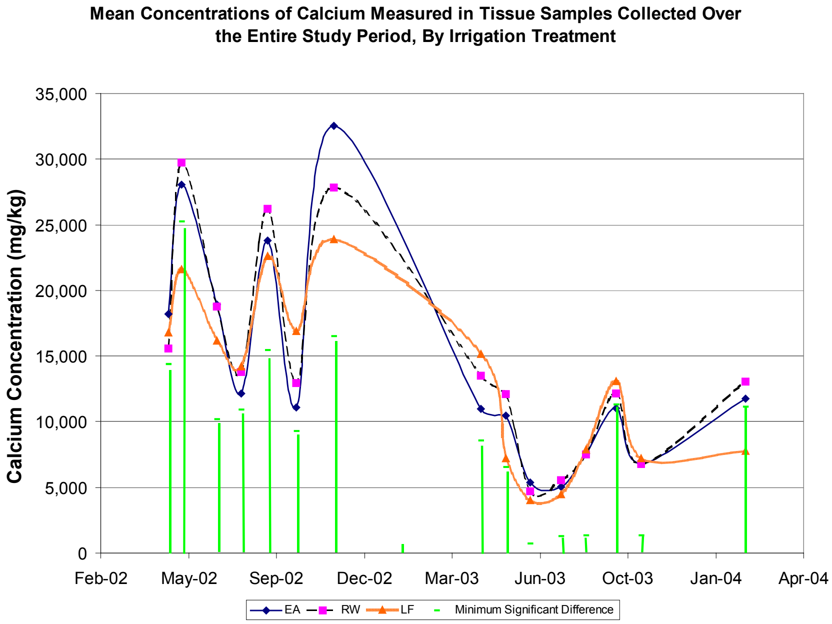


FIGURE 5.16

Concentrations of Calcium Measured in Tissue, By Irrigation Treatment

Edwards Aquifer Recharge Zone Irrigation Pilot Study



5.9.11 Phosphorus

Phosphorus concentrations in the plant tissue samples did not exhibit any significant 3-way interactions. Therefore, the data were pooled and sorted by date; following that, a separate analysis was run on each of the 15 individual sampling dates to determine if there were any major effects of irrigation treatment or grass species.

No significant differences in phosphorus concentrations in turf tissue due to irrigation treatment were found at any of the 15 sampling dates.

On 14 of the 15 sampling dates, there were no significant differences in phosphorus concentrations in the turf tissue due to grass species. Only on October 21, 2003 did the tissue from the bermudagrass plots have a significantly greater phosphorus concentration than that of the zoysiagrass.

The average tissue concentrations ranged from 769 to 3,765 mg/kg, which is below the ideal range of 3,000-6,000 mg/kg for well fertilized turf. Overall, turf tissue concentrations of P were adequate to maintain good quality turf under low to moderate traffic conditions. The low concentrations indicate the plants may benefit from additional phosphorus applications.

5.9.12 Nitrogen

Total Kjeldahl Nitrogen concentrations in the plant tissue samples did not exhibit any significant 3-way interactions. Therefore, the data were pooled and sorted by date; following that, a separate analysis was run on each of the 15 individual sampling dates to determine if there were any major effects of irrigation treatment or grass species.

On 2 of the 15 sampling dates, there were significant differences in Total Kjeldahl Nitrogen concentrations in turf tissue due to irrigation treatment. On both of the dates where differences did occur, the tissue from the plots treated with EA water had significantly lower Total Kjeldahl Nitrogen concentrations.

On 4 of the 15 sampling dates, there were significant differences in Total Kjeldahl Nitrogen concentrations in the turf tissue due to grass species. In all 4 dates, the tissue from the bermudagrass plots had significantly greater Total Kjeldahl Nitrogen concentrations. For all but 2 of the remaining dates where the differences were not statistically significant, there was a trend of higher Total Kjeldahl Nitrogen concentrations in the bermudagrass plots.

The majority of Total Kjeldahl Nitrogen concentrations fell in the range of 10,000-16,000 mg/kg, which is less than ideal. Overall, turf tissue concentrations of TKN were adequate to maintain good quality turf under low to moderate traffic conditions. The low concentrations indicate the plants may benefit from additional nitrogen applications, especially if rapid growth for injury recovery is needed.

5.10 Soil

5.10.1 Soil Salinity

The average electrical conductivity of the soil samples over the entire study period ranged from 0.2518 to 0.3377 dS/m and had no 3-way interactions. The analysis showed that there were significant effects due to sampling date and irrigation treatment (**Table 5.20**). There were also 2-way interactions between irrigation treatment and sampling date, and irrigation and grass type.

The data show no difference between the EC of soil in plots planted with bermudagrass versus zoysia (Table 5.20). There was a significantly higher EC in the soil from the 1XRW and LFRW plots as compared to those irrigated with EA water (Table 5.20); this is likely due to the higher EC of the recycled water. Therefore, water leaching past the root zone of turf areas will carry with it about 1.5 times the amount of salts if the same area were irrigated with Edwards Aquifer water.

Based on this information, turf areas irrigated with SAWS Recycled water will pose a small but significant potential for salt accumulation in the soil.

TABLE 5.20
Mean Electrical Conductivity (dS/m) of Soil Samples Collected Over the Study Period
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Differentiator	Number of Samples	Mean
Turfgrass		
Bermudagrass	81	0.2955 a[1]
Zoysiagrass	81	0.2925 a
Irrigation Treatment		
EA	54	0.2518 a
RW	54	0.3132 a
LF	54	0.3171 a

1. Mean values within a given turfgrass or irrigation treatment followed by the same letter do not differ significantly at p=0.05.

5.10.2 Iron

The average iron concentration in the soil samples over the entire study period ranged from 14,972 to 18,111 mg/kg and had no 3-way interactions. The analysis showed that there were significant effects due to sampling date and grass type (**Table 5.21**). There also was a 2-way interaction between sampling date and grass type.

The data show a higher iron concentration of soil in plots planted with zoysiagrass versus soils planted with bermudagrass (Table 5.21). There were no significant differences in iron concentrations of soil from the EA, 1XRW or LFRW (Table 5.21) water. This indicates that irrigation treatments did not result in excessive iron accumulation in the soil.

Based on this information, turf areas irrigated with SAWS Recycled water will not result in excessive iron accumulation in the soil.

5.10.3 Calcium

The average calcium concentrations of the soil samples over the entire study period ranged from 127,139 to 146,111 mg/kg and had no 3-way interactions. The analysis showed that there were significant effects due to sampling date and irrigation treatment (**Table 5.22**). There were no 2-way or 3-way interactions.

TABLE 5.21
Mean Iron Concentrations (mg/kg) of Soil Samples Collected Over the Study Period
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Differentiator	Number of Samples	Mean
Turfgrass		
Bermudagrass	81	15,741 b[1]
Zoysiagrass	81	16,286 a
Irrigation Treatment		
EA	54	15,908 a
RW	54	15,972 a
LF	54	16,161 a

1. Mean values within a given turfgrass or irrigation treatment followed by the same letter do not differ significantly at p=0.05.

The data show no difference between the calcium concentration of soil in plots planted with bermudagrass versus zoysia (Table 5.22). There was a significantly higher average calcium concentration in the soil from the LFRW treatment plots as compared to those from the EA or 1XRW plots (Table 5.22).

TABLE 5.22
Mean Calcium Concentrations (mg/kg) of Soil Samples Collected Over the Study Period
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Differentiator	Number of Samples	Mean
Turfgrass		
Bermudagrass	81	137,573 a[1]
Zoysiagrass	81	137,366 a
Irrigation Treatment		
EA	54	134,108 b
RW	54	135,467 b
LF	54	142,835 a

1. Mean values within a given turfgrass or irrigation treatment followed by the same letter do not differ significantly at p=0.05.

Based on this information, turf areas irrigated with SAWS Recycled water at a rate designed to replace the water used by evapotranspiration will exhibit a significant amount of Ca accumulation in the soil. Overall, soil concentrations of total Ca were adequate to maintain good quality turf.

5.10.4 Total Kjeldahl Nitrogen

The average total Kjeldahl nitrogen concentrations of the soil samples over the entire study period ranged from 1306 to 1989 mg/kg and had no 3-way interactions. The analysis showed that there were significant effects due only to the sampling date (**Table 5.23**). There were no 2-way or 3-way interactions.

The data show no difference between the TKN concentration of soil in plots planted with bermudagrass versus zoysia (Table 5.23). The average calcium concentration in soil did not differ between irrigation treatments (Table 5.23).

TABLE 5.23
Mean Total Kjeldahl Nitrogen Concentrations (mg/kg) of Soil Samples Collected Over the Study Period
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Differentiator	Number of Samples	Mean
Turfgrass		
Bermudagrass	81	1,515.8 a[1]
Zoysiagrass	81	1,580.8 a
Irrigation Treatment		
EA	54	1,554 a
RW	54	1,550 a
LF	54	1,541a

1. Mean values within a given turfgrass or irrigation treatment followed by the same letter do not differ significantly at p=0.05.

5.10.5 Manganese

The average manganese concentrations of the soil samples over the entire study period ranged from 253.7 to 303.6 mg/kg and had no 3-way interactions. The analysis showed that there were significant effects due to sampling date and grass type (**Table 5.24**). There were no 2-way or 3-way interactions.

The data show that there is a statistically significant difference between the manganese concentration of soil in plots planted with bermudagrass versus zoysia (Table 5.24). At the present time, there is no clear answer for why this phenomena occurred. There were no significant differences in manganese concentration in the soil from the LFRW treatment plots as compared to those from the EA or 1XRW plots (Table 5.24).

TABLE 5.24
Mean Manganese Concentrations (mg/kg) of Soil Samples Collected Over the Study Period
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Differentiator	Number of Samples	Mean
Turfgrass		
Bermudagrass	81	279.2 b[1]
Zoysiagrass	81	294.4a
Irrigation Treatment		
EA	54	288.9 a
RW	54	281.1 a
LF	54	290.4 a

1. Mean values within a given turfgrass or irrigation treatment followed by the same letter do not differ significantly at p=0.05.

5.10.6 Magnesium

The average magnesium concentrations of the soil samples over the entire study period ranged from 3,596 to 4,505 mg/kg and had no 3-way interactions. The analysis showed that there were significant effects due to sampling date and grass type (**Table 5.25**) but not irrigation treatment. There also was a single 2-way interaction between irrigation treatment and grass type.

The data show that there is a significantly higher magnesium concentration of soil in plots planted with zoysiagrass (Table 5.25). At the present time, there is no clear answer for why this phenomena occurred. There were no significant differences in magnesium concentration in the soil from the LFRW treatment plots as compared to those from the EA or 1XRW plots (Table 5.25). Thus, the differences may simply be due to spatial variability of soils. Overall, soil concentrations of total Mg were adequate to maintain good quality turf. There was no indication that irrigation with Type 1 SAWS recycled water would result in excessive accumulation of magnesium in the soil.

TABLE 5.25
Mean Magnesium Concentrations (mg/kg) of Soil Samples Collected Over the Study Period
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Differentiator	Number of Samples	Mean
Turfgrass		
Bermudagrass	81	3,826 b[1]
Zoysiagrass	81	3,967 a
Irrigation Treatment		
EA	54	3,881 a
RW	54	3,894 a
LF	54	3,914 a

1. Mean values within a given turfgrass or irrigation treatment followed by the same letter do not differ significantly at p=0.05.

5.10.7 Potassium

The average potassium concentrations of the soil samples over the entire study period ranged from 3,847 to 4,626 mg/kg and had no 3-way interactions. The analysis showed that there were significant effects due to sampling date and grass type (**Table 5.26**) but not irrigation treatment. There were also two 2-way interactions; one between irrigation treatment and grass type and the second between sampling date and grass type.

The data show that there is a significantly higher potassium concentration in the soil from plots planted with zoysiagrass (Table 5.26). At the present time, there is no clear answer for why this phenomena occurred. There were no significant differences in potassium concentration in the soil from the LFRW treatment plots as compared to those from the EA or 1XRW plots (Table 5.26). Thus, the differences may simply be due to spatial variability of soils. Overall, soil concentrations of total K were adequate to maintain good quality turf. There was no indication that irrigation with Type 1 SAWS recycled water would result in excessive accumulation of potassium in the soil.

TABLE 5.26
Mean Potassium Concentrations (mg/kg) of Soil Samples Collected Over the Study Period
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Differentiator	Number of Samples	Mean
Turfgrass		
Bermudagrass	81	4,127 b[1]
Zoysiagrass	81	4,370 a
Irrigation Treatment		
EA	54	4,217 a
RW	54	4,256 a
LF	54	4,273 a

1. Mean values within a given turfgrass or irrigation treatment followed by the same letter do not differ significantly at p=0.05.

5.10.8 Copper

The average copper concentrations of the soil samples over the entire study period ranged from 11.6 to 33.5 mg/kg and had no 2-way or 3-way interactions. The analysis showed that there were significant effects due only to the sampling date (**Table 5.27).**

The data show no difference between the copper concentration of soil in plots planted with bermudagrass versus zoysia (Table 5.27). The average copper concentration in soil did not differ between irrigation treatments (Table 5.27).

TABLE 5.27
Mean Copper Concentrations (mg/kg) of Soil Samples Collected Over the Study Period
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Differentiator	Number of Samples	Mean
Turfgrass		
Bermudagrass	81	26.4 a[1]
Zoysiagrass	81	25.9 a
Irrigation Treatment		
EA	54	27.2 a
RW	54	26.0 a
LF	54	25.2 a

1. Mean values within a given turfgrass or irrigation treatment followed by the same letter do not differ significantly at p=0.05.

5.10.9 Sodium

The average sodium concentrations of the soil samples over the entire study period ranged from 406.8 to 1,831.0 mg/kg and had no 2-way or 3-way interactions. The analysis showed that there were no significant effects due only to the sampling date, irrigation treatment, or grass (**Table 5.28**).

The data show no difference between the sodium concentration of soil in plots planted with bermudagrass versus zoysia (Table 5.28). In addition, the average sodium concentration in soil did not differ between irrigation treatments (Table 5.28).

TABLE 5.28
Mean Sodium Concentrations (mg/kg) of Soil Samples Collected Over the Study Period
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Differentiator	Number of Samples	Mean
Turfgrass		
Bermudagrass	81	792.0 a[1]
Zoysiagrass	81	641.1 a
Irrigation Treatment		
EA	54	723.7a
RW	54	711.9 a
LF	54	714.0 a

1. Mean values within a given turfgrass or irrigation treatment followed by the same letter do not differ significantly at p=0.05.

5.10.10 Zinc

The average zinc concentrations of the soil samples over the entire study period ranged from 45.4 to 128.2 mg/kg and had no 2-way or 3-way interactions. The analysis showed that there was a significant effect due to sampling date (**Table 5.29**) but not irrigation treatment or grass type.

The data show that there are similar zinc concentrations in soil from plots planted with either zoysiagrass or Bermuda grass (Table 5.29). There were no significant differences in zinc concentration in the soil from the LFRW treatment plots as compared to those from the EA or 1XRW plots (Table 5.29). Overall, soil concentrations of total Zn were adequate to maintain good quality turf. There was no indication that irrigation with Type 1 SAWS recycled water would result in excessive accumulation of zinc in the soil.

TABLE 5.29
Mean Zinc Concentrations (mg/kg) of Soil Samples Collected Over the Study Period
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Differentiator	Number of Samples	Mean
Turfgrass		
Bermudagrass	81	82.5 a[1]
Zoysiagrass	81	76.0 a
Irrigation Treatment		
EA	54	80.6 a
RW	54	83.1 a
LF	54	74.0 a

1. Mean values within a given turfgrass or irrigation treatment followed by the same letter do not differ significantly at p=0.05.

5.10.11 Ammonium Nitrogen

The average ammonium concentrations of the soil samples over the entire study period ranged from 30.2 to 266.5 mg/kg and had no 2-way or 3-way interactions. The analysis showed that there were significant effects due to sampling date (**Table 5.30**) but not irrigation treatment or grass type.

The data show that there is a similar ammonia concentration in soil from plots planted with zoysiagrass and bermudagrass (Table 5.30). There were no significant differences in ammonium concentration in the soil from the LFRW treatment plots as compared to those from the EA or 1XRW plots (Table 5.30). Overall, soil concentrations of ammonium were adequate to maintain good quality turf. There was no indication that irrigation with Type 1 SAWS recycled water would result in excessive accumulation of ammonium in the soil.

TABLE 5.30
Mean Ammonium Concentrations (mg/kg) of Soil Samples Collected Over the Study Period
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Differentiator	Number of Samples	Mean
Turfgrass		
Bermudagrass	81	78.3 a[1]
Zoysiagrass	81	117.8 a
Irrigation Treatment		
EA	54	88.4 a
RW	54	81.9 a
LF	54	123.7 a

1. Mean values within a given turfgrass or irrigation treatment followed by the same letter do not differ significantly at p=0.05.

5.10.12 Nitrate Nitrogen

The average nitrate concentrations of the soil samples over the entire study period ranged from 24.7 to 57.8 mg/kg and had no 2-way or 3-way interactions. The analysis showed that there were significant effects due to sampling date and grass type (**Table 5.31**) but not irrigation treatment.

The data show that there is a significantly higher nitrate concentration of soil in plots planted with bermudagrass (Table 5.31). This is likely due to the higher fertilization rate required to sustain a dense bermudagrass turf. There were no significant differences in nitrate concentration in the soil from the LFRW treatment plots as compared to those from the EA or 1XRW plots (Table 5.31). Overall, soil concentrations of nitrate were adequate to maintain good quality turf. There was no indication that under proper management, irrigation with Type 1 SAWS recycled water would result in excessive accumulation of nitrate in the soil.

TABLE 5.31
Mean Nitrate Concentrations (mg/kg) of Soil Samples Collected Over the Study Period
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Differentiator	Number of Samples	Mean
Turfgrass		
Bermudagrass	81	44.3 a[1]
Zoysiagrass	81	36.2 b
Irrigation Treatment		
EA	54	37.3 a
RW	54	43.7 a
LF	54	39.7 a

1. Mean values within a given turfgrass or irrigation treatment followed by the same letter do not differ significantly at p=0.05.

5.10.13 Phosphorus

The average phosphorus concentrations of the soil samples over the entire study period ranged from 299.7 to 1,052 mg/kg. There was a significant 3-way interaction between sampling date, irrigation treatment and grass type. Therefore, the data were separated by date and re-tested for each individual date. This individual analysis by date showed that there were no significant differences in phosphorus concentrations in soils at any date due to either grass type or irrigation treatment (**Tables 5.32** and **5.33**). Thus, irrigation of turf with SAWS Class 1 recycled water will not result in excessive phosphorus accumulation in soils.

TABLE 5.32
Mean Concentrations of Phosphorus (mg/kg) Measured in Soil Samples Collected Over the Entire Study Period, By Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Irrigation Treatment		
Date	EA	RW	LF
March 12, 2002	497.0 a	442.8 a	468.3 a
June 25, 2002	299.7 a	347.8 a	365.2 a
September 24, 2002	505.0 a	693.8 a	405.8 a
December 18, 2002	910.2 a	989.5 a	998.7 a
March 25, 2003	861.8 a	1029.2 a	912.8 a
June 17, 2003	879.5 a	894.3 a	838.8 a
September 23, 2003	977.0 a	997.7 a	1052.2 a
December 22, 2003	996.8 a	1046.3 a	1021.8 a
February 17, 2004	856.8 a	924.8 a	861.3a

Note: Means in a given row followed by the same letter do not differ significantly at p = 0.05.

TABLE 5.33
Mean Concentration of Phosphorus (mg/kg) Measured in Soil Samples Collected Over the Entire Study Period, By Grass
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Turfgrass	
Date	Bermudagrass	Zoysiagrass
March 12, 2002	433.3 a	505.4 a
June 25, 2002	363.9 a	311.3 a
September 24, 2002	535.0 a	534.7 a
December 18, 2002	969.1 a	963.1 a
March 25, 2003	939.8 a	929.4 a
June 17, 2003	845.0 a	896.8 a
September 23, 2003	1020.1 a	997.8 a
December 22, 2003	1013.0 a	1030.3 a
February 17, 2004	876.1 a	885.9 a

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$.

5.11 Mass Balance

To better determine the fate of the measured constituents from the Study Site, a mass balance was calculated for each constituent. Amounts present in the soil at the beginning of the study were added to amounts added via irrigation water, rainfall and fertilizer additions. From this, the Project Team subtracted the amounts lost in surface runoff, leachate past the 30-inch depth and the amount present in the soil at the end of the study period.

5.11.1 Runoff Losses

Table 5.34 presents the total volume of collected runoff for the Study Site area.

TABLE 5.34
Runoff Collected
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Plot	Turf	Water	Total Runoff Depth (inches)
17	Bermuda	Edwards	31.49
16	Bermuda	1XRW	9.39
11	Bermuda	LFRW	13.87
2	Zoysia	Edwards	17.87
9	Zoysia	1XRW	12.10
13	Zoysia	LFRW	18.09

During large rainfall events when the rainfall rates exceed the infiltration capacity of the soil, water and associated nutrients run off the site via surface flow. These nutrients contribute to non-point source pollution of surface water bodies and may eventually find their way to the groundwater via karst features in the aquifer recharge zone.

In the present study, runoff water collection devices were installed in one replication of each irrigation treatment and grass combination. The water collected in the runoff sampling containers was considered to be representative of the water quality that was leaving the area by surface runoff and may eventually migrate to the groundwater table.

The total amount of each of 14 chemical constituents lost in the surface runoff water was calculated. Using the volume of water collected from each runoff sampler and the surface area of the collection device, the volume of water that left the site via surface runoff for the entire 400 ft^2 plot was estimated for each sampling date. This was then multiplied by the concentration of each constituent measured in the collected water sample at that date to give an estimated mass of each constituent. These mass values were then summed over all sampling events for the period June 15, 2002 to February 17, 2004 to give an estimate of the total amount of each constituent that was lost via surface water runoff and that might potentially migrate to the groundwater table.

The total kilograms of each of the 14 chemical constituents in the surface runoff water are shown in **Tables 5.35** and **5.36**. A statistical analysis of the data could not be performed due to a lack of replications. Of all the measured constituents, the greatest amount was phosphorus, which ranged from 0.022 to 2.3635 kg. However, some of the higher values that contributed to the high averages for the EA and LFRW treatments are suspect, and are potentially due to laboratory error involving an unstable calibration. There were no obvious differences due to irrigation treatments for the amounts of calcium, copper, iron, magnesium, manganese, potassium, nitrite, TKN, ammonia, total N, or zinc that were lost in surface runoff. In the case of sodium and nitrate, the plots irrigated with Edwards Aquifer water consistently had the lowest amount of these nutrients in the runoff water followed by the 1XRW and LFRW treatments.

TABLE 5.35
Calculated Mass (kg) of 14 Chemical Constituents Lost In Runoff Water From Plots With 3 Separate Irrigation Water Treatments Between June 2002 and February 2004
Edwards aquifer Recharge Zone Irrigation Pilot Study

Treatment[1]	Ca	Cu	Fe	Mg	Mn	P	K
EA	0.6065	0.0004	0.0387	0.0621	0.0008	2.3564	0.1401
1XRW	0.2493	0.0004	0.0205	0.0233	0.0004	0.2276	0.0654
LFRW	0.4276	0.0002	0.0398	0.0326	0.0006	1.6130	0.0861

1. EA = Edwards Aquifer water irrigated to replace PET.
1XRW = SAWS Recycled Water irrigated to replace PET.
LFRW = SAWS Recycled water irrigated to replace PET plus 10% for leaching.

TABLE 5.36
Calculated Mass (kg) of 14 Chemical Constituents Lost In Runoff Water From Plots With 3 Separate Irrigation Water Treatments Between June 2002 and February 2004
Edwards aquifer Recharge Zone Irrigation Pilot Study

Treatment[1]	Sodium	Zinc	Nitrate	Nitrite	Ammonia	TKN	Total N
EA	0.0699	0.0009	0.0148	0.0014	0.0094	0.0393	0.0634
1XRW	0.0832	0.0003	0.0134	0.0010	0.0054	0.0172	0.0357
LFRW	0.1217	0.0003	0.0169	0.0014	0.0051	0.0239	0.0460

1. EA = Edwards Aquifer water irrigated to replace PET.
RW = SAWS Recycled Water irrigated to replace PET.
LFRW = SAWS Recycled water irrigated to replace PET plus 10% for leaching.

5.11.2 Leachate

2002 Leachate

Nutrients added to the test plots plus those native to the soil are distributed between those dissolved in the soil solution, those adsorbed to the cation exchange sites on the soil particles, and those in mineral form. Because of this equilibrium, there is always a fraction of nutrients in the soil water, and these nutrients move with the water. When rainfall or irrigation events of sufficient magnitude occur, a portion of the water and associated nutrients move below the root zone. Once past the root zone, there is little opportunity for adsorption or removal of nutrients from the water and the majority of nutrients will eventually migrate to the groundwater table. In the present study, the water collected in the 30-inch deep lysimeters was considered to be representative of the water quality that was passing the root zone and might eventually migrate to the groundwater table.

The total amount of each of 14 chemical constituents that moved below the 30-inch depth was calculated. Using the volume of water collected from each lysimeter and the surface area of the lysimeter, the volume of water moving past this depth for the entire 400 square-feet plot was estimated for each sampling date. This was then multiplied by the concentration of each constituent measured in the collected water sample at that date to give an estimated mass of each constituent. These mass values were then summed over all sampling events for the period June 15, 2002 to February 17, 2004 to give an estimate of the total amount of each constituent that passed the 30-inch depth and might potentially migrate to the groundwater table.

The data were subjected to an analysis of variance test to determine if there were significant differences between the amounts lost in each of the three irrigation treatments. For treatments that exhibited significant differences, the means were separated using Tukey's procedure for mean separation. The results showed no significant differences in the amount of constituents passing 30-inches due to grass type (zoysiagrass versus bermudagrass), but there were significant differences due to irrigation treatments. In addition, there was no significant interaction between irrigation treatment and grass type. Therefore, the remainder of this discussion will focus on the effects of irrigation treatment on the amount of constituents passing the 30-inch depth.

The total kilograms of each of the 14 chemical constituents in soil water passing the 30-inch depth is given in **Tables 5.37** and **5.38**. Of all the measured constituents, the greatest amount was calcium, which ranged from 0.7373 to 1.2134 kg. There were no significant differences due to irrigation treatments for the amounts of calcium, copper, iron, magnesium, sodium, nitrate, nitrite, total N, or zinc that moved past the 30-inch depth. Except for nitrite and nitrate, these are positively charged cations and typically have low mobility in soils. In the case of manganese, phosphorus, potassium, ammonium and total Kjeldahl nitrogen, the plots irrigated with Edwards Aquifer water consistently had the lowest amount of these nutrients passing the 30-inch depth. For phosphorus, potassium, ammonium and total Kjeldahl nitrogen, the amounts of each constituent in plots irrigated with recycled water and recycled water plus a leaching fraction were significantly greater than that from plots irrigated with Edwards Aquifer water. For manganese, the plots irrigated with recycled water plus a leaching fraction had significantly greater amounts of nutrients than that from plots irrigated with Edwards Aquifer water. However, the plots irrigated with recycled water at the PET rate lost intermediate amounts of nutrients and did not differ significantly from either the EA treatment or the LFRW treatment.

TABLE 5.37
Calculated Mass (kg) of 14 Chemical Constituents Passing The 30" Depth From Plots With 3 Separate Irrigation Water Treatments.
Edwards aquifer Recharge Zone Irrigation Pilot Study

Treatment[1]	Ca	Cu	Fe	Mg	Mn	P	K
EA	0.7373 a	0.0002 a	0.0060 a	0.0396 a	0.0002 b	0.1762 b	0.0606 b
RW	1.2134 a	0.0003 a	0.0067 a	0.0891 a	0.0004 ab	0.5834 a	0.1383 a
LFRW	1.0008 a	0.0003 a	0.0092 a	0.0881 a	0.0004 a	0.6424 a	0.1209 a

1. EA = Edwards Aquifer water irrigated to replace PET.
   RW = SAWS Recycled Water irrigated to replace PET.
   LFRW = SAWS Recycled water irrigated to replace PET plus 10% for leaching.
2. Values in a given column for a given constituent followed by the same letter do not differ significantly at p=0.05.

TABLE 5.38
Calculated Mass (kg) of 14 Chemical Constituents Passing The 30" Depth From Plots With 3 Separate Irrigation Water Treatments.
Edwards aquifer Recharge Zone Irrigation Pilot Study

Treatment[1]	Sodium	Zinc	Nitrate	Nitrite	Ammonia	TKN	Total N
EA	0.1669 a	0.0008 a	0.0099 a	0.0004 a	0.0012 b	0.0053 b	0.0167 a
RW	0.6769 a	0.0003 a	0.0827 a	0.0004 a	0.0023 a	0.0147 a	0.1000 a
LFRW	0.5947 a	0.0003 a	0.0474 a	0.0004 a	0.0022 a	0.0155 a	0.0655 a

1. EA = Edwards Aquifer water irrigated to replace PET.
   RW = SAWS Recycled Water irrigated to replace PET.
   LFRW = SAWS Recycled water irrigated to replace PET plus 10% for leaching.
2. Values in a given column for a given constituent followed by the same letter do not differ significantly at p=0.05.

5.12 Literature Reviews Performed

The current research study, the EARZIPS, was conducted on one soil type, using two water sources and two turfgrasses. It is anticipated that the results of this study will form the basis for decisions to be made concerning the suitability of recycled water for irrigation of turf throughout much of the central Texas area. Combining the data from the present study with that which is already published in the scientific literature is one way to broaden the usefulness of the study results to other areas where some of the site specific factors may be slightly different.

Since the major thrust of the present study was to document the movement and fate of nutrients applied via recycled water, a literature study entitled "Potential Groundwater Contamination from Irrigation of Turf with Recycled Water" was prepared and is presented in Appendix E. A comparison of the findings of other researchers, as documented in this review, serves as a validation of the data and conclusions that stem from the present study. Additionally, the principles of nutrient movement in soils can then be used to predict what is likely to happen at other locations where there are differences in soils, water quality and the hydrologic cycle.

Due to limitations in funding for the EARZIPS, it was not possible to evaluate all samples for a wide array of microbiological and toxicological constituents. However, their potential presence in recycled water and the potential to contaminate surface water or groundwater reserves is of great concern. Again, a review of the pertinent scientific literature can elucidate basic principles of how and where these materials move when placed in the environment. Therefore, a literature study entitled "Risk Evaluation of Microbiological and Toxicological Components of the San Antonio Water System's Recycled Water: A Literature Review" was undertaken and is presented in Appendix F.

While neither the EARZIPS nor the literature reviews can guarantee a "zero risk" of adverse environmental impact from irrigation of turf with Type I Saws Recycled water, they do indicate that the risk is low.

SECTION 6.0

Conclusions

6.1 Aesthetics

- The quality of the two turfgrasses studied was unaffected by the use of Type I SAWS recycled water at the irrigation rates and management level employed in this study.

6.2 Soil

- Soil concentrations of ammonium, calcium, copper, iron, nitrate, sodium and zinc remained nearly constant and showed no major effects from irrigation with SAWS Recycled Water.
- Soil concentrations of magnesium, phosphorus, and total Kjeldahl nitrogen steadily increased throughout the study period indicating that these elements are accumulating in the soil profile.
- Soil concentrations of manganese and potassium showed slightly decreasing concentrations over time which is indicative of plant uptake and/or leaching.
- Soil in plots receiving recycled water had significantly higher EC readings as compared to the soil from the plots irrigated with EA water.

6.3 Leachate

- Leachate from turf areas irrigated with SAWS Type 1 Recycled water had similar concentrations of ammonium, calcium, copper, iron, magnesium, manganese, and nitrite compared to that from plots irrigated with EA water. All concentrations were low and should not have any adverse environmental effects.
- Leachate from turf areas irrigated with SAWS Recycled water had higher nitrate concentrations; however, they remained well below the drinking water standard of 10 ppm. Nitrate concentrations were higher in the 6-inch lysimeter samples compared to the 18 and 30-inch samples, indicating that the soil has some filtering ability.
- There were no significant differences in leachate volumes due to irrigation treatment for the 6 and 18 inch lysimeters.
- Lysimeters at the 30-inch depth in the EA treatment produced significantly less leachate than did comparable lysimeters in 1XRW and LFRW treatments.
- Fecal coliform concentrations in leachate samples from the 1XRW and LFRW treatments were similar to those from the EA treatment in 25 of 31 sampling dates. In two of the 31 sampling dates, the fecal coliform counts were significantly higher in the Edwards

Aquifer treatment, and in only one case was the fecal coliform count greater in the 1XRW and LFRW treatments. This indicates that irrigation with SAWS Type I recycled water will have a very low probability of adversely affecting groundwater quality.

6.4 Runoff

- Irrigation treatment made no significant difference in the EC of the leachate water.
- EC values of the runoff water samples pose no significant hazard to receiving waters.
- Fecal coliform concentrations in runoff samples from the 1XRW and LFRW treatments were similar to those from the EA treatment, indicating a very low probability of adversely affecting groundwater quality.
- Runoff water samples from the test plots contained concentrations of total salts (EC), manganese, magnesium, copper, zinc, calcium, potassium, phosphorus, nitrite nitrogen, and nitrate nitrogen which should not endanger receiving surface or ground water bodies.
- Runoff water samples from the test plots contained elevated concentrations of sodium, iron, and total Kjeldahl nitrogen which may have adverse environmental effects.
- Fecal coliform concentrations in runoff samples from the 1XRW and LFRW treatments were similar to those from the EA treatment, indicating a very low probability of adversely affecting groundwater quality.

6.5 Tissue

- For most sampling dates, the sodium and zinc content of the tissue samples from the EA plots were lower than that of plots irrigated with recycled water.
- Irrigation treatments made little to no difference in the calcium, copper, magnesium, manganese, nitrogen, phosphorus, potassium, and total Kjeldahl nitrogen concentrations of turf tissue.
- Tissue concentrations of nitrogen, phosphorus and potassium were below the ideal ranges for well fertilized turf grass and indicate the need for increased fertilization in the future.

6.6 Overall Summary

Provided that turf areas are irrigated responsibly using PET or a fraction thereof, nutrient applications are made in moderation, and a responsible nutrient management program is employed, Type I recycled water may be used for irrigation with minimal environmental impact on groundwater quality according to the results of this study.

Based on the data from this study and provided that turf areas are irrigated responsibly using PET or a fraction thereof to guide the irrigation rate, and a responsible nutrient management program is employed, Type I recycled water may be used for irrigation with minimal prospect of groundwater contamination. In other words, if large scale turf irrigators located on the EARZ use SAWS recycled water, the data from this study indicate that it will result in no statistically significant impact to the Edwards Aquifer water quality as compared to the use of potable Edwards Aquifer water. Therefore, there should be minimal impact to the Edwards Aquifer water quality when using recycled water over the recharge zone.

SECTION 7.0

Turf Management Guidelines

As previously mentioned, one of the study's operational parameters was to manage the turf as a typical golf course fairway. While no golf course supervisors were interviewed for input as part of the study, guidelines were followed in the management of the turf based on experience of the team and professional recommendations.

7.1 Irrigation

Both turf types used in this study have been established in the southern U.S. for a substantial period of time such that guidelines related to irrigation of bermuda and zoysia grasses are generally consistent. Bermudagrass has been established in the U.S. since the early 1800s and zoysiagrass has been established in the U.S. since the early 1900s. Water requirements vary based on location and environmental conditions. Additionally, the more maintenance required by the turf equates to a greater water requirement. Therefore, golf courses and sport fields require a greater input of water than does a lawn.

Frequency of irrigation depends on soil characteristics, seasonal water use, and root depths. Generally, a deeper root is more drought tolerant than a shallow rooted plant. However, turfs that require greater maintenance and locations with shallow soils may not have the opportunity to develop a deep root system and, therefore, would require a higher irrigation frequency. In these situations, water may need to be applied every two to three days to maintain an unstressed turf. Recent innovations in irrigation technology now allow the use of strategically placed soil moisture sensors to control the amount and frequency of irrigation.

Water use for bermudagrass on an annual basis is estimated to be approximately 40 inches per year, while zoysiagrass uses approximately 45 inches of water (Duble, 1996). Depending on location, much of this requirement can be met through rainfall. However, because of rainfall patterns and intensities, a significant portion of this rainfall may not be available to the plant. Some of the rainfall can be lost due to runoff or deep percolation. Duble (1996) estimates that for a typical golf course in Texas, runoff can range from 15% to 25% of the annual rainfall. Turf does not require 100% of PET replacement to remain viable. Duble (1996) reports that golf course turfs can remain in good condition with 67% replacement of PET, and 50% replacement of PET will allow the turf to survive.

The deficit between the amount of water that is required by the turf and that supplied by rainfall can be applied through irrigation. Typical irrigation systems are established to have head to head coverage and are divided into zones based on topography, turf types, and soil characteristics. Without rain, bermudagrass and zoysiagrass generally require between 1 and 1.5 inches of irrigation per week to maintain growth during peak water use. An application rate of 0.25 inches per application is suggested by Duble (1996) to minimize runoff and to maintain a healthy root and soil system for high maintenance turfs. This application rate may require the turf to be irrigated daily during drought conditions.

The irrigation system for the turf study was set up to provide head to head coverage, as described above. The bermuda and zoysia grasses were irrigated with the same depth during each application. The plots were irrigated at 100% PET replacement (plus an additional 10% in the leaching fraction plots) to simulate the greatest amount of water that would typically be applied to a high maintenance turf.

Typical application rates in the summer were 0.35 inches per application, applied three times per week for the 100% PET replacement plots. The maximum water depth applied per week was 1.6 inches, but, as mentioned above, typical application depths were around 1 inch per week during the peak growing season. Approximately 0.3 inches per week was applied to the 100% PET plots during the dormant period to prevent desiccation and loss of stand.

7.2 Fertilization

As with water management, the more maintenance a turf requires results in a greater fertilization requirement. Because the soil analyses demonstrated that the soils had adequate phosphorus, potassium, and micronutrients for a healthy turf, this section will concentrate on nitrogen requirements of zoysia and bermuda grasses. As a general rule, fertilization should be based on the results of regularly scheduled soil test results. At a minimum, soil samples should be taken annually, tested for fertility, and the results used as the basis for designing the fertility plan for the coming year.

Inadequate nitrogen can produce a turf that is easily damaged by use, slow to recover, and will have leaves that are a lighter shade of green, all resulting in a turf that is not aesthetically acceptable. Excess nitrogen can produce turf that is more susceptible to diseases, in addition to an increase in mowing and irrigation requirements. Excess nitrogen can also cause nitrate contamination of leachate and runoff waters. To avoid these consequences of inadequate and excessive nitrogen fertilization, turf supervisors are constantly required to monitor the turf quality and levels of nitrogen in the soil and turf, and to follow best management practices.

Hybrid bermuda requires 5 to 6 lbs of nitrogen per 1,000 sq. ft/year for high maintenance turf surfaces. Zoysia requires 3 to 4 lbs of nitrogen per 1,000 sq. ft/year under the same conditions (Duble 1996). Both turfs can be maintained with applied nitrogen rates at 50% of the upper ranges.

Nitrogen may be applied two times per year, once in the spring and again in the fall, to maintain growth, but a high maintenance turf requires a monthly nitrogen application. Golf courses typically apply 1 to 1.5 pounds of nitrogen per 1,000 sq. ft per month on bermudagrass and 0.5 to 1.0 pounds of nitrogen per 1,000 sq. ft per month for zoysiagrass.

As discussed in Section 4, the fertilization goal in this study was to apply the maximum nitrogen that typically will be applied on a golf course, or 6 lbs per 1,000 sq. ft/year for bermudagrass and 4 lbs per 1,000 sq. ft/year for zoysiagrass. During the first year of the study, only 50% of that amount was applied, which is the level of fertilization required to maintain the turf. The second year of the study, the 6 lbs and 4 lbs per 1,000 sq. ft/year for bermudagrass and zoysiagrass, respectively, was applied to each plot, taking into consideration the nitrogen concentration in the Edwards Aquifer and Recycled water sources. The first year, three monthly applications were made, while in the second year, the recommended 6 monthly applications were made.

7.3 Pesticides

Most golf courses now use integrated pest management programs (IPM) to guide their use of pesticides, including herbicides, insecticides and fungicides. While IPM plans vary slightly between facilities, they are based on the principle that a turf manager and their staff routinely inspect their facility for signs of disease, insect damage, or weed invasion. Once a problem is documented, the appropriate pesticide may be applied to the affected area at the lowest effective rate to address the problem. IPM has proven to be very beneficial in that it reduces the total amount of pesticides applied, reduces costs to the operator, and is environmentally protective.

In the present study, weeds were controlled by cultural practices and intense insect attacks requiring chemical treatment were not experienced. However, in early spring of 2003, numerous plots were attacked by a fungus, resulting in a disease called Take All Patch. Turf tissue samples were collected and submitted to the Texas Plant Diagnostic Laboratory for diagnosis. After confirmation of the disease, a single application of the fungicide Heritage was made, following which the turf recovered rapidly.

Use of this type of IPM program in which pesticide applications are made in a very conservative and environmentally responsible manner is recommended for all users of SAWS recycled water, and especially those located on the recharge zone where there is an increased potential for aquifer contamination.

7.4 Mowing

The recommendations for golf course mowing management is almost identical for bermudagrass and zoysiagrass turfs. In general, during the growing season, the grass should be mowed often and low to maintain a wear-tolerant turf. Both turfs should be mowed to a height of 0.5 to 1.0 inches. Heights greater than 1.0 inches generate a turf that is less wear tolerant.

Frequency of mowing should be determined by the growth rate of the grass. Growth rate is a function of fertilizer and water applications; therefore, all three need to be managed concurrently. Returning clippings to the turf is also recommended. Lawns where clippings are removed may have an increase in fertilizer requirements as high as 30% over those requirements discussed previously (Duble 1996). Generally, mowing should not remove more than 30% of the grass height. This may require mowing every 3 to 5 days in the summer. During tournaments, it is not uncommon for golf courses to mow everyday to maintain the ultimate turf quality (Beard, 1982).

Mowing the turf plots at the study was maintained by Bladerunner Grass Farms. Mowing frequency was typically once per week. Clippings were returned to the plots. Mow height was set at 1.0 inch.

7.5 Recycled Water Irrigation Startup

As previously discussed in the Results Section, the leachate quality had a greater concentration of nitrates at the beginning of the study. It is assumed that this was the result of two events that should be avoided when preparing a site to receive recycled water for the first time. The first event was the over application of recycled water and Edwards Aquifer water to the plots. This situation caused water to quickly leach through the soil and runoff from the site, transporting nutrients with the water. The second event that occurred was exacerbated by the first event. The second event was the condition of the plots at the initiation of irrigation with Edwards Aquifer and recycled water. The plots had not been irrigated for over a year and the winter/spring had been dry leading up to the initiation of the study. This drying of the soil caused the soil to be cracked and exposed macropores in the soil, through which water and nutrients could leach quickly through the soil.

In addition to these two events, because the site had remained fallow for an extended period of time, some of the nitrogen in the soil was likely tied up in the soil in different forms. When water was applied to the site, and in great quantities, the nitrogen in the soil could have gone through mineralization. Combined with the nitrate existing within the dry soil profile, this could explain some of the higher nitrate concentrations. This helps to explain why the Edwards Aquifer plots exhibited elevated nitrate concentrations in the leachate, and, in some cases, higher nitrate levels compared to the recycled water plots.

It is recommended that turf areas be prepared to receive the nutrients in the recycled water and use them before recycled water is applied to soils. This may require that the turf be actively growing and the soil be in a moist state prior to the application of recycled water.

7.6 Summary

There are few differences between the management of turf irrigated with recycled water and turf irrigated with potable water. Typically, turf irrigated with recycled water can benefit from the additional nutrients, but may suffer from elevated salt build-up in the soils. A high quality and wear-tolerant turf can be maintained through proper management of the turf. This management also decreases the possibility or intensity of receiving water contamination from nutrients when using either recycled water or potable water for irrigation.

SECTION 8.0

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Appendix A

FIGURE A.1
Aesthetic Rating for Plot 9, April 2002, Score of 3
Edwards Aquifer Recharge Zone Irrigation Pilot Study

FIGURE A.2
Aesthetic Rating for Plot 9, May 2002, Score of 3
Edwards Aquifer Recharge Zone Irrigation Pilot Study

FIGURE A.3
Aesthetic Rating for Plot 9, June 2002, Score of 7
Edwards Aquifer Recharge Zone Irrigation Pilot Study

FIGURE A.4
Aesthetic Rating for Plot 9, August 2002, Score of 8
Edwards Aquifer Recharge Zone Irrigation Pilot Study

FIGURE A.5
Aesthetic Rating for Plot 9, September 2002, Score of 9
Edwards Aquifer Recharge Zone Irrigation Pilot Study

FIGURE A.6
Aesthetic Rating for Plot 9, November 2002, Score of 6
Edwards Aquifer Recharge Zone Irrigation Pilot Study

FIGURE A.7
Aesthetic Rating for Plot 9, December 2002, Score of 8
Edwards Aquifer Recharge Zone Irrigation Pilot Study

FIGURE A.8
Aesthetic Rating for Plot 9, January 2003, Score of 7
Edwards Aquifer Recharge Zone Irrigation Pilot Study

FIGURE A.9
Aesthetic Rating for Plot 9, February 2003, Score of 7
Edwards Aquifer Recharge Zone Irrigation Pilot Study

FIGURE A.10
Aesthetic Rating for Plot 9, March 2003, Score of 6
Edwards Aquifer Recharge Zone Irrigation Pilot Study

FIGURE A.11
Aesthetic Rating for Plot 9, May 2003, Score of 8
Edwards Aquifer Recharge Zone Irrigation Pilot Study

FIGURE A.12
Aesthetic Rating for Plot 9, June 2003, Score of 8
Edwards Aquifer Recharge Zone Irrigation Pilot Study

FIGURE A.13
Aesthetic Rating for Plot 9, July 2003, Score of 9
Edwards Aquifer Recharge Zone Irrigation Pilot Study

FIGURE A.14
Aesthetic Rating for Plot 9, August 2003, Score of 7
Edwards Aquifer Recharge Zone Irrigation Pilot Study

FIGURE A.15
Aesthetic Rating for Plot 9, September 2003, Score of 8
Edwards Aquifer Recharge Zone Irrigation Pilot Study

FIGURE A.16
Aesthetic Rating for Plot 9, October 2003, Score of 7
Edwards Aquifer Recharge Zone Irrigation Pilot Study

FIGURE A.17
Aesthetic Rating for Plot 9, November 2003, Score of 7
Edwards Aquifer Recharge Zone Irrigation Pilot Study

FIGURE A.18
Aesthetic Rating for Plot 9, December 2003, Score of 7
Edwards Aquifer Recharge Zone Irrigation Pilot Study

FIGURE A.19
Aesthetic Rating for Plot 9, January 2004, Score of 7
Edwards Aquifer Recharge Zone Irrigation Pilot Study

FIGURE A.20
Aesthetic Rating for Plot 9, February 2004, Score of 7
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Appendix B

FIGURE B.1

Mean Electrical Conductivity (umho/cm or dS/mX10^3) of Runoff Water Samples from Zoysiagrass Plots Subjected to Three Irrigation Treatments

Edwards Aquifer Recharge Zone Irrigation Pilot Study

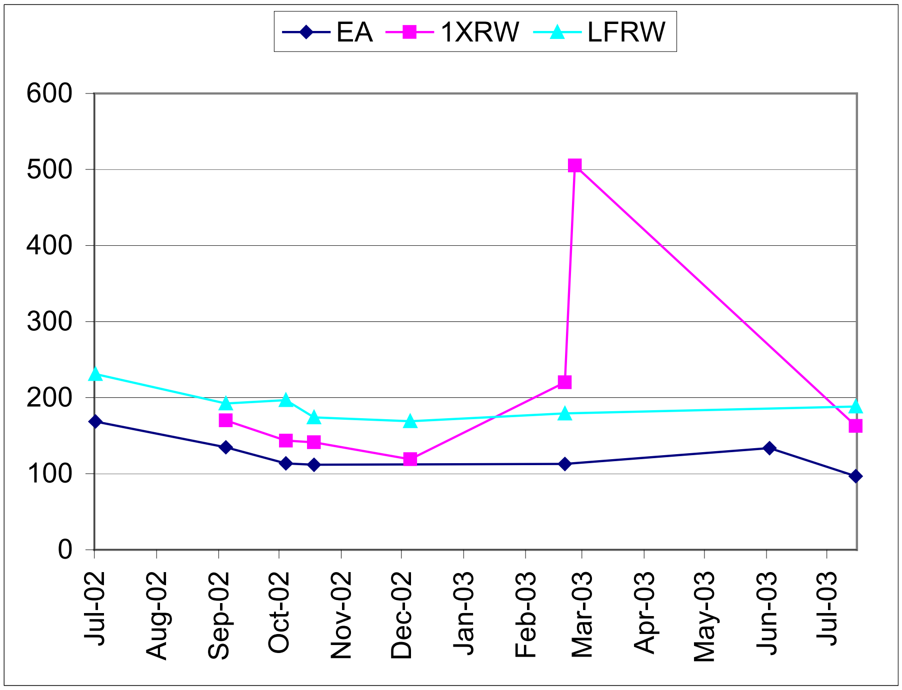


FIGURE B.2

Mean Electrical Conductivity (umho/cm or dS/mX10^3) of Runoff Water Samples from Bermudagrass Plots Subjected to Three Irrigation Treatments

Edwards Aquifer Recharge Zone Irrigation Pilot Study

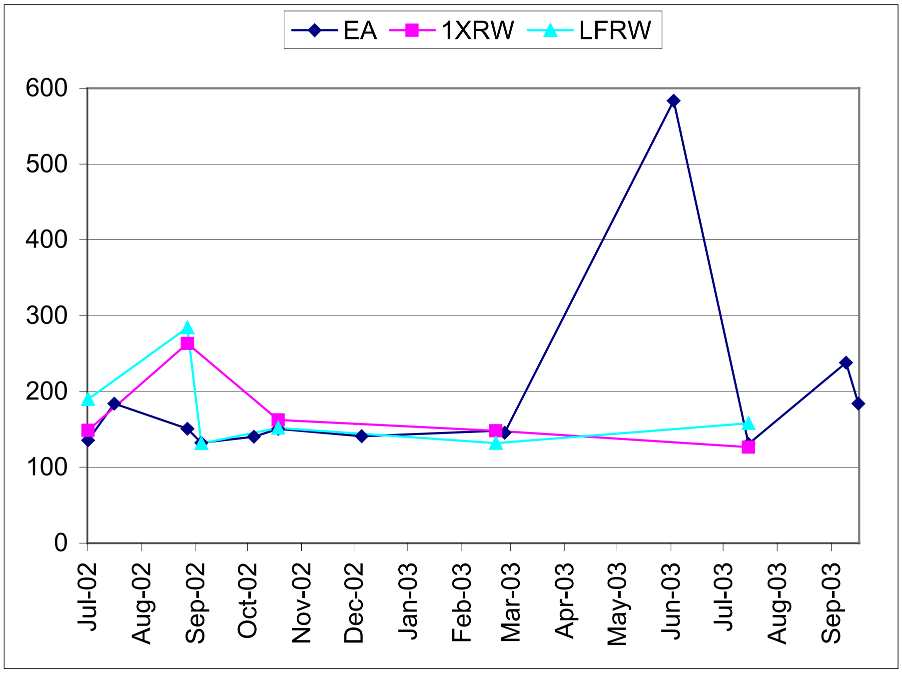


FIGURE B.3
Mean Concentrations of Sodium (mg/L) Measured in Zoysiagrass Plots in Runoff Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

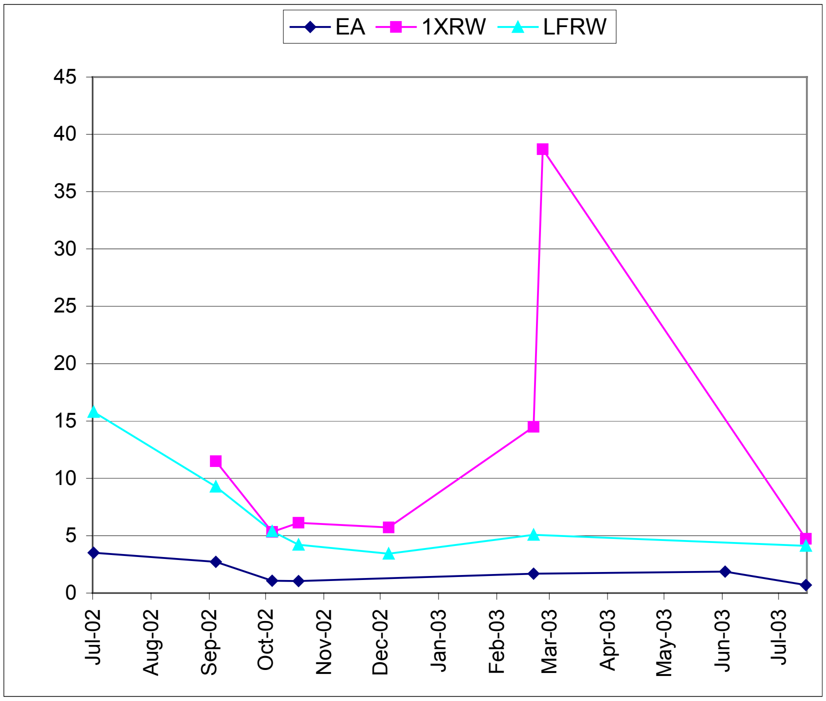


FIGURE B.4
Mean Concentrations of Sodium (mg/L) Measured in Bermudagrass Plots in Runoff Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

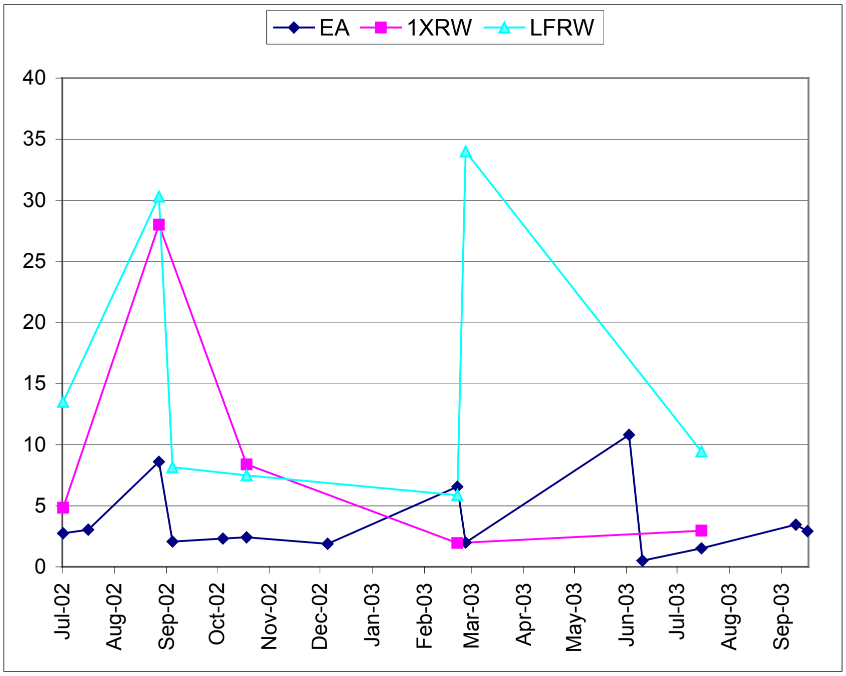


FIGURE B.5
Mean Concentrations of Manganese (mg/L) Measured in Zoysiagrass Plots in Runoff Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

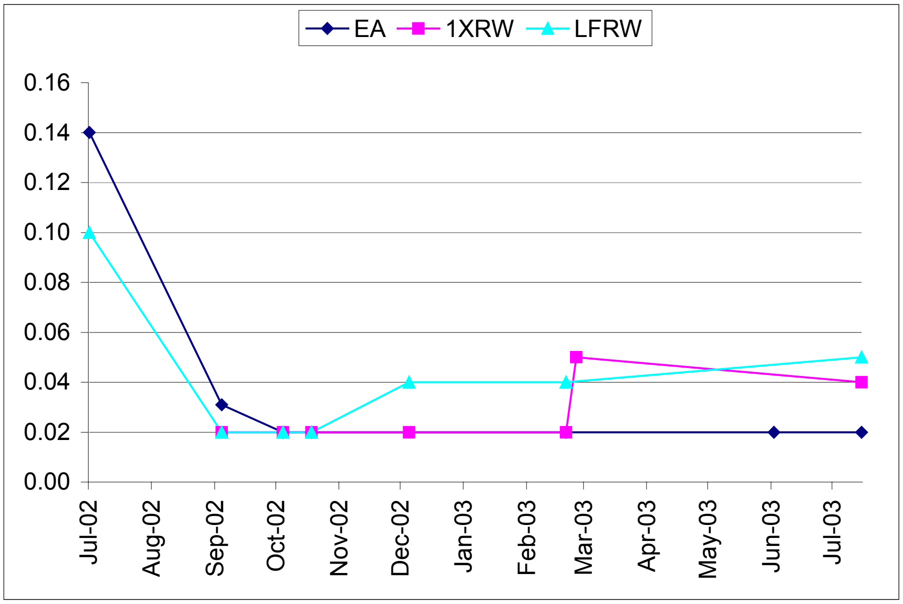


FIGURE B.6
Mean Concentrations of Manganese (mg/L) Measured in Bermudagrass Plots in Runoff Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

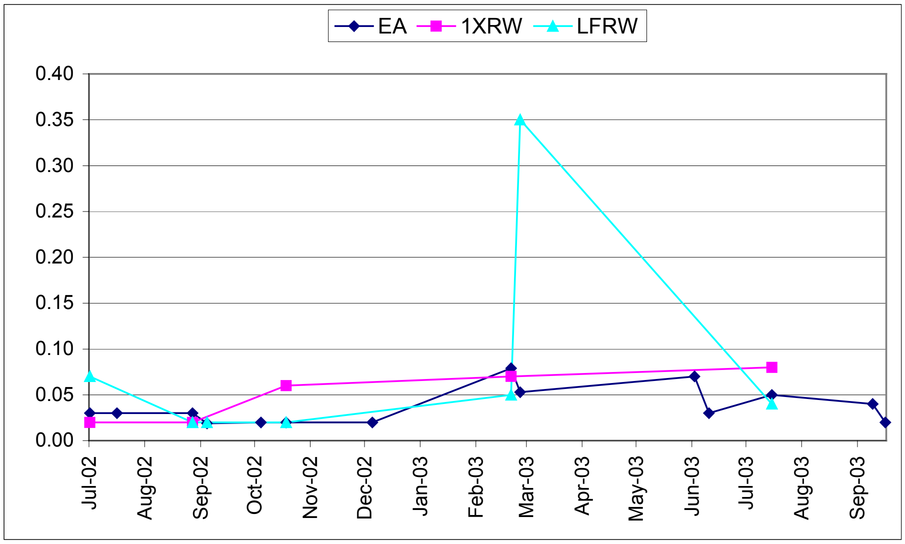


FIGURE B.7
Mean Concentrations of Magnesium (mg/L) Measured in Zoysiagrass Plots in Runoff Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

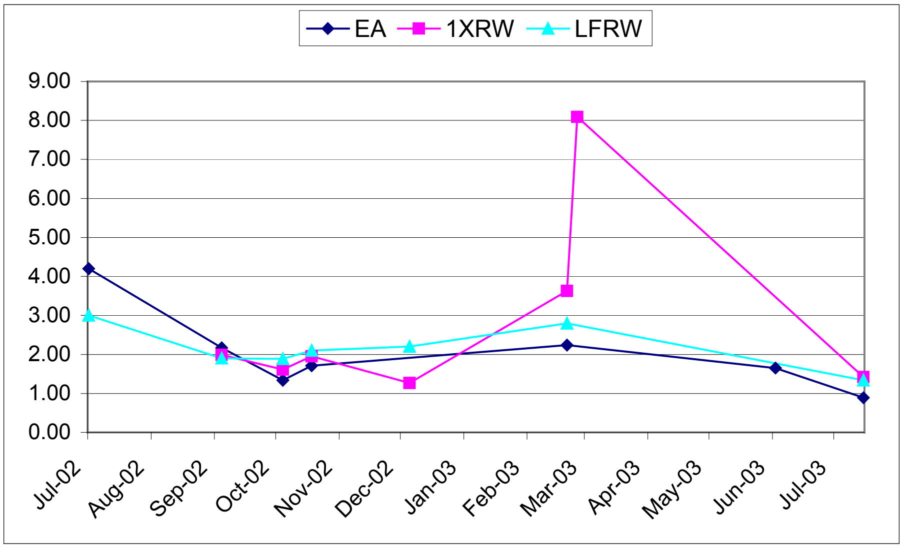


FIGURE B.8
Mean Concentrations of Magnesium (mg/L) Measured in Bermudagrass Plots in Runoff Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

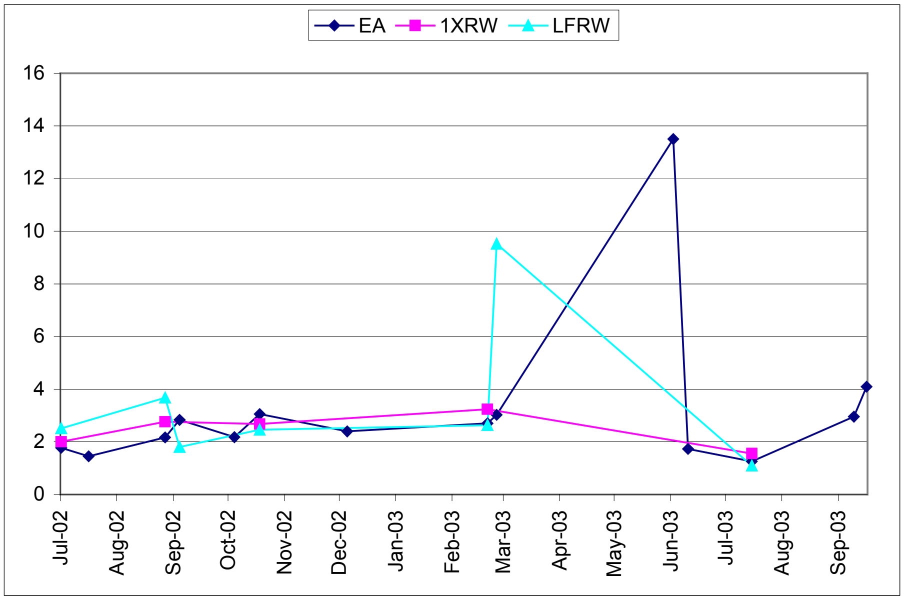


FIGURE B.9
Mean Concentrations of Iron (mg/L) Measured in Zoysiagrass Plots in Runoff Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

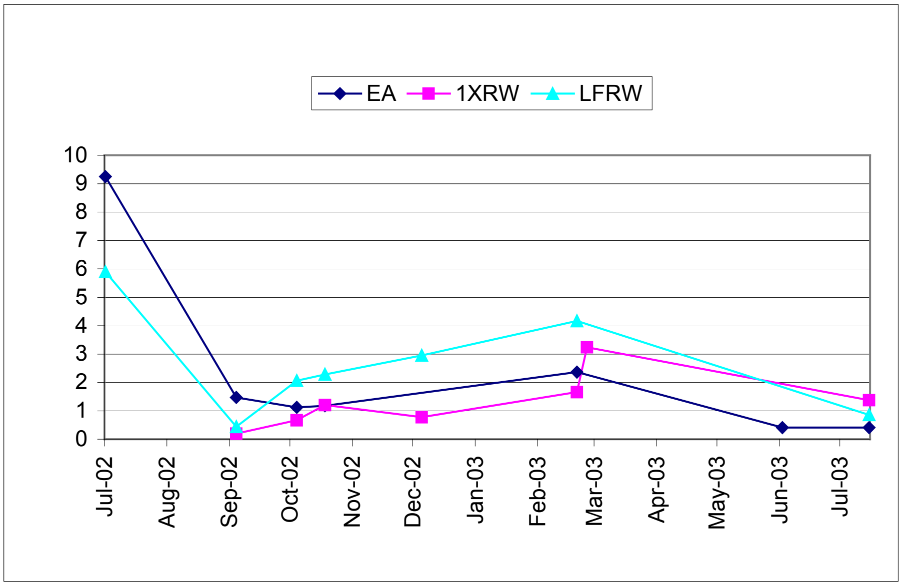


FIGURE B.10
Mean Concentrations of Iron (mg/L) Measured in Bermudagrass Plots in Runoff Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

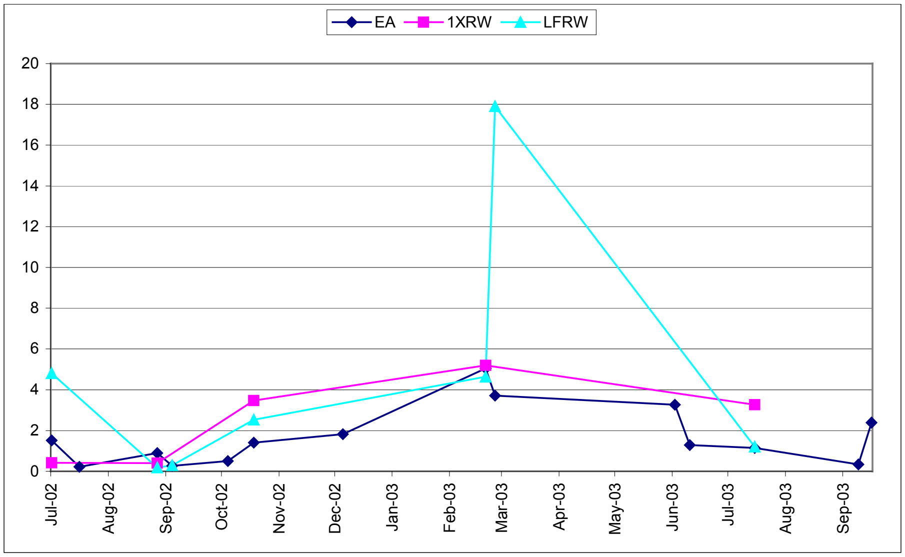


FIGURE B.11
Mean Concentrations of Copper (mg/L) Measured in Zoysiagrass Plots in Runoff Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

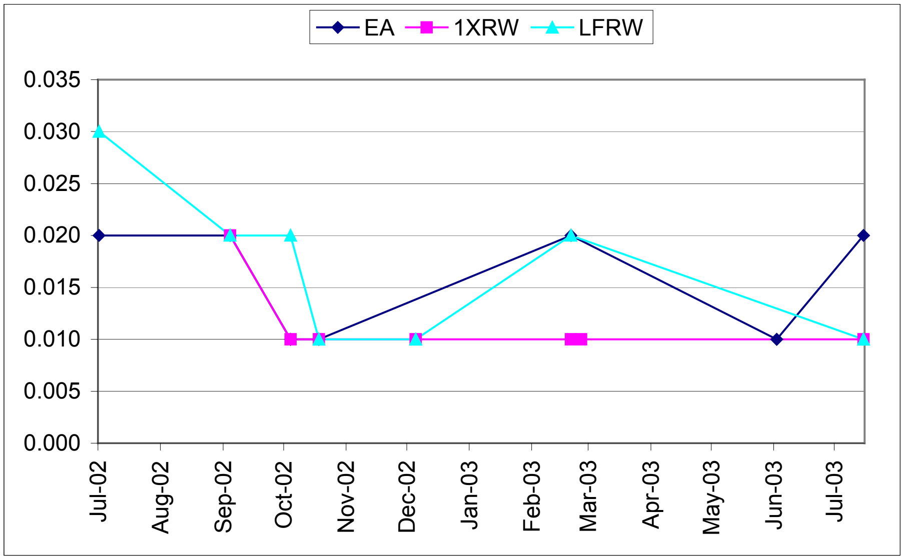


FIGURE B.12
Mean Concentrations of Copper (mg/L) Measured in Bermudagrass Plots in Runoff Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

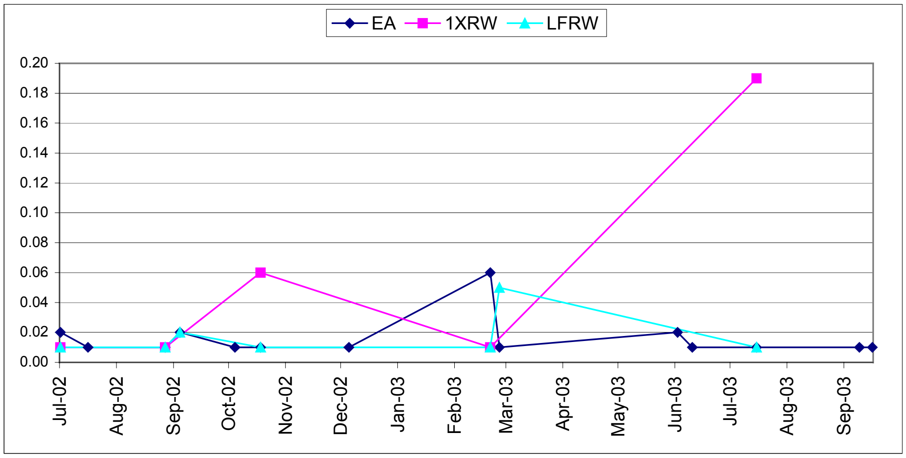


FIGURE B.13
Mean Concentrations of Zinc (mg/L) Measured in Zoysiagrass Plots in Runoff Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

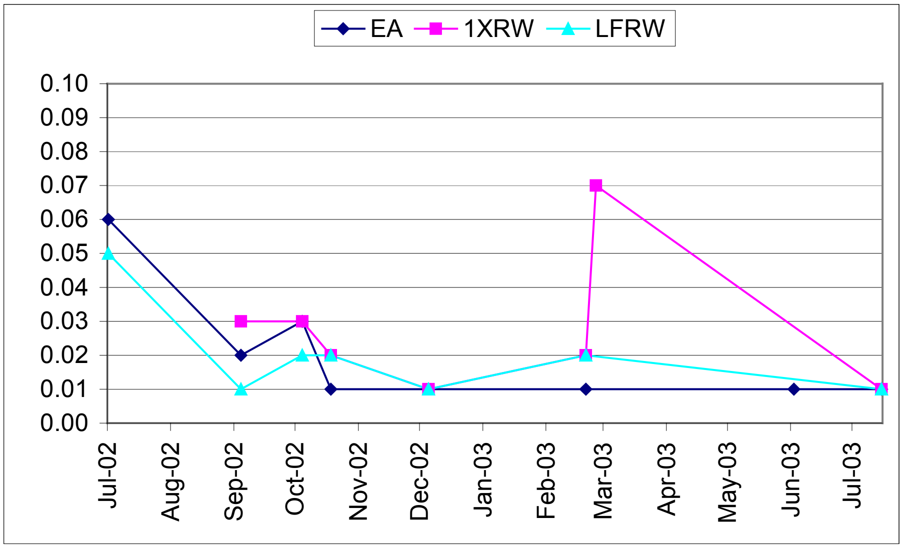


FIGURE B.14
Mean Concentrations of Zinc (mg/L) Measured in Bermudagrass Plots in Runoff Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

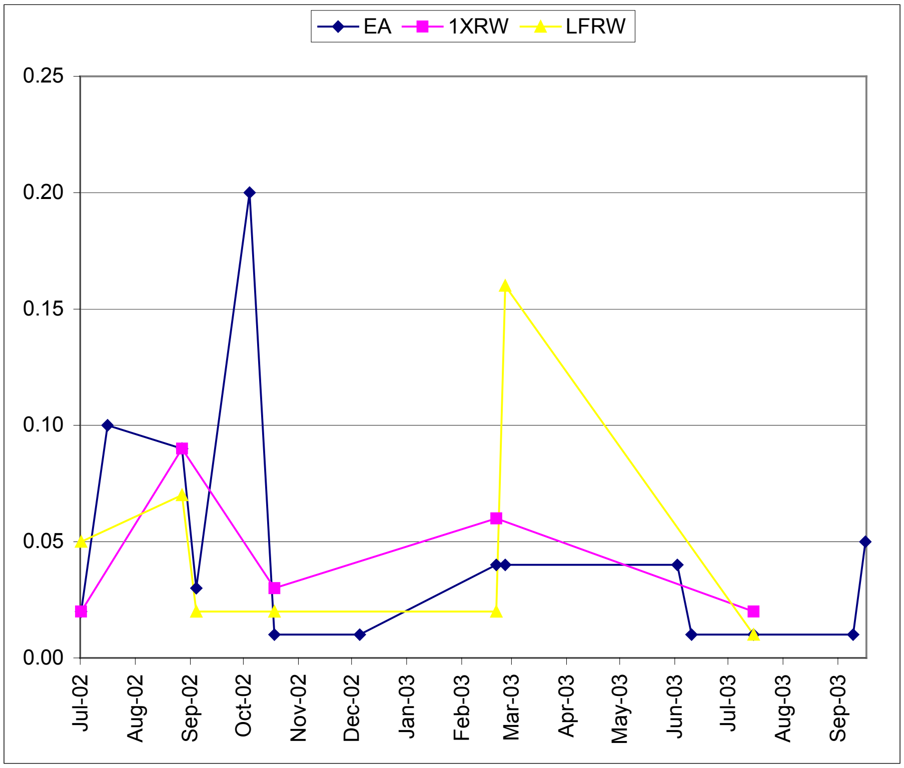


FIGURE B.15

Mean Concentrations of Calcium (mg/L) Measured in Zoysiagrass Plots in Runoff Samples Collected by Irrigation Treatment

Edwards Aquifer Recharge Zone Irrigation Pilot Study

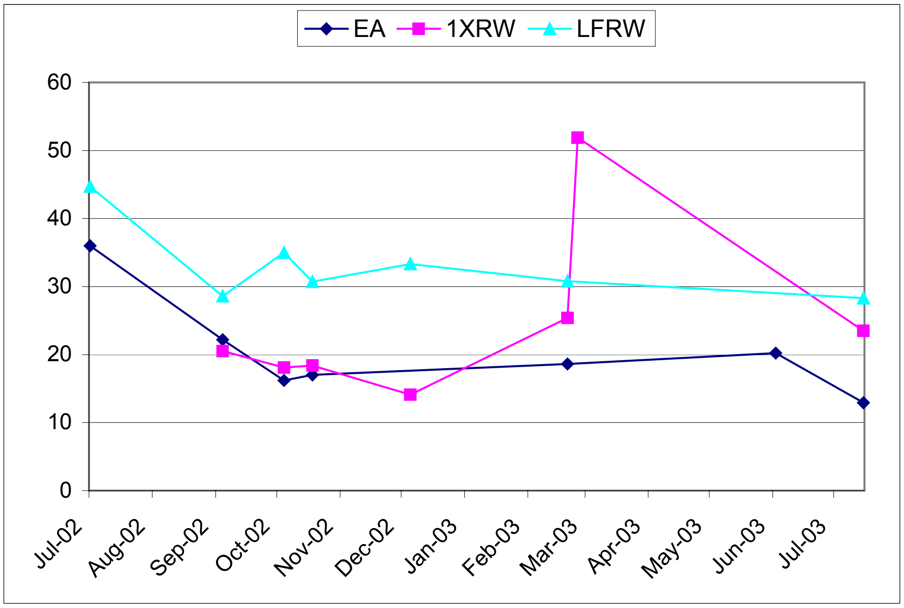


FIGURE B.16

Mean Concentrations of Calcium (mg/L) Measured in Bermudagrass Plots in Runoff Samples Collected by Irrigation Treatment

Edwards Aquifer Recharge Zone Irrigation Pilot Study

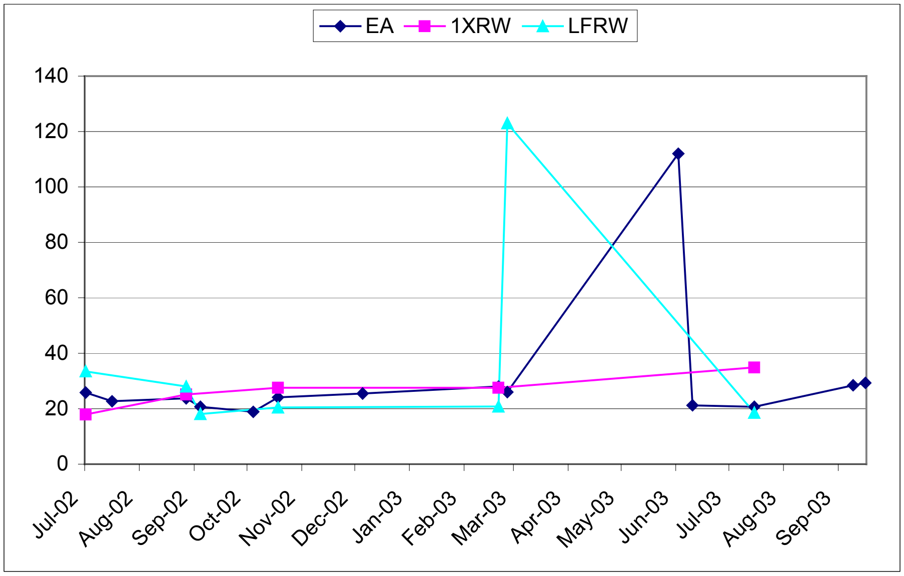


FIGURE B.17
Mean Concentrations of (mg/L) Potassium Measured in Zoysiagrass Plots in Runoff Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

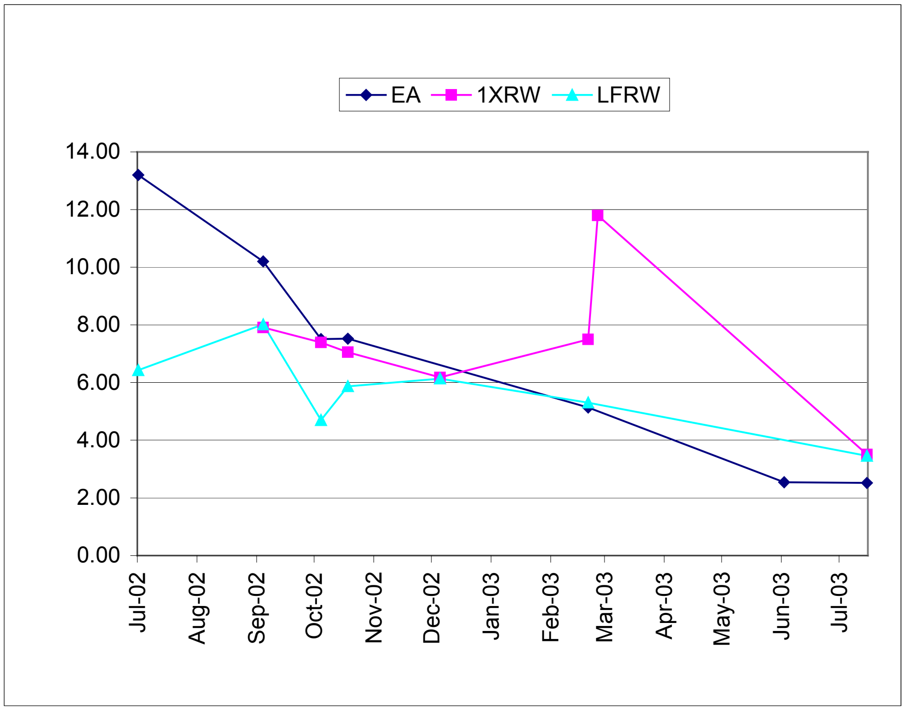


FIGURE B.18
Mean Concentrations of (mg/L) Potassium Measured in Bermudagrass Plots in Runoff Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

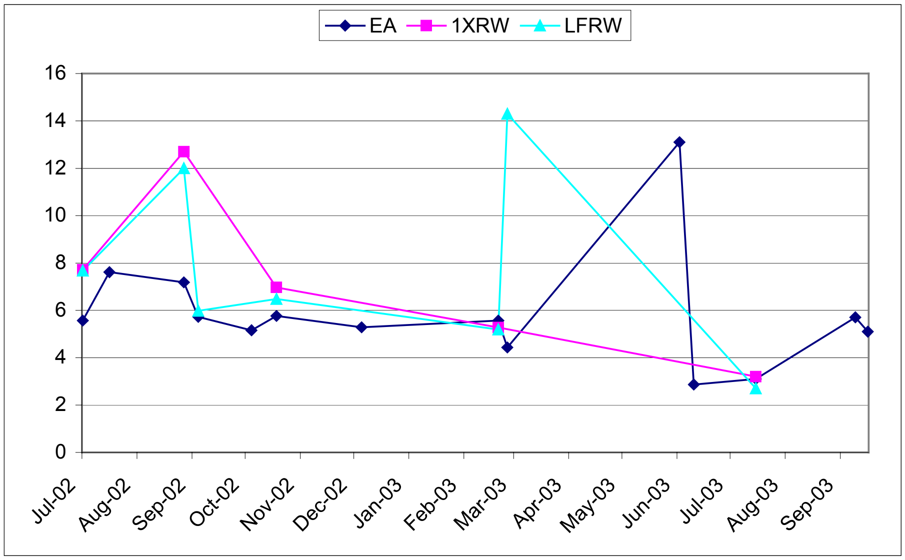


FIGURE B.19
Mean Concentrations of Phosphorus (mg/L) Measured in Zoysiagrass Plots in Runoff Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

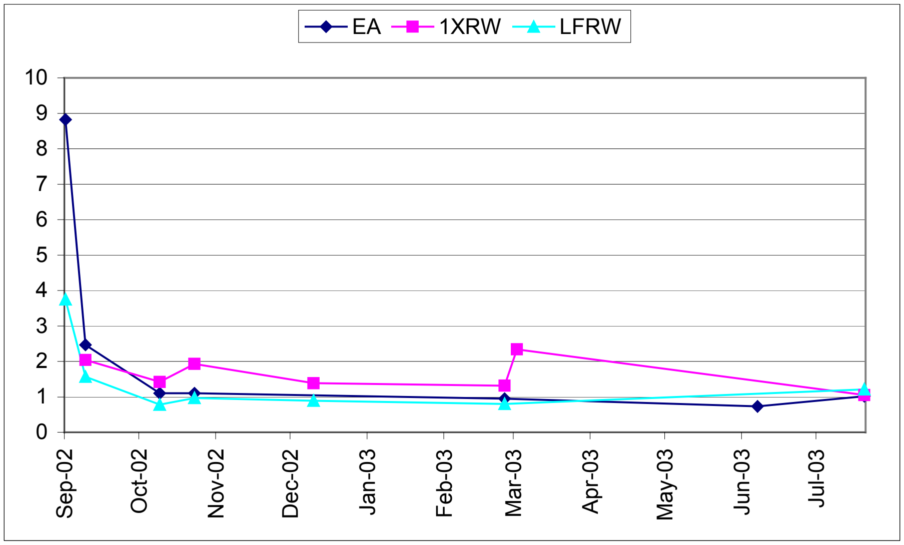


FIGURE B.20
Mean Concentrations of Phosphorus (mg/L) Measured in Bermudagrass Plots in Runoff Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

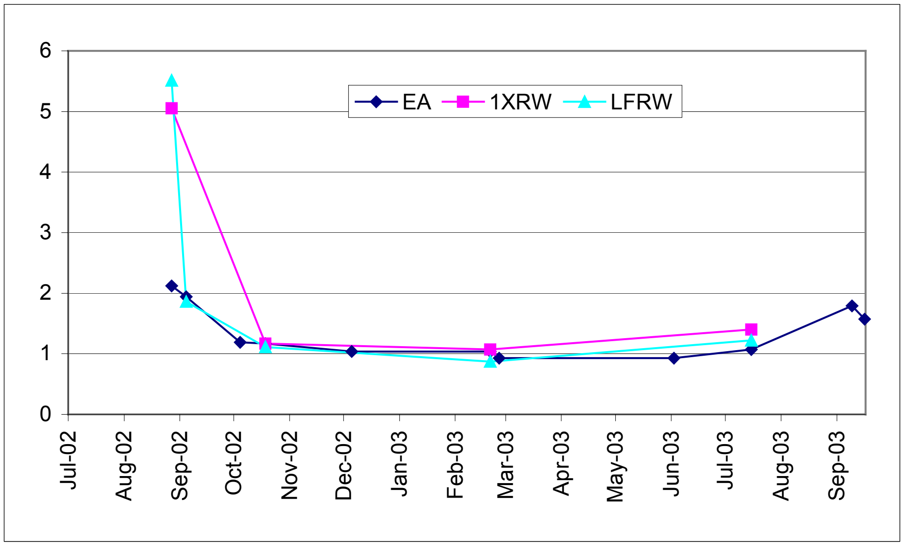


FIGURE B.21
Mean Concentrations of Total Kjeldahl Nitrogen (mg/L) Measured in Zoysiagrass Plots in Runoff Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

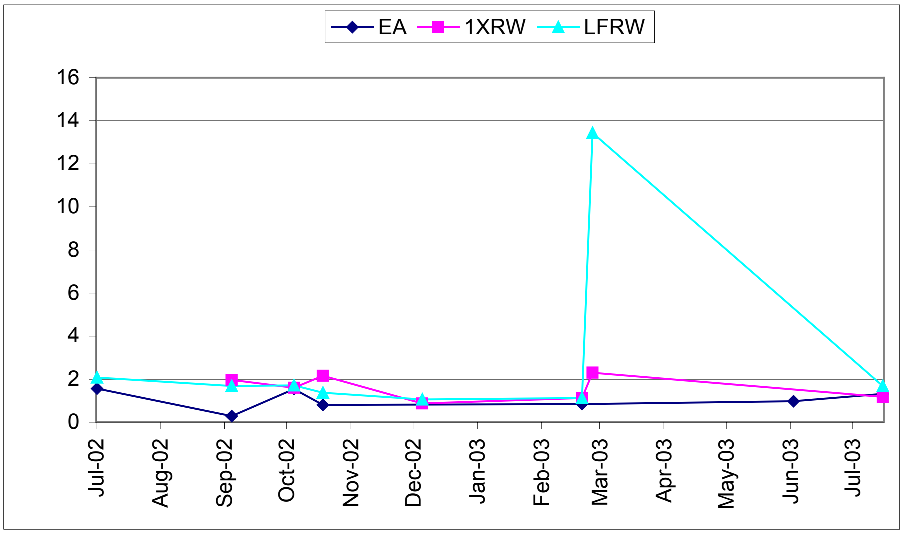


FIGURE B.22
Mean Concentrations of Total Kjeldahl Nitrogen (mg/L) Measured in Bermudagrass Plots in Runoff Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

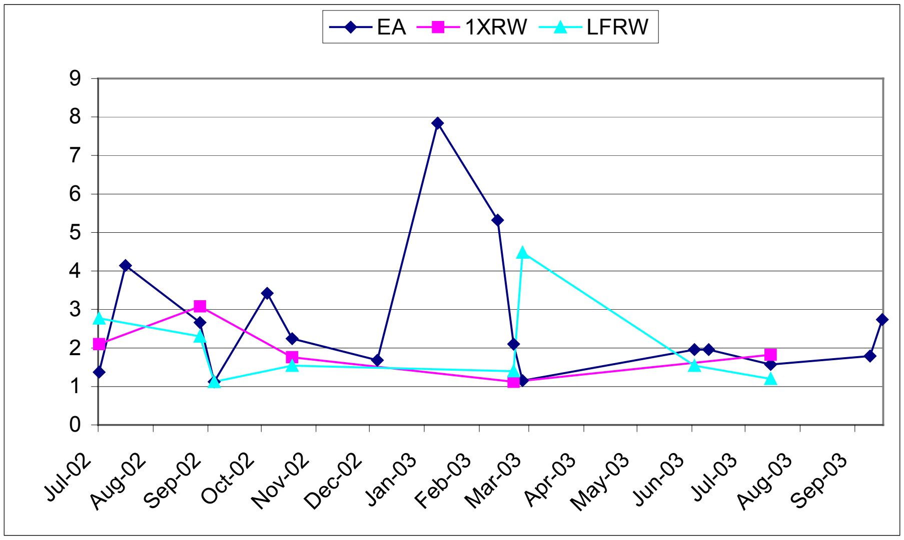


FIGURE B.23
Mean Concentrations of Nitrite (mg/L) Measured in Zoysiagrass Plots in Runoff Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

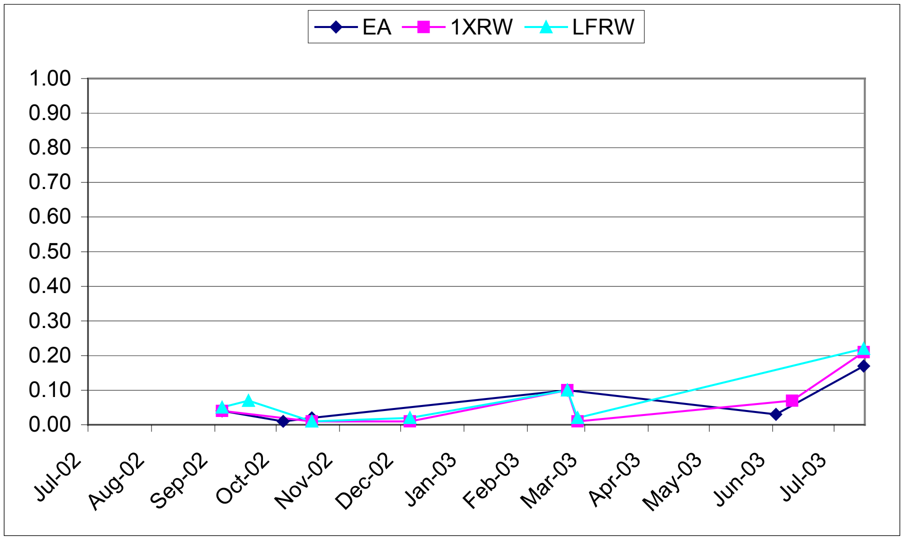


FIGURE B.24
Mean Concentrations of Nitrite (mg/L) Measured in Bermudagrass Plots in Runoff Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

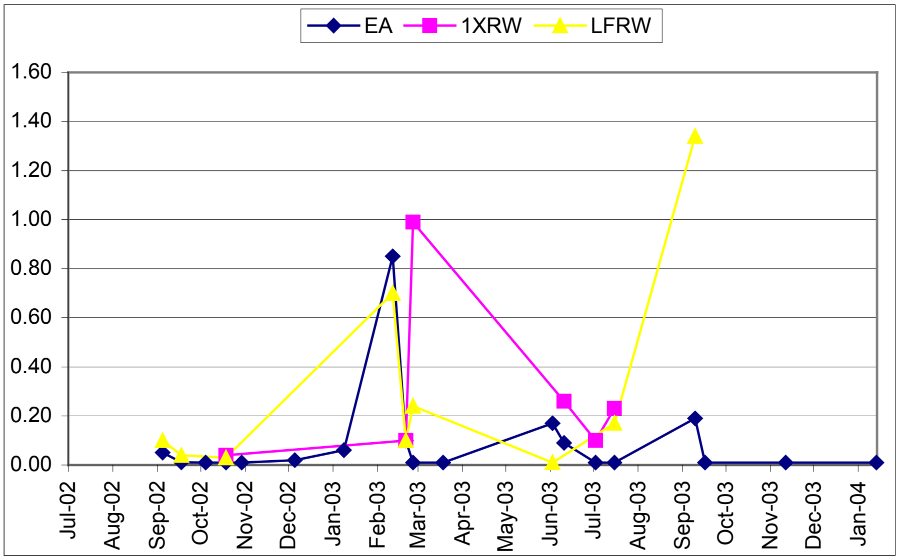


FIGURE B.25

Mean Concentrations of Nitrate (mg/L) Measured in Zoysiagrass Plots in Runoff Samples Collected by Irrigation Treatment

Edwards Aquifer Recharge Zone Irrigation Pilot Study

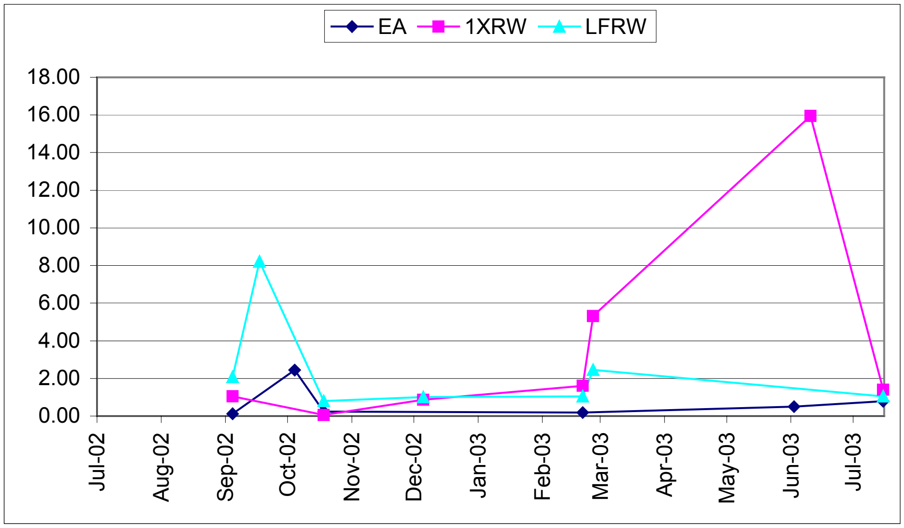


FIGURE B.26

Mean Concentrations of Nitrate (mg/L) Measured in Bermudagrass Plots in Runoff Samples Collected by Irrigation Treatment

Edwards Aquifer Recharge Zone Irrigation Pilot Study

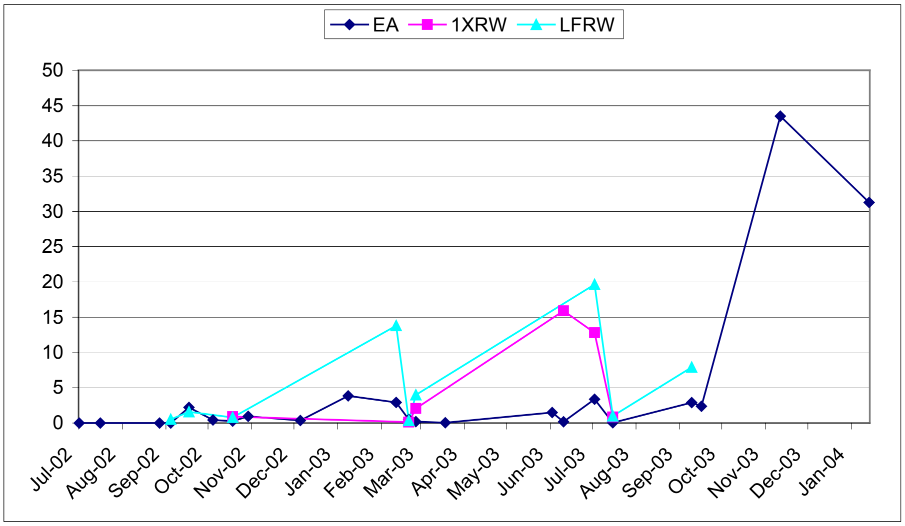


FIGURE B.27
Mean Concentrations of Ammonia Nitrogen (mg/L) Measured in Zoysiagrass Plots in Runoff Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

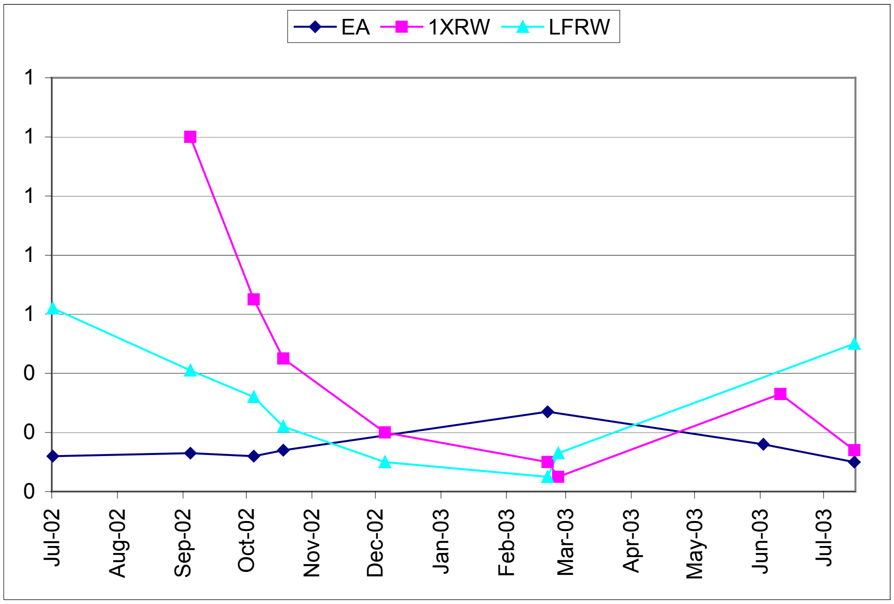


FIGURE B.28
Mean Concentrations of Ammonia Nitrogen (mg/L) Measured in Bermudagrass Plots in Runoff Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

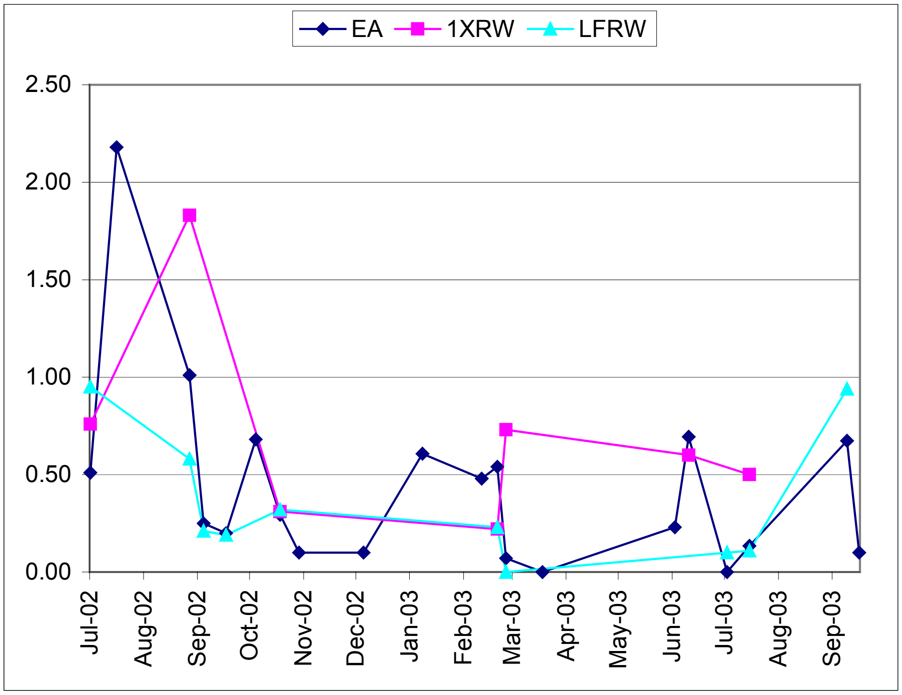


FIGURE B.29

Mean Concentrations of Fecal Coliform (mg/L) Measured in Zoysiagrass Plots in Runoff Samples Collected by Irrigation Treatment

Edwards Aquifer Recharge Zone Irrigation Pilot Study

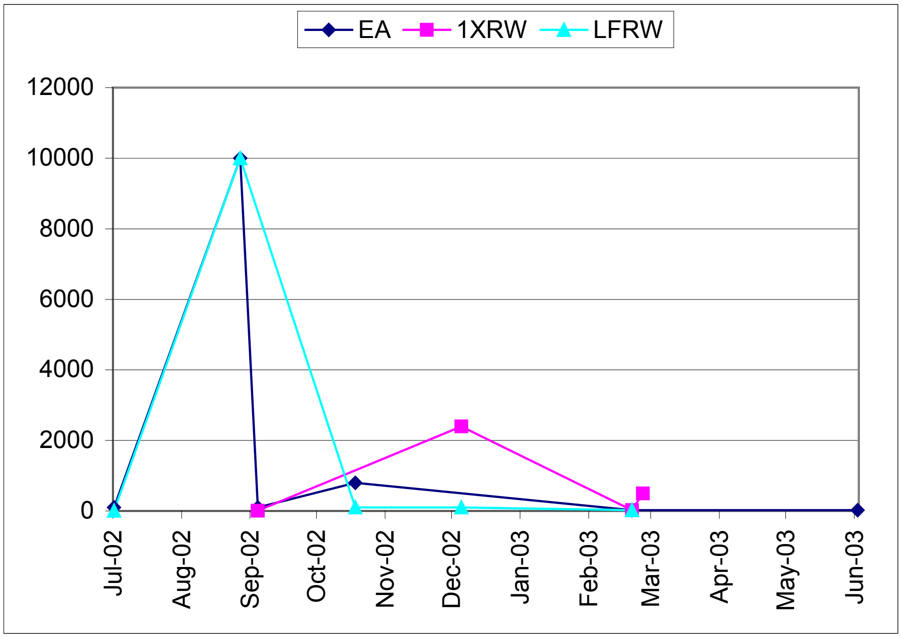
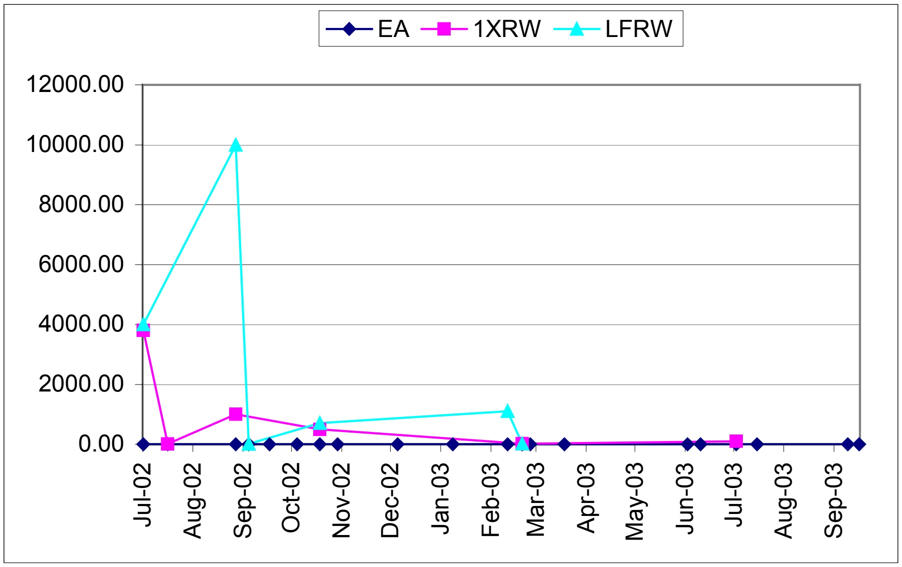


FIGURE B.30

Mean Concentrations of Fecal Coliform (mg/L) Measured in Bermudagrass Plots in Runoff Samples Collected by Irrigation Treatment

Edwards Aquifer Recharge Zone Irrigation Pilot Study



Appendix C

TABLE C.1

Leachate Volumes (Liters) Collected from Lysimeters Located at Three Depths in Experimental Plots - June 15, 2002 to December 31, 2002.

Edwards Aquifer Recharge Zone Irrigation Pilot Study

Plot Number	Depth	Jun 25	Jul 8	Jul 23	Aug 22	Sep 11	Sep 24	Oct 11	Oct 30	Nov 7	Nov 26	Dec 12	Dec 19	Total Volume
1	6 inch	0.16	0.96	0.15	0	1.95	0.06	0.45	0.15	0.15	0	1.8	0	5.83
	18 inch	2.85	2.961	0.5	0	4.8	tr	4.9	3.5	0.13	0	0.8	0	20.441
	30 inch	0.54	4.27	1.33	0	4.9	tr	5.11	4.6	0.05	0	1.6	0	22.4
2	6 inch	0.5	2.575	1.15	0	2.6	0.05	2.4	2.4	0.65	0	2.6	0	14.925
	18 inch	2.8	0.74	0.35	tr	2.95	0.9	3.7	3.5	0.8	0	1.6	0	17.34
	30 inch	0.12	1.5	0.15	0	1.5	0.12	1.45	1.15	0.8	0	1.9	0	8.69
3	6 inch	0.51	2	0.95	0.3	3.2	0.35	0.85	0.65	0.7	0	1.6	0	11.11
	18 inch	0.25	1.9	0.3	0.14	4.2	0.1	4.1	4.5	0.4	0	0.9	0	16.79
	30 inch	0.15	1.25	1.075	0.1	1.25	0.1	1.3	1.3	0.45	0	0.8	0	7.775
4	6 inch	0.15	1.5	0.15	0.1	2.5	0.175	1	0.5	0.4	0	1.2	0	7.675
	18 inch	trace	1.5	0	0	4.65	0.1	4	2.3	0.425	0	0.05	0	13.025
	30 inch	trace	1.15	0	0	4.1	0.075	3.2	3.1	0	0	0.05	0	11.675
5	6 inch	3.22	4.4	1.95	1.95	4.15	0.7	4.25	4.05	2.8	0	4.5	0.05	32.02
	18 inch	2.25	0.24	0	0	3.05	0.15	1.6	2.4	0.5	0	2.9	0.1	13.19
	30 inch	3.8	3.35	0	0	4.1	0.12	0.75	3.7	0.6	0	4.2	0.1	20.72
6	6 inch	3.4	2.32	0.04	tr	3.9	0.18	1.55	3.8	0.8	0	1.6	<50	17.59
	18 inch	4.1	4.885	0.025	0	4.8	0.075	4.4	4.05	0.25	0	4.6	<50	27.185
	30 inch	2.6	2.37	0.039	0	3.1	0.18	2.65	2.55	0.2	0	2.4	<50	16.089

TABLE C.1 CONTINUED

Leachate Volumes (Liters) Collected from Lysimeters Located at Three Depths in Experimental Plots - June 15, 2002 to December 31, 2002.

Edwards Aquifer Recharge Zone Irrigation Pilot Study

Plot Number	Depth	Jun 25	Jul 8	Jul 23	Aug 22	Sep 11	Sep 24	Oct 11	Oct 30	Nov 7	Nov 26	Dec 12	Dec 19	Total Volume
7	6 inch	trace	1.8	0.27	0.89	2.4	0.18	0.8	0.9	1.4	0	2.4	0.15	11.19
	18 inch	2.3	3.19	0.85	0.1	2.85	0.1	3.1	2.5	0.25	0	2.4	0	17.64
	30 inch	1.1	4.725	0.75	0	5.1	0	5	4	0.6	0	5	0	26.275
8	6 inch	2.15	4.05	0.91	0.05	3.7	0.15	1.75	0.9	0.35	0	0.4	0.5	14.91
	18 inch	0.23	1.7	0.55	0	2.8	0.1	1.6	2.5	0.6	0	0.8	0.5	11.38
	30 inch	0.36	2.45	0.2	0	4	0.15	4	3.9	0.4	0	0.9	0	16.36
9	6 inch	0.27	0.54	0.05	0	2.2	0.05	3.2	0.5	0.23	0	1.2	0	8.24
	18 inch	1.86	0.24	0.038	0	4	0.12	4.8	4.1	0.2	0	0.9	0	16.258
	30 inch	4.67	1.94	0.075	0	4.7	0.05	4.23	4.75	0.13	0	0.4	0.2	21.145
10	6 inch	0.74	1.75	0.629	1	4.2	0.25	2.41	3.9	0.8	0	0	0	15.679
	18 inch	0.06	3.26	0.635	0.8	2.6	0	4.3	4.6	0.4	0	0	0	16.655
	30 inch	0.09	1.83	0.132	tr	3.8	0.05	3.8	3.2	0.6	0	0	0	13.502
11	6 inch	trace	1.418	0.185	tr	2.2	0	3.45	3	0.15	0	1	0	11.403
	18 inch	trace	0.395	0.02	0	5.4	0.4	4.98	4	0.31	0	-	0	15.505
	30 inch	0.19	4.18	1.1	tr	2	2.85	4.42	4	1.05	0	2.4	0	22.19
12	6 inch	trace	0.705	0.235	0	1.85	0.05	1.15	4	0.58	0	1.5	0.05	10.12
	18 inch	0.13	0.825	0.038	0	4.6	0.05	4.795	4	0.23	0	4	0.2	18.868
	30 inch	trace	1.63	0.11	0	5	0.13	4.68	4	0.8	0	0.8	0	17.15
13	6 inch	0.13	1	0.3	0	1.5	0	0.85	1.6	0.6	0	0.7	0.15	6.83

TABLE C.1 CONTINUED

Leachate Volumes (Liters) Collected from Lysimeters Located at Three Depths in Experimental Plots - June 15, 2002 to December 31, 2002.

Edwards Aquifer Recharge Zone Irrigation Pilot Study

Plot Number	Depth	Jun 25	Jul 8	Jul 23	Aug 22	Sep 11	Sep 24	Oct 11	Oct 30	Nov 7	Nov 26	Dec 12	Dec 19	Total Volume
	18 inch	0.4	1.41	0.035	0	1.4	0.1	1.22	1.3	0.25	0	1.2	0.2	7.515
	30 inch	trace	3.73	0.2	0	3.8	0.2	3.6	3.3	0.3	0	3	0.2	18.33
14	6 inch	trace	0.095	0.38	0.75	3.3	0.2	3.4	0.6	0.4	0	0.6	0	9.725
	18 inch	3.75	3.9	0.2	0	4	0.05	4.2	3	0.5	0	3.8	0.1	23.5
	30 inch	3.85	4.11	1.94	0.1	4.6	0.08	2	3	1.2	0	3.7	0.15	24.73
15	6 inch	0.32	0.4	0.11	0	1.2	0	0.11	4	0.21	0	1.3	0	7.65
	18 inch	trace	0.58	0	0	3.1	0.05	3.2	3	0.1	0	3.3	0.15	13.48
	30 inch	0.82	3.5	0.152	0	5.8	0.1	4.6	4	0.72	0	4.2	0	23.892
16	6 inch	trace	1.05	0.312	tr	3.6	0	4.11	0.3	0.15	0	1	0	10.522
	18 inch	1.75	0.73	0	tr	4.2	0	4.09	3.5	0.2	0	1.2	0	15.67
	30 inch	3.37	2.53	0.85	0.25	4	0	3.58	3	2	0	2.3	0.1	21.98
17	6 inch	0.36	0.725	0.198	tr	2.1	0	0.115	0	0.025	0	0.5	0.1	4.123
	18 inch	0.15	0.53	0.06	0	4.2	0.15	4.29	0.6	0.025	0	3.6	0.1	13.705
	30 inch	0.72	0	0	0	3.8	0.14	3.4	3	0.12	0	3.4	0	14.58
18	6 inch	1.02	1.87	0.718	0.4	2.6	0.19	2.6	2.25	1	0	2.6	0.1	15.348
	18 inch	1.24	0.92	0.05	tr	3.1	0.1	3.48	4	0.1	0	0	0.15	13.14
	30 inch	7.41	3.22	0.15	0	3.8	0.28	3.73	4	0.1	0	1.5	0.05	24.24

Notes:
tr = trace amount. 0.05 was the value used when this was the volume listed.

TABLE C.2
Leachate Volumes (Liters) Collected from Lysimeters Located at Three Depths in Experimental Plots - January 2003 through October 2003
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Plot Number	Depth	Jan 28	Feb 27	Mar 25	Apr 22	May 20	Jun 9	Jun 17	Jul 9	Jul 22	Aug 18	Sep 16	Sep 23	Oct 21
1	6 inch	0.45	0.45	0.4	0.25	0	0.8	0.25	0	0.6	0	0.4	0.4	0
	18 inch	0	4.6	0	0	0	4.1	3.05	0.5	4.1	0.05	0.15	tr	0
	30 inch	0	4.5	0.3	0	0	3	2.85	0	3.4	0	0.4	tr	0
2	6 inch	0.6	2.4	2.8	0.6	0	0	1	0.1	0.8	0.2	2.9	2	1.5
	18 inch	0	3.3	2.8	0.4	0.1	3.9	2.6	0.075	0.4	0.15	0.4	1	1.2
	30 inch	0	1.6	1.45	0.175	0	1.6	1.7	0.05	1.5	0	1.8	2.3	1.3
3	6 inch	1.1	2	0.8	0.05	0	2	0.175	0.25	0.3	0.2	0.4	0.3	0.6
	18 inch	0.1	1.2	1.6	0.05	0	3.6	1.45	0	4.7	0	1.3	1.3	0
	30 inch	0	1.2	1.2	0.05	0	1.3	1.35	0.9	1.2	0.45	1.4	1.2	0
4	6 inch	0	0.6	0.25	0.05	0	4.1	0.8	0.15	0.4	0	0.4	0.6	0.4
	18 inch	0	0.2	0	0	0	1.1	0.2	0	0.6	0	0.4	0	0
	30 inch	0	0	0	0	0	1.3	0.1	0	0.6	0	0.55	0.2	0
5	6 inch	0.6	3.2	2.4	0.6	4.7	3.4	1.9	1.4	3	0.2	3.5	2.6	0.9
	18 inch	0	2.8	1.8	0.4	4	0	0	0	2.8	0.1	0.45	0.3	0
	30 inch	0	1.2	0	0	4.1	0.6	0	0	0.8	0	3.5	0.5	0
6	6 inch	0.9	1.5	1.6	0.2	6.2	1.3	0.6	0	3	0	1.3	1	0.1
	18 inch	0	1.5	3.6	0	1.2	4.8	1.9	0	2.5	0	1.8	0	0
	30 inch	0	1.4	2.1	0.05	2.5	0.4	1.2	1.5	3	0	0.4	0.15	0
7	6 inch	0.5	1.3	0	0.43	0	0.5	0.5	0	0.8	0.75	2.6	0.35	0.7

TABLE C.2 CONTINUED
Leachate Volumes (Liters) Collected from Lysimeters Located at Three Depths in Experimental Plots - January 2003 through October 2003
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Plot Number	Depth	Jan 28	Feb 27	Mar 25	Apr 22	May 20	Jun 9	Jun 17	Jul 9	Jul 22	Aug 18	Sep 16	Sep 23	Oct 21
	18 inch	0	3	0	0.2	0	2.2	0.6	0	3.8	0.06	0.05	0	0
	30 inch	0	5.2	0.6	0.77	0	1.4	4	0	4.2	0.3	4.5	0.6	0
8	6 inch	0.3	1.8	0.5	0.39	0	4.2	1.5	0.1	1.8	0.25	2.4	2.6	0.45
	18 inch	0	0.45		1	0	3.9	0.8	0	2	0	1.8	0.5	0
	30 inch	0	0.4		0	0	4	0.4	0	0.6	0	1.8	0	0
9	6 inch	0.5	0.25	0.375	0	0	0	0.2	0.1	0.8	0	0.2	0.3	0
	18 inch	0	0.2	2	0	0	0.2	1	0	1.2	0	0.4	0.8	0
	30 inch	0	2.1	1.3	0	0	0.4	0.4	0	1.7	0	0.7	0.7	0
10	6 inch	0.4	3.1	3.8	0.4	0	1.9	3.2	0.9	1.2	2	3.2	2.3	0.3
	18 inch	0	0.9	0.55	0	0	0.4	1.1	0.15	0.2	0	2.4	0	0
	30 inch	0	4.1	0.75	0	0	0.5	1.65	0	1.2	2	1.2	0	0
11	6 inch	0.1	0.6	0.9	0	0	0.35	0.4	2	0.75	0.25	2.5	0.4	0
	18 inch	0	1.65	2	0	0	0	2	3.6	4.9	0.5	4	0.8	0
	30 inch	0	0.825	3.1	0	0	0	1.05	3.1	4.95	0.25	2.7	2.5	0.8
12	6 inch	0.4	0.9	0.4	0	0	3.5	0.35	0	0.6	0.1	0.6	1.2	0
	18 inch	0	4	0.375	0	0	3.4	0.4	0	0.4	0	1.1	0.2	0
	30 inch	0	0.7	0.1	0	0	4.1	0.85	0	0.7	0.1	0.2	0.2	0
13	6 inch	0.2	1.3	0.5	0.4	0	0.5	0.55	0	0.8	0	0.3	0.7	0.2
	18 inch	0	1.5	0.5	0.2	0	0.4	1	0	1.2	0	0.2	1	0.2

TABLE C.2 CONTINUED
Leachate Volumes (Liters) Collected from Lysimeters Located at Three Depths in Experimental Plots - January 2003 through October 2003
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Plot Number	Depth	Jan 28	Feb 27	Mar 25	Apr 22	May 20	Jun 9	Jun 17	Jul 9	Jul 22	Aug 18	Sep 16	Sep 23	Oct 21
	30 inch	0	3.8	0.2	0	0	0	0.1	0	3.75	0	0.2	0	0
14	6 inch	0.4	0.15	0.2	0.25	0	1.3	0.15	0	0	0	0	0	0.3
	18 inch	0.1	4.6	4	0.4	0	1.2	4	0	4	0.15	0	1.8	0
	30 inch	0	4	4	0	0	2	4	0	1	2.2	0	2	0
15	6 inch	0	0.65	0.2	0	0	0.3	3	0.3	1.6	0	2.9	0.7	0
	18 inch	0	3.2	0	0.6	0	3.1	3.2	0.05	3.4	0	3.2	3.8	0
	30 inch	0	2.2	0	0.9	0	3.6	4.4	0	2	1.6	2.2	4.2	0
16	6 inch	0.1	0.2	0.15	0.2	0.3	1.6	1.8	1	0.45	0	1.3	0.9	0
	18 inch	0.2	3.55	1	0	0	3.7	3.8	0.1	4.1	0.4	2	3.4	0
	30 inch	0.1	3.4	1.9	0.25	0.1	3.5	3.9	0.5	2.2	0	1.8	2	0
17	6 inch	0.25	0.35	0	0	0	2	0.2	0	0.1	0	0.1	0.1	0
	18 inch	0	4.45	2	0	0	4.3	0.75	0	4.3	0	1.2	2	0.8
	30 inch	0	1.4	1	0	0	1.95	0.05	0	3.4	0	0.5	0	0.8
18	6 inch	0.15	3.1	1.8	0	0.1	0.6	1.95	4.1	2.1	0.9	3.7	3.2	0.5
	18 inch	0	0.95	0.3	0.4	0	0.35	0.1	3.7	0.3	0.1	2.5	0.5	0
	30 inch	0	2.4	1.1	0	0	0.4	1.8	3.9	3.8	0.4	4	0.4	0

Notes:
tr = trace amount. 0.05 was the value used when this was the volume listed.

TABLE C.3
Leachate Volumes (Liters) Collected from Lysimeters Located at 3Depths in Experimental Plots: Nov. 2003 - Feb. 2004
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Plot Number	Depth	Nov 18	Dec 22	Jan 20	Feb 17	Total for Study Period
1	6 inch	Tr	0	0.3	TR	10.13
	18 inch	0	0	0	TR	36.99
	30 inch	0	0	0	TR	36.85
2	6 inch	2.5	2	2.45	0	36.78
	18 inch	0.2	2	0.4	0	36.27
	30 inch	2.1	1.7	1.2	0	27.17
3	6 inch	0.5	0.1	0.55	0	20.44
	18 inch	0	0	0.15	TR	32.24
	30 inch	1	0.2	0.38	0	19.61
4	6 inch	Tr	0.2	0.15	0	15.78
	18 inch	0	0	0	TR	15.53
	30 inch	Tr	0	0	TR	14.43
5	6 inch	0.8	0.6	0.8	0	62.62
	18 inch	0	0	0	TR	25.84
	30 inch	0.1	0	0	TR	31.52
6	6 inch	tr	0.07	0.4	0	35.76
	18 inch	0	0	0	TR	44.49
	30 inch	tr	0	0.05	0	28.84
7	6 inch	0.8	0.5	0.5	0.3	21.72
	18 inch	0	0	0	0	27.55
	30 inch	0.1	0	0	0	47.95
8	6 inch	0.8	0.2	0.38	0.1	32.68
	18 inch	0	0	0.35	tr	22.18
	30 inch	0	0	0	tr	23.56
9	6 inch	0.1	0.1	0.4	0.4	11.97
	18 inch	0	0	0	tr	22.06
	30 inch	0	0	0	tr	28.45
10	6 inch	0.7	1.45	0.4	0.8	41.73
	18 inch	0	0	0	0.1	22.46
	30 inch	0	0.1	0	tr	25.00

TABLE C.3 CONTINUED

Leachate Volumes (Liters) Collected from Lysimeters Located at 3Depths in Experimental Plots: Nov. 2003 - Feb. 2004

Edwards Aquifer Recharge Zone Irrigation Pilot Study

Plot Number	Depth	Nov 18	Dec 22	Jan 20	Feb 17	Total for Study Period
11	6 inch	0	0	0.2	tr	19.85
	18 inch	0	1.2	0	tr	36.16
	30 inch	1.2	0.6	0	0.2	43.47
12	6 inch	0.3	0.4	0.4	0.175	19.45
	18 inch	0	0	0	tr	28.74
	30 inch	0	0	0.05	tr	24.15
13	6 inch	0.4	0	0.4	0.2	13.28
	18 inch	0.6	0	0.2	0.2	14.72
	30 inch	0	0	0	tr	26.38
14	6 inch	0	0.2	0.3	0.1	13.08
	18 inch	0	0	0.8	2.5	47.05
	30 inch	0	0	3	2.5	49.43
15	6 inch	0	3.5	1	0.15	21.95
	18 inch	3.4	3.3	2.1	2.5	45.33
	30 inch	3.2	0	1.5	2.5	52.19
16	6 inch	1	0	0.5	tr	20.02
	18 inch	2.3	0.4	1.8	2.5	44.92
	30 inch	2.4	1.1	2.2	2.5	49.83
17	6 inch	0	0	0.2	0.3	7.72
	18 inch	0	0	0	tr	33.51
	30 inch	0	0	0	tr	23.68
18	6 inch	0	1	1.4	0.55	40.50
	18 inch	0.6	0	0	tr	22.94
	30 inch	0	0.4	0.4	0.2	38.44

Notes:
tr = trace amount. 0.05 was the value used when this was the volume listed.

TABLE C.4
Mean Concentration of Zinc (mg/L) Measured in Leachate Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Irrigation Treatment		
Date	**EA**	**RW**	**LF**
April 9, 2002	0.12 a	0.02 a	001 a
April 30, 2002	0.01 c	0.03 a	0.02 b
May 16, 2002	0.02 b	0.04 a	0.03 ab
June 25, 2002	0.11	0.13	0.12
July 8, 2002	0.01 a	0.01 a	0.01 a
July 23, 2002	-	0.13	0.17
August 22, 2002	-	0.01	-
September 11, 2002	0.03 a	0.01 a	0.02 a
September 24, 2002	-	-	0.01
October 11, 2002	0.01 a	0.01 a	0.01 a
October 30, 2002	0.01 a	0.01 a	0.01 a
November 7, 2002	-	0.02	-
December 12, 2002	0.01 b	0.02 a	0.01 ab
January 28, 2003	-	-	-
February 27, 2003	0.02 a	0.01 a	0.01 a
March 25, 2003	0.010 b	0.010 b	0.013 a
April 22, 2003	-	-	-
May 20,2003	-	0.02	0.03
June 9, 2003	0.01 a	0.01 a	0.01 a
June 17, 2003	0.01 a	0.01 a	0.01 a
July 9, 2003	-	0.01	0.02
July 22, 2003	0.01 a	0.01 a	0.01 a
August 19, 2003	-	0.01	0.01
September 16, 2003	0.01 a	0.01 a	0.01 a
September 23, 2003	0.01 a	0.01 a	0.01 a
October 21, 2003	3.13	-	-
November 18, 2003	0.01	0.02	0.03
December 22, 2003	0.01	-	0.03
January 20, 2004	0.01	0.02	0.02
February 17, 2004	0.010	0.025	0.028

Note: Means in a given row followed by the same letter do not differ significantly at p = 0.05. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.5
Mean Concentration of Zinc (mg/L) Measured in Leachate Samples Collected by Grass
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Turfgrass	
Date	**Bermudagrass**	**Zoysiagrass**
April 9, 2002	0.01	0.02
April 30, 2002	0.02 a	0.02 a
May 16, 2002	0.03	0.03
June 25, 2002	0.10 a	0.15 a
July 8, 2002	0.01 a	0.01 a
July 23, 2002	0.14	0.15
August 22, 2002	0.01	-
September 11, 2002	0.03 a	0.01 b
September 24, 2002	0.01	-
October 11, 2002	0.01 a	0.01 a
October 30, 2002	0.01 a	0.01 a
November 7, 2002	0.02	-
December 12, 2002	0.01 a	0.01 a
January 28, 2003	-	-
February 27, 2003	0.011 b	0.014 a
March 25, 2003	0.01	0.01
April 22, 2003	-	-
May 20, 2003	0.02	0.02
June 9, 2003	0.013 a	0.010 b
June 17, 2003	0.01 a	0.01 a
July 9, 2003	0.13	0.02
July 22, 2003	0.01 a	0.01 a
August 19, 2003	0.01	0.01
September 16, 2003	0.01 a	0.01 a
September 23, 2003	0.01	0.01
October 21, 2003	2.53	3.54
November 18, 2003	0.02	0.02
December 22, 2003	0.02	0.02
January 20, 2004	0.02	0.02
February 17, 2004	0.03	0.02

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.6
Mean Concentration of Zinc (mg/L) Measured in Leachate Samples Collected by Depth
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Date	6" Depth	18" Depth	30" Depth
April 9, 2002	0.01	0.01	0.02
April 30, 2002	0.02 a	0.02 a	0.02 a
May 16, 2002	0.03 a	0.03 a	0.03 a
June 25, 2002	0.11 a	0.15 a	0.10 a
July 8, 2002	0.01 a	0.01 a	0.01 a
July 23, 2002	0.15	-	0.14
August 22, 2002	0.01	-	-
September 11, 2002	0.03 a	0.03 a	0.02 a
September 24, 2002	-	-	0.01
October 11, 2002	0.01 b	0.01 b	0.02 a
October 30, 2002	0.01 a	0.01 a	0.01 a
November 7, 2002	0.02	-	0.01
December 12, 2002	0.02 a	0.01 a	0.01 a
January 28, 2003	-	-	-
February 27, 2003	0.02 a	0.01 a	0.01 a
March 25, 2003	0.01	0.01	0.01
April 22, 2003	-	-	-
May 20, 2003	0.02	0.01	0.02
June 9, 2003	0.01 a	0.01 a	0.01 a
June 17, 2003	0.01 a	0.01 a	0.01 a
July 9, 2003	0.01	0.02	0.02
July 22, 2003	0.01 a	0.01 a	0.01 a
August 19, 2003	0.01	-	0.01
September 16, 2003	0.013 a	0.010 a	0.010 a
September 23, 2003	0.01 a	0.01 a	0.01 a
October 21, 2003	2.85	2.45	3.96
November 18, 2003	0.02	0.03	0.02
December 22, 2003	0.02	0.02	0.02
January 20, 2004	0.01	0.03	0.02
February 17, 2004	0.01 a	0.02 a	0.02 a

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.7
Mean Concentration of Nitrate (mg/L) Measured in Leachate Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Irrigation Treatment		
Date	**EA**	**RW**	**LF**
April 9, 2002	-	-	-
April 30, 2002	-	-	-
May 16, 2002	-	-	-
June 25, 2002	-	-	-
July 8, 2002	-	-	-
July 23, 2002	-	-	-
August 22, 2002	7.0	32.7	20.0
September 11, 2002	0.22	2.21	1.06
September 24, 2002	0.87	4.27	1.64
October 11, 2002	0.31 a	1.63 a	0.98 a
November 7, 2002	1.58 a	3.88 a	2.47 a
December 12, 2002	0.56 b	1.58 a	1.82 a
December 19, 2002	0.10	1.30	1.47
January 28, 2003	0.17 a	3.21 a	2.16 a
February 27, 2003	0.35 b	5.07 a	1.93 b
March 25, 2003	0.68 a	3.22 a	0.33 a
April 22, 2003	0.63 a	8.26 a	6.12 a
May 20, 2003	-	8.03	4.78
June 9, 2003	0.42 a	1.97 a	2.01 a
June 17, 2003	0.20 a	1.08 a	0.89 a
July 9, 2003	0.60 a	1.03 a	4.30 a
July 22, 2003	0.65 a	1.29 a	1.15 a
August 19, 2003	2.04 a	2.65 a	2.23 a
September 16, 2003	1.74 a	2.15 a	2.42 a
September 23, 2003	1.29 b	2.08 ab	2.55 a
October 21, 2003	3.04 a	3.79 a	2.99 a
November 18, 2003	2.44 a	14.39 a	7.93 a
December 22, 2003	3.38 c	24.80 a	15.07 b
January 20, 2004	6.94 b	19.28 a	9.74 ab
February 17, 2004	5.14 b	20.7 a	14.8 ab

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.8
Mean Concentration of Nitrate (mg/L) Measured in Leachate Samples Collected by Grass
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Turfgrass	
Date	**Bermudagrass**	**Zoysiagrass**
April 9, 2002	-	-
April 30, 2002	-	-
May 16, 2002	-	-
June 25, 2002	-	-
July 8, 2002	-	-
July 23, 2002	-	-
August 22, 2002	25.13	6.23
September 11, 2002	1.32 a	0.53 a
September 24, 2002	2.28	1.13
October 11, 2002	1.58 a	0.50 b
November 7, 2002	4.11	1.78
December 12, 2002	1.18 a	1.52 a
December 19, 2002	0.79	1.41
January 28, 2003	1.47 a	2.08 a
February 27, 2003	2.61 a	2.40 a
March 25, 2003	1.01 a	1.73 a
April 22, 2003	3.16 a	8.64 a
May 20, 2003	6.23	8.56
June 9, 2003	0.79 a	2.08 a
June 17, 2003	0.25 a	1.16 a
July 9, 2003	1.94 a	3.69 a
July 22, 2003	0.70 b	1.34 a
August 19, 2003	2.56 a	1.72 a
September 16, 2003	2.61 a	1.56 b
September 23, 2003	2.62 a	1.27 b
October 21, 2003	5.20 a	0.86 b
November 18, 2003	10.35 a	5.85 a
December 22, 2003	17.8	6.5
January 20, 2004	14.1 a	9.6 a
February 17, 2004	19.3 a	8.3 b

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.9
Mean Concentration of Nitrate (mg/L) Measured in Leachate Samples Collected by Depth
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Date	6” Depth	18” Depth	30” Depth
April 9, 2002	-	-	-
April 30, 2002	-	-	-
May 16, 2002	-	-	-
June 25, 2002	-	-	-
July 8, 2002	-	-	-
July 23, 2002	-	-	-
August 22, 2002	10.51	26.28	36.76
September 11, 2002	0.76 a	1.19 a	1.00 a
September 24, 2002	2.65	0.89	2.02
October 11, 2002	2.18 a	0.49 a	1.02 a
November 7, 2002	2.45	1.74	4.10
December 12, 2002	1.05 a	1.03 a	1.99 a
December 19, 2002	0.28	1.34	1.44
January 28, 2003	1.58	2.98	-
February 27, 2003	2.82 a	2.14 a	2.58 a
March 25, 2003	1.95 a	1.17 b	0.92 b
April 22, 2003	7.61 a	2.54 a	5.70 a
May 20, 2003	9.57	4.99	7.13
June 9, 2003	1.66 a	1.17 a	1.47 a
June 17, 2003	0.75 a	0.46 a	1.00 a
July 9, 2003	0.81 a	3.99 a	5.49 a
July 22, 2003	0.58 a	1.05 a	1.41 a
August 19, 2003	1.39 a	2.70 a	2.93 a
September 16, 2003	1.90 a	1.90 a	2.50 a
September 23, 2003	1.45 b	1.73 ab	2.78 a
October 21, 2003	3.45	2.10	3.09
November 18, 2003	6.29 a	14.54 a	8.86 a
December 22, 2003	7.81	15.91	15.31
January 20, 2004	16.17 a	4.86 b	8.44 ab
February 17, 2004	13.5 a	13.6 a	13.8 a

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.10
Mean Number of Fecal Coliform (col/100 ml) Measured in Leachate Samples by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Irrigation Treatment		
Date	**EA**	**RW**	**LF**
April 9, 2002	71.3 a	2359.3 a	75.3 a
April 30, 2002	141.3 a	267.9 a	265.0 a
May 16, 2002	234.7 a	220.0 a	180.6 a
June 25, 2002	36.9 a	147.5 a	519 a
July 8, 2002	351.2 a	152.8 a	246.1 a
July 23, 2002	35.7 a	30.7 a	38.8 a
August 22, 2002	200.0 a	374.0 a	245.0 a
September 11, 2002	97.3 a	67.3 a	56.5 a
September 24, 2002	72.5 a	61.8 a	43.3 a
October 11, 2002	93.3 a	80.5 a	151.9 a
October 30, 2002	62.4 a	35.0 a	41.2 a
November 7, 2002	37.1 a	47.5 a	90.6 a
December 12, 2002	112.5 a	36.1 a	30.0 a
December 19, 2002	20.0 b	53.3 a	22.5 b
January 28, 2003	14.3 a	20.0 a	12.0 a
February 27, 2003	47.1 a	33.3 a	35.6 a
March 25, 2003	26.2 a	28.6 a	77.5 a
April 22, 2003	128.9 a	20.0 b	22.2 b
May 20, 2003	20.0	46.7	20.0
June 9, 2003	34.1 a	60.0 b	1138.3 a
June 17, 2003	56.9 a	64.6 a	48.6 a
July 9, 2003	52.0 a	46.7 a	125.5 a
July 22, 2003	107.7 a	230.7 a	96.9 a
August 19, 2003	33.3 a	20.0 a	20.0 a
September 16, 2003	74.1 a	166.7 a	533.3 a
September 23, 2003	65.3 a	56.7 a	76.9 a
October 21, 2003	50.0 a	73.3 a	60.0 a
November 18, 2003	260.0 a	2556.0 a	753.3 a
December 22, 2003	15.7 a	18.0 a	13.3 a
January 20, 2004	27.3 a	14.3 a	22.5 a
February 17, 2004	16.7 a	11.1 a	80.0 a

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.11
Mean Number of Fecal Coliform (col/100 ml) Measured in Leachate Samples Collected by Grass
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Turfgrass	
Date	**Bermudagrass**	**Zoysiagrass**
April 9, 2002	94.3 a	1442.6 a
April 30, 2002	241.7 a	205.2 a
May 16, 2002	325.7 a	100.5 a
June 25, 2002	295.0 a	135.8 b
July 8, 2002	376.5 a	124.4 a
July 23, 2002	46.2 a	25.2 a
August 22, 2002	327.1	90.0
September 11, 2002	46.5 a	98.3 a
September 24, 2002	61.3 a	63.3 a
October 11, 2002	102.2 a	87.1 a
October 30, 2002	52.3 a	40.0 a
November 7, 2002	87.4 a	33.8 a
December 12, 2002	85.3 a	29.6 a
December 19, 2002	36.7	22.2
January 28, 2003	20.0 a	10.0 b
February 27, 2003	43.1 a	34.1 a
March 25, 2003	32.3 a	59.1 a
April 22, 2003	20.0 b	103.3 a
May 20, 2003	73.3	20.0
June 9, 2003	578.2 a	112.4 b
June 17, 2003	62.4 a	52.2 a
July 9, 2003	88.0 a	86.7 a
July 22, 2003	194.0 a	106.7 a
August 19, 2003	26.7 a	20.0 b
September 16, 2003	397.7 a	125.8 a
September 23, 2003	57.7 a	47.7 a
October 21, 2003	73.3 a	40.0 a
November 18, 2003	1342.0 a	826.7 a
December 22, 2003	16.6	14.4
January 20, 2004	25.4 a	19.2 b
February 17, 2004	15.71 b	60.7 a

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.12
Mean Number of Fecal Coliform (col/100 ml) Measured in Leachate Samples Collected by Depth
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Date	6” Depth	18” Depth	30” Depth
April 9, 2002	92.9a	183.1 a	2210.0 a
April 30, 2002	280.6 a	242.1 a	148.7 a
May 16, 2002	372.9 a	80.7a	180.0 a
June 25, 2002	175.8 a	42.0 a	452.1 a
July 8, 2002	178.9 a	458.3 a	98.8 a
July 23, 2002	36.5 a	36.7 a	32.7 a
August 22, 2002	258.0 a	250.0 a	300.0 a
September 11, 2002	66.4 a	101.8 a	48.1 a
September 24, 2002	77.1 a	74.0 a	44.2 a
October 11, 2002	112.3 a	97.5 a	68.0 a
October 30, 2002	52.5 a	57.1 a	30.0 a
November 7, 2002	36.0 a	75.6 a	66.9 a
December 12, 2002	61.1 a	100.6 a	14.7 a
December 19, 2002	45.7 a	22.5 b	23.3 b
January 28, 2003	12.4 a	40.0 a	10.0 a
February 27, 2003	34.4 a	37.8 a	43.5 a
March 25, 2003	70.0 a	36.9 a	27.1 a
April 22, 2003	20.0 b	20.0 b	186.7 a
May 20, 2003	46.7	46.7	20.0
June 9, 2003	464.3 a	126.3 a	504.6 a
June 17, 2003	50.8 a	46.7 a	69.3 a
July 9, 2003	96.4 a	111.4 a	20.0 a
July 22, 2003	86.7 a	97.3 a	258.6 a
August 19, 2003	31.4 a	20.0 b	20.0 b
September 16, 2003	272.5 a	144.7 a	384.7 a
September 23, 2003	54.6 a	36.2 a	60.6 a
October 21, 2003	56.4	73.3	46.7
November 18, 2003	738.0 a	3010.0 a	1065.7 a
December 22, 2003	15.5	16.0	15.0
January 20, 2004	14.6 a	25.0 a	34.3 a
February 17, 2004	10.7 a	135.0 a	20.0 a

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.13
Mean Electrical Conductivity of Leachate Samples (dS/m) Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Irrigation Treatment		
Date	**EA**	**RW**	**LF**
April 9, 2002	0.35	0.41	0.41
April 30, 2002	0.72 a	1.02 a	1.08 a
May 16, 2002	0.69 b	1.17 a	1.20 a
June 25, 2002	0.71	1.12	1.15
July 8, 2002	0.57 a	0.97 a	0.71 a
July 23, 2002	-	0.45	-
August 22, 2002	-	1.33	-
September 11, 2002	0.36 b	0.46 ab	0.51 a
September 24, 2002	-	-	0.45
October 11, 2002	0.29 a	0.33 a	0.29 a
October 30, 2002	0.34 a	0.42 a	0.35 a
November 7, 2002	-	0.59	-
December 12, 2002	0.16 a	0.32 a	0.36 a
January 28, 2003	-	-	-
February 27, 2003	0.35 b	0.63 a	0.47 ab
March 25, 2003	0.33	0.68	0.53
April 22, 2003	-	-	-
May 20, 2003	-	1.22	1.25
June 9, 2003	0.55 a	0.34 a	0.27 a
June 17, 2003	0.20 a	0.36 a	0.54 a
July 9, 2003	-	-	1.06
July 22, 2003	0.25 a	0.31 a	0.28 a
August 19, 2003	-	0.48	0.58
September 16, 2003	0.56 a	0.48 a	0.48 a
September 23, 2003	0.43	0.53	0.55
October 21, 2003	-	-	-
November 18, 2003	-	0.98	0.89
December 22, 2003	0.58	-	1.06
January 20, 2004	0.62	0.57	0.67
February 17, 2004	0.49	0.95	0.87

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.14
Mean Electrical Conductivity (dS/m) Measured in Leachate Samples Collected by Grass
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Turfgrass	
Date	**Bermudagrass**	**Zoysiagrass**
April 9, 2002	0.43	0.36
April 30, 2002	1.02 a	0.94 a
May 16, 2002	1.09	1.12
June 25, 2002	1.08 a	1.16 a
July 8, 2002	0.81 a	0.72 a
July 23, 2002	0.45	-
August 22, 2002	1.33	-
September 11, 2002	0.48 a	0.41 a
September 24, 2002	0.45	-
October 11, 2002	0.33 a	0.27 a
October 30, 2002	0.40 a	0.36 a
November 7, 2002	0.59	-
December 12, 2002	0.33	0.26
January 28, 2003	-	-
February 27, 2003	0.52 a	0.45 a
March 25, 2003	0.56	0.50
April 22, 2003	-	-
May 20, 2003	1.23	1.22
June 9, 2003	0.44 a	0.45 a
June 17, 2003	0.43	0.44
July 9, 2003	1.05	1.07
July 22, 2003	0.31	0.23
August 19, 2003	0.67	0.19
September 16, 2003	0.21 a	0.46 a
September 23, 2003	0.53	0.42
October 21, 2003	-	-
November 18, 2003	0.89	0.98
December 22, 2003	1.03	0.78
January 20, 2004	0.57	0.656
February 17, 2004	0.95	0.64

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.15
Mean Electrical Conductivity (dS/m) Measured in Leachate Samples Collected by Depth
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Date	6” Depth	18” Depth	30” Depth
April 9, 2002	0.58	293.6	392.4
April 30, 2002	0.99 a	991.3 a	964.4 a
May 16, 2002	0.98 a	1093.3 a	1187.9 a
June 25, 2002	0.94 b	1135.0 a	1180.3 a
July 8, 2002	0.85 a	562.2 a	841.5 a
July 23, 2002	0.42	-	486.9
August 22, 2002	1.33	-	-
September 11, 2002	0.49 a	415.8 a	434.4 a
September 24, 2002	-	-	448.8
October 11, 2002	0.39 a	244.9 a	308.6 a
October 30, 2002	0.41 a	336.3 a	392.6 a
November 7, 2002	0.60	-	573.0
December 12, 2002	0.40 a	188.8 a	369.0 a
January 28, 2003	-	-	-
February 27, 2003	0.66 a	408.4 b	455.0 ab
March 25, 2003	0.61	427.3	645.8
April 22, 2003	-	-	-
May 20, 2003	1.26	1308.0	1143.5
June 9, 2003	0.58 a	400.8 a	403.4 a
June 17, 2003	0.68 a	233.1 b	432.5 ab
July 9, 2003	1.08	1062.5	1052.5
July 22, 2003	0.45 a	214.3 a	342.0 a
August 19, 2003	0.81	-	465.4
September 16, 2003	0.61 a	347.7 a	479.1 a
September 23, 2003	0.58 a	489.4 a	438.0 a
October 21, 2003	-	-	-
November 18, 2003	1.067	0.99	0.68
December 22, 2003	0.79	0.92	0.82
January 20, 2004	0.62	0.55	0.66
February 17, 2004	0.48 a	0.82 a	0.82 a

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.16
Mean pH of Leachate Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Irrigation Treatment		
Date	**EA**	**RW**	**LF**
April 9, 2002	7.49	7.36	7.35
April 30, 2002	7.88 a	7.51 b	7.73 ab
May 16, 2002	7.48 a	7.40 a	7.50 a
June 25, 2002	8.20	7.95	8.07
July 8, 2002	7.72 a	7.29 b	7.48 ab
July 23, 2002	-	7.61	-
August 22, 2002	-	7.74	-
September 11, 2002	7.43 a	7.46 a	7.44 a
September 24, 2002	-	-	6.97
October 11, 2002	6.79 a	6.61 a	6.79 a
October 30, 2002	6.82 a	6.95 a	6.74 a
November 7, 2002	-	7.16	-
December 12, 2002	6.53 a	6.98 a	7.05 a
January 28, 2003	-	-	-
February 27, 2003	7.02 b	7.25 a	7.11 ab
March 25, 2003	6.67	7.07	7.11
April 22, 2003	-	-	-
May 20, 2003	-	7.54	7.30
June 9, 2003	7.43 a	6.89 a	6.60 a
June 17, 2003	6.80 a	6.90 a	6.95 a
July 9, 2003	-	-	7.38
July 22, 2003	6.65 a	6.72 a	6.46 a
August 19, 2003	-	7.19	7.15
September 16, 2003	6.93 a	6.75 a	6.67 a
September 23, 2003	7.18	7.12	7.03
October 21, 2003	-	-	-
November 18, 2003	-	7.04	7.16
December 22, 2003	7.18	-	7.11
January 20, 2004	6.77	6.69	6.99
February 17, 2004	7.62	7.59	7.37

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.17
Mean pH Measured in Leachate Samples Collected by Grass
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Turfgrass	
Date	**Bermudagrass**	**Zoysiagrass**
April 9, 2002	7.37	7.43
April 30, 2002	7.60 a	7.77 a
May 16, 2002	7.46	7.44
June 25, 2002	7.93 a	8.04 a
July 8, 2002	7.47 a	7.48 b
July 23, 2002	7.61	-
August 22, 2002	7.74	-
September 11, 2002	7.40 a	7.48 a
September 24, 2002	6.97	-
October 11, 2002	6.69 a	6.75 a
October 30, 2002	6.79 a	6.89 a
November 7, 2002	7.16	-
December 12, 2002	6.98	6.82
January 28, 2003	-	-
February 27, 2003	7.10 a	7.16 a
March 25, 2003	7.02	6.86
April 22, 2003	-	-
May 20, 2003	7.45	7.51
June 9, 2003	7.11 a	7.15 a
June 17, 2003	6.95	6.88
July 9, 2003	7.49	7.31
July 22, 2003	6.62	6.52
August 19, 2003	7.33	6.65
September 16, 2003	6.83 a	6.50 a
September 23, 2003	7.27	6.78
October 21, 2003	-	-
November 18, 2003	7.16	7.04
December 22, 2003	7.25	7.10
January 20, 2004	6.69	6.91
February 17, 2004	7.59	7.52

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.18
Mean pH Measured in Leachate Samples Collected by Depth
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Date	6" Depth	18" Depth	30" Depth
April 9, 2002	7.44	7.38	7.40
April 30, 2002	7.71 a	7.71 a	7.66 a
May 16, 2002	7.44 b	7.37 c	7.52 a
June 25, 2002	8.09 a	8.14 a	7.72 a
July 8, 2002	7.64 a	7.51 ab	7.32 b
July 23, 2002	7.53	-	7.69
August 22, 2002	7.74	-	-
September 11, 2002	7.54 a	7.35 a	7.43 a
September 24, 2002	-	-	6.97
October 11, 2002	6.83 a	6.69 a	6.92 a
October 30, 2002	6.95 a	6.76 a	6.86 a
November 7, 2002	7.46	-	6.86
December 12, 2002	7.23 a	6.66 a	7.05 a
January 28, 2003	-	-	-
February 27, 2003	7.34 a	7.03 b	7.09 ab
March 25, 2003	6.98	6.84	7.12
April 22, 2003	-	-	-
May 20, 2003	7.75	7.16	7.40
June 9, 2003	7.33 a	7.08 a	7.05 a
June 17, 2003	7.22 a	6.70 a	6.88 a
July 9, 2003	7.27	7.46	7.36
July 22, 2003	7.20 a	6.42 a	6.67 a
August 19, 2003	7.33	-	7.10
September 16, 2003	6.93 a	6.42 a	6.73 a
September 23, 2003	7.25 a	6.95 a	7.14 a
October 21, 2003	-	-	-
November 18, 2003	7.04	7.20	6.95
December 22, 2003	7.34	7.08	7.03
January 20, 2004	6.77	6.58	6.96
February 17, 2004	7.69 a	7.57 a	7.50 a

Note: Means in a given row followed by the same letter do not differ significantly at p = 0.05. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.19
Mean Concentration of Potassium (mg/L) Measured in Leachate Samples Collected by Grass
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Turfgrass	
Date	**Bermudagrass**	**Zoysiagrass**
April 9, 2002	5.79	10.76
April 30, 2002	9.75 a	9.73 a
May 16, 2002	12.94	14.85
June 25, 2002	13.9 a	13.7 a
July 8, 2002	8.39 a	10.22 a
July 23, 2002	8.91	12.50
August 22, 2002	21.8	-
September 11, 2002	7.82 a	9.93 a
September 24, 2002	8.86	-
October 11, 2002	7.29 a	8.16 a
October 30, 2002	7.35 a	8.17 a
November 7, 2002	12.25	-
December 12, 2002	6.23	6.03
January 28, 2003	-	-
February 27, 2003	7.50 a	7.53 a
March 25, 2003	7.30	8.27
April 22, 2003	-	-
May 20, 2003	13.95	12.55
June 9, 2003	8.12 a	6.83 a
June 17, 2003	5.63	5.85
July 9, 2003	10.91	12.80
July 22, 2003	5.24 a	4.93 a
August 19, 2003	5.97	10.66
September 16, 2003	6.81 a	6.67 a
September 23, 2003	7.42	8.61
October 21, 2003	6.71	12.80
November 18, 2003	13.26	15.78
December 22, 2003	18.3	17.6
January 20, 2004	9.59	14.3
February 17, 2004	13.7	14.8

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.20
Mean Concentration of Potassium (mg/L) Measured in Leachate Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Irrigation Treatment		
Date	**EA**	**RW**	**LF**
April 9, 2002	8.19 a	9.16 a	7.15 a
April 30, 2002	6.39 b	14.31 a	8.90 b
May 16, 2002	7.88 b	17.73 a	13.62 ab
June 25, 2002	3.00	14.37	14.70
July 8, 2002	8.57 a	9.91 a	8.98 a
July 23, 2002	-	10.6	7.6
August 22, 2002	-	21.80	-
September 11, 2002	7.22 a	10.29 a	9.00 a
September 24, 2002	-	-	8.86
October 11, 2002	8.28 a	8.44 a	6.55 a
October 30, 2002	6.72 a	9.11 a	7.20 a
November 7, 2002	-	12.25	-
December 12, 2002	4.25 a	6.68 a	7.08 a
January 28, 2003	-	-	-
February 27, 2003	5.57 b	9.50 a	7.48 ab
March 25, 2003	5.33 a	10.13 a	6.05 a
April 22, 2003	-	-	-
May 20, 2003	-	13.76	10.50
June 9, 2003	8.40 a	6.03 a	8.69 a
June 17, 2003	5.42 a	4.98 a	6.60 a
July 9, 2003	-	12.79	5.30
July 22, 2003	5.65 a	5.00 a	4.88 a
August 19, 2003	-	3.91	8.83
September 16, 2003	8.70 a	6.09 a	6.38 a
September 23, 2003	8.09 a	7.44 a	8.13 a
October 21, 2003	10.4	-	-
November 18, 2003	13.2	15.9	14.0
December 22, 2003	15.2	-	19.8
January 20, 2004	17.3	9.6	12.8
February 17, 2004	14.3	13.7	15.6

Note: Means in a given row followed by the same letter do not differ significantly at p = 0.05. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.21
Mean Concentration of Potassium (mg/L) Measured in Leachate Samples Collected by Depth
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Date	6” Depth	18” Depth	30” Depth
April 9, 2002	5.6	8.1	9.6
April 30, 2002	10.2 a	8.9 a	10.3 a
May 16, 2002	14.0 a	15.2 a	12.8 a
June 25, 2002	11.5 c	15.4 a	13.3 b
July 8, 2002	9.24 a	10.0 a	8.67 a
July 23, 2002	8.99	-	10.1
August 22, 2002	21.8	-	-
September 11, 2002	10.0 a	8.7 a	7.9 a
September 24, 2002	-	-	8.86
October 11, 2002	7.89 a	7.77 a	7.54 a
October 30, 2002	7.84 a	7.80 a	7.76 a
November 7, 2002	11.4	-	13.1
December 12, 2002	7.57 a	5.71 a	5.85 a
January 28, 2003	-	-	-
February 27, 2003	8.92 a	7.28 ab	6.59 b
March 25, 2003	8.93	7.28	7.53
April 22, 2003	-	-	-
May 20, 2003	17.40	11.00	9.88
June 9, 2003	10.81 a	7.02 b	4.50 c
June 17, 2003	8.81 a	4.12 b	4.84 b
July 9, 2003	12.83	9.52	12.25
July 22, 2003	5.68 a	4.67 a	5.30 a
August 19, 2003	13.95	-	3.78
September 16, 2003	8.68 a	5.66 a	6.09 a
September 23, 2003	10.3 a	6.7 a	6.0 a
October 21, 2003	15.30	10.38	7.88
November 18, 2003	15.65	19.20	11.61
December 22, 2003	15.5	19.3	17.9
January 20, 2004	17.3	10.6	11.1
February 17, 2004	14.6 a	14.6 a	14.0 a

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.22
Mean Concentration of Ammonia Nitrogen (mg/L) Measured in Leachate Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Irrigation Treatment		
Date	**EA**	**RW**	**LF**
April 9, 2002	0.14 a	0.24 a	0.20 a
April 30, 2002	0.10 a	0.12 a	0.12 a
May 16, 2002	0.22 a	0.13 a	0.16 a
June 25, 2002	0.21 a	0.19 a	0.20 a
July 8, 2002	0.12 a	0.11 a	0.13 a
July 23, 2002	0.09 b	0.15 a	0.10 b
August 22,2002	-	0.10	0.12
September 11, 2002	0.10 a	0.14 a	0.20 a
September 24, 2002	0.10	0.12	0.10
October 11, 2002	0.10 a	0.10 a	0.10 a
October 30, 2002	0.13 a	0.10 a	0.10 a
November 7, 2002	0.10 a	0.18 a	0.12 a
December 12, 2002	0.10 a	0.13 a	0.10 a
January 28, 2003	0.10 a	0.10 a	0.10 a
February 27, 2003	0.10 a	0.10 a	0.14 a
March 25, 2003	0.13 a	0.10 a	0.10 a
April 22, 2003	0.10	0.10	0.10
May 20, 2003	-	0.15	0.10
June 9, 2003	0.10 a	0.17 a	0.17 a
June 17, 2003	0.11 a	0.17 a	0.12 a
July 9, 2003	0.10 a	0.10 a	0.11 a
July 22, 2003	0.11 a	0.10 a	0.10 a
August 19, 2003	0.10	0.11	0.10
September 16, 2003	0.10 a	0.12 a	0.15 a
September 23, 2003	0.10 a	0.12 a	0.10 a
October 21, 2003	0.10	0.10	0.10
November 18, 2003	0.10 a	0.14 a	0.10 a
December 22, 2003	0.10	0.10	0.10
January 20, 2004	0.10 a	0.17 a	0.13 a
February 17, 2004	0.1 a	0.1 a	0.1 a

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.23
Mean Concentration of Ammonia Nitrogen (mg/L) Measured in Leachate Samples Collected by Grass
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Turfgrass	
Date	**Bermudagrass**	**Zoysiagrass**
April 9, 2002	0.22 a	0.16 a
April 30, 2002	0.11 a	0.11 a
May 16, 2002	0.20 a	0.12 a
June 25, 2002	0.18 a	0.21 a
July 8, 2002	0.13 a	0.11 a
July 23, 2002	0.10	0.15
August 22, 2002	0.12	0.10
September 11, 2002	0.16 a	0.13 a
September 24, 2002	0.11	0.10
October 11, 2002	0.10 a	0.10 a
October 30, 2002	0.12 a	0.10 a
November 7, 2002	0.15 a	0.10 b
December 12, 2002	0.10 a	0.12 a
January 28, 2003	0.10	0.10
February 27, 2003	0.13 a	0.10 b
March 25, 2003	0.11 a	0.10 b
April 22, 2003	0.10	0.10
May 20, 2003	0.24	0.10
June 9, 2003	0.16 a	0.12 b
June 17, 2003	0.15 a	0.11 b
July 9, 2003	0.11	0.10
July 22, 2003	0.10 a	0.10 a
August 19, 2003	0.10	0.10
September 16, 2003	0.14 a	0.10 a
September 23, 2003	0.10 b	0.11 a
October 21, 2003	0.10	0.10
November 18, 2003	0.12 a	0.10 a
December 22, 2003	0.10	0.10
January 20, 2004	0.14 a	0.12 a
February 17, 2004	0.1 a	0.1 a

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.24
Mean Concentration of Ammonia Nitrogen (mg/L) Measured in Leachate Samples Collected by Depth
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Date	6" Depth	18" Depth	30" Depth
April 9, 2002	0.21 a	0.17 a	0.17 a
April 30, 2002	0.13 a	0.10 a	0.10 a
May 16, 2002	0.14 a	0.19 a	0.18 a
June 25, 2002	0.26 a	0.15 b	0.18 b
July 8, 2002	0.12 a	0.13 a	0.11 a
July 23, 2002	0.10 a	0.10 a	0.14 a
August 22, 2002	0.12	0.10	-
September 11, 2002	0.14 a	0.13 a	0.16 a
September 24, 2002	0.12	0.10	0.10
October 11, 2002	0.10 a	0.10 a	0.10 a
October 30, 2002	0.10 a	0.10 a	0.13 a
November 7, 2002	0.10 a	0.19a	0.11 a
December 12, 2002	0.12 a	0.10 a	0.10 a
January 28, 2003	0.10	-	-
February 27, 2003	0.10 a	0.14 a	0.10 a
March 25, 2003	0.10 b	0.11 a	0.11 a
April 22, 2003	0.10	0.10	0.10
May 20, 2003	0.24	0.10	0.10
June 9, 2003	0.12 a	0.16 a	0.13 a
June 17, 2003	0.10 a	0.15 a	0.14 a
July 9, 2003	0.12	0.10	0.10
July 22, 2003	0.10 a	0.11 a	0.10 a
August 19, 2003	0.10	-	0.10
September 16, 2003	0.10 a	0.13 a	0.15 a
September 23, 2003	0.11 a	0.10 a	0.11 a
October 21, 2003	0.10	0.10	0.10
November 18, 2003	0.11 a	0.13 a	0.10 a
December 22, 2003	0.10	0.10	0.10
January 20, 2004	0.13 a	0.17 a	0.13 a
February 17, 2004	0.1 a	0.1 a	0.1 a

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.25
Mean Concentration of Nitrite (mg/L) Measured in Leachate Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Irrigation Treatment		
Date	**EA**	**RW**	**LF**
April 9, 2002	-	-	-
April 30, 2002	-	-	-
May 16, 2002	-	-	-
June 25, 2002	-	-	-
July 8, 2002	-	-	-
July 23, 2002	-	-	-
August 22, 2002	0.01	0.01	0.01
September 11, 2002	0.01	0.02	0.02
September 24, 2002	0.01	0.01	0.03
October 11, 2002	0.01 a	0.01 a	0.01 a
November 7, 2002	0.01 a	0.01 a	0.01 a
December 12, 2002	0.01 a	0.01 a	0.02 a
December 19, 2002	0.01	0.02	0.01
January 28, 2003	0.33 a	0.71 a	0.56 a
February 27, 2003	0.10 a	0.10 a	0.10 a
March 25, 2003	0.06 a	0.05 a	0.04 a
April 22, 2003	0.01 a	0.01 a	0.01 a
May 20, 2003	-	0.01	0.01
June 9, 2003	0.02 a	0.03 a	0.01 a
June 17, 2003	0.01 a	0.01 a	0.02 a
July 9, 2003	0.03	0.02	0.01
July 22, 2003	0.01 a	0.01 a	0.01 a
August 19, 2003	0.01 a	0.01 a	0.01 a
September 16, 2003	0.02 a	0.01 a	0.03 a
September 23, 2003	0.01 a	0.01 a	0.01 a
October 21, 2003	0.01 a	0.01 a	0.01 a
November 18, 2003	0.01 a	0.01 a	0.01 a
December 22, 2003	0.01 a	0.01 a	0.01 a
January 20, 2004	0.01 a	0.01 a	0.01 a
February 17, 2004	0.01 a	0.01 a	0.01 a

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.26
Mean Concentration of Nitrite (mg/L) Measured in Leachate Samples Collected by Grass
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Turfgrass	
Date	**Bermudagrass**	**Zoysiagrass**
April 9, 2002	-	-
April 30, 2002	-	-
May 16, 2002	-	-
June 25, 2002	-	-
July 8, 2002	-	-
July 23, 2002	-	-
August 22, 2002	0.01	0.01
September 11, 2002	0.02 a	0.02 a
September 24, 2002	0.02	0.02
October 11, 2002	0.01 a	0.01 a
November 7, 2002	0.01	0.01
December 12, 2002	0.01 a	0.01 a
December 19, 2002	0.02	0.01
January 28, 2003	0.45 a	0.62 a
February 27, 2003	0.10 a	0.10 a
March 25, 2003	0.04 a	0.06 a
April 22, 2003	0.01 a	0.01 a
May 20, 2003	0.02	0.01
June 9, 2003	0.02 a	0.02 a
June 17, 2003	0.02 a	0.01 a
July 9, 2003	0.013 b	0.016 a
July 22, 2003	0.01 a	0.01 a
August 19, 2003	0.01 a	0.01 a
September 16, 2003	0.02 a	0.02 a
September 23, 2003	0.01 a	0.01 a
October 21, 2003	0.01 a	0.01 a
November 18, 2003	0.01 a	0.01 a
December 22, 2003	0.01	0.01
January 20, 2004	0.01 a	0.01 a
February 17, 2004	0.01 a	0.01 a

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.27
Mean Concentration of Nitrite (mg/L) Measured in Leachate Samples Collected by Depth
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Date	6” Depth	18” Depth	30” Depth
April 9, 2002	-	-	-
April 30, 2002	-	-	-
May 16, 2002	-	-	-
June 25, 2002	-	-	-
July 8, 2002	-	-	-
July 23, 2002	-	-	-
August 22, 2002	0.01	0.01	0.01
September 11, 2002	0.02 a	0.02 a	0.01 a
September 24, 2002	0.03	0.01	0.02
October 11, 2002	0.01 a	0.01 a	0.01 a
November 7, 2002	0.01	0.01	0.01
December 12, 2002	0.01 a	0.01 a	0.01 a
December 19, 2002	0.01	0.01	0.02
January 28, 2003	0.54	0.39	-
February 27, 2003	0.10 a	0.10 a	0.10 a
March 25, 2003	0.07 a	0.04 a	0.03 a
April 22, 2003	0.01 a	0.01 a	0.01 a
May 20, 2003	0.02	0.01	0.01
June 9, 2003	0.02 a	0.01 a	0.02 a
June 17, 2003	0.01 a	0.02 a	0.01 a
July 9, 2003	0.01	0.02	0.02
July 22, 2003	0.01 a	0.01 a	0.01 a
August 19, 2003	0.01 a	0.01 a	0.01 a
September 16, 2003	0.01 a	0.02 a	0.03 a
September 23, 2003	0.01 a	0.01 a	0.01 a
October 21, 2003	0.01	0.01	0.01
November 18, 2003	0.01 a	0.01 a	0.01 a
December 22, 2003	0.01	0.01	0.01
January 20, 2004	0.01 a	0.01 a	0.01 a
February 17, 2004	0.01 a	0.01 a	0.01 a

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.28
Mean Concentration of Iron (mg/L) Measured in Leachate Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Irrigation Treatment		
Date	**EA**	**RW**	**LF**
April 9, 2002	2.03 a	2.85 a	1.09 a
April 30, 2002	0.23 a	0.22 a	0.13 a
May 16, 2002	1.76 a	0.15 b	0.11 b
June 25, 2002	0.03	0.07	0.33
July 8, 2002	0.32 a	0.45 a	0.20 a
July 23, 2002	-	0.09	0.10
August 22, 2002	-	0.17	-
September 11, 2002	0.46 a	0.44 a	0.45 a
September 24, 2002	-	-	0.08
October 11, 2002	1.21 a	0.79 a	0.81 a
October 30, 2002	0.48 a	0.74 a	0.65 a
November 7, 2002	-	0.95	-
December 12, 2002	0.48 a	0.97 a	0.56 a
January 28, 2003	-	-	-
February 27, 2003	0.55 a	0.50 a	0.66 a
March 25, 2003	0.22 a	0.16 a	0.14 a
April 22, 2003	-	-	-
May 20, 2003	-	0.03	0.02
June 9, 2003	0.05 a	0.30 a	0.36 a
June 17, 2003	0.27 a	0.99 a	0.50 a
July 9, 2003	-	0.12	0.03
July 22, 2003	0.59 a	0.44 a	0.50 a
August 19, 2003	-	0.02	0.10
September 16, 2003	0.17 a	0.48 a	0.31 a
September 23, 2003	0.22 a	0.56 a	0.62 a
October 21, 2003	0.18	-	-
November 18, 2003	0.02	0.03	0.02
December 22, 2003	0.03	-	0.05
January 20, 2004	0.15	2.06	0.77
February 17, 2004	0.10	0.09	0.22

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.29

Mean Concentration of Iron (mg/L) Measured in Leachate Samples Collected by Grass

Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Turfgrass	
Date	**Bermudagrass**	**Zoysiagrass**
April 9, 2002	0.97	3.03
April 30, 2002	0.16 a	0.21 a
May 16, 2002	0.09	1.00
June 25, 2002	0.07 a	0.18 a
July 8, 2002	0.28 a	0.36 a
July 23, 2002	0.09	0.08
August 22, 2002	0.17	-
September 11, 2002	0.32 b	0.58 a
September 24, 2002	0.08	-
October 11, 2002	0.82 a	1.01 a
October 30, 2002	0.59 a	0.68 a
November 7, 2002	0.95	-
December 12, 2002	0.74	0.62
January 28, 2003	-	-
February 27, 2003	0.63 a	0.53 a
March 25, 2003	0.20	0.14
April 22, 2003	-	-
May 20, 2003	0.04	0.02
June 9, 2003	0.21 a	0.17 b
June 17, 2003	0.47	0.91
July 9, 2003	0.05	0.04
July 22, 2003	0.43 a	0.60 a
August 19, 2003	0.02	0.18
September 16, 2003	0.30 a	0.40 a
September 23, 2003	0.37	0.56
October 21, 2003	0.36	0.06
November 18, 2003	0.03	0.02
December 22, 2003	0.05	0.04
January 20, 2004	2.06	0.56
February 17, 2004	0.22	0.09

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.30
Mean Concentration of Iron (mg/L) Measured in Leachate Samples Collected by Depth
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Date	6” Depth	18” Depth	30” Depth
April 9, 2002	0.75	1.35	3.19
April 30, 2002	0.14 a	0.11 a	0.28 a
May 16, 2002	0.08 a	0.16 a	0.96 a
June 25, 2002	0.14 ab	0.05 b	0.22 a
July 8, 2002	0.18 a	0.42 a	0.36 a
July 23, 2002	0.14	-	0.07
August 22, 2002	0.17	-	-
September 11, 2002	0.42 a	0.54 a	0.41 a
September 24, 2002	-	-	0.08
October 11, 2002	0.94 a	0.70 a	1.14 a
October 30, 2002	0.60 a	0.73 a	0.58 a
November 7, 2002	1.00	-	0.90
December 12, 2002	0.80 a	0.87 a	0.48 a
January 28, 2003	-	-	-
February 27, 2003	0.15 b	0.83 a	0.70 ab
March 25, 2003	0.12	0.27	0.09
April 22, 2003	-	-	-
May 20, 2003	0.04	0.02	0.03
June 9, 2003	0.18 a	0.22 a	0.17 a
June 17, 2003	0.35 c	0.96 a	0.67 b
July 9, 2003	0.06	0.03	0.05
July 22, 2003	0.41 a	0.51 a	0.55 a
August 19, 2003	0.02	-	0.13
September 16, 2003	0.14 b	0.52 a	0.31 ab
September 23, 2003	0.40 a	0.58 a	0.38 a
October 21, 2003	0.07	0.07	0.36
November 18, 2003	0.02	0.03	0.02
December 22, 2003	0.04	0.05	0.03
January 20, 2004	0.15	1.86	1.33
February 17, 2004	0.10 a	0.25 a	0.06 a

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.31

Mean Concentration of Magnesium (mg/L) Measured in Leachate Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Irrigation Treatment		
Date	**EA**	**RW**	**LF**
April 9, 2002	4.1 a	4.5 a	5.8 a
April 30, 2002	9.8 a	12.9 a	13.5 a
May 16, 2002	12.5 a	15.5 a	16.1 a
June 25, 2002	15.4	13.3	16.5
July 8, 2002	7.74 a	6.62 a	10.31 a
July 23, 2002	-	4.0	10.7
August 22, 2002	-	20.20	-
September 11, 2002	4.81 a	4.44 a	5.02 a
September 24, 2002	-	-	4.81
October 11, 2002	3.60 a	3.59 a	3.25 a
October 30, 2002	3.19 a	4.29 a	4.16 a
November 7, 2002	-	8.58	-
December 12, 2002	2.88 a	3.69 a	5.08 a
January 28, 2003	-	-	-
February 27, 2003	5.64 a	6.73 a	6.37 a
March 25, 2003	5.75 a	8.41 a	8.75 a
April 22, 2003	-	-	-
May 20, 2003	-	13.28	10.80
June 9, 2003	8.91 a	4.31 a	7.05 a
June 17, 2003	6.08 a	3.37 a	6.26 a
July 9, 2004	-	5.24	13.94
July 22, 2003	4.96 a	3.37 a	4.11 a
August 19, 2003	-	3.41	8.95
September 16, 2003	9.21 a	3.49 b	5.21 b
September 23, 2003	8.07 a	5.63 a	7.29 a
October 21, 2003	10.02	-	-
November 18, 2003	13.5	13.4	13.0
December 22, 2003	15.8	-	18.8
January 20, 2004	16.3	7.0	10.2
February 17, 2004	14.5	12.9	15.0

Note: Means in a given row followed by the same letter do not differ significantly at p = 0.05. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.32
Mean Concentration of Magnesium (mg/L) Measured in Leachate Samples Collected by Grass
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Turfgrass	
Date	**Bermudagrass**	**Zoysiagrass**
April 9, 2002	5.34	4.33
April 30, 2002	12.5 a	12.1 a
May 16, 2002	14.5	15.8
June 25, 2002	14.2 a	14.0 a
July 8, 2002	8.83 a	7.58 a
July 23, 2002	6.99	1.81
August 22, 2002	20.2	-
September 11, 2002	5.10 a	4.39 a
September 24, 2002	4.81	-
October 11, 2002	4.39 a	2.50 b
October 30, 2002	4.15 a	3.79 a
November 7, 2002	8.58	-
December 12, 2002	4.16	3.71
January 28, 2003	-	-
February 27, 2003	6.44 a	6.09 a
March 25, 2003	6.91	8.60
April 22, 2003	-	-
May 20, 2003	13.3	12.5
June 9, 2003	7.8 a	5.7 a
June 17, 2003	5.17	4.80
July 9, 2003	11.88	13.80
July 22, 2003	4.05 a	4.13 a
August 19, 2003	5.97	10.65
September 16, 2003	5.75 a	5.06 a
September 23, 2003	6.43	8.00
October 21, 2003	5.51	13.03
November 18, 2003	11.26	15.28
December 22, 2003	18.2	17.2
January 20, 2004	7.00	12.20
February 17, 2004	12.93	14.72

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.33
Mean Concentration of Magnesium (mg/L) Measured in Leachate Samples Collected by Depth
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Date	6” Depth	18” Depth	30” Depth
April 9, 2002	5.88	5.03	4.11
April 30, 2002	13.8 a	11.9 b	11.5 b
May 16, 2002	15.2 a	16.0 a	14.5 a
June 25, 2002	15.1 a	13.8 a	13.8 a
July 8, 2002	10.9 a	6.7 b	7.4 b
July 23, 2002	3.84	-	6.31
August 22, 2002	20.2	-	-
September 11, 2002	6.78 a	3.98 b	3.16 b
September 24, 2002	-	-	4.81
October 11, 2002	6.30 a	2.61 a	2.62 a
October 30, 2002	6.21 a	3.47 b	3.19 b
November 7, 2002	10.2	-	7.0
December 12, 2002	7.29 a	2.22 a	3.88 a
January 28, 2003	-	-	-
February 27, 2003	10.47 a	4.44 b	4.55 b
March 25, 2003	10.01	6.09	8.04
April 22, 2003	-	-	-
May 20, 2003	17.25	10.10	9.66
June 9, 2003	11.13 a	5.67 b	3.68 c
June 17, 2003	9.27 a	2.51 b	3.96 b
July 9, 2003	13.98	10.33	13.15
July 22, 2003	5.97 a	3.16 a	4.05 a
August 19, 2003	15.05	-	3.04
September 16, 2003	8.55 a	3.76 a	4.49 a
September 23, 2003	10.51 a	5.29 a	4.45 a
October 21, 2003	16.10	10.67	6.34
November 18, 2003	15.15	16.85	10.54
December 22, 2003	17.0	17.8	17.6
January 20, 2004	16.3	7.7	8.6
February 17, 2004	14.8 a	14.3 a	13.4 a

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.34
Mean Concentration of Manganese (mg/L) Measured in Leachate Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Irrigation Treatment		
Date	**EA**	**RW**	**LF**
April 9, 2002	0.02 a	0.04 a	0.02 a
April 30, 2002	0.03 a	0.02 b	0.02 b
May 16, 2002	0.04 a	0.02 b	0.02 b
June 25, 2002	0.02	0.02	0.02
July 8, 2002	0.02 a	0.03 a	0.02 a
July 23, 2002	-	0.05	0.02
August 22, 2002	-	0.02	-
September 11, 2002	0.03 a	0.02 a	0.02 a
September 24, 2002	-	-	0.03
October 11, 2002	0.02 a	0.02 a	0.02 a
October 30, 2002	0.02 a	0.02 a	0.02 a
November 7, 2002	-	0.02	-
December 12, 2002	0.02 a	0.02 a	0.02 a
January 28, 2003	-	-	-
February 27, 2003	0.02 a	0.02 a	0.02 a
March 25, 2003	0.02 a	0.02 a	0.02 a
April 22, 2003	-	-	-
May 20, 2003	-	0.02	0.02
June 9, 2003	0.02 a	0.02 a	0.07 a
June 17, 2003	0.02 a	0.03 a	0.04 a
July 9, 2003	-	0.02	0.02
July 22, 2003	0.05 a	0.03 a	0.03 a
August 19, 2003	-	0.02	0.02
September 16, 2003	0.02 a	0.02 a	0.02 a
September 23, 2003	0.031 a	0.020 c	0.022 b
October 21, 2003	0.03	-	-
November 18, 2003	0.02	0.02	0.02
December 22, 2003	0.02	-	0.02
January 20, 2004	0.02	0.02	0.02
February 17, 2004	0.02	0.02	0.02

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.35
Mean Concentration of Manganese (mg/L) Measured in Leachate Samples Collected by Grass
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Turfgrass	
Date	**Bermudagrass**	**Zoysiagrass**
April 9, 2002	0.02	0.03
April 30, 2002	0.020 b	0.023 a
May 16, 2002	0.02	0.03
June 25, 2002	0.02 a	0.02 a
July 8, 2002	0.02 a	0.02 a
July 23, 2002	0.02	0.10
August 22, 2002	0.02	-
September 11, 2002	0.03 a	0.02 a
September 24, 2002	0.03	-
October 11, 2002	0.02 a	0.02 a
October 30, 2002	0.020 b	0.021 a
November 7, 2002	0.02	-
December 12, 2002	0.02 a	0.02 a
January 28, 2003	-	-
February 27, 2003	0.02 a	0.02 a
March 25, 2003	0.02	0.02
April 22, 2003	-	-
May 20, 2003	0.02	0.02
June 9, 2003	0.03 a	0.02 b
June 17, 2003	0.05	0.02
July 9, 2003	0.02	0.02
July 22, 2003	0.04 a	0.03 b
August 19, 2003	0.02	0.02
September 16, 2003	0.02 a	0.02 a
September 23, 2003	0.02	0.03
October 21, 2003	0.02	0.04
November 18, 2003	0.02	0.02
December 22, 2003	0.02	0.02
January 20, 2004	0.02	0.02
February 17, 2004	0.02	0.02

Note: Means in a given row followed by the same letter do not differ significantly at p = 0.05. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.36
Mean Concentration of Manganese (mg/L) Measured in Leachate Samples Collected by Depth
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Date	6" Depth	18" Depth	30" Depth
April 9, 2002	0.02	0.02	0.04
April 30, 2002	0.020 b	0.020 b	0.024 a
May 16, 2002	0.02 b	0.02 b	0.03 a
June 25, 2002	0.02 a	0.02 a	0.02 a
July 8, 2002	0.02 a	0.03 a	0.02 a
July 23, 2002	0.02	-	0.05
August 22, 2002	0.02	-	-
September 11, 2002	0.02 a	0.03 a	0.02 a
September 24, 2002	-	-	0.03
October 11, 2002	0.02 a	0.02 a	0.02 a
October 30, 2002	0.02 a	0.02 a	0.02 a
November 7, 2002	0.02	-	0.02
December 12, 2002	0.02 a	0.02 a	0.02 a
January 28, 2003	-	-	-
February 27, 2003	0.02 a	0.02 a	0.02 a
March 25, 2003	0.02	0.02	0.02
April 22, 2003	-	-	-
May 20, 2003	0.02	0.02	0.02
June 9, 2003	0.04 a	0.02 b	0.02 b
June 17, 2003	0.02 a	0.03 a	0.05 a
July 9, 2003	0.02	0.02	0.02
July 22, 2003	0.02 a	0.04 a	0.04 a
August 19, 2003	0.02	-	0.02
September 16, 2003	0.02 a	0.02 a	0.03 a
September 23, 2003	0.020 c	0.022 b	0.033 a
October 21, 2003	0.02	0.02	0.05
November 18, 2003	0.02	0.02	0.02
December 22, 2003	0.02	0.02	0.02
January 20, 2004	0.02	0.02	0.02
February 17, 2004	0.02 a	0.02 a	0.02 a

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.37
Mean Concentration of Copper (mg/L) Measured in Leachate Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Irrigation Treatment		
Date	**EA**	**RW**	**LF**
April 9, 2002	0.07 a	0.02 a	0.02 a
April 30, 2002	0.02 a	0.02 a	0.01 a
May 16, 2002	0.026 a	0.011 b	0.011 b
June 25, 2002	0.020	0.017	0.013
July 8, 2002	0.012 a	0.012 a	0.010 a
July 23, 2002	-	0.01	0.01
August 22, 2002	-	0.01	-
September 11, 2002	0.01 a	0.01 a	0.02 a
September 24, 2002	-	-	0.02
October 11, 2002	0.02 a	0.02 a	0.02 a
October 30, 2002	0.02 a	0.01 a	0.01 a
November 7, 2002	-	0.01	-
December 12, 2002	0.01 a	0.02 a	0.01 a
January 28, 2003	-	-	-
February 27, 2003	0.02 a	0.01 a	0.02 a
March 25, 2003	0.012 a	0.0125 b	0.0175 a
April 22, 2003	-	-	-
May 20, 2003	-	0.01	0.02
June 9, 2003	0.01 a	0.01 a	0.01 a
June 17, 2003	0.02 a	0.01 a	0.01 a
July 9, 2003	-	0.03	0.01
July 22, 2003	0.01 a	0.01 a	0.02 a
August 19, 2003	-	0.02	0.02
September 16, 2003	0.01 a	0.02 a	0.02 a
September 23, 2003	0.02 a	0.02 a	0.02 a
October 21, 2003	0.03	-	-
November 18, 2003	0.01	0.02	0.02
December 22, 2003	0.01	-	0.02
January 20, 2004	0.01	0.02	0.05
February 17, 2004	0.01	0.01	0.01

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.38
Mean Concentration of Copper (mg/L) Measured in Leachate Samples Collected by Grass
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Turfgrass	
Date	**Bermudagrass**	**Zoysiagrass**
April 9, 2002	0.05	0.01
April 30, 2002	0.01 a	0.02 a
May 16, 2002	0.01	0.02
June 25, 2002	0.02 a	0.02 a
July 8, 2002	0.01 a	0.01 a
July 23, 2002	0.01	0.02
August 22, 2002	0.01	-
September 11, 2002	0.015 a	0.014 a
September 24, 2002	0.02	-
October 11, 2002	0.03 a	0.02 b
October 30, 2002	0.01 a	0.02 a
November 7, 2002	0.01	-
December 12, 2002	0.01 a	0.02 a
January 28, 2003	-	-
February 27, 2003	0.01 a	0.02 a
March 25, 2003	0.01	0.02
April 22, 2003	-	-
May 20, 2003	0.01	0.02
June 9, 2003	0.01 a	0.01 a
June 17, 2003	0.01	0.02
July 9, 2003	0.015	0.010
July 22, 2003	0.011 b	0.016 a
August 19, 2003	0.02	0.02
September 16, 2003	0.013 b	0.018 a
September 23, 2003	0.02	0.02
October 21, 2003	0.04	0.02
November 18, 2003	0.02	0.01
December 22, 2003	0.02	0.01
January 20, 2004	0.02	0.03
February 17, 2004	0.01	0.01

Note: Means in a given row followed by the same letter do not differ significantly at p = 0.05. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.39
Mean Concentration of Copper (mg/L) Measured in Leachate Samples Collected by Depth
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Date	6" Depth	18" Depth	30" Depth
April 9, 2002	0.10	0.02	0.01
April 30, 2002	0.018 a	0.018 a	0.015 b
May 16, 2002	0.012 b	0.010 c	0.019 a
June 25, 2002	0.015 a	0.016 a	0.018 a
July 8, 2002	0.013 a	0.010 b	0.011 b
July 23, 2002	0.01	-	0.01
August 22, 2002	0.01	-	-
September 11, 2002	0.01 a	0.01 a	0.02 a
September 24, 2002	-	-	0.02
October 11, 2002	0.03 a	0.01 a	0.03 a
October 30, 2002	0.02 a	0.01 a	0.01 a
November 7, 2002	0.01	-	0.01
December 12, 2002	0.02 a	0.01 a	0.02 a
January 28, 2003	-	-	-
February 27, 2003	0.02 a	0.01 a	0.02 a
March 25, 2003	0.02	0.01	0.02
April 22, 2003	-	-	-
May 20, 2003	0.01	0.01	0.02
June 9, 2003	0.01 a	0.01 a	0.01 a
June 17, 2003	0.02 a	0.01 a	0.01 a
July 9, 2003	0.02	0.01	0.01
July 22, 2003	0.02 a	0.01 a	0.01 a
August 19, 2003	0.02	-	0.02
September 16, 2003	0.02 a	0.01 a	0.01 a
September 23, 2003	0.027 a	0.014 b	0.013 c
October 21, 2003	0.02	0.03	0.03
November 18, 2003	0.01	0.02	0.02
December 22, 2003	0.02	0.01	0.02
January 20, 2004	0.01	0.02	0.04
February 17, 2004	0.01 a	0.01 a	0.01 a

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.40
Mean Concentration of Sodium (mg/L) Measured in Leachate Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Irrigation Treatment		
Date	**EA**	**RW**	**LF**
April 9, 2002	31.5 a	38.1 a	39.4 a
April 30, 2002	56.0 a	92.6 a	99.2 a
May 16, 2002	50.3 b	118.4 a	114.4 a
June 25, 2002	39.0	108.2	108.8
July 8, 2002	57.4	68.0 a	102.4 a
July 23, 2002	-	18.0	75.1
August 22, 2002	-	93.4	-
September 11, 2002	15.2 b	36.0 a	36.4 a
September 24, 2002	-	-	30.7
October 11, 2002	7.9 a	17.3 a	14.9 a
October 30, 2002	5.7 b	19.9 a	19.7 ab
November 7, 2002	-	30.9	-
December 12, 2002	3.9 b	18.1 ab	21.7 a
January 28, 2003	-	-	-
February 27, 2003	7.3 b	41.6 a	33.0 a
March 25, 2003	5.3 a	50.8 a	34.9 a
April 22, 2003	-	-	-
May 20, 2003	-	112.3	94.7
June 9, 2003	16.0 a	30.8 a	38.1 a
June 17, 2003	5.35 a	22.7 a	36.9 a
July 9, 2003	-	42.40	103.57
July 22, 2003	10.06 a	26.90 a	30.37 a
August 19, 2003	-	7.08	60.1
September 16, 2003	7.72 a	29.0 a	39.2 a
September 23, 2003	7.72 a	47.6 a	49.5 a
October 21, 2003	11.3	-	-
November 18, 2003	10.3	87.6	76.7
December 22, 2003	10.7	-	101.8
January 20, 2004	12.1	43.5	57.8
February 17, 2004	9.4	80.7	78.4

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE 41
Mean Concentration of Sodium (mg/L) Measured in Leachate Samples Collected by Grass
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Turfgrass	
Date	**Bermudagrass**	**Zoysiagrass**
April 9, 2002	43.1	29.0
April 30, 2002	83.7 a	85.9 a
May 16, 2002	99.2	103.8
June 25, 2002	99.6 b	109.4 a
July 8, 2002	80.7 a	72.7 a
July 23, 2002	41.0	6.2
August 22, 2002	93.4	-
September 11, 2002	30.1 a	28.6 a
September 24, 2002	30.7	-
October 11, 2002	16.0 a	11.4 a
October 30, 2002	17.2 a	15.0 a
November 7, 2002	30.9	-
December 12, 2002	15.5	15.3
January 28, 2003	-	-
February 27, 2003	31.3 a	24.6 a
March 25, 2003	34.4	32.8
April 22, 2003	-	-
May 20, 2003	122.5	99.6
June 9, 2003	27.3 a	21.0 b
June 17, 2003	25.8	26.9
July 9, 2003	92.6	97.9
July 22, 2003	19.3 a	30.6 a
August 19, 2003	32.3	75.3
September 16, 2003	27.9 a	34.6 a
September 23, 2003	29.2	38.0
October 21, 2003	8.27	13.30
November 18, 2003	74.1	54.3
December 22, 2003	100.0	47.8
January 20, 2004	43.5	42.5
February 17, 2004	80.7	36.97

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.42
Mean Concentration of Sodium (mg/L) Measured in Leachate Samples Collected by Depth
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Date	6" Depth	18" Depth	30" Depth
April 9, 2002	56.1	34.3	27.2
April 30, 2002	89.3 a	88.2 a	78.5 a
May 16, 2002	95.2 a	106.2 a	102.0 a
June 25, 2002	93.8 a	108.1 a	106.8 a
July 8, 2002	91.6 a	56.7 b	78.8 ab
July 23, 2002	27.8	-	33.8
August 22, 2002	93.4	-	-
September 11, 2002	36.3 a	25.1 a	25.5 a
September 24, 2002	-	-	30.7
October 11, 2002	18.3 a	10.4 a	14.8 a
October 30, 2002	22.1 a	13.5 a	15.1 a
November 7, 2002	29.7	-	32.0
December 12, 2002	32.2 a	6.5 a	15.1 a
January 28, 2003	-	-	-
February 27, 2003	37.5 a	22.4 b	25.4 ab
March 25, 2003	41.13	27.14	36.34
April 22, 2003	-	-	-
May 20, 2003	127.00	113.00	88.40
June 9, 2003	32.06 a	22.04 a	19.96 a
June 17, 2003	46.33 a	14.74 b	21.45 b
July 9, 2003	95.47	97.95	90.75
July 22, 2003	41.78 a	16.87 b	22.38 ab
August 19, 2003	100.45	-	15.49
September 16, 2003	42.84 a	19.69 a	28.8 a
September 23, 2003	47.0 a	27.5 a	20.1 a
October 21, 2003	13.80	11.25	10.07
November 18, 2003	54.2	102.3	50.1
December 22, 2003	52.5	73.4	57.0
January 20, 2004	12.1	43.9	52.7
February 17, 2004	9.45 b	64.26	60.29 a

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.43
Mean Concentration of Calcium (mg/L) Measured in Leachate Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Irrigation Treatment		
Date	**EA**	**RW**	**LF**
April 9, 2002	36.4 a	40.4 a	45.7 a
April 30, 2002	82.5 b	96.9 a	102.1 a
May 16, 2002	97.0 a	112.3 a	118.0 a
June 25, 2002	101.0	127.4	117.5
July 8, 2002	88.5 a	81.5 a	109.3 a
July 23, 2002	-	62.1	108.0
August 22, 2002	-	191.0	-
September 11, 2002	63.3 a	59.5 a	50.2 a
September 24, 2002	-	-	58.4
October 11, 2002	62.4 a	51.6 a	38.5 a
October 30, 2002	65.9 a	62.0 a	48.6 a
November 7, 2002	-	66.5	-
December 12, 2002	42.0 a	48.1 a	47.8 a
January 28, 2003	-	-	-
February 27, 2003	63.9 a	68.7 a	55.7 a
March 25, 2003	62.7 a	76.2 a	66.6 a
April 22, 2003	-	-	-
May 20, 2003	-	126.5	152.0
June 9, 2003	86.4 a	53.1 a	63.2
June 17, 2003	49.2 a	36.2 a	54.7 a
July 9, 2003	-	61.6	125.4
July 22, 2003	63.5 a	51.3 a	39.3 a
August 19, 2003	-	89.1	85.8
September 16, 2003	95.1 a	38.0 b	44.9 b
September 23, 2003	74.9 a	76.5 a	59.4 a
October 21, 2003	78.7	-	-
November 18, 2003	74.6	83.6	81.9
December 22, 2003	80.3	-	103.5
January 20, 2004	80.6	55.8	54.3
February 17, 2004	69.5	101.6	75.1

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.44
Mean Concentration of Calcium (mg/L) Measured in Leachate Samples Collected by Grass
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Turfgrass	
Date	**Bermudagrass**	**Zoysiagrass**
April 9, 2002	46.2	35.4
April 30, 2002	96.5 a	93.1 a
May 16, 2002	113.5	108.3
June 25, 2002	123.0 a	124.4 a
July 8, 2002	95.9 a	90.8 a
July 23, 2002	85.2	38.9
August 22, 2002	191.0	-
September 11, 2002	60.1 a	55.8 a
September 24, 2002	58.4	-
October 11, 2002	51.3 a	48.5 a
October 30, 2002	61.4 a	55.7 a
November 7, 2002	66.5	-
December 12, 2002	53.1	37.6
January 28, 2003	-	-
February 27, 2003	66.4 a	57.6 a
March 25, 2003	71.9	67.8
April 22, 2003	-	-
May 20, 2003	127.0	134.7
June 9, 2003	76.7 a	61.5 a
June 17, 2003	49.8	41.7
July 9, 2003	122.2	108.4
July 22, 2003	49.0 a	49.4 a
August 19, 2003	96.0	72.1
September 16, 2003	60.9 a	36.3 a
September 23, 2003	75.2	64.7
October 21, 2003	51.5	96.9
November 18, 2003	80.0	81.4
December 22, 2003	114.5	85.2
January 20, 2004	55.8	63.1
February 17, 2004	101.6	71.7

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.45
Mean Concentration of Calcium (mg/L) Measured in Leachate Samples Collected by Depth
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Date	6” Depth	18” Depth	30” Depth
April 9, 2002	50.0	40.8	36.4
April 30, 2002	88.6 b	95.4 ab	98.6 a
May 16, 2002	103.4 a	104.1a	120.0 a
June 25, 2002	109.0 a	122.3 a	135.5 a
July 8, 2002	91.0 ab	78.3 b	103.8 a
July 23, 2002	56.7	-	79.2
August 22, 2002	191.0	-	-
September 11, 2002	61.8 a	53.3 a	57.8 a
September 24, 2002	-	-	58.4
October 11, 2002	64.7 a	42.6 a	48.8 a
October 30, 2002	53.6 a	53.1 a	65.8 a
November 7, 2002	67.4	-	65.6
December 12, 2002	55.5 a	25.9 b	58.8 a
January 28, 2003	-	-	-
February 27, 2003	79.7 a	47.6 b	61.0 ab
March 25, 2003	75.2	58.5	79.8
April 22, 2003	-	-	-
May 20, 2003	123.5	142.0	134.5
June 9, 2003	90.7 a	62.1 ab	58.3 b
June 17, 2003	66.8 a	22.8 b	50.7 a
July 9, 2003	107.6	129.0	116.5
July 22, 2003	49.4 a	36.3 a	64.4 a
August 19, 2003	103.5	-	75.1
September 16, 2003	62.6 a	47.2 a	50.0 a
September 23, 2003	76.8 a	68.5 a	66.7 a
October 21, 2003	95.7	82.7	66.3
November 18, 2003	82.9	89.3	75.3
December 22, 2003	106.0	89.0	87.9
January 20, 2004	80.6	48.2	59.9
February 17, 2004	67.4 a	86.5 a	87.9 a

Note: Means in a given row followed by the same letter do not differ significantly at p = 0.05. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.46
Mean Concentration of Total Kjeldahl Nitrogen (mg/L) Measured in Leachate Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Irrigation Treatment		
Date	**EA**	**RW**	**LF**
April 9, 2002	1.25 a	1.64 a	1.33 a
April 30, 2002	0.91 b	1.72 a	1.41 ab
May 16, 2002	0.72 b	1.51 a	1.48 a
June 25, 2002	0.67	0.84	1.16
July 8, 2002	0.63 b	0.84 ab	0.94 a
July 23, 2002	1.03	0.95	0.89
September 11, 2002	0.53 b	0.82 ab	0.92a
September 24, 2002	-	-	0.64
October 11, 2002	0.54 a	0.72 a	0.68 a
October 30, 2002	0.17 a	0.80 a	0.81 a
November 7, 2002	-	0.84	0.93
December 12, 2002	0.70	0.96	1.02
January 28, 2003	0.56	0.98	1.01
February 27, 2003	0.65 a	0.96 a	0.92 a
March 25, 2003	0.40 a	0.72 a	0.86 a
April 22, 2003	1.18	-	1.28
May 20, 2003	-	1.44	1.06
June 9, 2003	0.48 b	1.36 a	1.51 a
June 17, 2003	0.55 b	1.11 a	1.09 a
July 9, 2003	1.32 a	1.79 a	1.02 a
July 22, 2003	0.76 a	0.83 a	1.05 a
August 19, 2003	-	0.42	0.81
September 16, 2003	1.11 a	1.22 a	1.13 a
September 23, 2003	0.99 a	1.54 a	1.44 a
October 21, 2003	0.67	1.82	2.06
November 18, 2003	0.66	1.93	1.21
December 22, 2003	0.43	1.23	1.29
January 20, 2004	0.58 a	2.28 a	1.80 a
February 17, 2004	0.66	1.30	1.25

Note: Means in a given row followed by the same letter do not differ significantly at p = 0.05. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.47
Mean Concentration of Total Kjeldahl Nitrogen (mg/L) Measured in Leachate Samples Collected by Grass
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Turgrass	
Date	**Bermudagrass**	**Zoysiagrass**
April 9, 2002	1.21 a	1.57 a
April 30, 2002	1.32 a	1.33 a
May 16, 2002	1.21 a	1.32 a
June 25, 2002	0.93 a	0.90 a
July 8, 2002	0.84 a	0.77 a
July 23, 2002	0.88	1.33
September 11, 2002	0.81 a	0.71 a
September 24, 2002	0.64	-
October 11, 2002	0.67 a	0.63 a
October 30, 2002	0.73 a	0.71 a
November 7, 2002	0.92 a	0.79 a
December 12, 2002	0.97 a	0.82 a
January 28, 2003	0.80	0.84
February 27, 2003	0.94 a	0.78 a
March 25, 2003	0.67	0.67
April 22, 2003	1.57	0.59
May 20, 2003	1.82	1.16
June 9, 2003	1.03 a	0.79 b
June 17, 2003	1.03 a	0.86 a
July 9, 2003	1.36	0.82
July 22, 2003	0.95 a	0.85 a
August 19, 2003	0.77	0.53
September 16, 2003	1.20 a	1.05 a
September 23, 2003	1.39	1.23
October 21, 2003	1.23	0.95
November 18, 2003	1.68	1.07
December 22, 2003	1.33	0.83
January 20, 2004	2.28	1.39
February 17, 2004	1.25	0.82

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.48
Mean Concentration of Total Kjeldahl Nitrogen (mg/L) Measured in Leachate Samples Collected by Depth
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Date	6” Depth	18” Depth	30” Depth
April 9, 2002	1.16 a	1.07 a	1.29 a
April 30, 2002	1.62 a	1.12 b	1.23 ab
May 16, 2002	1.47 a	1.13 b	1.22 b
June 25, 2002	1.18 a	0.83 a	0.86 a
July 8, 2002	1.14 a	0.69 b	0.60 b
July 23, 2002	1.22	1.04	0.80
September 11, 2002	0.83 a	0.74 ab	0.71 b
September 24, 2002	-	-	0.64
October 11, 2002	0.76 a	0.59 a	0.62 a
October 30, 2002	0.90 a	0.70 a	0.62 a
November 7, 2002	1.14	-	0.71
December 12, 2002	0.97 a	0.85 a	0.87 a
January 28, 2003	0.81	-	-
February 27, 2003	0.94 a	0.84 b	0.84 b
March 25, 2003	0.70 a	0.66 a	0.66 a
April 22, 2003	-	1.18	1.28
May 20, 2003	2.06	1.12	0.95
June 9, 2003	1.08 a	0.91 ab	0.79 b
June 17, 2003	0.90 a	1.00 a	0.92 a
July 9, 2003	1.48	0.70	1.06
July 22, 2003	1.31 a	0.70 b	0.74 b
August 19, 2003	1.40	-	0.48
September 16, 2003	1.04 a	1.18 a	1.23 a
September 23, 2003	1.43 a	1.13 a	1.47 a
October 21, 2003	1.42	0.86	0.56
November 18, 2003	0.66	1.21	1.93
December 22, 2003	1.12	0.97	0.91
January 20, 2004	1.34 a	2.61 a	1.86 a
February 17, 2004	1.11 a	1.04 a	1.07 a

Note: Means in a given row followed by the same letter do not differ significantly at p = 0.05. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.49
Mean Concentration of Phosphorus (mg/L) Measured in Leachate Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Irrigation Treatment		
Date	**EA**	**RW**	**LF**
April 9, 2002	1.06	1.40	1.63
April 30, 2002	0.70 c	2.02 a	1.54 b
May 16, 2002	0.80 a	2.47 a	2.04 a
June 25, 2002	0.59	2.01	2.42
July 8, 2002	440.7 a	338.6 a	327.9 a
July 23, 2002	-	191.9	-
August 22, 2002	-	0.82	-
September 11, 2002	6.21 a	8.40 a	4.13 a
October 11, 2002	0.87 b	1.27 a	1.04 ab
October 30, 2002	1.04 a	2.84 a	1.36 a
November 7, 2002	-	2.01	-
December 12, 2002	1.27 a	1.54 a	1.33 a
January 28, 2003	-	-	-
February 27, 2003	0.92 b	1.55 a	1.32 b
March 25, 2003	0.86	1.55	0.68
April 22, 2003	-	-	-
May 20, 2003	-	1.82	0.94
June 9, 2003	0.63 a	1.08 a	1.20 a
June 17, 2003	0.78	1.24	1.10
July 9, 2003	-	0.86	0.69
July 22, 2003	0.74 a	1.05 a	1.24 a
August 19, 2003	-	1.18	1.06
September 16, 2003	0.60 a	1.44 a	1.54 a
September 23, 2003	1.27	1.85	1.67
October 21, 2003	-	-	-
November 18, 2003	-	3.36	2.12
December 22, 2003	2.04	-	3.18
January 20, 2004	-	3.54	4.88
February 17, 2004	2.66	3.16	4.16

Note: Means in a given row followed by the same letter do not differ significantly at p = 0.05. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.50
Mean Concentration of Phosphorus (mg/L) Measured in Leachate Samples Collected by Grass
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Turgrass	
Date	**Bermudagrass**	**Zoysiagrass**
April 9, 2002	1.14	1.56
April 30, 2002	1.76 a	1.29 a
May 16, 2002	1.95	2.11
June 25, 2002	2.00 a	2.04 a
July 8, 2002	395.6 a	302.0 a
July 23, 2002	191.9	-
August 22, 2002	0.82	-
September 11, 2002	6.31 a	6.27 a
October 11, 2002	1.18 a	0.97 a
October 30, 2002	1.39 a	2.21 a
November 7, 2002	2.01	-
December 12, 2002	1.35	1.49
January 28, 2003	-	-
February 27, 2003	1.37 a	1.21 b
March 25, 2003	1.28	1.07
April 22, 2003	-	-
May 20, 2003	1.39	1.81
June 9, 2003	0.72 a	1.02 a
June 17, 2003	1.14 a	1.16 a
July 9, 2003	0.62	0.85
July 22, 2003	0.94	1.32
August 19, 2003	0.84	1.83
September 16, 2003	1.36 a	1.52 a
September 23, 2003	1.52	1.80
October 21, 2003	-	-
November 18, 2003	2.12	3.36
December 22, 2003	1.65	3.11
January 20, 2004	3.54	4.88
February 17, 2004	3.16	3.26

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.51
Mean Concentration of Phosphorus (mg/L) Measured in Leachate Samples Collected by Depth
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Date	6" Depth	18" Depth	30" Depth
April 9, 2002	1.27	1.53	1.31
April 30, 2002	1.28 a	1.37 a	1.78 a
May 16, 2002	1.74 a	2.19 a	2.09 a
June 25, 2002	1.85 a	1.97 a	2.20 a
July 8, 2002	299.15 a	356.8 a	399.8 a
July 23, 2002	218.1	-	165.7
August 22, 2002	0.82	-	-
September 11, 2002	6.23 a	6.60 a	6.04 a
October 11, 2002	1.06 a	1.08 a	1.11 a
October 30, 2002	1.30 a	1.48 a	2.45 a
November 7, 2002	1.55	-	2.47
December 12, 2002	1.41 a	1.42 a	1.38 a
January 28, 2003	-	-	-
February 27, 2003	1.26 a	1.28 a	1.33 a
March 25, 2003	1.12	1.13	1.35
April 22, 2003	-	-	-
May 20, 2003	2.15	0.67	1.63
June 9, 2003	1.15 a	0.72 a	0.86 a
June 17, 2003	0.89 b	1.20 ab	1.31 a
July 9, 2003	0.59	0.56	1.07
July 22, 2003	0.50 b	1.14 a	1.11 a
August 19, 2003	0.55	-	1.27
September 16, 2003	1.17 a	1.72 a	1.44 a
September 23, 2003	1.11 a	2.09 a	1.75 a
October 21, 2003	-	-	-
November 18, 2003	3.65	2.61	2.08
December 22, 2003	1.38	3.29	3.11
January 20, 2004	-	4.25	3.96
February 17, 2004	3.09 a	3.30 a	3.16 a

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.52

Mean Number of Fecal Streptococcus (col/100 ml) Measured in Leachate Samples Collected by Irrigation Treatment

Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Irrigation Treatment		
Date	**EA**	**RW**	**LF**
April 9, 2002	-	-	-
April 30, 2002	-	-	-
May 16, 2002	-	-	-
June 25, 2002	-	-	-
July 8, 2002	-	-	-
July 23, 2002	-	-	-
September 11, 2002	-	-	-
October 11, 2002	-	-	-
November 7, 2002	-	-	-
December 12, 2002	-	-	-
January 28, 2003	-	-	-
February 27, 2003	11.7 a	28.9 a	25.6 a
March 25, 2003	88.5 a	10.7 a	10.0 a
April 22, 2003	212.2 a	13.3 b	68.9 ab
May 20, 2003	10	214.3	292.5
June 9, 2003	20.6 a	27.5 a	279.3 a
June 17, 2003	17.2 a	194.7 a	135.6 a
July 9, 2003	140.0 a	127.1 a	29.1 a
July 22, 2003	92.8 a	40.0 a	27.2 a
August 19, 2003	104.3 a	13.3 a	99.3 a
September 16, 2003	28.3 a	14.4 a	152.8 a
September 23, 2003	-	-	-
October 21, 2003	21.3 a	13.3 a	55.0 a
November 18, 2003	688.3 a	375.0 a	144.0 a
December 22, 2003	20 a	20 a	20 a
January 20, 2004	10.0 a	12.7 a	24.0 a
February 17, 2004	11.1 a	10.0 a	16.4 a

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.53

Mean Number of Fecal Streptococcus (col/100 ml) Measured in Leachate Samples Collected by Grass

Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Turfgrass	
Date	**Bermudagrass**	**Zoysiagrass**
April 9, 2002	-	-
April 30, 2002	-	-
May 16, 2002	-	-
June 25, 2002	-	-
July 8, 2002	-	-
July 23, 2002	-	-
September 11, 2002	-	-
October 11, 2002	-	-
November 7, 2002	-	-
December 12, 2002	-	-
January 28, 2003	-	-
February 27, 2003	14.8 a	29.3 a
March 25, 2003	11.0 b	55.9 a
April 22, 2003	54.0 b	153.3 a
May 20, 2003	130.0	262.5
June 9, 2003	45.8 a	161.7 a
June 17, 2003	91.2 a	132.8 a
July 9, 2003	91.7 a	79.2 a
July 22, 2003	22.7 a	83.3 a
August 19, 2003	54.4 a	119.2 a
September 16, 2003	15.9 a	114.4 a
September 23, 2003	-	-
October 21, 2003	47.8 a	13.8 a
November 18, 2003	527.5 a	149.0 a
December 22, 2003	20 a	20 a
January 20, 2004	11.9 a	18.8 a
February 17, 2004	10.7 a	14.7 a

Note: Means in a given row followed by the same letter do not differ significantly at p = 0.05. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

TABLE C.54
Mean Number of Fecal Streptococcus (col/100 ml) Measured in Leachate Samples Collected by Depth
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Date	6" Depth	18" Depth	30" Depth
April 9, 2002	-	-	-
April 30, 2002	-	-	-
May 16, 2002	-	-	-
June 25, 2002	-	-	-
July 8, 2002	-	-	-
July 23, 2002	-	-	-
September 11, 2002	-	-	-
October 11, 2002	-	-	-
November 7, 2002	-	-	-
December 12, 2002	-	-	-
January 28, 2003	-	-	-
February 27, 2003	20.0 a	17.2 a	28.9 a
March 25, 2003	11.25 a	86.9 a	10.7 a
April 22, 2003	48.5 b	18.8 b	311.7 a
May 20, 2003	275.0	110.0	221.7
June 9, 2003	231.9 a	41.3 a	38.1 a
June 17, 2003	80.0 a	142.1 a	118.2 a
July 9, 2003	70.0 a	111.4 a	83.3 a
July 22, 2003	65.9 a	77.8 a	17.8 a
August 19, 2003	59.0 a	12.2 a	177.8 a
September 16, 2003	16.7 a	142.8 a	36.1 a
September 23, 2003	-	-	-
October 21, 2003	41.8	16.7	10.0
November 18, 2003	489.2 a	366.7 a	121.4 a
December 22, 2003	20 a	20 a	20 a
January 20, 2004	12.4 a	24.3 a	13.8 a
February 17, 2004	13.3 a	10.0 a	13.8 a

Note: Means in a given row followed by the same letter do not differ significantly at p = 0.05. Rows without letter designations indicate insufficient data to be able to make a valid statistical comparison.

Appendix D

TABLE D.1
Concentrations of Sodium (mg/kg) Measured in Bermudagrass Tissue Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Date	Irrigation Treatment			Mean
	EA	RW	LF	
May 1, 2002	1,150 b	1,707 a	1,693 a	1,517
May 16, 2002	947.7 a	1,733 a	1,268 a	1,316
June 25, 2002	430.0 b	1,870 a	1,547 a	1,282
July 23, 2002	1,111 b	1,640 ab	2,013 a	1,588
August 22, 2002	586.7 a	1,373 a	1,427 a	1,129
September 24, 2002	380.7 b	1,420 a	1,477 a	1,092
November 5, 2002	242.7 b	741.0 a	803.0 a	595.6
April 22, 2003	1,057 b	1,740 a	1,877 a	1,558
May 20, 2003	1,167 b	2,470 a	2,507 a	2,048
June 17, 2003	1,260 b	2,033 a	1,917 a	1,737
July 22, 2003	1,533 a	1,241 a	1,687 a	1,487
August 19, 2003	423.3 b	1,467 a	1,410 a	1,100
September 23, 2003	967.0 b	1,667 a	1,950 a	1,528
October 21, 2003	836.3 b	1,703 ab	1,920 a	1,487
February 17, 2003	668.3 a	790.3 a	735.0 a	731.2

Note: Values in a given row followed by the same letter do not differ significantly at p = 0.5.

TABLE D.2
Concentrations of Sodium (mg/kg) Measured in Zoysiagrass Tissue Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Date	Irrigation Treatment			Mean
	EA	RW	LF	
May 1, 2002	751.7 b	1,480 a	1,363 a	1,198
May 16, 2002	388.0 b	1,089 a	1,207 a	894.4
June 25, 2002	385.7 b	1,183 a	1,353 a	974.1
July 23, 2002	1,107 b	1,747 a	1,740 a	1,531
August 22, 2002	634.0 a	1,457 a	1,340 a	1,144
September 24, 2002	310.0 b	1,061 a	883.3 a	751.3
November 5, 2002	191.0 b	524.7 a	479.7 a	398.4
April 22, 2003	655.3 b	1,363 a	1,467 a	1,162

TABLE D.2 CONTINUED

Concentrations of Sodium (mg/kg) Measured in Zoysiagrass Tissue Samples Collected by Irrigation Treatment

Edwards Aquifer Recharge Zone Irrigation Pilot Study

Date	Irrigation Treatment			Mean
	EA	RW	LF	
May 20, 2003	760.7 b	1,873 a	1,733 a	1,456
June 17, 2003	1,032 b	1,933 a	1,787 a	1,584
July 22, 2003	798.7 b	1,342 ab	1,927 a	1,356
August 19, 2003	305.7 b	1,677 a	1,470 a	1,151
September 23, 2003	732.3 b	1,473 a	1,447 a	1,217
October 21, 2003	561.3 b	1,266 a	956.3 ab	928
February 17, 2003	698.0 a	742.7 a	808.0 a	750

Note: Values in a given row followed by the same letter do not differ significantly at p = 0.5.

TABLE D.3

Analysis of Variance for Sodium Content of Tissue Samples Collected

Edwards Aquifer Recharge Zone Irrigation Pilot Study

Source of Variation	Degrees of Freedom	F Value	Probability of Obtaining a Greater F Value
Grass (G)	1	112.92	<0.0001
Irrigation (I)	2	263.47	<0.0001
Date (D)	14	44.92	<0.0001
G x I	2	0.67	0.5146
G x D	14	5.12	<0.0001
I x D	28	3.49	<0.0001
G x I x D	28	2.48	0.0007

TABLE D.4

Concentrations of Manganese (mg/kg) Measured in Bermudagrass Tissue Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Irrigation Treatment			
Date	**EA**	**RW**	**LF**	**Mean**
May 1, 2002	84.4 a	82.0 a	100.5 a	89
May 16, 2002	730.6 a	342.3 a	782.0 a	618.3
June 25, 2002	87.0 b	99.9 ab	115.3 a	100.7
July 23, 2002	79.9 a	106.2 a	127.3 a	104.5
August 22, 2002	107.7 a	143.0 a	147.3 a	132.7
September 24, 2002	76.3 a	98.6 a	107.4 a	94.1
November 5, 2002	125.0 a	131.7 a	120.7 a	125.8
April 22, 2003	66.6 a	84.9 a	79.5 a	77
May 20, 2003	71.3 b	88.6 a	82.7 ab	80.8
June 17, 2003	71.6 a	85.3 a	71.6 a	82.5
July 22, 2003	92.0 a	84.0 a	80.6 a	85.5
August 19, 2003	79.3 b	100.1 a	101.4 a	93.6
September 23, 2003	98.5 a	108.5 a	125.7 a	110.9
October 21, 2003	77.4 a	88.1 a	105.8 a	90.4
February 17, 2003	106.7 a	107.9 a	100.0 a	104.9

Note: Values in a given row followed by the same letter do not differ significantly at p = 0.5.

TABLE D.5

Concentrations of Manganese (mg/kg) Measured in Zoysiagrass Tissue Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Irrigation Treatment			
Date	**EA**	**RW**	**LF**	**Mean**
May 1, 2002	110.6 a	88.5 a	79.8 a	93
May 16, 2002	417.3 a	1,065 a	77.7 a	520.1
June 25, 2002	87.6 ab	92.7 a	69.0 b	83.1
July 23, 2002	85.4 a	81.8 a	78.5 a	81.9
August 22, 2002	94.9 a	90.3 a	176.9 a	120.7
September 24, 2002	63.6 a	73.1 a	72.2 a	69.6
November 5, 2002	122.0 a	132.3 a	115.5 a	123.3
April 22, 2003	82.5 a	92.1 a	88.4 a	87.6

TABLE D.5 CONTINUED
Concentrations of Manganese (mg/kg) Measured in Zoysiagrass Tissue Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Irrigation Treatment			
Date	**EA**	**RW**	**LF**	**Mean**
May 20, 2003	86.0 a	83.8 a	66.2 a	78.7
June 17, 2003	68.1 a	52.6 ab	45.9 b	55.6
July 22, 2003	64.0 a	73.7 a	66.6 a	68.1
August 19, 2003	74.8 a	87.1 a	87.1 a	83
September 23, 2003	75.8 a	97.7 a	90.0 a	87.8
October 21, 2003	79.4 a	77.6 a	84.8 a	80.6
February 17, 2003	87.6 a	106.0 a	85.8 a	93.2

Note: Values in a given row followed by the same letter do not differ significantly at p = 0.5.

TABLE D.6
Analysis of Variance for Manganese Content of Tissue Samples Collected
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Source of Variation	Degrees of Freedom	F Value	Probability of Obtaining a Greater F Value
Grass (G)	1	1.52	0.2214
Irrigation (I)	2	0.33	0.7172
Date (D)	14	8.41	<0.0001
G x I	2	4.25	0.0172
G x D	14	0.2	0.9992
I x D	28	0.34	0.9988
G x I x D	28	3.95	<0.0001

TABLE D.7
Mean Concentrations of Magnesium (mg/kg) Measured in Tissue Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Irrigation Treatment		
Date	EA	RW	LF
May 1, 2002	1,583 a	1,549 a	1,412 a
May 16, 2002	2,013 a	2,112 a	1,852 a
June 25, 2002	1,627 a	1,792 a	1,760 a
July 23, 2002	1,265 a	1,470 a	2,708 a
August 22, 2002	1,574 a	1,888 a	1,630 a
September 24, 2002	1,086 a	1,280 a	1,312 a
November 5, 2002	1,565 a	1,650 a	1,468 a
April 22, 2003	1,152 b	1,647 a	1,360 ab
May 20, 2003	1,353 b	1,715 a	1,398 b
June 17, 2003	1,100 a	1,202 a	1,042 a
July 22, 2003	926.2 a	1,029 a	1,076 a
August 19, 2003	1,001 b	1,221 a	1,087 ab
September 23, 2003	1,202 a	1,408 a	1,465 a
October 21, 2003	1,032 a	1,108 a	1,036 a
February 17, 2003	984.0 a	876.8 a	839.8 a

Note: Means in a given row followed by the same letter do not differ significantly at p = 0.5.

TABLE D.8
Mean Concentrations of Magnesium (mg/kg) Measured in Tissue Samples Collected, by Grass
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Turfgrass	
Date	Bermudagrass	Zoysiagrass
May 1, 2002	1,272 b	1,757 a
May 16, 2002	1,636 b	2,349 a
June 25, 2002	1,413 b	2,039 a
July 23, 2002	1,986 a	1,643 a
August 22, 2002	1,655 a	1,740 a
September 24, 2002	1,155 a	1,296 a
November 5, 2002	1,437 a	1,686 a
April 22, 2003	1,220 a	1,552 a

TABLE D.8 CONTINUED
Mean Concentrations of Magnesium (mg/kg) Measured in Tissue Samples Collected, by Grass
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Turfgrass	
Date	**Bermudagrass**	**Zoysiagrass**
May 20, 2003	1,241 b	1,737 a
June 17, 2003	931.7 b	1,298 a
July 22, 2003	871.7 a	1,149 a
August 19, 2003	975.0 a	1,231 a
September 23, 2003	1,339 a	1,377 a
October 21, 2003	945.7 b	1,171 a
February 17, 2003	931.4 a	869.0 a

Note: Means in a given row followed by the same letter do not differ significantly at p = 0.5.

TABLE D.9
Analysis of Variance for Magnesium Content of Tissue Samples Collected
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Source of Variation	Degrees of Freedom	F Value	Probability of Obtaining a Greater F Value
Grass (G)	1	17.4	<0.0001
Irrigation (I)	2	2.42	0.0974
Date (D)	14	7.33	<0.0001
G x I	2	5.31	0.0066
G x D	14	1.27	0.2447
I x D	28	1.1	0.3713
G x I x D	28	1.24	0.224

TABLE D.10
Mean Concentrations of Iron (mg/kg) Measured in Tissue Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Irrigation Treatment		
Date	**EA**	**RW**	**LF**
May 1, 2002	3907 a	2221 a	2201 a
May 16, 2002	3445 a	3684 a	2575 a
June 25, 2002	1681 a	1385 a	1302 a
July 23, 2002	1311 a	1609 a	1649 a
August 22, 2002	2807 a	2917 a	2954 a
September 24, 2002	951 a	1172 a	1625 a
November 5, 2002	4128 a	4193 a	3207 a
April 22, 2003	890.3 a	1115 a	1394 a
May 20, 2003	758.2 a	1114 a	351.7 a
June 17, 2003	137.9 a	117.0 a	79.3 a
July 22, 2003	107.8 a	126.6 a	82.3 a
August 19, 2003	300.7 a	268.8 a	363.8 a
September 23, 2003	1279 a	1286 a	1998 a
October 21, 2003	220.7 a	188.5 a	235.5 a
February 17, 2003	1047 a	942.7 a	287.3 a

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$.

TABLE D.11
Mean Concentrations of Iron (mg/kg) Measured in Tissue Samples Collected, by Grass
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Turfgrass	
Date	**Bermudagrass**	**Zoysiagrass**
May 1, 2002	2408 a	3144 a
May 16, 2002	2605 b	3864 a
June 25, 2002	1701 a	1210 a
July 23, 2002	1752 a	1294 a
August 22, 2002	4169 a	1616 b
September 24, 2002	1505 a	994 a
November 5, 2002	3854 a	3831 a
April 22, 2003	950 a	1316 a

TABLE D.11 CONTINUED
Mean Concentrations of Iron (mg/kg) Measured in Tissue Samples Collected, by Grass
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Turfgrass	
Date	**Bermudagrass**	**Zoysiagrass**
May 20, 2003	783.0 a	699.4 a
June 17, 2003	140.6 a	82.2 b
July 22, 2003	144.3 a	66.8 a
August 19, 2003	422.0 a	200.2 a
September 23, 2003	2117 a	924 a
October 21, 2003	196.1 a	233.7 a
February 17, 2003	813.7 a	704.3 a

Note: Means in a given row followed by the same letter do not differ significantly at p = 0.05.

TABLE D.12
Analysis of Variance for Iron Content of Tissue Samples Collected
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Source of Variation	Degrees of Freedom	F Value	Probability of Obtaining a Greater F Value
Grass (G)	1	2.47	0.1195
Irrigation (I)	2	0.59	0.5562
Date (D)	14	31.17	<0.0001
G x I	2	2.51	0.0866
G x D	14	2.37	0.0076
I x D	28	0.73	0.8212
G x I x D	28	0.92	0.5849

TABLE D.13
Mean Concentrations of Copper (mg/kg) Measured in Tissue Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Irrigation Treatment		
Date	**EA**	**RW**	**LF**
May 1, 2002	16.0 a	19.6 a	17.5 a
May 16, 2002	34.6 a	27.8 a	22.8 a
June 25, 2002	10.8 a	10.3 a	12.4 a
July 23, 2002	9.9 a	10.8 a	9.9 a
August 22, 2002	17.2 a	13.4 b	14.8 ab
September 24, 2002	12.2 a	11.7 a	11.0 a
November 5, 2002	20.0 a	19.5 a	19.5 a
April 22, 2003	10.2 a	9.8 a	10.7 a
May 20, 2003	9.2 a	10.1 a	8.5 a
June 17, 2003	7.9 a	8.5 a	7.9 a
July 22, 2003	8.8 a	9.6 a	9.0 a
August 19, 2003	9.3 a	10.9 a	9.6 a
September 23, 2003	10.0 a	10.9 a	11.4 a
October 21, 2003	9.2 a	10.4 a	9.3 a
February 17, 2003	9.0 a	10.3 a	6.9 a

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$.

TABLE D.14
Mean Concentrations of Copper (mg/kg) Measured in Tissue Samples Collected, by Grass
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Turfgrass	
Date	**Bermudagrass**	**Zoysiagrass**
May 1, 2002	14.8 a	20.6 a
May 16, 2002	26.1 a	30.7 a
June 25, 2002	13.0 a	9.3 a
July 23, 2002	12.9 a	7.6 b
August 22, 2002	17.6 a	12.7 a
September 24, 2002	14.8 a	8.5 b
November 5, 2002	20.5 a	18.8 a
April 22, 2003	11.7 a	8.8 b

TABLE D.14 CONTINUED
Mean Concentrations of Copper (mg/kg) Measured in Tissue Samples Collected, by Grass
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Turfgrass	
Date	**Bermudagrass**	**Zoysiagrass**
May 20, 2003	11.1 a	7.4 b
June 17, 2003	9.1 a	7.1 b
July 22, 2003	10.5 a	7.8 b
August 19, 2003	12.2 a	7.7 b
September 23, 2003	13.9 a	7.7 b
October 21, 2003	11.9 a	7.4 b
February 17, 2003	9.7 a	7.7 a

Note: Means in a given row followed by the same letter do not differ significantly at p = 0.05.

TABLE D.15
Analysis of Variance for Copper Content of Tissue Samples Collected
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Source of Variation	Degrees of Freedom	F Value	Probability of Obtaining a Greater F Value
Grass (G)	1	8.34	0.0049
Irrigation (I)	2	0.65	0.525
Date (D)	14	14.63	<0.0001
G x I	2	2.08	0.1308
G x D	14	0.97	0.4938
I x D	28	0.57	0.9466
G x I x D	28	0.51	0.9762

TABLE D.16
Mean Concentrations of Zinc (mg/kg) Measured in Tissue Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Irrigation Treatment		
Date	**EA**	**RW**	**LF**
May 1, 2002	65.5 a	64.5 a	58.8 a
May 16, 2002	62.4 a	57.5 a	53.2 a
June 25, 2002	43.9 a	43.7 a	39.5 b
July 23, 2002	51.3 a	57.9 a	53.6 a
August 22, 2002	56.8 a	66.4 a	61.5 a
September 24, 2002	56.4 b	78.5 a	66.4 ab
November 5, 2002	70.2 a	78.8 a	78.9 a
April 22, 2003	60.8 b	68.9 ab	72.3 a
May 20, 2003	50.9 b	62.1 a	58.6 ab
June 17, 2003	32.8 a	43.6 a	36.5 a
July 22, 2003	59.5 a	78.6 a	67.9 a
August 19, 2003	131.3 a	120.8 a	138.2 a
September 23, 2003	73.8 b	85.8 a	84.2 ab
October 21, 2003	100.6 b	131.9 ab	163.7 a
February 17, 2003	158.0 a	104.3 a	71.7 a

Note: Means in a given row followed by the same letter do not differ significantly at p = 0.5.

TABLE D.17
Mean Concentrations of Zinc (mg/kg) Measured in Tissue Samples Collected, by Grass
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Turfgrass	
Date	**Bermudagrass**	**Zoysiagrass**
May 1, 2002	71.7 a	54.2 a
May 16, 2002	63.1 a	52.3 a
June 25, 2002	54.5 a	30.3 b
July 23, 2002	75.1 a	33.4 b
August 22, 2002	83.2 a	39.9 b
September 24, 2002	95.7 a	38.4 b
November 5, 2002	99.3 a	52.6 b
April 22, 2003	78.8 a	55.8 b

TABLE D.17 CONTINUED
Mean Concentrations of Zinc (mg/kg) Measured in Tissue Samples Collected, by Grass
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Turfgrass	
Date	**Bermudagrass**	**Zoysiagrass**
May 20, 2003	71.8 a	42.6 b
June 17, 2003	50.5 a	24.7 b
July 22, 2003	86.7 a	50.6 b
August 19, 2003	164.1 a	96.0 b
September 23, 2003	103.9 a	58.6 b
October 21, 2003	145.1 a	119.0 a
February 17, 2003	97.4 a	125.2 a

Note: Means in a given row followed by the same letter do not differ significantly at p = 0.5.

TABLE D.18
Analysis of Variance for Zinc Content of Tissue Samples Collected
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Source of Variation	Degrees of Freedom	F Value	Probability of Obtaining a Greater F Value
Grass (G)	1	83.08	<0.0001
Irrigation (I)	2	0.57	0.57
Date (D)	14	13.79	<0.0001
G x I	2	0.16	0.8491
G x D	14	2.87	0.0013
I x D	28	1.71	0.042
G x I x D	28	1.13	0.326

TABLE D.19
Mean Concentrations of Calcium (mg/kg) Measured in Tissue Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Irrigation Treatment		
Date	**EA**	**RW**	**LF**
May 1, 2002	18,228 a	15,567 a	16,802 a
May 16, 2002	28,083 a	29,763 a	21,623 a
June 25, 2002	18,950 a	18,750 a	16,167 a
July 23, 2002	12,177 a	13,800 a	14,207 a
August 22, 2002	23,783 a	26,200 a	22,643 a
September 24, 2002	11,095 a	12,927 a	16,900 a
November 5, 2002	32,550 a	27,850 a	23,933 a
April 22, 2003	10,993 a	13,517 a	15,167 a
May 20, 2003	10,482 a	12,082 a	7,198 a
June 17, 2003	5,352 a	4,728 ab	4,007 b
July 22, 2003	5,022 a	5,570 a	4,455 a
August 19, 2003	7,558 a	7,527 a	7,897 a
September 23, 2003	11,042 a	12,133 a	13,120 a
October 21, 2003	6,848 a	6,755 a	7,250 a
February 17, 2003	11,758 a	13,052 a	7,758 a

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$.

TABLE D.20
Mean Concentrations of Calcium (mg/kg) Measured in Tissue Samples Collected, by Grass
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Turfgrass	
Date	**Bermudagrass**	**Zoysiagrass**
May 1, 2002	15,209 a	18,522 a
May 16, 2002	21,442 b	31,538 a
June 25, 2002	19,444 a	16,467 a
July 23, 2002	14,526 a	12,263 b
August 22, 2002	32,800 a	15,618 a
September 24, 2002	15,306 a	11,976 a
November 5, 2002	26,222 a	30,000 a
April 22, 2003	12,133 a	14,318 a

TABLE D.20 CONTINUED
Mean Concentrations of Calcium (mg/kg) Measured in Tissue Samples Collected, by Grass
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Turfgrass	
Date	**Bermudagrass**	**Zoysiagrass**
May 20, 2003	10,482 a	9,359 a
June 17, 2003	5,571 a	3,820 b
July 22, 2003	5,724 a	4,307 b
August 19, 2003	9,143 a	6,178 a
September 23, 2003	14,316 a	9,881 b
October 21, 2003	7,883 a	6,019 a
February 17, 2003	11,456 a	10,257 a

Note: Means in a given row followed by the same letter do not differ significantly at p = 0.05.

TABLE D.21
Analysis of Variance for Calcium Content of Tissue Samples Collected
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Source of Variation	Degrees of Freedom	F Value	Probability of Obtaining a Greater F Value
Grass (G)	1	3.73	0.0567
Irrigation (I)	2	0.85	0.4334
Date (D)	14	28.96	<0.0001
G x I	2	0.78	0.462
G x D	14	4.13	<0.0001
I x D	28	0.52	0.9705
G x I x D	28	1.42	0.1077

TABLE D.22
Mean Concentrations of Potassium (mg/kg) Measured in Tissue Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Irrigation Treatment		
Date	**EA**	**RW**	**LF**
May 1, 2002	9,781 a	10,170 a	9,224 a
May 16, 2002	9,170 a	9,745 a	9,803 a
June 25, 2002	9,408 a	10,725 a	11,255 a
July 23, 2002	9,840 a	11,428 a	9,368 a
August 22, 2002	11,378 a	12,763 a	15,800 a
September 24, 2002	10,122 a	11,213 a	10,367 a
November 5, 2002	7,207 a	7,717 a	7,770 a
April 22, 2003	5,290 b	6,012 a	5,762 ab
May 20, 2003	5,850 a	5,902 a	5,620 a
June 17, 2003	6,950 ab	7,390 a	6,737 b
July 22, 2003	7,365 a	7,048 a	7,006 a
August 19, 2003	5,242 a	5,298 a	4,790 a
September 23, 2003	5,155 a	5,302 a	5,167 a
October 21, 2003	5,034 a	4,762 a	4,677 a
February 17, 2003	1,747 a	1,258 a	1,772 a

Note: Means in a given row followed by the same letter do not differ significantly at p = 0.5.

TABLE D.23
Mean Concentrations of Potassium (mg/kg) Measured in Tissue Samples Collected, by Grass
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Turfgrass	
Date	**Bermudagrass**	**Zoysiagrass**
May 1, 2002	8,211 b	11,239 a
May 16, 2002	8,524 b	10,621 a
June 25, 2002	8,159 b	12,767 a
July 23, 2002	7,280 b	13,144 a
August 22, 2002	10,974 a	15,653 a
September 24, 2002	9,647 b	11,488 a
November 5, 2002	7,227 a	7,902 a
April 22, 2003	5,874 a	5,501 a

TABLE D.23 CONTINUED
Mean Concentrations of Potassium (mg/kg) Measured in Tissue Samples Collected, by Grass
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Turfgrass	
Date	**Bermudagrass**	**Zoysiagrass**
May 20, 2003	5,186 a	6,396 a
June 17, 2003	6,059 b	7,992 a
July 22, 2003	6,096 b	8,184 a
August 19, 2003	4,311 b	5,909 a
September 23, 2003	4,802 b	5,613 a
October 21, 2003	4,652 b	4,996 a
February 17, 2003	1,452 a	1,732 a

Note: Means in a given row followed by the same letter do not differ significantly at p = 0.5.

TABLE D.24
Analysis of Variance for Potassium Content of Tissue Samples Collected
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Source of Variation	Degrees of Freedom	F Value	Probability of Obtaining a Greater F Value
Grass (G)	1	176.78	<0.0001
Irrigation (I)	2	2.81	0.0679
Date (D)	14	79.2	<0.0001
G x I	2	2.79	0.0668
G x D	14	9.11	<0.0001
I x D	28	1.59	0.0668
G x I x D	28	1.37	0.1349

TABLE D.25
Mean Concentrations of Phosphorus (mg/kg) Measured in Tissue Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Irrigation Treatment		
Date	**EA**	**RW**	**LF**
May 1, 2002	791.9 a	769.6 a	898.7 a
May 16, 2002	1,665 a	1,716 a	1,718 a
June 25, 2002	2,172 a	1,949 a	2,115 a
July 23, 2002	1,112 a	1,194 a	1,238 a
August 22, 2002	1,537 a	1,619 a	1,542 a
September 24, 2002	1,325 a	1,463 a	1,368 a
November 5, 2002	1,381 a	1,338 a	1,095 a
April 22, 2003	2,900 a	2,923 a	3,143 a
May 20, 2003	2,681 a	2,600 a	2,965 a
June 17, 2003	3,329 a	3,202 a	3,245 a
July 22, 2003	3,600 a	3,503 a	3,591 a
August 19, 2003	2,871 a	2,926 a	2,892 a
September 23, 2003	2,633 a	2,825 a	2,742 a
October 21, 2003	2,940 a	3,066 a	2,805 a
February 17, 2003	3,083 a	3,296 a	3,247 a

Note: Means in a given row followed by the same letter do not differ significantly at p = 0.5.

TABLE D.26
Mean Concentrations of Phosphorus (mg/kg) Measured in Tissue Samples Collected, by Grass
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Turfgrass	
Date	**Bermudagrass**	**Zoysiagrass**
May 1, 2002	818.0 a	822.1 a
May 16, 2002	1,718 a	1,681 a
June 25, 2002	2,173 a	1,984 a
July 23, 2002	1,152 a	1,211 a
August 22, 2002	1,511 a	1,621 a
September 24, 2002	1,421 a	1,350 a
November 5, 2002	1,318 a	1,225 a
April 22, 2003	3,038 a	2,939 a

TABLE D.26 CONTINUED
Mean Concentrations of Phosphorus (mg/kg) Measured in Tissue Samples Collected, by Grass
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Turfgrass	
Date	**Bermudagrass**	**Zoysiagrass**
May 20, 2003	2,662 a	2,836 a
June 17, 2003	3,021 a	3,496 a
July 22, 2003	3,765 a	3,365 a
August 19, 2003	3,252 a	2,540 a
September 23, 2003	2,674 a	2,793 a
October 21, 2003	3,180 a	2,694 b
February 17, 2003	3,244 a	3,173 a

Note: Means in a given row followed by the same letter do not differ significantly at p = 0.5.

TABLE D.27
Analysis of Variance for Phosphorus Content of Tissue Samples Collected
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Source of Variation	Degrees of Freedom	F Value	Probability of Obtaining a Greater F Value
Grass (G)	1	3.94	0.0501
Irrigation (I)	2	0.18	0.8331
Date (D)	14	143.7	<0.0001
G x I	2	0.22	0.8035
G x D	14	3.3	0.0003
I x D	28	0.34	0.9988
G x I x D	28	1.18	0.2725

TABLE D.28
Mean Concentrations of Total Kjeldahl Nitrogen (mg/kg) Measured in Tissue Samples Collected by Irrigation Treatment
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Irrigation Treatment		
Date	**EA**	**RW**	**LF**
May 1, 2002	14,162 a	14,854 a	15,415 a
May 16, 2002	12,742 a	12,802 a	13,474 a
June 25, 2002	12,055 b	15,670 a	14,856 a
July 23, 2002	12,982 a	10,350 a	11,515 a
August 22, 2002	11,499 a	12,953 a	13,519 a
September 24, 2002	12,299 a	14,789 a	15,257 a
November 5, 2002	11,650 a	13,624 a	11,650 a
April 22, 2003	15,212 b	18,010 a	18,435 a
May 20, 2003	14,297 a	17,644 a	16,340 a
June 17, 2003	16,478 a	17,787 a	17,034 a
July 22, 2003	14,861 a	14,922 a	13,693 a
August 19, 2003	13,377 a	14,478 a	13,983 a
September 23, 2003	14,328 a	15,219 a	15,809 a
October 21, 2003	16,616 a	17,488 a	17,431 a
February 17, 2003	17,380 a	18,237 a	16,001 a

Note: Means in a given row followed by the same letter do not differ significantly at $p = 0.05$.

TABLE D.29
Mean Concentrations of Total Kjeldahl Nitrogen (mg/kg) Measured in Tissue Samples Collected, By Grass
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Turfgrass	
Date	**Bermudagrass**	**Zoysiagrass**
May 1, 2002	13,903 a	15,718 a
May 16, 2002	13,832 a	12,179 a
June 25, 2002	14,613 a	13,774 a
July 23, 2002	12,497 a	10,735 a
August 22, 2002	12,137 a	13,177 a
September 24, 2002	15,308 a	12,923 a
November 5, 2002	14,533 a	11,214 b
April 22, 2003	19,258 a	15,179 b

TABLE D.29
Mean Concentrations of Total Kjeldahl Nitrogen (mg/kg) Measured in Tissue Samples Collected, By Grass
Edwards Aquifer Recharge Zone Irrigation Pilot Study

	Turfgrass	
Date	**Bermudagrass**	**Zoysiagrass**
May 20, 2003	17,218 a	14,969 a
June 17, 2003	18,270 a	15,929 a
July 22, 2003	15,490 a	13,494 a
August 19, 2003	15,386 a	12,506 a
September 23, 2003	16,771 a	13,467 b
October 21, 2003	19,638 a	14,718 b
February 17, 2003	18,091 a	16,322 a

Note: Means in a given row followed by the same letter do not differ significantly at p = 0.05.

TABLE D.30
Analysis of Variance for Total Kjeldahl Nitrogen Content of Tissue Samples Collected
Edwards Aquifer Recharge Zone Irrigation Pilot Study

Source of Variation	Degrees of Freedom	F Value	Probability of Obtaining a Greater F Value
Grass (G)	1	70.54	<0.0001
Irrigation (I)	2	10.28	0.0001
Date (D)	14	21.44	<0.0001
G x I	2	3.1	0.0499
G x D	14	3.44	0.0002
I x D	28	1.36	0.1581
G x I x D	28	1.34	0.1529

Appendix E

Potential Groundwater Contamination from Irrigation of Turf with Recycled Water

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July 22, 2003

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Introduction

Water is essential for life. Quantity is not a problem since 2/3 of the earth is covered with water, however, the quality of our fresh water reserves must be protected to ensure both public health and an adequate supply of potable water for future generations. For the United States as a whole, groundwater has been a large source of high quality water (Keswick and Gerba, 1980; Scott, 1985; Moody, 1990). Moody (1990) reported that approximately 53% of the total population and 97 % of the rural population in the United States relies on groundwater sources to provide drinking water. Groundwater use will continue to increase as the population increases and high quality groundwater will become an even more precious commodity.

San Antonio, Texas (located in Bexar County) is an area where groundwater is essential for life. The Edwards Aquifer provides 90 to 100% of the drinking water for the San Antonio area (Diehl, 2000; K. Diehl, personal communication). In 1989, Bexar County used 84.9 billion gallons of water (261,000 ac.-ft./yr) from the Edwards Aquifer for municipal, military, industrial, and irrigation uses (Nalley and Thomas, 1990), and demands on the aquifer to produce sustained amounts of high quality water are only going to increase. Conservation measures are being taken, and more will have to be taken, to assure that the quantity of water being withdrawn from the Edwards Aquifer is kept to a sustainable amount.

One major conservation measure being pursued by the city of San Antonio is the use of recycled water for irrigation. Recycled water is municipal wastewater that has been treated to meet state and federal requirements and is being marketed for reuse with irrigation and industrial plants being the two most common uses. Reusing water may actually pose less environmental threat because the water is not discharged directly into surface water as is typical of most wastewater treatment plants (Bernarde, 1973, United States Golf Association, 1994). In the San Antonio area, recycled water has the potential to provide 35,000 ac.-ft./yr (13.4% of the annual use)(Diehl, 2000), and will be a valuable source of relief for the taxed Edwards aquifer.

One very valid concern with the use of recycled water is the potential for contamination of groundwater or the Edwards aquifer through leaching or overland flow. Leaching is the downward movement of water and dissolved constituents in soil and occurs when more water is applied to a soil than that soil can hold (Ritter and Shirmohammadi, 2001). Overland flow is the movement of water above the soil surface and occurs when the precipitation rate exceeds the infiltration rate of the soil. Contamination of the Edwards aquifer from recycled water is of concern because recycled water usually contains nutrients, salts, bicarbonate, and may contain bacteria or viruses. When proper management practices are used, the plant-soil system acts as a filter to remove and/or bind some of these constituents, therefore preventing them from moving into the groundwater. However, if proper management practices are not used, the potential does exist for some of these constituents to be leached into the groundwater. This risk is particularly high when the recycled water is applied to the aquifer recharge zone as the recharge zone is the major entry point to the aquifer. Recycled water has been used around the world in many situations (Koerner and Haws, 1979; Schalscha et al., 1979; El-Nennah et al., 1982; Reed, 1982; Moody, 1990; Feigin et al., 1991; United States Golf Association, 1994; Al-A'ama and Nakhla, 1995; Sloss et al., 1996) and with proper management practices, irrigating with recycled water poses very little threat to groundwater.

This review will focus on several aspects of irrigating with recycled water, the associated risks, and best management practices to minimize those risks. More specifically, it will address the following: (1) sources of groundwater contamination, (2) the vulnerability of the Edwards aquifer to contamination, (3) groundwater and recycled water quality, and (4) the potential risks associated with nitrogen, phosphorus, potassium, boron, salts, bicarbonates, bacteria and viruses, and heavy metals (all of which may be present in recycled water).

Groundwater Contamination

Agricultural activities have been a major source of groundwater contamination. Hubbard and Sheridan (1989) reported nitrogen concentrations higher than the maximum allowable level of 10 ppm for drinking water in Arkansas (Wagner et al., 1976), Georgia (Hubbard et al., 1987), New England (Spalding and Exner, 1980), New York (Meisinger, 1976), Oklahoma (Naney et al., 1987; Sharpley et al., 1987), Wisconsin (Saffigna and Keeney, 1977), Canada (Hill, 1982), and England (Oakes et al., 1981; Edmunds et al., 1982) and attributed those higher concentrations to agricultural activities. However, agricultural activities are not the only source of potential groundwater contamination. Geraghty and Miller (1978) cited septic tanks, cesspools, landfills, industrial wastes (ponds, pits, lagoons, spills), buried pipelines, storage tanks, mining activities, and highway deicing salts as potential sources of groundwater contamination.

Agricultural contamination of groundwater can easily occur, but is not inevitable. Using properly managed recycled water for irrigation allows for a low amount of nutrients to be applied over an extended period of time. Frequent, light fertilizer applications (as would be the case when irrigating with recycled water) allow plants to take up a higher percentage of the total amount of nutrient applied (Snyder and Burt, 1976; Snyder et al., 1977; Smika and Watts, 1978; Gerwing et al., 1979; Ritter, 1988; Schepers et al., 1995). If fertilization exceeds plant needs, or irrigation leaches nutrients out of the root zone before plants can take up those nutrients, the nutrients will most likely migrate to the groundwater. However, if fertilization supplies just what the plant needs and irrigation is not excessive, nutrient leaching is minimal (Brown et al., 1977; Brown, 1982; Brown et al., 1982; Keeney, 1982; Ritter, 1988; Gold et al., 1990).

Soil texture and depth to groundwater also affect the potential for groundwater contamination. Generally, sandy soils allow more leaching than clay textured soils (Brown et al., 1977; Brown et al., 1982; Aldrich, 1984; Adriano, 1994; Brown et al., 1984; Petrovic, 1990; Bergstrom, 1995; Ritter and Shirmohammadi, 2001), and as soil depth to groundwater increases, the likelihood of contamination decreases (Fritch et al., 2000). The likelihood of groundwater contamination is also affected by the geologic formation where the groundwater is stored. For example, the part of the Edwards aquifer that lies under downtown San Antonio, Texas, is confined (Kreitler and Browning, 1983; MaClay and Small, 1986; Butler, 1987). That means the water is between two layers (usually rock or clay) that prohibit vertical water movement. Anything that may leach down from the surface cannot pass through the confining layer to contaminate the groundwater.

The level of groundwater contamination can also be affected by the crop being grown. Crops differ in their nutrient needs and their ability to take up nutrients efficiently. For example, grains have lower nitrogen use efficiencies (33%) than turfgrasses (63 to 84%) (Raun and Johnson, 1999; Bowman et al., 2002). This is not to say that it is impossible to leach nutrients through turfgrass, because if turfgrass is over-fertilized or over-irrigated, leaching will occur (Baier and Rykbost, 1976; Snow, 1976; Hayes et al., 1990b).

Properly managed irrigation with recycled water on turfgrass poses very little risk of groundwater contamination due to nutrients. Actively growing turfgrasses are very efficient at taking up nutrients applied in frequent, light applications. Using recycled water provides frequent, light applications of nutrients (fertilizers). Properly managed irrigation will prevent over-watering and therefore leaching even on sandy soils. Golf course greens are typically sands but the other portions of golf courses are natural soils that may or may not be sands. Improper irrigation management is the most likely source of groundwater contamination when irrigating with recycled water, so education must be an integral part of any recycled water program.

Edwards Aquifer

The Edwards aquifer covers portions of six counties in central Texas (Kinney, Uvalde, Medina, Bexar, Comal, and Hays counties) (Garza, 1962; Small, 1986; MaClay and Land, 1988; Nalley and Thomas, 1990; Bader et al., 1993; Kuniansky and Holligan, 1994) and supplies 90 to 100% of the drinking water for the San Antonio area (Diehl, 2000; K. Diehl, personal communication). In Bexar County there are three dominant groundwater features, all of which are oriented Southwest to Northeast. The first is the unconfined, recharge zone of the Edwards aquifer which is located North and West of downtown San Antonio. The second is the confined zone which is right beneath downtown San Antonio and extends Southwest and Northeast to the county lines. The third is saline groundwater which is found in the Southeast third of the county with its Northwest boundary being underneath the Southeast corner of San Antonio (Small, 1986; Kreitler and Browning, 1983; MaClay and Land, 1988; Nalley and Thomas, 1990; Bader et al., 1993; Kuniansky and Holligan, 1994).

The Edwards aquifer is a carbonate aquifer (Kreitler and Browning, 1983; MaClay and Land, 1988; Burkart and Stoner, 2001). Burkart and Stoner (2001) describe carbonate aquifers as “bedrock aquifers commonly formed in limestone, dolomite, and chalk. Karst features, such as solution-enlarged fractures, sink holes, and caves, form in these rocks at land surface and in the subsurface.”

All of the appreciable recharge to the Edwards aquifer occurs in the unconfined, recharge zone. Stream flow across, and into karst features is the primary mechanism for aquifer recharge (Garza, 1966; Kreitler and Browning, 1983; Butler, 1987; Kuniansky and

Holligan, 1994). Some recharge occurs through soil percolation in the recharge zone, but with the water table generally deeper than 98 ft. and annual precipitation of 28 in. (Garza, 1962; Kreitler and Browning, 1983), percolation is not a major means of recharge on a large scale (Kreitler and Browning, 1983). Percolation may be an issue on a local scale if over-irrigation occurs, but with proper irrigation management, percolation to groundwater would be negligible. Because most of the recharge flows more directly into the aquifer, through karst features, there is little opportunity for contaminants in stream water to be filtered before reaching the aquifer (Butler, 1987).

Negligible recharge in the confined zone of the aquifer is due to the relatively impermeable clay and limestone layers above and below the aquifer (Butler, 1987). Water flows into the confined zone from recharge zones to the North and West, and once water is in the aquifer, it generally flows in a West-Southwest to Northeast direction (Kreitler and Browning, 1983; MaClay and Small, 1986). The confined zone is generally under artesian pressure (Kreitler and Browning, 1983; Butler, 1987), which means that if there were cracks in the impermeable layer above the aquifer, water movement would be towards the surface rather than into the aquifer.

The largest concern for groundwater contamination is in the recharge zone of the Edwards aquifer. There is no recharge in the confined zone and the majority of the recharge in the recharge zone occurs by high volume flow from streams into joints or cracks (karst features). Regionally, percolation to groundwater through soil is minimal because of the depth to groundwater and moderate annual precipitation. Percolation to groundwater can occur locally, but would be avoided with proper irrigation management. The potential for contamination of the Edwards aquifer is high because essentially none of the recharge water is filtered through a soil system before entering the aquifer because recharge occurs primarily from stream flow into karst features. Therefore the greatest risk for aquifer contamination is most likely due to impairment of streams or other waters flowing through karst features and into the aquifer.

Groundwater and Recycled Water Quality

The largest concern with using recycled water for irrigation is the potential for the recycled water constituents to reach the aquifer and contaminate the groundwater. Diehl (2000) and Bader et al. (1993) reported on the typical water quality of recycled water and Edwards aquifer water and found that recycled water had higher concentrations of nitrogen, phosphorus, potassium, boron, and total dissolved solids than stream water, but had no higher concentrations of fecal coliforms than stream water (Table 1). Kreitler and Browning (1983) reported nitrate concentrations in the major streams recharging the Edwards aquifer ranging from 0.6 to 7.9 ppm, and Reeves (1976) reported nitrate concentrations ranging from 0.4 to 13.6 ppm for the same streams. The amount of nitrogen applied in recycled water is insufficient for growth of some turfgrasses (Tables 1 and 2) and conventional fertilization will have to accompany irrigation with recycled water to supply sufficient nitrogen for acceptable turfgrass.

TABLE 1

Water quality of recycled and Edwards aquifer water. Taken from Diehl (2000) and Bader et al. (1993).

Water Quality Measurement	Recycled water (ppm)	Applied in recycled water [a] (lb./ac./yr)	Edwards aquifer water (ppm)
Nitrogen (N)	17	124.78	0-0.2
Phosphorus (P)	2	14.35	0
Potassium (K)	10	73.48	1-2
Boron (B)	0.25	1.83	0
Total Dissolved Solids [b]	700	5130.40	250-400
Fecal Coliforms	<1.64 cfu/in.^{3} [c]		0-25 cfu/ in.^{3} [d]

[a] based on 32.43 inches/year irrigation

[b] Total Dissolved Solids measures water salinity

[c] cfu = colony forming units.

[d] EPA standards for drinking water are 0 fecal coliforms/6.1 in.^{3}.

Recycled water can be treated to one of three levels (primary, secondary, or tertiary). Primary treated water has had most of the solid waste removed by sedimentation. Secondary treated water has had microorganisms introduced into primary treated water, which remove essentially all of the solid waste and decrease the number of bacteria and viruses. Tertiary treated water applies ultra-violet light and/or chlorination to secondary treated water, which removes essentially all bacteria and viruses. Chlorination is the method of choice with the San Antonio recycled water (K. Diehl, personal communication, 2003).

The recycled water from San Antonio has higher concentrations of nitrogen, phosphorus, potassium, boron, and total dissolved solids (TDS) than the Edwards aquifer (Table 1). However, fecal coliforms in recycled water are no more numerous than in aquifer water. The higher amounts of nitrogen, phosphorus, and potassium in recycled water could be used by plants as nitrogen, phosphorus, and potassium are the main nutrients in conventional fertilizers. Boron doesn’t cause plant damage unless the concentration in the irrigation water exceeds 2 ppm (Diehl, 2000). Diehl (2000) also reported that most turfgrasses are not adversely affected unless TDS levels are above 1,920 ppm. Total dissolved solids applied in the recycled water can be leached out of the root zone if it reaches intolerable levels for turfgrass (Hoffman and van Genuchten, 1983; Asano and Pettygrove, 1987). However, leached TDS will eventually reach the aquifer so care must be taken in leaching and limiting the acreage irrigated with recycled water.

The largest difference between tertiary recycled water and Edwards aquifer water is the amount of nutrients (nitrogen, phosphorus, and potassium). Proper irrigation and fertility management of turfgrass will ensure that these nutrients are taken up by the turf and not leached into the groundwater. Using recycled water for irrigation could also reduce the amount of conventional fertilizer applied to the turfgrass and will provide the frequent, light applications necessary for the most efficient fertilizer use.

Nitrogen

In a soil-crop system, nitrogen is usually the most deficient nutrient, and therefore most fertilization programs target nitrogen. Nitrogen is also extremely mobile in soils because it is most commonly found in its anionic state (negatively charged particle) called nitrate (NO_3^-) (Follett, 1989; Ritter and Shirmohammadi, 2001). Nitrate leaches readily in soil because soil is generally negatively charged and like charges repel one another. Since nitrate leaches readily in soils and fertilization applies large quantities of nitrogen to the soil, it is not surprising that commercial fertilizer is the primary agricultural source of groundwater nitrogen pollution (Puckett, 1995).

Nitrate losses can be reduced by applying the nitrogen in different forms. Quick release forms of nitrogen (ammonium nitrate, ammonium sulfate, ammonium phosphates, potassium nitrate, and urea) have a higher potential for leaching as they are highly soluble (Havlin et al., 1999; Turgeon, 1999). Slow release forms of nitrogen (sulfur-coated urea (SCU), polymer-coated urea (PCU), urea formaldehyde (UF), isobutylidine diurea (IBDU), and activated sewage sludge (Milorganite)) reduce leaching potential because they reduce the solubility (UF and IBDU), create a barrier preventing soluble nitrogen from being released until the barrier is broken (SCU and PCU), or tie the nitrogen up in organic compounds (Milorganite) (Havlin et al., 1999; Turgeon, 1999). Snyder et al. (1984) found that less nitrogen was leached through bermudagrass with SCU than with ammonium nitrate. They also found that less nitrogen was leached when soluble nitrogen was applied through the irrigation system (daily irrigation) than when either fast or slow release fertilizers were applied conventionally. This indicates that bermudagrass is the most efficient at preventing nitrate leaching when the nitrogen is applied in low, frequent applications as would be the case when irrigating with recycled water.

Although nitrate leaching is the major avenue of nitrogen loss from the soil system, it is not the only one. Nitrogen can also be lost through ammonia volatilization, which is the conversion of ammonium (NH_4^+) to ammonia gas (NH_3), which is then lost to the atmosphere. A third pathway for nitrogen loss is denitrification, which is the conversion of nitrate (NO_3^-) to N_2 and N_20 gases, which are then lost to the atmosphere. Nitrogen can also be lost from the soil by plant uptake in the nitrate and ammonium forms (Allison, 1966; Meek et al., 1982; Bock, 1984; Broadbent and Reisenauer, 1985; Bowman et al., 1987; Petrovic, 1990; Feigin et al., 1991). Since nitrogen from ammonia volatilization, denitrification, and plant uptake does not affect groundwater quality, nitrate leaching will be the focus of this review.

Nitrate leaching from agricultural fertilizer application has been studied extensively and there is no question that nitrate leaches readily and can contaminate groundwater under certain conditions (Allison, 1966; Zwerman et al., 1972; Endelman et al., 1974; Rieke and Ellis, 1974; Baier and Rykbost, 1976; Burwell et al., 1976; Snow, 1976; Saffigna and Keeney, 1977; Snyder et al., 1977; Cameron et al., 1978; Duble et al., 1978; McNeal and Pratt, 1978; Spalding et al., 1978; Exner and Spalding, 1979; Schalscha et al., 1979; Keeney, 1983; Bock, 1984; Flipse et al., 1984; Gascho et al., 1984; Hubbard et al., 1984; Gold et al., 1990; Spalding and Exner, 1993; McNeal et al., 1995). Nitrate leaching primarily occurs following excessive fertilizer application or with excessive irrigation.

Although nitrate does readily leach from the soil, the amount of nitrate that leaches can be drastically reduced or eliminated by proper management practices.

Applying only enough fertilizer (amount and timing) to meet crop needs, and avoiding over-irrigation will have the greatest effect on reducing nitrate leaching (Calvert, 1975; Burwell et al., 1976; Snyder et al., 1977; Duble et al., 1978; Keeney, 1982; Keeney, 1983; Aldrich, 1984; Pratt, 1984; Snyder et al., 1984; Follett, 1989; Moody, 1990; Petrovic, 1990; Adriano, 1994; Tamminga, 1995; Burkart and Stoner, 2001; Ritter and Shirmohammadi, 2001). Table 2 shows the recommended nitrogen application rates for several turfgrasses that may be used in the San Antonio area.

TABLE 2
Recommended nitrogen application rates for some common grasses.

Species	lb. N/ac./yr
St. Augustinegrass	130-217
Common bermudagrass	174-261
Hybrid bermudagrass	217-348
Zoysiagrass	87-217
Buffalograss	44-130
Centipedegrass	44-130
Bentgrass	174-348

Recycled water would supply sufficient nitrogen for zoysiagrass, buffalograss, and centipedegrass, but insufficient nitrogen for St. Augustinegrass, bermudagrass and bentgrass (Tables 1 and 2). There are other influences in the soil-plant system that affect nitrate leaching (soil texture, crop, etc.), but proper fertilizer and irrigation practices are the primary controlling factors, on any soil and with any crop, in determining the amount of nitrate leaching that occurs.

Applying the correct amount of fertilizer at the time when plants need the fertilizer will reduce or eliminate nitrate leaching. If an excessive amount of fertilizer is applied, the plants cannot take up all of it and the excess will leach. If the timing of nitrogen application is incorrect the fertilizer will not be there when the plants are taking up nitrogen. For instance, if a crop requires 150 lb. N/ac./yr and 300 lb. N/ac./yr is applied, nitrate will leach (Zwerman et al., 1972; Duble et al., 1978; Smika and Watts, 1978; Gerwing et al., 1979; Snyder et al., 1981; Keeney, 1982; Meek et al., 1982; Owen and Barraclough, 1983; Morton et al., 1988; Ritter, 1988; Petrovic, 1990; Adriano, 1994; Ritter and Shirmohammadi, 2001). If 150 lb. N/ac./yr is applied in a single application, more nitrate will leach than if the 150 lb. was applied in smaller quantities throughout the growing season as needed by the crop (Snyder and Burt, 1976; Snyder et al., 1977; Smika and Watts, 1978; Gerwing et al., 1979; Timmons and Dylla, 1981; Tucker and Murdock, 1984; Ritter, 1988; Adriano, 1994; Ritter and Shirmohammadi, 2001). Proper fertilizer management will ensure minimal leaching because the nutrients will be taken up by plants before leaching from the root zone and into groundwater.

Proper irrigation management is the second factor controlling nitrate leaching. Nitrate moves with leached water and more leaching means more nitrate movement out of the root zone. Efficient irrigation systems leach less water (and therefore nitrate) than inefficient ones and low water application rates leach less than high water application rates (Calvert, 1975; Duble et al., 1978; Lund et al., 1981; Timmons and Dylla, 1981; Keeney, 1982; Gardner and Roth, 1984; Snyder et al., 1984; Hergert, 1986; Montgomery et al., 1988; Morton et al., 1988; Ritter, 1989; Petrovic, 1990; Adriano, 1994; Adamsen and Rice, 1995; Bergstrom, 1995; Burkart and Stoner, 2001; Ritter and Shirmohammadi, 2001). The key to preventing leaching is to supply only enough water to meet plant needs. Water is lost from the soil by evaporation and transpiration (collectively called evapotranspiration, or ET). Proper irrigation management consists of irrigating only when ET has depleted soil water content to a point where plants are stressed and only irrigating enough to replenish the soil water content (not over-irrigating). Sensor controlled irrigation (either soil moisture or ET) allows managers to apply only enough water to replenish the soil water lost through ET. A soil moisture sensor controlled system turns on the irrigation system when the soil water content reaches a given depletion limit and turns off the system when the soil water content is optimum. An ET controlled system turns on the irrigation system when a set amount of ET has occurred and the system runs for a set amount of time to replenish the soil water. Using sensor controlled irrigation is the most efficient way to prevent over-irrigating and therefore nitrate leaching. Proper irrigation management does not require a sensor controlled irrigation system, but it is highly recommended. Proper irrigation management, either through a sensor controlled irrigation system or a carefully monitored manual system, will ensure minimal nitrate leaching because water leaching will be minimized.

The amount of nitrate leaching is also affected by soil texture, but to a lesser degree than fertilization and irrigation. Nitrate leaches more readily through porous soils such as sand and peat than through less porous soils such as clay (Brown et al., 1977; Brown et al., 1982; Aldrich, 1984; Brown et al., 1984; Petrovic, 1990; Adriano, 1994; Bergstrom, 1995; Ritter and Shirmohammadi, 2001). Nitrate leaches more readily through porous soils because these soils have less water holding capacity (Ritter and Shirmohammadi, 2001) and lower cation exchange capacities (Havlin et al., 1999). Cation exchange capacity is the amount of exchangeable cations per unit dry weight of soil (Turgeon, 1999). Proper fertilization and irrigation management are more important than soil texture because nitrate leaching is not inevitable on sandy soils, nor is it impossible on clay soils. For example, a golf course (mostly sand soils) that is properly managed to apply the correct amount of fertilizer when the turf needs the fertilizer, and uses sensor controlled irrigation to minimize over-watering (leaching) will leach much less nitrate than a home lawn on a clay soil where the homeowner applies excessive amounts of fertilizer once or twice a year and irrigates every other day for two hours. Management practices must be adjusted to soil texture, but a person can find very different outcomes from studies on the same soil texture. Appendix A illustrates this point. Comparing only the studies conducted on sand, the range of nitrate leaching was broad. Nitrate leaching through sands ranged from 0 to 326 ppm and from 0 to 72 lb. N/ac./yr., which shows that factors such as fertilization, irrigation, and crop selection have a significant impact on nitrate leaching in any soil. Soil texture is important because leaching does occur more easily through sand than through clay soils, but fertilization, irrigation, and crop selection can have greater impacts on nitrate leaching than soil texture alone.

Crop selection affects nitrate leaching because nitrogen use efficiency is not equal for all crops, or even species within a crop (Appendix A; Bowman et al., 2002). Generally, turfgrass responds fairly rapidly to nitrogen application and is relatively efficient at taking up that nitrogen (Starr and DeRoo, 1981; Cisar et al., 1985; Erickson et al., 2001; Bowman et al., 2002). Cropping techniques can also affect the amount of nitrate leaching in an agricultural system. In general, more nitrate leaching occurs under row crops that are spaced at lower plant densities than under cover crops, like turfgrass, where higher plant densities are desired (Appendix A; Gold et al, 1990, Puckett, 1995). Proper fertilizer and irrigation management of cover crops can reduce or eliminate nitrate leaching (Sidle and Johnson, 1972; Rieke and Ellis, 1974; Snyder et al., 1977; Anderson et al., 1981; Snyder et al., 1981; Starr and DeRoo, 1981; Brown et al., 1982; Snyder et al., 1984; McLaughlin et al., 1985; Brinsfield et al., 1988; Morton et al., 1988; Gold et al., 1990; Mancino and Troll, 1990; Petrovic, 1990; McCracken, 1995; Miltner et al., 1996), but care must be taken to assure proper management because nitrate leaching can occur even under cover crops (Rieke and Ellis, 1974; Baier and Rykbost, 1976; Snow, 1976; Brown et al., 1977; Snyder et al., 1977; Brown et al., 1982; Flipse et al., 1984; Petrovic, 1990; Adriano, 1994). Crop selection can have a significant effect on the amount of nitrate leaching that occurs in any given soil. Turfgrasses are less likely to leach nitrate than other crops because of the high densities at which they are grown and their nitrogen use efficiency.

Leaching of nitrates supplied by recycled water is of utmost concern in the San Antonio area. Application of recycled water to various crops has been shown to affect nitrate leaching (Overman et al., 1976; Burton and Hook, 1979; Hook and Burton, 1979; Schalscha et al., 1979; Lund et al., 1981; El-Nennah et al., 1982; Feigin et al., 1984; Pruitt et al., 1988; Hayes et al., 1990b). However, proper application of recycled water is very unlikely to cause any significant increases in groundwater nitrate levels (Sidle and Johnson, 1972; Overman et al., 1976; Hook and Burton, 1979; Anderson et al., 1981; Follett, 1989; Hayes et al., 1990a; Shahalam et al., 1998). Nitrate leaching from turfgrass that has been properly irrigated with recycled water would be minimal for several reasons: (1) healthy turfgrass competes very well for nitrogen, (2) recycled water applies nitrogen in frequent, small applications so no large amounts of nitrogen are in the soil at any one time to be leached, and (3) proper irrigation would minimize movement of water and thus nitrogen from the root zone. Managers of recycled water in the San Antonio area will have to be very careful because the recycled water is fairly high in nitrogen (17 ppm) (Diehl, 2000). However, with proper management, recycled water will allow managers to reduce conventional fertilization, conserve high quality aquifer water for other purposes, and pose minimal risks to groundwater.

Phosphorus

Over the past decade, phosphorus has received increased attention for its role in eutrophication. As a result, much research has been done on the loss of phosphorus from agricultural lands due to fertilization and management practices. Phosphorus is much more likely to contaminate lakes, streams, and therefore the Edwards aquifer through overland flow than through percolation through the soil as phosphorus is much less mobile in soils than nitrogen. In soil, phosphorus is predominantly in its phosphate form (PO_4^+). Phosphate, being a cation, is readily adsorbed to the negatively charged soil particles, and therefore not readily leached into subsurface soils (Pratt et al., 1956; Humphreys and Pritchett, 1971; Russell, 1973; Syers et al., 1973; Snyder and Burt, 1976; Barrow, 1978; Duble et al., 1978; Parfitt, 1978; Reddy et al., 1980; Ryden and Pratt, 1980; Sibbesen, 1981; Latterel et al., 1982; Feigin et al., 1984; Sharpley et al., 1984; Nagpal, 1985; Sharpley, 1985; Sharpley, 1986; Sharpley and Menzel, 1987; Weaver et al., 1988; Eghball and Sander, 1989; Eghball et al., 1990; Guertal et al., 1991; Mozaffari and Sims, 1994; Tamminga, 1995). Phosphorus can be leached from very sandy soils, because of excessive irrigation, or where excessive amounts of phosphorus are present in fertilizer, recycled water, or soil (Calvert, 1975; Reddy et al., 1980; Ryden and Pratt, 1980; Latterell et al., 1982; Nagpal, 1985; Weaver et al., 1988; Hayes et al., 1990; Mansell et al., 1991; Heckrath et al., 1995; Stanley et al., 1995; Eghball et al., 1996; He et al., 1999). Since low amounts of phosphorus will be applied in the San Antonio recycled water (Table 1) compared to what turfgrass takes up from the soil (tall fescue and bermudagrass remove 30 and 46 lb. P/ac./yr respectively; Ryden and Pratt, 1980; Sharpley, 1985), leaching of phosphorus supplied by recycled water would likely be insignificant. As recycled water supplies less than 15 lb./ac./yr (Table 1), the major source of phosphorus to turfgrass would be the soil. Unless clippings are removed the phosphorus being taken up by the recycled water and being extracted from the soil is not being removed from the system. As the clippings decompose, the phosphorus would be released again to the soil system and over time would increase the phosphorus content near the surface where surface flow and erosion are most likely. As recycled water will supply insufficient amounts of phosphorus for plant growth, the problem is dealing with phosphorus buildup at the surface which would be a concern whether recycled water was used or not. Reducing the potential for phosphorus contamination in areas like San Antonio with very high naturally occurring soil phosphorus contents (192 ppm; J. Thomas, unpublished data) can be accomplished by basing fertilizer application of phosphorus on soil tests and proper irrigation.

The most likely path for phosphorus to reach the Edwards aquifer would be through soil erosion or surface flow into karst features. Turfgrass has been found to prevent runoff in all but the most severe rainfall events (Beard & Green, 1994) and grasses have been used extensively to control soil erosion (Dabney et al., 1997; Grace et al., 1998; Simon and Collison, 2002). Researchers have also looked at phosphorus content of runoff from turfgrass and found that turfgrass is very efficient at preventing nutrient movement in surface flow. Gaudreau et al. (2002) fertilized bermudagrass plots on an 8.5% slope with varying amounts of phosphorus as inorganic superphosphate fertilizer or manure. Three days following an application of 44.5 lb./ac. of phosphorus the plots received 1.6 in. of rain. The phosphorus application produced an available phosphorus level of 183 ppm in the soil with only 30 ppm in the runoff water. Except for this one rain event, phosphorus concentrations in runoff never exceeded 7 ppm. Harrison et al. (1993) fertilized turfgrass on 9 to 14% slopes with 6.73 lb. P/ac./yr. in four applications simulating professional turfgrass management practices. They then measured phosphorus concentrations in runoff after natural and simulated rainfall events. They found the average phosphorus concentration in runoff to be 1.67 ppm with the highest concentration being 6 ppm. If plots on slopes with recent phosphorus fertilization only had phosphorus concentrations of 6 and 30 ppm in the runoff water, it is highly unlikely that recycled water with a phosphorus concentration of 2 ppm would cause a significant increase in phosphorus content of runoff water. The risk of significant increases of phosphorus in the Edwards aquifer due to the use of recycled water is minimal.

Potassium

Potassium, like phosphorus, is also less problematic than nitrogen. Like phosphorus, potassium is a cation (K^+), and therefore is adsorbed to soil particles. Generally, very little potassium is leached through finer textured soils (Barber et al., 1971; MacLean, 1977; Allen et al., 1978; King, 1982; Bertsch and Thomas, 1985), but sandy soils, high potassium concentrations, or over-irrigation, can cause leaching to occur (Bertsch and Thomas, 1985).

Plants, especially grasses, take up a lot of potassium, so a lot more potassium is applied to crops than phosphorus. Potassium leaches more readily than phosphorus, but much less than nitrogen (Duble et al., 1978). Grasses eliminate almost all potassium leaching (Terman and Allen, 1970; Allen et al., 1978; Robinson, 1985) because they scavenge so efficiently for the nutrient. Overman et al. (1976) and Feigin et al. (1979) reported potassium uptake by grass exceeded the amount of potassium applied in recycled water. Overman et al. (1976) applied 1 to 4 in./week of recycled water with a potassium concentration of 5.5 ppm, and reported that for most irrigation rates potassium uptake exceeded the amount added through the recycled water. Feigin et al. (1979) applied 35 in. of recycled water with a potassium concentration ranging from 11 to 27 ppm, and found that grass removed twice the amount added through the recycled water. Potassium concentration in San Antonio recycled water is 10 ppm (Diehl, 2000), and turfgrass should have no problem removing all of the available potassium.

Problems may occur with San Antonio recycled water if proper management practices are not followed. Over-fertilization will cause potassium to leach and over-irrigating will move potassium through the root zone too quickly for the turf to take it all up. However, proper fertilization and irrigation management practices on turfgrass would result in insignificant amounts of potassium leaching.

Boron

Boron is an element found in recycled water that can be toxic to plants at only slightly higher levels than are required for healthy plants (Oster and Rhoades, 1985). Typical recycled water concentrations range from <0.1 to 2.5 ppm boron, with an average concentration of 1 ppm (Page and Chang, 1981). San Antonio recycled water has an average boron concentration of 0.25 ppm, and recycled water with boron concentrations lower than 0.5 ppm will not damage any plant species (Diehl, 2000).

Boron is mobile in soils, can be leached as uncharged boric acid ($B(OH)_3$) (Page et al., 1981), and does accumulate in soils irrigated with recycled water (El-Nennah et al., 1982; Neilsen et al., 1991). El-Nennah et al. (1982) reported concentrations of 0.25 and 0.6 ppm from soil depths of 0 to10 and 10 to 20 in., respectively, after 47 years of irrigating with recycled water having a boron concentration of 0.33 ppm. As was previously mentioned, limiting the acreage irrigated with recycled water will decrease the likelihood of appreciable amounts of boron reaching the Edwards aquifer. Boron leaches and it does accumulate in soils, but with proper irrigation practices and reduced acreage, boron concentrations in San Antonio recycled water pose little threat to turfgrass or Edwards aquifer water.

Salts

Recycled water has a higher salt content than municipal water. Salt content of recycled water, measured as total dissolved solids (TDS), is typically 200 to 500 ppm higher than municipal water (Oster and Rhoades, 1985) and San Antonio recycled water is no exception. San Antonio recycled water has a higher TDS (700 ppm) than Edwards aquifer water (250 to 400 ppm)(Bader et al., 1993; Diehl, 2000). Many studies have shown salt accumulation in soils irrigated with recycled water (King, 1982; Pescod and Arar, 1985; Hayes et al,. 1990a; Neilsen et al., 1991; Mancino and Pepper, 1992; United States Golf Association, 1994; Singh et al., 2001). The only feasible way to keep salts from adversely affecting plants is to leach them out of the root zone (van Schilfgaarde et al., 1974; Hoffman and van Genuchten, 1983; Jame et al., 1984; Oster, 1984; Oster et al., 1984; Asano and Pettygrove, 1987; Follett, 1989; Harivandi et al., 1992). An irrigation manager must apply the correct amount of water because he/she wants to leach the salts below the root zone, but not let them leach too far by applying too much water. The best approach to leach salts is to irrigate with a leaching fraction at each irrigation application. This will allow for salts to leach out of the root zone but will not be sufficient water to leach nitrogen, phosphorus, and potassium that are present in recycled water. Salts may leach to groundwater if too much water is applied in the leaching process, if over-irrigation occurs at other times, or if a heavy precipitation event occurs. The San Antonio area receives periodic heavy precipitation events that will, inevitably, leach salts out of the root zone and eventually into the aquifer. The best way to deal with this is to control the acreage irrigated with recycled water. If only a small percentage of recharge water has a higher salt content it will be dissipated as it mixes with less salty recharge water resulting in minimal overall increase in aquifer salinity.

Using salt tolerant turfgrass is one way to deal with the higher salt content of recycled water. Harivandi et al. (1992) reported on the salt tolerance of various turfgrass species (Table 3).

Using a species like bermudagrass, seashore paspalum, or St. Augustinegrass would be recommended when using recycled water as those turf species can better deal with the higher salt content of the recycled water. Proper irrigation and leaching and limiting the acreage irrigated with recycled water will help prevent significant increases in salt content of the Edwards aquifer due to recycled water.

TABLE 3
Salt tolerance of various turfgrasses. Ratings are based on soil salt levels (EC, measured in dS/m). (Haravandi et al., 1992)

Species	Sensitivity
Creeping bentgrass	Moderately sensitive
Kentucky bluegrass	Sensitive
Perennial ryegrass	Moderately tolerant
Tall fescue	Moderately tolerant
Bermudagrass	Tolerant
Blue grama	Moderately tolerant
Buffalograss	Moderately tolerant
Centipedegrass	Sensitive
Seashore paspalum	Tolerant
St. Augustinegrass	Tolerant
Zoysiagrass	Moderately tolerant

Bicarbonate

Bicarbonate levels of San Antonio recycled water are very similar to Edwards aquifer water (250 to 400 ppm) (Bader et al., 1993; Diehl, 2000). Therefore, there would be no higher risk of aquifer contamination from recycled water than from aquifer water.

Heavy Metals

Heavy metal contamination of the Edwards aquifer is another concern when dealing with recycled water. Heavy metals are very immobile in soils. Generally, heavy metals are not taken up in large amounts by plants (Brown et al., 1983a), however, heavy metals that are essential micro-nutrients like copper, manganese, iron and zinc are taken up by plants in small amounts. Recycled water should be able to supply plant requirements for these micro-nutrients. Most of the studies dealing with heavy metals in recycled water have studied sludge because of the higher concentration of heavy metals in sludge than recycled water (Bouwer and Chaney, 1974). Leaching of heavy metals to groundwater is highly unlikely (Brown et al., 1983b; Tamminga, 1995; Weng and Chen, 2000). Brown et al. (1983b) and Weng and Chen (2000) reported that heavy metals did not travel more than 0.8 ft. and 1 ft., respectively. The heavy metal concentrations in the study by Brown et al. (1983b) were at least 40 times higher than those recommended by the National Academy of Science (Diehl, 2000), yet none were found in soil samples taken at 5 ft. As long as heavy metal concentrations are kept within the recommended limits, they will pose no threat to the Edwards aquifer.

Bacteria and Viruses

Asano and Pettygrove (1987) wrote "There is some risk of human exposure to pathogens in every wastewater reclamation and reuse operation, but the health concern is in proportion to the degree of human contact with the reclaimed water and the adequacy and reliability of the treatment process." Primary and secondary treated recycled water contain bacteria and viruses and there is potential for human infection and/or groundwater contamination from these two types of recycled water (Yates, 1994). San Antonio recycled water is chlorinated tertiary treated recycled water. Tertiary treated recycled water is relatively free of bacteria and viruses because it has been treated with UV light and/or chlorine, which kills all bacteria or viruses that may be present in the recycled water. There is very little bacterial or viral threat to the residents of San Antonio, or to the Edwards aquifer, from San Antonio recycled water, but precautions should be taken to assure limited human contact.

Pathogen flow from recycled water to groundwater increases with over-watering, porous soils, and increased macropore flow (cracks, tunnels, etc.) (Butler et al., 1954; Young and Burbank, 1973; Hoadley and Goyal, 1976; Schaub and Sorber, 1977; Vaughn and Landy, 1978; Vaughn et al, 1978; Koerner and Haws, 1979; Keswick and Gerba, 1980; Funderberg et al., 1981; Hagedorn et al., 1981; Wang et al., 1981; Vaugh and Landry, 1983; Goyal et al., 1984; Frankenberger, 1985; Pescod and Arar, 1985; Smith et al., 1985; Tamminga, 1995). However, the plant-soil system, in general, is very efficient at prohibiting the pathogens found in typical recycled water from entering groundwater (Romero, 1970; Bouma et al., 1972; Dazzo et al., 1973; Aulenbach et al., 1974; Bouwer et al., 1974; Reneau and Pettry, 1975; Reneau et al., 1975; Hoadley and Goyal, 1976; Lance et al., 1976; Bell and Bole, 1978; Brown et al., 1979; Funderberg et al., 1981; Pepper et al., 1981; Wang et al., 1981; Reed, 1982; Frankenberger, 1985; Pruitt et al., 1988; Pepper et al., 1993; Tamminga, 1995; Sloss et al., 1996; Rothmaier et al., 1997). Increased sand content, temperature and sunlight also decrease pathogen survival (Young and Burbank, 1973; Ziebell et al., 1974; Kowal et al., 1981; Reddy et al., 1981; Vaughn and Landry, 1983; Frankenberger, 1985; Shuval et al., 1986; Badaway et al., 1990; Pepper et al., 1993).

Precautions taken with usage of secondary recycled water should also be taken when using tertiary recycled water in order to decrease the bacterial and viral threat to humans. Some precautions that should be taken are: (1) workers should wear protective clothing when irrigating, (2) irrigation should occur at night, (3) no one should be in the irrigation area while recycled water is being applied, (4) and irrigation faucets, ponds, and irrigated areas should be properly posted.

Human exposure to bacteria and viruses that may be present in recycled water can be minimized or eliminated. Tertiary recycled water (San Antonio recycled water is tertiary water) is much safer than primary or secondary recycled water, but precautions must be taken to minimize potential contamination. Groundwater contamination of bacteria or viruses is highly unlikely because of the low amounts of pathogens in the recycled water and the efficiency of the soil-plant system in removing those pathogens.

Summary

Recycled water is a valuable resource that must be utilized wisely to lighten the burden that growing populations are putting on potable water resources. This is especially true of the San Antonio area where the majority of municipal water comes from the Edwards aquifer. Wise use of recycled water will diminish the amount of Edwards aquifer water used for irrigation and allow more of the Edwards aquifer water to go towards drinking and household purposes. Using recycled water for irrigation will be essential in assuring that the Edwards aquifer can provide sufficient municipal water for the San Antonio area as the population increases.

Recycled water is wastewater that has been treated and is being used for irrigation purposes in most cases. Recycled water is of lower quality than municipal water because recycled water may contain higher amounts of nitrogen, phosphorus, potassium, boron, salts, and may contain bacteria and viruses that are not present in municipal water. San Antonio recycled water quality is high because it has low boron concentrations, is not extremely salty, and nearly all bacteria or viruses have been removed by tertiary treatment.

Higher amounts of nitrogen, phosphorus, and potassium in recycled water make it ideal for irrigation purposes because these nutrients are essential for plant growth. Larger amounts of nutrients supplied by recycled water means less need for fertilization. Irrigation with recycled water applies these nutrients in frequent, small amounts, which is also ideal for plant growth and leaching prevention.

One very valid concern with the use of recycled water is the potential for groundwater contamination by nutrients contained in recycled water, especially nitrogen and phosphorus. This is especially true in the San Antonio area which depends on the Edwards aquifer to supply the majority of its municipal water. All of the nutrients and contaminants in recycled water can be leached, but with proper fertilization and irrigation management there is minimal threat of these elements reaching groundwater.

Nitrogen is the most mobile nutrient in recycled water. Groundwater contamination by nitrogen is not inevitable, and steps can be taken to reduce, or eliminate, the risk of nitrogen from recycled water contaminating groundwater. Nitrogen leaches when two things occur: (1) the concentration of nitrogen in the soil is high and/or (2) excessive water is applied to the soil which carries the nitrogen out of the root zone. As long as both of these two criteria are not met, nitrogen leaching will be minimal. Plants can take up all the nitrogen applied in recycled water as long as the nitrogen is within the root zone. With proper fertilization and irrigation practices (no over-fertilization or over-irrigation), nitrogen in recycled water poses minimal threat to groundwater.

Phosphorus is fairly immobile in soils and turfgrass requires more phosphorus than is supplied by recycled water so leaching of phosphorus supplied by recycled water is very unlikely. The largest concern with phosphorus is surface flow into streams and lakes and then into the aquifer. Phosphorus in the runoff water or attached to soil particles that have been eroded are the most likely paths for aquifer contamination by phosphorus. As turfgrass is very efficient at preventing erosion and phosphorus movement in surface flow, it is unlikely that irrigation with recycled water will cause any significant increases in phosphorus content of the Edwards aquifer.

Potassium, boron, and any bacteria or viruses that may be present are much less mobile than nitrogen. As long as proper management practices are followed, there is minimal threat of leaching these elements into the groundwater.

Salt levels of soils irrigated with recycled water can reach intolerable levels. The only feasible way to reduce those levels is to leach the salts below the root zone. If this is not done carefully, salts could be leached into the groundwater. Sufficient water must be applied to leach the salts out of the root zone, but if too much water is applied the salts will move too far. The best approach to managing salts is by irrigating with a leaching fraction at each irrigation application. However, the San Antonio area receives periodic heavy precipitation events that will, inevitably, leach salts out of the root zone and eventually into the aquifer. The best way to prevent significant salt increases of the Edwards aquifer is to limit the acreage irrigated with recycled water. Selection of salt tolerant turfgrass species will also allow turfgrass managers to better deal with the recycled water salinity.

Recycled water is a valuable resource that must be utilized in the San Antonio area. There are concerns with leaching of recycled water constituents into groundwater, but with proper fertilization and irrigation management practices, these risks are minimal and pose no real threat to the quality of Edwards aquifer water.

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APPENDIX A

Selected studies showing the differences in nitrate leaching due to soil texture, fertilization, and irrigation practices.

Soil	Crop	Irrigation [a]	Fertilizer [b]	Leachate concentration [c]	Leachate mass [d]	Reference
sand	K. bluegrass	40 in/yr	347	max conc - 111		Rieke & Ellis (1974)
	St. Augustine				13	
	zoysiagrass	leaching fraction of 50%	312		72	Bowman et al. (2002)
	bermudagrass	0.35 in/applic	145 lb/ac	max conc - 326		Brown et al. (1977)
		leaching fraction of 50%	312		48	Bowman et al. (2002)
		replace ET daily	45 lb/ac		5.1 lb/ac	Snyder et al. (1984)
		tensiometer controlled			1.67 lb/ac	
		N/A	45 lb/ac (NH4NO3)		6.6 lb/ac	Snyder et al. (1984)
			(SCU)		2.6 lb/ac	
			(fertigation)		1.2 lb/ac	
		daily	540 (daily)	max conc - 15-20		Snyder et al. (1977)
			(every 3wk)	max conc - 25-40		
		daily	214		0-9	Snyder et al. (1981)
			427		0.4-45	
		2.73 (sum) & 1.37(win)	699		62	Brown et al. (1982)
gravel sandy loam	turf	59 in/yr	recycled water	avg conc - 22.3		Hayes et al. (1990a)
			none	avg conc - 14.5		
sand/peat	bentgrass	1.58	420 (weekly)		0-0.8	Mancino & Troll (1990)
			(biweekly)		0-1.34	
sand/clay/peat	bermudagrass	0.35 in/applic	145 lb/ac	max conc - 314		Brown et al. (1977)
		0.28 in/applic (low)	145 lb/ac	max conc - 15		Brown et al. (1977)
		0.35 in/applic (med)		max conc - 325		
		0.43 in/applic (high)		max conc - 413		
		0.35 in/applic	21 lb/ac		9 lb/ac	Brown et al. (1977)
			44 lb/ac		12 lb/ac	
			65 lb/ac		15 lb/ac	
				Leachate	Leachate	

Soil	Crop	Irrigation [a]	Fertilizer [b]	Leachate concentration [c]	Leachate mass [d]	Reference
sand/clay/peat	bermudagrass	0.35 in/applic	87 lb/ac		14 lb/ac	Brown et al. (1977)
		2.73 (sum) & 1.37(win)	699		53	Brown et al. (1982)
sandy loam	bermudagrass	0.35 in/applic	145 lb/ac	max conc - 160		Brown et al. (1977)
		0.35 in/applic	21 lb/ac		3.6 lb/ac	Brown et al. (1977)
			44 lb/ac		0 lb/ac	
			65 lb/ac		3.6 lb/ac	
			87 lb/ac		4.5 lb/ac	
		2.73 (sum) & 1.37(win)	699		20	Brown et al. (1982)
sandy loam	turf	none	0		1.2	Gold et al. (1990)
			217		1.8-8	
		1.48	N/A		14.4	Morton et al. (1988)
		tensiometer controlled			2.9	
		N/A	0		2.1	Morton et al. (1988)
			86		8.4	
			217		18.4	
		none	169	avg conc - 2		Starr & DeRoo (1981)
sandy loam	grassland	none	223		3.6	Owen & Barraclough (1983)
			445		24	
			801		132	
fine sandy loam	K. bluegrass	34 in/yr	258	max conc - 66		Rieke and Ellis (1974)
		none	174 (spring)	avg conc - 0.31		Miltner et al. (1996)
			174 (fall)	avg conc - 0.63		
silt loam	K. bluegrass	none	0		34-38	Geron et al. (1993)
			194		53-58	
clay	turf	0.55	584	max conc - 11		King (1982)
			1522	max conc - 25		
Soil	Crop	Irrigation a	Fertilizer b	Leachate	Leachate	Reference
sand	corn	tensiometer controlled	150-312	avg conc - 15-70		Gascho et al. (1984)
		85% replacement	178	avg conc - 65		Hergert (1986)

Soil	Crop	Irrigation [a]	Fertilizer [b]	Leachate concentration [c]	Leachate mass [d]	Reference
		130% replacement	178	avg conc - 63		
	grains and vegetables	67 in/yr	361	avg conc - 15		Hubbard et al. (1984)
		57 in/yr	87	avg conc - 20		
		61 in/yr	200	avg conc - 16		
		65 in/yr	473	avg conc - 26		
	vegetables	none	267-356	avg conc 0-28		McNeal et al. (1995)
	citrus	none	178-223	avg conc 6-24		McNeal et al. (1995)
peat	barley	N/A	89		46	Bergstrom (1995)
loamy fine sand	corn	low	107		19	Montgomery et al. (1988)
		high			30	
sandy loam	corn	17 in/yr	159 (1 applic)	max conc - 100		Gerwing et al. (1979)
			159 (2 applic)	max conc - 60		
			239 (1 applic)	max conc - 125		
			239 (2 applic)	max conc - 65		
		none	None		27	Timmons & Dylla (1981)
			231 (granular)		62	
		50% replacement	231 (granular)		73	
			231 (liquid)		74	
		100% replacement	231 (granular)		101	
			231 (liquid)		91	
		none	203		62	Gold et al. (1990)
	corn w/out cover crop	none	150	avg conc - 23		McCracken (1995)
	corn w/ cover crop			avg conc - 9		
Soil	Crop	Irrigation a	Fertilizer b	Leachate	Leachate	Reference
loam	poplar trees w/out cover crop	tensiometer control	0	max conc - 125		McLaughlin et al. (1985)
	poplar trees w/cover crop			max conc - 5		
	poplar trees w/out cover crop	tensiometer control	100	max conc - 240		McLaughlin et al. (1985)
	poplar trees w/ cover crop			max conc - 20		
silty loam	corn w/out cover crop	none	141	avg conc - 24		Brinsfield et al. (1988)

Soil	Crop	Irrigation [a]	Fertilizer [b]	Leachate concentration [c]	Leachate mass [d]	Reference
	corn w/ cover crop			avg conc - 1		
silt loam	corn, beans, wheat	none	77	avg conc - 10		Zwerman et at. (1972)
			216	avg conc - 25		
clay	barley	N/A	89		15	Bergstrom (1995)

a in/wk unless indicated
b lb N/ac/yr unless indicated
c ppm unless indicated
d lb/ac/yr unless indicated

Appendix F

Risk Evaluation of Microbiological and Toxicological Components of the San Antonio Water System's Recycled Water: A Literature Review

By

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Performed in Support of the Edwards Aquifer Recharge Zone Irrigation Pilot Study

Submitted to

CH2M HILL and the San Antonio Water System

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SECTION I

Introduction

During the last decade the use of reclaimed water for non-potable purposes has become more popular. Highly treated sewage effluent is being utilized for irrigation, aquifer recharging, industrial use, and surface water replenishment in the United States and throughout the world.

The presence of chemical and microbial agents that could possibly pose a hazard to human health and the environment is a major consideration when evaluating the practicality of using recycled water. Primarily, these concerns apply to potable use; however, human exposure may occur from non-potable uses such as agricultural irrigation. The potential for hazardous exposure from non-potable reuse is minimal, thus the associated health risks are significantly lower (NRC, 1994).

The use of recycled municipal wastewater still presents a wide spectrum of possible technical and health challenges that must be carefully evaluated. Concerns over the impacts of contaminants on long-term human health represent possible constraints that may limit expanding the use of recycled municipal wastewater.

Four water quality factors are significant when evaluating recycled water: (a)human pathogens, (b) mineral content, (c) heavy metals, and (d) trace organic compounds.

Among these factors, human pathogens and trace organic compounds are of particular concern when groundwater recharge involves domestic water supply aquifers (Tsuchihashi et al., 2002).

The need persists for definitive information on the extent of contaminant removal by the soil and underlying geological formations, and on the fate of pollutants during groundwater recharge.

The importance of microbiological and toxicological standards for recycled water has been frequently emphasized (Asano, 1998). Varieties of microbial pathogens are present in wastewater and can be detected in reclaimed water. Therefore advanced treatment, including filtration and disinfection, is required to produce reclaimed water that does not have a negative impact on public health. The aim of this literature review is to assess the potential microbiological and toxicological hazards associated with the use of recycled water.

SECTION II

Identification of Potential Toxicological Health Issues Associated with Recycled Water

There is a sizeable range of gastrointestinal pathogens that can be recovered from human sewage. These pathogens include viruses, bacteria, protozoa and helminthes. While several gastrointestinal pathogens are capable of causing severe illness or death, many people who are exposed to the pathogens will not develop any symptoms. The majority of populations who are affected are expected to suffer only short-term, mild to moderate gastroenteritis without long-term effects. Some toxicological issues of concern include pharmaceuticals, hormones, and endocrine disrupters. The concerns with respect to pharmaceuticals involve the metabolism of drugs and subsequently their stability in sewage media. While acetaminophen is the most used pharmaceutical, its impact is small; whereas the presence of un-metabolized synthetic estrogens is likely to have substantial effects on the environment. Human effects, on the other hand, remain to be determined.

Different wastewater treatment processes will have differing effects on individual pathogens as well as pharmaceuticals and hormones. Compliance with standard microbiological indicators may not guarantee water quality. Therefore, treated wastewater is likely to contain toxicological contaminants and other potentially hazardous compounds.

Pharmaceuticals in the Environment

The occurrence and fate of pharmaceutically active compounds (PhACs) in the aquatic environment has been recognized as one of many emerging issues when evaluating water quality (Stan and Heberer, 1997; Halling-Sørensen et al., 1998; Daughton and Ternes, 1999; Daughton and Jones-Lepp, 2001; and Kümmerer, 2001). There are several potential pathways for pharmaceuticals to appear in the aquatic environment (fig. 1). Many of the pharmaceuticals applied in human medical care are not completely metabolized within the human body. Often a portion of these pharmaceuticals are excreted either as slightly transformed compounds or as unchanged forms that are conjugated to polar molecules such as glucuronides. These conjugates can easily be cleaved during sewage treatment and the original PhACs will then be released into the aquatic environment as a component of effluents from municipal sewage treatment plants (STPs). Several investigations have shown some evidence that substances of pharmaceutical origin are often not eliminated during wastewater treatment (Ternes, 1998; Daughton and Ternes, 1999; and Zwiener et al., 2000). Under recharge conditions residues of PhACs may also leach into groundwater aquifers. Some reports indicate the presence of pharmaceuticals in ground and drinking water samples from water works using bank filtration or artificial groundwater recharge downstream from municipal STPs (Heberer, and Stan, 1997; and Heberer et al., 1997).

The presence of PhACs in groundwater may also originate from other sources including landfill leachates (Eckel et al., 1993; Ahel and Jelicic, 2001), manufacturing residues, and the agricultural use of PhACs as veterinary drugs and feed additives.

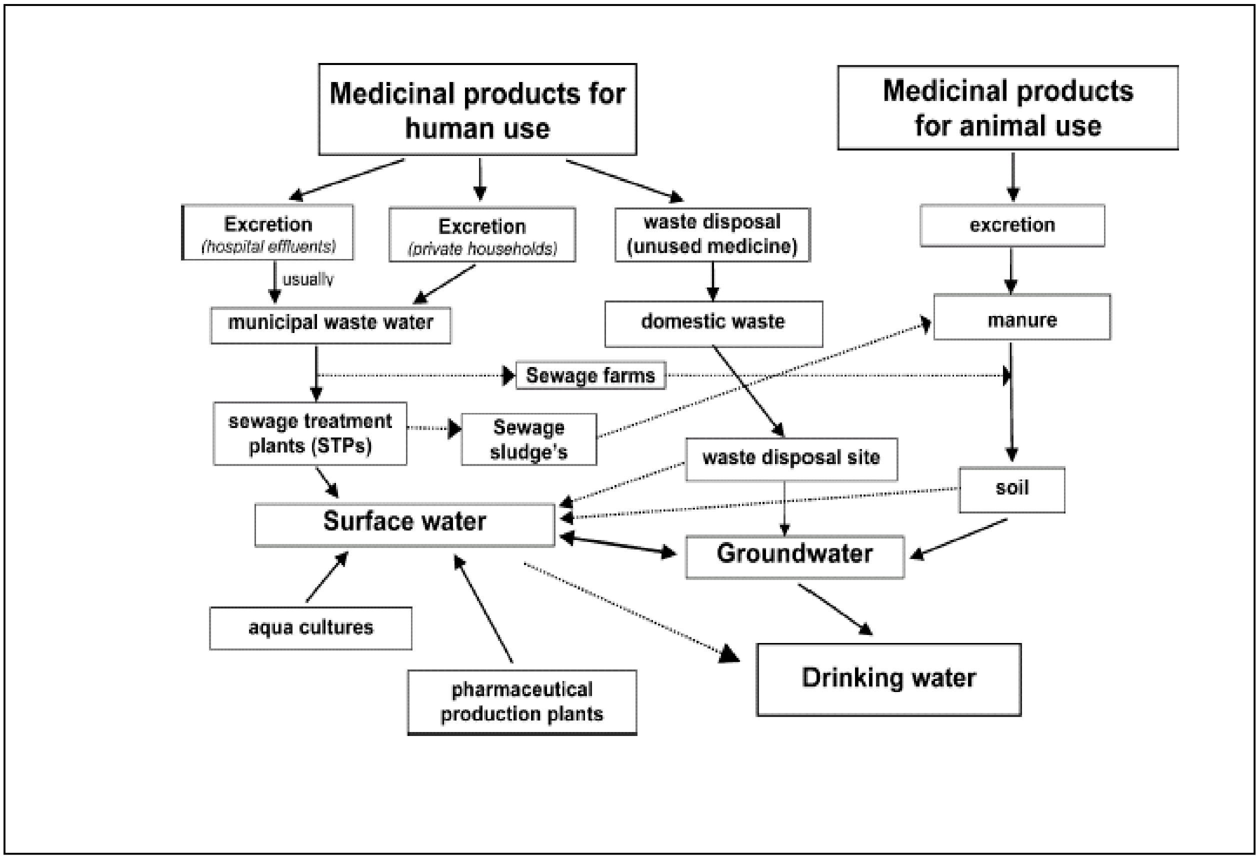

FIGURE 1
Illustration of potential sources and pathways for the occurrence of phamacutically active compounds (PhACs) in the aquatic environment (Heberer, 2002).

The occurrence of PhACs in the aquatic environment has been investigated worldwide including, Austria, Brazil, Canada, Croatia, England, Germany, Greece, Italy, Spain, Switzerland, the Netherlands and the U.S. More than 80 PhACs from various prescription classes have been detected up to the µg/l-level in sewage effluent, surface water, and groundwater (Heberer, 2002).

Analgesics and anti-inflammatory drugs

Most analgesics (pain killers) also have anti-inflammatory and antipyretic properties. Large amounts of pain killers are prescribed, however they are most often sold in much larger quantities without prescriptions as over-the-counter (OTC) drugs. (Stan and Heberer, 1997).

Acetaminophen (paracetamol) and acetylsalicylic acid (ASA) are the two most popular pain killers. These pain killers are primarily sold as OTC drugs. In Germany, the total quantities of ASA sold per year have been estimated at >500 tons (Ternes, 2001). However, other analgesics that have been recognized as being just as important include diclofenac or ibuprofen. These pain relievers are sold in Germany at annual quantities of approximately 75 and 180 tons, respectively (Ternes, 2001). ASA was detected at a median concentration of only 0.22µg/l in sewage effluents in Germany (Ternes, 1998). In the same study the median concentration of ASA in surface water samples was below the detection limits.

ASA is easily degraded by deacetylation into its more active form salicylic acid and into two other metabolites namely ortho-hydroxyhippuric acid and the hydroxylated metabolite gentisic acid. Ternes (1998), and Ternes et al., (1999b) detected salicylic acid, ortho- hydroxyl hippuric acid and gentisic acid in sewage influent samples at concentrations up to 54, 6.8, and 4.6µg/l, respectively. Terns et al. (1999b) observed that all three compounds were efficiently removed by the municipal STPs. However salicylic acid was detected at very low concentrations in sewage effluents and rivers. Residues of salicylic acid do not necessarily have to derive from ASA, as the use of salicylic acid as a food preservative is likely to contribute to the occurrence of this compound in the aquatic environment (Heberer, 2002).

Acetaminophen is also easily degraded and removed by the STPs. In investigations of sewage effluents and rivers in Germany acetaminophen was only detected in less than 10% of all sewage effluents and not detected in river water (Ternes, 1998). Heberer (2002) investigated 142 streams in the U.S. susceptible for contaminations by municipal sewage effluents, and detected acetaminophen in 17% of all samples at maximum concentration of 10 µg/l.

Annually, 75 tons of the prescription drug diclofenac are sold in Germany (Ternes, 2001). In long-term monitoring investigations of sewage and surface water samples from Berlin, Germany, diclofenac was identified as one of the most important PhAC present (Heberer, 2002). Average concentration of 3.02 and 2.51 µg/l were detected in the influents and effluents of the municipal STPs, respectively. The low removal rate of only 17% demonstrates the persistence of diclofenac in the STPs and was also reported by Buser et al., (1998b), Stumpf et al. (1999), Zwiener et al. (2000), whereas Ternes (1998) reported a removal of 69% for diclofenac in the STPs. Diclofenac was also frequently detected at concentrations up to the µg/l-level in investigations of sewage effluents and surface water in Austria, Brazil, Germany, Greece, Spain, Switzerland, and the U.S. (Buser et al., 1998a; Heberer et al., 1997, 2001a; Ternes, 1998; Möhle et al., 1999; Stumpf et al., 1999; Ahrer et al., 2001; Farré et al., 2001; Öllers et al., 2001; and Sedlak and Pinkston, 2001). Under recharge conditions, diclofenac has also been detected in groundwater samples (Heberer et al., 1997; Sacher et al., 2001). Results from laboratory column experiments (Scheytt et al., 2001) and field experiments (Heberer et al., 2001b) on bank filtration signify a substantial sorption and an efficient attenuation of diclofenac residues in the subsoil (Heberer, 2002). So far, diclofenac was only sporadically found at trace-level concentrations in raw or treated drinking water (Brauch et al., 2000; Kuehn and Mueller, 2000; Heberer et al., 2001a, b; Ternes 2001). Zwiener et al., (2000) have shown that diclofenac can be removed from drinking water by ozonation. Together with several other PhACs diclofenac was also efficiently removed from surface or municipal sewage effluents using membrane filtration (Heberer, 2002; Sedlak and Pinkston, 2001).

Ibuprofen was found in sewage effluents and rivers in Austria, Brazil, Germany, and Switzerland at concentrations much lower than those determined for diclofenac (Heberer et al., 1997; Heberer 2002; Terns, 1998; Buser et al., 1999; Stumpf et al., 1999; Öllers et al., 2001). Farré et al. (2001) detected 1.5, 0.87, and 85 µg/l of ibuprofen in sewage effluent samples in Spain. This study also found ibuprofen at relatively high concentrations up to 2.7 µg/l in Spanish surface waters. Ibuprofen is degraded in the human body to its principal metabolites hydroxy- and carboxy-ibuprofen and to carboxy-hydratrophic acid (Buser et al., 1999) which are found together with ibuprofen in raw sewage. A significant removal of ibuprofen and especially of carboxy-ibuprofen during sewage treatment was observed whereas the concentrations of hydroxyl-ibuprofen in the sewage effluents (median: 0.92 µg/l) were almost similar to those in the influents. Thus, hydroxyl-ibuprofen was found in 12 German surface waters at much higher concentration (median: 0.34 µg/l) than ibuprofen or carboxy-ibuprofen (median: 0.02 µg/l).

Several other analgesics, namely 4-aminoantiyrine, aminophenazone, codeine, fenoprofen, hydrocodone, indometacine, ketoprofen, mefenamic acid, naproxen, phenazone and propyphenazone have also been detected in sewage and surface water samples (Heberer et al., 1997, 2001a, Heberer, 2002; Ternes, 1998; Möhle et al., 1999; Stumpf et al., 1999; Ahrer et al., 2001; Farré et al., 2001; Öllers et al., 2001; Ternes et al., 2001; Sedlak and Pinkston, 2001; Heberer, 2002). Under recharge conditions or at landfill leachates several analgesics such as diclofenac, ibuprofen, detoprofen, phenazone, propyphenazone, gentisic acid or N-methylphenacetin (both metabolites), have also been detected in ground water samples in Croatia, Denmark and Germany (Heberer et al., 1997, 2001a,b; Ahel and Jelicic, 2001; Sacher et al., 2001). In Germany diclofenac, ibuprofen, and phenazone residues have been detected at trace-level concentrations in a few drinking water samples (Heberer et al., 2001a; Ternes, 2001). In laboratory experiments, propyphenazone was adsorbed on sediments but there is some evidence that it might be remobilized by particle transport (Scheytt et al., 2001). In field experiments on bank filtration, propyphenazone was not totally removed. It was detected in the shallow wells and also reached the water supply wells (Heberer et al., 2001b; Heberer, 2002).

Antibacterial drugs

Numerous studies have been carried out in Germany (Steger-Hartmann et al., 1997; Hirsch et al., 1999), Switzerland (Alder et al., 2001); and the U.S. (Lindsey et al., 2001; Kolpin et al., 2002) to investigate the occurrence and fate of antibacterial drugs in STPs or surface waters. Macrolide antibiotics (clarithromycin, de-hydro-erythromycin [metabolite of erythromycin], roxithromycin, and lincomycin), sulfonamides (sulfamethoxazole, sulfadimethoxine, sulfamethazine, and sulfathiazole), fluoroquinolones (ciprofloxacin, norfloxacin, and enrofloxacin), chloramphenicol, tylosin and trimethoprim have been found up to the low µg/l-level in sewage and surface water samples. Monitoring investigations of various sewage, surface and groundwater samples in Germany, Hirsch et al. (1999) did not detect penicillins or tetracyclines. Penicillins are easily hydrolyzed and tetracyclines readily precipitate with cations such as calcium and accumulate in sewage sludge's or sediments (Daughton and Ternes, 1999; Stuer-Lauridsen et al., 2000). However, Lindsey et al. (2001) and Kolpin et al. (2002) also detected tetracycline drugs (chlortetracycline, oxytetracycline, and tetracycline) in U.S. surface water samples. Fluoroquinolone antibiotics in primary and tertiary wastewater effluents were analyzed in Switzerland. Ciprofloxacin and norfloxacin occurred at concentration between 249 and 405 ng/l and from 45 to 120 ng/l, respectively. Antibiotics have also been identified at high concentrations in hospital effluents (Hartmann et al., 1998; Alder et al., 2001). Hartmann et al. (1998) detected between 3 and 87 µg/l, of the fluoroquinolone antibiotic ciprofloxacin in hospital effluents.

Sacher et al. (2001) reported the occurrence of sulfamethoxazole (up to 410ng/l) and dehydro-erythromycin (up to 49 ng/l) in groundwater samples in Baden-Württemberg, Germany.

Sulfamethoxazole and sulfamethazine have also been detected at low concentrations in a few ground water samples in the U.S. (Hartig et al., 1999; Hirsch et al., 1999; Lindsey et al., 2001). Heberer (2002) observed efficient removal of various antibiotic and bacteriostatic drugs during bank filtration at a field site in Berlin, Germany.

Antiepileptic drugs

The antiepileptic drug carbamazepine has frequently been detected in municipal sewage and surface water samples (Ternes, 1998; Möhle et al., 1999; Heberer et al., 2001a; Ahrer et al., 2001; Öllers et al., 2001). Investigations of influent and effluent samples from different municipal STPs have shown that carbamazepine is not significantly removed (less than 10%) during sewage treatment (Ternes 1998). Carbamazepine has been detected at concentrations up to 1075ng/l in surface water samples in Berlin, Germany (Heberer, 2002). Primidone, another antiepileptic drug, has also been detected in samples from municipal sewage influents and effluents and in surface waters (up to 635 ng/l) in Germany (Möhle et al., 1999; Heberer et al., 2001a)

Several field studies have shown that carbamazepine (Kuehn and Mueller, 2000; Brauch et al., 2000; Heberer et al., 2001b) and primidone (Heberer et al., 2001b) are not attenuated during bank infiltration. The two compounds have been detected in the shallow wells and water supply wells of a transect built to study the behavior of PhACs during bank filtration (Heberer et al., 2001b). Because carbamazepine is not attenuated it has been detected in a number of groundwater samples at a maximum concentration up to 1.1 μg/l (Seiler et al., 1999; Sacher et al., 2001; Ternes 2001) and was also found with a concentration of 30 ng/l in drinking water.

Beta-blockers

Several beta-blockers (metoprolol, propanolol, betaxolol, and nadolol) have been detected in municipal sewage effluents up to the μg/l-level (Hirsch et al., 1998; Ternes, 1998; Sedlak and Pinkston, 2001). Only metoprolol, propanolol, and bisoprolol have been found at relatively low concentration in surface water samples (Hirsch et al., 1998; Ternes, 1998). Hirsch et al. (1998) did not recognize any relevance of concern when involving beta-blockers for groundwater recharge or drinking water supply. Yet, Sacher et al. (2001) reported the detection of sotalol at maximum concentrations of 560 ng/l in three groundwater samples from Baden-Württemberg Germany.

Blood lipid regulators

Clofibic acid, the active metabolite of the blood lipid regulators clofibrate, etofyllin clofibrate, and etofibrate, have been recovered in Germany at concentrations up to 4μg/l in groundwater samples collected from former sewage irrigation fields near Berlin (Heberer et al., 1997). Clofibic acid could also be found in samples from the fourth or fifth groundwater aquifer down to a depth of 125 m underneath sewage farm areas. Up to 270 ng/l of clofibric acid have been detected in Berlin drinking water samples (Heberer et al., 1997). Buser et al. (1998a) detected clofibic acid at the low ng/l-range in Swiss lakes from populated areas and also in the North Sea. Clofibric acid was recognized as a refractory contaminant in a number of investigations of municipal sewage influents and effluents (Ternes, 1998; Stumpf et al., 1999). Biodegradation studies using a pilot sewage plant and biofilm reactors operated under oxic or anoxic conditions were carried out to evaluate the presence of clofibic acid (Zwiener et al., 2000). In spiking experiments with synthetic sewage water they confirmed the persistence of clofibric acid under both anoxic and oxic conditions. Clofibric acid has also been recovered from sewage, surface and groundwater from Austria, Brazil and Germany (Heberer and Stan, 1997; Heberer et al., 1997, 2001a; Ternes 1998, 2001; Stumpf et al., 1999; Ahrer et al., 2001; Öllers et al., 2001)

Bezafibrate, gemfibrozil, and fenofibric acid, the metabolite of fenofibrate, have also been detected up to the µg/l-level in sewage effluents and surface water samples (Ternes, 2001; Sedlak and Pinkston, 2001). Bezafibrate and gemfibrozil have also been found in groundwater samples at maximum concentrations of 190 and 340 ng/l, respectively (Ternes, 2001).

Clofibric acid did not show any significant sorption in laboratory experiments using soil columns (Scheytt et al., 2001). This compound leached almost tracerlike through the soil columns without retardation. This observation was also confirmed in several studies on bank filtration where clofibric acid was reaching the water supply wells without being removed in the sub-soil (Heberer et al., 2001b). However, bezafibrate was found to be easily attenuated during bank filtration (Heberer et al., 2001b).

Cytostatic drugs

Cytostatics are frequently used in chemotherapy. Thus, residues of cytostatic drugs almost exclusively originate from hospital applications and may occur in hospital sewage at concentrations up to the low µg/l-level (Steger-Hartmann et al., 1997). In effluents from municipal STPs receiving and purifying hospital effluents, cytostatic drugs have been found at trace concentrations mostly at the low ng/l-level (Steger-Hartmann et al., 1997; Kümmerer et al., 1997; Ternes, 1998). Steger-Hartmann et al. (1997) detected ifosfamide and cyclophosphamide in sewage samples from a university hospital at concentration of 24 and 146 ng/l respectively. Kümmerer et al. (1997) found ifosfiamide at mean concentrations of 109 ng/l in effluents from a oncological hospital. In the influents and effluents of the receiving municipal STP, ifosfiamide was measured at mean concentrations between 6.2 and 9.3 ng/l without observing any significant reduction during sewage treatment. Ternes (1998) detected cyclophosphamide at maximum concentrations of 20 ng/l in 4 out of 16 effluent samples from German STPs. Ifosfamide was only detected in two samples, but one sample with a concentration of 2.9 µg/l. To date cytostatics have not been detected in surface waters but Kümmerer et al. (1997) calculated a predicted environmental concentration (PEC) of 0.8 ng/l for ifosfamide in German surface waters. Due to their high pharmacological potency such compounds often exhibit mutagenic or embryotoxic properties. Additional investigations on cytostatics occurrence and fate is necessary to address their risk potential for humans and the environment (Kümmerer, 2001).

Occurrence and fate of hormone steroids in the environment.

Steroid hormones are a group of biologically active compounds that are synthesized from cholesterol. Natural steroids are secreted by the adrenal cortex, testis, ovary, and placenta in humans and animals and include progestogens, glucocorticoids, mineralocorticoids, androgens and estrogens (Raven and Johnson, 1999). Estrogens (estradiol, estrone and estriol) are predominantly female hormones, which are important for maintaining the health of the reproductive tissues, breasts, skin and brain. Progestogens (progesterone) can be thought of as a hormonal balancer, particularly of estrogens. Androgens (testosterone, dehydroepiandrosterone and androstenedione) play an important role in tissue regeneration, especially the skin, bones and muscles. Glucocorticoids (cortisol) are produced by the adrenal glands in response to stressors such as emotional upheaval, exercise, surgery, illness or starvation. All the steroid hormones exert their action by passing through the plasma membrane and binding to intracellular receptors. In addition, there are some synthetic steroids such as ethynylestradiol (EE2) and mestranol (MeEE2) used as contraceptives.

All humans as well as animals can excrete hormone steroids from their bodies which end up in the environment through sewage discharge and animal waste disposal. The most powerful metabolite of oestrogen excreted by vertebrates is 17α-oestradiol, a female hormone that is excreted by males as well (Heberer, 2002). This hormone has an effect on aquatic

organisms at very low concentrations (4-10 µg/l level). Hormones are assumed to cause an effect in humans only at higher levels. However, up to now no threshold value for acceptable daily intake for humans has been fixed. Natural hormones are very important components in the case of aquifer recharge and potable reuse. A treatment aiming at removing them from the water in case of aquifer recharge is therefore strongly recommended. Steroids have been detected in effluents of sewage treatment plants (STPs) and surface waters (Desbrow et al., 1998; Kuch and Ballschmiter, 2000; Ternes et al., 1999a). The steroids of concern for the aquatic environment due to their endocrine disruption potential are mainly estrogens and contraceptives, which include 17α-estradiol (E2), estrone (E1), estriol (E3), 17α-ethynylestradiol (EE2) and mestranol (MeEE2) (Desbrow et al., 1998; Jobling et al., 1998). Concentrations as low as 1 ng/l of E2 led to induction of vitellogenin in male trout (Hansen et al., 1998; Purdom et al., 1994). Hormone steroids in the environment may affect not only wildlife and humans but also plants (Shore et al., 1995b; Lim et al., 2000). Alfalfa irrigated with sewage effluent, which contained hormone steroids was observed to have elevated levels of phytoestrogens (Shore et al., 1995b). In addition to estrogenic steroids, there is also a concern about the use of steroid drugs used as growth promoters in livestock (Schiffer et al., 2001). However, little research has been conducted on the fate of these steroids excreted by animals and their effect on wildlife and human health.

Human Waste

The presence of estrogenic compounds in the environment has become a concern because they may interfere with the reproduction of man, livestock and wildlife. The hormones 17α-estradiol and estrone are naturally excreted by women (2–12 and 3–20 µg/person/day, respectively) and female animals, as well as by men (estrone 5 µg/person/day) (Gower, 1975). Based on the survey and previous measurements of human estrogen excretion, Johnson et al. (2000) estimated the daily excretion of estrogens from males and females. Males were excreting 1.6 µg/day of E2, 3.9 µg/day of E1 and 1.5 µg/day of E3 in their urine. Menstruating females were excreting 3.5 µg/day of E2, 8µg/day of E1 and 4.8 µg/day of E3 in their urine. The menopausal women were taken as excreting 2.3 µg/day of E2, 4 µg/day of E1 and 1 µg/day of E3. Pregnant women were excreting 259 µg/day E2, 600 µg/day of E1 and 600 µg/day of E3. After reviewing the quantity of EE2 in the oral contraceptive pills, 35 µg/day was estimated as the daily excretion of EE2. Based on daily excretion of estrogens by humans, dilution factor and previous measurements, ng/l levels of estrogens are expected to be present in aqueous environmental samples from English rivers (Johnson et al., 2000). Estrogenic steroids have been detected in influents and effluents of STPs in different countries (Baronti et al., 2000; Belfroid et al., 1999; Desbrow et al., 1998; Kuch and Ballschmiter, 2000; Nasu et al., 2000;Snyder et al., 1999; Ternes et al., 1999a). Average concentrations of estrogenic steroids (E3, E2, E1 and EE2) in influents of six Italian activated sludge STPs were 80, 12, 52 and 3 ng/l, respectively (Baronti et al., 2000). However, E3 was rarely reported to occur in such a high concentration (80 ng/l). E3 was not detected in most of the influents studied. In the raw sewage of the Brazilian STPs, estrogenic steroids E2, E1 and EE2 were detected with average concentrations of 21, 40 and 6 ng/l, respectively (Ternes et al.,1999a). Estrogenic steroids were detected in three Dutch STPs with concentrations ranging from < LOD to 48 ng/l for E2, from 11 to 140 ng/l for E1 and from < 0.2 to 8.8 ng/l for EE2 (Johnson et al.,2000). The concentrations of E2 in influents of Japanese STPs ranged from 30 to 90 ng/l in autumn and from 20 to 94 ng/l in summer (Nasu et al., 2000).

The concentrations of estrogenic steroids in the effluents ranged from below detection limit (LOD) to 64 ng/l for E2, from < LOD to 82 ng/l for E1, from 0.43 to 18 ng/l for E3 and from < LOD to 42 ng/l for EE2. E2 was present at higher concentrations in the effluents from STPs in Canada, UK and Japan than those from other countries. E2 was detected in Japanese STP effluent samples with concentrations ranging from 3.2 to 55 ng/l in summer and from 2.8 to 30 ng/l in autumn (Tabata et al., 2001). Average concentrations in the effluents were 18 and 12 ng/l, respectively. Nasu et al. (2000) also measured estrogenic steroids in effluents of Japanese STPs with similar concentration ranges. In British STPs, the concentrations of E1 in the effluents varied widely from 1.4 to 76 ng/l, while E2 concentrations lie in a similar range to that of Japanese STPs (Desbrow et al., 1998). However, EE2 was only found in 7 of 21 effluent samples from domestic STPs in UK, with concentrations ranging from < LOD to 7 ng/l. In Canadian STPs, E1 and E2 were determined with maximum concentrations of 48 and 64 ng/l, respectively. EE2 was detected in 9 of 10 effluent samples with a maximum concentration of 42 ng/l (Ternes et al., 1999a). In comparison, the concentrations of E2 in the effluents from German, Italian, Dutch, Swedish and American STPs were lower, ranging from < LOD to 5.2 ng/l (Baronti et al., 2000; Belfroid et al., 1999; Kuch and Ballschmiter, 2000; Larsson et al., 1999; Snyder et al., 1999; Ternes et al., 1999a,b). However, Spengler et al. (2001) reported a maximum concentration of 15 ng/l for E2 in effluents of STPs in SE Germany, and mestranol was also detected with a maximum concentration of 2.7 ng/l. The levels of estrone in the effluents from different countries are quite comparable. Estriol (E3) was only reported in Italian STP influents and effluents (Baronti et al., 2000).

Animal Waste

Livestock waste is the other major contributor of hormone steroids found in the environment. Livestock such as sheep, cattle, pigs and poultry, as well as other animals, excrete hormone steroids. In poultry waste, a concentration ranging from 14 to 533 ng/g dry waste with an average of 44 ng/g for E2 was reported by Shemesh and Shore (1994) and Shore et al. (1988, 1995a). The E2 concentration in urine of cattle was found to be 13 ng/l on average by Erb et al. (1977). Steroid drugs are frequently used in cattle as well as other livestock, to control the oestrous cycle, treat reproductive disorders and induce abortion (Refsdal, 2000). Many cattle in United States are also fed muscle-building androgens such as trenbolone acetate (TbA) and melengestrol acetate (MGA) (Schiffer et al., 2001). Manure from cattle treated with TbA and MGA were collected and found to contain 5–75 ng/g TbOH and 0.3–8 ng/g MGA (Schiffer et al., 2001). After 4.5–5.5 months of storage, levels up to 10 ng/g trenbolone and 6 ng/g MGA were detected with a half-life of 267 days for trenbolone.

Surface water

The presence of estrogenic steroids in surface waters has been reported by several researchers (Baronti et al., 2000; Belfroid et al., 1999; Kuch and Ballschmiter, 2000; Tabata et al., 2001). Tabata et al. (2001) conducted an extensive survey of estrogenic steroids in 109 Japanese rivers and found E2 in 222 of 256 samples in summer with a mean concentration of 2.1 ng/l and in 189 of 261 samples in autumn with a mean concentration of 1.8 ng/l. Estrone (E1) was detected in 7 of 11 Dutch coastal/estuarine and freshwater samples with a median concentration of 0.3 ng/l, while E2 and EE2 were only detected in 4 and 3 of 11 samples, with most of the concentrations below the quantification limit of < 1 ng/l (Belfroid et al., 1999). The measurements in Germany resemble the situation in the Netherlands (Belfroid et al., 1999; Kuch and Ballschmiter, 2000). Estrogenic steroids were also detected in some drinking water samples from southern Germany with an average concentration of 0.4, 0.7 and 0.35 ng/l, respectively (Kuch and Ballschmiter, 2000). E3 was found in Tiber river water in Italy with a concentration of 0.33 ng/l, while E2 and E1 were 0.11 and 1.5 ng/l in the river water, respectively (Baronti et al., 2000).

Groundwater

Some studies indicate that disposal of animal manure to agricultural land could lead to movement of estrogenic steroids into surface and ground water (Bushe´e et al., 1998; Nichols et al., 1997, 1998; Peterson et al., 2001; Shore et al.,1995a). E2 has been found to be mobile and detected in runoff from manured land (Nichols et al., 1997, 1998). Nichols et al. (1998) determined an average E2 concentration of 3500 ng/l in the runoff from a pasture to which 5 Mg/ha of manure (poultry litter) had been applied. Ground water has been reported to be contaminated with E2 (Peterson et al., 2001; Shore et al., 1995a). Shore et al. (1995a) believed that a constant E2 concentration of about 5 ng/l in spring waters was caused by infiltration of E2 through the soil profile to the ground water. Peterson et al. (2001) measured E2 concentrations ranging from 6 to 66 ng/l in mantled karst aquifers in northwest Arkansas. The contamination was associated with poultry litter and cattle manure waste applied on the area.

Fate of Hormones in the Environment

Sorption

The fate of estrogenic steroids in the environment are determined by their physicochemical properties and site-specific environmental conditions. Williams et al. (1999) estimated the likely distribution of the steroid estrogens, E1, E2 and EE2, in three English rivers and predicted that the concentrations of these steroids under average conditions varied between 0.21 and 0.37 ng/l for E2, 0.27 and 0.44 ng/l for E1 and 0.024 and 0.038 ng/l for EE2. Bed sediments were shown to account for between 13% and 92% of the chemical loads in the river system. Lai et al.(2000) measured sorption coefficients of E1, E2, E3, EE2 and MeEE2 on a sediment and the log Kf values were 1.71, 1.56, 1.33, 1.72 and 2.26, respectively. The sorption on sediments was nonlinear with sorption constants ranging from 0.57 to 0.83, indicating that estrogenic steroids adsorb moderately onto sediment. The sorption of estrogens correlated with the presence of organic carbon content and also increased with salinity in water (Lai et al., 2000).

Degradation

Estrogens undergo various transformations mainly in the liver of humans and animals. They are frequently oxidized, hydroxylated, deoxylated and methylated prior to the final conjugation with glucuronic acid or sulphate. 17α-Estradiol is rapidly oxidized to estrone, which can be further converted into estriol, the major excretion product. Many other polar metabolites like 16-hydroxy-estrone, 16-ketoestrone or 16-epiestriol are formed and can be present in urine and feces. The contraceptive ingredient mestranol is converted after administering into 17a-thynylestradiol by demethylation (Ternes et al., 1999a). 17a-Ethynylestradiol is mainly eliminated as conjugates, whereas other metabolic transformations occur, but are of minor relevance. Therefore, estrogens are excreted mainly as inactive conjugates of sulphuric and glucuronic acids. Although steroid conjugates do not possess a direct biological activity, they can act as precursor hormone reservoirs able to be reconverted to free steroids by bacteria in the environment (Baronti et al., 2000; Ternes et al., 1999a). Since microorganisms are present in raw sewage and STPs, these inactive conjugates of estrogenic steroids are cleaved, and active estrogenic steroids are released to the environment (Baronti et al., 2000; Ternes et al., 1999a). In an aerobic batch experiments with activated sludge, E2 was oxidized to E1, which was further eliminated without any degradation products observed (Ternes et al.,1999b). The contraceptive EE2 was principally persistent under selected aerobic conditions, where mestranol was rapidly eliminated and small portions of EE2 were formed by demethylation. In another experiment (Layton et al.,2000), 70–80% of added E2 was mineralized to CO2 within 24 h by biosolids from wastewater treatment plants, whereas the mineralization of EE2 was 25–75-fold less. EE2 was also reported to be degraded completely within 6 days by nitrifying activated sludge and resulted in the formation of hydrophilic compounds (Vader et al., 2000). The half-lives of estrogenic steroids were estimated to be 2–6 days in water and sediment (Williams et al., 1999).

Microorganisms in water samples from English rivers were capable of transforming E2 to E1 with half-lives of 0.2–9 days when incubated at 20 ˚C, and E1 was then further degraded at similar rates (Jürgens et al., 2002). E2 could also be degraded when incubated with aerobic and anaerobic riverbed sediments. Compared to E2, EE2 was much more resistant to biodegradation in water from English rivers (Jürgens et al., 2002). Removal during sewage treatment is used as a collective term to describe the disappearance of chemicals due to processes such as biodegradation and adsorption on sludges. Removal depends on the plant performance and input of wastes. By comparing influent and effluent estrogen concentrations, Baronti et al. (2000) calculated that removal rates of E3, E2, EE2 and E1 from wastewater in activated STPs were 95%, 87%, 85% and 61%, respectively. Low removal rates for E1 may be related to transformations of estradiol in STPs. In the Brazilian STPs, the observed removal rates ranged from 64% to 78% for EE2, from 67% to 83% for E1 and from 92% to 99.9% for E2 (Ternes et al., 1999a).

Conversely, in German STPs, the removal rates were very low, e.g. only 64% for E2. In the Japanese STPs, the removal rates were reported to be more than 99% in autumn and from 7% to >99% in summer (Nasu et al., 2000). The reason behind this large difference in removal rates is still unclear. Johnson and Sumpter (2001) recently reviewed the removal of endocrine-disrupting chemicals in activated sludge treatment works and suggested that the activated sludge treatment process can consistently remove over 85% of E2, E3 and EE2, but the removal performance for estrone (E1) appears to be less and is more variable. In many countries, biosolids, recycled water and animal waste, which contain hormone steroids are often applied to agricultural land. The persistence of estradiol, estrone and 17a-ethynylestradiol in soils was examined recently in laboratory incubations (Colucci and Topp, 2001; Colucci et al., 2001). E2 was rapidly removed in the agricultural soils incubated under a range of conditions. At 30 ˚C, following 3 days incubation, more than 56% of E2 applied (1 mg/kg) in three agricultural soils with a moisture content of 13% was non-extractable with its half-life of less than 0.5 days in all cases (Colucci et al., 2001). E2 was abiotically transformed into estrone (E1) in both sterile and non-sterile soils. In contrast, E1 and EE2 were found to be microbially degraded (Colucci and Topp, 2001; Colucci et al., 2001). The dissipation half-life of EE2 ranged from 7.7 days at 4 ˚C to 3 days at 30 ˚C (Colucci and Topp, 2001). However, the behavior and persistence of E1 in the soils studied were unknown.

Summary on Endocrine Disrupting Compounds

Endocrine disrupting chemicals, also called hormonally active agents, are able to influence the endocrine systems of organisms. A clear relationship has been found between the presence of endocrine disrupting compounds and developmental changes in a number of animal species like seals in the North Sea or sea slugs in the Scheldt estuary (Guang-Guo et al., 2002). Hormone steroids have been detected in wastewater effluents and surface water as well as ground water at various levels. The behavior and fate of these hormone steroids in the environment depend on their physiochemical properties and environmental media. Natural estrogenic steroids (E1, E2 and E3) have higher solubilities than synthetic steroids 17a-ethynylestradiol (EE2) and mestranol (MeEE2). Limited studies indicated that they all have moderate sorption on sediments and short half-lives in soils and water. These natural and synthetic steroids undergo rapid transformations in sewage treatment plants. Their removal rates in STPs are dependent on the plant design and waste load. There have been limited reports on the occurrence of hormone steroids in the environment. Detailed surveys are necessary to understand the distribution of hormone steroids in the environment, especially in STP effluents, soils, surface water and ground water. Animal waste and biosolids as well as recycled wastewater have been increasingly applied to agricultural land; therefore, it is vital to estimate the input of steroids and their possible movement into surface and ground water through runoff and leaching. There is also a scarcity of data on daily excretion of steroids from different domestic animals, which could be used to calculate the steroid loads on agricultural land. Although estrogenic steroids were reported to degrade rapidly in soil and water in laboratory incubations, more research is needed to investigate the dissipation and pathways of these steroids in different media such as river water, seawater and ground water as well as sediments and soils. Factors (biotic and abiotic) influencing their degradation need to be explored further. In addition, most of the studies in the literature focused on estrogenic steroids; little research has been conducted on androgens. Steroid growth promoters are widely used in livestock in some countries and have become a recent public concern. Persistence of these steroid drugs in the environment and their possible effects on wildlife and human health still remain unclear.

Other Pharmaceutically Active Compounds

The bronchodilator drugs (β2-sympathomimetics) salbutamol (albuterol in the U.S.) and terbutaline, and in a few cases clenbuterol and fenoterol were reported by Ternes (1998) to occur at concentrations <20 ng/l in municipal sewage effluents. For all four compounds, the median sewage effluent concentrations were below the detection limits. In surface water only sporadic detections have been reported (Hirsch et al., 1998; Ternes, 1998). In investigations of STP effluents and surface waters, Ternes et al. (2001) detected the tranquilizer diazepam, the antidiabetic drug glibenclamide , and calcium influx inhibitor nifedipine. All three compounds were only found in a few samples at maximum concentrations clearly below 100 ng/l. Möhle et al. (1999) detected the drug pheneturide and the hemorrheologic agent pentoxifylline in sewage influents and effluents in Germany.

In terms of surface water investigations in the U.S., commissioned by the U.S. Geological Survey, Kolpin et al. (2002) detected low ng/l-concentrations of several other drugs such as the histamine H2-receptor antagonists cimetidine and ramitidine, the calcium ion influx inhibitor diltiazem, the angiotensin converting enzyme inhibitor enalaprilat, the nifedipine metabolite dehydronifedipinem the antidiabetic drug metformin and the antidepressant fluoxetine.

Eckel et al. (1993) detected pentobarbital at a concentration of 1µg/l in ground water from a landfill in Florida. In groundwater samples near Reno Nevada, Seiler et al. (1999) identified residues of the antidiabetic drug chlorpropamide and the anticonvulsant phensuximide. 5,5-Diallylbarbituric acid was found together with several other pharmaceuticals and drug intermediates in groundwater from a landfill in Grinsted, Denmark (Holm et al., 1995).

Personal care products

Products used for personal care like soap, shampoo, cosmetics, shaving foam, etc. have to be tested by the manufacturer on their toxicity (Hutzinger, 1992; Talmage, 1994). These tests are limited to what is considered normal cosmetic use such as skin contact or accidental swallowing. For that reason, data on chronic exposure through the digestive system are not available.

Research has been carried out on the presence of synthetic perfumes or musks in raw wastewater and surface water. These compounds are resistant to degradation, liposoluble and therefore regarded as persistent environmental contaminants. They have been detected in wastewater treatment plant effluent in the µg/l range (Heberer et. al, 1999). What this means in relation to human health is not clear, since no data are available for acceptable doses.

Detergents

Ecotoxicological data for detergents are readily available. The concentrations found in raw wastewater exceed the no-effect concentrations for the aquatic environment. The toxicological data on chronic exposure to detergents by drinking water are limited. The toxicity of detergents has been tested on small mammals. No carcinogenic, mutagenic or teratogenic effects or effects on the reproduction have been observed (Hutzinger, 1992). Nonylphenol, a

biodegradation product of the detergent Nonylphenol ethoxylate is persistent and has-been found to have an endocrine disrupting effect on fish. The effects on humans have yet to be determined (National Research Council, 1998 and 1999).

SECTION III

Identification of Potential Microbial Risks Associated with Recycled Water

Organisms of concern in relation with recycled water are the opportunistic pathogens. These organisms are not pathogenic for healthy individuals, but they can easily infect individuals with a decreased immunity, elderly, or infants. Examples of opportunistic pathogens include microsporidia, Echoviruses, Coxsackievirus (Lechevalier, 1999a,b) and mycobacterium avium intracellulare (Lechevalier, 1999a).

The pathogenic microorganisms that are often found in waste water consist of Cryptosporidium spp., Giardia spp., Legionella spp. and enteric viruses. These microorganisms are also relevant components in the case of aquifer recharge.

Another group of relevant pathogens are the Norwalk-like viruses (or Caliciviruses). Recent literature suggests that these viruses are probably one of the main causes of epidemics of gastro-enteritis in industrialized countries. In a study of 43 epidemics in the Netherlands, the presence of Norwalk was demonstrated in 32 out of the 43 cases (Heberer, 2002). To date the infective dose of the Norwalk virus is not known, however it is believed that only a few virus particles can cause infection. Because of the low infectious dose and the ubiquitous nature of these organisms in wastewater, the removal required during wastewater treatment for water reuse is high.

When considering the effects of pathogens one must also consider the magnitude and speed of their effects. Given the diversity, regionalization and variability of the microorganisms that may be involved, each geographical region when preparing it own norms should give priority to those organisms that have health implications (low infectious doses, the possibility of causing epidemics and high persistence and resistance levels). Special consideration should be given to certain groups of the population such as the children and the elderly.

Recently emerging pathogens, those pathogens that are not really new, but, are now known to cause diseases and are related to the consumption of drinking water complicates the issue of water reuse even further. In the United States, Giardia lamblia, Cryptosporidium parvum, Cyclospora cayetanensis (protozoa), Blastocystis hominis (fungi) and Mycobacterium avium-intracellulare or M. avium are considered as emerging pathogens (Jawetz et al., 1996). There are three main groups of microorganisms that can be transmitted via water consumption: viruses, bacteria and protozoa. Although it is possible to become infected with helminths through water consumption, it is not very likely if the recycled water is not turbid. Table 1 lists pathogens that may be found in wastewater. The table is based on different references that produced inconsistent information. Therefore it is important to undertake wide research to regionalize the prevalence of each microorganism to a particular location of interest.

Types and Occurrence of Pathogens in Wastewater

The major source of pathogenic microorganisms in domestic wastewater is the fecal material of infected individuals; however, urine may also be a source of certain pathogenic viruses (Hurst, 1989). The numbers and types of pathogens found in waste water will vary both spatially and temporally depending on the disease incidence in the population producing the wastewater, season, water use, economic status of the population and quality of the potable water (Rose and Carnahan, 1992).

Bacteria

Bacteria are microscopic (generally 0.1 to 10 micrometers in size), single celled organisms. Given the necessary nutrients (e.g., carbon, nitrogen, oxygen) and appropriate environmental conditions, bacteria are capable of growth and reproduction. The bacteria of most concern in domestic wastewater are the enteric bacteria, those that infect the gastrointestinal tract of humans, and are shed in the fecal material. Enteric bacteria are adapted to the conditions of the gastrointestinal tract: high organic carbon and other nutrients, as well as a relatively high temperature (37˚C). When these organisms are introduced to the wastewater, water or soil environment, the conditions are generally very different from those in the gastrointestinal tract. As a result, the enteric bacteria are not always capable of competing with the indigenous bacteria for the scarce nutrients available. Thus, their ability to reproduce, and even survive in the environment tends to be limited.

Human fecal material typically contains up to 1012 bacteria per gram, the majority of which are non-pathogenic. However, an infected individual may excrete high numbers of pathogenic bacteria in his/her feces. These pathogens are transmitted by direct contact with an infected individual, by consumption of contaminated water and by consumption of contaminated food.

Viruses

Viruses can be excreted in very high numbers in feces. For example, the concentration of rotaviruses may be as high as 1012 particles per gram feces (Flewett, 1982). The duration of excretion of viruses varies. Rotavirus excretion usually lasts for 1 to 3 weeks; however two months of excretion has been observed in some individuals (Kapikian and Chanock, 1990). The excretion of enteroviruses (i.e. poliovirus, echoviruses, and coxsackieviruses) may persist for 16 weeks (Melnick and Rennick, 1980).

There are more than 140 types of enteric viruses that can contaminate wastewater. A list of pathogenic human enteric viruses is shown in Table 1. The symptoms of infection caused by enteric viruses range widely- from inapparent, undetectable infections to a variety of disease including gastroenteritis, respiratory illness, hepatitis, paralysis, encephalitis, and conjunctivitis.

Parasites

A third group of pathogenic microorganisms that can be found in domestic wastewater is the parasites. The parasites that are pathogenic to humans can be classified in two groups; protozoa and the helminthes. Protozoa are single-celled organisms whose life cycles include a vegetative stage (trophozoite) as well as a resting stage(cyst). The resting stage of the organism is generally relatively resistant to inactivation during conventional wastewater treatment processes. Most of the intestinal protozoa are transmitted by fecally contaminated water, food, or other materials.

The helminthes are a group of multi-celled parasitic worms, which includes the nematodes (roundworms), the trematodes (flukes), and the cestodes (tapeworms).

The concentration of parasites in the fecal material of infected individuals can also be quite high. The reported concentration for Giardia and Cryptosporidium are 106 and 107 per gram feces (Jakubowski, 1984; Robertson et al., 1995). Excretion of Giardia may persist for up to six months (Pickering et al., 1984). A list of the parasites that can be found in domestic wastewater, the diseases they cause and the reported concentration in wastewater are given in Table 1.

Viruses as an Environmental Hazard

Viruses are the smallest infectious agents. Over one hundred and forty types of human enteric viruses are known to exist and these have been classified into several major taxonomic groups based on morphological, physio-chemical, genetic and antigenic properties. They come in different shapes and sizes that vary from 0.01 to 0.3 µm in diameter. They consist of a nucleic acid (DNA or RNA) surrounded by a layer of protein that may in turn be surrounded by a lipid type membrane. All viruses are obligate intracellular parasites that only multiply once inside the infected host cell. They use the biochemical system of the infected cells for their own purposes as if they were complex macromolecules.

Unlike bacteria, pathogenic viruses are not usually found in the waste of healthy human beings, only those who are intentionally exposed such as the case of vaccination or infected through water and food. The time it takes to expel them varies considerably and expulsion may be constant if the virus is endemic to a given community. In the case of infection, the viruses are found in large quantities (Flewett, 1982).

The presence of viruses and their concentration in wastewater widely varies and their development is linked to the season and age distribution of the population. Concentrations are usually high during summer and low in the autumn months.

TABLE 1
Classification of microorganisms found in wastewater and the illnesses they cause.

Agent	Classification	Illness
Adenoviruses (31 to 51 types)	Viruses	Respiratory illness, conjunctivitis, vomiting, diarrhea
Arbovirus	Viruses	Arboviral disease
Astroviruses (5 types)	Viruses	Vomiting, diarrhea
Calcivirus or Norwalk agent	Viruses	Vomiting, diarrhea
Coronavirus	Viruses	Gastroenteritis, vomiting, diarrhea
Coxsackie A (enterovirus)	Viruses	Meningitis, fever, herpangina, respiratory illness
Coxsackie B (enterovirus)	Viruses	Myocarditis, congenital heart abnormalities, rash, diarrhea, fever
Echovirus (enterovirus)	Viruses	Meningitis, encephalitis, respiratory illness, rash, diarrhea, fever
Enterovirus 68-71	Viruses	Meningitis, encephalitis, respiratory illness, acute hemorrhagic conjunctivitis, fever
Flavirus	Viruses	Dengue fever
Hepatitis A virus	Viruses	Infectious hepatitis
Hepatitis E virus	Viruses	Hepatitis
Norwalk virus	Viruses	Epidemic vomiting and diarrhea, gastroenteritis
Parvoviruses (3 types)	Viruses	Gastroenteritis

Agent	Classification	Illness
Poliovirus (enterovirus)	Viruses	Poliomyelitis, Paralysis, meningitis, fever
Reoviruses (3 types)	Viruses	Not clearly established
Reovirus (4 types)	Viruses	Diarrhea, vomiting, gastroenteritis
Snow Mt. Agent	Viruses	Gastroenteritis
Small and round viruses	Viruses	Diarrhea, vomiting
Yellow fever virus	Viruses	Yellow fever
Brucella tularensis	Bacteria	Tularemia
Campylobacter jejuni	Bacteria	Gastroentertis, Daiarrhea
Escherichia coli	Bacteria	Gastroenteritis
Legionella pneumophila	Bacteria	Acute respiratory illness, Legionnaire's disease
Leptospira spp. 150 types	Bacteria	Leptospirosis (septic meningitis, jaundice, neck stiffness, hemorrhages in the eyes and skin)
Clostridium perfringens	Bacteria	Gaseous gangrene, food poisoning
Mycobacterium leprae	Bacteria	Leprosy
Mycobacterium tuberculosis	Bacteria	Pulmonary and disseminated tuberculosis
Salmonella typhimurium	Bacteria	Typhoid fever, paratyphoid or salmonellosis
Shigella spp. 4 types	Bacteria	Bacillary dysentery, Shigellosis
Treponema pallidum-pertenue	Bacteria	Yaws (frambuesia)
Yersinia enterocolitica	Bacteria	Gastroenteritis, Yersiniosis
Vibrio cholerae	Bacteria	Cholera
Aspergillus fumigatus	Fungi	Aspergillosis
Candida albincans	Fungi	Candidiasis
Balantidium coli	Protozoa	Mild diarrhea, colonic ulceration, dysentery, balantidiasis
Cyclospora cayetanesis	Protozoa	Severe infections, dehydration, diarrhea, nausea, vomiting
Cryptosporidium parvum	Protozoa	Diarrhea and cryptosporidiosis
Entamoeba histolytica	Protozoa	Amoebic dysentery
Giardia lamblia	Protozoa	Giardiasis
Naegleria fowleri	Protozoa	Amoebic meningo-encephalitis
Plasmodium malariae	Protozoa	Malaria
Trypnosoma spp.	Protozoa	Trypanosomiasis
Toxoplasma gondii	Protozoa	Congenital or postnatal, toxoplasmosis
Ancylostoma duodenale	Helminths	Anemia, ancylostomiasis
Ascaris lumbricoides	Helminths	Ascariasis
Echinococcus granulosis	Helminths	Hyadatidosis
Enterobius vermicularis	Helminths	Enterobiasis
Necator americnus	Helminths	Anemia
Schistosoma spp.	Helminths	Schistosomiasis
Stongyloides stercoralsis	Helminths	Diarrhea, abdominal pain, nausea, Strongylodiasis
Taenia solium	Helminths	Taenisis, cysticercosis
Trichuris trichiura	Helminths	Diarrhea
Toxocara spp.	Helminths	Fever, abdominal pain, nausea

Source: Asano (1998); Jawetz et al., (1996); Kadleck and Knight (1996); Craun (1988).

The enteric viruses most relevant to humans are enteroviruses (polio, echo and coxsackievirus), Norwalk, rotavirus, reovirus, calicivirus, adenovirus and hepatitis A. Enteroviruses are high risk viruses, as only a relatively low dose is required to cause illness, they are more resistant to the environment and disinfection than most bacteria and it is difficult to measure them using conventional laboratory techniques.

Rotaviruses are the biggest cause of infant gastroenteritis worldwide. They are responsible for between 0.5 and 1 billion cases of diarrhea per year in children under five years old in Africa, Asia and Latin America and up to 3.5 million deaths. Usually between 50 to 60% of cases of children with gastroenteritis that are hospitalized are caused by this virus (Jawetz et al., 1996). Rotaviruses are closely related to reoviruses. Reoviruses and adenoviruses, which are the main causes of respiratory illness, gastroenteritis and eye infections, have been isolated from wastewater as well. To date there is no evidence the human immunodeficiency virus (HIV), the pathogen that causes the acquired immunodeficiency syndrome (AIDS), can be transmitted via a waterborne route, although its presence is considered feasible; however, given its low concentration maybe it has not been possible to detect it (Kadlec and Knight, 1996).

Regarding recharge, viruses that have migrated long distances in aquifers have been isolated. Horizontal migration varies between 3 and 400 m while vertical migration varies between 0.5 and 30 m depending on soil conditions (Table 2).

It is recognized that low viruses levels may cause an infection or illness. Since wastewater contains thousands of viruses, some of which are much more resistant to disinfection than bacteria, monitoring of the virus content of recycled water is highly relevant. However, when recycled water contains low viruses levels, there is no agreement among public health officials as to what this means to public health, even when there is information about how many viruses remain after different stages of treatment.

TABLE 2
The transport of viruses in soil after wastewater application.

Place	Type of Virus	Wastewater Type	Soil Type	Transported Distance (m)	
				Vertical	Horizontal
Tucson, AZ	BacteriophagesMS2 and PRD	Secondary effluentTertiaryeffluent	Coarse alluvial sand and gravel	4.6 6.1	
Gainsville, FL	Coxsackie viruses B4, Poliovirus 1, 2	Secondary effluent	Sand	3	7
Tuscon, AZ	Bacteriophages PRD1	Secondary chlorinated effluent	Coarse alluvial sand and gravel	6.1	46
Kerville, TX	Enteroviruses	Secondary effluent	Loam to Clay	1.4	
East Meadow, NY	Echoviruses 12	Secondary effluent	Coarse sand and fine gravel	11.3	3
Holbrook, NY	Echoviruses 6, 21, 24, 25	Tertiary effluent	Coarse sand and fine gravel	6.1	
Fort Devens, MA	Bacteriophages 12	Secondary effluent	Silty sand and gravel	28.9	183

Place	Type of Virus	Wastewater Type	Soil Type	Transported Distance (m)	
				Vertical	Horizontal
Phoenix, AZ	Coxsackie viruses B3	Secondary effluent	Fine loamy sand over coarse sand and gravel	18.3	3
Colton, CA	Enteroviruses	Secondary effluent	Coarse Sand	24.4	
Lubbock, TX	Coxsackie virus B3	Secondary effluent	Loam	1.4	
San Angelo, TX	Enteroviruses	Secondary effluent	Clay Loam	27.5	

Bacteria that pose an Environmental Hazard

A range of pathogenic bacteria capable of causing human illness may be found in human sewage. Some of these pathogens are also carried by other mammals and some by birds. Those posing the biggest risk are the enteric bacteria; in other words, those that live or can live in the intestines. They usually live in environments that are rich in organic matter and at temperatures of 37 ˚C, and so in order to survive in the environment, they have to adapt and modify their growth rate.

Pathogenic bacteria are present in the feces of infected individuals. The major types of recognized bacterial pathogens (e.g. Salmonella, Campylobacter) are capable of growth outside a host animal under laboratory conditions but are unlikely to be able to grow under ambient conditions. Some bacterial species which are capable of growth in the environment such as Aeromonas may be associated with diarrhea illness in humans; however there is insufficient evidence to determine whether isolates from environmental sources are a significant cause of disease. For Pseudomonas aeruginosa there is no dose-response data as the health implication do not relate to ingestion. The organism may grow in water that is warm and has inadequate chlorine levels. P. aeruginosa cause skin rashes etc. in spa pools. One of the most common pathogens found in municipal wastewater is the genus Salmonella spp. The Salmonella spp. group, contains a wide variety of species harmful to humans and animals. A sick individual can expel up to 109 Salmonellas g-1 (Bitton, 1994). The most severe form of salmonellosis is typhoid fever caused by Salmonella typhi. A less common relative is Shigella, which produces bacillary dysentery or shigellosis, related to swimming in polluted water.

Fecal coliform bacteria are commonly used as indicators of fecal contamination and the potential presence of pathogens. This group responds in a similar way to the environment and treatment as most bacteria but is unable to simulate viruses or protozoa. In particular, fecal coliforms may be absent in water where Giardia lamblia and Cryptosporidium parvum are present. Regarding recharge, bacteria are easily retained in the soil; some authors even state that only 8 cm of the soil is required for them to be separated from water during infiltration (Feachem et al., 1983). The following paragraphs detail some pathogenic bacteria.

Escherichia coli

Gram-negative bacteria usually considered non pathogenic include E. coli and some strains of Pseudomonas spp. Four groups of E. coli strains implicated in diarrhea are defined below:

(1) Enteropathogenic E. coli (EPEC);

(2) Strains that produce heat-labile or heat-stable enterotoxin called enterotoxigenic E. coli (ETEC);

(3) Strains capable of invading the intestinal mucus lining like Shigella spp. Called enteroinvasive E. coli (EIEC); and,

(4) (Strains that produce a similar toxin to Shiga ("Shiga coli") that can cause hemorrhagic colitis and are known as enterohemorrhagic E. coli (EHEC).

The different types of E. coli strains can cause gastroenteritis in both animals and humans and pose a big risk to newborns and children less than 5 years of age. ETEC is the common cause of traveler's diarrhea, which is liquid and profuse with some mucosity; symptoms also include nausea and dehydration. The main problem lies in the fact that small doses are infectious (102 organisms) and so they could constitute a problem in recycled water. In the case of Pseudomonas spp., some opportunist such as P. cepacia that was cultivated from patients suffering from cystic fibrosis, and P.mallei, causes a fatal infection in humans. The illness begins as skin ulcer or in mucus followed by lymphagitis and sepsis. Inhaling these microorganisms can cause primary pneumonia (Jawetz et al., 1996).

Campylobacter jejuni

Campylobacter jejuni have been identified as the cause of diarrhea in humans, although it is usually a pathogen in animals (Craun, 1988). Worldwide it is one of the most common causes of severe gastroenteritis and in Europe it is the main cause of gastroenteritis before Salmonella spp. The main source of infection is non-chlorinated water supplies. Campylobacter spp. has an incubation period of 2 to 5 days and affects mainly children and young people (Nachamkin, 1993).

Salmonella spp.

These bacteria are gram-negative bacilli that move using peritrichous flagella, are 2 to 3 µm long and 0.6 µm wide and are abundant in different environments. They are perhaps the most relevant group of pathogens for both humans and animals due to the large quantity of strains that exist. Typical symptoms of salmonellosis are chronic gastroenteritis with diarrhea, stomach cramps, fever, nausea, vomiting, headache and in severe cases, collapse and death. The incidence in humans is lower than in animals and the seasonal variation is different. Various strains are harmful to humans and their frequency varies year to year and from one country to another. Dissemination occurs due to the presence of a high number of microorganisms in the water or food in developing countries. An infective dose of salmonellas varies between 105 and 108 microorganisms (Lima and Lima, 1993).

Shigella spp.

This bacterium is similar to Salmonella spp. with the exception that only rarely does it

infect animals and does not live long in the environment. Shigella spp. are gram-negative

inert thin rods that eventually take on cocobacillary shapes. There more than 40 strains but S. sonnei and S. flexeneri represent almost 90% of total wastewater isolations. Shigellosis often begins with light watery diarrhea that can develop into full blown dysentery. The symptoms are usually limited to the infected person; however, Shigellosis can become serious and complicated in children and adults. Fever, nausea, vomiting and abdominal pain, migraine and myalgia are frequent manifestations of this bacterium. The classic form of dysentery caused by Shigella spp. is characterized by the expulsion of feces containing blood with or without mucus. An infection caused by Shigella spp. can easily be passed on. The infectious dose is lower than for salmonellas, less than 103 microorganisms (Sansonetti, 1997; Jawetz et al., 1996).

Mycobacterium tuberculosis

Tuberculosis bacilli measure around 0.4 x 3 µm (Jawetz et al., 1996). In artificial environments they form cocci and filaments with a morphology that varies from one species to another. Mycobacterium tuberculosis is an agent that has been isolated from wastewater that causes illness in people that swim in polluted water (CDH and Cooper, 1975). Together with M. balnei and M. boris they cause pulmonary and disseminated tuberculosis. In the case of M. Tuberculosis, contaminated water is the main source of infection.

Vibrio cholera

The Vibrio spp. strain is comprised of a series of 2-4 µm long curved gram-negative bacilli in the shape of a comma. Their presence depends on temperature and the degree of salinity. Gastroenteritis caused by Vibrio sp. can be choleric or non choleric. Epidemics mainly affect infants and are caused by V. cholerae strain groups O1 and O139 and some V. cholerae non-O1 strains. Main clinical symptoms are a secretive liquid diarrhea that is very abundant with significant loss of hydroelectrolytes and severe dehydration associated with vomiting. Vibrio cholerae is rare in developed countries but frequent in developing countries. Humans are the only known hosts and the most frequent vehicle for transmission is water, either through direct consumption or products irrigated with dirty or polluted water.

Helicobacter pylori

Organisms in this genus are helicoidal, curved, or straight unbranched gram-negative rods 0.3 to 1.0 µm wide and 1.5 to 5.0 µm long. There are at least nine species within the genus Helicobacter spp., as detailed in Table 3. The feces of birds and pigs also contain helicobacter-like organisms, and it is predicted that with further evaluation, these strains may be designated new species. The primary habitat of H. pylori is the human gastric mucosa. Three species are significant human pathogens: H. pylori (previously named Campylobacter pylori and Campylobacter pyloridis), H. fennelliae (previously named Campylobacter fennelliae), and H. cinaedi (previously named Campylobacter cinaedi). H. pylori has worldwide distribution, and although the mode of acquisition and transmission is not entirely clear, it appears to be acquired by the fecal-oral or the oral-oral route (Graham et al., 1991). Preliminary studies have indicated that prevalence H. pylori increases with age (Al-Moagel et al., 1990), but detailed information on the prevalence of bacteria in any defined population and on the factors that may influence the pattern of distribution is limited.

TABLE 3
Host and habitat of commonly isolated Helicobacter Species. Source or habitat

Species	Host	Habitat
H. Pylori	Humans	Gastric mucosa
H. mustelae	Ferrets	Gastric mucosa
H. felis	Cats, dogs	Gastric mucosa
H. Nemestrinae	Macaque monkeys	Gastric mucosa
H. murderer	Rats, mice	Intestinal mucosa
H. ascinonyx	Cheetahs	Gastric mucosa
H. cinaedi	Humans, rodents	Intestinal mucosa
H. fenelliae	Humans	Intestinal mucosa
H. rappini	Sheep, dogs, humans	Liver (sheep), Stomach (dogs), Feces (humans)

Source: Goodwin and Worsley, 1993.

Parasites that Pose an Environmental Hazard

Protozoa

Sewage may contain a wide range of pathogenic protozoa. In industrialized countries, the most common human parasitic protozoa transmitted by water belong to the genera Giardia and Cryptosporidium (Slifko et al., 2000). Giardiasis and cryptosporidiosis are also common infections of domestic and wild animals, which shed a large number of cysts and oocysts in the environment. These cysts are insensitive to disinfectants at the concentration commonly used in water treatment plants to reduce bacterial contamination, although it has been shown that at higher concentrations of chlorine and ozone, Giardia cysts are less resistant that Cryptosporidium oocysts (Sterling, 1990). Moreover, Giardia cysts have been shown to survive in water for up to 2 months at temperatures as low as 8˚C (Meyer and Jarroll, 1980), and Cryptosporidium oocysts can survive for up to 1 year in 4˚C artificial seawater (Tamburrini and Pozio, 1999). Furthermore, the infectious dose has been estimated to be as low as 10 cysts for Giardia (Adam, 2001) and 30 oocysts for Cryptosporidium (DuPont et al., 1995). Giardia and Cryptosporidium spp. Can be transmitted to humans through contaminated water and food, in addition to the classical oral-fecal route. Transmission is sustained by both a zoonotic and an athroponotic cycle (Fayer et al., 2001;Thompson, 2000). The infected hosts, whether animals or humans, shed very large numbers of oocysts with their feces, thereby increasing the environmental contamination. Moreover, oocysts can withstand normal water disinfection processes, and they have been found in significant quantities in the final effluents of sewage treatment works. Most studies on Giardia contamination of water have been limited to estimating the prevalence (Hashimoto et al., 2001; Isaac-Renton et al., 1996; Le Chevallier et al., 1991) and little information has been published on the specific contaminating species. However, this is of particular importance, since only Giardia duodenalis (lamblia) is associated with human infection (Thompson, 2000), and only two of the seven G. duodenalis(lamblia) assemblages (i.e. assemblages A and B) have been found in humans (Thompson et al., 2000). Therefore, the simple presence of Giardia cysts in the absence of data on the species or assemblage does not imply a risk of transmission to humans (Cacciò et al., 2003).

Like viruses they do not reproduce in the environment. However, they are able to survive and remain active for weeks, months or even for periods of up to 7 years, depending on environmental conditions (Bausum et al.,, 1983). In well-treated recycled water protozoa are unlikely to occur. Other species of pathogenic protozoa including Entamoeba, Cyclospora, and Microsporidia may also be present in sewage, but there has been little research on the prevalence of these organisms in different human populations. Just as with most viruses, tests for protozoa are generally not carried out on a routine basis by pathology laboratories, and it is likely the prevalence of these organisms among people with gastroenteritis is underestimated. For Naegleria Fowleri there is no dose-response data as the health implication do not relate to ingestion. The organism may grow in water that is warm and has inadequate chlorine levels. N. fowleri risk relates to people getting water into sinus cavities where an infection can establish and spread to the brain.

Amoebas

Diverse protozoa parasites have been detected in municipal wastewater, one of the most important being Entamoeba histolytica, which is morphologically defined as a single celled eukaryote with single celled trophozoites of 20 to 40 µm in diameter and cysts of 10 to 16 µm. Amoebas are usually present in the large intestine; occasionally they penetrate the intestinal mucus and spread to other organs. They are the cause of amoebic and hepatic dysentery. Entamoeba histolytica is present in 10% of the world's population resulting in approximately 500 million infected persons, between 40 and 50 million cases of invasive amebiasis a year and up to 100,000 annual deaths placing it second after malaria in mortality caused by protozoan parasites (WHO, 1997; Tellez et al., 1997; Ravdin, 1994).

Cryptosporidium spp.

Cryptosporidium spp, as previously mentioned, is one of many potential contaminants of reclaimed water. Physical removal by chemical pretreatment and filtration is the primary means of reducing the levels of oocysts in environmental water (Simmons et al., 2001). A possible risk to human health exists if filtration fails to function efficiently. This risk is greater still with reclaimed water. As to date no monitoring for C. parvum oocysts has been required and little information is available on the filtration efficiency in these facilities (Gennaccaro et. al., 2003).

This parasite is widespread in nature. It infects a large spectrum of farm animals and pets and was recently discovered to be a human pathogen. Although it is known that the infectious dose varies between 1 and 10, outbreaks have always been associated with large concentrations in water. The main symptoms of cryptosporidiosis are stomach cramps, nausea, dehydration and headaches. Once an individual has been infected they carry the parasite for life and can be subject to relapses. In England it is thought that Cryptosporidium spp. is responsible for 2% of all cases of diarrhea and their presence in groundwater is common (Gray, 1994). The first outbreak of Cryptosporidium spp. in the USA occurred in 1984 in Texas and consisted of 2,000 cases. The source was discovered to be result of unintentional recharge to an old well.

Not all segments of the population as well as different cultures react to Cryptosporidium in the same way. For example, the presence of Cryptosporidium spp. in the USA led to an epidemic of 400,000 cases in the 1993 Milwaukee cryptosporidiosis outbreak. It wasn't until a year later that the presence of these protozoa in the water supply was demonstrated by analyzing a sample from a lake taken from a depth of 40 m. In Mexico City the presence of cryptosporidium in the water supply has been detected but the associated illness has not been reported; neither has there been an increase in the intestinal illness mortality rate above the national mean (Cifuentes et al., 2002). There is no cure for cryptosporidiosis at this time, thus Cryptosporidium poses considerable danger to the public (Yao Yu et. al., 2003).

Giardia spp.

Like Cryptosporidium spp., Giardia spp. is present in the intestines of a large number of animals, where it lives like a trophozoites. These cysts can survive in water bodies for long periods of time, especially in winter. Giardiasis is a worldwide endemic with infection prevalence rates of 10% in developed countries and 20% in different developing regions, where it especially affects children under five suffering from malnutrition. The total number of sick people is 1.1 billion, 87% of which live in developing countries (WHO, 1997).

Giardia spp. is the most common parasite in humans, even though the water is not necessarily the main means of dissemination. Between 1980 and 1985 there were 502 outbreaks of which 52% were due to Giardia spp. Before the symptoms show, Giardia spp. has an incubation period of one to four weeks. The disease is characterized by a very liquid and smelly explosive diarrhea, stomach and intestine gases, nausea and loss of appetite. Unlike Cryptosporidium spp., Giardia spp. can be treated with several medicines. According to some public health officials, Giardia lamblia are no more prevalent in reclaimed effluents than in other irrigation waters. Occasional findings of oocysts in reclaimed water may, however, present a health risk due to the high viability of the organism and various routes of exposure. Monitoring for protozoan pathogens is necessary for estimating the risk of infection resulting from exposure to reclaimed water. With the development of new methods for detecting waterborne Cryptosporidium and Giardia, there is a great interest in applying these methods for the evaluation of pathogen reduction by wastewater reclamation processes and for compliance monitoring of effluents from reclamation facilities that provide water for public access irrigation (Quintero-Betancourt et al., 2003).

Occurrence of Cryptosporidium oocysts and Giardia Cysts in Reclaimed Effluents

Quintero-Betancourt et al. (2003), evaluated the occurrence of Cryptosporidium oocysts and Giardia cysts in reclaimed effluents from four water reclamation facilities by using method 1623 of the U.S. Environmental Protection Agency (USEPA, 1999). Based on the results there was a presence of viable and infectious Cryptosporidium oocysts in the reclaimed effluents tested. The percentage of samples positive for infectious oocysts was 50% (6 of 12), and the numbers detected were below the numeric pathogen standard (maximum limit of 22 viable oocysts/100 liters) proposed for reclaimed effluents by York and Walker-Coleman (2000). According to Gennaccaro et al., 2003, the state of Florida has mandated monitoring for protozoan parasites, including Cryptosporidium. In one study, C. parvum oocysts were detected in untreated wastewater (67% of the samples were positive) and in reclaimed water (25% of final effluent samples were positive) (Connell et al., 2000). Robertson et al. (2000) evaluated wastewater samples for viable C.parvum by using vital stains; 35% of influent samples and 46% of the effluent samples contained viable oocysts (Chapell et al., 1999). Gennaccaro et. al., 2003 went on to demonstrate the presence of infectious C. parvum oocysts in final reclaimed effluent from six reclamation facilities in the United States. Samples were collected from influent, secondary effluent, post-filtration, and final disinfected effluent waters. Six reclamation facilities in the United States, utilizing a variety of filtration systems (shallow- or deep-bed sand and anthracite filters or fabric disk filters) and disinfection methods (chlorine gas or UV radiation) were monitored. Three facilities were monitored five times over a 1-year time period. Three additional facilities were monitored over a 5-month time period. C. parvum oocysts were found in all sites monitored throughout the treatment process. As well and more importantly, infectious C. parvum oocysts were found in all sampling sites. Roughly 14% of all oocysts observed were infectious in nature. At the conclusion of treatment, roughly 25% of the oocysts detected were infectious in nature. This study reported initial findings of infectious C. parvum oocyst in final reclaimed effluent. Additional monitoring to produce a more statistically significant database is necessary.

Caccio et al. 2003, reported on the prevalence of Giardia and Cryptosporidium in wastewaters from four wastewater treatment plants in Italy. This investigation of the four plants revealed that Giardia cysts were ubiquitous, whereas Cryptosporidium oocysts were quite rare. Most studies on Giardia contamination of water have been limited to estimating the prevalence (Hashimoto et al., 2001; Isaac-Renton et al., 1996; Le Chevallier et al., 1991), and little information has been published on the specific contaminating species. However, this is of particular importance, since only Giardia duodenalis(lamblia) is associated with human infection (Thompson, 2000). Only two of the seven G. duodenalis(lamblia) assemblages (i.e., assemblages A and B) have been found in humans (Thompson et al., 2000). Therefore the simple presence of Giardia cysts in the absence of data on the species or assemblage does not imply a risk of transmission to humans. The results of this study indicate that water processed at the four treatment plants could be a potential source of human infection with G. duodenalis, although the viability of the cysts was not investigated.

Rose et al. 1996, evaluated the removal of microorganisms at various stages of treatment throughout a full-scale advanced water reclamation facility which produces reclaimed water for landscape irrigation. Human enteroviruses, enteric protozoa (Cryptosporidium and Giardia), total coliforms, fecal coliforms, heterotrophic plate count bacteria, coliphage, and physical and chemical parameters were examined. Risk assessment models were used to examine the public health impact associated with exposure to the reclaimed water containing various levels of pathogens as indicated by this study. A total of 60 samples were collected over the 1 year study period. The numbers of Giardia cysts and Cryptosporidium oocysts were reduced by 99.993 and 99.950% (4.14 and 3.27 log10), respectively. Some removal was observed at each stage of treatment but 25% of the samples from the storage tank were still positive for Giardia cysts and 17% were positive for Cryptosporidium oocysts.

Risk and Exposure Assessment of Protozoa

Risk is defined by the levels of the microorganisms in the reclaimed water and the amount of public exposure. The pathogens of interest are spread by the fecal-oral route and therefore ingestion is considered the primary means of exposure in this instance. Some studies have suggested that aerosols may also lead to inhalation and ingestion of pathogen, yet the exposure in this case would be much less than direct ingestion of reclaimed water (Asano et al., 1992). There are no guidelines for the acceptable level of risk from reclaimed waters using risk assessment procedures. However, the current acceptable level of microbial risk for drinking water has been suggested by the Environmental Protection Agency as a 10-4 yearly risk, with 21 daily exposure for 365 days (USEPA, 1989). The risk estimates for the reclaimed water were estimated at between 10-6 and 10-5 for a single exposure to 100 ml. This is below the suggested safety level for drinking water; however, the exposure is considerably less (21 daily for drinking water versus 100 ml yearly for reclaimed water). These estimates represent the risk of infection only; 50% of the individuals infected may become ill, and of those 1-10% may become ill enough to be hospitalized.

Based on the data Sheikh et al., 1990 , found in the Tertiary Water Food Safety Study, Giardia spp. is reduced by five to six orders of magnitude (100,000 to a million-fold) from influent to the plant to the finished disinfected tertiary recycled water. The Giardia spp. found remaining in the tertiary recycled water are empty cysts. There are three classes of organisms based upon the status of the internal structure. The first is the absence of any internal structure and the object can be classified as “empty”. It is generally believed that an empty (oo)cyst is a non-viable shell of the target organism. The next class is assigned to those organisms with no organized internal structure and these are referred to as “amorphous”. Again, these may be considered non-viable. The last classification is based upon the presence of obvious internal structure and can further be described by the degree of internal organization. Giardia spp. and Cryptosporidium spp. of all types were observed in the raw influent and to a lesser extent in the secondary effluent. In all of the tertiary effluent samples, 100 percent of the Giardia spp. observed were empty, non-viable cysts.

Helminths

Helminths are parasitic worms that are endemic in many areas of the developing world but relatively rare in developed nations. There are two major divisions of helminths, the roundworms (nematodes) and the flatworms. Flatworms can be further divided into those which are segmented (cestodes) and those that are unsegmented flukes (trematodes). The infective stage of helminthes can be either the adult organism or larvae, while the eggs or ova are the infective stage of others. Some helminthes have life cycles that will involve more than one species of host. Many helminths do not multiply in the human host; instead eggs are shed in the feces to locate other hosts. Helminths are not usually associated with acute health effects and may be asymptomatic and of no health significance if the person is well nourished and the pathogen load is low. Helminths may have long term debilitating effects if the pathogen load is high, however they are of little health significance to intentional water recycling and reuse, as their large size is associated with the existence of particles expressed as suspended solids or turbidity (Jiménez and Chávez, 1998). Although there are different types whose relative frequency depends on regional conditions, Ascaris spp. is almost always dominant. The importance of helminths in developing countries is high, as levels of helminthiasis are as high as 25 % to 33% of the population (Bratton and Nesse, 1993; Wani and Chrungoo, 1992). They are present (Table 4) in around 650 million individuals (Khuroo et al., 1990), whereas in developed countries they are present in no more than 1.5% of people (WHO, 1997).

TABLE 4
Global Scope and Size estimates of the occurrence of humans infected with intestinal parasites.

Disease	Number of infected people	Annual cases	Annual Deaths
Ambeiasis	500 million	40-50 million	40,000 – 100,000
Giardiasis	200 million	0.5 million	-
Ascariasis	800-1000 million	1 million	20,000
Hookworm infection	700-900 million	1.5 million	50,000-60,000
Trichuriasis	500 million	0.1 million	-

Source: WHO, 1997; Salas et al., 1990.

SECTION IV

Exposure, Infection and Illness Associated with Microorganisms

Outcomes of Exposure

When humans become exposed to pathogenic microorganisms, a number of outcomes are possible:

- No infection and no illness - the microorganism may fail to establish an infection, and therefore no illness will result.
- Infection and no illness - infection may be established (as defined by successful replication of the microorganism in the host), but no symptoms or illness may be experienced; however, the infected person may be capable of passing the microorganism on to others, some of whom may become ill.
- Infection and illness - an infection may be established, and the infected person may experience a range of symptoms; symptoms will vary in intensity and duration among different people infected with the same microorganism.

Infectious doses

Pathogens' ability to infect depends on a large number of factors. Both the host and the parasite are living creatures and therefore do not respond to the environment in the same manner or to the same degree in all cases. In addition, microorganisms mutate in order to adapt to the environment thereby ensuring their survival and propagation. This adaptation takes place in a relatively sort period of time known as an incubation period. During incubation, biochemical changes can occur in the pathogen that enables the pathogen to utilize the host's resources, this is known as infection. While the pathogen is adapting, the host's immunization system tries to defend it from the infection by producing antibodies. If the pathogen colonizes and efficiently reproduces, the host shows symptoms and manifests the illness. An unsuccessful attempt to colonize and to reproduce leads to asymptomatic carriers that only show biochemical evidence of the infection such as antibodies.

Generally infection is accepted as a symptom of illness, such as diarrhea, vomiting or fever Infection is then, directly determined by the detection of a microorganism in body waste or fluids or indirectly through the detection of antibodies. Data on infectious doses is not very precise. Usually the doses are determined by exposing a group of individuals or animals to different doses of microorganisms. When the study uses individuals they are normally groups of young, healthy volunteers who on average represent the best possible situation and their application to other population segments in more unfavorable conditions, means little. Another problem when trying to distinguish the exact value of the dose is the ability of microorganisms to form colonies within agglomerates, which due to the analytical method used are measured as if they were a single element instead of several. Virtually no attention is given to the exposure to a group of

microorganisms rather than to just one microorganism. Most of the studies to date are using pathogens isolated and grown in laboratories, although in nature they are almost always mixed with other organisms and adapted to environmental conditions. Some available data on infectious doses are given in Table 5. There are some differences among authors for the same type of microorganism as well as between different groups of microorganisms. In the case of water reuse little is known on the significance of low concentrations of microorganisms (Haas, 1983), and available information on dose refers to high levels.

TABLE 5.
Infectious dose of Pathogenic Microorganisms found in Wastewater.

Microorganism	Classification	Infectious dose	Reference
Enteric viruses	Viruses	1-10 <10	Feachem et al., 1983 Kadlec and Knight, 1996
Campylobacter jejuni	Bacteria	100	Kadlec and Knight, 1996
Clostridium perfrigens	Bacteria	1-1010	Feachem et al., 1983
Escherichia coli (enteroathogen)	Bacteria	100-1010 106-1010 100	Crook, 1998 Feachem et al., 1983 Gray, 1994
Salmonella spp.	Bacteria	104-107 103 105-107	Kadlec and Knight, 1996 Cooper and Oliveri, 1998 Feachem et al., 1983 Gray, 1994
Shigella spp.	Bacteria	100-1000 10-100	Cooper et al., 1995 Shiaris, 1985; Kadlec and Knight, 1996
Shigella flexneri	Bacteria	180	Feachem et al., 1983
Shigella dysenteriae	Bacteria	20 10	Feachem et al., 1983 Crook, 1998
Vibrio cholerae	Bacteria	103-107 108 108-109	Feachem et al., 1983 Kadlec and Knight, 1996 Gray, 1994
Yersinia spp.	Bacteria	109	Kadlec and Knight, 1996
Balantidium coli	Protozoa	25-100	Kadlec and Knight, 1996
Cryptosporidium parvum	Protozoa	1-10	Rose, 1990
Entamoeba histolytica	Protozoa	20 10-100	Feachem et al., 1983 Kadlec and Knight, 1996
Giardia lamblia	Protozoa	10 <10 25-100	Feachem et al., 1983 Crook, 1998 Kadlec and Knight, 1996
Entamoeba histolytica	Protozoa	20 10-100	Feachem et al., 1983 Crook, 1998 Kadlec and Knight, 1996

Microorganism	Classification	Infectious dose	Reference
Giardia lamblia	Protozoa	10 <10 25-100	Feachem et al., 1983 Crook, 1998 Kadlec and Knight, 1996
Ascaris lumbricoides	Helminths	1-10	Feachem et al., 1983
Hymenolepis nana	Helminths	1	Kadlec and Knight, 1996
Trichuris trichiura	Helminths	1	Kadlec and Knight, 1996

Organism Group Infectious dose Reference

Pathogen Concentration in Wastewater

The types and concentrations of pathogens present in raw sewage will vary with the prevalence of infection in the source population. Difference in sanitation practices, drinking water quality, food safety and access to health care between different populations have substantial influences on infection rates. Outbreaks of gastrointestinal disease in the local population may lead to a substantial rise in the amount of a particular pathogen in sewage. Some pathogens appear to have fairly regular seasonal patterns of infection in the population such as the rotavirus. The rotavirus is more common in winter in temperate climates thus their levels in sewage would be expected to vary in a similar manner.

Pathogenic microorganisms will be removed or inactivated to varying extents during sewage treatment and subsequent wastewater treatment. The probability of infectious pathogens surviving treatment will depend upon the initial pathogen load in the raw sewage and the type of treatment processes used. Data that refer to the content of different microorganisms in wastewater prior to treatment are variable (Table 6).

Survival of pathogens in the environment

Not only the presence but also the survival of pathogens in the environment is an important issue in regards to water reuse (Table 7). This is very variable for each group and

genus and depends on numerous environmental factors including: humidity (a dry environment kills microorganisms), organic matter content (its presence favors survival), temperature (greater resistance to low temperature), pH (bacteria survive better in alkaline soils than in acid ones), soil moisture content (the presence of water and soil saturation promotes mobility), sunlight (it disinfects), foliage protection and competition between native flora and fauna.

TABLE 6
The concentration of Pathogenic Microorganisms found in wastewater.

Organism	Content	Country	Reference
Campylobacter spp.	3700	Germany	Höller and Waltraud, 1998
Fecal coliforms (MPN/100ml)	107-109	Mexico	Jimémez et al., 1997
	103-105	USA	USEPA, 1986
	104-107	Egypt	Stott et al., 1997
	104-106	USA	Berg and Metcalf, 1978
	105-107	USA	Geldreich, 1978
	106-107	USA	Davis, 1979
	107	Brazil	Mara and Silva, 1979
	105-108	Developing	Feachem et al, 1983
	108	Bangladesh	Daniel and Lloy, 1980
E. coli (MPN/100ml)	106-107	Scotland	Wheater et al., 1980
	>108	Kenya	Evison and James, 1973
	104	South Africa	Grabow and Nupen, 1972
Total coliforms (MPN/100ml)	107-1010	England	Geldreich, 1978
Clostridium perfringens	103-105	USA	Feachem et al., 1983
Cryptosporidium parvum (Oocysts/L)	0.91-28	USA	Rose, 1988
	2 x 102	USA	US EPA (1991 and 1992) and Cooper and
	103	USA	Mayer and Palmer, 1996
	4.1-	USA	Madore et al., 1987
	1-103	Worldwide	Feachem et al., 1983
	10-170	England	Bukhari et al., 1997
	2.5-8000	England	Parker, 1993, Carrington and Gray, 1993
	13-73	Kenya	Grimason et al., 1993
	103-104	USA	US EPA, 1992
	4 x 103	USA	US EPA (1991 and 1992) and Cooper and
	2	Finland	Hirn, 1980
	2-41	South Africa	Grabow and Nupen, 1972
	7-250	India	Phirke, 1974
	500	USA	Davis, 1979
	670	Holland	Kampelmacher and van Noorle Jansen, 1970
	7,240	England	Jones, 1977
	8,000	USA	Davis, 1979
	2.0-8,000	Worldwide	Feachem et al., 1983
Shigella spp. (No./100ml)	1-103	USA	Feachem et al., 1983
Helminths Ova (HO/L)	8 x 102	Syria	Bradley and Hadidy, 1981
	1-8	USA	US EPA, 1992
	9	France	Schwartzbrod et al., 1989
	6-42	Egypt	Stott et al., 1997
	60	Ukraine	Ellis et al., 1993
	166-202	Brazil	Blumenthal et al., 1996
	6-380	Mexico	Jiménez et al., 1997 and 1999
	840	Marroco	Schwartzbrod et al., 1989

Organism	Content	Country	Reference
	1-800	Mundial	Feachem et al., 1983
Poliovirus (No./100 ml)	182-	England	Irving, 1982
Protozoan (cysts/L)	103-105	Worldwide	Feachem et al., 1983
	978-	Mexico	Jiménez et al., 1997 and 1999
	28.4	USA	Rose, 1988
Entamoeba histolytica (Cysts/L)	1-10	USA	Feachem et al., 1983
	4-28	Israel	Kott and Kott, 1969
	52	USA	Wang and Dunlop, 1954
Enteric viruses (vu/L)	3 x104	USA	US EPA (1991 and 1992) and Cooper and
	103	USA	Heyward et al., 1979
	27-104	USA	Fujioka and Loh, 1978
	103-105	Israel	Feachem et al., 1983
	600-100	Israel	Buras, 1976
Enterococci (No./100ml)	105-106	USA	Davis, 1979
Fecal streptococci (No./100ml)	104-106	USA	Geldreich, 1978
	106	Brazil	Mara and Silva, 1979
	>107	Kenya	Evison and James, 1973
Giardia lamblia (cysts/L)	2 x 102	USA	US EPA (1991 and 1992) and Cooper and
	1-103	Worldwide	Feachem et al., 1983
	10-	England	Bukhari et al., 1997
	1-43,907	England	Parker, 1993; Dawson et al., 1994; Robertson et
	1-14,000	USA	Rose, 1988;Sykora et al., 1991; Robertson et al.,
	213-	Kenya	Grimason et al., 1992
	1	USA	Ongerth, 1990
	104	USA	Mayer and Palmer, 1996
	103-105	USA	Jakubowski and Ericksen, 1979
Psuedomonas aeruginosa	103-104	Scotland	Wheater et al., 1980
Salmonella spp. (MPN/100ml)	100-109	Mexico	Jiménez et al., 1997 and 1999.

Content Country Reference

TABLE 7
Typical survival rates at 20-30°C of common pathogens found in wastewater Pathogens Survival, days

Pathogens	Survival, days		
	Fresh and Wastewater	Cultures	Soil
Viruses			
Enterovirusesa	<50b	<15	<20
Bacteria			
Fecal Coliforms	<30	<15	<20
Salmonella spp.	<30	<15	<20
Shigella spp.	<10	<5	<10
Vibrio choleraec	<10	<2	<10
Protozoa			
E. histolytica cysts	<15	<2	<10
Helminths			
A. lumbricoides ova	Several months	<30	Several months

[a] Includes polio, echo and coxsackie viruses
[b] In sea water viruses have a much lower survival rate than bacteria
[c] There is some uncertainty about the survival of Vibrio cholera in water.
Source: Feachem et al., 1983

Microbiological analytical techniques for identifying and measuring pathogens

The quality and type of microorganisms found in domestic wastewater is so variable that standardizing methods for all purposes may not be useful and routine monitoring of each of them is not only impractical but also impossible. In particular, the time required to analyze an interesting pathogen is so long that measurement is not a useful tool for providing treatment plants with feedback.

Viruses. Identification and quantification of viruses in wastewater is complicated by the low level of recovery as well as the need to use complicated and costly techniques, and so very few laboratories can undertake the study. A laboratory requires 14 days on average to determine the presence or absence of a virus in the water and another 14 to identify it. The application of recombined DNA techniques may possibly help to facilitate detection but how to study the infectious potential of the particles and how to apply these advances to environmental samples has yet to be determined (Asano, 1998).

Protozoa. There are also enormous difficulties to quantify protozoa in clean and recycled water due to the size of the sample that must be filtered (100 a 500 liters) in order to retain the oocysts and cysts as well as identification of the species and their viability. In the future, the use of molecular techniques using polymer reactions could be an option. This would enable a larger number of pathogens to be determined, identified and to know their viability and ability to infect. However, good analytical techniques do not solve the problem of selecting one or several indicators and their significance for health.

Microbiological indicators

Microbiological quality indicators are considered when determining if pathogens are present in recycled water.

An indicator should have the following properties:

- be present only when there is contamination of a fecal origin;
- have the same or a greater capacity to survive than pathogens that are trying to
- be avoided;
- do not reproduce outside the host; and
- be easily determined and monitored in environmental samples.

There is currently no indicator that has all of these characteristics. The most widely accepted indicator organisms for monitoring drinking water and wastewater are: coliforms, fecal streptococci and Clostridium perfringens respectively. In the case of reuse, there is no consensus about what indicators should be used. Therefore the properties of traditional indicators are looked at and subsequently other options, currently the subject of debate, are presented.

Traditional indicators

Dealing with conventional indicators the coliforms (fecal and total) and the fecal

streptococci are considered.

Coliforms

The fecal coliform group has been used to indicate the presence of bacteria of a fecal origin and consequently the possible presence of other pathogenic microbes. Initially, total coliforms were used; however it was discovered that they were not of fecal origin, thus, the FC group was used. This group corresponds to the thermotolerant coliforms that are measured via incubation at 44.5 ± 0.5 ˚C. In feces, strains such as Klebsiella sp., whose significance to health is questionable, are found. In the case of recycled water the US EPA recommends using fecal coliform as an indicator, and if their representation is in doubt, resorting to the specific determination of E. coli. This is because due to the water's origin, there is certainty as to the fact that there are or were fecal coliform present. However, viruses, protozoa and helminths ova are more resistant to any disinfection process and environmental conditions than are fecal coliforms. It has also been shown that in effluents not containing chlorine, such as those that may be used in recharge, there is the possibility of regrowth and so when it comes to reused water, fecal coliforms are not as effective in determining risk to public health. Additionally, regrowth could be interpreted as the presence of pathogens even when they are unable to reproduce in recycled water.

Fecal streptococci

These are intestinal bacteria that belong to the Lansfield's group (corresponding to a strain classification) and are found in the feces of all warm-blooded mammals. Within this group is a subgroup known as enterococci, which is characterized by growing both at 10 ˚C and at 45˚C, in an environment of 6.5% NaCl and a pH of 9.6. This subgroup has been indicated as a useful tool for indicating the quality of water for recreational use (Cabelli, 1983; Dufour, 1984) and which for its environmental permanence may be useful to water reuse.

Non-conventional indicators

According to Hazen and Toranzos (1990) in hot countries it has been demonstrated that E. coli, the most universal indicator, is a native of tropical waters. Also, Mazari-Hiriart et al. (1999) demonstrated that MS-2 coliphages (male specific coliphages) presence could not be correlated to traditional indicators (coliforms and fecal streptococci) in the same samples. The Mexico City aquifer supplies 18 million people; infiltrations of wastewater have been found and minor recharge work using recycled water is being carried out. Using the same samples, researchers found that male specific coliphages were present in 72% of the cases, total coliforms in 48%, fecal streptococci in 28% while fecal coliforms were present in just 14%. Hence, they conclude that bacteriophages are better indicators of fecal pollution due to their high prevalence (Snowdown and Cliver 1989 and Yahya et al. 1993). In fact, Mazari-Hiriart et al. (1999) recommend the combined use of fecal streptococci and male specific coliphages in reused water standards. The latter can be detected using easy analytical methods and at a relatively low cost.

Helicobacter pylori

Helicobacter pylori is a bacteria present in wastewater that has been found in different contaminated water supply sources due to wastewater infiltration. It is a pathogen that causes chronic superficial gastritis and duodenal ulcer. It is also a risk factor in stomach cancer (Jerris, 1995). As a recycled water indicator, H. pylori may be of interest in developing countries given the marked difference between disease incidences to that of developed countries. In developing countries the prevalence level for children between 1 and 10 is 50% while in developed countries it is just 10% (Graham et al., 1991). In the case of adults (>25 years), developing countries have a prevalence level of 80%. Mazari et al., (2001) demonstrated that complying with a set content of fecal coliform and wastewater chlorine (between 0.2 and 1 mg.l-1) does not reflect the absence of Helicobacter pylori.

This application could also be used in developed countries, as Helicobacter pylori is present throughout the world. In Sweden for example, it has been detected in wells, wastewater and water supply despite the high level of treatment in that country (Hulten et al., 1998).

Clostridium perfringens

Anaerobic bacilli like Clostridium perfringens that form spores are commonly found in feces. Particularly in Great Britain, this bacterium has been used as a recent indicator of fecal contamination (Bisson and Cabelli, 1980). Its usefulness lies in the fact that it is easily quantified and is more resistant to disinfection and environmental conditions than many pathogens. Clostridium perfringens form a resistant endospore and so the presence of vegetative cells indicates recent contamination while spores imply past contamination. Grabow (1990) questions its usefulness in water recycling and reuse, as although it is resistant to disinfection, the initial number is low, making detection difficult. Only modern techniques can overcome this problem. What is true is that to date there is little available information on its content in reused and wastewater.

Viruses

As mentioned, there are a great variety of viruses that may be present in waste and recycled water. Like bacteria, it is impossible to measure all viruses and bacteria indicators are not useful for determining the presence of viruses; therefore, it is thought that a virus indicator would be useful in the case of water reuse.

Bacteriophages are viruses that infect bacteria and even though they have not been linked to human diseases, and therefore have no health implications, they are used as indicators because laboratories can easily detect them. Also, the coliphage group has been proposed as an indicator. It is always present in wastewater where it is relatively abundant. Its detection is easy, relatively cheap and information can be obtained in just 24 h. Nevertheless, it does not adequately simulate the behavior of animal viruses. F+ Specific coliphages are good candidates as indicators of human enteroviruses. They are found in wastewater in numbers that vary between 100 and 1000 per mL. They have the same or better resistance to environmental factors and disinfection than as human viruses.

Protozoan cysts and helminths ova

The pathogens most resistant to disinfection, and which easily survive different environmental conditions are protozoan cysts and helminths ova. Therefore, the absence of bacteria or enteroviruses does not reflect their absence. Protozoan cysts would pose the biggest problem in reused water for their smaller size and the fact that of what little is known, it appears that Cryptosporidium spp. is very resistant. The main problem associated with protozoans, is that the detection technique to determine presence and viability is very complex.

Regarding helminths, those used for their resistance are Ascaris spp. ova; however, Details regarding this organism as an indicator are not available.

Risk studies

The National Research Council (1982) states that in order to define the risk involved in the use of recycled water, the following should be considered: (a) the long term effects of chemical compounds are the main concern, (b) the risk from consuming recycled water should be evaluated in comparison to the risk of consuming water from conventional resources being used, and (c) the need for an intensive toxic tests program. The risk from exposure to different reused water is shown in Table 8.

In order to establish the risk in a region the following is necessary: (a) establish the type and quantity of microorganisms in a given region, (b) know the infectious dose, and (c) define and evaluate a possible route of infection. These three aspects are not easy to define (Tanaka et al., 1998).

TABLE 8.
Annual risks of contracting at least one infection from exposure to recycled wastewater at two different enteric viruses concentrations.

Viruses	Exposure scenarios			
	Landscape irrigation for golf courses	Spray irrigation for food crops	Unrestricted recreational impoundments	Groundwater Recharge
Maximum enteric viruses concentration of 1.1vu/L in chlorinated tertiary effluent				
Echovirus 12	1 x 10-3	4 x 10-6	7 x 10-2	6 x 10-8
Poliovirus 1	3 x 10-5	2 x 10-7	3 x 10-3	5 x 10-9
Poliovirus 3	No data	1 x 10-4	8 x 10-4	2 x 10-8
Minimum enteric viruses concentration of 0.01 vu/L in chlorinated tertiary effluent				
Echovirus 12	9 x 10-5	4 x 10-8	7 x 10-4	5 x 10-10
Poliovirus 1	3 x 10-7	1 x 10-9	2 x 10-5	5 x 10-11
Poliovirus 3	2 x 10-4	1 x 10-6	2 x 10-2	2 x 10-10

Source: Asano et al., 1992

SECTION V

Removal of Pathogens by Treatment Processes

There have been a number of reviews on the removal of pathogenic microorganisms by activated sludge and other wastewater treatment processes (Feachem et al., 1983; Leong, 1983). This information suggests that significant removals , especially of enteric bacterial pathogens can be achieved by these processes (Table 9). However, disinfection and/or advanced tertiary treatment are necessary for many reuse applications (irrigation, aquifer recharge, etc.) to ensure pathogen reduction.

Pathogen removal

Both environmental conditions and treatment processes conditions are hostile for most pathogens, and decrease their chance for survival (Kadlec and Knight, 1996). The factors involved include: temperature, ultraviolet light, water quality, ecological competence and sedimentation. Literature in this area points out the efficiency of pathogen removal in different treatment steps and the technology is available to reduce pathogens to levels considered safe (Table 9).

TABLE 9.
Pathogen removal by different stages of the wastewater treatment processes

Stage of Treatment	Enterovirus	Salmonella spp.	Giardia spp.	Cryptosporidium spp.	Helminths
Concentration in wastewater	105-106	103-104	103-105	1-4000	----------
Remaining after primary treatmenta	103-105	102-104	104-105	----	---------
Efficiency	50-98%	50-99.8%	27-64%	0.7	90
After secondary treatmentb	102-103	100-103	103-105	----	----------
Efficiency	53%-1 log	98%-2 log	45-97%	-----	99.99
After tertiary treatmentc	10-3-102	10-5-100	10-2	103	----------
Efficiency	1-3 log	2-6 log	1-4 log	2-7d	----------

[a] Primary sedimentation and disinfection
[b] Primary sedimentation, trickling filter/activated sludge, and disinfection
[c] Primary sedimentation, trickling filter/activated sludge, disinfection, coagulation, filtration and disinfection
[d] Filtration only
Source: Yates et al., 1998; Leong, 1983; US EPA, 1991 and Feachem et al., 1983.

Treatment processes

Harleman and Murcott (1999), recommend application of a primary treatment assisted with chemicals (Advance Primary Treatment, APT or chemical enhanced treatment) toreuse water for irrigation. This treatment removes relevant contaminants, but permits beneficial soluble organic matter to pass into the soil. This process generates low content of suspended solids or turbidity, which leads to greater disinfection efficiency, either with chlorine or UV light. Likewise, the process allows the use of sprinkling irrigation in high-tech countries or countries where water is scarce. The effluent quality is improved by filtration through the soil, and the aquifers can be used as water supply storage.

According to Leong (1983), primary processes involving grit elimination and simple sedimentation remove from 5 to 10% of viruses; however, in practice, these values range from 0 to 80%, with a median of 10%. Efficiency is highly dependent on the degree of separation of solids, since viruses get adsorbed in particles where their infectious capacity is not diminished. There are no data available for virus removal by APT, although it can be assumed to be greater than that obtained from a simple primary treatment, as it removes 70 to 80% of suspended solids versus 30% obtained in the first case. Gerba et al. (1975) state that viruses are associated in general with particles >8μ and particles between 0.45 and 0.65 μm. It has been demonstrated that from 60 to 100% of viruses are adsorbed on particles suspended in wastewater (Wellings et al., 1976), thus colloidal particle removal is highly recommended to enhance virus removal.

Activated sludge

Compared with other secondary biological processes, activated sludge is effective for pathogen removal (Table 10). For example, it removes 10% more than trickling filters (Leong, 1983). Both sedimentation and aeration play an important role in this. Sedimentation eliminates heavy and large pathogens, while aeration promotes antagonistic reactions between different microorganisms, causing their elimination. As a result of getting pathogens entrapped in the flocs, there is a high removal of small non-sedimentable microorganisms, such as the Giardia spp. and Cryptosporidium spp., which remain concentrated within the sludge. Helminths are basically eliminated from activated sludge by sedimentation, in concentrations which are not detectable in the USA; while in countries like Mexico, due to the initial concentrations of helminthes, small concentrations are found in the effluent of properly operated treatment plants (Jiménez, 1997).

TABLE 10
Pathogen removal rate in activated sludge.

Pathogen	Removal Rate	Reference
Viruses	90-99%	Rao et al., 1986 and Leong, 1983
Giardia spp. and Cryptosporidium spp.	90%	Rose and Carnahan, 1992; Casson et al., 1990
Helminths	90%	Jiménez et al., 1997

Irving and Smith (Leong, 1983) have found that although overall virus removal is 60% in activated sludge, each virus type is removed differently, with reported removal rates of 92% for enterovirus, 81.5% for adenovirus and 26% for rheovirus. Rotavirus is very significant to matters of health, and it behaves like rheovirus, therefore activated sludge in not so good in this case.

Stabilization ponds

Stabilization ponds are very efficient for removing almost all kinds of pathogens (Tables 11 and 12). Pathogen inactivation or removal occurs because of different factors including temperature, excess exposure to the sunlight, pH, predator microorganisms, adsorption and trapping into flocs. However, the determining factor is sedimentation, as a result of the lengthy retention time. Shuval et al, 1986, found in stabilization ponds with 20 days hydraulic retention time helminths ova are completely removed.

To remove helminths ova a minimum retention time of 8 to 10 days is set, with at least twice as much time to reduce fecal coliform to less than 1000/100 mL. To control Cryptosporidium spp., almost 38 days are needed (Grimason et al., 1992). However, practical experiences (Camp, Dresser and Mckee, 1993; Huntington and Crook, 1993) demonstrate that this is hard to achieve when there are hydraulic problems such as flow bypasses (Yates et. al., 1998). Additionally, care must be taken in arid zones with high evaporation-transpiration rates, as in these areas ponds may represent a net loss of water. For example, in the eastern part of Mexico City, a 920 ha pond built for agricultural reuse of water has an evaporation rate of 25% of incoming water (700 L/s) in the dry season (when water is needed for irrigation); additionally, salinity increases as a result of evaporation (Jiménez and Chávez, 1998).

TABLE 11.
Pathogen removal rates in stabilization ponds and conventional wastewater treatments

Pathogens	Stabilization pond removal	Conventional treatment removal
Bacteria	Up to 6 log units	1-2 log units
Viruses	Up to 4 log units	1-2 log units
Protozoa cysts	100%	90-99%
Helminths ova	100%	90-99%

Source: Feachem et al., 1983

TABLE 12.
Bacterial and viral content in raw wastewater and the effluent of five waste stabilization ponds in Northeast Brazil at 26˚C.

Organisma	Raw Wastewater	Anaerobic Pondb	Facultative Pondc	Maturation pond 1c	Maturation pond 2c	Maturation pond 3c
Fecal coliform	2 x 107	4 x 100	8 x 105	2 x 105	3 x 104	7 x 105
Campylobacter spp.	70	20	0.2	0	0	0
Salmonella spp.	20	8	0.1	0.002	0.1	0
Enterovirus	1 x 104	6 x 103	1 x 103	50	50	9
Rotavirus	800	200	70	10	10	3

[a] Bacterial number per 100 L, viral numbers per 10 liters
[b] Anaerobic pond with a mean hydraulic retention time of 1 day
[c] Facultative pond and Maturation ponds with a retention time of 5 days
Source: Pearson et al., 1995

Slow filtration

Slow filtration is recognized in water potabilization as an efficient method of microbiological control in rural and low-income communities. However, there is little information available about its use for purifying wastewater effluents (with high organic and turbidity content), and in particular about its benefits in preparing water for recharging or irrigation. Adin (1998) states that because of their proven capacity to remove pathogens, it may be advisable to use slow filters after wastewater is stored in reservoirs and before it is used for irrigation. The few studies carried out on slow filtration of wastewater have demonstrated a removal range of 60 to 80% of suspended solids and one E. coli log, with coarse sand (Farooq and Yousef, 1993; Farooq et al. (1993); Adin et al., 1995).

In an application of a 0.95 m-high filters to a secondary biological effluent, in connection with initially low BOD and TSS (from 16 to 22 mg/L), and 105 fecal coliform. 65% of BOD and TSS, and 95% of fecal coliform were eliminated in filter runs of up to twenty days, using filtration rates of 3.5 to 7 meters per day (Ellis, 1987). Using a horizontal filter with a rate of 2.4 m/h and a contact time of 33 min he obtained an efficiency of 82% in TSS. The interesting part of this research was the demonstration that it is possible to obtain a constant reliable quality in effluent with slow filtration, and that there is no substantial difference between using sand of 0.3 or 0.6 mm size.

Constructed wetlands

Interest is growing in the use of constructed wetlands as a secondary or tertiary treatment method, as they are particularly useful in the removal of pathogens without generating by-products (Table 13). These types of systems, that imitate nature, have a broad and diverse biological activity. In the USA and Canada the most popular systems used are the free-water surface systems (FWS) often referred to as wetlands (Haberl, 1997; Cole, 1998). FWS are highly diverse in shape and habitat, and are used for refining effluents from treatment systems in small or medium communities, although they have also been used for treating industrial wastewater.

Wetlands generally consist of reservoirs or ponds where plants are grown. Wetlands are built on a slant so that water may flow by gravity, and they are generally shallow to allow for better removal of contaminants. The plants typically used are:

- large plants with floating or aerial leaves;
- plants with well-developed and submerged roots, such as rushes, water hyacinth, reeds, and water lilies; and
- very small floating plants with few roots or no roots at all, such as genera Lamenacea family, Lemna spp. or duckweed Spirodela spp., Wolffia spp., Wolffiela spp., and Salvinia spp. (Rico et al., 1992 and Brix, 1993).

FWS systems are very efficient for the removal of nitrogen, phosphorus and heavy metals. Water lilies eliminate up to 350 kg of phosphorus and 200 kg of nitrogen per year (Brix, 1997). The main limitation of wetlands is the large area required, and the generation of mosquitoes and unpleasant odors when they are not operated correctly (Olguin and Hernández, 1998). The efficiency of coliform removal is very high in wetlands; however, there are great variations depending on climate, season, wetland type and retention time. Thus, it is difficult to control the stability of the process. This problem limits their applicability to reuse systems. Several wetlands have been installed in different places, but the high cost of microbiological studies has restricted the availability of information. Some data about pathogen removal in wetlands is shown in Table 13; variations in percentages are due to the type of plant used and the different climates.

TABLE 13
Pathogen removal rates in wetland treatment systems.

Organism	Removal (%)	Wetland Condition	Reference
Fecal coliform	98-99	Duck weed.	Karpiscak et al., 1996
	92-99	Reed.	Rivera et al., 1995 and 1997
	90-98	Reed	Haberl and Perfler, 1991 and Hiley, 1991
MS2 Coliphages	67-84	Duckweed	Gersburgh et al., 1989
Cryptosporidium spp.	53-87	Duckweed	Karpiscak et al., 1996
Giardia spp.	58-98	Duckweed	Karpiscak et al., 1996
E. coli E. histolytica	100	Combined system with gravel and reed	Rivera et al., 1995
Ascaris lumbricoides ova	100	Combined system with gravel and reed	Rivera et al., 1995

Tertiary coagulation-flocculation process

Several studies show that coagulation-flocculation is a very good way to remove enteric viruses and phages. Coagulation-flocculation is considered as the best removal process after chlorination. Iron salts eliminate 99.5% of pathogens, lime removes 98.8% and aluminum salts, 95%. Coagulation , particularly with lime, can result in significant reductions of pathogens, The high pH conditions (pH 11-12) which can be achieved with lime can result in significant inactivation of enteric viruses. To achieve removal of 90% or greater, the pH should be maintained above 11 for at least an hour (Leong, 1983). Inactivation of the viruses occurs by denaturation of the viral protein coat. The use of iron and aluminum salts for coagulation can also result in 90% or greater reductions in enteric viruses.

Tertiary treatment processes involving physical/chemical processes can be effective in further reducing the concentration of pathogen and enhancing the effectiveness of disinfection processes by the removal of soluble and particulate organic matter (Table 14) (Gerba et al., 1975). Filtration is probably the most common tertiary treatment process. Mixed media filtration is most effective in the reduction of protozoan parasites. Usually greater removal of Giardia cysts than Cryptosporidium oocysts occurs because of the large size of the cysts (Rose and Carnahan, 1992; Gerba and Rose, 1996). Removal of enteroviruses and indicator bacteria is usually 90% or less. Addition of coagulant can increase the removal of poliovirus to 99% (USEPA, 1992).

Rapid filtration

Filtration is one of the most useful treatments for the removal of protozoa and helminths, even when combined only with a previous primary treatment (Landa et al., 1997) or in a tertiary step. Rapid filtration removes 90% of indicator bacteria, pathogenic bacteria (Salmonella spp. and Pseudomonas aeruginosa), protozoa cysts (Giardia spp. And Entamoeba spp.), and enterovirus. This removal can be increased to over 99% with the addition of coagulants (US, EPA, 1992; Jiménez et al., 2001). The median value in tertiary treatment is 73%, but the range is very broad (0 to 99%) depending on the design and operation criteria, such as filtration rate, media size and type of chemical pretreatment. (Leong, 1983).

Since viruses are not substantially eliminated in the absence of chemicals, it is proposed that both, coagulants and filter, be used in water reclaiming projects. Removal is carried out by destabilization and chemical adhesion. Coagulation-flocculation, sedimentation and filtration together achieve a virus removal of 2 log. A sedimentation unit with a sludge blanket known as a pulsator removes from 3 to 4 log using ferric chloride (Gerber et al., 1975).

TABLE 14.
Pathogen removal during physio-chemical processes of wastewater treatment.

Organism	Raw Wastewater	Advanced Primary Treatment	Advanced Primary Treatment plus filtration	Chlorination
Helminth ova (ova/L)	30-20	1-4	0.2	0.2
Fecal coliform (MPN/100 ml)	107-109	106-108	106-108	103
Salmonella spp. (MPN/100 ml)	106	105	104	ND-103
Giardia cysts	1007-1814	400-524	190-524	1-30
Psuedomonas aeruginosa	104-106	103-105	103-104	ND-2 x 102

ND: Not Detected
Source: Jiménez et al., 2001a, b

Activated carbon

The removal of enteric viruses by granular activated carbon has been found to be highly variable and not very effective. Viruses are believed to be adsorbed to the activated carbon, but it appears that sites available for adsorption are quickly exhausted (Gerba et al., 1975).

Membrane processes

Reverse osmosis and ultrafiltration are also believed to result in significant reduction in enteric pathogens. Removals of enteric viruses in excess of 99.9% can be achieved via these methods (Leong, 1983). However, Sorber et al., (1972) reported a faulty efficiency in virus removal using reverse osmosis and ultrafiltration. They were only able to achieve a decrease of 5 to 6 log under good operating conditions. Although the pore size of the membranes used in this process are smaller than even viruses, the smallest waterborne pathogen, they should not be considered absolute barriers. It is possible that viruses may find a few openings in the membranes through which to pass or they may pass through the seals. Van Houtte (2001) studied an aquifer recharge system with an effluent treated with microfiltration or ultrafiltration as a pre-treatment to reverse osmosis. The reverse osmosis effluents were free of total and fecal coliforms, as well as Streptococcus.

Disinfection

Disinfection is the main process used to reduce microorganisms in wastewater. Efficiency depends on the disinfecting agent, the type and variety of microorganism, the dosage and the exposure time. The most commonly used disinfection processes are:

Chlorine

Chlorine is a chemical agent which is so active that it combines with many substances that are dissolved or suspended in water, for example, organic material, hydrogen sulfide, manganese, iron, nitrites and ammonia. During wastewater treatment many of these compounds remain in the water and are consequently found in the recycled water. When chlorine is added to water for reuse, an amount thereof is consumed by the reductor compounds known as chlorides, organo-chlorinated compounds and chloramines. These compounds reduce chlorine disinfection efficiency. Epidemiological studies have shown a relationship between chlorination by-products and the increase in cancer risk (Batterman et al., 2002; Gibbons and Laha, 1999; Goldman and Murr, 2002; Korn et al., 2002; Monarca et al., 1998).

There are several paths of exposure for chlorination by-products, i.e. ingestion of contaminated foods or drinking water, inhalation of vapors, washing, swimming, and during personal hygiene (Batterman et al., 2002). When considering the microbiological risks of not chlorinating water, one also has to consider the relation of long-term risks from consumption of by-products.

In regards to virus removal by chlorine, one hour contact time, with residual chlorine in a tertiary effluent yields 5 to 7 log units of virus elimination. This leaves less than one infectious unit per 1000 liters.

Ozone

Ozone is very effective in virus control (Garay and Cohn, 1992) provided there is a low demand of oxidizing agents in the recycled water, or if there is such oxidation activity, provided that the appropriate dose and contact time are used.. It inactivates from 3 to 4 log units in a very short time period. The doses for several different ozone applications are shown in

Table 15. cBy-products generated during ozone disinfection include diverse aldehydes, ketones, and acids (Hoigné and Bader, 1977; Hoigné and Bader, 1978; Langlais et al., 1991); many of them produce toxic effects, but their concentration is so low that the effect is minimal.

Another by-product found is polyvinyl chloride, which has also been found in very low concentrations. This compound is found in the ozonation of industrial effluents, so industrial discharges must be minimized in wastewater that will eventually have human consumption reuse.

Ultraviolet (UV)

Over the last 20 years, UV light disinfection has become a more popular alternative to chlorination because it does not generate by-products (Droste, 1997). In comparison with chlorination, UV light disinfects wastewater with no need for storage or handling of hazardous chemicals; and because of the short contact time periods (in the range of seconds or minutes), it reduces the size of the treatment tanks and, therefore, the cost (Rajeshwar and Ibañez, 1997). UV light disinfection systems have proven to be inexpensive and competitive in comparison with chlorination. Comparative values of disinfection doses required to kill different microorganisms are shown in Table 16.

TABLE 15.
Ozone doses required for elimination of various microorganisms present in wastewater.

Organism	Theoretical ozone doses (mg/L)	Reference
Bacteriophage f2	0.033	Garay and Cohn, 1992
Fecal coliforms	3-5	Rakness et al., 1993
Escherichia coli	0.53	Garay and Cohn, 1992
Coxsackie virus	0.51	Garay and Cohn, 1992
Polio virus	0.015	Garay and Cohn, 1992

TABLE 16.
Comparative value of UV disinfection dose necessary to remove various microorganisms from wastewater.

Microorganism	Applied dose (mWs/cm2)	Inactivation (Log)	Conditions	Reference
Bacteria				
Fecal coliform Fecal streptococcus	30-45 30-45	3-5 3-5	Secondary and tertiary effluents	Lazarova et al., 1999
Fecal coliforms Fecal streptococcus Salmonella typhi	15 15 32	3 2 3	Secondary effluents	Jiménez and Beltrán, 2002; Maya et al., 2002
Virus				
Bacteriophage MS2	17-200	2-5	Secondary and tertiary effluents	Lazarova et al., 1999
Protozoa				
Acanthamoeba spp.	60	2	Secondary effluent	Maya et al., 2002
Cryptosporidium parvum	3	3	Monochromatic light. Test in saline solution and phosphate buffer at room temperature.	Shin et al., 2000

m A
dose
(mWs/cm2)Inactivation

Factors influencing survival and transportation of viruses

Due to their size, it is very difficult to separate viruses with primary and secondary processes. Soil filtration is efficient in absorbing viruses by means of binding virus to the cations present in the soil particles. In accordance with Yates et al., (1985), several factors affect the survival and migration of viruses in the subsoil. In general, these factors are: climate (temperature and rainfall), hydraulic conditions (water application rates and duration of wet and dry cycles), sun radiation, pH, organic matter, antagonistic microflora, soil type, and the type of virus involved. Viruses may migrate long distances; there have been reports of migrations of up to 67 m deep and 480 m horizontally. Many researchers have studied their survival in soil, but little has been done with regard to what happens in underground water. The main factors that are influencing the survival and transportations of viruses are:

Virus adsorption into the soil. It is generally accepted that virus adsorption into the soil increases their survival and delays their transportation. However, this is not a permanent phenomenon since changes in the ion force, pH, humidity saturating the pores, or increase in saline concentration may dislodge viruses and make them move in the soil.

Virus aggregation. The formation of virus clusters in water makes them more resistant to disinfection.

Temperature. The most important factor in the inactivation of viruses is temperature, as compared with pH, sulfate content, iron, hardness, and dissolved solids. It accounts for 78% of the process (Yates et al., 1985), although how it acts remains unknown.

Microbiological activity. It is believed that the presence of other microorganisms and their interaction with viruses is a removal mechanism, although it is not clear how this mechanism works. (Yates et al., 1985).

Humidity. It is commonly accepted that the absence of humidity has a negative effect on the persistence viruses in soils, because saturation allows the viruses to reach greater depths, as they are not absorbed. This allows for virus transportation to be controlled in a range of a few centimeters to several meters. Clean and dry sand has low virus removal capacity (Berg, 1973), while wet sand has better retention capacity (Nestor and Constin, 1971).

pH. The effect of pH on virus survival has not been well studied. Sobsey (1983), indicates that an acid pH tends to deactivate viruses. However, as in other cases, the values and intensity of responses are different for each type of organism. According to Gerba and Bitton (1984), pH affects virus mobility because their external layer is of a protein nature, and the carboxyl and amine groups determine the surface charge. As a result, at a pH of 7 in almost every type of soil, most viruses have a negative charge and are not absorbed by simple electric repulsion. If the ambient pH decreases, the virus charge becomes less negative due to the increase in ionization of the amine groups, and the decrease in ionization of the carboxyl groups; and although soils also become less negative, they do so at a lower intensity that makes it possible for them to attract viruses. This is true in general, as when cations and humic and fulvic acids are present in soil, the attraction mechanisms are modified.

Dissolved salts. It has been observed that aluminum and iron salts tend to inactivate viruses. In regards to their transportation, it is delayed in proportion to the increase in salt content and cation balance, due to alteration of the adhesion properties.

Organic material. The influence of organic material on viruses is not yet well understood. In some studies it appears to have a protective action, while in others there is no effect at all. The humic and fulvic acids cause a loss of infectiousness, but this can be recovered by changing the ambient conditions. Organic material also prevents adsorption, a property that is even used to obtain field samples of the same (Bixby and O'Brien, 1979).

Hydraulic conditions. The rate at which water is applied to the soil has a definitive effect on the amount of viruses removed as well as on their adsorption. Removal efficiency increases as the rate decreases (Lance and Gerba 1984). However, they also observed that when using non-saturated soil, virus penetration was much lower in distance. The total virus removal rate, when combining wastewater treatment with infiltration in non-saturated soil, and the distance between the discharge and extraction site, along with the water retention time, is estimated between 13 and 17 log (Asano and Mujeriego, 1988; State of California, 1989).

Types of viruses. Different types of viruses behave in different ways under the same conditions. This is true not only for different genera (adenovirus, enterovirus, rotavirus) as well as for different strains (Goyal and Gerba, 1979).

Soil properties. Soil has a substantial influence on virus survival and transportation. In general, viruses are more mobile in soils that have a coarse texture, than in finely textured carstic systems. Drewry and Eliassen (1968) reported that soils with clay and silt have better virus retention efficiency. Clays have proven to be excellent adsorbent materials due to their large surface area (Bitton, 1975). The composition of the soil affects virus survival, as aluminum-rich soils decrease survival, and soils high in phosphorus favor survival (Hurst et al., 1980).

SECTION VI

Assessing Risk Associated with the Use of Recycled Water

Risk assessment is not an exact science because there are different methods to determinerisk, and they do not always lead to the same results. For one particular risk assessment there may be a need for several levels of protection and consequently different regulations (Sakaji and Funamizu,1998). When considering risk assessment several things must be considered, the pathogen in question, the concentration of pathogens in recycled water, the amount of pathogens ingested, inhaled or contacted, and the probability of infection as determined from statistical modeling (Sakaji and Funamizu, 1998). The use of statistical models does not provide better results if the reliability and accuracy of the assumptions and initial data are not assured.

The National Research Council (NRC) lists 4 primary components of risk assessment (NRC, 1982):

(a) risk identification, (b) assessment of magnitude of exposure and routes (identification- dose-response), (c) human response to compounds (exposure assessment), and (d) risk characterization.

- Risk identification: Consists of defining the classes or species of pathogen microorganisms in water, which cause infections or diseases.
- Dose-response. Establishes the relation between the selected dose of microbiological agents administered and the response in the exposed population.
- Exposure assessment. Determines intensity, frequency and duration of human exposure to the microbiological agent. Describes the magnitude, duration, schedule, uncertainty and exposure route for the relevant population. These estimates are a direct result of the combination of environmental data and dose-response information, in an exposure scenario (risk in a negative scenario). These estimations show whether the risk is lower than that existing at endemic levels, and help to establish a policy to improve the situation.
- Risk characterization. Attempts to describe the magnitude of the risk and how it may be related to other scenarios. Provides a qualitative description of the uncertainty associated with the estimated risk. Even when these four elements are the same, the procedure for its use depends on the type of contaminant. There is a great deal of research to be done in connection with the establishment of risk certainty. However, as the pressure on hydraulic resources increases, the use of recycled water will become more common and the population will have to accept greater risks, regardless of how they are calculated.

Other parameters

All the parameters that must be considered when using recycled wastewater:

- Microbiological. Once the relevant pathogens are defined, their indicators and the appropriate analytical techniques have been set, one still has to establish the acceptable level for reuse. Ideally, these standards must be based on awareness of the relationship between the contents of the indicators and pathogens, as well as the infectious doses (Feachem et al., 1983; Cooper and Olivieri, 1998).
- Toxicity. Foster et al., 2002 states that one of the three parameters that may serve as a control to regulate treated wastewater recharge, may be soluble organic carbon as a measurement of potential toxic components, along with nitrogen and fecal coliforms. These three elements are an inexpensive way to keep an adequate control of the recharge.
- Salts. Increase in salinity is a long-term problem with water reuse, and it should considered as well.

Monitoring water quality

Determining how to monitor reused water is an important aspect of the outlining criteria and standards. It requires definition of parameters of water quality, numerical limits, monitoring frequency, and compliance site. It is impossible to monitor each individual toxic chemical compound and pathogen. Monitoring programs for recycled water should verify the efficiency of the treatment processes and detect potentially harmful contaminants. Intensive monitoring of water quality, and contingency plans should be incorporated to respond to possible failures.

Public information

Communication to the public about water reuse is of paramount importance. Public policy evolves more slowly than knowledge and generation of technical information; thus it is fundamental to promote research oriented data to address issues of concern.

Research needs

Developing appropriate reuse criteria will take time and will require a substantial amount of research. Some topics for this research are:

- how to more precisely establish the microbiological risks for water reuse
- presence and concentration of pathogen and toxic substances by region, with real-time and online monitoring;
- health significance of toxic and pathogenic concentrations present in recycled water;
- types of endocrine disruptors, pharmaceuticals, and personal care products, and their behavior in wastewater;
- behavior of each type of pathogenic organism during the treatment processes;
- sustainable attenuation rate of specific pathogens and organic materials in the soil and the aquifer;
- determine soil and aquifer attenuation for diverse locally relevant contaminants.

SECTION VII

Conclusions

The removal of specific trace organic compounds through full-scale advanced wastewater treatment AWT processes including chemical clarification, filtration, air stripping, activated carbon adsorption, and reverse osmosis has been demonstrated. These studies show that there is the capability to control most synthetic organic compounds (SOC) to below current limits of acceptability. However, the majority of organic compounds in AWT effluents are unidentified and of generally unknown health significance. The presence of natural products compounds also contributes to the formation of disinfection byproducts (DBPs) including trihalomethanes (THM) and other organic halogens (TOX) of potential health significance. The widely observed mutagenic activity of AWT effluents is of unknown health significance and a matter of continuing research interest. The potential for pathogens in reclaimed water to contaminate the underlying ground water is dependent on a number of factors including the physical characteristics of the site (soil texture), the hydraulic conditions (e.g., wastewater application rate, wetting/drying cycles), the environmental conditions (e.g., rainfall, temperature) at the site, and the characteristics of the specific pathogens present in the reclaimed water. The factors that influence the fate and transport of pathogens in the subsurface have been the subject of a number of reviews (Bitton and Harvey 1992; Gerba and Goyal, 1985; Yates and Yates, 1988; Vaughn and Landry, 1983).

Control of viruses and protozoa in recycled water is of paramount concern even though such product water may meet microbiological standards set for drinking water, e.g. one coliform per 100 ml, or no detectable E. coli per 100 ml. One reason for concern is that recycled water is derived directly from municipal wastewater in which virus concentrations are higher than even heavily polluted natural waters, and the typical microbiological indicators alone are inadequate for that application. Temperature is probably the most important factor influencing virus inactivation in the environment (Bitton, 1980). In a study using groundwater samples collected throughout the U.S., none of the characteristics including pH, nitrate, ammonia, sulfate, iron, harness, turbidity, and total dissolved solids, except temperature were significantly correlated ($p<0.01$) with the inactivation rate of the viruses (polioviruses, echoviruses and MS2 bacteriophages) (Yates et al., 1985; Jansons et al., 1989; Yahya et al., 1993).

Temperature also affects the persistence of viruses in soils. Lefler and Kott (1974) found that it took 42 days for 99% inactivation of poliovirus in saturation at 20-25˚C, whereas more that 175 days were required at 1-8˚C. Poliovirus was found to persist for more than 180 days in saturated sand and sandy loam soils at 4˚C, whereas no viruses could be recovered from the soils incubated at 37˚C in loamy sand. They also found that the inactivation rate was significantly correlated ($p<0.01$) with incubation temperature, noting faster inactivation rates at the higher temperatures.

More extensive regimens for controlling and monitoring microbial agents must be applied, and additional standards are required. Because monitoring for pathogens is not feasible, is very expensive and does not occur in real time, it is more important to design multiple barrier systems to assure continuous production of safe water.

Emerging contaminants relevant to groundwater recharge will include: (a) Trace organics such as: Endocrine disrupting compounds (EDC's), Pharmaceutically active compounds (PhAC's), and N-nitrosdimethylamine (NDMA), (b) Trace inorganics such as: Arsenic, and (c) Microbes, e.g., Nanobacteria.

Appropriate combinations of treatment methods should be tested to eliminate the potential threats posed by toxicological and pathogenic agents. These factors will ensure a reliable minimum degree of treatment to be adhered to before the recycled water is used. Biological assays can be used to assess the health risk associated with the use of a certain type of water or to monitor the quality of the water produced. Assays using endogenous estrogen equivalents should be evaluated. Such studies will contribute in developing the basis for tracing organics in recycled water.

As previously mentioned, future research should include topics such as: how to more precisely establish the microbiological risks; presence, concentration and health significance of pathogens and toxic substances by region; types and behavior of pathogenic bacteria and viruses in recycled and other waters; the fate of micropollutants including pathogens in the soil and underlying geological formations; development of models for establishing residence times and extraction distances, chlorination alternatives; and determination of soil and aquifer attenuation.

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