Design and Operation of Land Application Systems from a Water, Nitrogen & Salt Balance Approach

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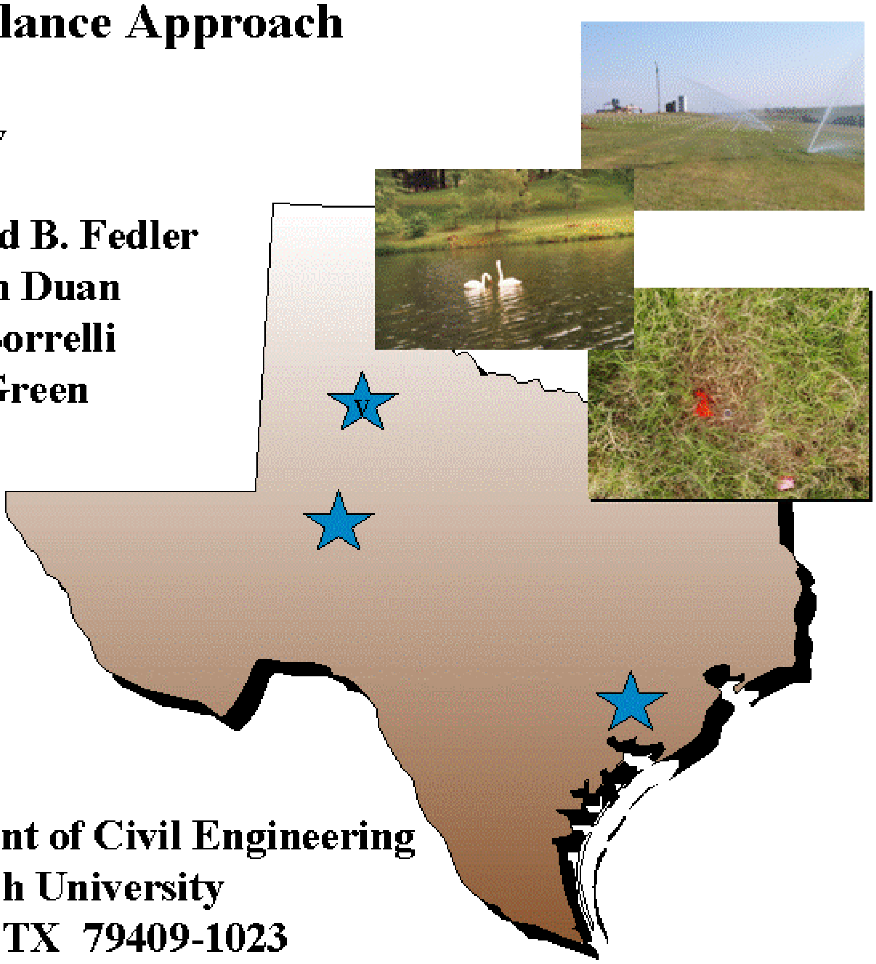

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EXECUTIVE SUMMARY

Land application of wastewater has been considered as one of the pathways to reduce the pressure on fresh water resources that are used for irrigation throughout the world. Two concerns with land application of wastewater are the potential of nitrogen contamination of groundwater and salt accumulation in soils. Design procedures for surface application systems should be developed to optimize the protection of the various water resources from potential pollution and protect soils from degradation. A new model was developed for designing surface application systems under common climate and soil conditions for safe utilization and ultimately disposal of wastewater while preserving fresh water resources. The procedure centers on the balances of applied water, nitrogen, and salt. Another objective of this research was to model the quality and quantity of leachate water passing through root zone in a surface application system based on the proposed design approach. Data were collected from a local surface application site where Bermuda grass is grown and a solid set irrigation system was used to distribute the wastewater that was taken from an aerobic pond treatment system. This system most closely simulates the typical aerobic treatment on-site sewage facility (OSSF) used in Texas. Deep percolate water was collected in lysimeter-type samplers and analyzed approximately monthly for over two years. Soil samples were also collected for analysis in the mass balance analyses.

The volume weighted concentration of total nitrogen in the water collected from the sampling devices was less than 5 mg/L during each individual sampling period and the long term volume weighted concentration of total nitrogen collected was less than 3.5 mg/L. This is highly significant since the drinking water standards require less than 10 mg/L of only one component of the total nitrogen, nitrate-nitrogen. The total nitrogen removal ranged from 80% to 100% during individual sampling periods. The overall cumulative total nitrogen removal ratio was over 96%. Therefore, this study showed that the land application of treated wastewater effluent had no adverse effects on groundwater with respect to nitrogen contamination.

Salt concentration varies with the designed leaching rate and ranged from 1261 to 2794 µS/cm on this research site. The salt balance was designed according to long-term accepted practices and thus no detrimental effects were found on the Bermuda grass throughout the testing period. An interesting result found from this research was that even though there were several periods of high precipitation, the soils data exhibited and increase in the overall salt concentration with no negative effect on plant growth. Another interesting finding resulting from this research was that there was considerable spatial and temporal variability of the quantity of water leached through the soil profile, which then affected the quantity of nitrogen and salt moving past the plant root zone. When the leaching data was analyzed over the entire period of testing, the cumulative leaching resulted in an average of 10%, which was the designed rate for the plant, soil, and climatic conditions of the test site.

One of the more important design considerations that affects the spatial variability found from a surface application system for wastewater is the uniformity of the distribution of the applied wastewater. To determine the distribution uniformity of the applied wastewater, the Christensen's Uniformity Coefficient (UCC) is calculated based on the water collected from the application site. In addition, when testing a designed irrigation system for its distribution uniformity, testing under very specific climatic conditions (such as very low wind conditions) will not necessarily provide the appropriate results found under field conditions. In order to provide appropriate data for a complete analysis of the system, field test of the irrigation system should be conducted multiple times throughout the year, usually tied to the various seasons of the year, in order to produce an annual UCC value and that value should be used for design purposes. Individual UCC tests completed for this study resulted in individual UCC values ranging from 31% to 75%. Yet, when the data were analyzed as an annual operation, the resulting UCC was 84%. To minimize the spatial variability found under filed conditions for the distribution of wastewater, the recommended UCC value should be designed to be at least 80%. In addition to designing the system for uniform distribution, runoff from the application site should be avoided. To minimize and even avoid runoff, the irrigation application time and frequency, and the rate of application need to be designed for the existing soil and climatic conditions that exist throughout the year.

The most compelling result obtained from this research is that all surface applied systems can be designed to have minimal effect on the environment as long as the principle of mass balance is followed within the design. Even though some spatial variability will exist at any site receiving wastewater, caution should be taken when analyzing individual samples and drawing extensive conclusions from that data.

Testing of soil samples collected from the Midland and Houston areas showed similar results to that found at the Littlefield test site. The most pronounced difference came from the Houston area soil, which was principally a clay soil. In this case, the application of the water had to be adjusted for the soil infiltration properties. In particular, the application rate had to be decreased while the frequency of application was increased.

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CHAPTER I

INTRODUCTION AND RESEARCH OBJECTIVES

1.1 Introduction

The quality and quantity of leachate water in the land application of wastewater are important parameters to fully understand in order to design the most environmentally friendly and functional system. The wastewater land application system utilized in this study was designed primarily with the innovative design approach, which includes a mass balance method, integrated with scheduled irrigation events, field sampling, lab analysis, and statistics analysis.

1.2 Background of the study

It has been widely accepted by designers of wastewater treatment systems that treated wastewater has the potential to provide a safe and feasible option to supply crops and turf with water and nutrients (Toze 2004). Therefore, land treatment of municipal wastewater is regarded as an alternative option for treating wastewater. Primarily, land application of wastewater has been one solution used to reduce the pressure on available fresh water resources. On one hand, many areas where humans dwell on this earth is drying up due to global warming while on the other hand, the global economy and population are increasing; therefore, the demand for water is sharply increasing. This pronounced problem places high pressure on existing natural water resources in many regions of the world (Toze 2004). Perth, Australia is one typical example, where the major drinking water aquifer is being depleted because of public needs and agriculture irrigation (Toze 2004). Saudi Arabia is another example of a country with a water crisis due to increasing demands on groundwater by agricultural irrigation (Bushnak 2002). Accordingly, many countries have to manage water resources more efficiently than they did before in order to resolve the water crisis problems confronting them. Fortunately, wastewater reuse as agricultural irrigation water becomes a vital alternative resource to conserve water and improve the efficiency of water use (Lazarova and Bahri 2005).

Wastewater reuse for irrigation can result in many environmental, economic, and social benefits. The environmental benefits of wastewater reuse can be easily identified. For example, wastewater application on land plays a significant role in reducing or completely removing the potential pollution components of wastewater to receiving water bodies such as lakes, rivers, and coastal marine environments (Toze 2004) because wastewater is disposed on the land rather than discharged to receiving water bodies. More importantly, the wastewater applied to the land can effectively substitute some parts of natural water used for irrigation, which is needed to be extracted from natural water sources (Gregory 2000; U.S.EPA 1992), as a result, land application of wastewater is helpful to reduce the pressure of agricultural irrigation on natural water resources. Additionally, wastewater can supply the soil with organic and inorganic nutrients in terms of nitrogen, phosphate, etc., which are used as a fertilizer source when wastewater is recycled as crop irrigation water (Toze 2004). Besides environmental benefits, surface application of wastewater can provide economic benefits by lowering costs for such things as advanced wastewater treatment and discharge, increasing land and property values, and obtaining additional revenue from sale of recycled water and agricultural products (Lazarova and Bahri 2005). Land application of wastewater can increase local food production, which is particularly important for people and communities in arid or semi-arid and undeveloped regions around the world.

Although land application of wastewater has significant benefits, there are a few risks resulting from an improperly designed land application system. Those risks may include nitrogen contamination of groundwater, salt accumulation in the soil, the contaminations to groundwater of E. coli and pharmaceuticals and personal care products (PPCPs), and the degradation of soil properties.

Currently, land treatment of wastewater is mainly executed by full-scale land (or surface) application systems or on-site sewage facilities (OSSFs). Surface application of wastewater for irrigation is possibly the oldest approach to treat and dispose of wastewater. It was introduced in the United States in 1872 (Fedler et al. 2006). Although once considered an unacceptable treatment method for wastewater, surface application of wastewater has been recognized as a complete wastewater treatment alternative and the most common disposal method in the United States (USEPA 1999). Surface application of wastewater utilizes the land, not just as a treatment unit, but also a disposal area. This process has the advantage of satisfying treatment effects, low costs and easy operations; therefore, many states in the U.S. mandate that land application of wastewater be considered while new treatment facilities are planned since the mid-1970s. On-site sewage facility (OSSF) is a technical term in the state of Texas, USA, which is actually the form of on-site wastewater treatment and disposal system for usually single family homes, especially those in rural or non-sewered areas. Also, OSSF is referred to as on-site Wastewater Treatment Systems (OWTS) by the U.S. Environmental Protection Agency (Wheeler 2005). OSSF is utilized by about 25 percent of all homes in the United States (Fedler and Borrelli 2001). OSSF is typically classified as standard, non-standard, or proprietary by the Texas Commission on Environmental Quality (Wheeler 2005). Standard OSSF systems generally include a septic tank and some type of drainfield, mainly absorptive, evapotranspirative, or pumped drainfield. Non-standard OSSF systems mostly contain either a septic tank in combination with low-pressure dosing, absorptive mounds, and soil substitution, or a septic tank followed by secondary treatment, filtration, and surface application. Proprietary OSSF systems consist of septic tanks with leaching chambers, gravelless pipe, or some aerobic systems with a final disposal method (Wheeler 2005).

1.3 Research objectives

Although land application of wastewater has been one method used to save fresh water resources in the world, it is still questioned as an environmentally safe disposal method for municipal wastewater. One concern is the contamination of groundwater by applied wastewater onto land. In order to reduce or even remove the risk factors identified for wastewater reuse for agricultural irrigation, an alternative design approach, combined mass balance approach, is proposed with consideration of three important components of surface wastewater land application system, which are water, nitrogen, and salt. All these three components are important individually to impact the quantity and quality of leachate water passing through the plant root zone to enter groundwater, and at same time, there are combined effects and interactions among those components in the system. The accumulation of salts in soil and the loss of nitrogen from the root zone down to the groundwater are closely related to the quantity of leachate water. Generally speaking, more leached water is expected to flush more salts down to the groundwater with a result of reducing the salt accumulation in soil, but over leached water may flush more nitrogen to contaminate the groundwater. In addition, the nitrogen contamination of groundwater in some way depends on the quality of leachate water.

The combined mass balance approach for the design has been proposed for a few years, however, there is no field research conducted on the approach, and no field data to illustrate this method. The overall objective of this research is to investigate the quantity and quality of leachate water that moves below the plant root zone of a land application system designed from a mass balance approach. The potential environmental impact in a wastewater land application system was to be evaluated in terms of salt accumulation in soil and nitrogen contamination to groundwater. The evaluation was based on measurement of the mass and concentration of nitrogen and salt in leachate water. Specific data would be collected and the following data analysis was to be processed for combined mass balance approach in order to provide the proof of the feasibility of such a design method in some particular cases.

1.4 The professional significance of this study

First of all, this study was to investigate the feasibility of wastewater land application as the potential water resources to irrigate turf. Although wastewater land application has been widely accepted in the world as a methodology to reduce water demand upon limited fresh water supplies, it is still a questioned approach.

Secondly, this study was to investigate the effects of wastewater land treatment system with a new design approach, a mass balance method. In reality, there are a few design methods for wastewater land treatment systems, however, some of them are accepted, and the others are still in trial phase or in discussion. The mass balance method, which was proposed by Texas Tech University, is supposed to be an innovative way to design wastewater land application systems and to guide irrigation events and practice. This study was undertaken to evaluate the effects of the proposed design method under field conditions.

Thirdly, this study attempted to explore the models of quality and quantity of leached water in the wastewater land treatment system designed with mass balance method by field investigation, lab analysis, and statistical analysis. As stated above, the mass balance method is a new design method. Once the method is proved to be feasible and reasonable; the models of quality and quantity of leach water will be set up for the predictions of quality and quantity of leach water in full-scale practice.

1.5 The delimitations of the study

In this research, the wastewater effluent is from a pond treatment system located at the Littlefield, Texas municipal wastewater treatment plant. The wastewater from Littlefield is collected and treated by an aerated pond system, and then goes to a storage pond prior to irrigation. The quality of wastewater effluent used in irrigation depends on the treatment process and climatic conditions at Littlefield.

The irrigation system involved in this research is a solid set sprinkler system using popup rotary sprinklers. The characteristics and operation of this type of surface application system determined the inherent water application efficiency, and furthermore, ultimately impacted the quality and quantity of leached water in the soil-water-plant system. The uniformity of the system is the primary concern, and it is distinctly impacted by the design and the arrangement of sprinkler system, and local climate conditions such as wind speed, wind direction, and temperature at the time of irrigation event, which cannot be controlled by the researchers.

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CHAPTER II

LITERATURE REVIEW

2.1 General land application systems

Land application is used to apply wastewater to land to achieve treatment of wastewater by natural physical, chemical and biological processes in the soil-plant-water matrix. Types of land application systems include slow rate (SR), overland flow (OF), and rapid infiltration (RI) (Reed et al. 1995). Another method often used in OSSFs is subsurface drip irrigation (DI).

Slow rate is the main type of wastewater application; the technology of which is similar to that of agriculture irrigation, and which can be used in the widest range of acceptable soil types and permeabilities (Reed et al. 1995). Rapid infiltration is used to treat wastewater by allowing wastewater to percolate through permeable soils at loading rates of 6-125 m/year. Although both SR and RI utilize the soil matrix for treatment during infiltration of the wastewater down to groundwater, vegetation plays an important role in SR while it is usually not a part of the RI systems (Reed et al. 1995). One of the main differences between them is loading rate, which is generally 0.5-6 m/year for the SR system (Reed et al. 1995), much less than that of RI. Overland flow is to apply wastewater to a well-designed slope with vegetation, and then to collect treated wastewater at the bottom of the slope. Soil surface and vegetation are used for treatment in an OF system similar to a trickling filter.

2.2 Current design procedures for SR systems

Reed et al. (1995) stated that there were two types of SR systems. The type 1 system is so designed that the maximum possible amount of wastewater is applied to the minimum possible land area with the consideration of the limiting design factor (LDF), which includes hydraulic capacity of the soil profile and constituents of the wastewater. The type 2 system is designed to take full advantage of wastewater as an irrigation source such that wastewater is applied to the maximum possible amount of land. For Type 1 systems, Reed et al. (1995) proposed that most SR systems had two LDFs, hydraulic or nitrogen loading rates. Loading rate is determined by choosing the smaller of both loading rates, wastewater hydraulic loading rate (L_w) and hydraulic loading rate controlled by nitrogen as the LDF (L_{wn}), calculated by regarding hydraulic capacity and nitrogen content in wastewater as LDFs, respectively. Hydraulic loading rate for the Type 1 SR systems is (Reed et al. 1995):

$$L_w = ET - P_r + P_w \qquad (2.1)$$

where L_w = wastewater hydraulic loading rate, cm/week or m/yr (inches/week or ft/yr);

ET = evapotranspiration rate, cm/week or m/yr (inches/week or ft/yr);

P_r = precipitation rate, cm/week or m/yr (inches/week or ft/yr);

P_w = percolation rate, cm/week or m/yr (inches/week or ft/yr).

The design percolation rate P_w is calculated by the flowing equation (Reed et al. 1995):

$$P_w(daily) = K(24\,h/d)(0.04\ to\ 0.10) \qquad (2.2)$$

where P_w = design daily percolation rate, cm/d;

K = permeability of limiting soil layer, cm/h (in/h);

0.04 to 0.10 = adjustment factor to account for wet/dry ratio and ensure a conservative value for infiltration of wastewater.

Hydraulic loading rate controlled by nitrogen as the LDF, L_{wn}, is (Reed et al. 1995):

$$L_{wn} = \frac{C_p(P_r - ET) + 10(U)}{(1 - f)(C_n) - C_p} \tag{2.3}$$

where L_{wn} = hydraulic loading rate controlled by nitrogen as the LDF, cm/year;

C_p = percolate nitrogen concentration, mg/L, usually set at 10 mg/L;

ET = evapotranspiration rate, cm/yr;

P_r = precipitation rate, cm/yr;

U = crop uptake, kg/ha.yr;

f = fraction of applied nitrogen lost to denitrification, volatilization, and soil storage, from 0 to 1, exclusive;

C_n = nitrogen concentration in applied wastewater, mg/L.

For the Type 2 systems, Reed et al. (1995) recommended the following equations for design:

$$L_w = (ET - P_r)(1 + LR)(100 / E) \tag{2.4}$$

where LR = leaching requirement, it may range from 0.05 to 0.30;

E = efficiency of the irrigation system, it represents the fraction of the applied water accounted for in crop consumptive use or ET. For surface irrigation systems, it ranges from 0.65 to 0.75; for sprinkler systems, usually 0.7 to 0.8; for drip irrigation systems, from 0.9 to 0.95.

The land area is determined by the following equation (Reed et al. 1995):

$$A = \frac{Q + V_s}{CL_w} \qquad (2.5)$$

where A = field area, ha (ac);

Q = annual flow, m^3/year (million gal/year);

V_s = net loss or gain in stored wastewater volume due to precipitation on and evaporation and seepage from the storage pond, m^3/year (million gal/year);

C = constant, 100 (0.027 in U.S. units);

L_w = design hydraulic loading rate based on the LDF, cm/year (inches/year).

2.3 On-site sewage facility (OSSF) systems

On-site sewage facility generally consists of a septic tank, and a gravity, subsurface soil adsorption system (Reed et al. 1995), but domestic wastewater is sometimes disposed by surface application to land where soils have poor adsorption capacity (Fedler and Borrelli 2001). About 25% of the nation's homes are using OSSF systems for disposal of domestic wastewater (Fedler and Borrelli 2001).

For design of surface application for an OSSF system, in order to reduce the amount of identified contaminants passing through the root zone, the design should have included many other considerations such as irrigated crop type, water uptake rate of soils, variability of daily wastewater amount, uniformity of irrigation, etc. Therefore, Fedler and Borrelli (2001) recommended that the design of surface application in OSSF systems should consider both a water balance and a nutrient balance, take measures to achieve a uniformity coefficient of 80 percent or greater, and get base water intake rate of the soil, soil infiltration rate and saturated hydraulic conductivity specific to the site.

2.4 Environmental impact of wastewater quality

Wastewater land application can bring a community many benefits, but it also may cause many adverse impacts on soils, groundwater, crops and human health if not handled properly (Lazarova and Bahri 2005). The most important adverse effect on soils and crops results from salinity (Lazarova and Bahri 2005). Irrigation-induced salinity in soils restricts some crops from growing. One practice to avoid an over-accumulation of salts within the root zone due to wastewater irrigation is to apply more water onto the land in order to flush those salts down below the root zone. As a result, the groundwater beneath the root zone will result in higher salt concentrations. Generally, the higher TDS (total dissolved solids) in wastewater and the higher accumulation of salts within the root zone result in higher volumes of wastewater required to be applied to flush salt from the root zone (Lazarova and Bahri 2005). In addition, under normal irrigation of field crops, water is also leached and causes the potential for higher TDS concentrations to occur in groundwater because mostly the salt content in applied water is concentrated due to the function of evapotranspiration after the water passes through the root zone.

Nitrogen must be considered in any land application system. In summary, environmental issues concerning nitrogen at wastewater land application sites include contamination to groundwater, contamination to surface water bodies, and greenhouse gas such as N_2O, which is one of the end products of denitrification. Nitrate leaching to groundwater is an environmental concern for wastewater land application, because in many locations groundwater is an important and main water source for human beings. Nitrate in drinking water poses a potential health risk identified as “blue baby disease” (Broadbent and Reisenauer 1985). Additionally, it has been related to cancer (Broadbent and Reisenauer 1985). Environmental protection agency or regulatory agencies of many countries set a maximum allowable concentration of nitrate in groundwater. Therefore, in wastewater land treatment or application, the leached nitrate-nitrogen concentration should be controlled to be below the drinking water standard of 10 mg/L of nitrate-nitrogen. If runoff is not well controlled in a wastewater land application system, there is the possibility that nitrogen can contaminate the surrounding surface water bodies. Another new concern in recent years is greenhouse gas. As stated, nitrous oxide (N_2O), which is a product of denitrification in the land application system, contributes to global warming and the destruction of the ozone layer (Cicerone 1989), therefore, some researchers have started to work on the emissions of nitrous oxide from wastewater land application sites.

Wastewater application can cause adverse impact on soil properties. It can reduce the soil infiltration rate which leads to either lower application rates or more runoff on the soil surface and potential contamination of water bodies around the irrigation sites. There are three mechanisms contributing to lower permeability (K_s) of soils by wastewater irrigation and they are physical, chemical, and biological processes. Soil filtration of suspended solids in wastewater and their accumulation in the upper layer (0-20 mm) of soil profile are the main reasons to explain physical clogging (De Vries 1972; Rice 1974). Relatively higher concentrations of sodium or organic matter in wastewater often induce chemical clogging by causing swelling and dispersing of clay particles (Menneer et al. 2001; Tarchitzky et al. 1999). Bacterial growth or accumulation of their by-products under aerobic or anaerobic conditions in soils cause soil pore size to decrease, and finally form biological clogging (Rice 1974; Vandevivere and Baveye 1992).

2.5 Leach water quality

2.5.1 BOD and Nutrients

Biochemical Oxygen Demand (BOD) represents biological degradable organics. BOD in leaching water is relatively much lower than raw sewage, but the addition of organic matter can affect soil structure and stability. It was concluded (Potts et al. 2004) that aeration in soils plays an important role to significantly remove BOD_5 from applied wastewater causing lower BOD in leach water of wastewater land application systems.

Nitrogen exists in the soil-plant-water matrix mainly in the forms of nitrate, ammonia, and organic nitrogen. Both nitrate (NO_3^-) and ammonia (NH_4^+) can be taken up by plants, and eventually become organic nitrogen. There are a few transformations of nitrogen in soils: ammonia volatilization, mineralization-immobilization, nitrification, and denitrification. Ammonia volatilization is the release of ammonia to air when the pH is higher resulting in more NH_3 gas formation. Mineralization is the process of organic nitrogen changed into inorganic nitrogen by bacteria. Immobilization is the process of inorganic nitrogen changed into organic nitrogen, mostly by which inorganic nitrogen is absorbed by plants and utilized by bacteria, and then become the part of plant tissue or microorganisms. Nitrification occurs when bacteria change ammonia into nitrate with oxygen as electron acceptor and hydrogen as electron donor. Denitrification is the process of nitrogen changed into nitrogen gas (N_2) or N_2O by microorganisms. In most negatively charged soils, nitrate-nitrogen is susceptible to leaching through the root zone down to groundwater (Feigin et al. 1991); the reason is that nitrate is not readily adsorbed by soil particles and is soluble in water. The leaching of nitrogen is related to soil type, crop type, and irrigation management (Feigin et al. 1991). It was found that "the addition of a layer of carbon material at least 0.3 m thick below a standard leachfields" (Bedessem et al. 2005) substantially improved total N removal, and reduced the leaching of nitrogen in an OSSF system. Also, Potts et al. (2004) found that aeration in soils significantly helped to remove nitrogen from wastewater in leachfield.

In addition to nitrogen, another main nutrient, phosphorus, in soil-water-plant matrix is essential for plants and soil microorganisms. Feigin et al. (1991) pointed out that the amount of phosphorus added to the soil by wastewater land application was usually excessive. Due to adsorption and precipitation of phosphorus in soil, soluble phosphorus concentration decreases rapidly within a short time after phosphorus addition by wastewater irrigation; also in the long term, plants use soluble phosphorus in soil water and thus, reduce the level of soluble phosphorus in soil. As a result, soluble phosphorus movement downward is limited and even phosphorus leaching has been considered negligible (Feigin et al. 1991). However, when wastewater land treatment is used as the primary approach to remove phosphorus in wastewater with high concentration, phosphorus leaching becomes a concern. Excessive application of phosphorus may cause deficiencies of other nutrients such as copper and zinc in the soil (Lazarova and Bahri 2005).

2.5.2 Pharmaceuticals and personal care products

Recently, pharmaceuticals and personal care products (PPCPs) have become a concern for wastewater land application systems. Wastewater contains a variety of hormones; therefore, their application may cause fertility problems in animals feeding on crops irrigated by wastewater (Lazarova and Bahri 2005). Other concerns with PPCPs in wastewater used for irrigation are endocrine disruptors, "at least 45 chemicals have been identified as potential endocrine-disrupting contaminant (EDC), including industrial contaminants like dioxins and PCBs, insecticides like carbaryl and DDT, and herbicides like 2, 4-D and atrazine" (Lazarova and Bahri 2005).

The investigation completed by the U.S. Geological Survey found that organic wastewater contaminants (OWCS), which include pharmaceuticals, hormones, and other organic contaminants, were found in 80% of the streams sampled during the study (Kolpin et al. 2002). An investigation completed in Germany illustrated that pharmaceutical residuals were found in surface water, sewage, and groundwater, and the amount of pharmaceuticals have the same order of magnitude as pesticides applied in agriculture (Stan and Heberer 1997). It was addressed (Godfrey et al. 2007) that in Western Montana, twelve compounds (acetaminophen, caffeine, codeine, carbamazepine, cotinine, erythromycin-18, nicotine, paraxanthine, ranitidine, sulfamethoxazole, trimethoprim, and warfarin) were detected in a high school septic tank effluent. The fate of PPCPs in arable land application system in Braunschweig, Germany was investigated (Ternes et al. 2007), which was irrigated with treated municipal wastewater mixed with digested sludge in summer and without digested sludge in winter for more than 45 years. The selected PPCPs included 52 pharmaceuticals and two personal care products, most of which were not detected in groundwater (Ternes et al. 2007). The PPCPs primaryly detected were the ICM diatrizoate and iopamidol, the antiepileptic carbamazepine and the antibiotic sulfamethoxazole with concentrations up to several mg/L, and some of PPCPs like the acidic pharmaceuticals, musk fragrances, estrogens and betablockers were possibly adsorbed to soil particles or transformed in the land application system (Ternes et al. 2007). When discussing the fate of PPCPs in wastewater land application system, the soil properties should be considered; those properties mainly contain soil grain size distribution, pH, and the content of organic carbon (Oppel et al. 2004). During the research on the leaching of PPCPs, Oppel et al. (2004) found that the leaching potential of diazepam, ibuprofen, ivermectin and carbamazepine could be rated as low if the soil layers are sufficient above the groundwater table; however, clofibric acid and iopromide were very mobile with high leaching potential under the experimental conditions. There is a discrepancy that the occurrence of carbamazepine is frequently detected in groundwater, the reason may be that carbamazepine leaches down to the groundwater by river sediments and subsoil from receiving waters in reality rather than similar soils used in the research (Oppel et al. 2004).

In Germany, clofibric acid concentrations up to 165 ng/L (Stan et al. 1994) and 270 ng/L (Heberer et al. 1998) have been confirmed in drinking water, the source of which is groundwater recharged by contaminated wastewater treatment plant effluents (Daughton and Ternes 1999), clofibric acid is an antilipaemic agent and the biologically active metabolite of clofibrate, which is a fibric acid derivative used in the treatment of type III hyperlipoproteinaemia and severe hypertriglyceridem. The results of another study in Germany showed that “many pharmaceuticals could not be biodegraded during conventional biological treatment, nor could they be adsorbed by sewage sludge” (Adams et al. 2002; Kummerer et al. 1997). Although the research on the fate of PPCPs in soils after wastewater irrigation is scarce, many mechanisms are not clear; the pathways after they are applied to land via wastewater stimulate researchers’ interests. It was stated (Kinney et al. 2006) that four kinds of PPCPs were detected at three sites in the Front Range of Colorado, USA, from May through September 2003, where they intended to assess the presence and distribution of pharmaceuticals in soil irrigated with reclaimed water derived from urban wastewater. Those PPCPs were erythromycin, carbamazepine, fluoxetine, and diphenhydramine, whose typical concentrations were as low as 0.02-15 mg/kg dry soil. However, the investigation also illustrated that those chemicals’ concentrations in soil varied through seasons and persisted for a few months after wastewater irrigation events. Recently, research has focused on the adsorption and desorption of PPCPs in soils after wastewater land application (Drillia et al. 2005; Figueroa et al. 2004; Hashsham and Freedman 2003; Kay et al. 2005; Williams et al. 2006). It is accepted that sorption partly determines the movement of PPCPs in soils. The higher adsorption and the less desorption, the less PPCPs will leach down to contaminate groundwater. This explains why clofibric acid can be found in some groundwater in Germany since it is weakly adsorbed by soil particles. Some of estrogenic hormones go through chemical processes to be removed and some of them are removed by biochemical process. For example, 17β-Estradiol is oxidized to estrone in soils with an abiological transformation (Colucci et al. 2001), however, the removal of estrone (Colucci et al. 2001) and 17α-ethynylestradiol (Colucci and Topp 2001) are microbially mediated; “17α-ethynylestradiol is rapidly dissipated in agricultural soils under a range of conditions typical of a temperate growing season” (Colucci and Topp 2001). The bioavailability and mobility of PPCPs depend on their sorption potential to soil particles. Gao and Pedersen (2004) found that sulfonamides have week sorption potential to both clay minerals and natural organic matter and the sorption was strongly pH dependent (Gao and Pedersen 2004).

2.6 Escherichia coli in soils after wastewater irrigation

2.6.1 Introduction

It has been accepted that wastewater is an important source of irrigation water and fertilizer in agriculture (Malkawi and Mohammad 2003), especially in arid or semi-arid areas in the world. However, it is reasonable to speculate that secondary wastewater effluent probably contains residual pathogen even if wastewater is fully treated in developed countries; due to the economic reasons, in developing countries, untreated domestic wastewater is often used as agriculture irrigating water (Santamaria and Toranzos 2003). On the other hand, wastewater land application is also considered as a potential way to remove pathogens. As a result, a pathogen might be brought to the environment again by wastewater irrigation and threaten human health. Agricultural soils are places for producing food for customers and places where farm workers work thus, it is not difficult to understand that irrigating wastewater is identified as one of sources of pathogens in agricultural fields (Gerba and Smith 2005).

Although wastewater has been applied to land systems for many years, and recently more and more wastewater is irrigated to relieve the water resources pressure in the world, data on pathogen in soils after wastewater irrigation is scarce and the relative research and study are limited (Van Cuyk et al. 2004). One reason of concern about the effect of wastewater irrigation on public health lies in the fact that the fate of pathogens in the soils is not well understood (Santamaria and Toranzos 2003) after wastewater irrigation.

2.6.2 Total coliform, fecal coliform, and E. coli

Total coliform (TC), fecal coliform (FC) and E. coli are main indexes to judge contamination of enteric pathogens in water. TC are aerobic or facultatively anaerobic, gram-negative, non-spore forming, rod-shaped bacteria that ferment lactose with gas production in 24 to 48 hours (Entry and Farmer 2001); FC is a subset of TC, which originates from intestinal tracts of homothermic animals. Their presence in water implies the potential presence of pathogenic contamination from warm-blooded animals (Entry and Farmer 2001).

E. coli is the subset of FC, and often used as indicator of fecal contamination of water due to the relatively simple, fast, and reliable detection technique. E. coli are gram-negative, facultative anaerobic, straight, rod-shape bacteria, and considered as fecal origin. Most members of E. coli are harmless, but some of them are enteric pathogens. Currently, the most well-known pathogenic E. coli is O157:H7 (Foppen and Schijven 2006). E. coli are hydrophilic and strongly negatively charged (Foppen and Schijven, 2006). Those particular characteristics of E. coli determine the initial adhesion of E. coli to the surface of soil media (Foppen and Schijven 2006), and their fate in soils.

2.6.3 Distribution of E. coli at different depth of soil

It was observed (Schaub and Sorber 1977) that the largest concentration of enteric pathogen often occurred at the soil surface, and the concentration of pathogenic bacteria dropped sharply below the soil surface and declined at a slower rate as sampling depth increased. Another similar observation was made (Malkawi and Mohammad 2003) that bacterial counts were higher in surface soil than in the first few centimeters of soil from soil surface after wastewater irrigation events.

Malkawi and Mohammad (2003) found that although wastewater irrigation didn't significantly stimulate or inhibit the total aerobic bacteria at the soil surface, the numbers of total coliforms and fecal coliforms were so high, 2.1×10^3 CFU/g to 4.2×10^3 CFU/g and 1.2×10^2 CFU/g to 4.2×10^2 CFU/g respectively, that they strongly suggested that it was necessary to treat wastewater to the degree at which no or few pathogens would be detected in soils after wastewater irrigation. The concentrations of fecal coliform in leaching water may be estimated by the concentrations in soil solids (Van Cuyk et al. 2004).

2.6.4 Factors impacting persistence of E. coli in soils

A few mechanisms can explain the removal of E. coli in soils after wastewater irrigation and the distribution difference at different depth in wastewater irrigated soils. Soils have the ability to remove part of the pathogens in irrigated wastewater going through it down to the groundwater with filtration, sedimentation and adsorption (Gilbert et al. 1976; Page et al. 1986).

There are many factors impacting transport, survival, and persistence of E. coli in soils. Those factors include soil water holding capacity, pH, soil organic matter content, nutrient availability (Gilbert et al. 1976), the nature of pathogen, temperature, antagonism in soil (Gerba and Goyal 1984), soil moisture, concentration of salts in soil-water environment (Bartone and Arlosoroff 1987; Gilbert et al. 1976; Tate 1978), climate conditions including rainfall (Gilbert et al. 1976; Saini et al. 2003), tillage (McMurry et al. 1998), sunlight, toxic substance, dissolved oxygen (Foppen and Schijven 2006), CEC and texture of soils (Page et al. 1986) and so on.

In 2001, Entry and Farmer found that the slower flow and finer-grain-sized sand aquifer might filter more TC and FC from wastewater than the faster flow and coarser basalt aquifer. It was concluded (Powelson and Mills 2001) that constant unsaturated flow was better to remove pathogens than saturated and variable unsaturated flow during simulated infiltration to investigate the relation of soil volumetric water content to bacteria (E. coli) removal by soil systems. It is interesting and pointed out (Sharples et al. 2004) that E. coli had the ability to grow in soils; therefore, the contamination with fecal pathogen could be either recent or past.

It can be safe to conclude that the fate and removal of E. coli in soils are determined by multi-factors. Therefore, early in 1976, Gilbert et al. recommended that such studies should be executed individually, and, similarly, the optimum amounts and application rate of wastewater, which would not have severe health risks to human, should be determined individually. Later in 2003, Santamaria and Toranzos also suggested that the similar studies were supposed to be carried out in different types of soil.

2.6.5 The fate of E. coli O157:H7 and model of E. coli transport in soils

E. coli O157:H7 is listed here on purpose because it is a pathogen from wastewater irrigation that causes many human diseases such as diarrhea, hemorrhagic colitis, and complications including hemolytic uremic syndrome (Wikipedia 2008). This fact stimulated interests of researchers in recent years. E. coli O157:H7 is a robust pathogen (Maule 2000) and can survive in soil samples for 154-196 days (Islam et al. 2005). After a few experiments on its survival in soil systems, it was found (Ibekwe et al. 2004) that E. coli O157:H7 had higher concentration in the rhizosphere soils than in the non-rhizosphere soils and leaf surfaces, and persisted longer in clay soil than other types of soils. It was concluded (Gagliardi and Karns 2000) after the research that there was a correlation of ammonia and nitrate levels with E. coli O157:H7 and total coliform levels in leaching water. They also speculated that soluble nitrogen might promote E. coli O157:H7's transport. Turbidity in leaching water did not correlate with the movement of this type of E. coli and its movement was probably not as they anticipated as compared to the particles' movement in soils. In addition, it was discovered (Gagliardi and Karns 2002) that clay, plant roots, and freezing increased persistence and activity of E. coli O157:H7 and other coliforms.

Wang et al. (2003) tried to use a kinetic second-order model along with one-dimension convection-dispersion equation to describe E. coli transport through 20 cm sand columns. They thought that the most likely mechanism was physical entrapment of bacteria within sands and sand size was the main factor in E. coli transport under saturated flow conditions in sand columns. Their research proved that the finer the sand size, the greater the entrapment capacity of E. coli in designed sand columns (Wang et al. 2003).

2.6.6 Concluding remarks

It is obvious that there is much more work to be done investigating the fate of E. coli in soils irrigated with wastewater. There is currently insufficient data and no effective models to understand and describe transport and survival of E. coli in soils.

The distribution at different locations in soils is so complex that it is tough to carry out the relative research. Maybe future research should be focused on the individual or particular research as Gilbert et al. proposed in 1976.

2.7 Relationships in soil-water-plant-air system

In reality, the relationships between the components of a soil-water-plant-air system are complex. The following is the description of those relationships based on the consideration of them in land application systems.

2.7.1 Water-plant relationship

Water is the media of chemical and biochemical processes that support plant metabolism. Water is a component of plant tissue. Water moves the plant-requiring substances and nutrients in soils to the roots of plants, and then moves them up to the leaves, finally, some of water transpires from plants. Such a pathway of water in plants in conjunction with water evaporation from surrounding soil surface, and water consumptive use by plants as a part of their bodies, form an important design parameter, evapotranspiration (ET). The evapotranspiration from a crop is defined by Brouwer et al. (1985) as the total amount of soil water used for transpiration by the plants and evaporation from the surrounding soil surface. In reality, the crop ET is the amount of water utilized by the crop and its environment (Brouwer et al. 1985).

This part of water loss is one important component in water balance during wastewater land treatment design. ET is influenced by climate conditions (temperature, wind speed, relative humidity, and solar radiation), soil moisture and texture, and crop type and growth.

ET varies for different crops and grass, even for the same plant, ET still varies because of the growth stage and plants spacing (Brouwer et al. 1985). Generally, ET determination for field type crops and grass crops is different and the related methods for Texas were determined by Borrelli (1998).

2.7.2 Soil air-soil water relationship

More oxygen can enter into wastewater when it is surface-applied onto land because the contact area between air and water is increased. Oxygen in wastewater in soil-water system is an important factor controlling substance redox reactions and microorganism biochemical processes. More oxygen in wastewater causes less denitrification because denitrification is principally an anaerobic process.

There are two types of pore spaces in soil: capillary spaces and non-capillary spaces (Ferguson 1950). The former is important to soil water holding capacity; the latter is important to soil aeration (Ferguson 1950). Soil pore spaces are filled with water and/or air. When water goes in soil, air goes out of soil; when water goes out of soil, air goes in (Ferguson 1950). Soil water has three classes: gravitational water, capillary water, and hygroscopic water (Ferguson 1950). Soil water and soil air should be available for plants growth in the soil-water-plant-air system; therefore, land should not be over-irrigated causing plants to have no soil oxygen available on their root surface which causes plant wilt (Ferguson 1950). It is necessary to keep a balance between soil water and soil air.

2.7.3 Soil-plant

Soil is the media that supports plant growth. Soil provides plants a place to develop a root system and absorb water and nutrients.

One important consideration of soil and plant relationship in wastewater land treatment design is soil salinity. Once enough salts accumulate in the root zone, soil salinity will become a severe problem for some plants growth. Those excess salts in the root zone hamper the plants ability to absorb water from the surrounding soil due to the increased osmotic pressure required by the plant to take up the water. Plants need more energy to pump water from soil to the plant tissue. As a result, excess salts in soil can "decrease plant available water and cause plant stress" (Pearson 2003). The adverse effects of salts on plants are inhibition of germination, reduced rates of plant growth, reduced yields, and even total crop failure (Rhoades and Loveday 1990).

Therefore, to avoid excess salt accumulation in soil, more water is required to be applied onto land to flush salts down through the root zone. The following equation can be used to determine the leaching requirements for typical sprinkler irrigation systems (Ayers and Westcot 1976):

$$LR = \frac{EC_w}{5EC_e - EC_w} \qquad (2.6)$$

where, LR is the minimum leaching requirement needed to control salt accumulation in the soil; EC_w is the electrical conductivity of the effluent (micromhos/cm) (note, 1 dS/m is equal to 1 mmho/cm); EC_e is the electrical conductivity of the saturation extract of soil for a given crop appropriate to the tolerable degree of yield reduction--usually 10% or less (micromhos/cm).

The potential yield reduction of a crop as a function of ECe is found in Ayers and Westcot (1976). In the design of wastewater land treatment, crops should be carefully selected according to the soil salinity. The plants should be tolerant of the salinity level in soil. Field type crops and grass crops have different tolerance of salt levels in soils. In addition, the size and distribution of the root zone of field type crops are different from grass crops.

2.7.4 Soil-water relationship

For someone to develop the successful irrigation practice and irrigation scheduling required for land treatment of wastewater effluent, they need to understand the principles involved with the relationship between soil and water. The quality of irrigated water may have important impacts on the change of soil properties such as salinity and infiltration.

2.7.4.1 Entry of wastewater into soil

Two important concepts related to the movement of water in soil: infiltration and soil hydraulic conductivity. Those two soil physical properties are related to the irrigation scheduling such as the maximum application rate and the lengths of irrigation events.

The Food and Agriculture Organization (FAO) defines the infiltration rate of a soil as the velocity at which water can seep into it. It is commonly expressed as a depth per time and it is influenced by soil texture, soil structure, and soil moisture content. Another concept is soil hydraulic conductivity, which is an important soil property to reflect the potential movement of water in soils. When all pores are filled with water, the soil hydraulic conductivity is called saturated hydraulic conductivity, otherwise, unsaturated conductivity.

2.7.4.2 Determination of application rate

The wastewater application rate may be estimated by the following equation (Fedler and Borrelli 2001):

$$Q_R = (I_B \times T_A + SS)/T_A \tag{2.7}$$

where Q_R = application rate, inches per hour;

I_B = base intake rate of soil, inches per hour;

T_A = time of application, hours;

SS = maximum surface storage for sprinkler system, inches.

The base intake rate of soil can be assumed equal to the saturated hydraulic conductivity, K (Karmeli et al. 1978).

The saturated hydraulic conductivity, K, can be calculated by the method below (Saxton et al. 1986):

$$K = 0.3937\left\{\exp\left[A + \left[\frac{B}{\Theta}\right]\right]\right\} \tag{2.8}$$

$$A = 12.012 - 0.0755(sand) \tag{2.9}$$

$$B = \left[-3.8950 + 0.03671(sand) - 0.1103(clay) + 8.7546\times10^{-4}(clay)^2\right] \tag{2.10}$$

$$\Theta = 0.332 - 7.251x10^{-4}(sand) + 0.1276\log_{10}(clay) \tag{2.11}$$

where K = saturated hydraulic conductivity, inches/hr;

Θ = soil moisture content, ft^3/ft^3;

sand = sand content in the soil, percent;

clay = clay content in the soil, percent.

2.7.4.3 Soil moisture content to understand the water moisture in water balance

There are three soil moisture conditions, which are saturated, field capacity, and permanent capacity (Figure 2.1). Saturated condition means all soil pores are filled with water; field capacity is the soil moisture condition, which refer to "after the drainage has stopped (approximately 2 days), the large soil pores are filled with both air and water while the smaller pores are still full of water. At this stage, the soil is said to be at field capacity. At field capacity, the water and air contents of the soil are considered to be ideal for crop growth" (Brouwer et al. 1985); And Permanent wilting point is the point when the soil water content at the stage where it is not available for plants uptake and plant dies. The amount of water available to plants is calculated by the difference in moisture content between field capacity and permanent wilting point. It is controlled by soil nature (soil porosity, texture, structure, and organic matter content) and the root- zone depth.

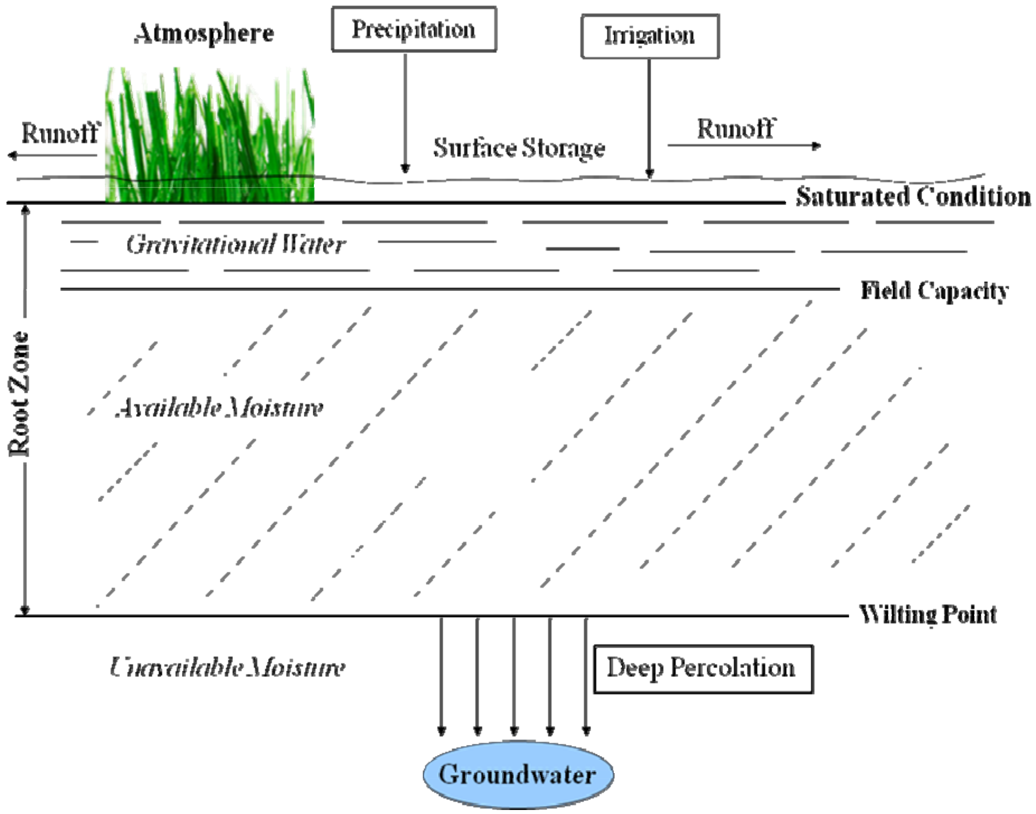

Figure 2. 1 Water conditions in the soil profile of a surface application system.

2.7.4.4 Soil salinity, sodicity, and their influence on the physical properties of soil

Wastewater irrigation may increase soil salinity and sodicity. Sodicity is the amount of sodium present in soil. High salinity and sodicity in wastewater can increase the soil salinity and sodicity, and cause problems for plants and soil physical properties. Soil water salinity has positive effect on soil aggregation and stabilization, but high level of salts has severe effects on plants (Pearson 2003). "The three main problems due to sodium-induced dispersion are reduced infiltration, reduced hydraulic conductivity, and surface crusting" (Pearson 2003). Because Ca and Mg have no similar effects on soil properties as Na, they generally keep soil flocculated, so increased amounts of Ca and Mg can reduce the effects due to Na on soils (Pearson 2003).

To reduce the negative effects of soil salinity and sodicity on soil physical properties induced by wastewater irrigation, some more wastewater is applied in order to leach more water down through the root zone resulting in flushing out of salts including sodium bound in the soil. The leaching requirement is determined by Equation 2.6.

TDS is a term defining total dissolved solids in water or wastewater; sometimes, TDS can be used to express salinity of wastewater. Salinity in irrigating water is an important parameter influencing the soil infiltration rate. Sodium is a unique cation due to its effect on soil properties (Lazarova and Bahri 2005). When sodium is present in an exchangeable form, sodium may cause adverse physical-chemical changes, particularly to soil structure resulting dispersion of particles and low soil infiltration rate (Lazarova and Bahri 2005). If sodium in applied water is at high levels, soil hydraulic ability or infiltration ability tends to decrease as Exchangeable Sodium Percentage (ESP) increases, as a result, clay swells, disperses, and plugs the conducting pores in soils, all of which causes low soil infiltration rate (Al-Haddabi et al. 2004).

The reliable index of the sodium hazard of irrigation water is the sodium adsorption ratio SAR, defined by Equation 2.12:

$$SAR = \frac{Na}{\sqrt{(Ca + Mg)/2}} \qquad (2.12)$$

where, the ion concentrations are expressed in mEq/L.

The threshold value of SAR of less than 3 indicates no restriction on the use of wastewater for irrigation, while SAR with a value larger than 9 has a severe damage on infiltration rate (Lazarova and Bahri 2005). At a given SAR, the infiltration rate increases as salinity increases or decreases when salinity decreases. SAR and salinity should be used in combination to evaluate the potential soil infiltration problem (Lazarova and Bahri 2005).

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CHAPTER III

METHODOLOGY

3.1 An alternative design approach

At least three components, water, nitrogen, and salt, should be carefully considered when designing a wastewater land application system. Water is the vehicle for the movement of nitrogen and salt in the soil. Nitrogen is one of the main concerns in the system because of the potential pollution that could be caused to both groundwater and surface water if the land application system is not appropriately designed. Salt is a key factor with respect to potential changes of soil properties. Moreover, all three components have the combined effects and interactions in land application systems. Those combined effects and interactions are complex and need more understanding.

Generally, a land application system design needs to consider many design factors and interactions, which include soil infiltration rate, soil water holding capacity, plant nitrogen uptake, plant water uptake (evapotranspiration, ET), nitrogen consumption by microbes within the soil (such as nitrification, denitrification, etc.), salt tolerance of the plants, the leaching of salt and nitrogen, and the accumulation of salt in soil. The data of those design factors for one location will be quantified in this research for the understanding of the system and design procedure. As a result, the design procedures and the surface application process may be complicated, however, the mass balance approach proposed by Fedler (2000), allows the design of surface application systems to be easily executed resulting in an environmentally sound system design. The mass balance approach includes a water balance, a nitrogen balance, and a salt balance (Fedler 2000). The design procedure is similar for both on-site systems and large-scale land application systems for municipal wastewater.

3.1.1 Water balance

The water balance for a land treatment system is the capstone for the whole design of the surface application treatment system. In the wastewater land application system, there are a few components to be considered while doing a water balance (**Figure 3. 1**). If the root zone is regarded as a system while the input is wastewater applied and effective precipitation. Some water fallen onto soil surface is utilized by plants while some is evaporated from soil. The incorporation of plant transpiration and soil surface evaporation is called evapotranspiration (ET). In addition, some water deep percolates through the root zone and down to groundwater while some water stays in the root zone of the plants. Because ET and applied water (including precipitation) vary throughout the season due to the stage of the plant growth and the variation of climate conditions, the water stored in the root zone also varies.

Therefore, the basic equation used to produce a water balance and develop the irrigation schedule is proposed as below (Fedler and Borrelli 2001):

$$SM_i = SM_{i-1} + P_i + I_i - ET_i - L_i \qquad (3.1)$$

where, SM_i is the soil moisture in month i, (inches/month);

SM_{i-1} is the soil moisture in the previous month, (inches/month);

P_i is the precipitation in month i, (inches/month);

I_i is the irrigation in month i, (inches/month);

ET_i is the evapotranspiration in month i, (inches/month);

and L_i is the leaching that occurs in month i, (inches/month).

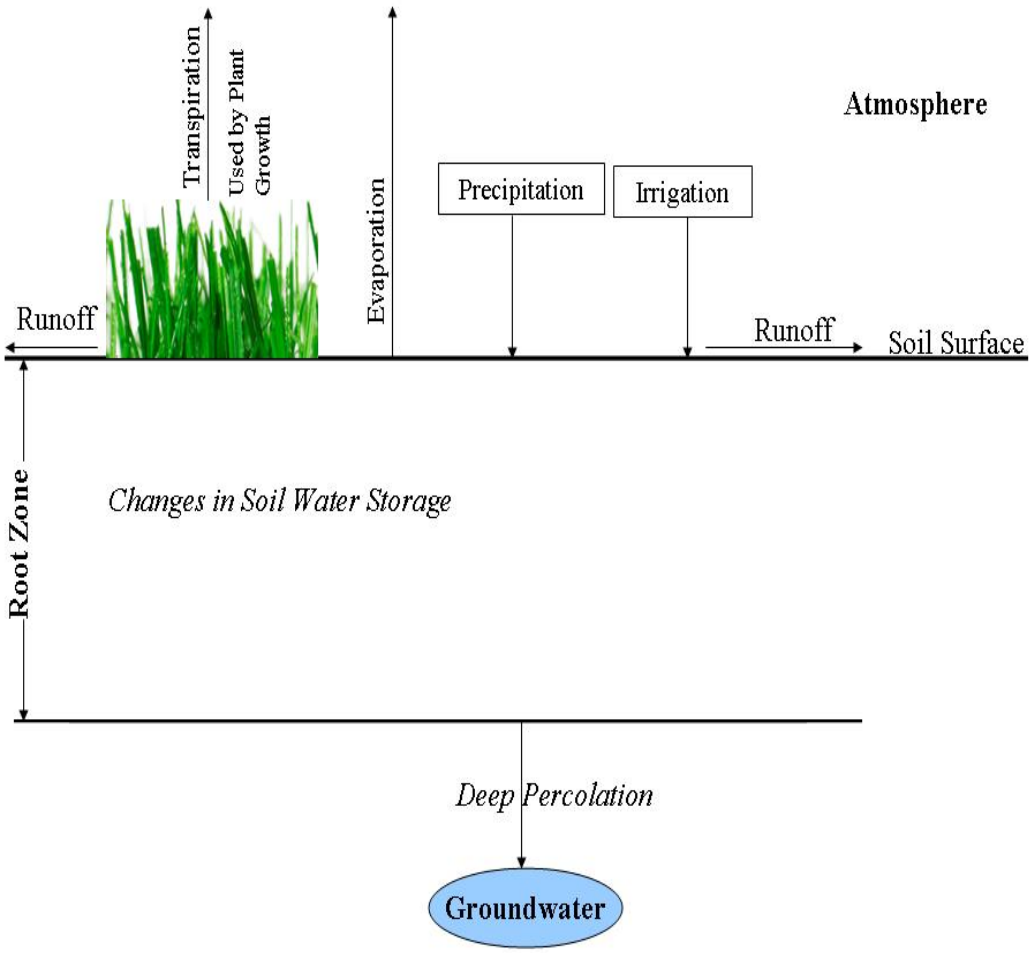

Figure 3. 1 Water balance and components in the wastewater land application system

Note that all the variables in Equation 3.1 have units of depth per time (e.g. inches per month or centimeters per month) and the value of soil moisture cannot be less than zero nor more than the available water holding capacity of the soil in the plant root zone. The change of soil water storage in the root zone with time of month can be calculated by the difference of the soil moisture in month i and the soil moisture in month i-1. Any water applied in excess of the water holding capacity and less than saturation condition is called deep percolation, or leaching water, and this water passes through the plant root zone eventually reaching the ground water. There are two assumptions inherent to Equation 3.1; that irrigation events are designed and controlled well enough to have no runoff on the soil surface and the groundwater level is low enough to make sure there is no groundwater entering into the crops root zone. By determining the variables in Equation 3.1, the irrigation schedule can be determined. Equation 3.1 will be used to make the irrigation schedule and then be evaluated to understand if it can be used to estimate the quantity of leachate water in the field.

In the field, wastewater application is influenced by irrigation distribution uniformity; a subtask in the water balance section is to determine the irrigation distribution uniformity of the specific research site.

3.1.2 Nitrogen balance

Nitrogen in the municipal wastewater has a few of forms such as organic nitrogen, ammonia-nitrogen, nitrate-nitrogen, and nitrite-nitrogen. The residual nitrogen of treated municipal wastewater mainly includes incompletely degraded or undegraded organic nitrogen, ammonia-nitrogen, and nitrate-nitrogen. The transformations and cycle of nitrogen are complicated in the land application system (**Figure 3. 2**).

It is required to state the nitrogen cycle in the land application system in order to completely understand the model of nitrogen balance used in this research. The boundary of the nitrogen balance model is the plant root zone plus the plants growing on the surface of the soil involved with the plant root zone.

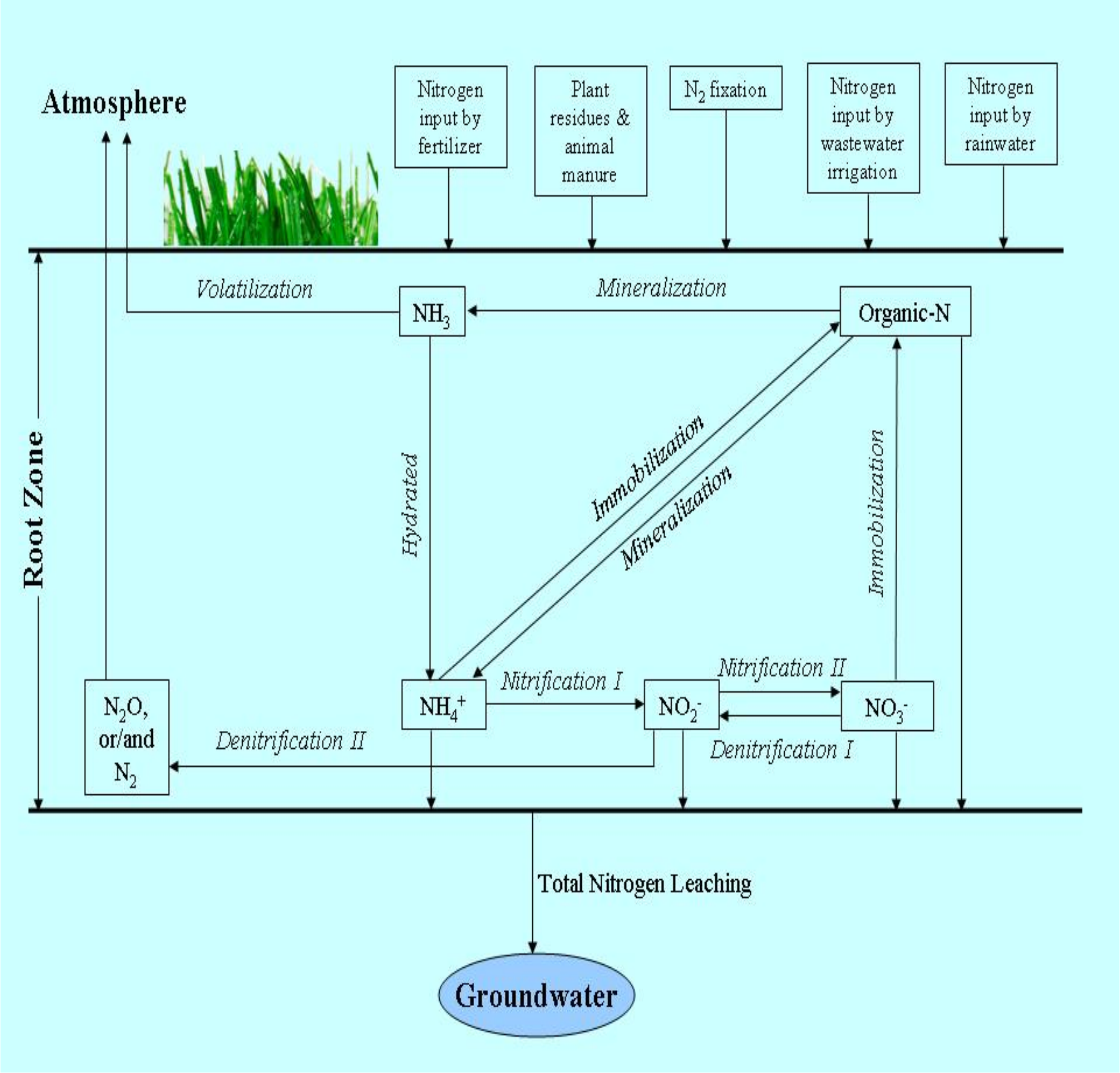

Figure 3. 2 Nitrogen cycle and balance at the wastewater land application site

Nitrogen may be input into the land application system in the forms of organic nitrogen, nitrate-nitrogen, and ammonia-nitrogen by the pathway of wastewater application, rainwater, plants residues and animal manures, possibly fertilizers, and even nitrogen fixation by the bacteria growing on the surface of leguminous plant root system if leguminous plants are grown. Some nitrogen is released from the system in the forms of gaseous NH_3, nitrogen gas, N_2O, and NO to the atmosphere as a result of denitrification (Barton et al. 1999), and some of nitrogen is leached down to the groundwater. In the root zone, organic nitrogen can be converted to ammonia and ammonium ion, which is defined as mineralization (Broadbent and Reisenauer 1985), but nitrate and ammonium ion can be absorbed by some microorganisms, the process is immobilization (Mulvaney et al. 1993). Ammonium ion can be converted to nitrite in nitrification I and finally nitrate in nitrification II (Quastel and Scholefield 1951); Nitrite can be converted to nitrate in nitrification II (Quastel and Scholefield 1951) and to nitrogen gas or N_2O in denitrification II (Barton et al. 1999); Nitrate can be converted to nitrite in denitrification I, and then nitrogen gas or N_2O in denitrification II (Barton et al. 1999), due to its high mobility, nitrate can be leached down within leachate to groundwater.

The complete model of nitrogen balance for a wastewater land application system may be explained with Equation 3.2.

$$V_n C_n = V_p C_p + V_g C_g + V_i C_i + N_r + N_f + N_l - N_{pl} - N_d - N_a - \Delta N_s \quad (3.2)$$

where, N = mass of total nitrogen (mg);

n = total nitrogen in the leaching water;

V = volume (L);

C = concentration of total nitrogen (mg/L);

p = precipitation;

g = groundwater;

i = irrigation;

r = total nitrogen from plant residuals fallen onto or into soils;

f = total nitrogen from fertilizer if applicable;

l = total nitrogen due to nitrogen gas fixation with legume growing;

pl = total nitrogen loss by harvesting crops;

d = total nitrogen loss by denitrification;

a = total nitrogen loss by ammonia volatilization;

ΔNs = loss of total nitrogen from soil water to soil in the root zone due to nitrogen immobilized by soil microbes (+) or adsorption, or add total nitrogen from soil to soil water due to nitrogen mineralization or desorption (-).

Equation 3.2 can be used to readily and completely understand the mass balance of nitrogen, however, it is not practical for use in the research, and therefore, this equation needs to be simplified. Assuming the nitrogen input in the land application system (**Figure 3. 2**) is just from wastewater, and the plant is grass, then it could be found that the output of nitrogen from the system is nitrogen loss by denitrification and nitrogen leaching if the grass is mowed but not carried away from the system. If there is no fertilizer applied and no groundwater entering the plant root zone and if the concentration of total nitrogen in precipitation and the storage change of total nitrogen in the root zone are not considered in the design procedure, then nitrogen mass balance Equation 3.2 may be expressed by the following equation for practical design consideration. Therefore, Equation 3.3 may be used for making nitrogen mass balances.

$$V_n C_n = V_i C_i - N_d - N_{pl} \qquad (3.3)$$

In the nitrogen balance section, the related data of nitrogen in wastewater and in leached water was collected and analyzed. The denitrification amount of each month can be derived from Equation 3.3.

3.1.3 Salt balance

The salt balance and salt pathways in the land application system can be seen in **Figure 3. 3**. For the land application system, the input of salt into soil water is possibly from precipitation, fertilizer or soil amendments, soil salt dissolving, and groundwater moving up, and from wastewater applied.

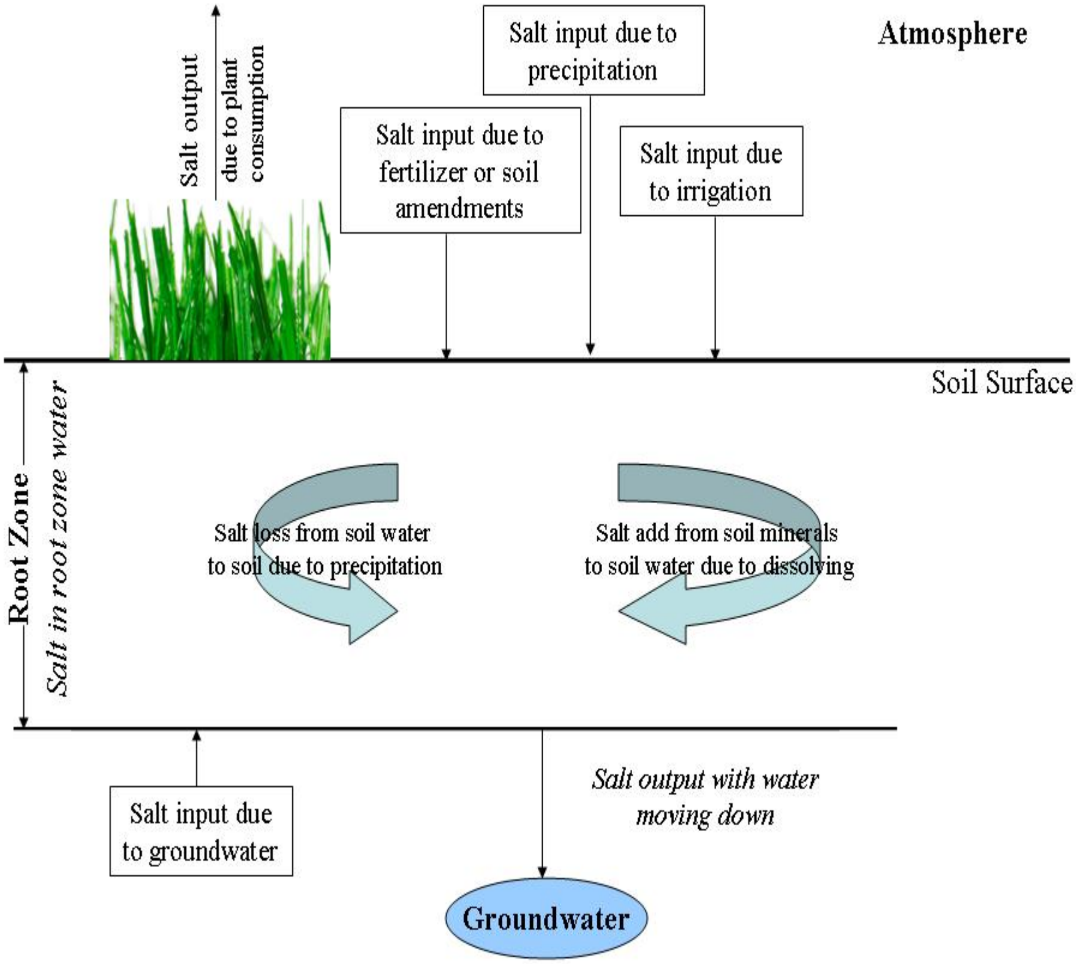

Figure 3. 3 Salt balance at the wastewater land application site

The equation (Umali-Deininger 1993) used to understand the salt mass balance is:

$$S_s = V_p C_p + V_g C_g + V_i C_i + S_m + S_f - V_l C_l - S_{sp} - S_c \qquad (3.4)$$

where, S = mass of salt (mg);

s = salt in the root zone water;

V = volume (L);

C = concentration of salt (mg/L);

p = precipitation;

g = groundwater;

i = irrigation;

m = salt dissolved from soil minerals;

f = salt from fertilizer or soil amendments;

l = salt loss by leaching water;

sp = salt loss by salt precipitation;

and c = salt loss by harvesting crops.

The salt mass balance can be simplified as shown below for the utilization in this research:

$$S_{rootzone} = V_i C_i - V_l C_l \tag{3.5}$$

Note in Equation 3.5, S_{rootzone} is the salt in the root zone water and soil. In the salt balance section, the related data of salt in wastewater and in leachate water was collected and analyzed. The salt accumulation amount in each month was derived from Equation 3.5.

3.2 Experimental design

3.2.1 Field sites

The field site is at the wastewater treatment plant in Littlefield, Texas. The city of Littlefield, Texas, is located at 33°55′10″N, 102°19′58″W, in Lamb County, Texas, United States. The population was 6,507 at the 2000 census. The city has a total area of 15.5 km² (6.0 mi²).

The wastewater treatment plant for the City of Littlefield has a treatment capacity of 1.5-million gallons per day, which was built in 2001. The flow chart is shown in **Figure 3. 4**. The municipal wastewater is treated by the process of aerated pond system followed by a large storage pond. The Littlefield wastewater treatment plant consists of two aerated ponds (**Figure 3. 5**) and a storage pond (**Figure 3. 6**). Most of the secondary wastewater effluent is pumped three miles to the City of Littlefield farm and is applied to crops. Some wastewater effluent is applied to grass around ponds at the wastewater treatment plant, where leached water samples were collected as shown at Location B in **Figure 3. 4**. In addition, secondary wastewater samples were taken at Location A in **Figure 3. 4**.

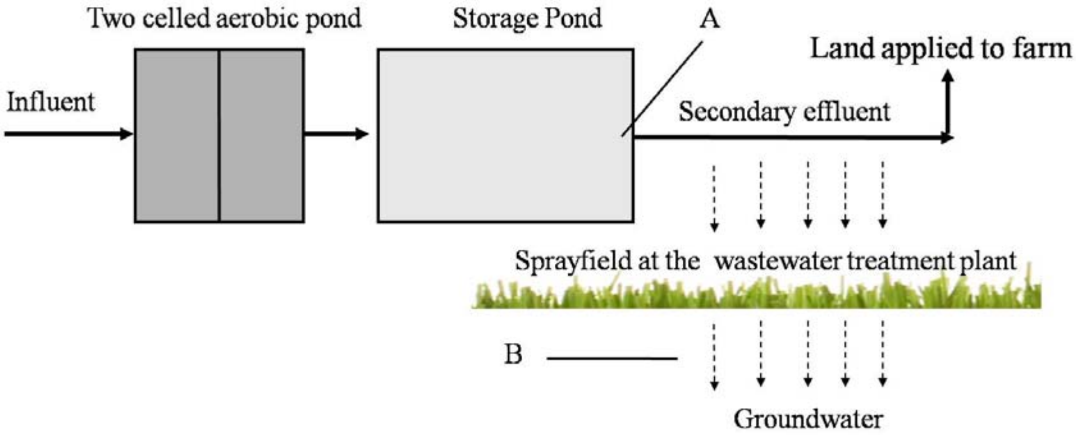

Figure 3. 4 Flow chart of wastewater at the wastewater treatment plant, Littlefield, Texas. A: sampling point for the secondary effluent; B: sampling position for the leached water

Figure 3. 5 Aerobic ponds at the Littlefield wastewater treatment plant

Figure 3. 6 Storage pond at the Littlefield wastewater treatment plant

Figure 3. 7 A part of sprayfield at the Littlefield wastewater treatment plant

3.2.2 Experimental layout and design at the Littlefield site

A lysimeter system was installed *in situ* to collect samples of the leachate from the irrigated grass adjacent to the ponds (**Figure 3. 8**). Sixteen samplers (lysimeters) were initially installed in a straight line with the top of the sampler flush with the soil surface. Each sampler has a diameter of eight inches and a depth of eighteen inches. The distance between two adjacent samplers was 10 ft. The distance between two adjacent sprinklers is about 59 ft. Those sixteen samplers were installed at Littlefield site on April 15th, 2005.

There are two parts in each sampler (**Figure 3. 9**). The top part was initially filled with 12 inches of nearly an undisturbed soil plug with grass taken from the same location. The bottom part of each sampling device consists of support layers made up of approximate two inches high of sand, fine gravel, and coarse gravel. A 1/2 inch diameter PVC pipe is placed along the inside of each sampler in order to extract the leachate water collected within the sampler (**Figure 3. 9**). The installation process is as shown in **Figure 3.10**, **Figure 3.11**, and **Figure 3.12.** At Littlefield site, Bermuda grass was established in the plots as out of the plots. And the soil core in the plots consists mainly of sandy clay loam and clay same as the sprayfield.

The effluent from the storage pond was applied to the irrigation site by a solid-set sprinkler system. When the experiments were initially started, effluent was applied for 20 minutes per day as prescribed by the original designers' water balance. After operating with this application rate for 9 months, then a predetermined irrigation schedule (**Table 3. 1**) was prescribed according to a calculated water balance for the specific site and associated weather conditions.

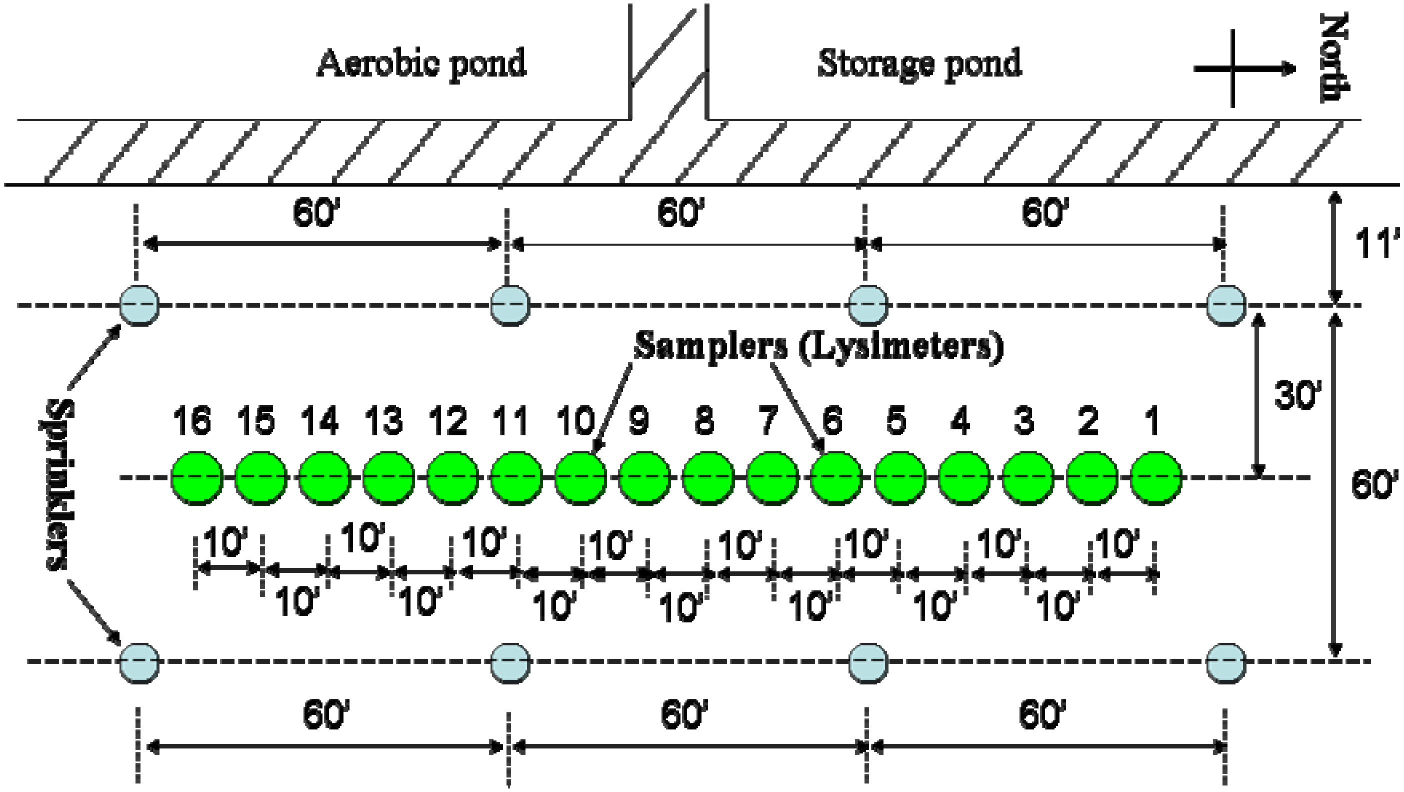

Figure 3. 8 The layout of samplers (lysimeters) at Littlefield wastewater treatment plant (not scaled)

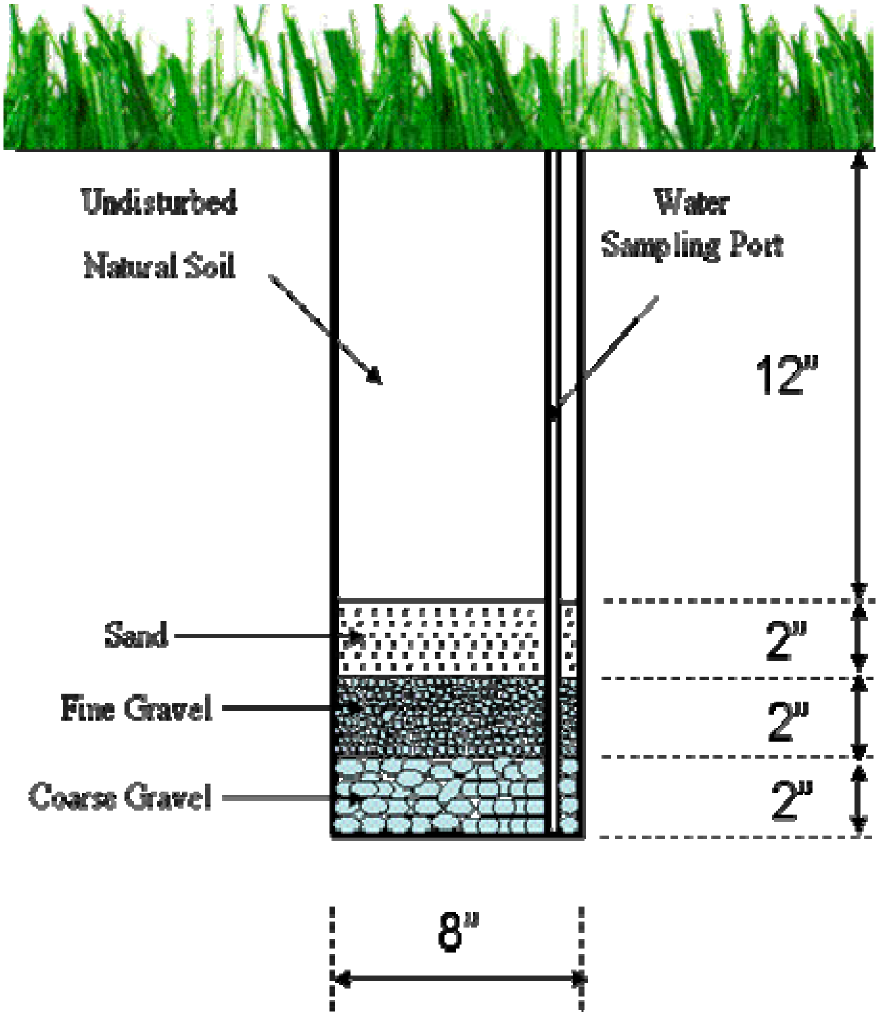

Figure 3. 9 Side view of the sampling device (lysimeter) installed under soil surface (not scaled)

Figure 3. 10 The installation of supporting layers within a sampler (lysimeter)

Figure 3. 11 Right after installation of a sampler into ground

Figure 3. 12 Right after installation of samplers at the Littlefield site

Water samples were extracted approximately once per month and then analyzed for both quantity and quality. Water samples were collected by hand pump (2006G2 pressure-vacuum hand pump, the product of Soilmoisture Equipment Corp., CA, USA). Water quality parameters tested includes COD, total nitrogen (TN), nitrate-nitrogen, ammonia-nitrogen, and electricity conductivity (EC), which were analyzed or measured according to standard procedures. The analytical measurement methods used are listed in **Table 3. 2**.

Soil samples were collected for analysis before and when the sampling devices were installed at the Littlefield site; twenty randomized soil samples at the Littlefield site were collected down to 4 feet deep annually after the installation of samplers, and analyzed. The randomized soil sampling is shown in **Figure 3.13**. Also, three samplers (lysimeters) at the Littlefield site are extracted annually for same constituents' analysis.

Table 3. 1 Predetermined irrigation schedule for the Littlefield site

1	ET_0 data in Lubbock (inches)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	2.49	2.92	4.78	6	7.05	7.65	7.94	7.33	5.63	4.55	3.15	2.5
	K_{cb} for Burmuda											
	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
	ET (inches)											
	1.99	2.34	3.82	4.80	5.64	6.12	6.35	5.86	4.50	3.64	2.52	2.00
2	PPT data (inches)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	0.61	0.73	0.93	1.31	2.32	2.98	1.63	2.02	2.25	1.78	0.96	0.68
	PPT is the average of 30 years in Lubbock due to no PPT data in Littlefield available.											
3	Expected leaching (inches)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	0.5	0.5	0.5	0.5	0.5	0	0	0	0.5	1	1	1
4	Irrigation water (inches)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	1.88	2.11	3.40	3.99	3.83	3.14	4.72	3.85	2.75	2.86	2.56	2.32
5	Irrigation Rate = 0.66 inches per hour at Pressure of 58 PSI											
	Calculation of irrigation time in a month (hours)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	2.85	3.19	5.15	6.04	5.80	4.76	7.15	5.83	4.17	4.33	3.87	3.51
	Days in this month											
	31	28	31	30	31	30	31	31	30	31	30	31
	Irrigation time everyday in this month (minutes)											
	5.51	6.84	9.97	12.09	11.22	9.51	13.84	11.28	8.35	8.38	7.75	6.80
	Roundoff of irrigation time everyday in this month (minutes)											
	6	7	10	12	11	10	14	11	8	8	8	7

Note: ET_0 and K_{cb} are from the project report written by Borrelli et al. in 1998 (Borrelli et al. 1998).

Table 3. 2 The methods used to measure the quality of leachate water and wastewater

	TN mg/L	NO_3-N mg/L	NH_3-N mg/L	COD mg/L	EC µS/cm
Method	Hach: M10071	Hach: M8039	Hach: M10023	Hach: M8000	ORION model 162

Figure 3. 13 Deep soil sampling in process

Additionally, to probe the causes of potential variability of leach water quality and quantity, the irrigation uniformity coefficient (or UCC) was measured at different times of the year. Each UCC test consisted of 100 sampling points evenly arranged at the center of 100 squares measuring 6 feet by 6 feet. Generally, thirty minutes were used to operate one row of sprinklers with the other row closed, and another 30 minutes to operate the second row of sprinklers with the initial row not operating in order to operate the system at or close to the designed pressures. The two rows of sprinklers covered the whole test area. At each sampling point, one cup was positioned on a stake and used to collect the irrigation water. The volume in the cup was measured with a graduated cylinder and the UCC was calculated from those data. Additionally, wind speeds and air temperatures were measured with a Model 45158, Mini Hygro Thermo-Anemometer, made by EXTECH Instruments, while UCC test was in progress. **Figure 3. 14** shows the UCC measurement in process.

UCC means Christiansen's Uniformity Coefficient (Karmeli et al. 1978), it is calculated in the measurements by Equation 3.6, and a UCC of 70 or higher is regarded as good irrigation (Karmeli et al. 1978).

$$UCC = \left(1 - \frac{\sum_{i=1}^{n} \left| X_i - \overline{X} \right|}{n \times \overline{X}} \right) \times 100 \qquad (3.6)$$

where UCC = Christiansen's Uniformity Coefficient, %;

X_i = the i-th single observation depth or volume measured, inches or mL;

$\overline{X}$ = the mean of all the individual observations, inches or mL;

n = the total number of observations.

Figure 3. 14 UCC test grid and measurement in process

3.2.3 Experimental layout and design at the TTU site

TTU site is at the northwest corner of 4th Street and Avenue Quaker, Lubbock, Texas. This research is on the campus of Texas Tech University. A green house was built at this research site with an area of 150 ft × 34 ft. A natural wastewater treatment and reuse system keeps operating every day. This system functions to produce algae, aquatic plants such as duckweed, cattail, and water lilies, invertebrates, fishes while treating artificial wastewater. Also, artificial marine water system is available to simulate living environment of marine plants and fishes. There is a weather station installed outside of greenhouse.

Six sampling devices containing soils from Harris County, Texas, where St. Augustine Grass is grown, are installed in the greenhouse of the Lubbock site. Because soil plugs are from the place near Houston, the samplers are defined as Houston samplers. Another six samplers containing soils from Midland, Texas are set up outside of the greenhouse. Similarly, those six samplers are called Midland samplers. The installation positions are as shown in **Figure 3.15.**

Initially, all 12 samplers were irrigated a few months by hand with tap water for flushing salts in soils down through the root zone, then irrigated by hand with water from a wastewater recycling system according to the designed irrigation schedule by combined mass balance approach. After the end of August of 2006, those samplers are irrigated with the same water with the addition of fertilizer to obtain a similar nitrogen concentration to a typical municipal wastewater. A rain gage was also installed at the Lubbock site. Leach water samples are extracted by hand pump, their volumes are measured, and water quality is analyzed in the lab with the same method as samples from the Littlefield site.

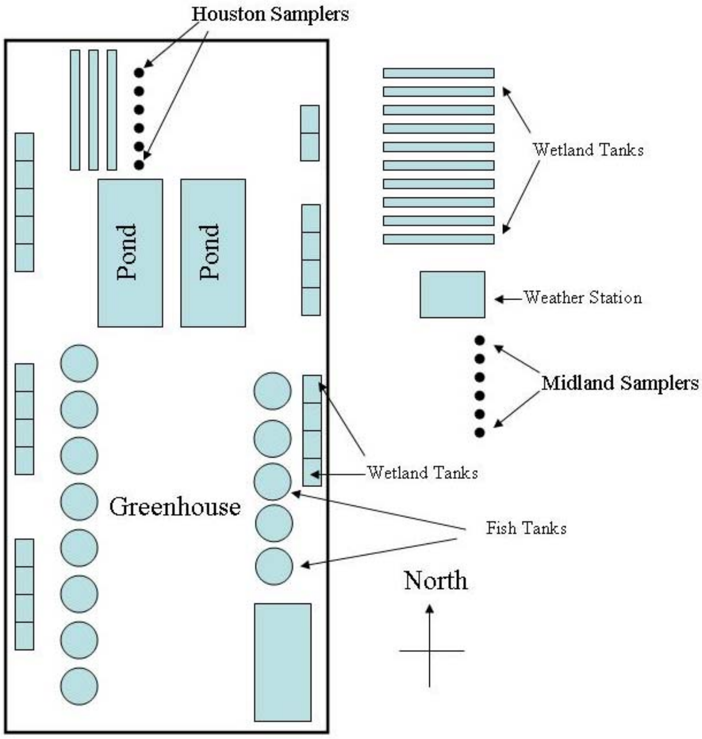

Figure 3. 15 Installation positions of Houston and Midland samplers at TTU site

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CHAPTER IV

DATA ANALYSIS AND RESULTS AT LITTLEFIELD SITE

The data analysis and results contains three sections, water balance, nitrogen balance, and salt balance. All these three sections covers the original results of mass balances, and the further discussion of the results will be conducted in the next chapter.

4.1 Water Balance

In the section of water balance, the test results of the irrigation distribution uniformity are summarized first. And this section also includes the spatial and temporal distribution of the leached water, and calculation of water mass balance.

4.1.1 UCC measurements

UCC measurements were executed six times to represent four seasons in a year. The UCC testing dates are Mar 3, 2006, Mar 24, 2006, Jun 20, 2006, Oct 10, 2006, Oct12, 2006, and Feb 23, 2007. Measurements on Mar 3, 2006 and Mar 24, 2006 represented Spring UCC; Measurements on Jun 20, 2006 represented Summer UCC; Measurements on Oct 10, 2006 and Oct 12, 2006 represented Fall UCC; Measurements on Feb 23, 2007 represented Winter UCC. The UCC values and climate data during tests are listed in **Table 4. 1**. For the tests of Mar 3, 2006 and Mar 24, 2006, the operating pressures were 35 psi. One test block was employed; in the other tests, the pressures were 58 psi, and two blocks with the same area, north block and south block, were used at the site where the samplers were installed. The applied water, nitrogen, and salt during UCC tests will be counted into the respective mass balance. The irrigation rates (Appendix A) were determined to calculate the applied water amount during UCC tests for the three mass balances and to calculate the length of the irrigating time for each irrigation event.

The individual UCC test results ranged from 31% to 56% in spring, 49% to 66% in summer, 52% to 75% in fall, and 37% to 51% in winter. The annual UCC is 83% and 84% if the first three tests are not considered because the operational pressure was 35 psi, much lower than the designed operation pressure of 65 psi. The annual UCC is determined by Equation 3.6, n is still equal to 100, and it is the number of sub-square. In order to determine the annual UCC, each block of the test data were summed to obtain a total application within a given test block. And first make the sum (X_i) of collected water volume in the same sub-square for the different test in the test year, then calculate the mean of all 100 sums, finally substitute them to Equation 3.6 to get the annual UCC. The annual UCC represents the cumulative effect or average effect of applied wastewater onto the land surface in the test year. Wind speed significantly impacts UCC test in the field. The recorded wind speed range is from 5.7 MPH in fall corresponding to highest seasonal UCC to 23.7 MPH in winter with lowest seasonal UCC. In some cases, UCC test had to be conducted with the conditions of wind speed exceeding 8 MPH, which is the upper limit in a standard UCC test. However, the resulting UCC under the field conditions was more representative of the real uniformity distribution so that the spatial distribution of leached water, nitrogen, and salts can be explained by the field data. Additionally, wind direction is another factor that significantly influences the water distribution pattern at the research site. The low UCC data partly demonstrates the fact that the leaching may have a high variability in the field, especially at this site, which is located in an area where the wind frequently blows.

UCC represents the distribution uniformity of an irrigation system. A low UCC leads to reduced yield because of the potential for soil moisture stress or water logging, and the resulting deep percolation (Ascough and Kiker 2002). Unexpected deep percolation water may transport more nitrogen down to groundwater. On the other hand, salt accumulation in the soil is another concern, which increases the difficulty of plants to extract soil moisture. In addition, runoff often occurs when the UCC is low. This may have the potential environmental impacts by contaminating nearby surface water. Therefore, it was recommended that the system be designed to achieve a uniformity coefficient of 80% or greater under ideal conditions (Fedler and Borrelli 2001). The UCC of a sprinkler system is the function of the pressure at the sprinkler, the variation in pressure in the operating set, the sprinkler spacing, the nozzle diameter influencing discharge and wetted diameter, the water distribution pattern, and the wind speed and direction (Ascough and Kiker 2002).

Table 4. 1 UCC values and climate data during tests

		Testing Time	Average wind speed	Average air temperature	UCC
Mar 3, 2006	Test 1	30 min	9.2 MPH	57 F	31%
Mar 24, 2006	Test 1	40 min	11.8 MPH	59 F	56%
	Test 2	43 min	7.5 MPH	59 F	56%
Jun 20, 2006	Test 1-South Block	60 min*	9.4 MPH	73 F	59%
	Test 1-North Block	60 min*	9.4 MPH	73 F	49%
	Test 2-South Block	90 min*	10.6 MPH	88.5 F	66%
	Test 2-North Block	90 min*	10.6 MPH	88.5 F	57%
Oct 10, 2006	Test 1-South Block	80 min*	8.8 MPH	69.8 F	66%
	Test 1-North Block	80 min*	8.8 MPH	69.8 F	75%
Oct 12, 2006	Test 1-South Block	50 min*	5.7 MPH	62.8 F	61%
	Test 1-North Block	50 min*	5.7 MPH	62.8 F	52%
	Test 2-South Block	60 min*	5.8 MPH	57.6 F	68%
	Test 2-North Block	60 min*	5.8 MPH	57.6 F	66%
Feb 23, 2007	Test 1-South Block	40 min*	23.7 MPH	77.2 F	37%
	Test 1-North Block	40 min*	23.7 MPH	77.2 F	40%
	Test 2-South Block	40 min*	19.5 MPH	77.5 F	41%
	Test 2-North Block	40 min*	19.5 MPH	77.5 F	51%
Annual UCC is 83%; Annual UCC is 84% if the first three tests are not considered					

4.1.2 Spatial and temporal distribution of leach water

The leach water is collected at the end of the sampling period, the volume (mL) of leach water; average leach water volume (mL) and standard deviation (mL) for all available samplers are shown in **Table 4. 1**2. Samplers 6, 7, and 14 were removed for internal soil lab analysis, right after water sample collection on June 16, 2006. Another three samplers, 3, 9, and 12 were removed from the Littlefield site for soil analysis on June 28, 2007 after water sample collection on the same day. Therefore, there were 13 samplers during the period from June 16, 2006 to June 28, 2007, and 10 samplers available after June 28, 2007.

The spatial distributions of leach water volume are listed in **Figure B.1 to Figure B.21** in Appendix B. The temporal distribution of leach water in each sampler is shown in **Figure C.1 to Figure C.16** in Appendix C. The average leach volume during each sampling period with standard error is illustrated in **Figure 4. 1**.

The leached water was available in each sampling period with the average volume of 23 mL to 1722 mL per sampler (Table 4.2); the coefficient of variation (C. V.) is from 28 % to 217%. It can be concluded that the variability of the collected leached water was relatively large in each sampling period. Such high variability might be caused by lower operation pressure of 58 psi or even 35 psi than the design pressure of 65 psi. The sprinkler system was laid out in the form of sprinkler head overlap in order to increase the distribution uniformity coefficient, however, the sprinkler pattern of such arrangement doesn't ensure that the accepted water are absolutely even over the wetted diameter. Once the designed pressure is not guaranteed during the irrigation event, the individual UCC decreases, then large variability of distributed water and subsequent leached water occurs. In addition, frequent wind, varying wind speed, and unstable wind direction are another reason to cause high variability for this specific site.

The pattern of deep percolation passing through the root zone was quite different from one sampling period to another (**Figure 4. 1**). The range of leaching amounts is from 0.03 inches to 2.10 inches. The leaching amount in each sampling period reflects the time effect. Because the days of each sampling period are not the same, from 20 to 55 days, therefore, the higher amounts in some sampling periods might be caused by relative more water input due to longer periods.

Table 4. 2 Collected leach water volume (mL) in each sampler at sampling date

Sampling Date	Sampler Number																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	**Mean**	**SD**
10/7/2005	223	220	350	305	332	410	701	887	810	379	54	698	326	689	605	300	456	242
11/28/2005	120	224	262	1063	650	1099	1490	1117	800	222	0	1326	693	927	440	545	686	455
12/29/2005	0	0	0	0	0	20	84	86	0	0	0	172	0	0	0	0	23	49
2/10/2006	1322	1758	1838	1750	1300	1602	1658	938	1584	0	0	1950	850	2590	1714	1902	1422	688
4/6/2006	905	825	1415	1510	1155	1430	1120	1631	2179	2047	1622	1110	1230	2148	1350	1539	1451	409
5/25/2006	410	235	495	360	222	485	170	347	0	0	0	1780	0	725	1123	0	397	481
6/16/2006	404	390	590	760	450	850	780	540	0	214	132	1422	220	860	860	0	530	382
7/21/2006	530	345	740	900	340			655	118	600	0	1104	580		549	272	518	305
9/1/2006	340	290	620	670	40			1350	270	1680	0	1234	300		530	670	615	515
9/22/2006	660	480	645	960	900			1400	1090	1590	1490	1540	740		890	990	1029	370
10/12/2006	1610	0	550	1540	0			2206	0	170	0	680	370		2790	440	797	935
11/22/2006	150	50	310	350	46			870	0	320	59	330	25		350	1170	310	349
1/9/2007	995	1435	1395	1455	0			1545	0	640	0	335	1435		1480	1335	927	638
2/23/2007	1161	1032	620	1146	760			1470	630	1470	820	67	1050		1100	1470	984	404
3/30/2007	1440	1550	1582	1780	1250			2050	2090	2550	2130	520	1685		2225	1532	1722	515
4/25/2007	670	980	805	1290	770			1450	185	590	855	50	490		1470	700	793	433
5/29/2007	1435	1500	1640	1670	730			1790	1820	2470	2110	440	1645		1760	1555	1582	522
6/28/2007	1360	870	1490	1520	1500			1480	1390	2345	1750	235	1550		1500	1480	1421	477
7/31/2007	450	870		675	235			1000		0	0		0		660	700	459	378
8/31/2007	1575	0		340	0			1950		0	0		0		840	570	528	719
9/28/2007	925	300		720	340			1420		1600	265		340		1420	470	780	527

Notes: SD means standard deviation.

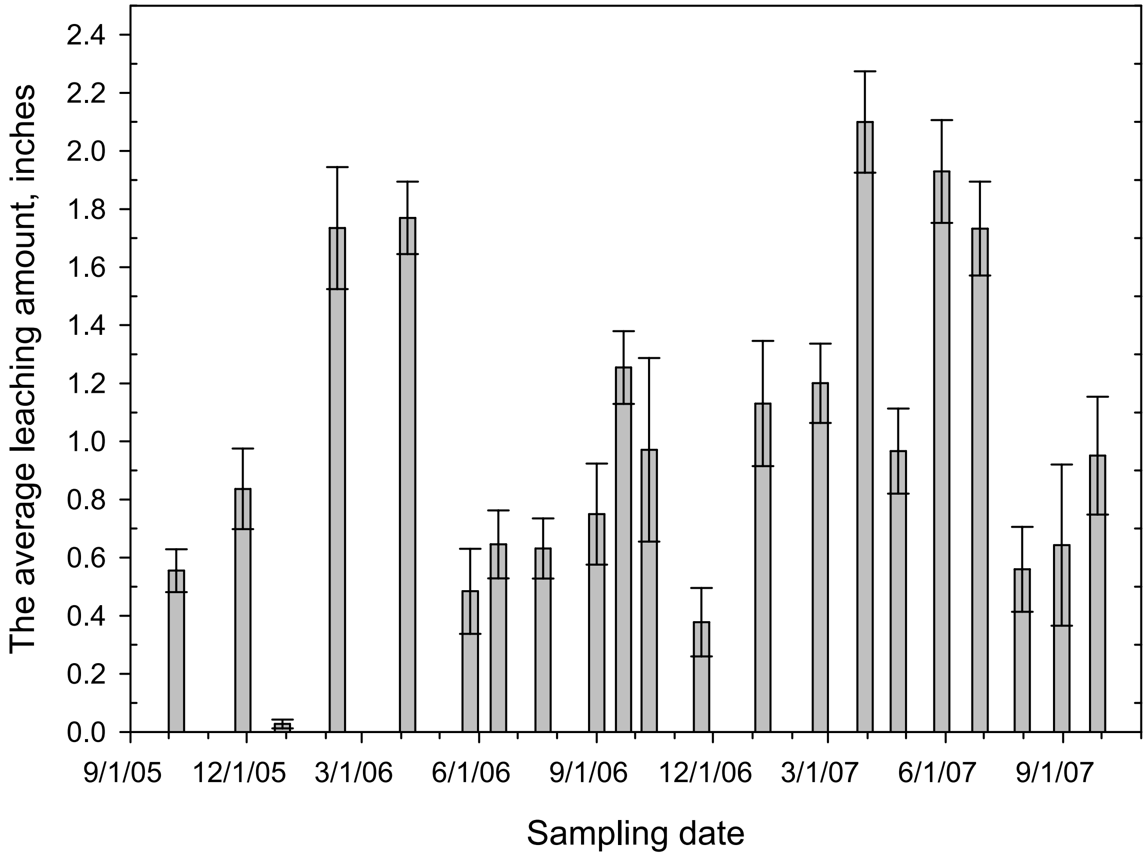

Figure 4. 1 The average leaching amount of each sampling period from Oct 2005 to Sept 2007 at the Littlefield site. The error bars represent ± one standard error.

4.1.3 Calculation of water mass balance

Soil saturation, field capacity, and wilting point of the soil at Littlefield site are determined from the results of soil analysis executed by the lab of the Department of Plant and Soil Science, Texas Tech University. The soil saturation, field capacity, and permanent wilting point are 0.491, 0.301, and 0.194 cubic inch water per cubic inch soil, respectively. The soil moistures in a sampler corresponding to soil saturation, field capacity, and wilting point can be calculated as below (the designed depth of the root zone is 12 inches).

The soil moisture at saturation in the sampler is:

$$0.491\frac{inch^3\text{ water}}{inch^3\text{ soil}}\times 12\,\text{inches} = 5.892\,\text{inches}$$

The soil moisture at field capacity in the sampler is:

$$0.301\frac{inch^3\text{ water}}{inch^3\text{ soil}}\times 12\,\text{inches} = 3.612\,\text{inches}$$

The soil moisture at wilting point in the sampler is:

$$0.194\frac{inch^3\text{ water}}{inch^3\text{ soil}}\times 12\,\text{inches} = 2.328\,\text{inches}$$

One inch of water in the sampler is equivalent to 820 mL in this research. The precipitation data used in this dissertation is from the site of the National Climatic Data Center. The water balance calculation is illustrated in **Table 4. 3**.

Table 4. 3 The calculation of water balance for the Littlefield site

1	2	3	4	5	6	7
Period	Soil moisture	PPT	Irrigation	ET	Average leaching	Runoff, other unknown losses
10/7/2005	4.752					
10/07/2005-11/28/2005		1.12	9.360	5.170	0.837	3.333
11/28/2005	5.892					
11/28/2005-12/29/2005		0.13	5.580	2.039	0.028	3.643
12/29/2005	5.892					
12/29/2005-2/10/2006		0.05	7.740	2.955	1.734	3.101
2/10/2006	5.892					
2/10/2006-4/6/2006		2.27	10.840	6.286	1.770	5.055
4/6/2006	5.892					
4/6/2006-5/25/2006		1.63	8.820	8.388	0.484	1.577
5/25/2006	5.892					
5/25/2006-6/16/2006		1.55	2.414	4.356	0.646	0.000
6/16/2006	4.854					
6/16/2006-7/21/2006		5.18	5.492	7.159	0.632	2.881
7/21/2006	5.892					
7/21/2006-9/1/2006		5.42	5.370	7.913	0.750	2.127
9/1/2006	5.892					
9/1/2006-9/22/2006		4.21	2.020	3.303	1.255	1.672
9/22/2006	5.892					
9/22/2006-10/12/2006		0.53	2.692	2.610	1.194	0.000
10/12/2006	5.310					
10/12/2006-11/22/2006		1.43	2.954	4.079	0.378	0.000
11/22/2006	5.237					
11/22/2006-1/9/2007		10.53	2.912	3.250	1.130	9.062
1/9/2007	5.892					
1/9/2007-2/23/2007		10.04	3.505	3.333	1.200	9.012

Continued

1 Period	2 Soil moisture	3 PPT	4 Irrigation	5 ET	6 Average leaching	7 Runoff, other unknown losses
2/23/2007	5.892					
2/23/2007-3/30/2007		4.59	3.641	4.090	2.100	2.041
3/30/2007	5.892					
3/30/2007-4/25/2007		1.2	3.434	4.123	0.967	0.000
4/25/2007	5.435					
4/25/2007-5/29/2007		4.56	4.243	6.076	1.929	0.798
5/29/2007	5.892					
5/29/2007-6/28/2007		4.81	3.176	6.076	1.733	0.177
6/28/2007	5.892					
6/28/2007-7/31/2007		0.72	4.929	6.760	0.560	0.000
7/31/2007	4.221					
7/31/2007-8/31/2007		0.59	3.847	5.864	0.644	0.000
8/31/2007	2.328					
8/31/2007-9/28/2007		2.61	2.570	4.204	0.951	0.000
9/28/2007	2.353					

Notes:

1. All values in Column 2-7 are in inches;
2. Start point of soil moisture is set as the average of the soil saturation and the field capacity;
3. If the soil moisture of the end of a sampling period is larger than the soil saturation, which is calculated by summing up the soil moisture at the starting point of a sampling period, PPT (precipitation), and irrigation, then subtracting ET and average leaching, the soil moisture at the end of a sampling period is set as saturation. Finally, Column 7 is equal to the result of Column 2 + Column 3 + Column 4 - Column 5 - Column 6 –Saturation; otherwise, Column 7 is equal to zero;
4. If the soil moisture at the end of a sampling period falls into the range between saturation and wilting point, then this value is kept. If it is smaller than wilting point, then it is set as wilting point.

4.2 Nitrogen Balance

The spatial and temporal distribution of leached nitrogen is illustrated in this section. Nitrogen mass balance is carried out in the term of total nitrogen. And the volume weighted average concentrations of total nitrogen, nitrate-nitrogen, and ammonia-nitrogen are summarized in this section.

4.2.1 Spatial and temporal distribution of leached nitrogen

The total nitrogen concentration in leached water of each sampler, the volume of leach water, total and average leached mass of total nitrogen, volume weighted average total nitrogen concentration in each sampling period, and total nitrogen concentration and mass in the applied wastewater are listed in **Table 4. 4**. The spatial distribution of total nitrogen mass leached is shown in **Figure D.1** to **Figure D.21** in Appendix D.

The temporal distribution of weighted average total nitrogen concentration in the leach water is shown in **Figure 4. 2**. The weighted average total nitrogen concentration can be determined by the following Equation 4.1.

$$\overline{\mathrm{C}}_{weighted} = \frac{\sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{C_i} V_i}{\sum_{i=1}^{n} V_i} \qquad (4.1)$$

where, $\overline{\mathrm{C}}_{weighted}$ is the volume weighted average total nitrogen concentration in the leached water, mg/L;

C_i is the concentration of total nitrogen in the i-th sampler, mg/L;

V_i is the volume of the leach water in the i-th sampler, L.

Also, the temporal distribution of average total nitrogen mass with one standard error per hectare is shown in **Figure 4. 3**. The average total nitrogen concentration in the secondary wastewater was from 5 mg/L to 19 mg/L. The total nitrogen concentration was higher in summer and fall than in winter and spring due to the effect of temperature on the treatment in the pond system. The volume weighted average concentration of total nitrogen in the leached water ranged from 0 mg/L to 5.12 mg/L. There occurred two peaks of total nitrogen in the leached water during the project, 4.97 mg/L in the period from Feb 10, 2006 to Apr 6, 2006, and 5.12 mg/L in the period from Nov 22, 2006 to Jan 9, 2007. Similarly, the peaks of the average leached mass occurred in winter and spring (**Figure 4. 3**). In winter and spring, the combined effect of nitrogen loss becomes weak with the decrease of plant nitrogen uptake rate and denitrification rate due to the low temperature, additionally, the total nitrogen concentration in winter and spring is relatively higher than in summer and fall, as a result, and the total nitrogen concentration goes up in winter and spring.

Table 4. 4 The list of total nitrogen in the leached water and in wastewater at the Littlefield site

Sampling Date		Sampler Number																		
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Total	Average	**W/W**
10/7/2005	Concentration, mg/L	0	0	2	1	0	0	1	1	0	0	0	0	0	0	0	0		0.356	7.5
	Volume, mL	223	220	350	305	332	410	701	887	810	379	54	698	326	689	605	300	7289		
	Mass, mg	0	0	0.7	0.305	0	0	0.701	0.887	0	0	0	0	0	0	0	0	2.593	0.162	
11/28/2005	Concentration, mg/L	0	0	0	0	0	0	0	0	0	0	n/a	0	0	0	0	0		0.000	12
	Volume, mL	120	224	262	1063	650	1099	1490	1117	800	222	0	1326	693	927	440	545	10978		7675.2
	Mass, mg	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0.000	92.102
12/29/2005	Concentration, mg/L	n/a	n/a	n/a	n/a	n/a	2	1	2	n/a	n/a	n/a	3	n/a	n/a	n/a	n/a		2.243	16
	Volume, mL	0	0	0	0	0	20	84	86	0	0	0	172	0	0	0	0	362		4575.6
	Mass, mg						0.04	0.084	0.172				0.516					0.812	0.051	73.210
2/10/2006	Concentration, mg/L	1	1	2	1	0	1	3	4	10	n/a	n/a	4	5	10	6	2		3.811	16.5
	Volume, mL	1322	1758	1838	1750	1300	1602	1658	938	1584	0	0	1950	850	2590	1714	1902	22756		6346.8
	Mass, mg	1.322	1.758	3.676	1.75	0	1.602	4.974	3.752	15.84			7.8	4.25	25.9	10.284	3.804	86.71	5.420	104.722
4/6/2006	Concentration, mg/L	18	0	0	0	0	0	0	10	14	*130	0	9	0	14	9	0		4.967	19
	Volume, mL	905	825	1415	1510	1155	1430	1120	1631	2179	2047	1622	1110	1230	2148	1350	1539	23216		8888.8
	Mass, mg	16.29	0	0	0	0	0	0	16.31	30.51		0	9.99	0	30.072	12.15	0	115.3	7.207	168.887
5/25/2006	Concentration, mg/L	2	1	0	0	0	0	1	0	n/a	n/a	n/a	0	n/a	1	0	n/a		0.307	18
	Volume, mL	410	235	495	360	222	485	170	347	0	0	0	1780	0	725	1123	0	6352		7232.4
	Mass, mg	0.82	0.235	0	0	0	0	0.17	0				0		0.725	0		1.95	0.122	130.183
6/16/2006	Concentration, mg/L	0	1	3	1	1	2	2	2	n/a	4	4	2	5	2	2	n/a		1.945	15
	Volume, mL	404	390	590	760	450	850	780	540	0	214	132	1422	220	860	860	0	8472		1979.48
	Mass, mg	0	0.39	1.77	0.76	0.45	1.7	1.56	1.08		0.856	0.528	2.844	1.1	1.72	1.72		16.48	1.030	29.692

Continued

Sampling Date		Sampler Number															
		1	2	3	4	5	8	9	10	11	12	13	15	16	Total	Average	**W/W**
7/21/2006	Concentration, mg/L	2	1	2	2	2	3	3	2	n/a	2	2	2	2		2.064	8.5
	Volume, mL	530	345	740	900	340	655	118	600	0	1104	580	549	272	6733		4503.4
	Mass, mg	1.06	0.345	1.48	1.8	0.68	1.965	0.354	1.2		2.208	1.16	1.098	0.544	13.894	1.069	38.279
9/1/2006	Concentration, mg/L	1	1	1	1	2	2	3	4	n/a	1	2	1	2		1.993	7
	Volume, mL	340	290	620	670	40	1350	270	1680	0	1234	300	530	670	7994		4403.4
	Mass, mg	0.34	0.29	0.62	0.67	0.08	2.7	0.81	6.72		1.234	0.6	0.53	1.34	15.934	1.226	30.824
9/22/2006	Concentration, mg/L	0	0	0	0	0	1	1	2	1	0	1	1	1		0.731	6
	Volume, mL	660	480	645	960	900	1400	1090	1590	1490	1540	740	890	990	13375		1656.4
	Mass, mg	0	0	0	0	0	1.4	1.09	3.18	1.49	0	0.74	0.89	0.99	9.78	0.752	9.938
10/12/2006	Concentration, mg/L	3	n/a	3	4	n/a	2	n/a	2	n/a	2	2	3	2		2.775	5
	Volume, mL	1610	0	550	1540	0	2206	0	170	0	680	370	2790	440	10356		2207.4
	Mass, mg	4.83		1.65	6.16		4.412		0.34		1.36	0.74	8.37	0.88	28.742	2.211	11.037
11/22/2006	Concentration, mg/L	0	2	0	0	1	0	N/A	0	10	0	50	0	0		0.493	12
	Volume, mL	150	50	310	350	46	870	0	320	59	330	25	350	1170	4030		2422.3
	Mass, mg	0	0.1	0	0	0.046	0		0	0.59	0	1.25	0	0	1.986	0.153	29.067
1/9/2007	Concentration, mg/L	2	16	3	3	N/A	4	N/A	3	N/A	2	3	3	8		5.120	16
	Volume, mL	995	1435	1395	1455	0	1545	0	640	0	335	1435	1480	1335	12050		2387.8
	Mass, mg	1.99	22.96	4.185	4.365		6.18		1.92		0.67	4.305	4.44	10.68	61.695	4.746	38.205
2/23/2007	Concentration, mg/L	0	2	2	2	0	0	2	2	2	2	0	0	8		1.823	10
	Volume, mL	1161	1032	620	1146	760	1470	630	1470	820	67	1050	1100	1470	12796		2874.1
	Mass, mg	0	2.064	1.24	2.292	0	0	1.26	2.94	1.64	0.134	0	0	11.76	23.33	1.795	28.741
3/30/2007	Concentration, mg/L	2	2	4	2	2	3	5	4	2	1	4	3	4		3.104	17
	Volume, mL	1440	1550	1582	1780	1250	2050	2090	2550	2130	520	1685	2225	1532	22384		2985.6
	Mass, mg	2.88	3.1	6.328	3.56	2.5	6.15	10.45	10.2	4.26	0.52	6.74	6.675	6.128	69.491	5.345	50.756
4/25/2007	Concentration, mg/L	0	0	0	0	0	0	2	2	0	17	1	0	0		0.280	17
	Volume, mL	670	980	805	1290	770	1450	185	590	855	50	490	1470	700	10305		2815.9
	Mass, mg	0	0	0	0	0	0	0.37	1.18	0	0.85	0.49	0	0	2.89	0.222	47.870
5/29/2007	Concentration, mg/L	1	1	1	1	1	1	3	3	1	2	1	2	2		1.600	12.5
	Volume, mL	1435	1500	1640	1670	730	1790	1820	2470	2110	440	1645	1760	1555	20565		3479.3
	Mass, mg	1.435	1.5	1.64	1.67	0.73	1.79	5.46	7.41	2.11	0.88	1.645	3.52	3.11	32.9	2.531	43.491
6/28/2007	Concentration, mg/L	2	1	2	2	1	1	3	2	2	2	2	2	2		1.867	8
	Volume, mL	1360	870	1490	1520	1500	1480	1390	2345	1750	235	1550	1500	1480	18470		2604.3
	Mass, mg	2.72	0.87	2.98	3.04	1.5	1.48	4.17	4.69	3.5	0.47	3.1	3	2.96	34.48	2.652	20.835

Continued

Sampling Date		Sampler Number												
		1	2	4	5	8	10	11	13	15	16	Total	Average	**W/W**
7/31/2007	Concentration, mg/L	2	1	1	1	2	n/a	n/a	n/a	2	2		1.612	6
	Volume, mL	450	870	675	235	1000	0	0	0	660	700	4590		4041.78
	Mass, mg	0.9	0.87	0.675	0.235	2	▨	▨	▨	1.32	1.4	7.4	0.74	24.251
8/31/2007	Concentration, mg/L	1	n/a	0	n/a	2	n/a	n/a	n/a	10	8		3.495	5
	Volume, mL	1575	0	340	0	1950	0	0	0	840	570	5275		3154.54
	Mass, mg	1.575	▨	0	▨	3.9	▨	▨	▨	8.4	4.56	18.44	1.8435	15.773
9/28/2007	Concentration, mg/L	4	1	1	3	3	4	2	3	4	4		3.271	7.5
	Volume, mL	925	300	720	340	1420	1600	265	340	1420	470	7800		2107.4
	Mass, mg	3.7	0.3	0.72	1.02	4.26	6.4	0.53	1.02	5.68	1.88	25.51	2.551	15.806

Notes:

1. Gray denotes that leach water is not available for calculation of total nitrogen mass;

2. Black denotes that the total nitrogen concentration is an outlier, and abnormal, and the value is not shown;

3. W/W denotes applied wastewater.

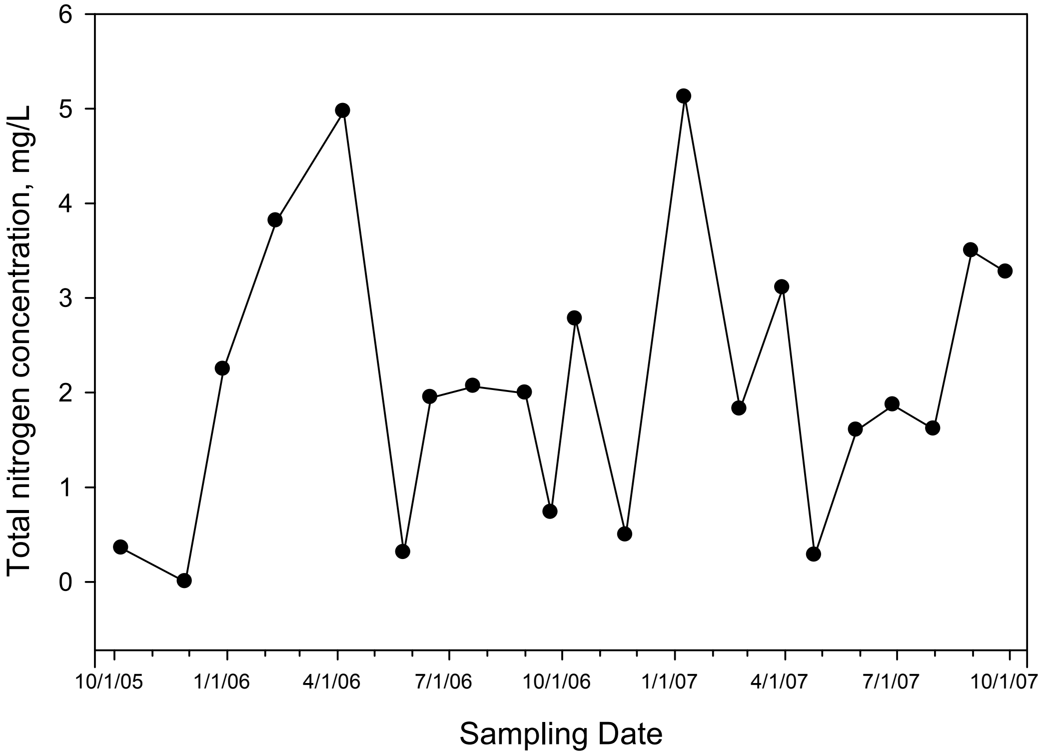

Figure 4. 2 The temporal distribution of volume weighted average total nitrogen concentration in leach water at the Littlefield site

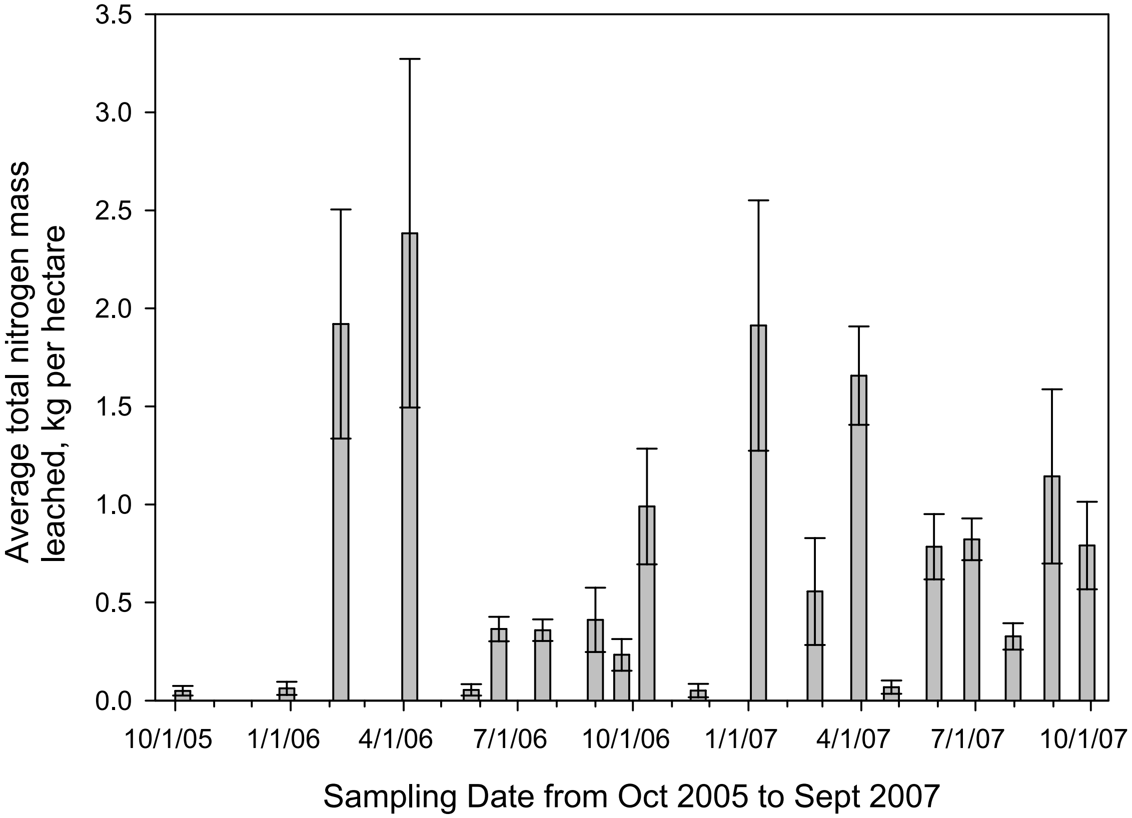

Figure 4. 3 Average total nitrogen mass leached in each sampling period at the Littlefield site. The symbol presents means of repeated measurements, and the error bars present standard errors.

4.2.2 Calculation of nitrogen mass balance

Nitrogen mass balance based on one sampler during each sampling period is calculated based on the Equation 3.3 in Chapter III; the calculation results are listed in **Table 4. 5**.

At this site, although grass is mowed monthly, total nitrogen is not removed by grass mowing, because the mowed grass remains on the surface of the ground, this part of the total nitrogen in the soil-water-plant system doesn't exit from the system as defined in Chapter III when three conceptual mass balances were discussed. Therefore, the nitrogen loss by plant uptake is not considered in nitrogen mass balance in the land application system if the mowed grass is not taken away. However, in reality, the nitrogen loss by plant uptake influences the total nitrogen concentration in the leached water. The fate of nitrogen from mowed grass, which still remains in the land application system, is complicated, and not included in this research.

Table 4. 5 Total nitrogen mass balance at the Littlefield site

Sampling period	Applied TN, mg per sampler	Leached TN, mg per sampler	Nitrogen stored or lost*, mg per sampler
10/07/2005-11/28/2005	92.102	0.000	92.102
11/28/2005-12/29/2005	73.210	0.051	73.159
12/29/2005-2/10/2006	104.722	5.420	99.303
2/10/2006-4/6/2006	168.887	7.207	161.680
4/6/2006-5/25/2006	130.183	0.122	130.061
5/25/2006-6/16/2006	29.692	1.030	28.662
6/16/2006-7/21/2006	38.279	1.069	37.210
7/21/2006-9/1/2006	30.824	1.226	29.598
9/1/2006-9/22/2006	9.938	0.752	9.186
9/22/2006-10/12/2006	11.037	2.211	8.826
10/12/2006-11/22/2006	29.067	0.153	28.915
11/22/2006-1/9/2007	38.205	4.746	33.460
1/9/2007-2/23/2007	28.741	1.795	26.946
2/23/2007-3/30/2007	50.756	5.345	45.410
3/30/2007-4/25/2007	47.870	0.222	47.648
4/25/2007-5/29/2007	43.491	2.531	40.960
5/29/2007-6/28/2007	20.835	2.652	18.182
6/28/2007-7/31/2007	24.251	0.740	23.511
7/31/2007-8/31/2007	15.773	1.844	13.929
8/31/2007-9/28/2007	15.806	2.551	13.255

*defines the N stored or lost here

4.2.3 Nitrate-nitrogen and ammonia-nitrogen

Although average total nitrogen concentration in the leached water was low, less than 5 mg/L, it is useful to summarize the results of nitrate-nitrogen and ammonia-nitrogen in the leached water. The concentration in leached water in each sampler, the volume of leached water, total and average leached mass, volume weighted average concentration in each sampling period, and concentration and mass per sampler in the applied wastewater are listed for nitrate-nitrogen and ammonia-nitrogen in **Table 4. 6** and **Table 4. 7**, respectively.

The range of volume weighted average nitrate-nitrogen in the leached water is 0 mg/L to 3.292 mg/L, and the average nitrate-nitrogen in the wastewater is 2.4 mg/L to 8.2 mg/L. The range of volume weighted average ammonia-nitrogen in the leached water is 0 mg/L to 0.327 mg/L, and the average nitrate-nitrogen in the wastewater is 0.01 mg/L to 6.4 mg/L. It can be concluded that both types of nitrogen have low concentration in the leached water, especially for ammonia-nitrogen, which is minor.

Table 4. 6 The list of nitrate-nitrogen in the leached water and in wastewater at the Littlefield site

Sampling Date		Sampler Number																		
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Total	Average	**W/W**
10/7/2005	Concentration,	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a		n/a	7.35
	Volume, mL	223	220	350	305	332	410	701	887	810	379	54	698	326	689	605	300	7289		
	Mass, mg	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	
11/28/2005	Concentration,	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a		n/a	5.75
	Volume, mL	120	224	262	1063	650	1099	1490	1117	800	222	0	1326	693	927	440	545	10978		7675.2
	Mass, mg	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.000	44.132
12/29/2005	Concentration,	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a		n/a	3.35
	Volume, mL	0	0	0	0	0	20	84	86	0	0	0	172	0	0	0	0	362		4575.6
	Mass, mg						n/a	n/a	n/a				n/a					n/a	0.000	15.328
2/10/2006	Concentration,	0	0	0	0	0	0	0	0	9.6	n/a	n/a	0	4.1	9.1	5.1	0		2.241	3.4
	Volume, mL	1322	1758	1838	1750	1300	1602	1658	938	1584	0	0	1950	850	2590	1714	1902	22756		6346.8
	Mass, mg	0	0	0	0	0	0	0	0	15.2064			0	3.485	23.569	8.7414	0	51.0018	3.188	21.579
4/6/2006	Concentration,	2.5	0	0	0	0	0	0	8.4	10.3	*131	0	6.5	0	10	6.9	0		3.292	2.4
	Volume, mL	905	825	1415	1510	1155	1430	1120	1631	2179	2047	1622	1110	1230	2148	1350	1539	23216		8888.8
	Mass, mg	2.2625	0	0	0	0	0	0	13.7004	22.4437	[redacted]	0	7.215	0	21.48	9.315	0	76.4166	4.776	21.333
5/25/2006	Concentration,	0	0	0	0	0	0	0	0	n/a	n/a	n/a	0	n/a	0	0	n/a		0.000	2.7
	Volume, mL	410	235	495	360	222	485	170	347	0	0	0	1780	0	725	1123	0	6352		7232.4
	Mass, mg	0	0	0	0	0	0	0	0				0		0	0		0	0.000	19.527
6/16/2006	Concentration,	0	0.2	0.9	0	0	0.4	0.8	0.1	n/a	0.7	1	0.2	2.1	0.3	0	n/a		0.344	5
	Volume, mL	404	390	590	760	450	850	780	540	0	214	132	1422	220	860	860	0	8472		1979.48
	Mass, mg	0	0.078	0.531	0	0	0.34	0.624	0.054		0.1498	0.132	0.2844	0.462	0.258	0		2.9132	0.182	9.897

Continued

		Sampler Number															
Sampling Date		1	2	3	4	5	8	9	10	11	12	13	15	16	Total	Average	**W/W**
7/21/2006	Concentration,	0.3	0.7	0	0.4	0	0.4	1.5	0.4	n/a	0	0	0	0.6		0.238	5
	Volume, mL	530	345	740	900	340	655	118	600	0	1104	580	549	272	6733		4503.44
	Mass, mg	0.159	0.2415	0	0.36	0	0.262	0.177	0.24		0	0	0	0.1632	1.6027	0.123	22.517
9/1/2006	Concentration,	0.5	0.6	0.5	0.8	0.4	1	1.8	2.1	n/a	0.5	1.4	0.6	1		1.075	5.2
	Volume, mL	340	290	620	670	40	1350	270	1680	0	1234	300	530	670	7994		4403.4
	Mass, mg	0.17	0.174	0.31	0.536	0.016	1.35	0.486	3.528		0.617	0.42	0.318	0.67	8.595	0.661	22.898
9/22/2006	Concentration,	0	0	0	0	0	0.8	0.8	1.4	0.7	0	0.6	0.8	0.8		0.539	3.9
	Volume, mL	660	480	645	960	900	1400	1090	1590	1490	1540	740	890	990	13375		1656.4
	Mass, mg	0	0	0	0	0	1.12	0.872	2.226	1.043	0	0.444	0.712	0.792	7.209	0.555	6.460
10/12/2006	Concentration,	2.3	n/a	2.2	2.6	n/a	1.7	n/a	0.4	n/a	0.6	1.5	2.5	1.4		2.056	4.15
	Volume, mL	1610	0	550	1540	0	2206	0	170	0	680	370	2790	440	10356		2207.44
	Mass, mg	3.703		1.21	4.004		3.7502		0.068		0.408	0.555	6.975	0.616	21.2892	1.638	9.161
11/22/2006	Concentration,	0	0.5	0	0	0.2	0	n/a	0	0.9	0	1.4	0	0		0.030	4.7
	Volume, mL	150	50	310	350	46	870	0	320	59	330	25	350	1170	4030		2422.28
	Mass, mg	0	0.025	0	0	0.0092	0		0	0.0531	0	0.035	0	0	0.1223	0.009	11.385
1/9/2007	Concentration,	0.4	3.9	1	0.6	n/a	1	n/a	0.3	n/a	0	0.7	0.9	3.8		1.445	4.1
	Volume, mL	995	1435	1395	1455	0	1545	0	640	0	335	1435	1480	1335	12050		2387.84
	Mass, mg	0.398	5.5965	1.395	0.873		1.545		0.192		0	1.0045	1.332	5.073	17.409	1.339	9.790
2/23/2007	Concentration,	0	1.3	1.5	1.3	0	0	1.1	1.3	1.1	1.6	0	0	7.9		1.484	5.75
	Volume, mL	1161	1032	620	1146	760	1470	630	1470	820	67	1050	1100	1470	12796		2874.1
	Mass, mg	0	1.3416	0.93	1.4898	0	0	0.693	1.911	0.902	0.1072	0	0	11.613	18.9876	1.461	16.526
3/30/2007	Concentration,	1.2	0.4	3	1.2	0.3	0.6	1.8	2.5	0.8	0.4	1	1.8	1.2		1.359	4.25
	Volume, mL	1440	1550	1582	1780	1250	2050	2090	2550	2130	520	1685	2225	1532	22384		2985.62
	Mass, mg	1.728	0.62	4.746	2.136	0.375	1.23	3.762	6.375	1.704	0.208	1.685	4.005	1.8384	30.4124	2.339	12.689
4/25/2007	Concentration,	0	0	0	0	0	0	1.8	1.5	0	1.8	0.6	0	0		0.155	4.7
	Volume, mL	670	980	805	1290	770	1450	185	590	855	50	490	1470	700	10305		2815.88
	Mass, mg	0	0	0	0	0	0	0.333	0.885	0	0.09	0.294	0	0	1.602	0.123	13.235
5/29/2007	Concentration,	1	0.8	0.9	0.9	0.4	0.6	1.8	1.7	0.7	1.6	0.9	1.7	1.3		1.125	8.2
	Volume, mL	1435	1500	1640	1670	730	1790	1820	2470	2110	440	1645	1760	1555	20565		3479.26
	Mass, mg	1.435	1.2	1.476	1.503	0.292	1.074	3.276	4.199	1.477	0.704	1.4805	2.992	2.0215	23.13	1.779	28.530
6/28/2007	Concentration,	1.3	0.4	1.7	0.9	0.2	0.6	2.9	1.1	0.6	0.5	1.2	1.3	0.8		1.082	5.1
	Volume, mL	1360	870	1490	1520	1500	1480	1390	2345	1750	235	1550	1500	1480	18470		2604.32
	Mass, mg	1.768	0.348	2.533	1.368	0.3	0.888	4.031	2.5795	1.05	0.1175	1.86	1.95	1.184	19.977	1.537	13.282

Continued

Sampling Date		Sampler Number												
		1	2	4	5	8	10	11	13	15	16	Total	Average	**W/W**
7/31/2007	Concentration,	1.3	0.3	0.7	0.6	1.7	n/a	n/a	n/a	1.5	1.5		1.133	4.7
	Volume, mL	450	870	675	235	1000	0	0	0	660	700	4590		4041.78
	Mass, mg	0.585	0.261	0.4725	0.141	1.7	▨	▨	▨	0.99	1.05	5.1995	0.51995	18.996
8/31/2007	Concentration,	0.4	n/a	0	n/a	1.2	n/a	n/a	n/a	5.5	3.1		1.774	3.15
	Volume, mL	1575	0	340	0	1950	0	0	0	840	570	5275		3154.54
	Mass, mg	0.63	▨	0	▨	2.34	▨	▨	▨	4.62	1.767	9.357	0.9357	9.937
9/28/2007	Concentration,	1.6	0.9	0.9	0.9	1.3	1.6	1.5	1.4	2.3	1.3		1.521	5.75
	Volume, mL	925	300	720	340	1420	1600	265	340	1420	470	7800		2107.4
	Mass, mg	1.48	0.27	0.648	0.306	1.846	2.56	0.3975	0.476	3.266	0.611	11.8605	1.18605	12.118

Notes:

1. Gray denotes that leach water is not available for calculation of total nitrogen mass;

2. Black denotes that the total nitrogen concentration is an outlier, and abnormal, and the value is not shown;

3. W/W denotes applied wastewater;

4. Nitrate-nitrogen analysis was not conducted for the samples before 2006.

Table 4. 7 The list of ammonia-nitrogen in the leached water and in wastewater at the Littlefield site

Sampling Date		Sampler Number																		
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Total	Average	**W/W**
10/7/2005	Concentration,	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a		n/a	0.1
	Volume, mL	223	220	350	305	332	410	701	887	810	379	54	698	326	689	605	300	7289		
	Mass, mg	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	
11/28/2005	Concentration,	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a		n/a	2.9
	Volume, mL	120	224	262	1063	650	1099	1490	1117	800	222	0	1326	693	927	440	545	10978		7675.2
	Mass, mg	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.000	22.258
12/29/2005	Concentration,	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a		n/a	4.5
	Volume, mL	0	0	0	0	0	20	84	86	0	0	0	172	0	0	0	0	362		4575.6
	Mass, mg						n/a	n/a	n/a				n/a					n/a	0.000	20.590
2/10/2006	Concentration,	0	0	0	0	0	0	0	0	0.01	n/a	n/a	0	0.01	0.04	0.11	0		0.014	5.3
	Volume, mL	1322	1758	1838	1750	1300	1602	1658	938	1584	0	0	1950	850	2590	1714	1902	22756		6346.8
	Mass, mg	0	0	0	0	0	0	0	0	0.01584			0	0.0085	0.1036	0.18854	0	0.31648	0.020	33.638
4/6/2006	Concentration,	4.4	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0.2	0		0.188	5.2
	Volume, mL	905	825	1415	1510	1155	1430	1120	1631	2179	2047	1622	1110	1230	2148	1350	1539	23216		8888.8
	Mass, mg	3.982	0	0	0	0	0	0	0	0	0	0	0.111	0	0	0.27	0	4.363	0.273	46.222
5/25/2006	Concentration,	0	0	0	0	0	0	0	0	n/a	n/a	n/a	0	n/a	0	0	n/a		0.000	6.4
	Volume, mL	410	235	495	360	222	485	170	347	0	0	0	1780	0	725	1123	0	6352		7232.4
	Mass, mg	0	0	0	0	0	0	0	0				0		0	0		0	0.000	46.287
6/16/2006	Concentration,	0	0.03	0.44	0.02	0.05	0.03	0.02	0.03	n/a	0.03	0.4	0.09	0.19	0.04	0.08	n/a		0.082	2.8
	Volume, mL	404	390	590	760	450	850	780	540	0	214	132	1422	220	860	860	0	8472		1979.48
	Mass, mg	0	0.0117	0.2596	0.0152	0.0225	0.0255	0.0156	0.0162		0.00642	0.0528	0.12798	0.0418	0.0344	0.0688		0.6985	0.044	5.543

Continued

Sampling Date		Sampler Number															
		1	2	3	4	5	8	9	10	11	12	13	15	16	Total	Average	**W/W**
7/21/2006	Concentration,	0.14	0.02	0.17	0.03	0.03	0.06	0.02	0.05	n/a	0.08	0.07	0.12	0.06		0.078	0.12
	Volume, mL	530	345	740	900	340	655	118	600	0	1104	580	549	272	6733		4503.44
	Mass, mg	0.0742	0.0069	0.1258	0.027	0.0102	0.0393	0.00236	0.03		0.08832	0.0406	0.06588	0.01632	0.52688	0.041	0.540
9/1/2006	Concentration,	0.03	0.01	0.01	0.03	0.03	0.03	0.08	0.17	n/a	0.05	0.04	0.05	0.06		0.066	0.14
	Volume, mL	340	290	620	670	40	1350	270	1680	0	1234	300	530	670	7994		4403.4
	Mass, mg	0.0102	0.0029	0.0062	0.0201	0.0012	0.0405	0.0216	0.2856		0.0617	0.012	0.0265	0.0402	0.5287	0.041	0.616
9/22/2006	Concentration,	0	0	0	0	0	0	0.01	0.01	0	0	0	0.02	0.02		0.005	0.02
	Volume, mL	660	480	645	960	900	1400	1090	1590	1490	1540	740	890	990	13375		1656.4
	Mass, mg	0	0	0	0	0	0	0.0109	0.0159	0	0	0	0.0178	0.0198	0.0644	0.005	0.033
10/12/2006	Concentration,	0.04	n/a	0.07	0.06	n/a	0.02	n/a	0	n/a	0	0.04	0.05	0.02		0.039	0.16
	Volume, mL	1610	0	550	1540	0	2206	0	170	0	680	370	2790	440	10356		2207.44
	Mass, mg	0.0644		0.0385	0.0924		0.04412		0		0	0.0148	0.1395	0.0088	0.40252	0.031	0.353
11/22/2006	Concentration,	0	0.02	0	0	0.1	0	n/a	0	0.54	0	2.6	0	0		0.025	1.8
	Volume, mL	150	50	310	350	46	870	0	320	59	330	25	350	1170	4030		2422.28
	Mass, mg	0	0.001	0	0	0.0046	0		0	0.03186	0	0.065	0	0	0.10246	0.008	4.360
1/9/2007	Concentration,	0.01	2.5	0.02	0	n/a	0.02	n/a	0.02	n/a	0.01	0.02	0.03	0.15		0.327	2.6
	Volume, mL	995	1435	1395	1455	0	1545	0	640	0	335	1435	1480	1335	12050		2387.84
	Mass, mg	0.00995	3.5875	0.0279	0		0.0309		0.0128		0.00335	0.0287	0.0444	0.20025	3.94575	0.304	6.208
2/23/2007	Concentration,	0	0	0	0	0	0	0.01	0	0	0.04	0	0	0.04		0.005	3.5
	Volume, mL	1161	1032	620	1146	760	1470	630	1470	820	67	1050	1100	1470	12796		2874.1
	Mass, mg	0	0	0	0	0	0	0.0063	0	0	0.00268	0	0	0.0588	0.06778	0.005	10.059
3/30/2007	Concentration,	0.02	0.01	0.02	0.02	0.02	0.01	0.03	0.02	0.01	0.02	0.02	0.06	0.06		0.025	4.1
	Volume, mL	1440	1550	1582	1780	1250	2050	2090	2550	2130	520	1685	2225	1532	22384		2985.62
	Mass, mg	0.0288	0.0155	0.03164	0.0356	0.025	0.0205	0.0627	0.051	0.0213	0.0104	0.0337	0.1335	0.09192	0.56156	0.043	12.241
4/25/2007	Concentration,	0	0	0	0	0	0	0.02	0.05	0	0.9	0.03	0	0		0.009	4.7
	Volume, mL	670	980	805	1290	770	1450	185	590	855	50	490	1470	700	10305		2815.88
	Mass, mg	0	0	0	0	0	0	0.0037	0.0295	0	0.045	0.0147	0	0	0.0929	0.007	13.235
5/29/2007	Concentration,	0	0	0	0	0	0	0	0.01	0	0.1	0	0.01	0.02		0.006	0.01
	Volume, mL	1435	1500	1640	1670	730	1790	1820	2470	2110	440	1645	1760	1555	20565		3479.26
	Mass, mg	0	0	0	0	0	0	0	0.0247	0	0.044	0	0.0176	0.0311	0.1174	0.009	0.035
6/28/2007	Concentration,	0.05	0.01	0.1	0.01	0	0.01	0.01	0.01	0.01	0.15	0.02	0.04	0.04		0.027	1.05
	Volume, mL	1360	870	1490	1520	1500	1480	1390	2345	1750	235	1550	1500	1480	18470		2604.32
	Mass, mg	0.068	0.0087	0.149	0.0152	0	0.0148	0.0139	0.02345	0.0175	0.03525	0.031	0.06	0.0592	0.496	0.038	2.735

Continued

Sampling Date		Sampler Number												
		1	2	4	5	8	10	11	13	15	16	Total	Average	**W/W**
7/31/2007	Concentration,	0.08	0.01	0.02	0	0.01	n/a	n/a	n/a	0.12	0.11		0.049	0.3
	Volume, mL	450	870	675	235	1000	0	0	0	660	700	4590		4041.78
	Mass, mg	0.036	0.0087	0.0135	0	0.01	▨	▨	▨	0.0792	0.077	0.2244	0.02244	1.213
8/31/2007	Concentration,	0.05	n/a	0	n/a	0.04	n/a	n/a	n/a	0.04	0.24		0.062	0.49
	Volume, mL	1575	0	340	0	1950	0	0	0	840	570	5275		3154.54
	Mass, mg	0.07875	▨	0	▨	0.078	▨	▨	▨	0.0336	0.1368	0.32715	0.032715	1.546
9/28/2007	Concentration,	0	0.01	0.02	0.04	0	0	0.01	0.07	0.03	0.02		0.014	1.44
	Volume, mL	925	300	720	340	1420	1600	265	340	1420	470	7800		2107.4
	Mass, mg	0	0.003	0.0144	0.0136	0	0	0.00265	0.0238	0.0426	0.0094	0.10945	0.010945	3.035

Notes:

1. Gray denotes that leach water is not available for calculation of total nitrogen mass;

2. W/W denotes applied wastewater;

3. Ammonia-nitrogen analysis was not conducted for the samples before 2006.

4.3 Salt Balance

This section illustrates how two types of salt concentration unit are converted. Spatial and temporal distribution of the leached salt mass is described. Salt mass balance is calculated.

4.3.1 Salt concentration unit conversion

In this research, salt concentration, which is also called salinity, is measured and recorded in µS/cm; however, in the mass balance of salt, it is necessary to convert electrical conductivity (EC) in µS/cm into total dissolved solid (TDS) in mg/L in order to calculate the mass of salt. The salinity of water samples taken on June 28th, 2007 was measured in µS/cm (EC) and mg/L (TDS) with the ORION model 162 instrument. The data of the measurement is shown in **Table 4. 8** and the plots of their relationship are shown in **Figure 4. 4**. The relationship can be found by making the regression model. The corresponding equation is

$$y = 0.68x + 5.68$$

x is µS/cm;

y is mg/L.

This relationship is used during the following salt mass balance to convert the units between µS/cm and mg/L of salt concentration.

Table 4. 8 The salinity expressed with electrical conductivity and total dissolved solid for a set of water samples

Water sample no.	Electrical conductivity (EC), µS/cm	Total dissolved solid (TDS), mg/L
1	1664	1135
2	2510	1696
3	1517	1033
4	1596	1085
5	2220	1511
6	1668	1136
7	2040	1388
8	1438	978
9	1606	1093
10	1465	996
11	2050	1397
12	1593	1085
13	2030	1382
14	964	656
15	960	654
16	1631	1109

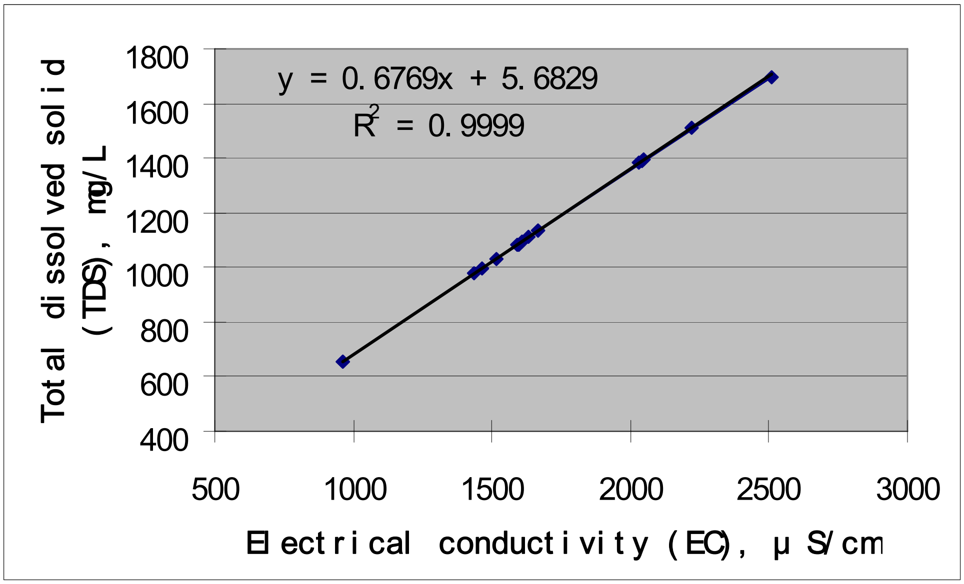

Figure 4. 4 The relationship between electrical conductivity, µS/cm, and total dissolved solid, mg/L

4.3.2 Spatial and temporal distribution of leached salt mass

The salinity and salt mass in the leach water of each sampler during each sampling period and the total and average salinity and salt mass are summarized in **Table 4. 9**. The spatial distribution of leached salt mass can be seen in **Figure E.1** to **Figure E.21** in Appendix E.

The volume weighted average salinity in leach water at each sampling date is plotted in **Figure 4. 5**, and the average leached mass of salt with ±standard error at each sampling date is shown in **Figure 4. 6**. The calculation of volume weighted average salinity in leach water at each sampling date is based on the following equation:

$$\overline{\mathrm{C}}_{weighted} = \frac{\sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{C_i} V_i}{\sum_{i=1}^{n} V_i} \qquad (4.2)$$

where, $\overline{\mathrm{C}}_{weighted}$ is the weighted average salinity in the leach water, μS/cm;

Ci is the salinity in the i-th sampler, μS/cm;

Vi is the volume of the leach water in the i-th sampler, L.

Table 4. 9 The summarization of salinity and salt mass in the leached water and applied wastewater at the Littlefield site

		Sampler Number																		
Sampling Date		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Total	Average	**W/W**
10/7/2005	Salinity (µS/cm)	2670	3050	2380	1639	1590	2650	2330	1967	1694	1504	1658	1518	2420	2020	1723	1328		1962	937.5
	Volume, mL	223	220	350	305	332	410	701	887	810	379	54	698	326	689	605	300	7289	456	
	Salinity (mg/L)	1813	2070	1617	1115	1082	1799	1583	1337	1152	1024	1128	1033	1644	1373	1172	905		1334	640
	Mass, mg	404	455	566	340	359	738	1110	1186	933	388	61	721	536	946	709	271	9724	608	
11/28/2005	Salinity (µS/cm)	2480	2810	2510	1604	1620	2500	2240	1915	1955	2200	n/a	1423	2680	1890	1981	1574		1990	1056
	Volume, mL	120	224	262	1063	650	1099	1490	1117	800	222	0	1326	693	927	440	545	10978	686	7675
	Salinity (mg/L)	1684	1908	1705	1091	1102	1698	1522	1302	1329	1495		969	1820	1285	1347	1071		1353	720
	Mass, mg	202	427	447	1160	716	1866	2268	1454	1063	332		1285	1261	1191	593	584	14849	928	5530
12/29/2005	Salinity (µS/cm)	n/a	n/a	n/a	n/a	n/a	2790	2390	2250	n/a	n/a	n/a	1514	n/a	n/a	n/a	n/a		1963	1146.5
	Volume, mL	0	0	0	0	0	20	84	86	0	0	0	172	0	0	0	0	362	23	4575.6
	Salinity (mg/L)						1894	1623	1529				1031						1334	782
	Mass, mg						38	136	131				177					483	30	3577
2/10/2006	Salinity (µS/cm)	1538	2450	1843	1335	1562	1973	1880	1623	1658	n/a	n/a	1207	2390	1579	1597	1386		1686	876
	Volume, mL	1322	1758	1838	1750	1300	1602	1658	938	1584	0	0	1950	850	2590	1714	1902	22756	1422	6347
	Salinity (mg/L)	1047	1664	1253	909	1063	1341	1278	1104	1128			823	1623	1075	1087	944		1147	599
	Mass, mg	1384	2925	2303	1591	1382	2149	2119	1036	1787			1604	1380	2783	1863	1795	26101	1631	3799
4/6/2006	Salinity (µS/cm)	946	2060	2080	1319	1555	1869	1789	1573	1632	2610	2070	1294	2100	1495	1496	1427		1733	840
	Volume, mL	905	825	1415	1510	1155	1430	1120	1631	2179	2047	1622	1110	1230	2148	1350	1539	23216	1451	8889
	Salinity (mg/L)	646	1400	1414	899	1058	1271	1217	1070	1110	1772	1407	882	1427	1018	1018	972		1179	574
	Mass, mg	585	1155	2000	1357	1222	1817	1363	1746	2420	3628	2282	979	1755	2186	1375	1495	27364	1710	5105
5/25/2006	Salinity (µS/cm)	1344	1591	1451	1408	1492	1748	1536	1386	n/a	n/a	n/a	1145	n/a	1544	1492	n/a		1402	1016
	Volume, mL	410	235	495	360	222	485	170	347	0	0	0	1780	0	725	1123	0	6352	397	7232
	Salinity (mg/L)	915	1083	988	959	1016	1189	1045	944				781		1051	1016			955	693
	Mass, mg	375	254	489	345	225	577	178	328				1390		762	1141		6063	379	5015
6/16/2006	Salinity (µS/cm)	918	1175	1097	1093	1450	1651	1422	1171	n/a	1639	1868	1104	1286	1029	1446	n/a		1261	851.5
	Volume, mL	404	390	590	760	450	850	780	540	0	214	132	1422	220	860	860	0	8472	530	1979
	Salinity (mg/L)	627	801	748	746	987	1123	968	798		1115	1270	753	876	702	984			859	582
	Mass, mg	253	312	441	567	444	955	755	431		239	168	1071	193	604	847		7279	455	1152

Continued

		Sampler Number															
Sampling Date		1	2	3	4	5	8	9	10	11	12	13	15	16	Total	Average	**W/W**
7/21/2006	Salinity (µS/cm)	1585	1332	1406	1507	2140	1733	1569	1038	n/a	1288	2080	1783	1544		1544	839
	Volume, mL	530	345	740	900	340	655	118	600	0	1104	580	549	272	6733	518	4503
	Salinity (mg/L)	1079	907	957	1026	1454	1179	1068	708		878	1414	1213	1051		1051	574
	Mass, mg	572	313	708	923	494	772	126	425		969	820	666	286	7074	544	2583
9/1/2006	Salinity (µS/cm)	1531	1275	1117	1390	1644	1914	1360	1263	n/a	1436	1747	1653	2020		1523	891
	Volume, mL	340	290	620	670	40	1350	270	1680	0	1234	300	530	670	7994	615	4403.4
	Salinity (mg/L)	1042	869	762	947	1119	1301	926	861		978	1188	1125	1373		1037	609
	Mass, mg	354	252	472	634	45	1757	250	1446		1206	356	596	920	8289	638	2681
9/22/2006	Salinity (µS/cm)	1644	1733	1270	1276	2120	1706	2080	1649	3010	1399	2020	1525	1972		1839	884.5
	Volume, mL	660	480	645	960	900	1400	1090	1590	1490	1540	740	890	990	13375	1029	1656.4
	Salinity (mg/L)	1119	1179	865	869	1441	1160	1414	1122	2043	953	1373	1038	1341		1250	604
	Mass, mg	738	566	558	835	1297	1625	1541	1784	3044	1467	1016	924	1327	16721	1286	1001
10/12/2006	Salinity (µS/cm)	1616	n/a	1352	1429	n/a	1570	n/a	1897	n/a	1463	2300	1652	2370		1625	884.5
	Volume, mL	1610	0	550	1540	0	2206	0	170	0	680	370	2790	440	10356	797	2207.44
	Salinity (mg/L)	1100		921	973		1068		1290		996	1563	1124	1610		1106	604
	Mass, mg	1770		506	1498		2357		219		677	578	3136	708	11451	881	1334
11/22/2006	Salinity (µS/cm)	1203	1526	1240	1291	1888	1328	n/a	1150	2170	1305	2280	1588	2200		1600	930.5
	Volume, mL	150	50	310	350	46	870	0	320	59	330	25	350	1170	4030	310	2422.28
	Salinity (mg/L)	820	1039	845	880	1284	905		784	1475	889	1549	1081	1495		1089	636
	Mass, mg	123	52	262	308	59	787		251	87	293	39	378	1749	4388	338	1539
1/9/2007	Salinity (µS/cm)	1511	984	800	1137	n/a	1320	n/a	1589	n/a	1340	2090	1351	2200		1421	1000
	Volume, mL	995	1435	1395	1455	0	1545	0	640	0	335	1435	1480	1335	12050	927	2387.84
	Salinity (mg/L)	1028	672	547	775		899		1081		913	1420	920	1495		968	683
	Mass, mg	1023	964	763	1128		1389		692		306	2038	1362	1996	11662	897	1630
2/23/2007	Salinity (µS/cm)	1800	1894	893	1086	3160	1168	2800	1355	2090	1251	2150	1603	1637		1715	857
	Volume, mL	1161	1032	620	1146	760	1470	630	1470	820	67	1050	1100	1470	12796	984	2874.1
	Salinity (mg/L)	1224	1288	610	741	2145	796	1901	923	1420	852	1461	1091	1114		1166	586
	Mass, mg	1421	1329	378	849	1630	1171	1198	1357	1165	57	1534	1200	1637	14925	1148	1684
3/30/2007	Salinity (µS/cm)	1787	2250	1485	1263	2170	1294	2250	1410	1633	1406	1999	1795	1709		1720	1036
	Volume, mL	1440	1550	1582	1780	1250	2050	2090	2550	2130	520	1685	2225	1532	22384	1722	2985.62
	Salinity (mg/L)	1215	1529	1011	861	1475	882	1529	960	1111	957	1359	1221	1163		1170	707
	Mass, mg	1750	2369	1599	1532	1843	1807	3195	2448	2367	498	2290	2716	1781	26195	2015	2111
4/25/2007	Salinity (µS/cm)	1915	2180	1213	1293	2020	1171	1933	1347	1492	1257	1937	1245	1707		1532	1053
	Volume, mL	670	980	805	1290	770	1450	185	590	855	50	490	1470	700	10305	793	2815.88
	Salinity (mg/L)	1302	1481	827	881	1373	798	1314	917	1016	857	1317	848	1161		1042	718
	Mass, mg	872	1452	666	1136	1057	1158	243	541	868	43	645	1247	813	10742	826	2023
5/29/2007	Salinity (µS/cm)	1943	2560	1646	1524	2290	1463	2090	1443	1663	1407	2080	1525	1852		1782	945.5
	Volume, mL	1435	1500	1640	1670	730	1790	1820	2470	2110	440	1645	1760	1555	20565	1582	3479.26
	Salinity (mg/L)	1321	1739	1120	1037	1556	996	1420	982	1131	958	1414	1038	1259		1212	646
	Mass, mg	1895	2608	1837	1732	1136	1783	2585	2427	2387	422	2325	1827	1958	24922	1917	2247
6/28/2007	Salinity (µS/cm)	1664	2510	1517	1596	2220	1668	2040	1438	1606	1465	2050	1593	2030		1779	962
	Volume, mL	1360	870	1490	1520	1500	1480	1390	2345	1750	235	1550	1500	1480	18470	1421	2604.32
	Salinity (mg/L)	1132	1705	1033	1086	1508	1135	1387	979	1093	997	1393	1084	1380		1210	657
	Mass, mg	1540	1483	1538	1651	2263	1679	1927	2296	1912	234	2160	1626	2042	22352	1719	1711

Continued

		Sampler Number												
Sampling Date		1	2	4	5	8	10	11	13	15	16	Total	Average	**W/W**
7/31/2007	Salinity (µS/cm)	1618	2280	1610	2960	2050	n/a	n/a	n/a	1694	2220		2008	1009.5
	Volume, mL	450	870	675	235	1000	0	0	0	660	700	4590	459	4041.78
	Salinity (mg/L)	1101	1549	1095	2009	1393				1152	1508		1365	689
	Mass, mg	495	1348	739	472	1393	▨	▨	▨	761	1056	6264	626	2785
8/31/2007	Salinity (µS/cm)	1604	n/a	5470	n/a	3080	n/a	n/a	n/a	2840	3440		2794	1121
	Volume, mL	1575	0	340	0	1950	0	0	0	840	570	5275	528	3154.54
	Salinity (mg/L)	1091		3708		2091				1928	2334		1897	764
	Mass, mg	1719	▨	1261	▨	4077	▨	▨	▨	1620	1331	10006	1001	2412
9/28/2007	Salinity (µS/cm)	1882	2520	2440	3480	2190	3250	3800	3590	1921	3230		2592	1075
	Volume, mL	925	300	720	340	1420	1600	265	340	1420	470	7800	780	2107.4
	Salinity (mg/L)	1280	1711	1657	2361	1488	2206	2578	2436	1306	2192		1760	733
	Mass, mg	1184	513	1193	803	2113	3529	683	828	1855	1030	13731	1373	1545

Note:

1. Gray denotes that there is no leach water available;
2. W/W means the applied secondary wastewater.

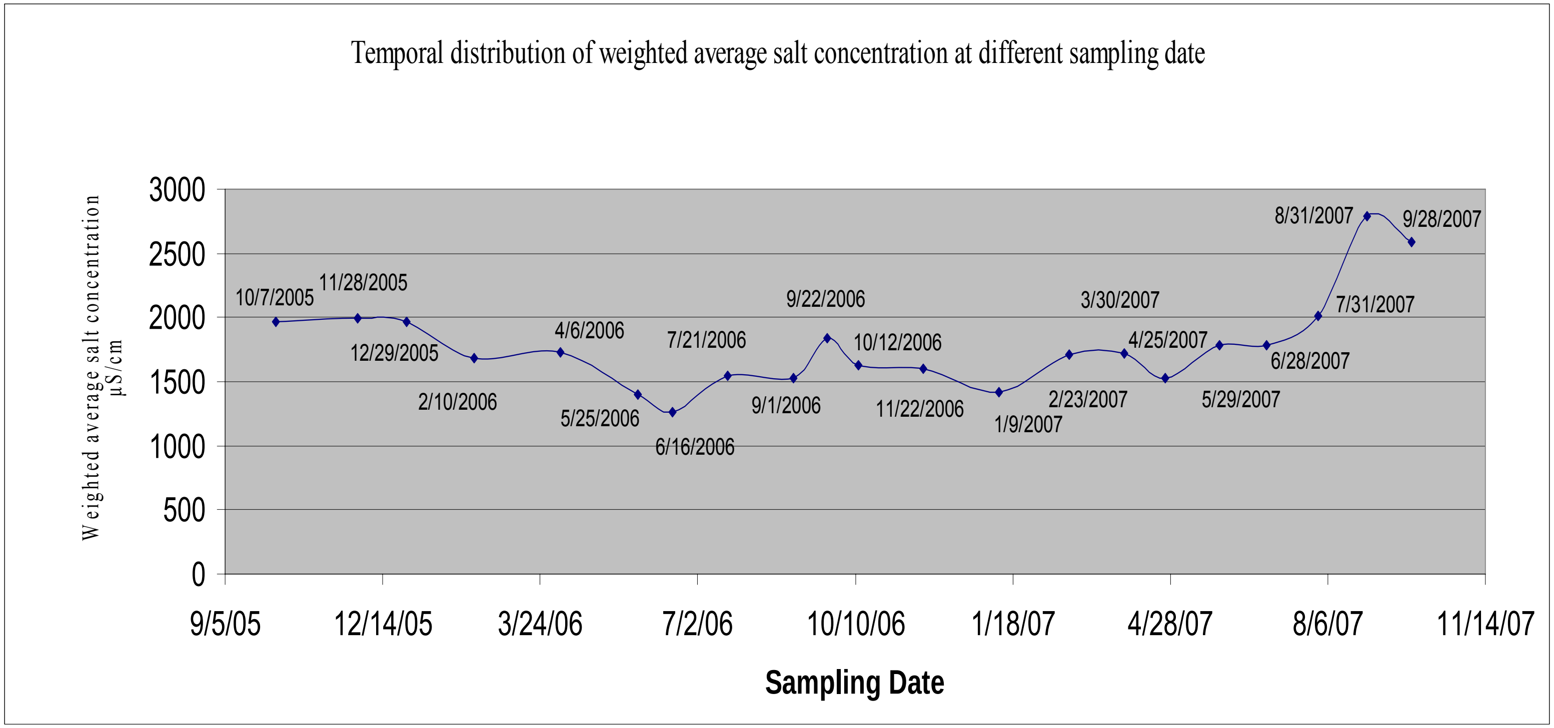

Figure 4. 5 The temporal distribution of volume weighted average salinity in the leach water at the Littlefield site

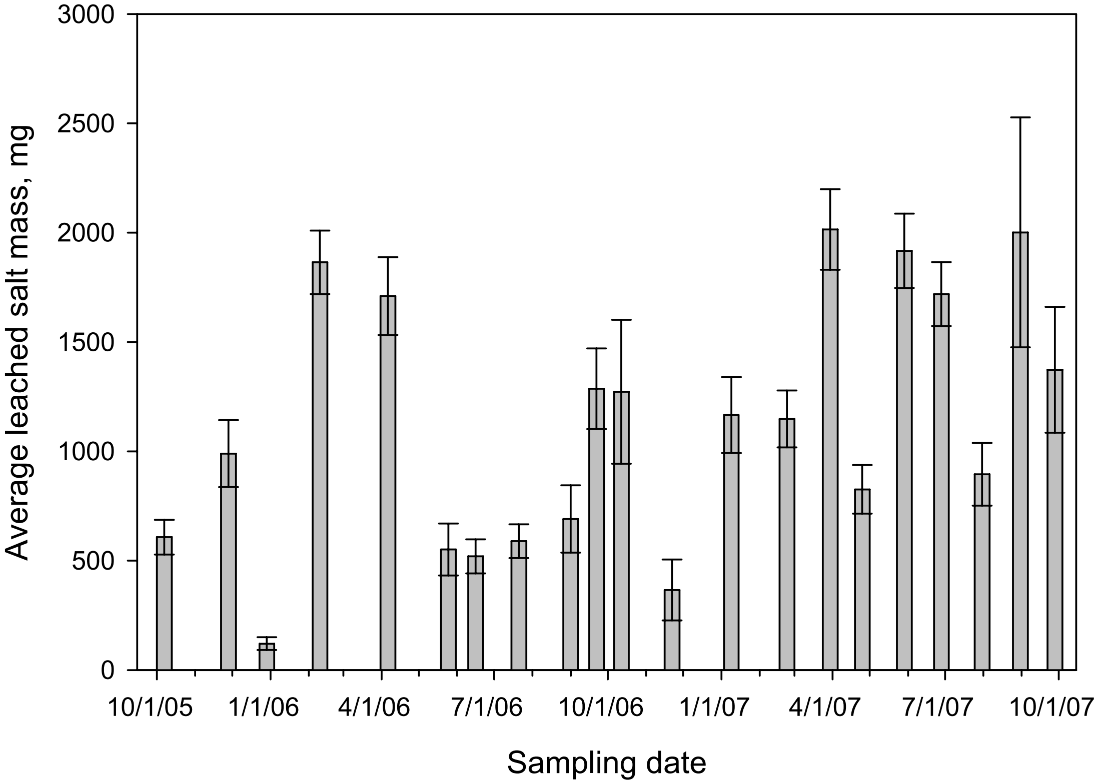

Figure 4. 6 Average leached mass of salt ± standard error in the leached water in each sampling period at the Littlefield site

4.3.3 Salt mass balance

Salt mass balance is based on one sampler. Equation 3.5 is employed to determine the salt mass balance. The applied salt is the average mass in the applied wastewater falling onto the soil surface of the samplers, the leached salt is the average mass in the leached water of the samplers, and the stored salt is the average salt mass stored in the root zone in the samplers. The result of calculation of salt mass balance is listed in **Table 4. 10** for each sampling period.

Table 4. 10 Mass balance of salt for each sampling period at the Littlefield site based on one sampler

Sampling period	Leached salt, mg	Applied salt, mg	Stored salt in soil, mg
10/07/2005-11/28/2005	928.075	5529.899	4601.824
11/28/2005-12/29/2005	30.186	3576.970	3546.784
12/29/2005-2/10/2006	1631.341	3799.495	2168.153
2/10/2006-4/6/2006	1710.275	5104.650	3394.375
4/6/2006-5/25/2006	378.957	5015.042	4636.086
5/25/2006-6/16/2006	454.967	1152.183	697.215
6/16/2006-7/21/2006	544.160	2583.182	2039.022
7/21/2006-9/1/2006	637.617	2680.793	2043.177
9/1/2006-9/22/2006	1286.239	1001.130	-285.109
9/22/2006-10/12/2006	880.834	1334.179	453.345
10/12/2006-11/22/2006	337.540	1539.452	1201.912
11/22/2006-1/9/2007	897.042	1629.899	732.857
1/9/2007-2/23/2007	1148.089	1683.608	535.520
2/23/2007-3/30/2007	2015.032	2110.688	95.655
3/30/2007-4/25/2007	826.275	2023.093	1196.818
4/25/2007-5/29/2007	1917.050	2246.530	329.480
5/29/2007-6/28/2007	1719.356	1710.675	-8.681
6/28/2007-7/31/2007	626.446	2784.841	2158.395
7/31/2007-8/31/2007	1000.647	2411.607	1410.961
8/31/2007-9/28/2007	1373.136	1545.463	172.327

4.4 Water Balance

4.4.1 Temporal distribution of average leach water volume

Temporal distribution of average leach water volume with standard deviation for Houston samplers and Midland samplers are shown in **Figure 4.7** and **Figure 4.8,** respectively.

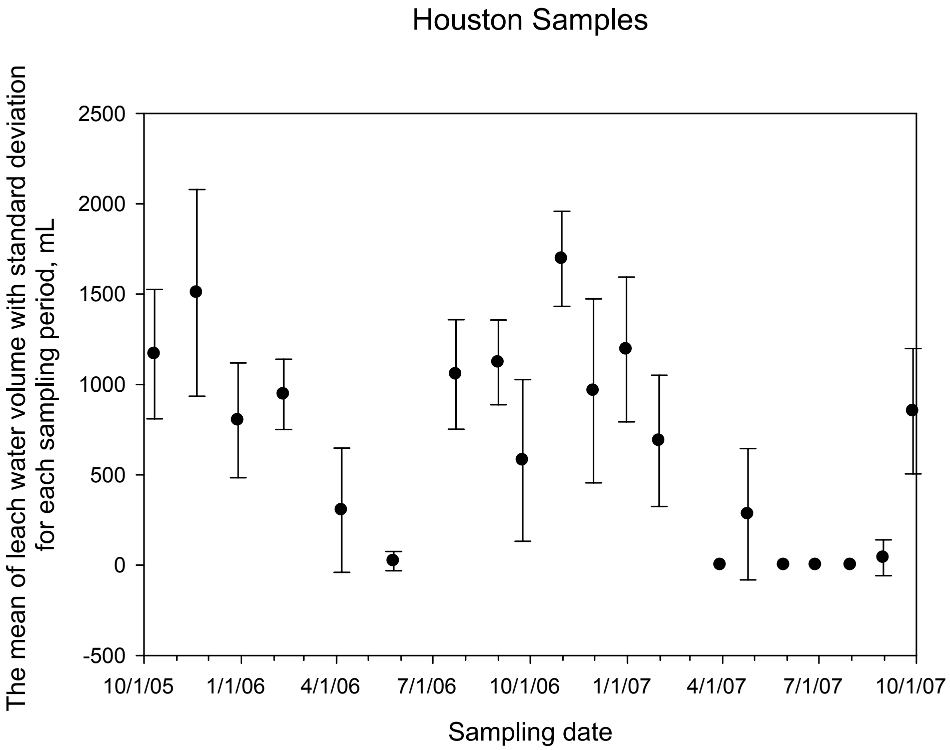

Figure 4. 7 The mean of leach water with one standard deviation for each sampling period for Houston soil

4.4.2 Calculation of water mass balance

The soil moisture at saturation in the sampler for Houston samplers is:

$$0.53\frac{m^3\text{ water}}{m^3\text{ soil}}\times 12\text{ inches} = 6.36\text{ inches}$$

The soil moisture at field capacity in the sampler for Houston samplers is:

$$0.41 \frac{m^3 \text{ water}}{m^3 \text{ soil}} \times 12 \text{ inches} = 4.92 \text{ inches}$$

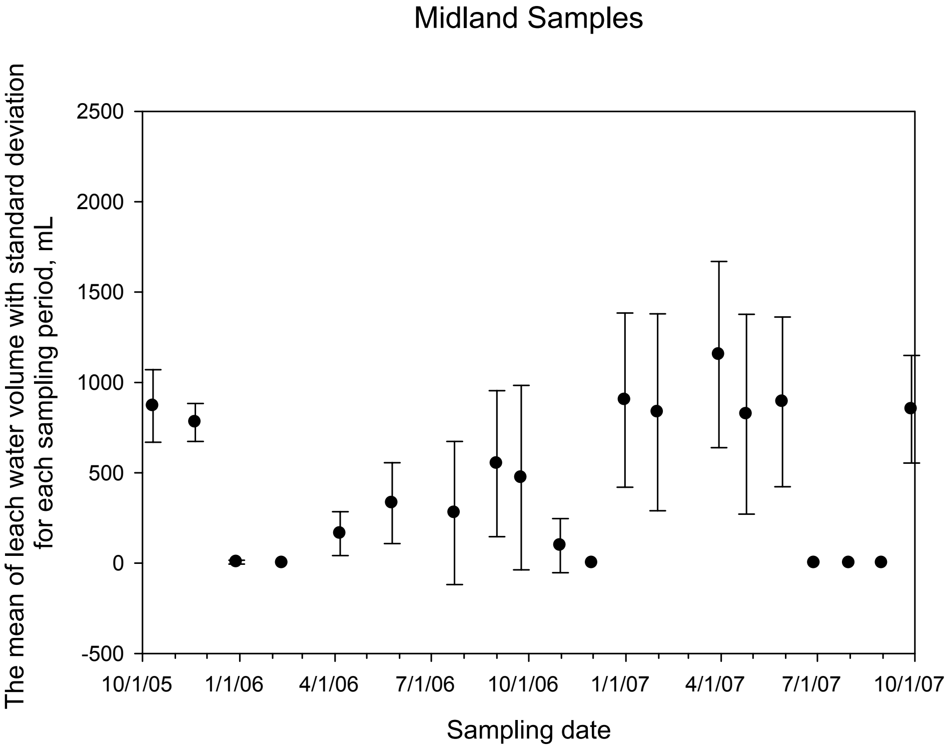

Figure 4. 8 The mean of leach water with one standard deviation for each sampling period for Midland soil

The soil moisture at wilting point in the sampler for Houston samplers is:

$$0.25 \frac{m^3 \text{ water}}{m^3 \text{ soil}} \times 12 \text{ inches} = 3.00 \text{ inches}$$

The soil moisture at saturation in the sampler for Midland samplers is:

$$0.4\frac{m^3\ \text{water}}{m^3\ \text{soil}}\times 12\ \text{inches} = 4.8\ \text{inches}$$

The soil moisture at field capacity in the sampler for Midland samplers is:

$$0.2\frac{m^3\ \text{water}}{m^3\ \text{soil}}\times 12\ \text{inches} = 2.4\ \text{inches}$$

The soil moisture at wilting point in the sampler for Midland samplers is:

$$0.1\frac{m^3\ \text{water}}{m^3\ \text{soil}}\times 12\ \text{inches} = 1.2\ \text{inches}$$

One inch of water in the sampler is equivalent to 820 mL of water. The precipitation is zero inches for Houston samplers since those six samplers are installed inside of Greenhouse at TTU site. And the precipitation data at TTU site for Midland samplers can be obtained at the web site of the National Climatic Data Center: http://www.ncdc.noaa.gov.

The water balance calculations for Houston samplers and Midland samplers are illustrated in **Table 4.11** and **Table 4.12**, respectively.

4.4.3 Irrigation and leach water quantity for sampling periods

The relationships between irrigation amount plus precipitation and leach water amount for each sampling period for Houston samplers and Midland samplers are shown in **Figure 4.9** and **Figure 4.10**, respectively.

4.4.4 Cumulative leach water and cumulative input water

The regression model of cumulative leach water volume and cumulative water application amount including precipitation can be obtained by Microsoft Office Excel

2003. The plots and the regression model for Houston samplers and Midland samplers are shown in the **Figure 4.11** and **Figure 4.12**, respectively.

Table 4. 11 Water balance calculation for Houston soil

Period	Soil Moisture, inches	PPT, inches	Irrigation, inches	ET, inches	Average Leaching, inches	Runoff or/and other unknown loss, inches
10/11/2005	5.640					
10/11/2005-11/20/2005		0	6.707	4.491	1.837	0.000
11/20/2005	6.019					
11/20/2005-12/29/2005		0	2.439	3.007	0.977	0.000
12/29/2005	4.474					
12/29/2005-2/10/2006		0	2.927	3.312	1.152	0.000
2/10/2006	3.000					
2/10/2006-4/6/2006		0	3.415	6.238	0.370	0.000
4/6/2006	3.000					
4/6/2006-5/25/2006		0	7.012	7.954	0.026	0.000
5/25/2006	3.000					
5/25/2006-7/23/2006		0	17.683	11.492	1.287	1.545
7/23/2006	6.360					
7/23/2006-9/1/2006		0	10.976	7.804	1.368	1.804
9/1/2006	6.360					
9/1/2006-9/242006		0	3.049	4.147	0.707	0.000
9/24/2006	4.555					
9/24/2006-10/31/2006		0	7.188	5.096	2.067	0.000
10/31/2006	4.580					
10/31/2006-11/30/2006		0	2.561	2.808	1.176	0.000
11/30/2006	3.157					
11/30/2006-12/31/2006		0	2.696	2.214	1.455	0.000
12/31/2006	3.000					
12/31/2006-1/31/2007		0	2.224	2.295	0.838	0.000
1/31/2007	3.000					
1/31/2007-3/30/2007		0	4.390	6.080	0.000	0.000
3/30/2007	3.000					

Continued

Period	Soil Moisture, inches	PPT, inches	Irrigation, inches	ET, inches	Average Leaching, inches	Runoff or/and other unknown loss, inches
3/30/2007-4/25/2007		0	6.312	3.916	0.343	0.000
4/25/2007	5.053					
4/25/2007-5/29/2007		0	6.341	5.760	0.000	0.000
5/29/2007	5.634					
5/29/2007-6/28/2007		0	6.209	5.780	0.000	0.000
6/28/2007	6.063					
6/28/2007-7/31/2007		0	7.462	6.634	0.000	0.531
7/31/2007	6.360					
7/31/2007-8/31/2007		0	7.407	6.192	0.049	1.166
8/31/2007	6.360					
8/31/2007-9/28/2007		0	6.902	4.838	1.039	1.025
9/28/2007	6.360					

Table 4. 12 Water balance calculation for Midland soil

Period	Soil Moisture, inches	PPT, inches	Irrigation, inches	ET, inches	Average Leaching, inches	Runoff or/and other unknown loss, inches
10/11/2005	3.600					
10/11/2005-11/20/2005		0.2	5.122	4.146	0.950	0.000
11/20/2005	3.826					
11/20/2005-12/29/2005		0	1.341	2.711	0.007	0.000
12/29/2005	2.449					
12/29/2005-2/10/2006		0.03	2.927	2.955	0.000	0.000
2/10/2006	2.451					
2/10/2006-4/6/2006		2.27	3.415	6.286	0.199	0.000
4/6/2006	1.651					
4/6/2006-5/25/2006		1.12	8.841	8.388	0.405	0.000
5/25/2006	2.819					
5/25/2006-7/23/2006		2.75	13.415	11.924	0.339	1.920
7/23/2006	4.800					
7/23/2006-9/1/2006		2.25	10.122	7.503	0.671	4.198
9/1/2006	4.800					
9/1/2006-9/242006		4.57	1.220	3.603	0.577	1.609
9/24/2006	4.800					
9/24/2006-10/31/2006		1.3	3.588	4.541	0.118	0.229
10/31/2006	4.800					
10/31/2006-11/30/2006		3.36	1.829	2.520	0.000	2.669
11/30/2006	4.800					
11/30/2006-12/31/2006		2.31	1.445	2.000	1.100	0.655
12/31/2006	4.800					
12/31/2006-1/31/2007		5.6	1.866	1.992	1.018	4.456
1/31/2007	4.800					
1/31/2007-3/30/2007		10.94	5.277	6.037	1.407	8.773
3/30/2007	4.800					
3/30/2007-4/25/2007		1.15	5.104	4.123	1.005	1.125

Continued

Period	Soil Moisture, inches	PPT, inches	Irrigation, inches	ET, inches	Average Leaching, inches	Runoff or/and other unknown loss, inches
4/25/2007	4.800					
4/25/2007-5/29/2007		5.22	3.415	6.076	1.089	1.469
5/29/2007	4.800					
5/29/2007-6/28/2007		3.76	3.152	6.076	0.000	0.837
6/28/2007	4.800					
6/28/2007-7/31/2007		0.94	5.717	6.760	0.000	0.000
7/31/2007	4.697					
7/31/2007-8/31/2007		1.99	5.065	5.864	0.000	1.088
8/31/2007	4.800					
8/31/2007-9/28/2007		2.2	3.976	4.204	1.039	0.933
9/28/2007	4.800					

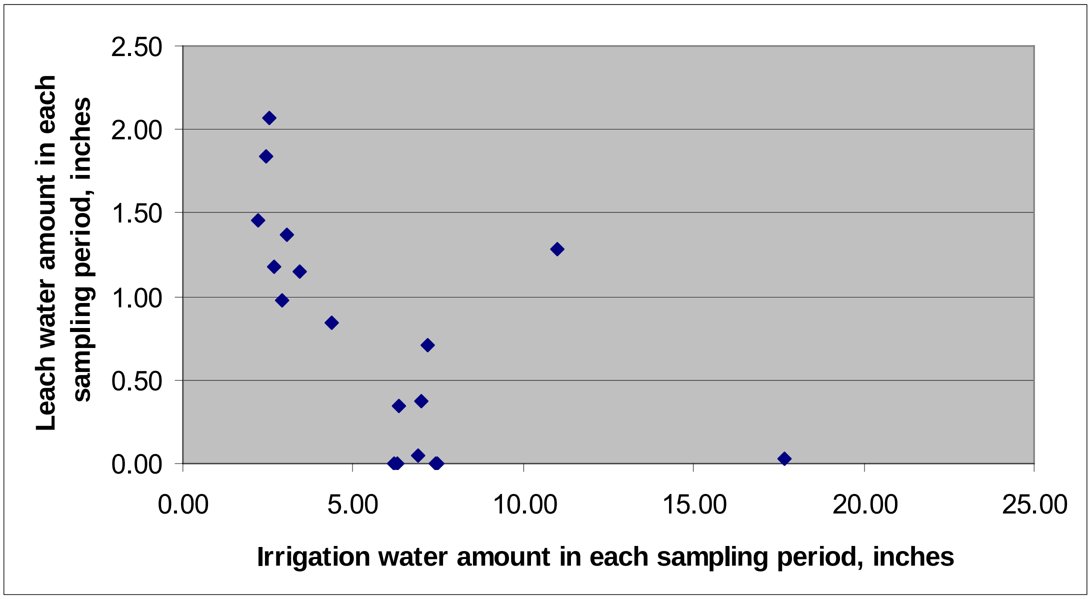

Figure 4. 9 Applied water and leached water amount for Houston soil

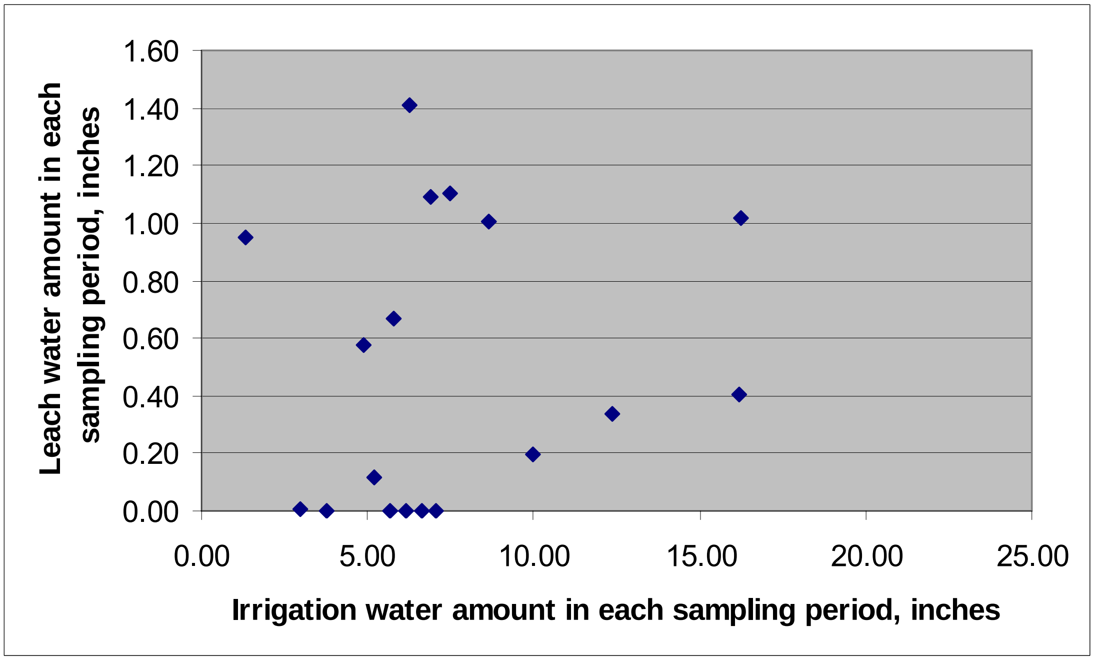

Figure 4. 10 Applied water plus precipitation and leached water amount for Midland soil

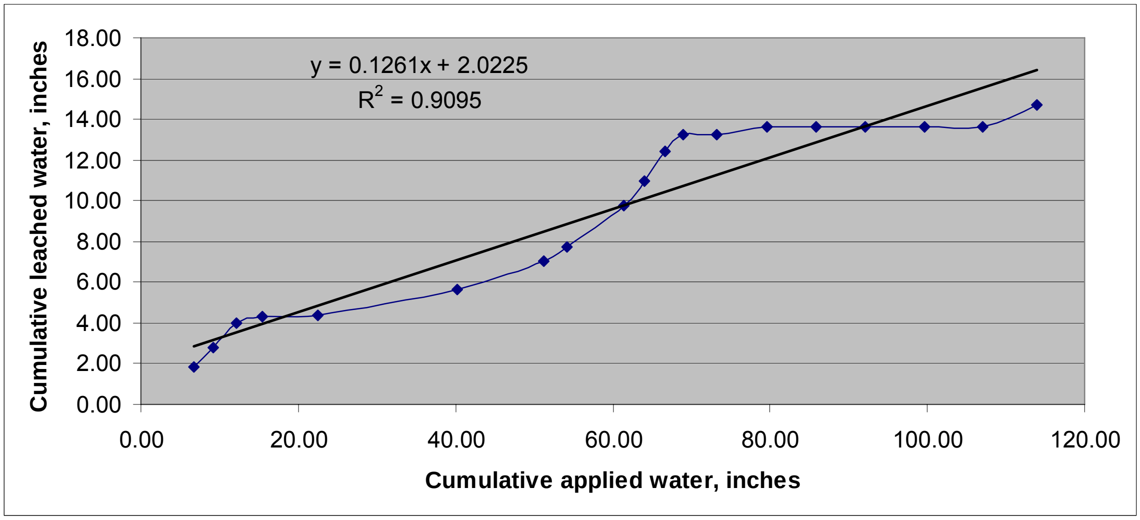

Figure 4. 11 The linear relationship between cumulative applied water and cumulative leached water for Houston soil

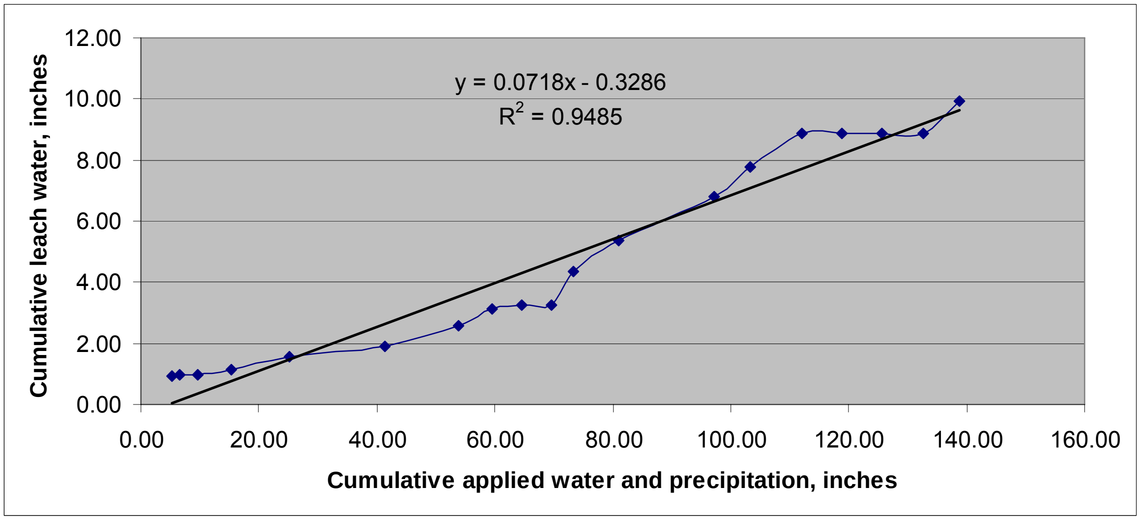

Figure 4. 12 The linear relationship between cumulative applied water plus precipitation and cumulative leached water for Midland soil

4.5 Nitrogen Balance

4.5.1 Temporal distribution of leached total nitrogen

The temporal distributions of weighted average total nitrogen concentration in the leach water for Houston samplers and Midland samplers are shown in **Figure 4.13** and **Figure 4.14**, respectively.

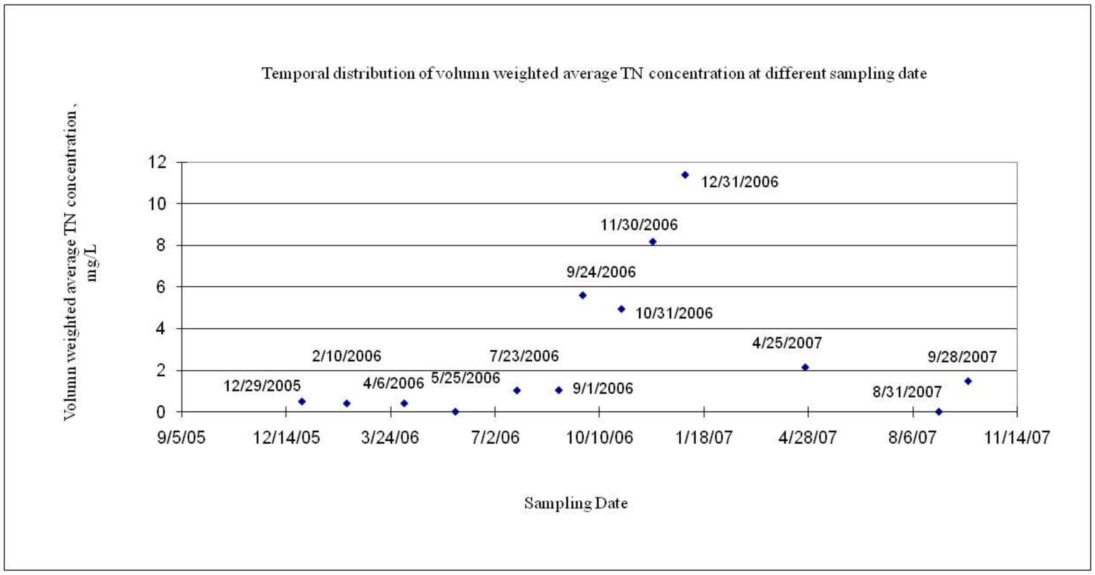

Figure 4. 13 Temporal distribution of weighted average total nitrogen concentration of Houston samples

4.5.2 Calculation of nitrogen mass balance

The results of the total and average mass of total nitrogen in a sampler for Houston samplers and Midland samplers are calculated and shown in **Table 4.13** and **Table 4.14**, respectively. The nitrogen mass balances based on one sampler during each sampling period for Houston and Midland samplers are shown in **Table 4.15** and **Table 4.16**, respectively.

The removal of total nitrogen by mowing is listed in **Table 4.17**.

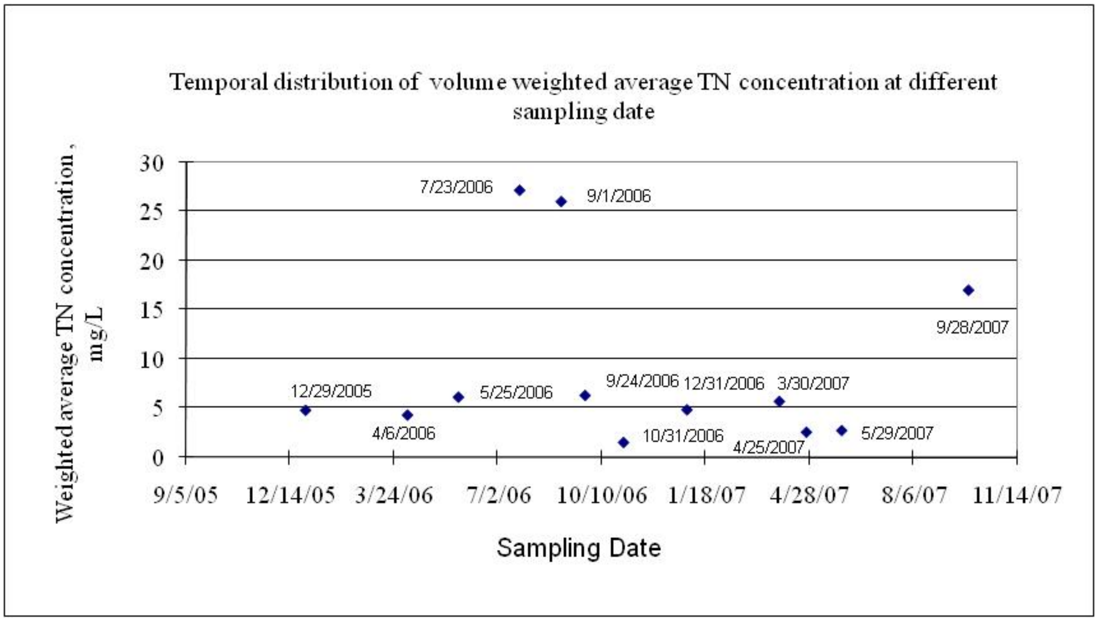

Figure 4. 14 Temporal distribution of weighted average total nitrogen concentration of Midland samples

4.5.3 Cumulative nitrogen mass input and output

The cumulative applied and leached total nitrogen mass in a sampler with regression model for Houston and Midland samplers are summarized in **Table 4.18** and **Table 4.19**, respectively, and the plots are shown in **Figure 4.15** and **Figure 4.16,** respectively.

The regression models obtained by Microsoft Excel 2003 for Houston and Midland samplers are:

$y = 0.029x + 2.977$ (Houston samples)

$y = 0.0514x + 6.6091$ (Midland samples)

x is the cumulative applied total nitrogen mass in a sampler;

y is the cumulative leached total nitrogen mass in a sampler.

4.5.4 Cumulative total nitrogen concentration in leached water

Cumulative total nitrogen concentrations in the leached water for Houston and Midland samples are calculated and shown in **Table 4.20** and **Table 4.21,** respectively; the total nitrogen removal ratios in both types of soils are determined based on the cumulative applied mass and cumulative leached mass of total nitrogen and the results are listed in **Table 4.22** and **Table 4.23**, respectively.

Table 4. 13 Calculation of mass of total nitrogen for Houston soil

		Sampler Number								
Sampling Date		1	2	3	4	5	6	Total	Average	**W/W**
12/29/2005	Concentration, mg/L	1	0	1	0	0	0		0.492	2
	Volume, mL	1227	478	1136	820	551	594	4806		2000
	Mass, mg	1.227	0	1.136	0	0	0	2.363	0.394	4.000
2/10/2006	Concentration, mg/L	1	0	1	0	0	0		0.399	1
	Volume, mL	1234	750	1028	1000	950	706	5668		2400
	Mass, mg	1.234	0	1.028	0	0	0	2.262	0.377	2.400
4/6/2006	Concentration, mg/L	0	0	n/a	1	n/a	n/a		0.404	1
	Volume, mL	625	460	0	735	0	0	1820		2800
	Mass, mg	0	0		0.735			0.735	0.123	2.800
5/25/2006	Concentration, mg/L	n/a	n/a	0	n/a	n/a	n/a		0.000	1
	Volume, mL	0	0	130	0	0	0	130		5750
	Mass, mg			0				0	0.000	5.750
7/23/2006	Concentration, mg/L	1	2	2	0	0	0		1.022	1
	Volume, mL	1330	1150	1420	985	810	635	6330		14500
	Mass, mg	1.33	2.3	2.84	0	0	0	6.47	1.078	14.500
9/1/2006	Concentration, mg/L	0	5	0	0	0	0		1.036	25
	Volume, mL	1300	1395	950	1280	995	810	6730		9000
	Mass, mg	0	6.975	0	0	0	0	6.975	1.163	225.000
9/24/2006	Concentration, mg/L	7	11	0	3	0	0		5.595	25
	Volume, mL	748	970	225	1185	190	160	3478		2500
	Mass, mg	5.236	10.67	0	3.555	0	0	19.461	3.244	62.500
10/31/2006	Concentration, mg/L	8	10	8	3	0	1		4.937	22.5
	Volume, mL	1460	1550	1910	2100	1700	1450	10170		5894
	Mass, mg	11.68	15.5	15.28	6.3	0	1.45	50.21	8.368	132.615
11/30/2006	Concentration, mg/L	16	8	18	0	0	2		8.173	20.5
	Volume, mL	1120	840	1216	1750	480	380	5786		2100
	Mass, mg	17.92	6.72	21.888	0	0	0.76	47.288	3.638	43.050
12/31/2006	Concentration, mg/L	13	5	28	3	4	3		11.384	23.000
	Volume, mL	1220	1020	1800	1510	790	820	7160		2211.000
	Mass, mg	15.86	5.1	50.4	4.53	3.16	2.46	81.51	13.585	50.853

Continued

Sampling Date		Sampler Number								
		1	2	3	4	5	6	Total	Average	**W/W**
3/30/2007	Concentration, mg/L	n/a	n/a	n/a	n/a	n/a	n/a			24
	Volume, mL	0	0	0	0	0	0	0		3600
	Mass, mg	▨	▨	▨	▨	▨	▨	0	0.000	86.400
4/25/2007	Concentration, mg/L	4	1	4	3	n/a	n/a		2.135	23.5
	Volume, mL	330	976	162	220	0	0	1688		5176
	Mass, mg	1.32	0.976	0.648	0.66	▨	▨	3.604	0.601	121.636
5/29/2007	Concentration, mg/L	n/a	n/a	n/a	n/a	n/a	n/a			23
	Volume, mL	0	0	0	0	0	0	0		5200
	Mass, mg	▨	▨	▨	▨	▨	▨	0	0.000	119.600
6/28/2007	Concentration, mg/L	n/a	n/a	n/a	n/a	n/a	n/a			23
	Volume, mL	0	0	0	0	0	0	0		5091
	Mass, mg	▨	▨	▨	▨	▨	▨	0	0.000	117.093
7/31/2007	Concentration, mg/L	n/a	n/a	n/a	n/a	n/a	n/a			17
	Volume, mL	0	0	0	0	0	0	0		6119
	Mass, mg	▨	▨	▨	▨	▨	▨	0	0.000	104.023
8/31/2007	Concentration, mg/L	0	n/a	n/a	n/a	n/a	n/a		0.000	17
	Volume, mL	243	0	0	0	0	0	243		6074
	Mass, mg	0	▨	▨	▨	▨	▨	0	0	103.258
9/28/2007	Concentration, mg/L	3	0	0	0	0	5		1.470	25
	Volume, mL	1395	510	1100	550	890	665	5110		5660
	Mass, mg	4.185	0	0	0	0	3.325	7.51	1.252	141.500

Notes:

1. Gray denotes that leach water is not available for calculation of total nitrogen mass;

2. W/W denotes applied wastewater.

Table 4. 14 Calculation of mass of total nitrogen for Midland soil

		Sampler Number								
Sampling Date		1	2	3	4	5	6	Total	Average	**W/W**
12/29/2005	Concentration, mg/L	4	n/a	n/a	n/a	5	n/a		4.758	2
	Volume, mL	8	0	0	0	25	0	33		1100
	Mass, mg	0.032				0.125		0.157	0.026	2.200
2/10/2006	Concentration, mg/L	n/a	n/a	n/a	n/a	n/a	n/a			1
	Volume, mL	0	0	0	0	0	0	0		2400
	Mass, mg							0	0.000	2.400
4/6/2006	Concentration, mg/L	0	n/a	13	12	0	0		4.270	1
	Volume, mL	350	0	225	105	200	100	980		2800
	Mass, mg	0		2.925	1.26	0	0	4.185	0.698	2.800
5/25/2006	Concentration, mg/L	1	6	14	n/a	1	5		6.094	1
	Volume, mL	455	265	495	0	180	598	1993		7250
	Mass, mg	0.455	1.59	6.93		0.18	2.99	12.145	2.024	7.250
7/23/2006	Concentration, mg/L	n/a	3	32	27	n/a	28		27.126	1
	Volume, mL	0	140	518	28	0	980	1666		11000
	Mass, mg		0.42	16.576	0.756		27.44	45.192	7.532	11.000
9/1/2006	Concentration, mg/L	5	2	36	32	6	32		25.982	25
	Volume, mL	282	434	985	360	122	1118	3301		8300
	Mass, mg	1.41	0.868	35.46	11.52	0.732	35.776	85.766	14.294	207.500
9/24/2006	Concentration, mg/L	2	1	9	n/a	3	6		6.269	25
	Volume, mL	215	335	1160	0	61	1065	2836		1000
	Mass, mg	0.43	0.335	10.44		0.183	6.39	17.778	2.963	25.000
10/31/2006	Concentration, mg/L	n/a	n/a	1	n/a	n/a	2		1.483	22.5
	Volume, mL	0	0	300	0	0	280	580		2942
	Mass, mg			0.3			0.56	0.86	0.143	66.195
11/30/2006	Concentration, mg/L	n/a	n/a	n/a	n/a	n/a	n/a			20.5
	Volume, mL	0	0	0	0	0	0	0		1500
	Mass, mg							0	0.000	30.750
12/31/2006	Concentration, mg/L	6	3	6	n/a	5	4		4.805	23.000
	Volume, mL	880	860	1074	0	1310	1290	5414		1185.000
	Mass, mg	5.28	2.58	6.444		6.55	5.16	26.014	4.336	27.255

Continued

Sampling Date		Sampler Number								
		1	2	3	4	5	6	Total	Average	**W/W**
3/30/2007	Concentration, mg/L	5	2	13	7	4	4		5.655	24
	Volume, mL	1156	1210	1354	180	1714	1311	6925		4327
	Mass, mg	5.78	2.42	17.602	1.26	6.856	5.244	39.162	6.527	103.848
4/25/2007	Concentration, mg/L	4	2	2	n/a	2	3		2.532	23.5
	Volume, mL	1024	780	868	0	1688	583	4943		4185
	Mass, mg	4.096	1.56	1.736	▨	3.376	1.749	12.517	2.086	98.348
5/29/2007	Concentration, mg/L	3	2	2	n/a	4	3		2.702	23
	Volume, mL	1210	1120	1240	0	765	1020	5355		2800
	Mass, mg	3.63	2.24	2.48	▨	3.06	3.06	14.47	2.412	64.400
6/28/2007	Concentration, mg/L	n/a	n/a	n/a	n/a	n/a	n/a			23
	Volume, mL	0	0	0	0	0	0	0		2585
	Mass, mg	▨	▨	▨	▨	▨	▨			59.455
7/31/2007	Concentration, mg/L	n/a	n/a	n/a	n/a	n/a	n/a			17
	Volume, mL	0	0	0	0	0	0	0		4688
	Mass, mg	▨	▨	▨	▨	▨	▨			79.696
8/31/2007	Concentration, mg/L	n/a	n/a	n/a	n/a	n/a	n/a			17
	Volume, mL	0	0	0	0	0	0	0		4153
	Mass, mg	▨	▨	▨	▨	▨	▨			70.601
9/28/2007	Concentration, mg/L	8	3	3	56	5	3		16.969	25
	Volume, mL	850	1000	700	1230	970	360	5110		3260
	Mass, mg	6.8	3	2.1	68.88	4.85	1.08	86.71	14.452	81.500

Notes:

1. Gray denotes that leach water is not available for calculation of total nitrogen mass;

2. W/W denotes applied wastewater.

Table 4. 15 Mass balance of Houston soil based on one sampler

Date	Leached TN, mg	Applied TN, mg
12/29/2005	0.394	4.000
2/10/2006	0.377	2.400
4/6/2006	0.123	2.800
5/25/2006	0.000	5.750
7/23/2006	1.078	14.500
9/1/2006	1.163	225.000
9/24/2006	3.244	62.500
10/31/2006	8.368	132.615
11/30/2006	3.638	43.050
12/31/2006	13.585	50.853
1/31/2007	Unknown	44.688
3/30/2007	0.000	86.400
4/25/2007	0.601	121.636
5/29/2007	0.000	119.600
6/28/2007	0.000	117.093
7/31/2007	0.000	104.023
8/31/2007	0.000	103.258
9/28/2007	1.252	141.500

Table 4. 16 Mass balance of Midland soil based on one sampler

Date	Leached TN, mg	Applied TN, mg
12/29/2005	0.026	2.200
2/10/2006	0.000	2.400
4/6/2006	0.698	2.800
5/25/2006	2.024	7.250
7/23/2006	7.532	11.000
9/1/2006	14.294	207.500
9/24/2006	2.963	25.000
10/31/2006	0.143	66.195
11/30/2006	0.000	30.750
12/31/2006	4.336	27.255
1/31/2007	Unknown	37.485
3/30/2007	6.527	103.848
4/25/2007	2.086	98.348
5/29/2007	2.412	64.400
6/28/2007	0.000	59.455
7/31/2007	0.000	79.696
8/31/2007	0.000	70.601
9/28/2007	14.452	81.500

Table 4. 17 TN removal by grass mowing on Aug 21, 2007 at TTU site

Site	Average harvest per sampler, kg	Moisture, %	Average dry harvest per sampler, kg	TKN, %	Removed TN per sampler, mg	Removed TN per acre, kg
Houston	0.1212	63.33	0.044	1.34	595.496	74.707
Midland	0.0108	37	0.007	1.19	81.2175	10.189

Table 4. 18 The cumulative mass balance for Houston soil based on a sampler

Sampling period	Cumulative TN output, mg	Cumulative TN input, mg
11/28/2005-12/29/2005	0.394	4.000
12/29/2005-2/10/2006	0.771	6.400
2/10/2006-4/6/2006	0.893	9.200
4/6/2006-5/25/2006	0.893	14.950
5/25/2006-7/23/2006	1.972	29.450
7/23/2006-9/1/2006	3.134	254.450
9/1/2006-9/24/2006	6.378	316.950
9/24/2006-10/31/2006	14.746	449.565
10/31/2006-11/30/2006	18.384	492.615
11/30/2006-12/31/2006	31.969	543.468
12/31/2006-1/31/2007	31.969	588.156
1/31/2007-3/30/2007	31.969	674.556
3/30/2007-4/25/2007	32.569	796.192
4/25/2007-5/29/2007	32.569	915.792
5/29/2007-6/28/2007	32.569	1032.885
6/28/2007-7/31/2007	32.569	1136.908
7/31/2007-8/31/2007	32.569	1240.166
8/31/2007-9/28/2007	33.821	1381.666

Table 4. 19 The cumulative mass balance for Midland soil based on a sampler

Sampling period	Cumulative TN output, mg	Cumulative TN input, mg
11/28/2005-12/29/2005	0.026	2.200
12/29/2005-2/10/2006	0.026	4.600
2/10/2006-4/6/2006	0.724	7.400
4/6/2006-5/25/2006	2.748	14.650
5/25/2006-7/23/2006	10.280	25.650
7/23/2006-9/1/2006	24.574	233.150
9/1/2006-9/24/2006	27.537	258.150
9/24/2006-10/31/2006	27.681	324.345
10/31/2006-11/30/2006	27.681	355.095
11/30/2006-12/31/2006	32.016	382.350
12/31/2006-1/31/2007	32.016	419.835
1/31/2007-3/30/2007	38.543	523.683
3/30/2007-4/25/2007	40.629	622.031
4/25/2007-5/29/2007	43.041	686.431
5/29/2007-6/28/2007	43.041	745.886
6/28/2007-7/31/2007	43.041	825.582
7/31/2007-8/31/2007	43.041	896.183
8/31/2007-9/28/2007	57.493	977.683

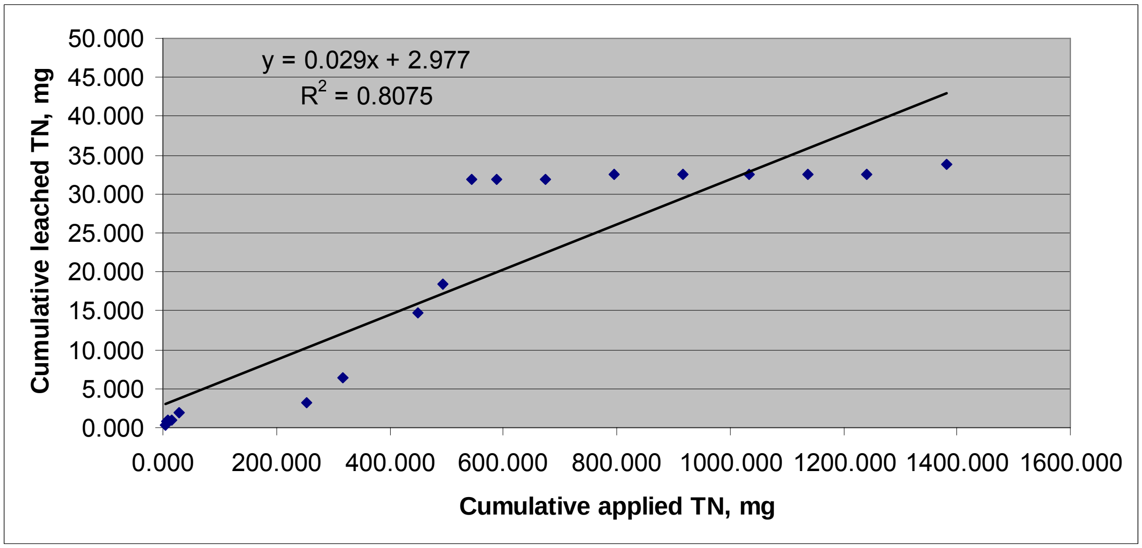

Figure 4. 15 The plots of cumulative applied TN and leached TN for Houston soil in a sampler

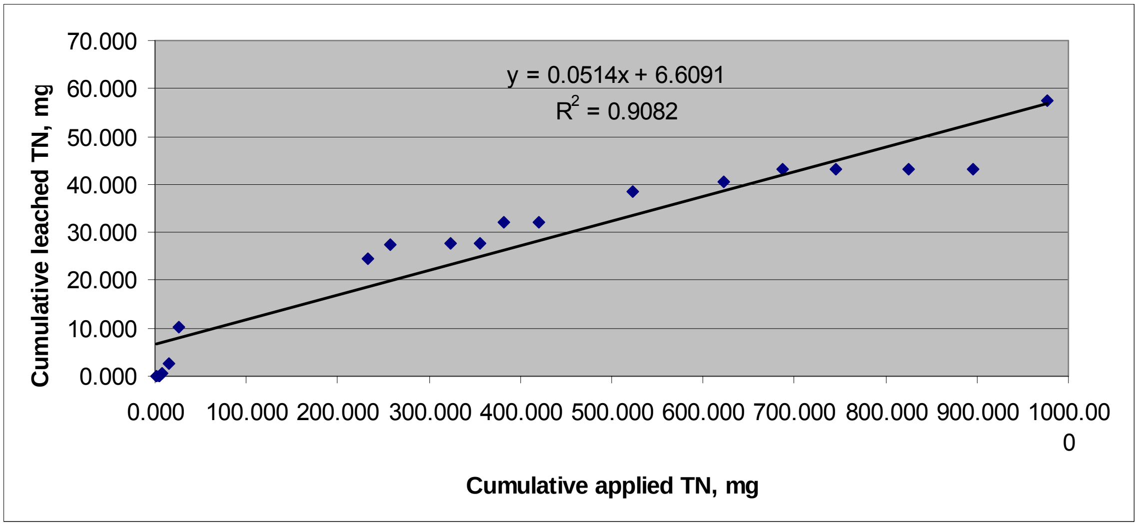

Figure 4. 16 The plots of cumulative applied TN and leached TN for Midland soil in a sampler

Table 4. 20 The cumulative TN concentration for Houston soil

Sampling date	Cumulative leached TN, mg	Cumulative leached water, mL	Cumulative TN concentration, mg/L
12/29/2005	0.394	801	0.492
2/10/2006	0.771	1746	0.442
4/6/2006	0.893	2049	0.436
5/25/2006	0.893	2071	0.431
7/23/2006	1.972	3126	0.631
9/1/2006	3.134	4247	0.738
9/24/2006	6.378	4827	1.321
10/31/2006	14.746	6522	2.261
11/30/2006	18.384	7486	2.456
12/31/2006	31.969	8680	3.683
1/31/2007	31.969	9367	3.413
3/30/2007	31.969	9367	3.413
4/25/2007	32.569	9649	3.376
5/29/2007	32.569	9649	3.376
6/28/2007	32.569	9649	3.376
7/31/2007	32.569	9649	3.376
8/31/2007	32.569	9689	3.361
9/28/2007	33.821	10541	3.209

Table 4. 21 The cumulative TN concentration for Midland soil

Sampling date	Cumulative leached TN, mg	Cumulative leached water, mL	Cumulative TN concentration, mg/L
12/29/2005	0.026	6	4.758
2/10/2006	0.026	6	4.758
4/6/2006	0.724	169	4.286
5/25/2006	2.748	501	5.485
7/23/2006	10.280	779	13.202
9/1/2006	24.574	1329	18.493
9/24/2006	27.537	1802	15.286
10/31/2006	27.681	1898	14.583
11/30/2006	27.681	1898	14.583
12/31/2006	32.016	2801	11.432
1/31/2007	32.016	3636	8.807
3/30/2007	38.543	4790	8.047
4/25/2007	40.629	5614	7.238
5/29/2007	43.041	6506	6.616
6/28/2007	43.041	6506	6.616
7/31/2007	43.041	6506	6.616
8/31/2007	43.041	6506	6.616
9/28/2007	57.493	7358	7.814

Table 4. 22 Cumulative removal ratio of TN of Houston soil

Sampling period	Cumulative leached TN, mg	Cumulative applied TN, mg	Removal ratio, %
11/28/2005-12/29/2005	0.394	4.000	90.15
12/29/2005-2/10/2006	0.771	6.400	87.96
2/10/2006-4/6/2006	0.893	9.200	90.29
4/6/2006-5/25/2006	0.893	14.950	94.02
5/25/2006-7/23/2006	1.972	29.450	93.31
7/23/2006-9/1/2006	3.134	254.450	98.77
9/1/2006-9/24/2006	6.378	316.950	97.99
9/24/2006-10/31/2006	14.746	449.565	96.72
10/31/2006-11/30/2006	18.384	492.615	96.27
11/30/2006-12/31/2006	31.969	543.468	94.12
12/31/2006-1/31/2007	31.969	588.156	94.56
1/31/2007-3/30/2007	31.969	674.556	95.26
3/30/2007-4/25/2007	32.569	796.192	95.91
4/25/2007-5/29/2007	32.569	915.792	96.44
5/29/2007-6/28/2007	32.569	1032.885	96.85
6/28/2007-7/31/2007	32.569	1136.908	97.14
7/31/2007-8/31/2007	32.569	1240.166	97.37
8/31/2007-9/28/2007	33.821	1381.666	97.55

Table 4. 23 Cumulative removal ratio of TN of Midland soil

Sampling period	Cumulative leached TN, mg	Cumulative applied TN, mg	Removal ratio, %
11/28/2005-12/29/2005	0.026	2.200	98.81
12/29/2005-2/10/2006	0.026	4.600	99.43
2/10/2006-4/6/2006	0.724	7.400	90.22
4/6/2006-5/25/2006	2.748	14.650	81.24
5/25/2006-7/23/2006	10.280	25.650	59.92
7/23/2006-9/1/2006	24.574	233.150	89.46
9/1/2006-9/24/2006	27.537	258.150	89.33
9/24/2006-10/31/2006	27.681	324.345	91.47
10/31/2006-11/30/2006	27.681	355.095	92.20
11/30/2006-12/31/2006	32.016	382.350	91.63
12/31/2006-1/31/2007	32.016	419.835	92.37
1/31/2007-3/30/2007	38.543	523.683	92.64
3/30/2007-4/25/2007	40.629	622.031	93.47
4/25/2007-5/29/2007	43.041	686.431	93.73
5/29/2007-6/28/2007	43.041	745.886	94.23
6/28/2007-7/31/2007	43.041	825.582	94.79
7/31/2007-8/31/2007	43.041	896.183	95.20
8/31/2007-9/28/2007	57.493	977.683	94.12

4.6 Salt Balance

4.6.1 Temporal distribution of average leached salt

A summary of the calculations of salinity at the TTU site are shown in **Table 4.24** and **Table 4.25**, respectively. The weighted average salinity in leach water at each sampling date for Houston and Midland samplers are plotted in **Figure 4.17** and **Figure 4.18**, respectively, and the average leached mass of salt with ±standard deviation at each sampling date in a sampler for both type of soils are as shown in **Figure 4.19** and **Figure 4.20**, respectively.

4.6.2 Calculation of salt mass balance

The salt mass balances for two types of soils are as shown in **Table 4.26** and **Table 4.27**, respectively.

4.6.3 Accumulated salt mass-in and salt mass out

The plots of the applied salt mass and leached salt mass in each sampling period for Houston and Midland samples is shown in **Figure 4.21** and **Figure 4.22**, respectively.

The plots of the average cumulative salt mass input and salt mass output and their relationship is shown in **Figure 4.23** and **Figure 4.24**, respectively, along with their regression model results.

4.6.4 Ratio of accumulated stored salt in the soil

The ratio of average accumulated salt in a sampler's soil for both types of samples are calculated in **Table 4.28** and **Table 4.29**, respectively.

Table 4. 24 The summarization of salinity for Houston soil

		Sampler Number								
Sampling Date		1	2	3	4	5	6	Total	Average	**W/W**
12/29/2005	Salinity (µS/cm)	2790	3710	3680	2680	3170	2760		3113	1492
	Volume, mL	1227	478	1136	820	551	594	4806	801	2000
	Salinity (mg/L)	1894	2517	2497	1820	2151	1874		2113	1016
	Mass, mg	2324	1203	2836	1492	1185	1113	10154	1692	2031
2/10/2006	Salinity (µS/cm)	2060	3080	2920	2390	2480	2710		2561	1346
	Volume, mL	1234	750	1028	1000	950	706	5668	945	2400
	Salinity (mg/L)	1400	2091	1982	1623	1684	1840		1739	917
	Mass, mg	1728	1568	2038	1623	1600	1299	9856	1643	2200
4/6/2006	Salinity (µS/cm)	2130	2600	n/a	2500	n/a	n/a		2398	1346
	Volume, mL	625	460	0	735	0	0	1820	303	2800
	Salinity (mg/L)	1447	1766	n/a	1698	n/a	n/a		1629	917
	Mass, mg	905	812		1248			2965	494	2567
5/25/2006	Salinity (µS/cm)	n/a	n/a	3630	n/a	n/a	n/a		3630	1148
	Volume, mL	0	0	130	0	0	0	130	22	5750
	Salinity (mg/L)	n/a	n/a	2463	n/a	n/a	n/a		2463	783
	Mass, mg			320				320	53	4501
7/23/2006	Salinity (µS/cm)	2850	3490	2600	2840	3480	2900		2994	903
	Volume, mL	1330	1150	1420	985	810	635	6330	1055	14500
	Salinity (mg/L)	1935	2368	1766	1928	2361	1969		2033	617
	Mass, mg	2573	2723	2507	1899	1913	1250	12866	2144	8945
9/1/2006	Salinity (µS/cm)	2780	3450	4440	2500	3110	2340		3096	885
	Volume, mL	1300	1395	950	1280	995	810	6730	1122	9000
	Salinity (mg/L)	1887	2341	3011	1698	2111	1590		2101	605
	Mass, mg	2454	3266	2861	2173	2100	1288	14141	2357	5443
9/24/2006	Salinity (µS/cm)	3370	3420	4850	2660	3270	2680		3201	1278
	Volume, mL	748	970	225	1185	190	160	3478	580	2500
	Salinity (mg/L)	2287	2321	3289	1806	2219	1820		2172	871
	Mass, mg	1711	2251	740	2140	422	291	7555	1259	2177
10/31/2006	Salinity (µS/cm)	3090	2650	3800	2780	3210	2330		3004	1758
	Volume, mL	1460	1550	1910	2100	1700	1450	10170	1695	5894
	Salinity (mg/L)	2097	1799	2578	1887	2179	1583		2039	1196
	Mass, mg	3062	2789	4924	3964	3704	2295	20737	3456	7047
11/30/2006	Salinity (µS/cm)	4050	3220	4010	3800	4080	3320		3800	1847
	Volume, mL	1120	840	1216	1750	480	380	5786	964	2100
	Salinity (mg/L)	2747	2185	2720	2578	2767	2253		2578	1256
	Mass, mg	3077	1836	3308	4511	1328	856	14916	2486	2637
12/31/2006	Salinity (µS/cm)	3480	3130	3660	3230	3840	2540		3355	1643
	Volume, mL	1220	1020	1800	1510	790	820	7160	1193	2211
	Salinity (mg/L)	2361	2124	2483	2192	2605	1725		2277	1118
	Mass, mg	2881	2167	4470	3310	2058	1415	16300	2717	2472

Continued

		Sampler Number								
Sampling Date		1	2	3	4	5	6	Total	Average	**W/W**
3/30/2007	Salinity (µS/cm)	n/a	n/a	n/a	n/a	n/a	n/a			1598
	Volume, mL	0	0	0	0	0	0	0	0	3600
	Salinity (mg/L)	n/a	n/a	n/a	n/a	n/a	n/a			1087
	Mass, mg	▨	▨	▨	▨	▨	▨	0	0	3915
4/25/2007	Salinity (µS/cm)	4540	4190	4520	3000	n/a	n/a		4135	1641
	Volume, mL	330	976	162	220	0	0	1688	281	5176
	Salinity (mg/L)	3079	2842	3065	2036	n/a	n/a		2805	1116
	Mass, mg	1016	2774	497	448	▨	▨	4734	789	5779
5/29/2007	Salinity (µS/cm)	n/a	n/a	n/a	n/a	n/a	n/a			1676
	Volume, mL	0	0	0	0	0	0	0	0	5200
	Salinity (mg/L)	n/a	n/a	n/a	n/a	n/a	n/a			1140
	Mass, mg	▨	▨	▨	▨	▨	▨	0	0	5929
6/28/2007	Salinity (µS/cm)	n/a	n/a	n/a	n/a	n/a	n/a			1645
	Volume, mL	0	0	0	0	0	0	0	0	5091
	Salinity (mg/L)	n/a	n/a	n/a	n/a	n/a	n/a			1119
	Mass, mg	▨	▨	▨	▨	▨	▨	0	0	5698
7/31/2007	Salinity (µS/cm)	n/a	n/a	n/a	n/a	n/a	n/a			1696
	Volume, mL	0	0	0	0	0	0	0	0	6119
	Salinity (mg/L)	n/a	n/a	n/a	n/a	n/a	n/a			1154
	Mass, mg	▨	▨	▨	▨	▨	▨	0	0	7060
8/31/2007	Salinity (µS/cm)	11580	n/a	n/a	n/a	n/a	n/a		11580	1696
	Volume, mL	243	0	0	0	0	0	243	41	6074
	Salinity (mg/L)	7844	n/a	n/a	n/a	n/a	n/a		7844	1154
	Mass, mg	1906	▨	▨	▨	▨	▨	1906	318	7008
9/28/2007	Salinity (µS/cm)	7300	9510	10870	8130	13190	12510		10082	1734
	Volume, mL	1395	510	1100	550	890	665	5110	852	5660
	Salinity (mg/L)	4947	6443	7364	5509	8934	8474		6830	1179
	Mass, mg	6901	3286	8100	3030	7951	5635	34903	5817	6676

Notes:

1. Gray denotes that leach water is not available for calculation of total nitrogen mass;

2. W/W denotes applied wastewater.

Table 4. 25 The summarization of salinity for Midland soil

		Sampler Number								
Sampling Date		1	2	3	4	5	6	Total	Average	**W/W**
12/29/2005	Salinity (µS/cm)	2500	n/a	n/a	n/a	11590	n/a		9386	1492
	Volume, mL	8	0	0	0	25	0	33	6	1100
	Salinity (mg/L)	1698	n/a	n/a	n/a	7851	n/a		6359	1016
	Mass, mg	14				196		210	35	1117
2/10/2006	Salinity (µS/cm)	n/a	n/a	n/a	n/a	n/a	n/a			1346
	Volume, mL	0	0	0	0	0	0	0	0	2400
	Salinity (mg/L)	n/a	n/a	n/a	n/a	n/a	n/a			917
	Mass, mg							0	0	2200
4/6/2006	Salinity (µS/cm)	4840	n/a	7530	6340	5820	6960		6035	1346
	Volume, mL	350	0	225	105	200	100	980	163	2800
	Salinity (mg/L)	3282	n/a	5103	4297	3945	4717		4091	917
	Mass, mg	1149		1148	451	789	472	4009	668	2567
5/25/2006	Salinity (µS/cm)	8150	8320	6600	n/a	7100	6010		7051	1148
	Volume, mL	455	265	495	0	180	598	1993	332	7250
	Salinity (mg/L)	5522	5637	4473	n/a	4812	4074		4778	783
	Mass, mg	2513	1494	2214		866	2436	9523	1587	5675
7/23/2006	Salinity (µS/cm)	n/a	6270	4450	7070	n/a	4450		4647	903
	Volume, mL	0	140	518	28	0	980	1666	278	11000
	Salinity (mg/L)	n/a	4250	3018	4791	n/a	3018		3151	617
	Mass, mg		595	1563	134		2958	5250	875	6786
9/1/2006	Salinity (µS/cm)	12770	7030	3820	6550	13370	4180		5779	885
	Volume, mL	282	434	985	360	122	1118	3301	550	8300
	Salinity (mg/L)	8650	4764	2591	4439	9056	2835		3918	605
	Mass, mg	2439	2068	2553	1598	1105	3170	12932	2155	5019
9/24/2006	Salinity (µS/cm)	12200	6320	4380	n/a	15720	3790		5224	1278
	Volume, mL	215	335	1160	0	61	1065	2836	473	1000
	Salinity (mg/L)	8264	4284	2971	n/a	10647	2571		3542	871
	Mass, mg	1777	1435	3446		649	2738	10045	1674	871
10/31/2006	Salinity (µS/cm)	n/a	n/a	2330	n/a	n/a	4520		3387	1758
	Volume, mL	0	0	300	0	0	280	580	97	2942
	Salinity (mg/L)	n/a	n/a	1583	n/a	n/a	3065		2299	1196
	Mass, mg			475			858	1333	222	3518
11/30/2006	Salinity (µS/cm)	n/a	n/a	n/a	n/a	n/a	n/a			1847
	Volume, mL	0	0	0	0	0	0	0	0	1500
	Salinity (mg/L)	n/a	n/a	n/a	n/a	n/a	n/a			1256
	Mass, mg							0	0	1884
12/31/2006	Salinity (µS/cm)	11230	8960	4340	n/a	14680	4060		8629	1643
	Volume, mL	880	860	1074	0	1310	1290	5414	902	1185
	Salinity (mg/L)	7607	6071	2943	n/a	9943	2754		5847	1118
	Mass, mg	6694	5221	3161		13025	3553	31654	5276	1325

Continued

		Sampler Number								
Sampling Date		1	2	3	4	5	6	Total	Average	**W/W**
3/30/2007	Salinity (μS/cm)	3360	4800	4280	17760	5330	4850		4935	1598
	Volume, mL	1156	1210	1354	180	1714	1311	6925	1154	4327
	Salinity (mg/L)	2280	3255	2903	12027	3614	3289		3346	1087
	Mass, mg	2636	3938	3930	2165	6194	4311	23174	3862	4705
4/25/2007	Salinity (μS/cm)	2610	4130	4510	n/a	3410	4280		3654	1641
	Volume, mL	1024	780	868	0	1688	583	4943	824	4185
	Salinity (mg/L)	1772	2801	3059	n/a	2314	2903		2479	1116
	Mass, mg	1815	2185	2655	▨	3906	1692	12253	2042	4672
5/29/2007	Salinity (μS/cm)	3180	5870	4310	n/a	4900	7050		4987	1676
	Volume, mL	1210	1120	1240	0	765	1020	5355	893	2800
	Salinity (mg/L)	2158	3979	2923	n/a	3322	4778		3381	1140
	Mass, mg	2611	4457	3625	▨	2542	4873	18108	3018	3192
6/28/2007	Salinity (μS/cm)	n/a	n/a	n/a	n/a	n/a	n/a			1645
	Volume, mL	0	0	0	0	0	0	0	0	2585
	Salinity (mg/L)	n/a	n/a	n/a	n/a	n/a	n/a			1119
	Mass, mg	▨	▨	▨	▨	▨	▨	0	0	2893
7/31/2007	Salinity (μS/cm)	n/a	n/a	n/a	n/a	n/a	n/a			1696
	Volume, mL	0	0	0	0	0	0	0	0	4688
	Salinity (mg/L)	n/a	n/a	n/a	n/a	n/a	n/a			1154
	Mass, mg	▨	▨	▨	▨	▨	▨	0	0	5409
8/31/2007	Salinity (μS/cm)	n/a	n/a	n/a	n/a	n/a	n/a			1696
	Volume, mL	0	0	0	0	0	0	0	0	4153
	Salinity (mg/L)	n/a	n/a	n/a	n/a	n/a	n/a			1154
	Mass, mg	▨	▨	▨	▨	▨	▨	0	0	4791
9/28/2007	Salinity (μS/cm)	12960	14730	12800	21400	11290	20500		15530	1734
	Volume, mL	850	1000	700	1230	970	360	5110	852	3260
	Salinity (mg/L)	8778	9976	8670	14491	7648	13882		10518	1179
	Mass, mg	7462	9976	6069	17824	7418	4998	53747	8958	3845

Notes:

1. Gray denotes that leach water is not available for calculation of total nitrogen mass;

2. W/W denotes applied wastewater.

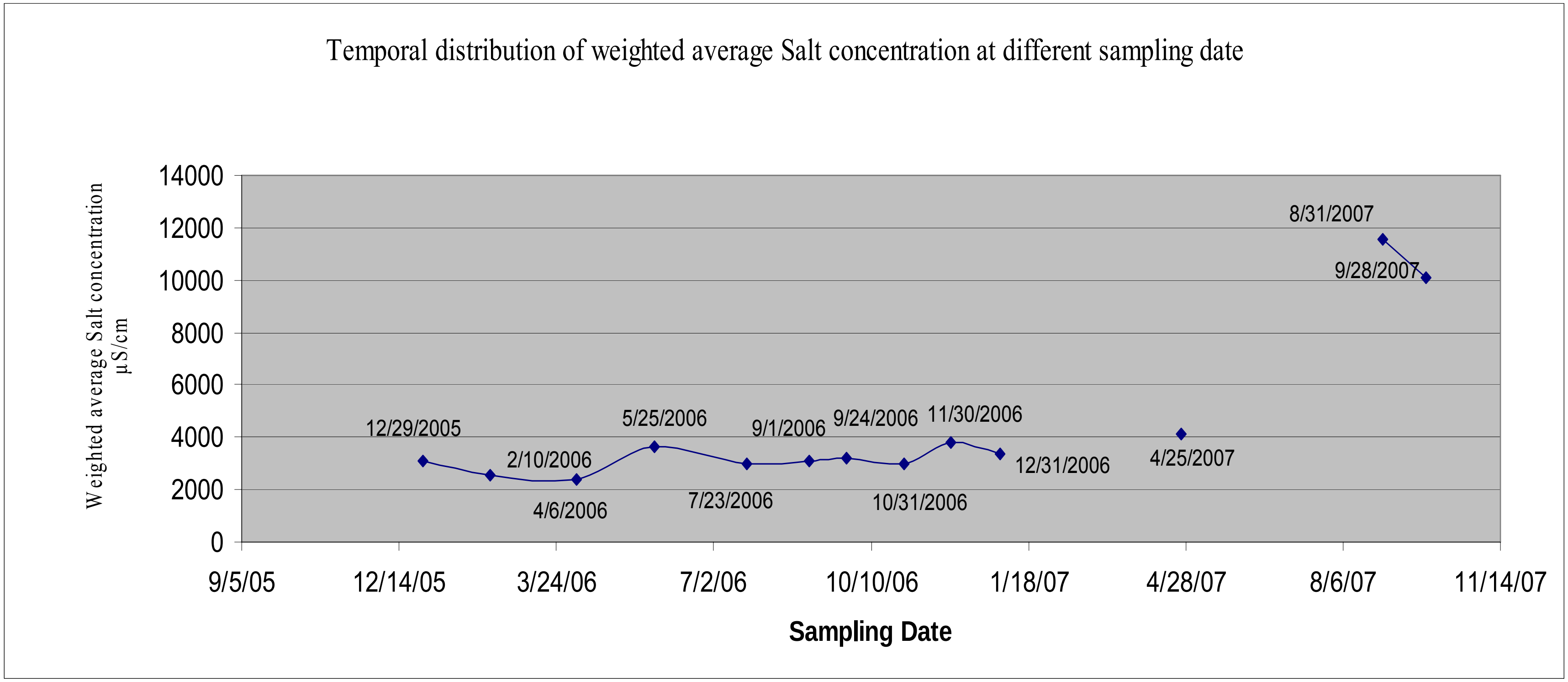

Figure 4. 17 Temporal distribution of weighted average salinity in leached water of Houston samplers

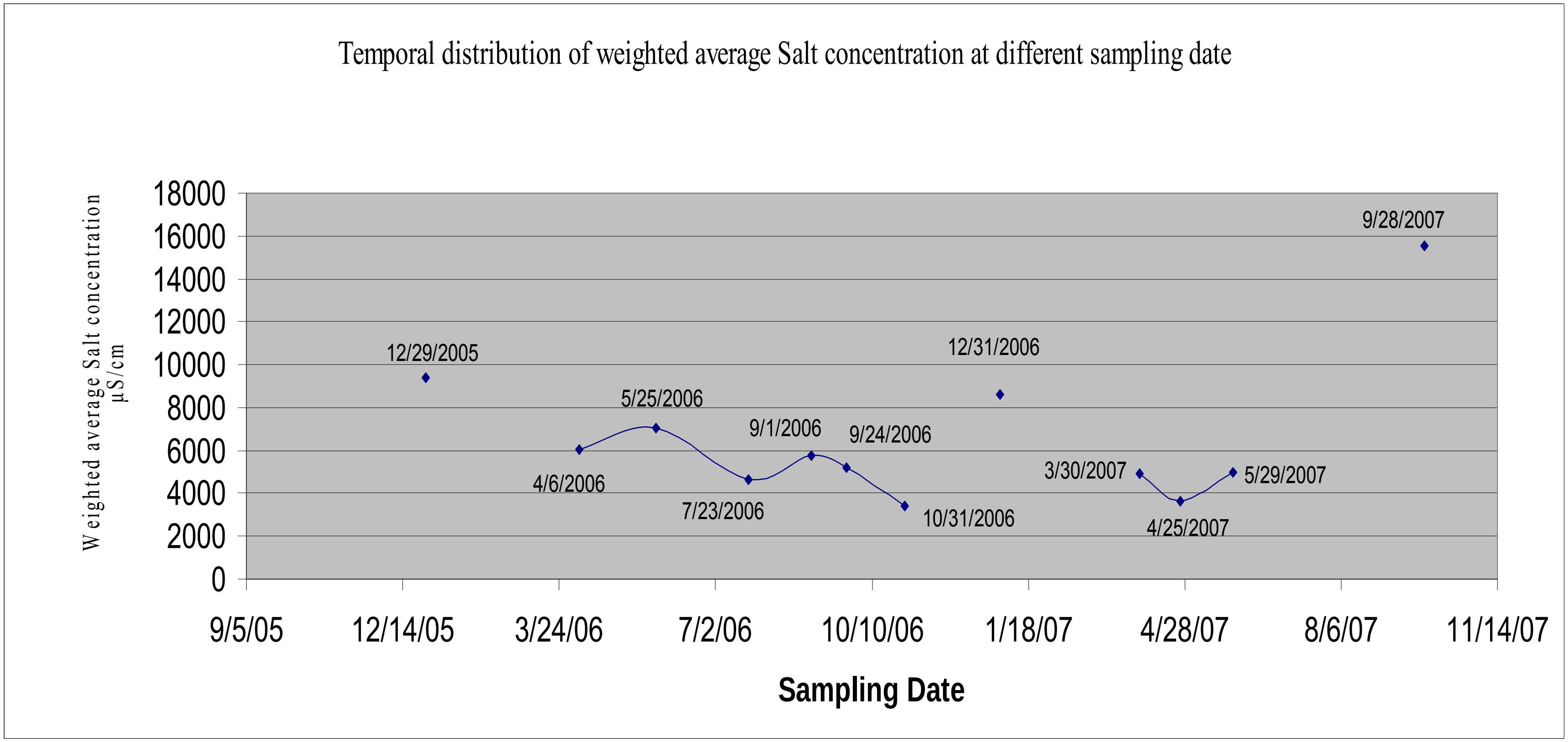

Figure 4. 18 Temporal distribution of weighted average salinity in leached water of Midland samplers

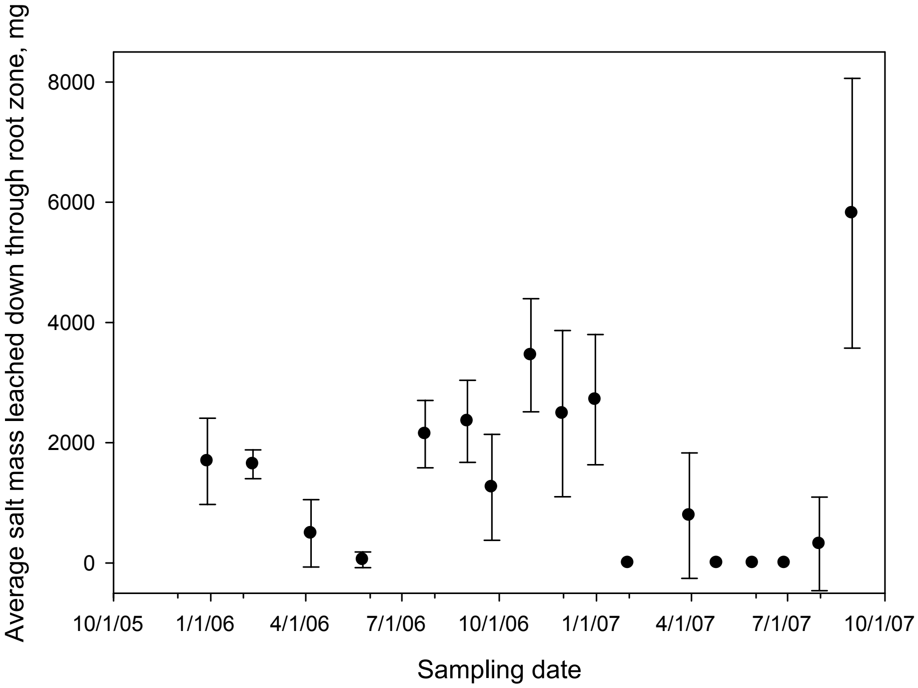

Figure 4. 19 Average leached mass of salt ± standard deviation at each sampling time for the Houston soil

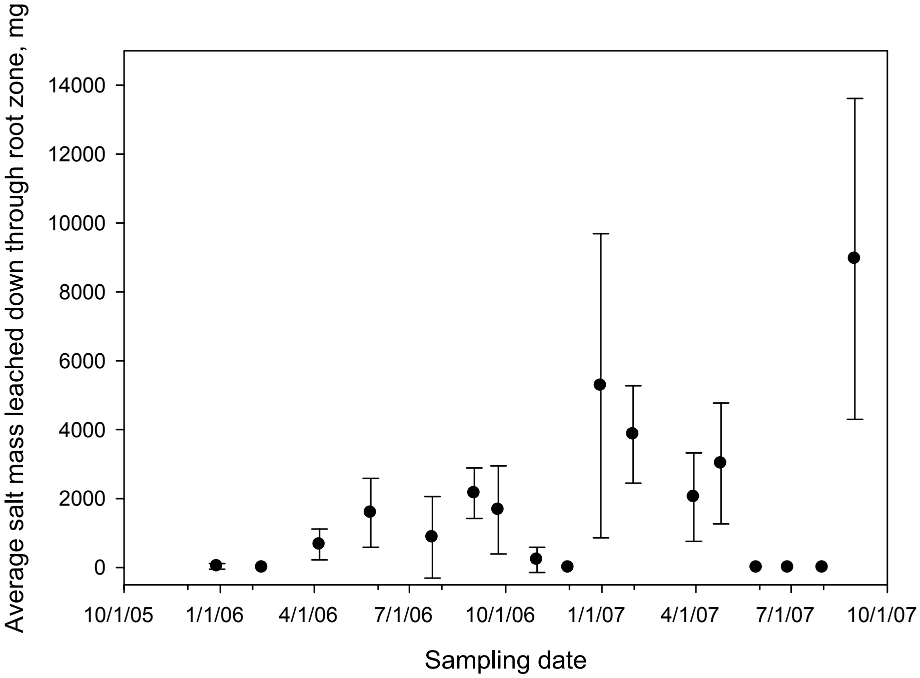

Figure 4. 20 Average leached mass of salt ± standard deviation at each sampling time for the Midland soil

Table 4. 26 Salt mass balance for Houston soil based on a sampler

Sampling period	Salt output, mg	Salt input, mg
11/28/2005-12/29/2005	1692.391	2031.235
12/29/2005-2/10/2006	1642.683	2200.297
2/10/2006-4/6/2006	494.140	2567.013
4/6/2006-5/25/2006	53.361	4500.894
5/25/2006-7/23/2006	2144.289	8945.392
7/23/2006-9/1/2006	2356.864	5442.655
9/1/2006-9/24/2006	1259.125	2176.903
9/24/2006-10/31/2006	3456.227	7047.297
10/31/2006-11/30/2006	2485.976	2637.426
11/30/2006-12/31/2006	2716.627	2471.521
12/31/2006-1/31/2007	0.000	1983.361
1/31/2007-3/30/2007	0.000	3914.529
3/30/2007-4/25/2007	789.046	5778.879
4/25/2007-5/29/2007	0.000	5928.870
5/29/2007-6/28/2007	0.000	5697.763
6/28/2007-7/31/2007	0.000	7059.523
7/31/2007-8/31/2007	317.689	7007.606
8/31/2007-9/28/2007	5817.194	6675.560

Table 4. 27 Salt mass balance for Midland soil based on a sampler

Sampling period	Salt output, mg	Salt input, mg
11/28/2005-12/29/2005	34.976	1117.179
12/29/2005-2/10/2006	0.000	2200.297
2/10/2006-4/6/2006	668.120	2567.013
4/6/2006-5/25/2006	1587.191	5675.040
5/25/2006-7/23/2006	874.989	6786.160
7/23/2006-9/1/2006	2155.357	5019.337
9/1/2006-9/24/2006	1674.208	870.761
9/24/2006-10/31/2006	222.189	3517.670
10/31/2006-11/30/2006	0.000	1883.876
11/30/2006-12/31/2006	5275.625	1324.628
12/31/2006-1/31/2007	0.000	1663.675
1/31/2007-3/30/2007	3862.413	4705.046
3/30/2007-4/25/2007	2042.155	4672.451
4/25/2007-5/29/2007	3017.965	3192.468
5/29/2007-6/28/2007	0.000	2893.089
6/28/2007-7/31/2007	0.000	5408.570
7/31/2007-8/31/2007	0.000	4791.338
8/31/2007-9/28/2007	8957.892	3844.934

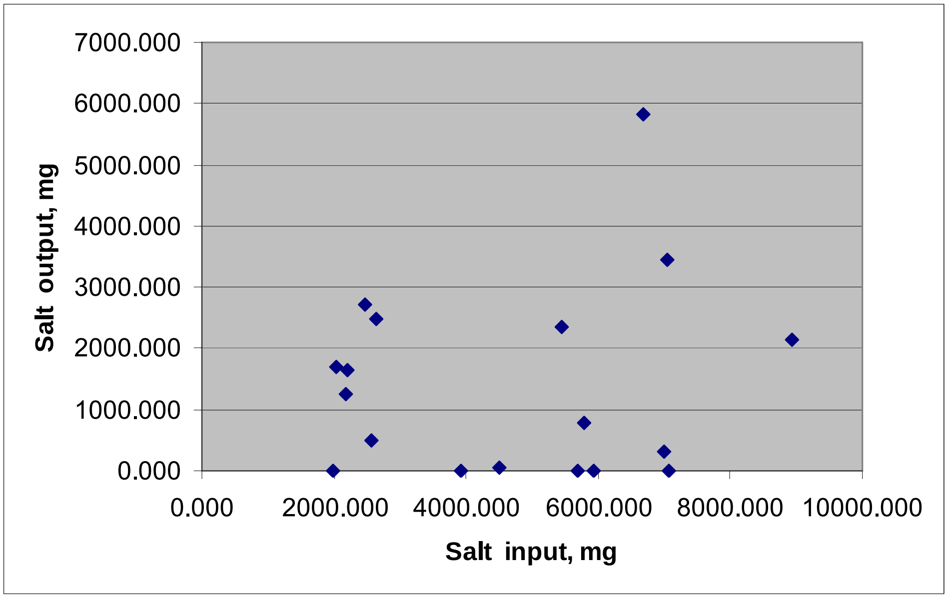

Figure 4. 21 Salt mass input and output in a sampler of Houston soil.

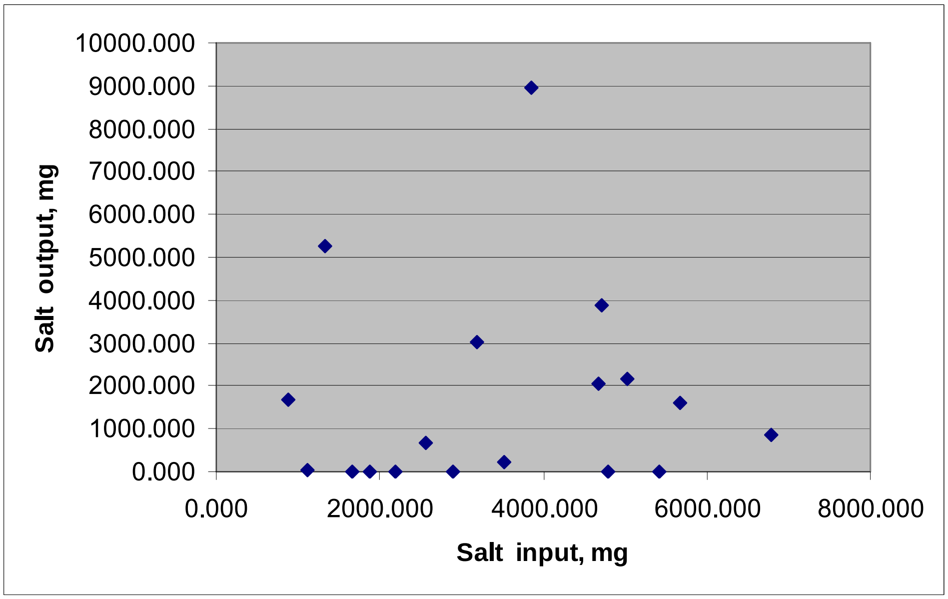

Figure 4. 22 Salt mass input and output in a sampler of Midland soil.

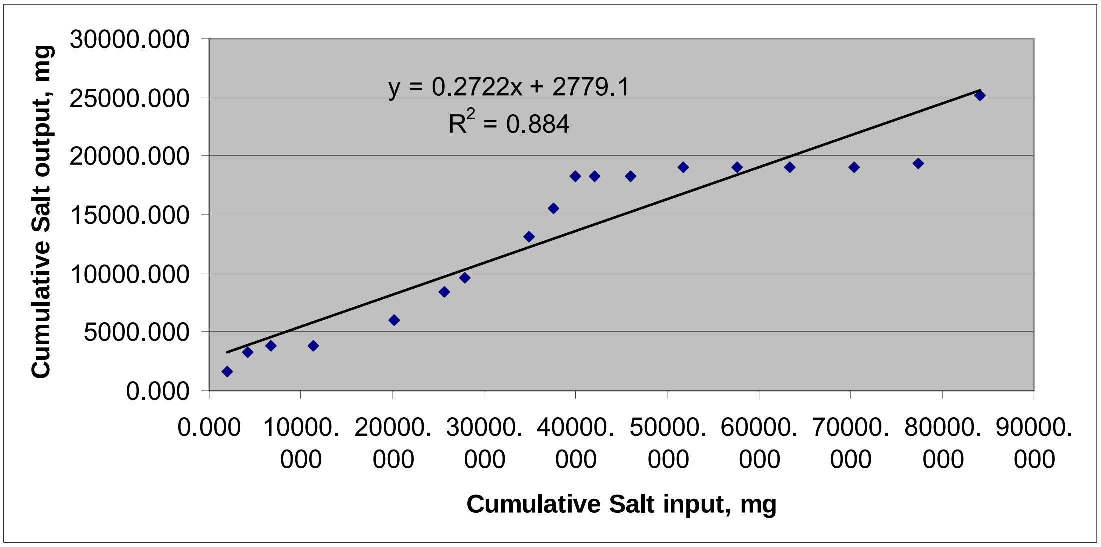

Figure 4. 23 The regression relationship between average accumulated salt mass input and output for a sampler of Houston soil.

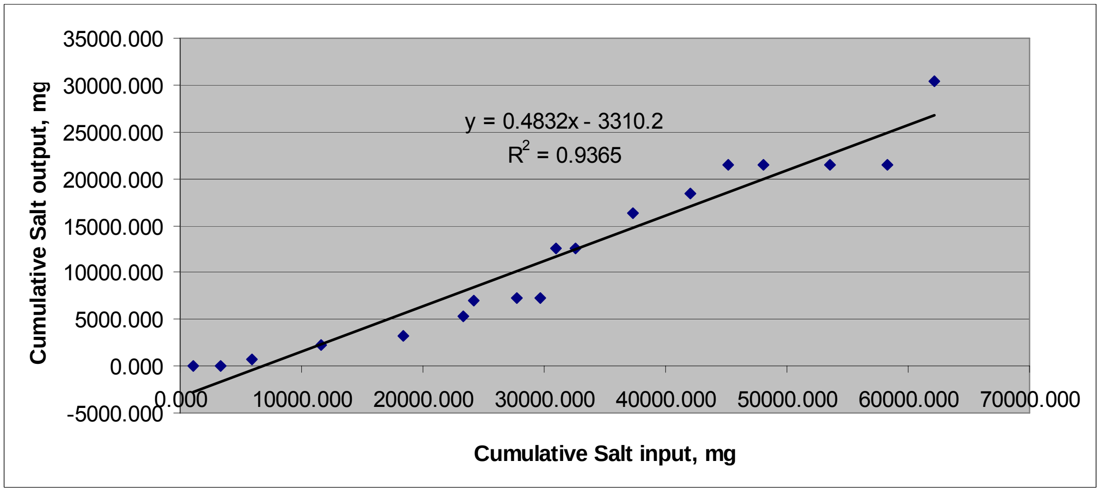

Figure 4. 24 The regression relationship between average accumulated salt mass input and output for a sampler of Midland soil.

Table 4. 28 Salt mass storage ratio for Houston soil

Sampling period	Accumulated Salt output, mg	Accumulated Salt input, mg	Storage ratio, %
11/28/2005-12/29/2005	1692.391	2031.235	16.68
12/29/2005-2/10/2006	3335.074	4231.532	21.19
2/10/2006-4/6/2006	3829.215	6798.545	43.68
4/6/2006-5/25/2006	3882.576	11299.439	65.64
5/25/2006-7/23/2006	6026.865	20244.831	70.23
7/23/2006-9/1/2006	8383.729	25687.485	67.36
9/1/2006-9/24/2006	9642.855	27864.388	65.39
9/24/2006-10/31/2006	13099.081	34911.685	62.48
10/31/2006-11/30/2006	15585.057	37549.111	58.49
11/30/2006-12/31/2006	18301.684	40020.633	54.27
12/31/2006-1/31/2007	18301.684	42003.994	56.43
1/31/2007-3/30/2007	18301.684	45918.523	60.14
3/30/2007-4/25/2007	19090.729	51697.401	63.07
4/25/2007-5/29/2007	19090.729	57626.271	66.87
5/29/2007-6/28/2007	19090.729	63324.034	69.85
6/28/2007-7/31/2007	19090.729	70383.557	72.88
7/31/2007-8/31/2007	19408.419	77391.163	74.92
8/31/2007-9/28/2007	25225.613	84066.722	69.99

Table 4. 29 Salt mass storage ratio for Midland soil

Sampling period	Accumulated Salt output, mg	Accumulated Salt input, mg	Storage ratio, %
11/28/2005-12/29/2005	34.976	1117.179	96.87
12/29/2005-2/10/2006	34.976	3317.476	98.95
2/10/2006-4/6/2006	703.097	5884.489	88.05
4/6/2006-5/25/2006	2290.287	11559.529	80.19
5/25/2006-7/23/2006	3165.276	18345.688	82.75
7/23/2006-9/1/2006	5320.633	23365.025	77.23
9/1/2006-9/24/2006	6994.842	24235.786	71.14
9/24/2006-10/31/2006	7217.031	27753.457	74.00
10/31/2006-11/30/2006	7217.031	29637.333	75.65
11/30/2006-12/31/2006	12492.655	30961.961	59.65
12/31/2006-1/31/2007	12492.655	32625.635	61.71
1/31/2007-3/30/2007	16355.068	37330.681	56.19
3/30/2007-4/25/2007	18397.223	42003.133	56.20
4/25/2007-5/29/2007	21415.188	45195.601	52.62
5/29/2007-6/28/2007	21415.188	48088.690	55.47
6/28/2007-7/31/2007	21415.188	53497.261	59.97
7/31/2007-8/31/2007	21415.188	58288.599	63.26
8/31/2007-9/28/2007	30373.080	62133.532	51.12

CHAPTER V

DISCUSSION

This chapter discusses some new findings during the research. Those findings are illustrated in the sections of water balance, nitrogen balance, and salt balance.

5.1 Water balance

In water balance, precipitation patterns, the difference between designed leaching and measured leaching, the leaching pattern, and the implication to the design are discussed. The precipitation is an important parameter to the water leaching.

5.1.1 Precipitation Patterns

The precipitation (PPT) data at Littlefield during the period of Oct 2005 to Sept 2007 shows that there were 14 months with PPT above the 30-year average and ten with PPT below the average (**Figure 5. 1** and **Figure 5. 2**). From Oct 2005 to June 2006, all months except May 2006, the PPT was lower than normal, but from July 2006 to Sept 2007, all months except July and August 2007 were above normal. The lowest normal PPT is in January with 0.61 inches and the highest normal PPT is in June with 2.98 inches. However, the lowest PPT during the project happened in Jan 2006 with 0.02 inches, and the highest PPT appeared in Dec 2006 with 7.11 inches. As shown in **Figure 5. 2**, the highest shift away from the recorded average PPT was in Dec 2006 with 6.43 inches and the highest one below average was in June 2006 with -2.432 inches. The PPT in the months of May and October of 2006 were the two months closest to the average. There were disparities between the two sets of PPT with 3.24% below normal in May 2006 and with 1041.54% above normal in Jan 2007.

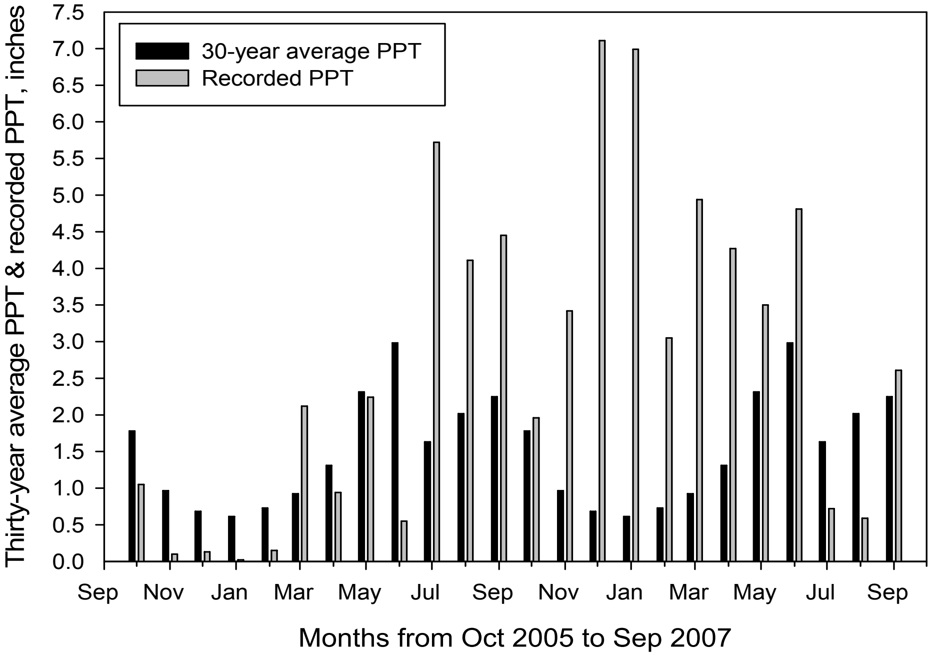

Figure 5. 1 The 30-year average precipitation at Lubbock and recorded precipitation at Littlefield during the period of Oct 2005 to Sept 2007

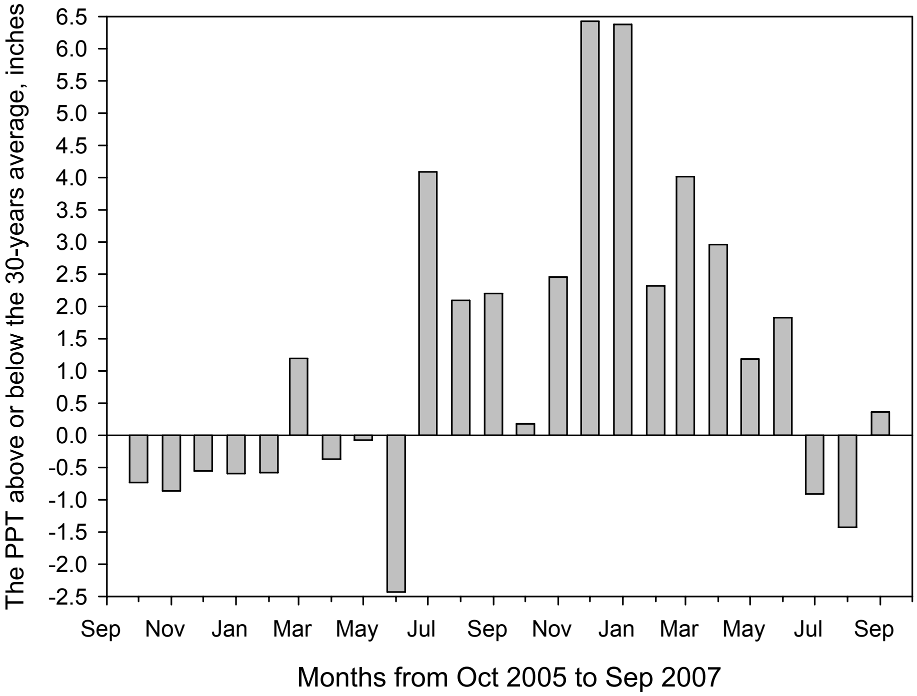

Figure 5. 2 The recorded precipitation at Littlefield above or below the 30-year average precipitation at Lubbock during Oct 2005 to Sept 2007

5.1.2 Expected leaching and measured leaching

To mathematically know the model of water leaching, the conceptual model of water balance (Equation 4.1) used in this research can be converted to Equation 5.1 and 5.2. Also, it can be found that the amount of leachate is the function of precipitation, applied wastewater, evapotranspiration, and the change of soil moisture. As calculated in Chapter IV, the soil moistures in the sampler at saturation, field capacity, and wilting point are 5.892 inches, 3.612 inches, and 2.328 inches, respectively. The soil water higher than field capacity and lower than saturation is supposed to be leached down through the root zone. The soil moisture is assumed not to be less than wilting point. Therefore, the range of the change of soil moisture for this type of sampler (ΔSM) is from 0 inches to 1.284 inches.

$$L_i = P_i + I_i - ET_i - (SM_i - SM_{i-1}) \qquad (5.1)$$

$$L_i = P_i + I_i - ET_i - \Delta SM \qquad (5.2)$$

where, L_i is the leaching that occurs in sampling period i, (inches/sampling period);

P_i is the precipitation in sampling period i, (inches/sampling period);

I_i is the irrigation in sampling period i, (inches/sampling period);

ET_i is the evapotranspiration in sampling period i, (inches/sampling period);

SM_i is the soil moisture in sampling period i, (inches/ sampling period);

SM_{i-1} is the soil moisture in the previous sampling period, (inches/ sampling period);

and ΔSM is the change of soil moisture, (inches/ sampling period).

The average water storage capacities (saturation) of three support layers, sand, pea gravel, and coarse gravel in such type of sampler, are estimated as 705 mL, 557 mL, and 459 mL, respectively. The total average storage capacity of the whole support section of the sampler is calculated as 1721 mL. The ranges of water storage capacities of sand layer, pea gravel layer, and coarse gravel layer, are 410 to 869 mL, 410 to 623 mL, and 393 to 590 mL. And the range of the total storage capacity of the three support layers is 1213 mL to 2082 mL, the lowest limit of which is the sum of the respective lowest limit of those three layers and the highest limit of which is the sum of the respective highest limit of three layers.

The differences of the recorded precipitation and the 30-year average precipitation (PPT), and the difference of measured leaching and designed leaching are summarized in **Table 5. 1**. In this table, if the difference is larger than zero, then "+" is put in the following column; in versus, "-" is set. **Table 5. 1** illustrates that 14 sets of data in twenty sampling periods for two differences in precipitation and leaching amount have the same change direction or trend, though there are different degrees of discrepancy. It illustrates that the difference between measured leaching and designed leaching is not just caused by the difference between the recorded precipitation and the 30-year average precipitation used in the determination of the irrigation scheduling. As shown in Equation 5.2, the leaching amount of deep percolation water is determined by individual and combined function of precipitation, applied wastewater, evapotranspiration, and the change of soil moisture.

Table 5. 1 The difference of the recorded and the 30-year average precipitation (PPT), and the difference of measured leaching and expected leaching

No.	1	2	3	4	5
	Recorded PPTminus 30-year Ave. PPT	Column 1 is positive or negative	Measured leaching minus expected leaching	Column 3 is positive or negative	Sampling period
1	-1.122	-	-0.838	-	10/07/2005-11/28/2005
2	-0.580	-	-0.975	-	11/28/2005-12/29/2005
3	-0.887	-	0.959	+	12/29/2005-2/10/2006
4	0.609	+	0.848	+	2/10/2006-4/6/2006
5	-1.289	-	-0.319	-	4/6/2006-5/25/2006
6	-0.488	-	0.550	+	5/25/2006-6/16/2006
7	2.685	+	0.632	+	6/16/2006-7/21/2006
8	2.874	+	0.750	+	7/21/2006-9/1/2006
9	2.560	+	0.888	+	9/1/2006-9/22/2006
10	-0.759	-	0.673	+	9/22/2006-10/12/2006
11	-0.365	-	-0.968	-	10/12/2006-11/22/2006
12	9.417	+	-0.281	-	11/22/2006-1/9/2007
13	9.007	+	0.434	+	1/9/2007-2/23/2007
14	3.560	+	1.527	+	2/23/2007-3/30/2007
15	0.078	+	0.534	+	3/30/2007-4/25/2007
16	2.171	+	1.378	+	4/25/2007-5/29/2007
17	1.879	+	1.701	+	5/29/2007-6/28/2007
18	-1.109	-	0.560	+	6/28/2007-7/31/2007
19	-1.430	-	0.644	+	7/31/2007-8/31/2007
20	0.510	+	0.485	+	8/31/2007-9/28/2007

It can be seen in **Table 5. 1** that even if the precipitation is much higher than normal one in No. 12 sampling period, 11/22/2006-1/9/2007, the measured leaching, 1.13 inches, is still less than expected one, 1.41 inches. One cause is that the wind blew the snow on and around the samplers and this part of snow did not really enter the sampler soil.

However, the measured leaching in five sampling periods is a little larger than expected when the precipitation is less than normal. There are five of such cases. In the case of sampling period, 12/29/2005-2/10/2006, the reason may be that ET was less than the normal due to low temperature than normal; as a result, it caused higher leaching. During the period of 9/22/2006-10/12/2006, more leaching occurred was caused by the intensive irrigation during UCC test. In the other three sampling periods, higher leaching amount might be the result of less ET than the normal due to insufficient growth of grass.

5.1.3 Leachate passing through the root zone

The pattern of deep percolation passing through the root zone was quite different from one sampling period to another. This is illustrated in Appendix B, Appendix C, and **Figure 4. 1**. The range of leaching amount is from 0.028 inches to 2.100 inches in sampling period. The leaching amount in each sampling period as shown in **Figure 4.1** reflects the time effect. Because the days of each sampling period are not same, from 20 to 55 days, therefore, the higher leaching amounts in some sampling periods might contribute to relatively more days. Accordingly, the daily average leaching amount is plotted as in **Figure 5. 3**. The daily average leaching amount is from 0.001 to 0.060 inches. One reason causing different leaching is identified as the UCC test. For example, three UCC tests conducted in March, three UCC tests between the first to the 12th of October in 2006, two UCC tests on Feb 23, 2007, right before the 14th sampling period, all of those UCC tests caused the high leaching because the wastewater was applied intensively in the relative short time and the ET was kept relative constant. Precipitation in the 9th, 16th, and 17th sampling periods was one of the causes of high leaching. The lower total inputs of water can explain the low leaching in the 2nd, 5th, and 11th sampling periods.

The ratio of leaching to water inputs is expected to be variable because the input of precipitation and irrigation are variable and cannot be controlled, and ET is also variable depending on the weather. The ratio of leaching to the total input in the whole test period is 14.62%, the average ratio of leaching to the total input in each sampling period over the period of study is 15.8%, the ratio of leaching to the total input in each sampling period over the period of study is shown in **Figure 5. 4**, with the range of 0.49 to 37.05%. The pattern is similar to the daily average leaching shown in **Figure 5. 3**. The leaching ratio reflected the combined effect of all kinds of field conditions including climatic conditions, irrigation events and schedule, and irrigation management in each sampling period. The ratio of cumulative leaching amount to the total water input was plotted in **Figure 5. 5**. There is a trend in this figure that the ratio is close to be identical since the third sampling period and finally stable on the range of 12-14%. Such relative stable trend reflects the cumulative effect for the individual sampling period and averages the effects of all kinds of field impacting factors for the ratio of leaching to the total input.

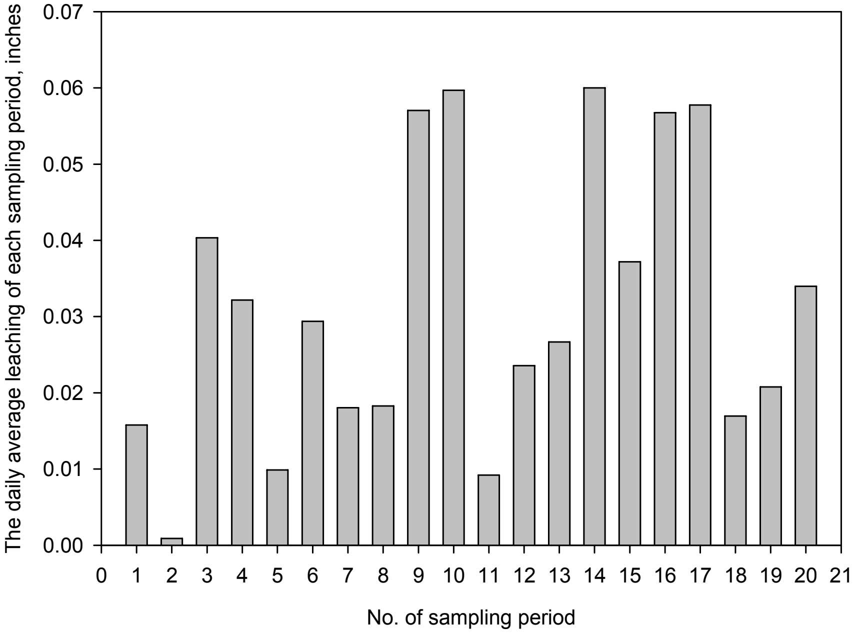

Figure 5. 3 The daily average leaching of each sampling period, the No. of sampling period can be referred to Table 5.1.

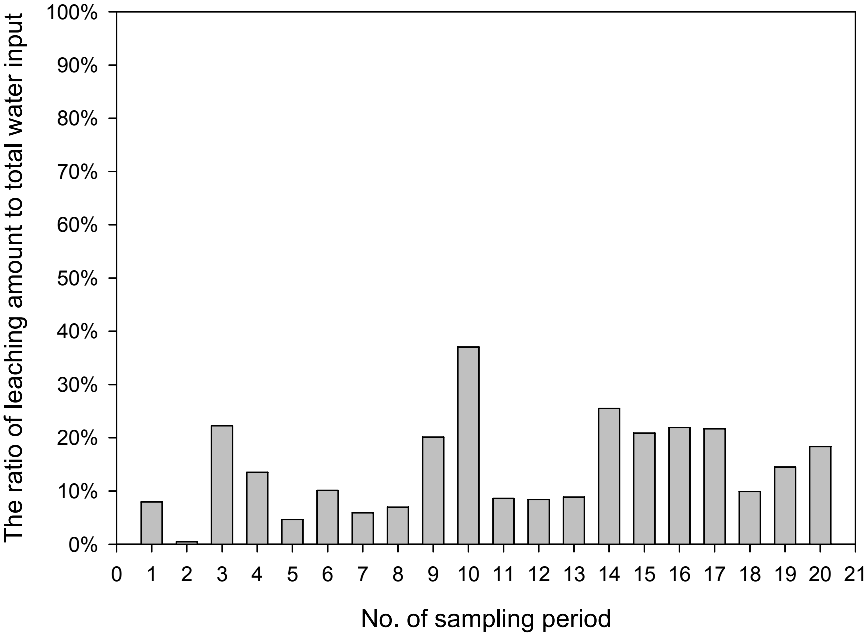

Figure 5. 4 The ratio of leaching amount to total water input including applied wastewater and precipitation, the No. of sampling period can be referred to Table 5.1.

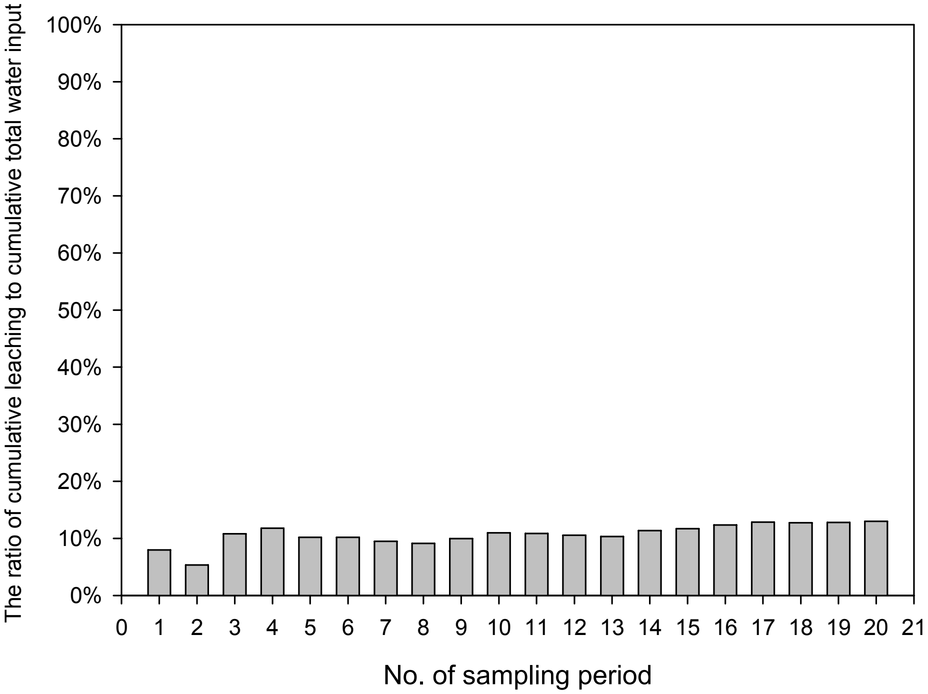

Figure 5. 5 The ratio of cumulative leaching amount to cumulative total water input. the No. of sampling period in Table 5.1.

5.2 Nitrogen balance

In this research, nitrogen grass uptake was tested for some periods; it is included in this section. And total nitrogen in the leached water and the applied wastewater, and the removal ratio of total nitrogen, nitrate-nitrogen, and ammonia-nitrogen are discussed in this section.

5.2.1 Grass yield and nitrogen uptake

Monthly grass (Bermuda grass) samples were harvested and carried away from the research site for the analysis of water moisture, yield, and TKN from April to Oct 2007; and the staff of the wastewater treatment plant at the city of Littlefield mowed the grass in the remaining months during the research. The highest moisture content in grass was in April, 70.41%, and the lowest was in Oct, 38.38% when grass was becoming dry (**Table 5. 2**). Peaked dry yield was in Oct, 572 kg per hectare per month; and lowest dry yield was in May, 178 kg per hectare per month. In reality, at this research site, grass is mowed and not carried; therefore, this part of nitrogen was not really removed from the land application system.

Wastewater effluent composition may be responsible for the variation of monthly nitrogen uptake (Barton et al. 2005). In the land application system, if nitrogen removal mechanism by plant uptake is taken good advantage of, a cut-and-carry approach should be employed (Williamson et al. 1998).

Table 5. 2 Removed TKN by grass mowing during the period of April 2007 to Oct 2007

Sampling Date	4/25/2007	5/29/2007	8/31/2007	9/28/2007	10/31/2007
Moisture, %	70.41	70.03	64.43	69.72	38.38
Wet yield, kg/acre	510	240	538	498	376
Dry yield, kg/acre	151	72	191	151	232
TKN, %	2.82	1.63	2.11	2.85	2.25
Removed TKN, kg/acre	4.26	1.17	4.04	4.30	5.21
Removed TKN, mg/one sampler	33.922	9.346	32.186	34.257	41.554

5.2.2 Total nitrogen leached

There are two apparent peaks of average leached total nitrogen (TN) concentration during the periods, Feb 10 to Apr 6, 2006 and Nov 22, 2006 to Jan 9, 2007, with the volume weighted average concentrations of 4.97 mg/L and 5.12 mg/L, respectively (**Figure 4. 2**). Totally, two summers in 2006 and 2007 have lower volume weighted average concentrations of leached TN concentrations. Due to the difference in length of each sampling period, concentration, and the leached water quantity, the daily average leached total nitrogen mass needs to be plotted to compare the leached nitrogen mass in different sampling period. In this research, the volume weighted average total nitrogen concentration was less than 5.12 mg/L, and the EPA's maximum contaminant level (MCL) for nitrate-nitrogen in public water supplies is 10 mg/L (Klocke et al. 1999), so there was no potential nitrogen contamination to the groundwater in this research.

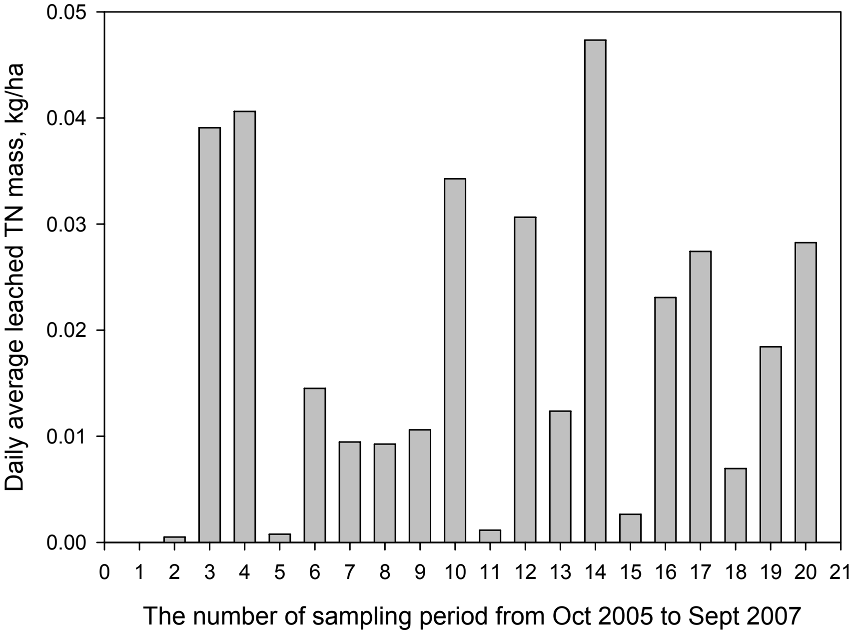

Figure 5. 6 Daily average leached total nitrogen mass during the project. The number of sampling period can be referred to Table 5. 1.

It can be seen in **Figure 5. 6** that the peaks of daily average leached TN mass occurred in the third, fourth, tenth, twelfth and fourteenth sampling periods. The higher daily leached total mass happened mainly in the winter and spring (**Figure 5. 6**). However, the tenth had a relative high leaching TN mass; the reason is because three UCC tests were conducted just in three days, therefore, more total water (the total of scheduled wastewater, wastewater used for UCC tests, and precipitation) flushed nitrogen down in the short sampling period. And the peaks in winter and spring were because the plants nitrogen uptake rate went down and denitrification rate may also slow down in the low temperature, which results in more total nitrogen leaching in winter. In this research, the total nitrogen concentration in wastewater effluent is high in winter and spring, but low in summer and fall. This specific applied wastewater composition is also responsible for this phenomenon. Therefore, in this research site, leached total nitrogen mass depends on the leachate volume, season, irrigated wastewater amount and composition, the capacity of plant nitrogen uptake, and denitrification.

The loss or removal of total nitrogen is mainly due to plant uptake with the management of cut and carry-away model and denitrification. In the wastewater land treatment system similar to this study, the ammonia volatilization is neglected because the applied ammonia concentration is relatively minor. Crop nitrogen uptake is not considered as an output if the grass was mowed but stays in the system during nitrogen mass balance. In such a system, denitrification is the main removal mechanism, and system should be designed so that denitrification is maximized. Denitrification is the function of substrate (carbon, nitrogen available to microorganisms), oxygen, temperature in the soil profile, water moisture content in the soil, and other soil characteristics (Luo et al. 1999).

5.2.3 Nitrogen removal

The total nitrogen, nitrate-nitrogen, and ammonia-nitrogen were tested in this study for the applied wastewater and the leached water in different sampling periods. **Table 5. 3** provides their concentrations in the influent of the designed land application system (the effluent of the pond system) and in the effluent of the land application system, and the mass removal efficiency.

Table 5. 3 Nitrogen removal data by the land application system. TN means total nitrogen; NO_3^- in the table is nitrate-nitrogen; NH_4^+ is ammonia-nitrogen.

No.	Sampling period	Influent			Effluent			Removal		
		Concentration, mg/L			Concentration, mg/L			%		
		TN	NO_3^-	NH_4^+	TN	NO_3^-	NH_4^+	TN	NO_3^-	NH_4^+
1	10/07/2005-11/28/2005	12.00	5.75	2.90	0.00	0.00	0.00	100	100	100
2	11/28/2005-12/29/2005	16.00	3.35	4.50	2.24	0.00	0.00	100	100	100
3	12/29/2005-2/10/2006	16.50	3.40	5.30	3.81	2.24	0.01	95	85	100
4	2/10/2006-4/6/2006	19.00	2.40	5.20	4.97	3.29	0.19	96	78	99
5	4/6/2006-5/25/2006	18.00	2.70	6.40	0.31	0.00	0.00	100	100	100
6	5/25/2006-6/16/2006	15.00	5.00	2.80	1.95	0.34	0.08	97	98	99
7	6/16/2006-7/21/2006	8.50	5.00	0.12	2.06	0.24	0.08	97	99	92
8	7/21/2006-9/1/2006	7.00	5.20	0.14	1.99	1.08	0.07	96	97	93
9	9/1/2006-9/22/2006	6.00	3.90	0.02	0.73	0.54	0.01	92	91	85
10	9/22/2006-10/12/2006	5.00	4.15	0.16	2.78	2.06	0.04	80	82	91
11	10/12/2006-11/22/2006	12.00	4.70	1.80	0.49	0.03	0.03	99	100	100
12	11/22/2006-1/9/2007	16.00	4.10	2.60	5.12	1.45	0.33	88	86	95
13	1/9/2007-2/23/2007	10.00	5.75	3.50	1.82	1.48	0.01	94	91	100
14	2/23/2007-3/30/2007	17.00	4.25	4.10	3.10	1.36	0.03	89	82	100
15	3/30/2007-4/25/2007	17.00	4.70	4.70	0.28	0.16	0.01	100	99	100
16	4/25/2007-5/29/2007	12.50	8.20	0.01	1.60	1.13	0.01	94	94	74
17	5/29/2007-6/28/2007	8.00	5.10	1.05	1.87	1.08	0.03	87	88	99
18	6/28/2007-7/31/2007	6.00	4.70	0.30	1.61	1.13	0.05	97	97	98
19	7/31/2007-8/31/2007	5.00	3.15	0.49	3.50	1.77	0.06	88	91	98
20	8/31/2007-9/28/2007	7.50	5.75	1.44	3.27	1.52	0.01	84	90	100
Max		19.00	8.20	6.40	5.12	3.29	0.33	100	100	100
Min		5.00	2.40	0.01	0.00	0.00	0.00	80	78	74

The range of total nitrogen, nitrate-nitrogen, and ammonia-nitrogen in the applied wastewater were 5 mg/L to 19 mg/L, 2.4 mg/L to 8.2 mg/L, and 0.01 mg/L to 6.40 mg/L, respectively. The concentrations of total nitrogen, nitrate-nitrogen, and ammonia-nitrogen in the leached water were 0 mg/L to 5.12 mg/L, 0 mg/L to 3.29 mg/L, and 0 mg/L to 0.33 mg/L, respectively. Their mass removal efficiencies were 80% to 100%, 78% to 100%, and 74% to 100% in different sampling period, respectively. And the average mass removals of total nitrogen, nitrate-nitrogen, and ammonia-nitrogen by the land application system were 94%, 92%, and 96%, respectively. The cumulative mass removals in the two-year period were 96%, 93%, and 100% for total nitrogen, nitrate-nitrogen, and ammonia-nitrogen.

Total nitrogen concentration fluctuated with the change of the time in the two-year period in the applied wastewater (**Figure 5. 7**), which is also the effluent of the pond system. Total nitrogen concentration was high from the winter to spring and even early summer, but low in the summer and fall. The ammonia-nitrogen also exhibited a similar tendency of variation. The tendency of change of ammonia-nitrogen is in agreement with the previous research results of the lagoon effluent (Surampalli et al. 2007). The nitrate-nitrogen concentration in the applied wastewater was relatively stable in this research. Removal of nitrogen is a function of pH, temperature, and detention time in a pond system with the nitrogen removal up to 95% (USEPA 2006). And the primary long-term and permanent removal of nitrogen is caused by ammonia volatilization in the pond system (USEPA 2006). Ammonia volatilization mainly depends on pH and temperature and increases with the increase of pH and temperature. This illustrates the varying tendency of total nitrogen and ammonia-nitrogen in this study. The pond system is often employed as a type of pre-application treatment. The removal of nitrogen in the pond system directly influences the design of the following slow rate land application system due to the importance of nitrogen as one of the Limiting Design Parameters (USEPA 2006).

The long-term and permanent removal of nitrogen in the land application system is primarily controlled by the plant nitrogen up-take and the denitrification in the plant root zone, which are positively influence by the temperature in the system. In addition, the nitrogen concentration is higher in winter and spring than other seasons of the year in the incoming secondary wastewater effluent from the pond system; therefore, generally, the total nitrogen concentration may be higher in winter and spring in the leached water. Ammonia-nitrogen in this study was almost completely removed after the wastewater land treatment system. The main removal mechanisms for ammonia-nitrogen in the land application system are plant up-take, ammonia volatilization, and nitrification; and are plant up-take, denitrification, and immobilization for nitrate-nitrogen. The nitrate-nitrogen in the leached water was much lower than 10 mg/L, which is the requirement by USEPA. Tzanakakis et al. (2007) found that high nitrate concentration in the soil solution in the slow rate wastewater land application system, therefore, they proposed that the appropriate pre-treatment of wastewater should be conducted to reduce the potential risks of nitrate contamination to the groundwater. There was a pond system working to pre-treat the wastewater for the following land application system. Therefore, the nitrate-nitrogen in the leached water was below the level of risks for potential contamination.

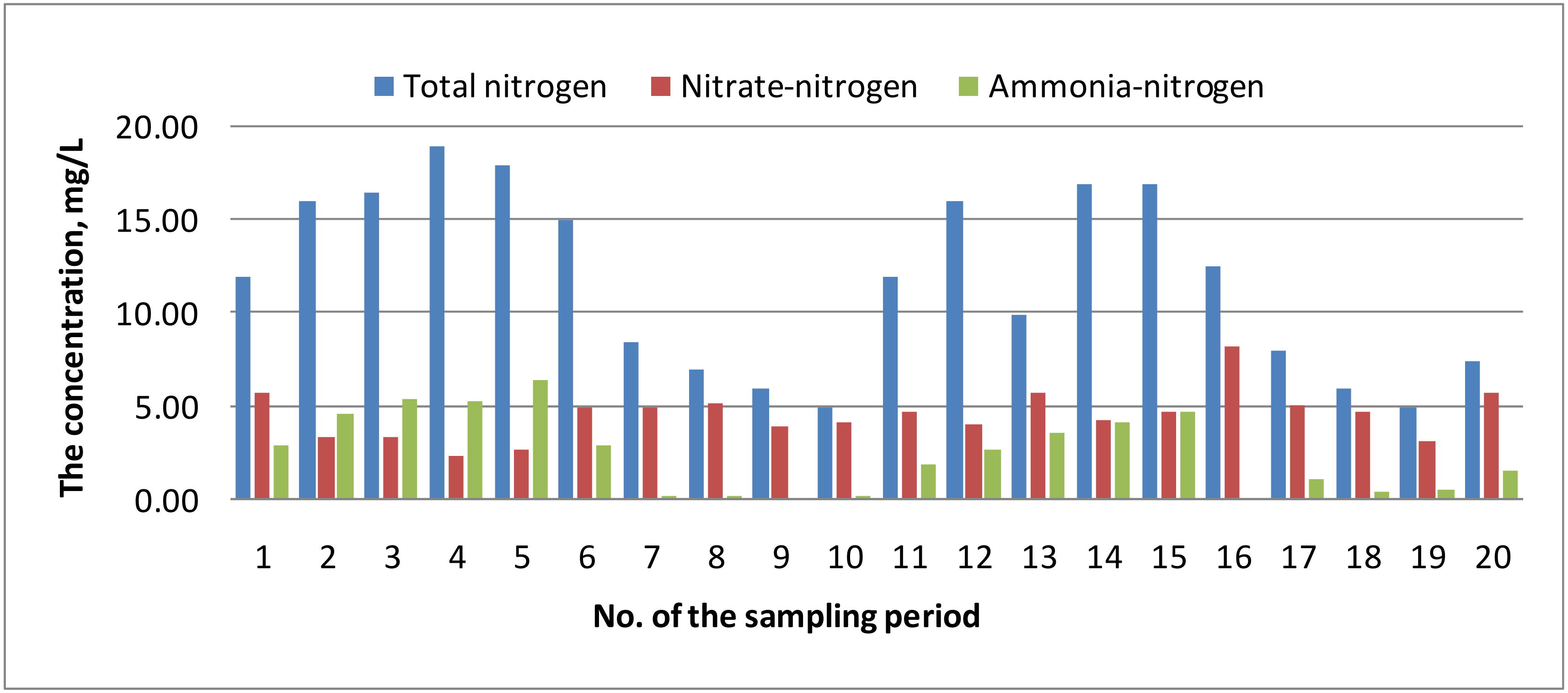

Figure 5. 7 The concentration of total nitrogen, nitrate-nitrogen, and ammonia-nitrogen in the applied wastewater. The number of the sampling period can be referred to Table 5.1

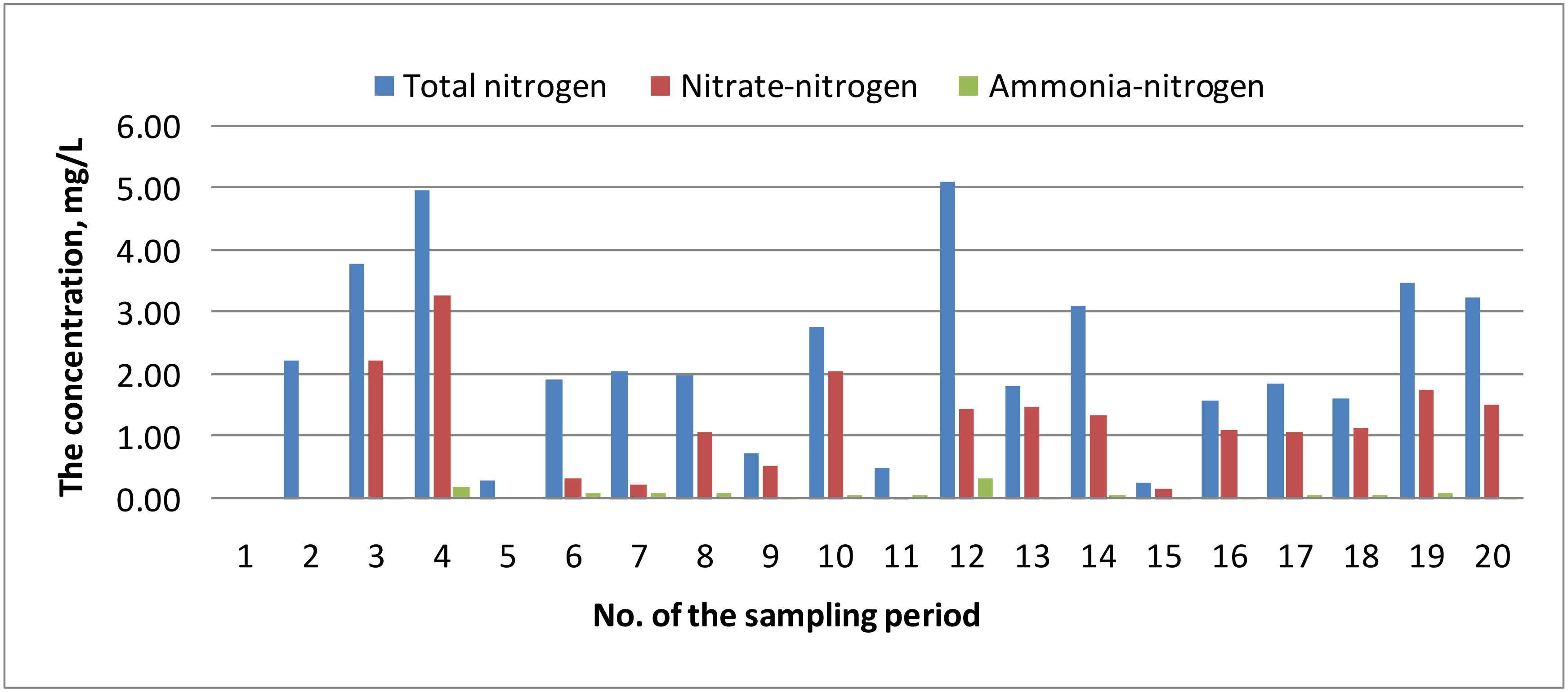

Figure 5. 8 The concentration of total nitrogen, nitrate-nitrogen, and ammonia-nitrogen in effluent of the land application system to the groundwater passing through the grass root zone. The number of the sampling period can be referred to Table 5. 1

5.3 Salt Balance

This section includes the discussion of salt concentration and mass in the applied wastewater and the leached wastewater, salt mass balance in the root zone of the land application system, and the leaching requirement and the leaching factor. Some concepts concerning salt balance and salt accumulation are reviewed and examined in this research.

5.3.1 Salt concentration and mass

Salt concentration was represented by salinity (electrical conductivity, µS/cm). Salt concentration of the applied wastewater showed lower levels and less variation than that of the leached water (**Figure 5. 9**). The salinity in the applied wastewater used for discussion was the average of the salinity of samples collected in two adjacent sampling periods. The salinity in the leached water is the volume weighted average of the salinity in all samplers. The salinity in the applied wastewater was 963±95 µS/cm (Mean ± SD) from Oct 7, 2005 (day 0) to Sept 28, 2007 (day 721) with the coefficient of variation (CV) of 9.88% and the standard error of 2.16%. The ranges of salinity in the leached water and in the applied wastewater were 1261 to 2794 µS/cm and 839 to 1147µS/cm, respectively.

The leached salt mass and the applied salt mass were summarized in **Table 5. 4** in unit of g/m^2 and in **Table 4.10** in unit of g/sampler. The range of CV for the salt mass in the leached water was from 31% to 199%. It showed a large variability of salt mass collected in the different samplers. One of the reasons for the large variability was the low individual field irrigation distribution uniformities caused by highly variable wind directions and the frequent winds with speed higher than 10 MPH at the Littlefield site. The low irrigation distribution uniformity caused by the specific climatic conditions resulted in some samplers receiving more applied wastewater and thus salt while other samplers received less water during a given irrigation event.

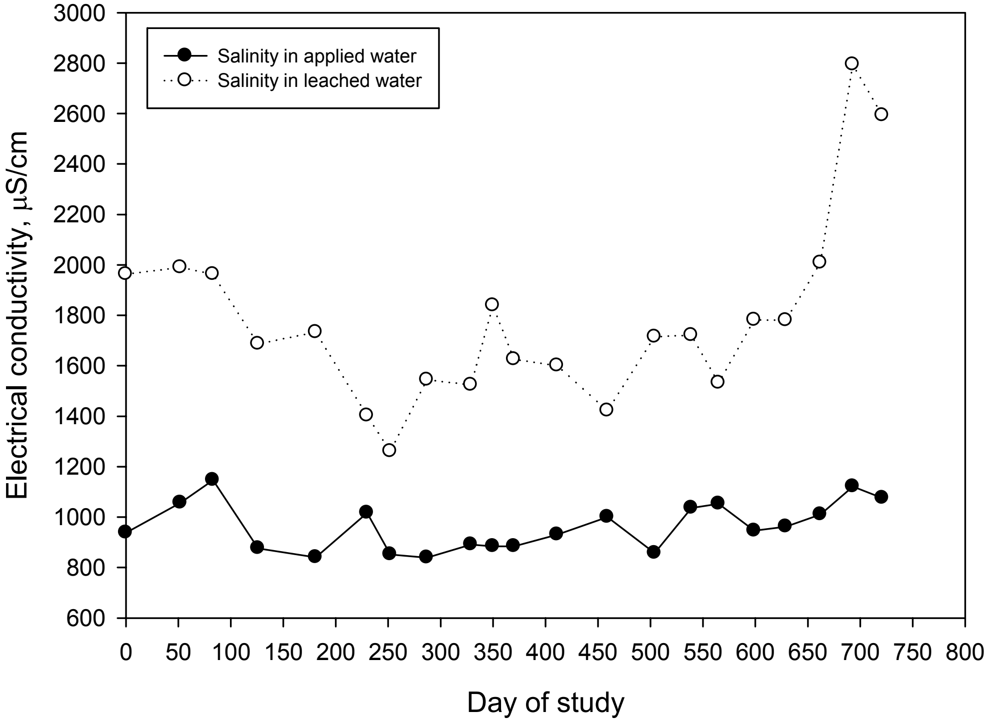

Figure 5. 9 Salinity (electrical conductivity) in applied water and volume weighted average salinity in leached water

5.3.2 Salt mass balance in the root zone

The salt in the root zone was concentrated primarily by the mechanism of evapotranspiration (Corwin et al. 2007). Salt accumulation can be investigated by the method of a salt mass balance. The concept of salt mass balance in a hydrological representative volume, which is $\mathrm{Salt}_{\mathrm{In}} - \mathrm{Salt}_{\mathrm{Out}} =$ Salt balance, was proposed by Scofield for 68 years (Scofield 1940; Thayalakumaran et al. 2007; Wilcox 1963) and was originally utilized at the scale of the root zone (Scofield 1940). There are two terms employed to indicate if salt accumulation happens during wastewater land application. They are the salt balance index (SBI) and salt export ratio (SER) (Gilfedder et al. 1999; Peck and Hurle 1973; Thayalakumaran et al. 2007; Wilcox 1963; Williamson et al. 1997). The SBI and SER is defined as the result of salt output divided by salt input, and indicates that salt accumulation occurs when the SBI or SER is less than one and no salt accumulation when the resulting SBI or SER is larger than one.

SBI or SER represents the change of the amount of salt in the root zone in a wastewater land application system (Rhoades et al. 1997; Thayalakumaran et al. 2007). However, one of its limitations is that SBI or SER cannot indicate whether such change of salt amount brings short term detriment to the land application system or not. Therefore, to evaluate the operation and management of the land application systems, the leaching fraction (LF) and the leaching requirement (LR) should be considered. The leaching fraction (LF) is calculated with Equation 5. 3 for the crop root zone (Corwin et al. 2007; Thayalakumaran et al. 2007). And the LR is determined by Equation 5. 4 (Ayers and Westcot 1976).

$$LF = \frac{V_{dw}}{V_{iw}} = \frac{EC_{iw}}{EC_{dw}} \qquad (5.\ 3)$$

Where, V_{dw} is the volume of drainage water (mm or inches);

V_{iw} is the volume of infiltrating irrigation water (mm or inches);

EC_{iw} is the electrical conductivity (EC) of the irrigation water (dS/m);

and EC_{dw} is the electrical conductivity (EC) of the drainage water (dS/m).

$$LR = \frac{EC_w}{5EC_e - EC_w} \qquad (5.\ 4)$$

where, LR is the minimum leaching requirement needed to control salt accumulation in the soil;

EC_w is the electrical conductivity of the irrigation water (micromhos/cm);

and EC_e is the electrical conductivity of the saturation extract of soil for a given crop appropriate to the tolerable degree of yield reduction--usually 10% or less (micromhos/cm). The relationship between ECe and yield reduction of a crop can be obtained in Ayers and Westcot (1976).

During the period from Oct 10, 2005 to Sept 28, 2007, the masses of total applied salt, total leached salt, and total mass stored salt, were 1608 g/m^2, 636 g/m^2, and 973 g/m^2, respectively. In twenty sampling periods, the salt was accumulated except the periods of Sept 1, 2006 to Sept 22, 2006 and May 29, 2007 to June 28, 2007 with the SBI or SER of 1.28 and 1.01, respectively.

Although salt was found to accumulate in this study of approximately two years, the salt accumulation was not proof of failure of the design of this system. The time for a land application system to reach salt equilibrium (Salt mass in = salt mass out) varies from a year to a few years (Sheng and Xiuling 1997; Thayalakumaran et al. 2007), or even "longer (15-30 years) in discharge areas where soils are poorly leached and the water table is close to the root-zone" (Thayalakumaran et al. 2007). Therefore, to investigate the time to reach salt equilibrium in the system designed by mass balance approach, more research should be conducted. Applying more water onto the land is considered to be one practice to shorten the time of salt mass balance to reach the equilibrium; also soil texture plays an important role for salt mass out of the root zone. The better the soils are leached, the shorter time to realize the favorable salt mass balance. In addition, climatic conditions have significant influences on the salt balance in the root zone (Jolly et al. 1998; Sheng and Xiuling 1997; Thayalakumaran et al. 2007; Tyagi 2003; Williams 2005).

The salt mass balance can be utilized as the indicator of salinization in the root zone (Scofield 1940; Thayalakumaran et al. 2007) and to assess the appropriateness of leaching and irrigation practices (Rhoades et al. 1997; Thayalakumaran et al. 2007). However, the salt mass balance can not be used to evaluate the absolute salinity levels and the spatial distribution of salinity in the root zone (Thayalakumaran et al. 2007).

Table 5. 4 The salt mass in the leached water and in the applied wastewater

Sampling Date	The leached salt			The applied salt
	Mass, g/m^2	SD, g/m^2	CV, %	Mass,g/m^2
10/07/2005-11/28/2005	29	19	67	173
11/28/2005-12/29/2005	1	2	199	112
12/29/2005-2/10/2006	51	25	50	119
2/10/2006-4/6/2006	53	22	42	160
4/6/2006-5/25/2006	12	13	110	157
5/25/2006-6/16/2006	14	10	71	36
6/16/2006-7/21/2006	17	9	56	81
7/21/2006-9/1/2006	20	17	85	84
9/1/2006-9/22/2006	40	21	52	31
9/22/2006-10/12/2006	28	32	115	42
10/12/2006-11/22/2006	11	15	140	48
11/22/2006-1/9/2007	28	22	78	51
1/9/2007-2/23/2007	36	15	41	53
2/23/2007-3/30/2007	63	21	33	66
3/30/2007-4/25/2007	26	13	48	63
4/25/2007-5/29/2007	60	19	32	70
5/29/2007-6/28/2007	54	17	31	53
6/28/2007-7/31/2007	20	17	85	87
7/31/2007-8/31/2007	31	41	131	75
8/31/2007-9/28/2007	43	28	66	48

5.3.3 Leaching requirement and leaching fraction

The leaching requirement (LR) in all twenty sampling periods ranged from 0.02 to 0.03 (**Table 5. 5**). The LR was calculated using Equation 5. 4, and the EC_e of 8.5 dS/m (8500 μS/cm) was taken from Ayers and Westcot (1976). In the **Table 5. 5**, LF-1 is obtained with the definition of leaching fraction, and it is the result of the measured leached water divided by irrigated water during the sampling period, but LF-2 is the result of the collected water divided by total water input including applied wastewater and precipitation. Therefore, it is impossible for LF-2 to be higher than LF-1. LF-1 ranged from 0.00 to 0.62, and LF-2 ranged from 0.00 to 0.30 during the research period. The SBI/SER had the range of 0.01 to 1.28. There were two sampling periods in which the SBI/SER was larger than 1.00. Therefore, in those two sampling periods, 9/1/2006-9/22/2006 and 5/29/2007-6/28/2007, there were no salt accumulation. In addition, in the sampling period of 2/23/2007-3/30/2007, the SBI/SER was 0.95 close to 1 and the salt accumulation was relatively small. In the sampling period of 9/1/2006-9/22/2006, 5/29/2007-6/28/2007, and 2/23/2007-3/30/2007, LF-1 and LF-2 were 0.62 and 0.20, 0.55 and 0.22, and 0.58 and 0.26, respectively. Those data showed that the relative high ratio of the leached water to irrigated wastewater caused no salt accumulation in the sampling period, but the relative leaching fraction was caused by relative high precipitation.

The leaching fraction was higher than the leaching requirement in all sampling periods but the sampling period of 11/28/2005-12/29/2005. This showed that the target soil salinity in the root zone was achieved, which was always less than 8500 μS/cm. The data of salinity in the leached water was less than 8500 μS/cm (**Figure 5. 9**). The LR was determined with consideration of the salinity in applied wastewater and the salinity in the root zone that plant can tolerance with 10% of yield reduction. However, salt was accumulated during the period of the whole study (**Figure 5. 10**). It illustrated that even if the LR was satisfied under the field conditions with the LF was higher than LR, the salt accumulation still happened. Therefore, it is possible for the land to have the risk of salinization even if the LR is satisfied.

Table 5. 5 Leaching requirements, leaching fraction, and SBI/SER

Sampling Date	LF-1	LF-2	LR	SBI/SER
10/07/2005-11/28/2005	0.09	0.08	0.03	0.17
11/28/2005-12/29/2005	0.00	0.00	0.03	0.01
12/29/2005-2/10/2006	0.22	0.22	0.02	0.43
2/10/2006-4/6/2006	0.16	0.14	0.02	0.34
4/6/2006-5/25/2006	0.05	0.05	0.02	0.08
5/25/2006-6/16/2006	0.27	0.16	0.02	0.39
6/16/2006-7/21/2006	0.12	0.06	0.02	0.21
7/21/2006-9/1/2006	0.14	0.07	0.02	0.24
9/1/2006-9/22/2006	0.62	0.20	0.02	1.28
9/22/2006-10/12/2006	0.36	0.30	0.02	0.66
10/12/2006-11/22/2006	0.13	0.09	0.02	0.22
11/22/2006-1/9/2007	0.39	0.21	0.02	0.55
1/9/2007-2/23/2007	0.34	0.25	0.02	0.68
2/23/2007-3/30/2007	0.58	0.26	0.02	0.95
3/30/2007-4/25/2007	0.28	0.21	0.03	0.41
4/25/2007-5/29/2007	0.45	0.22	0.02	0.85
5/29/2007-6/28/2007	0.55	0.22	0.02	1.01
6/28/2007-7/31/2007	0.11	0.10	0.02	0.22
7/31/2007-8/31/2007	0.17	0.14	0.03	0.41
8/31/2007-9/28/2007	0.37	0.18	0.03	0.89

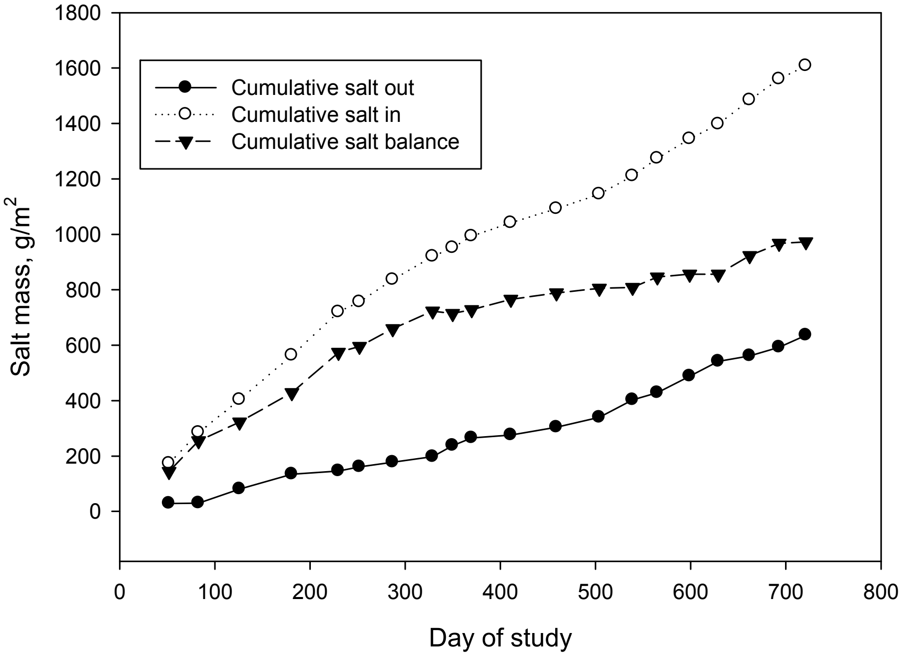

Figure 5. 10 Cumulative salt mass in, mass out, and mass stored in the root zone

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CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

The major objectives in this field study were completed in a two-year period. In the case study of a wastewater land application system designed by an innovative design approach from water balance, nitrogen balance, and salt balance, the quantity and quality, including nitrogen and salinity, of the leached water was investigated. The components in the water balance, which was proposed by Texas Tech University, were quantified under real field conditions with a land application system. The conceptual models for nitrogen balance and salt balance were set up, and the simplified models were utilized by quantifying the respective components to investigate the environmental impacts of wastewater land application in terms of nitrogen and salt. It can be concluded from this field study that wastewater can be effectively surface applied to land as long as it is done in an environmentally sound method, such as with a mass balance approach. The findings are summarized in the following.

6.1 Water balance

Water balance is considered as the primary step to design an environmentally sound wastewater land application system. The leaching amount passing through the plant root zone in the land application is the function of precipitation, irrigation, evapotranspiration, and the change of the soil moisture in a period. During this study, the monthly irrigation schedule was determined by the mass balance model with the assumption that the change of soil moisture is zero. The 30-year average monthly precipitation was employed in the determination of monthly irrigation schedule, and evapotranspiration was adopted from the manual of mean crop consumptive use and free water evaporation for Texas in the scheduling and mass balance. The designed leaching amount was based on the consideration of nitrogen leaching and salt accumulation. The precipitation was the measured value in the data analysis for water balance.

The irrigation uniformity distribution coefficient was measured at the different season of a year. The individual irrigation uniformity distribution coefficient ranged from

31% to 56% in spring, 49% to 66% in summer, 52% to 75% in fall, and 37% to 51% in winter. However, the annual irrigation uniformity distribution coefficient was 83%. The range of leaching amounts was from 0.03 inches to 2.10 inches for different sampling period with the length of 20 days to 55 days. The daily average leaching amount was from 0.001 to 0.060 inches. The range of coefficient of variation was from 28% to 217%. It can be concluded that the variability of the collected leached water was relatively large. This type of variability might be due to the poor individual irrigation distribution uniformity under field conditions. Generally, the high leaching happened in the winter and spring and the low leaching in summer and fall. The excess water leaching was a result of excess precipitation over the 30-year average precipitation, the applied wastewater for the tests of the irrigation distribution uniformity coefficient, and less evapotranspiration than the calculated amount from the published design manual (Borrelli et al. 1988). The ratio of leaching to the total input in each sampling period over the period of study ranged from 0.49% to 37.05%. The ratio of cumulative leaching amount to the total water input was linear following the third sampling period and finally stabilized in the range of 12-14%.

6.2 Nitrogen balance

This study investigated nitrogen leaching based on total nitrogen, nitrate-nitrogen, and ammonia-nitrogen under field conditions in a municipal wastewater land treatment system at the city of Littlefield, Texas. The range of total nitrogen, nitrate-nitrogen, and ammonia-nitrogen in the applied wastewater were 5 mg/L to 19 mg/L, 2.4 mg/L to 8.2 mg/L, and 0.01 mg/L to 6.40 mg/L, respectively. The concentrations of total nitrogen, nitrate-nitrogen, and ammonia-nitrogen in the leached water were 0 mg/L to 5.12 mg/L, 0 mg/L to 3.29 mg/L, and 0 mg/L to 0.33 mg/L, respectively. Their mass removal efficiencies by the land application system were 80% to 100%, 78% to 100%, and 74% to 100% in different sampling period, respectively. And the average mass removals of total nitrogen, nitrate-nitrogen, and ammonia-nitrogen by the land application system were 94%, 92%, and 96%, respectively. The cumulative mass removals in the two-year period were 96%, 93%, and 100% for total nitrogen, nitrate-nitrogen, and ammonia-nitrogen. The average concentration of nitrate-nitrogen in the leached water is far less than the maximum allowed concentration of nitrate-nitrogen in drinking water, 10 mg/L set by USEPA. Therefore, this study did not show that the wastewater land application with wastewater secondary effluent had the problem of nitrogen contamination to groundwater. Although there is variability, the nitrogen leaching can be well controlled in such an application system when designed using the mass balance approach.

6.3 Salt balance

The salinity in the applied wastewater was 963±95 μS/cm (Mean ± SD) during the research with the coefficient of variation (C.V.) of 9.88% and the standard error of 2.16%. The range of salinity in the leached water was 1261 to 2794 μS/cm. The range of C.V. of salt mass in the leached water was from 31% to 199%. Similar to total nitrogen, the variability of salt in leached water depends on irrigation system, climatic conditions, and irrigation operations. There are two sampling periods in which salt-out was larger than salt-in in both individual sampling periods, but salt-out was less than salt-in in all other sampling periods. The former case was caused by excess precipitation which was sufficient to flush out the applied salt mass in that sampling period. During this research, although the leaching requirement was satisfied under the field conditions with the leaching fraction higher than the leaching requirement, the salt accumulation still happened. Therefore, it is possible for the land to have the risk of salinization in a short term if the leaching requirement is satisfied. However, such salt accumulation doesn't prove that the design approach is not feasible in the short and long term; on the contrary, the mass balance method can be theoretically utilized to control the salt mass balance in the plant root zone.

APPENDIX A

DETERMINATION OF IRRIGATION RATE AT SITE

To determine the monthly irrigation schedule, the irrigation rate at Littlefield site is required to be determined. There are two operating pressure values which were measured and recorded in irrigation events, 35 psi and 58 psi, at Littlefield site during the project period. However, the design operation pressure was 65 psi according to the design instruction.

At the Littlefield site, two types of nozzles are employed, which are Gray and Dk. Brown I-25 plus nozzle series produced by Hunter Industries with inner diameter of 1/4 inches and 17/64 inches, respectively. The performance data is list in **Table A. 1**, those data were obtained from the product information brochure provided by Hunter Company.

Table A. 1 The performance data of two types of nozzle used at the research site

Nozzle	Inner Diameter inches	Pressure psi	Radius ft	Flow GPM
Gray, I-25 plus nozzle	1/4	50	56'	13.4
		60	57'	14.3
		70	57'	15.2
		80	58'	16.4
Dk Brown, I-25 plus nozzle	17/64	60	62'	17.8
		70	63'	19.2
		80	64'	20.5
		90	65'	21.8

Relationship between nozzle pressure and irrigation radius

For Gray I-25 plus nozzle series, the relationship between nozzle pressure and irrigation radius is plotted as in **Figure A. 1** with the data in **Table A. 1** provided by the manufacturer, and the linear regression model between nozzle pressure (x, psi) and irrigation radius (y, ft) is:

$$y = 0.06x+53.1 \qquad (A.1)$$

When nozzle pressure is 35 psi, then irrigation radius y for Gray I-25 plus nozzle series is:

y = 0.06*35+53.1 = 55.2 ft

When nozzle pressure is 58 psi, then irrigation radius y for Gray I-25 plus nozzle series is:

y = 0.06*58+53.1 = 56.6 ft

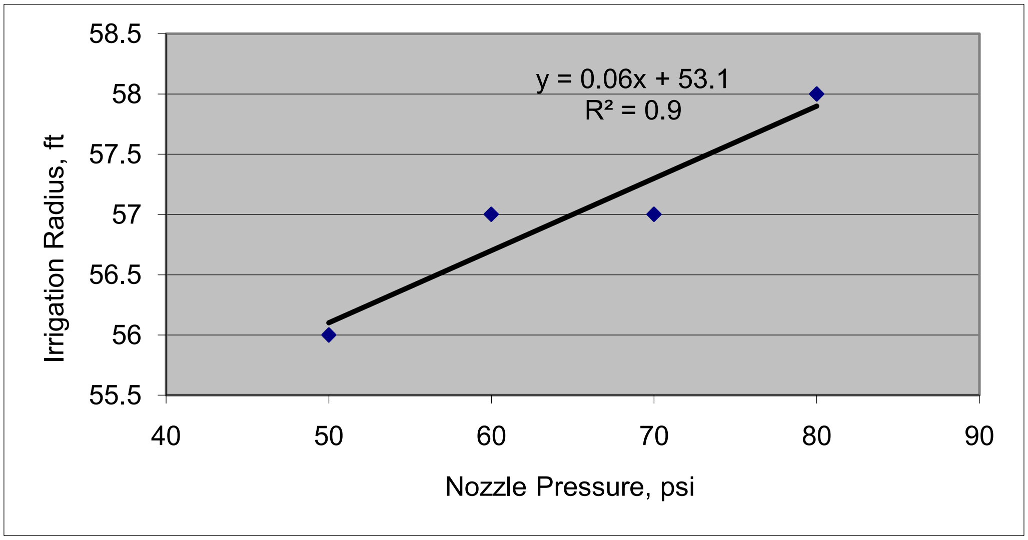

Figure A. 1 Plot of relationship between nozzle pressure and irrigation radius for Gray I-25 plus nozzle series

Similarly, for Dk. Brown I-25 plus nozzle series, the relationship between nozzle pressure and irrigation radius is plotted as in **Figure A. 2**.

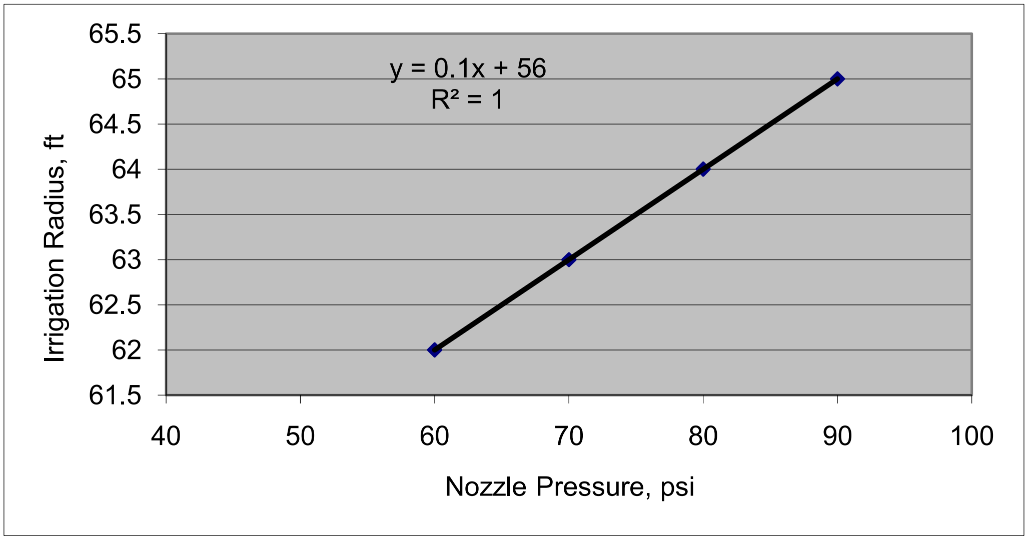

Figure A. 2 Plot of relationship between nozzle pressure and irrigation radius for Dk. Brown I-25 plus nozzle series

The linear regression model between nozzle pressure (x, psi) and irrigation radius (y, ft) for Dk. Brown I-25 plus nozzle series is:

$$y = 0.1x+56 \qquad (A.2)$$

When nozzle pressure is 35 psi, then irrigation radius y for Dk. Brown I-25 plus nozzle series is:

$$y = 0.1*35+56 = 59.5 \text{ ft}$$

When nozzle pressure is 58 psi, then irrigation radius y for Dk. Brown I-25 plus nozzle series is:

$$y = 0.1*58+56 = 61.8 \text{ ft}$$

Relationship between flow rate and nozzle pressure

For Gray I-25 plus nozzle series, the linear relationship between flow rate and square root of nozzle pressure is plotted as in **Figure A. 3** with the performance data in **Table A. 1**. The linear regression model between square root of nozzle pressure (x) and flow rate (y, GPM) is:

$$y = 1.5809x+2.1273 \qquad (A.3)$$

When nozzle pressure is 35 psi, x = 5.916 $(\text{psi})^{1/2}$, then flow rate y for Gray I-25 plus nozzle is:

y = 1.5809*5.916+2.1273 = 11.5 GPM

When nozzle pressure is 58 psi, x = 7.616 $(\text{psi})^{1/2}$, then flow rate y for Gray I-25 plus nozzle is:

y = 1.5809*7.616+2.1273 = 14.2 GPM

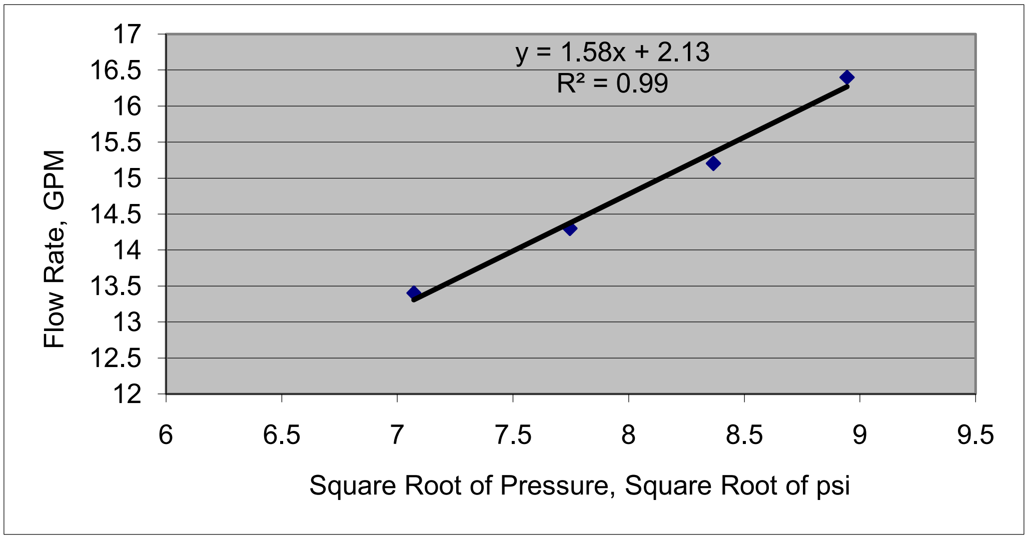

Figure A. 3 Plot of relationship between square root of nozzle pressure and flow rate for Gray I-25 plus nozzle series

Similarly, for Dk. Brown I-25 plus nozzle, the relationship between flow rate and square root of nozzle pressure is plotted as in **Figure A. 4**.

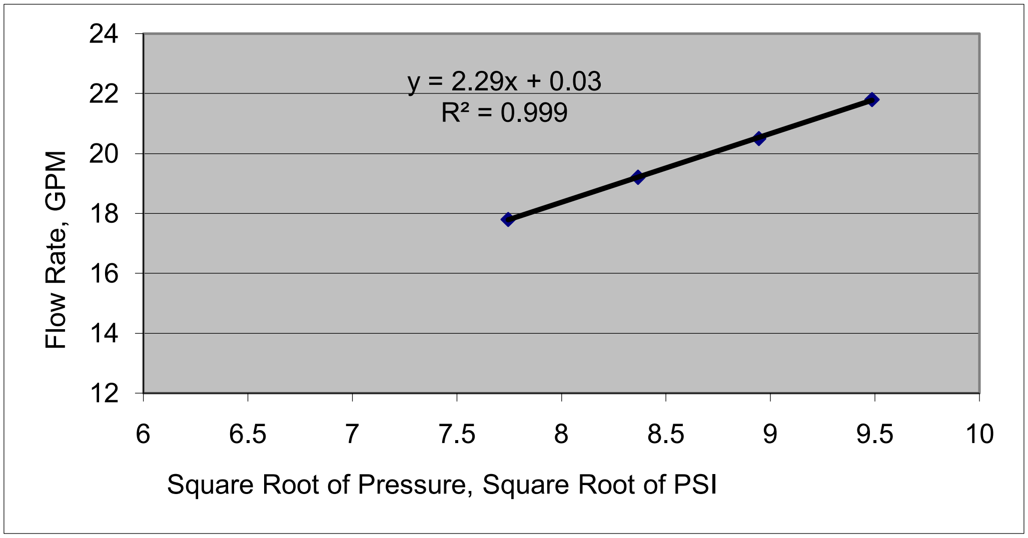

Figure A. 4 Plot of relationship between square root of nozzle pressure and flow rate for Dk. Brown I-25 plus nozzle series

The linear relationship between square root of nozzle pressure (x) and flow rate (y, GPM) for Dk. Brown I-25 plus nozzle is:

$$y = 2.2921x+0.0306 \qquad (A.4)$$

When nozzle pressure is 35 psi, $x = 5.916\ (psi)^{1/2}$, then flow rate y for Dk. Brown I-25 plus nozzle is:

$$y = 2.2921*5.916+0.0306\ = 13.6\ GPM$$

When nozzle pressure is 58 psi, $x = 7.616\ (psi)^{1/2}$, then flow rate y for Dk. Brown I-25 plus nozzle is:

$$y = 2.2921*7.616+0.0306\ = 17.5\ GPM$$

The calculated values of irrigation radius and flow rate under the pipe pressure of 35 psi and 58 psi, and the numbers of nozzles installed at Littlefield research site are summarized in **Table A.2**.

Table A. 2 Summary of irrigation radius, flow rate, and number of nozzles at the research site

	Nozzle pressure psi	Irrigation radius ft	Flow rate GPM	Number of Nozzles
Gray	35	55.2	11.5	52
Dk. Brown	35	59.5	13.6	79
Gray	58	56.6	14.2	52
Dk. Brown	58	61.8	17.5	79

Irrigated area for different nozzle pressure

With the aid of AutoCAD software, the layout of nozzles and ponds were drawn with the same scale, each circle represents an irrigated area by a nozzle with the irrigated radius of 55.2 ft for Gray nozzles and 59.5 ft for Dk. Brown at pressure of 35 psi. Dk. Brown popup sprinklers are positioned around the storage pond and aerated ponds while the Gray popup sprinklers are installed on the banks between storage pond and aerated pond, and shared bank between two aerated ponds (**Figure A. 5**). The net irrigated area is shown in **Figure A. 6**. The size of ponds, the key points for those three ponds, and irrigation installation points are extracted from the design of Littlefield Wastewater Treatment Plant designed by Oller Engineering on June 2000.

The irrigated area with nozzle pressure of 35 psi is 298720 ft^2. With the similar method by changing the irrigated radius into 56.58 ft for Gray nozzles and 61.8 ft for Dk. Brown when the nozzle pressure is 58 psi, the irrigated area with nozzle pressure of 58 psi is retrieved as 308193 ft^2.

Determination of wastewater application depth per unit time

When nozzle pressure is 35 psi, total flow rate is:

52 nozzles*11.5 GPM/nozzle (Gray) +79 nozzles*13.6 GPM/nozzle (Dk. Brown)

= 1672.4 GPM

Total irrigated area is 298720 ft^2.

Average wastewater application depth per unit time is:

1672.4 GPM/(298720 ft^2) = 0.00898 inches/min = 0.54 inches/hour

When nozzle pressure is 58 psi, total flow rate is:

52 nozzles*14.2 GPM/nozzle (Gray) +79 nozzles*17.5 GPM/nozzle (Dk. Brown)

= 2120.9 GPM

Total irrigated area is 308193 ft^2.

Average wastewater application depth per unit time is:

2120.9 GPM/(308193 ft^2) = 0.011 inches/min = 0.66 inches/hour

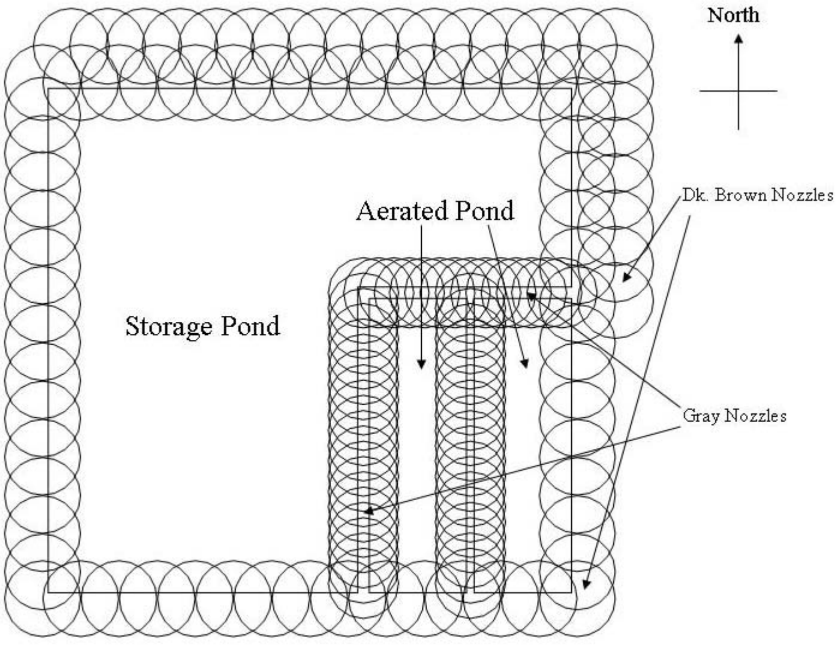

Figure A. 5 The layout of sprinklers at the Littlefield site.

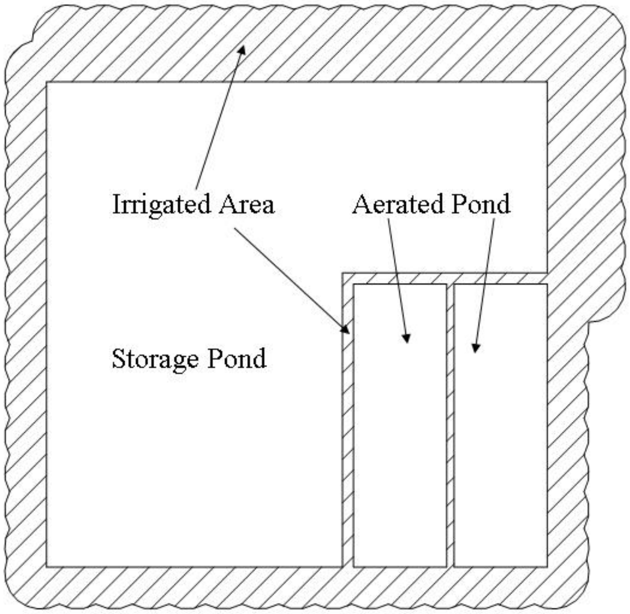

Figure A. 6 The irrigated area served at the Littlefield site.

APPENDIX B

THE PLOTS OF SPATIAL DISTRIBUTION OF LEACHED WATER

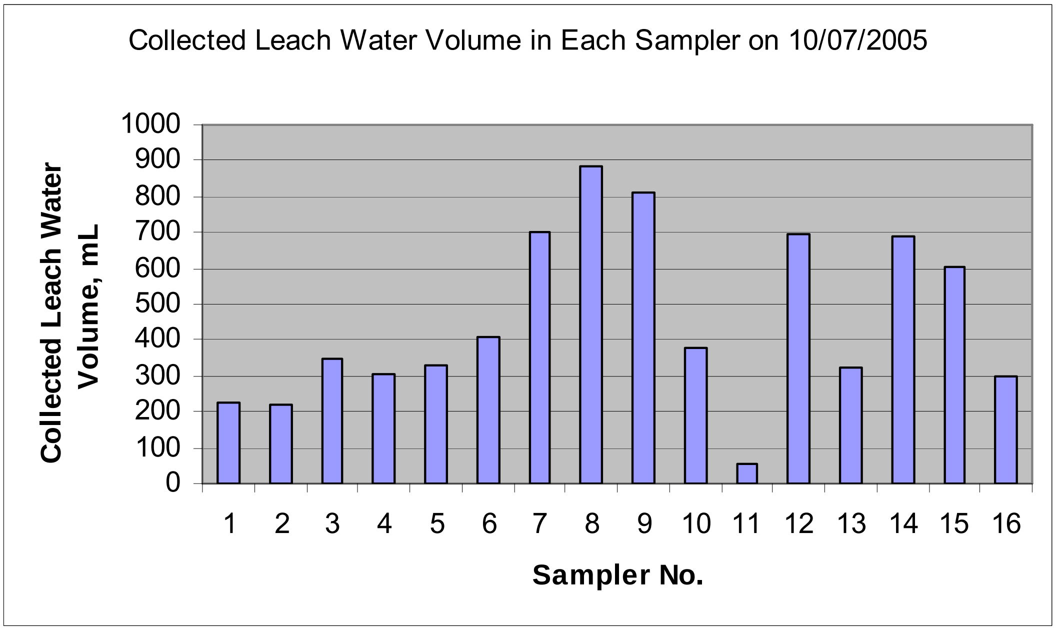

Figure B. 1 Collected leach water volume in each sampler on 10/07/2005

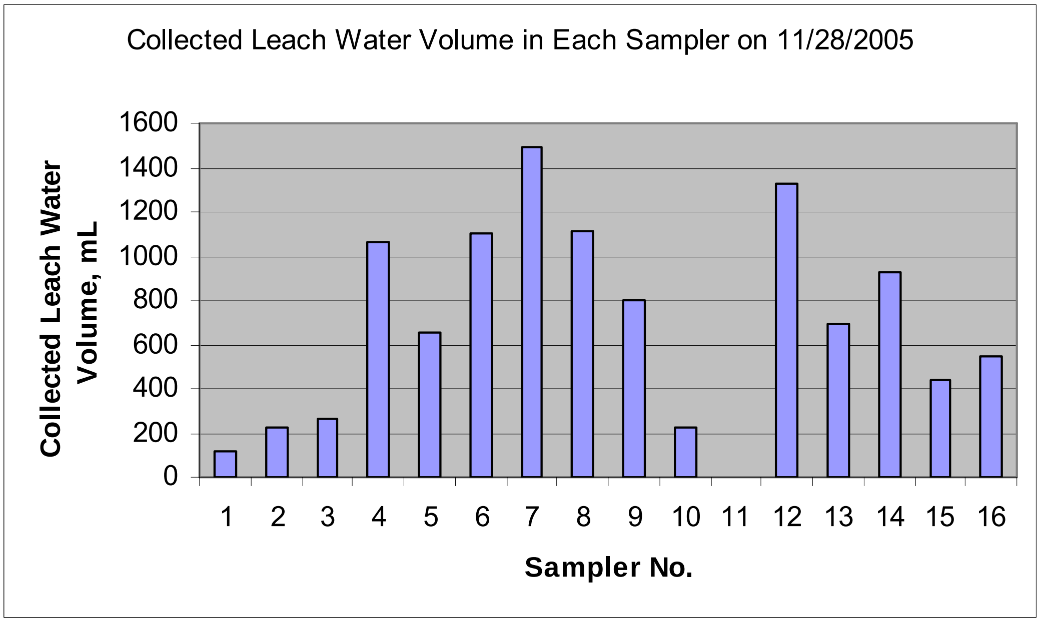

Figure B. 2 Collected leach water volume in each sampler on 11/28/2005

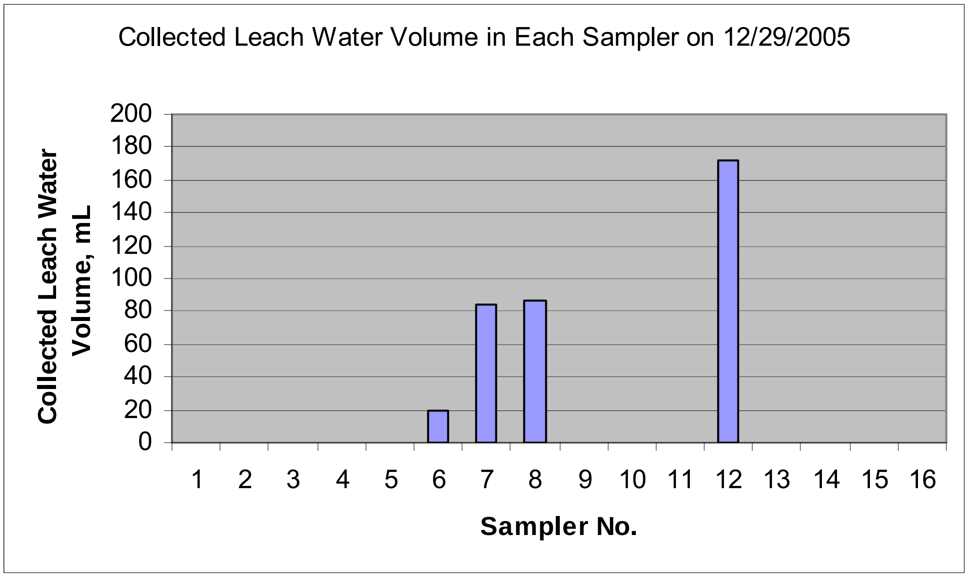

Figure B. 3 Collected leach water volume in each sampler on 12/29/2005

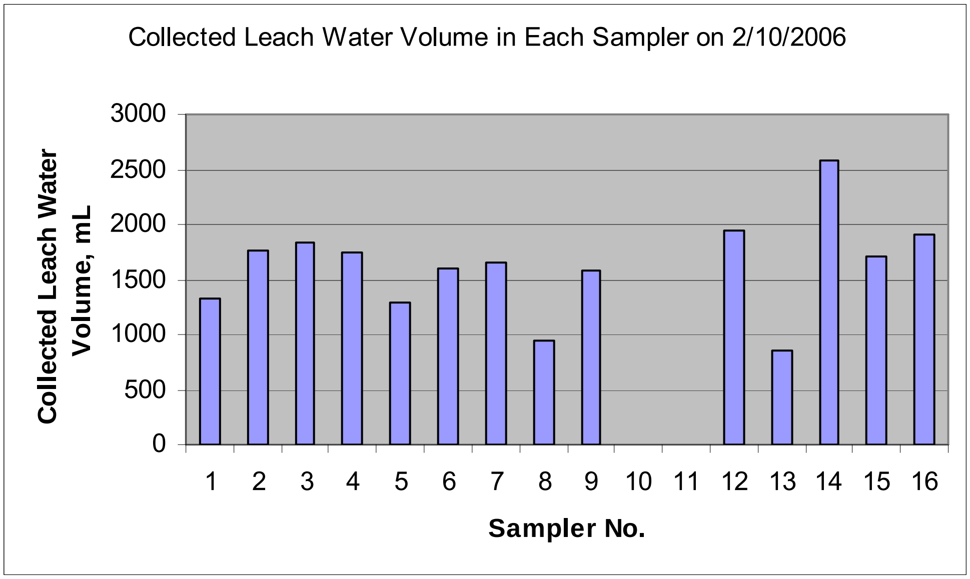

Figure B. 4 Collected leach water volume in each sampler on 2/10/2006

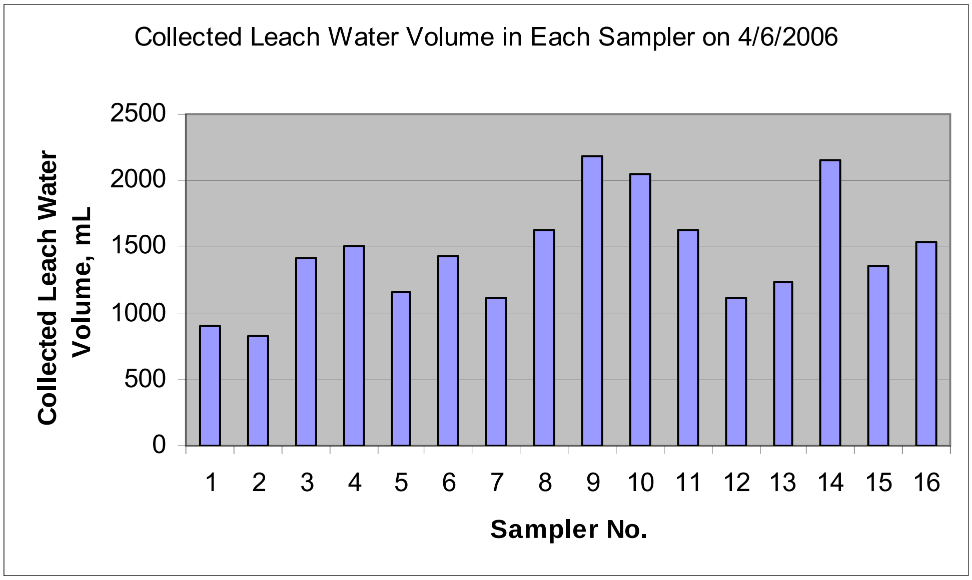

Figure B. 5 Collected leach water volume in each sampler on 4/6/2006

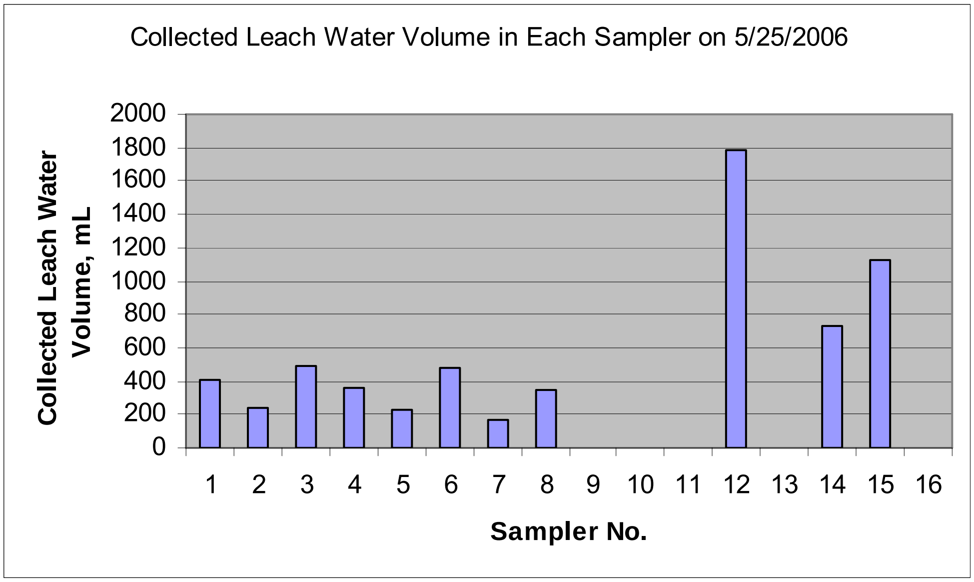

Figure B. 6 Collected leach water volume in each sampler on 5/25/2006

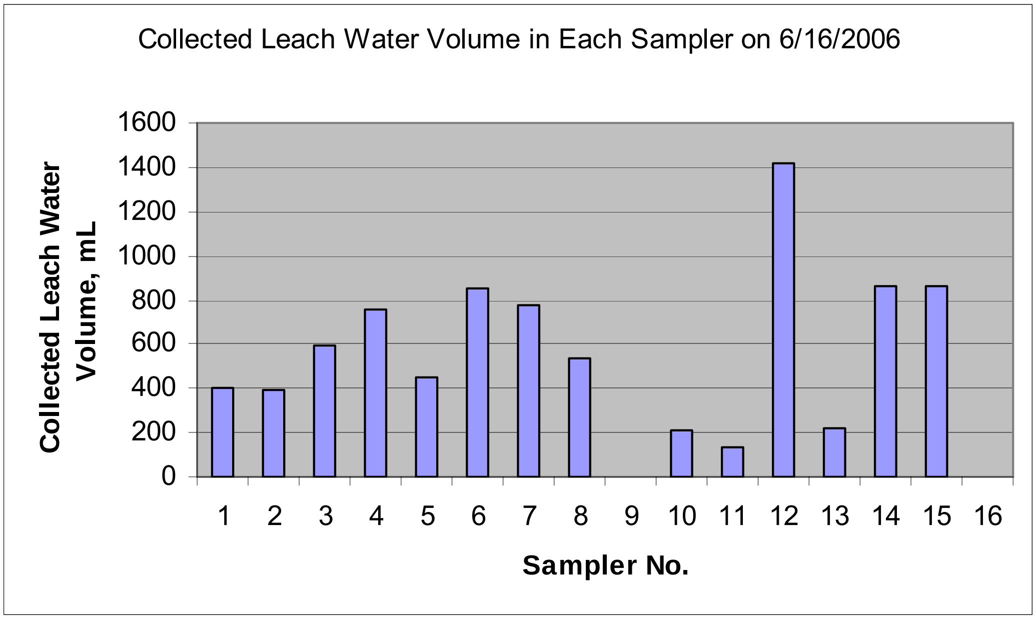

Figure B. 7 Collected leach water volume in each sampler on 6/16/2006

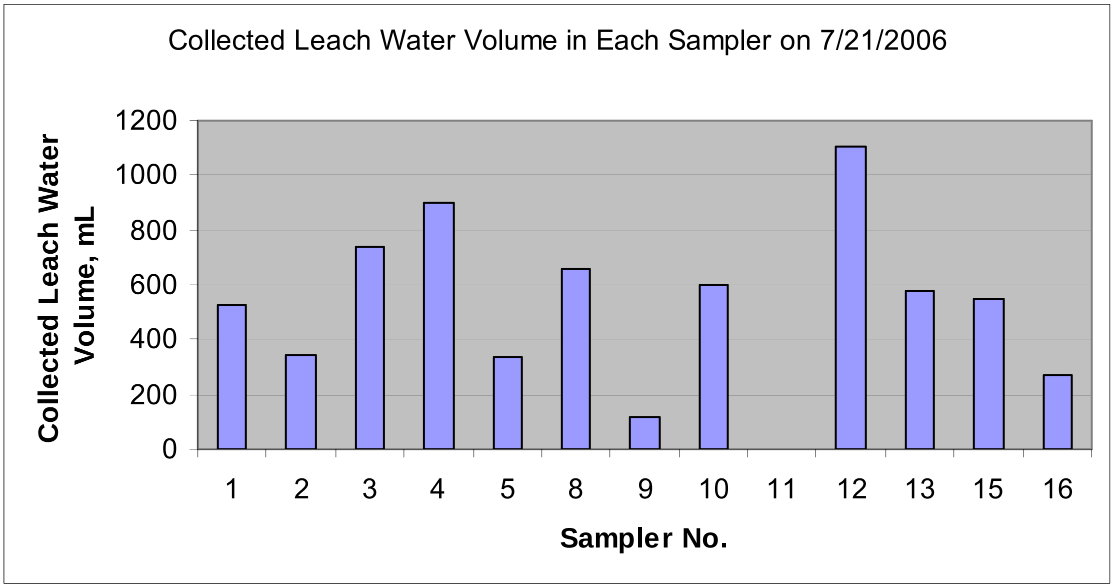

Figure B. 8 Collected leach water volume in each sampler on 7/21/2006

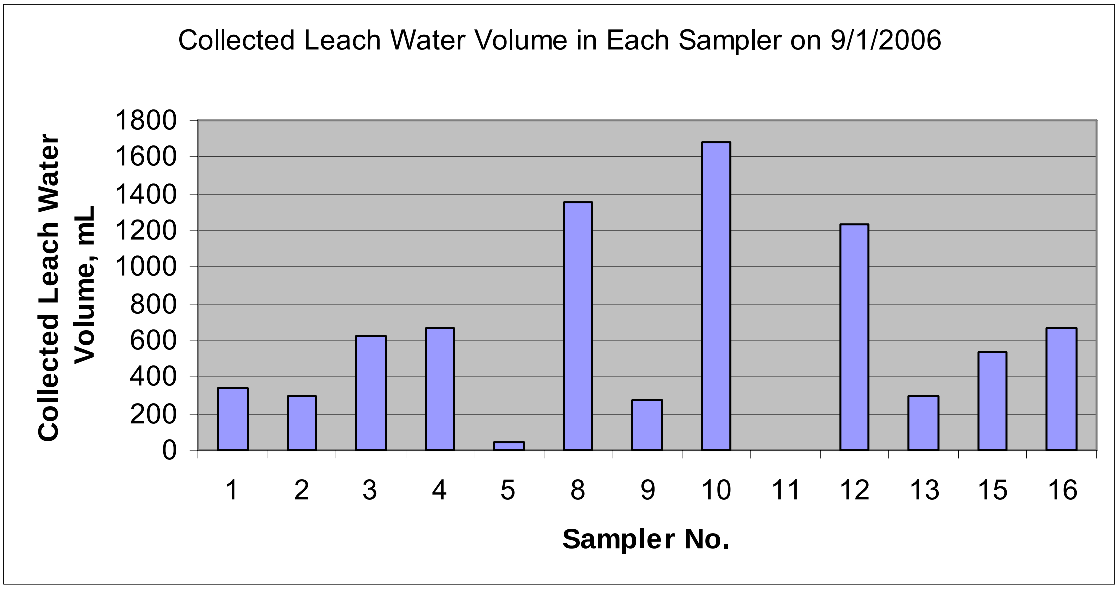

Figure B. 9 Collected leach water volume in each sampler on 9/1/2006

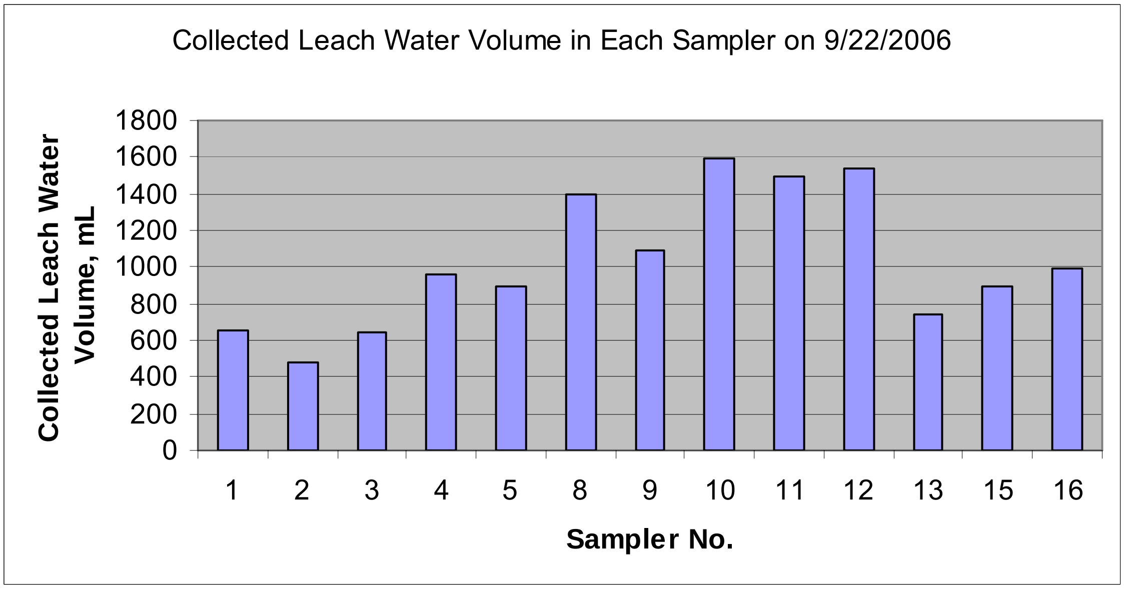

Figure B. 10 Collected leach water volume in each sampler on 9/22/2006

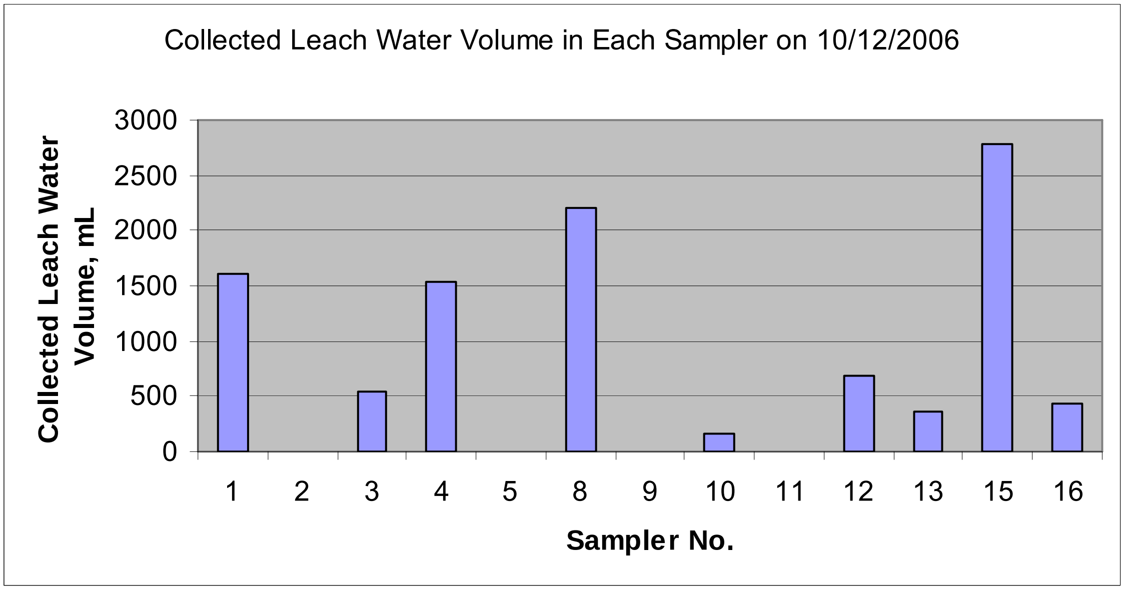

Figure B. 11 Collected leach water volume in each sampler on 10/12/2006

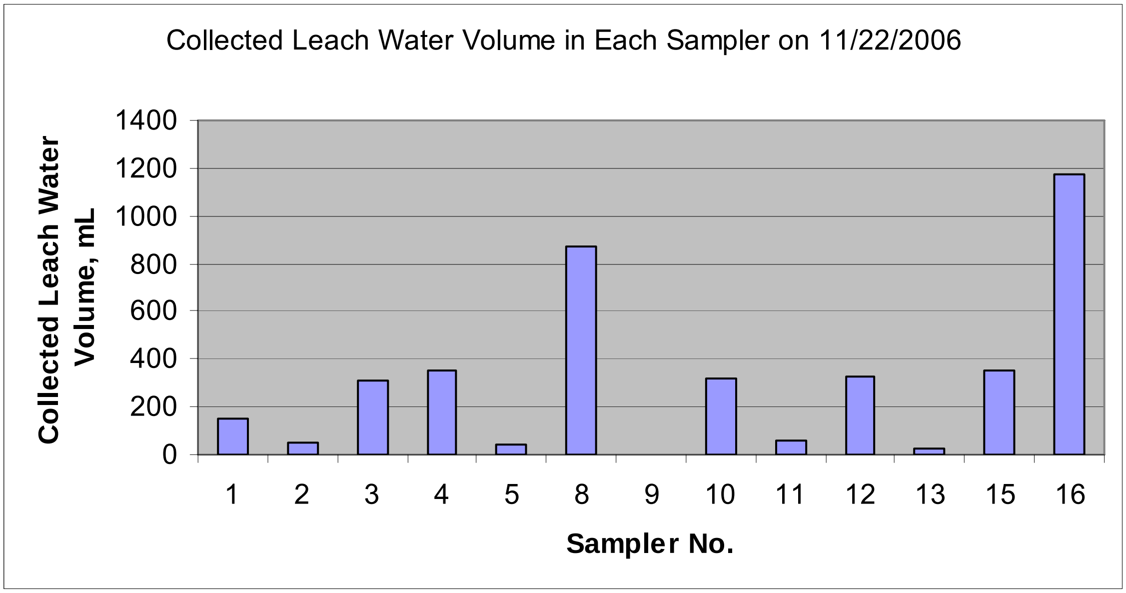

Figure B. 12 Collected leach water volume in each sampler on 11/22/2006

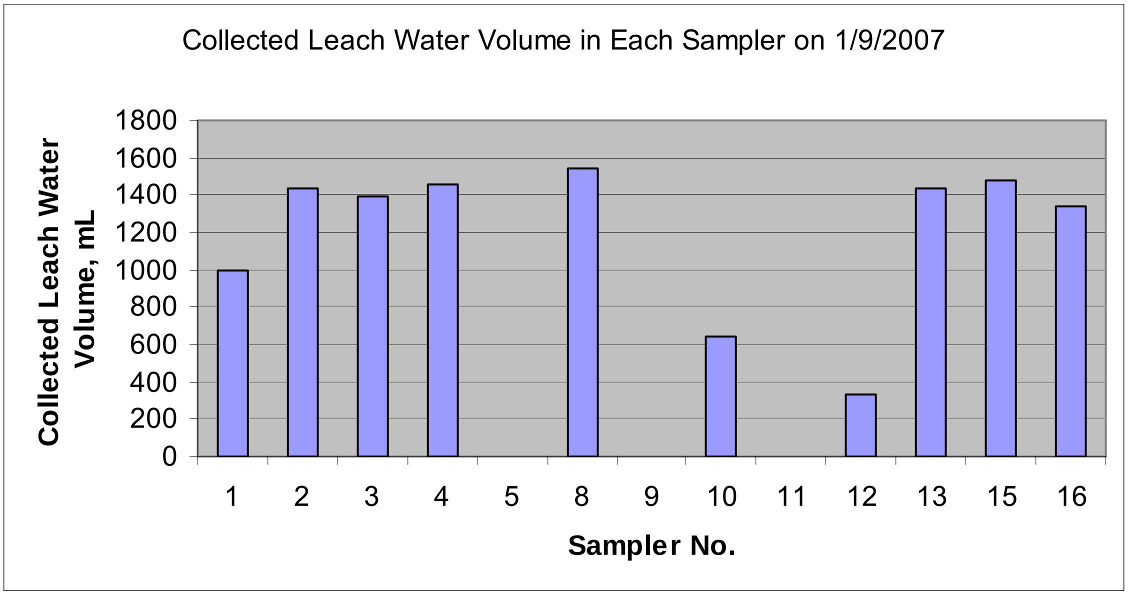

Figure B. 13 Collected leach water volume in each sampler on 1/9/2007

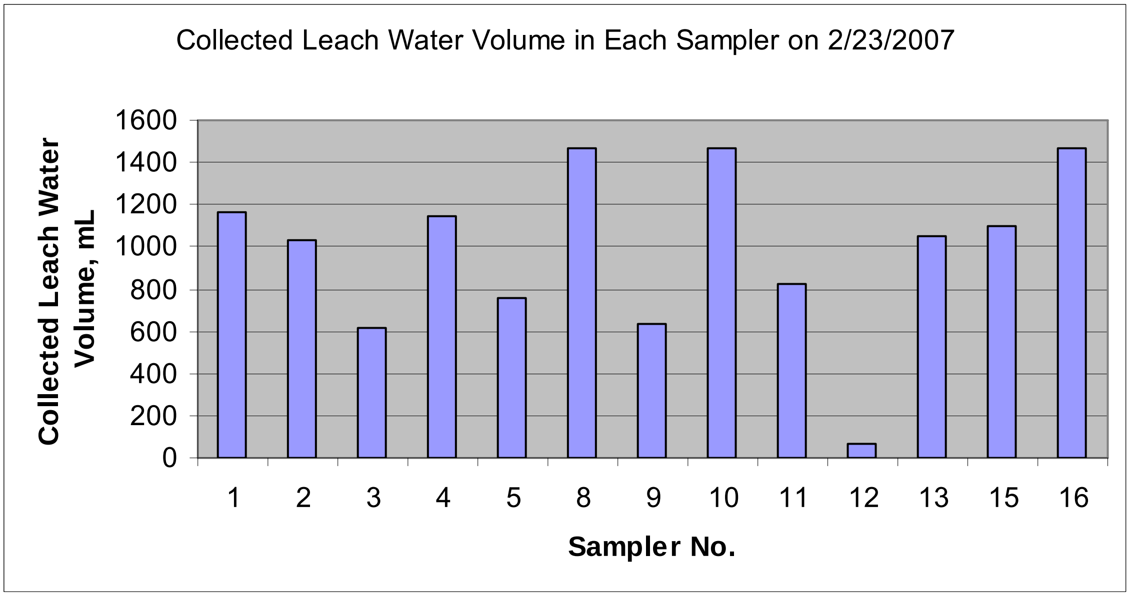

Figure B. 14 Collected leach water volume in each sampler on 2/23/2007

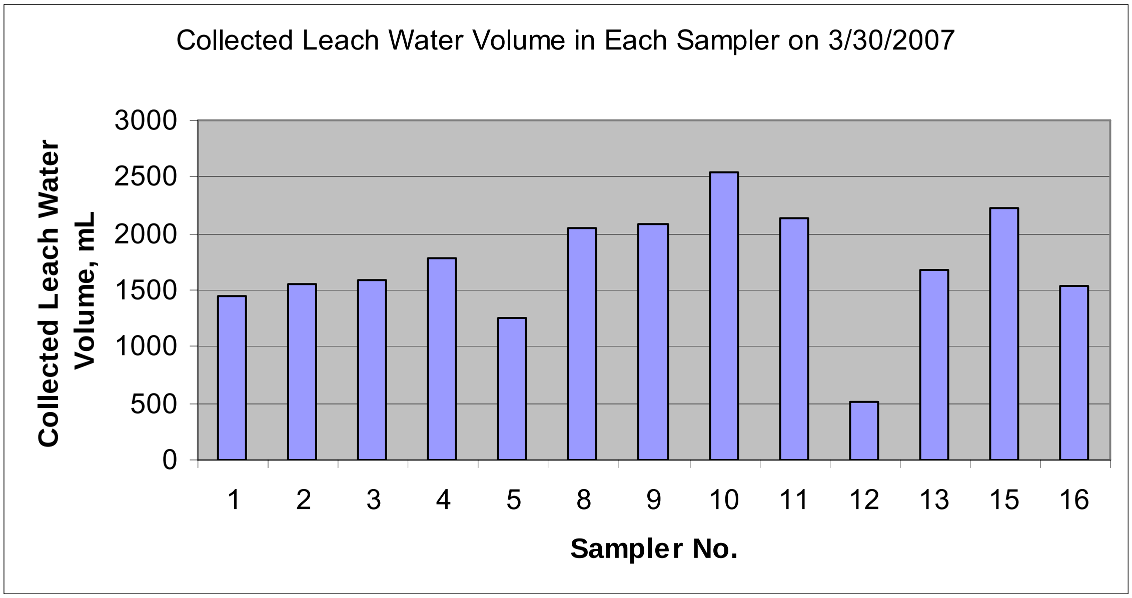

Figure B. 15 Collected leach water volume in each sampler on 3/30/2007

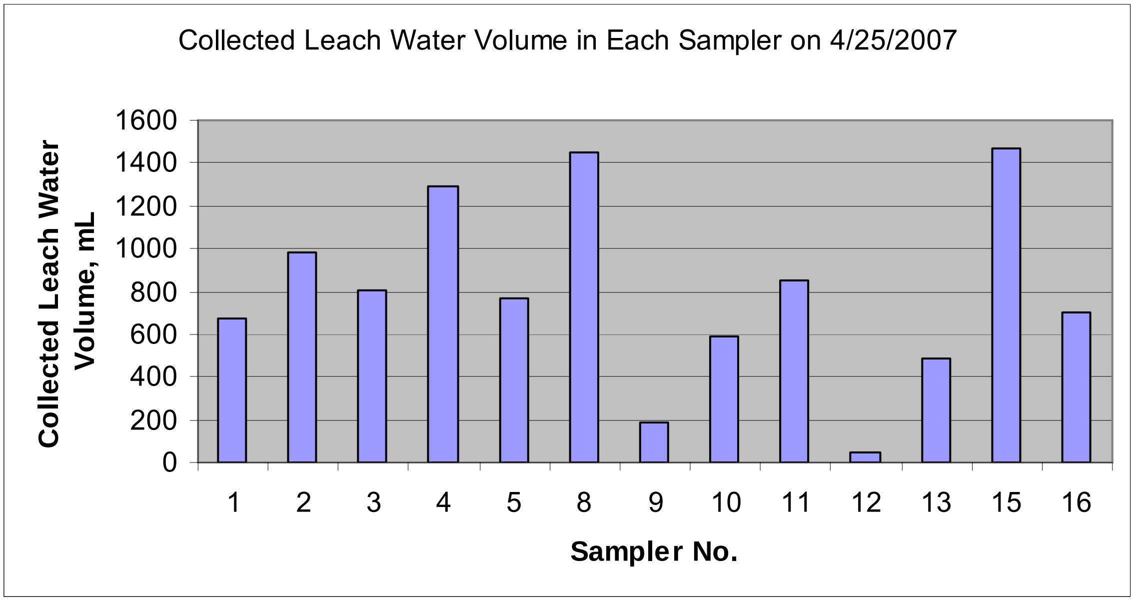

Figure B. 16 Collected leach water volume in each sampler on 4/25/2007

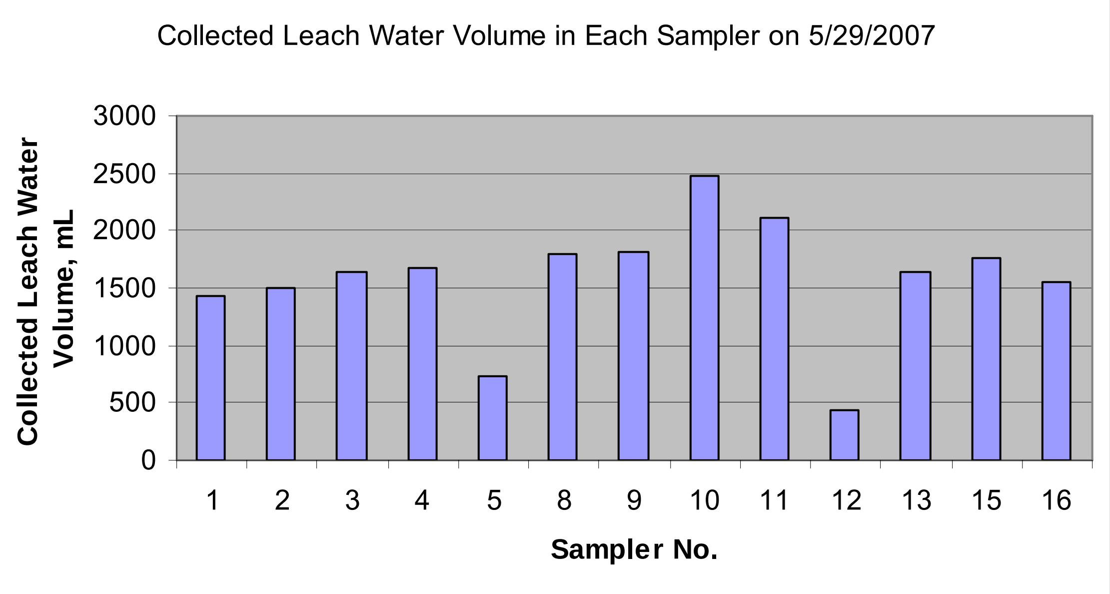

Figure B. 17 Collected leach water volume in each sampler on 5/29/2007

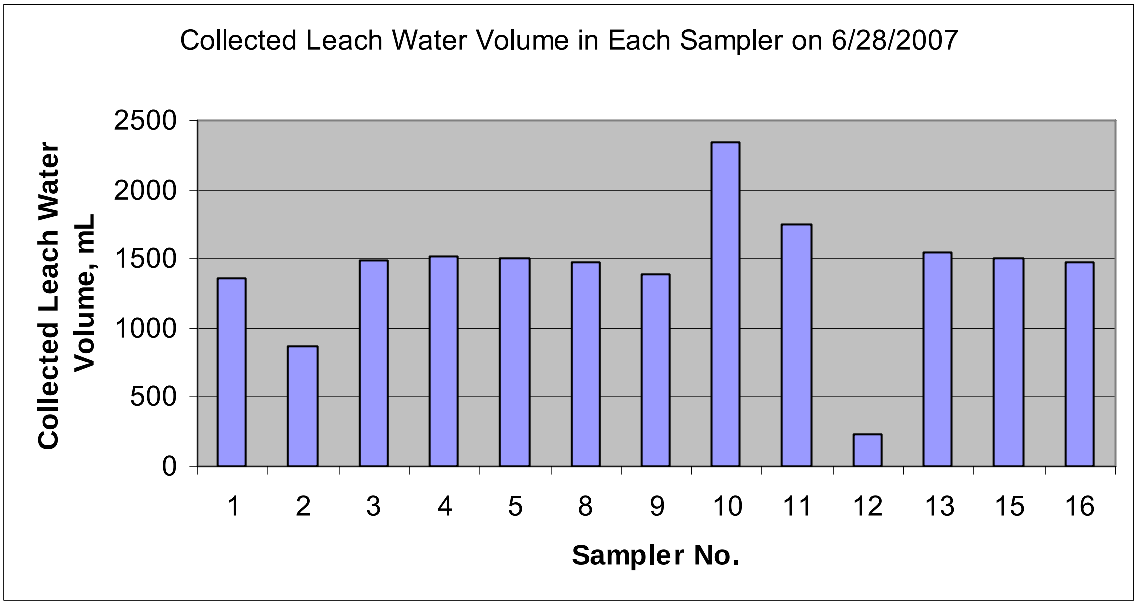

Figure B. 18 Collected leach water volume in each sampler on 6/28/2007

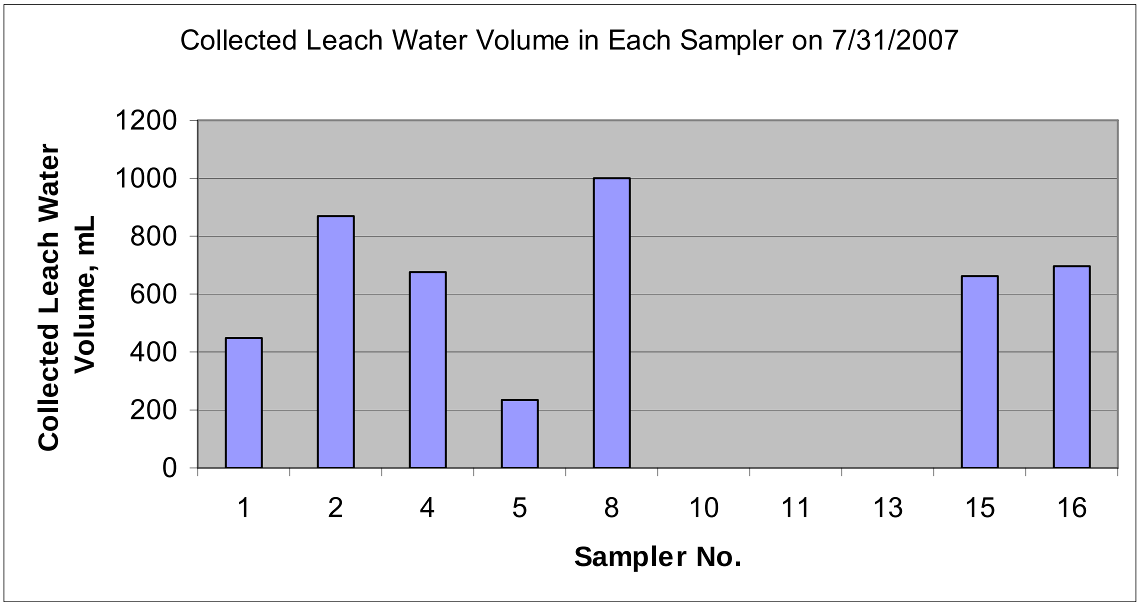

Figure B. 19 Collected leach water volume in each sampler on 7/31/2007

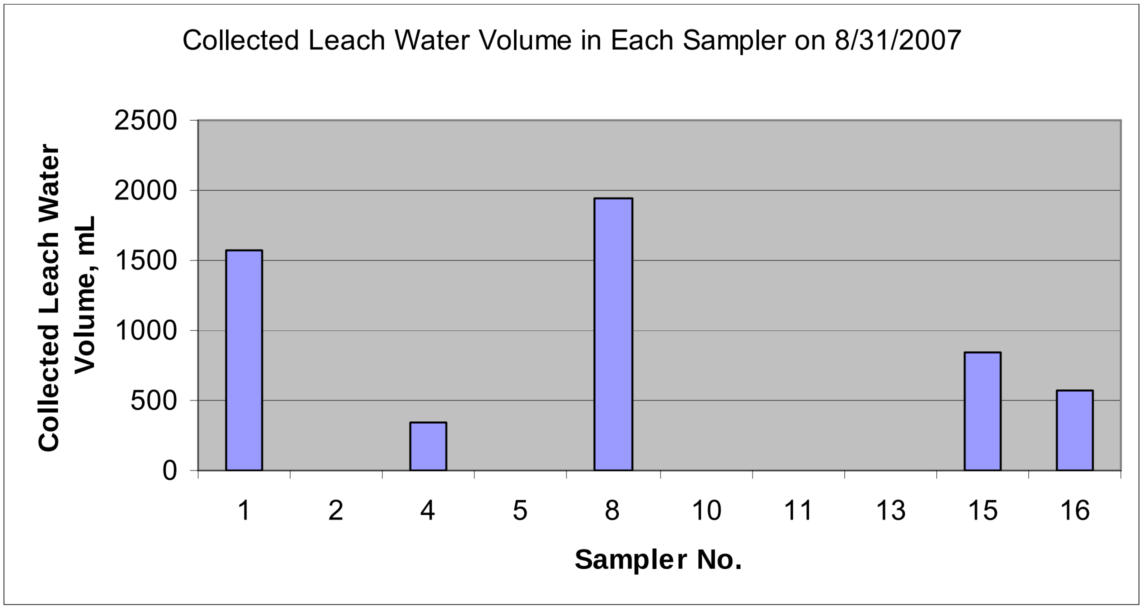

Figure B. 20 Collected leach water volume in each sampler on 8/31/2007

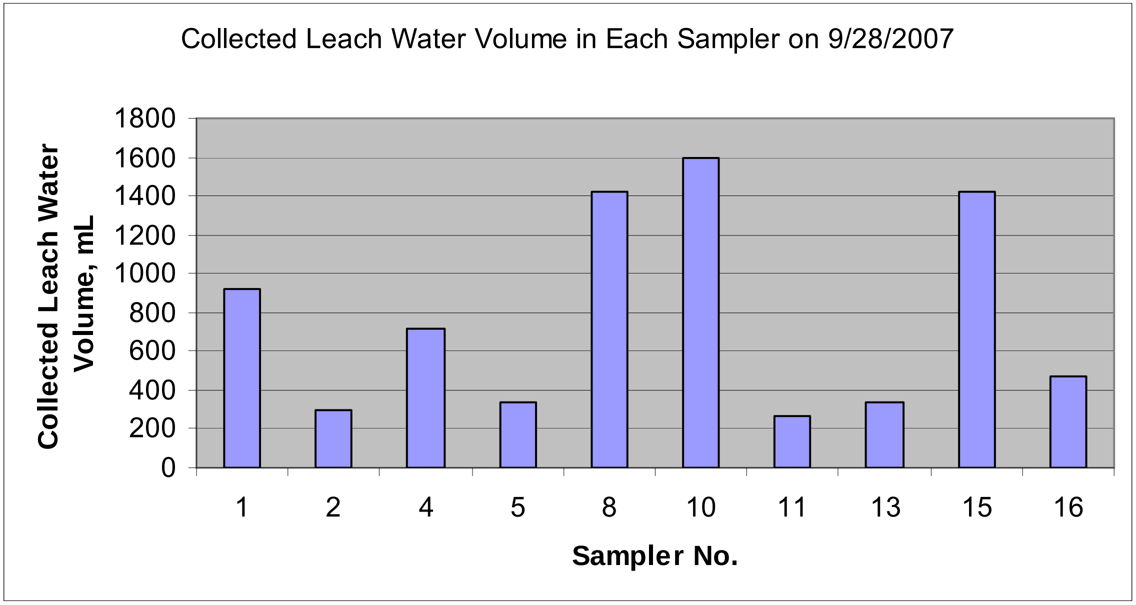

Figure B. 21 Collected leach water volume in each sampler on 9/28/2007

APPENDIX C

THE PLOTS OF TEMPORAL DISTRIBUTION OF LEACHED WATER

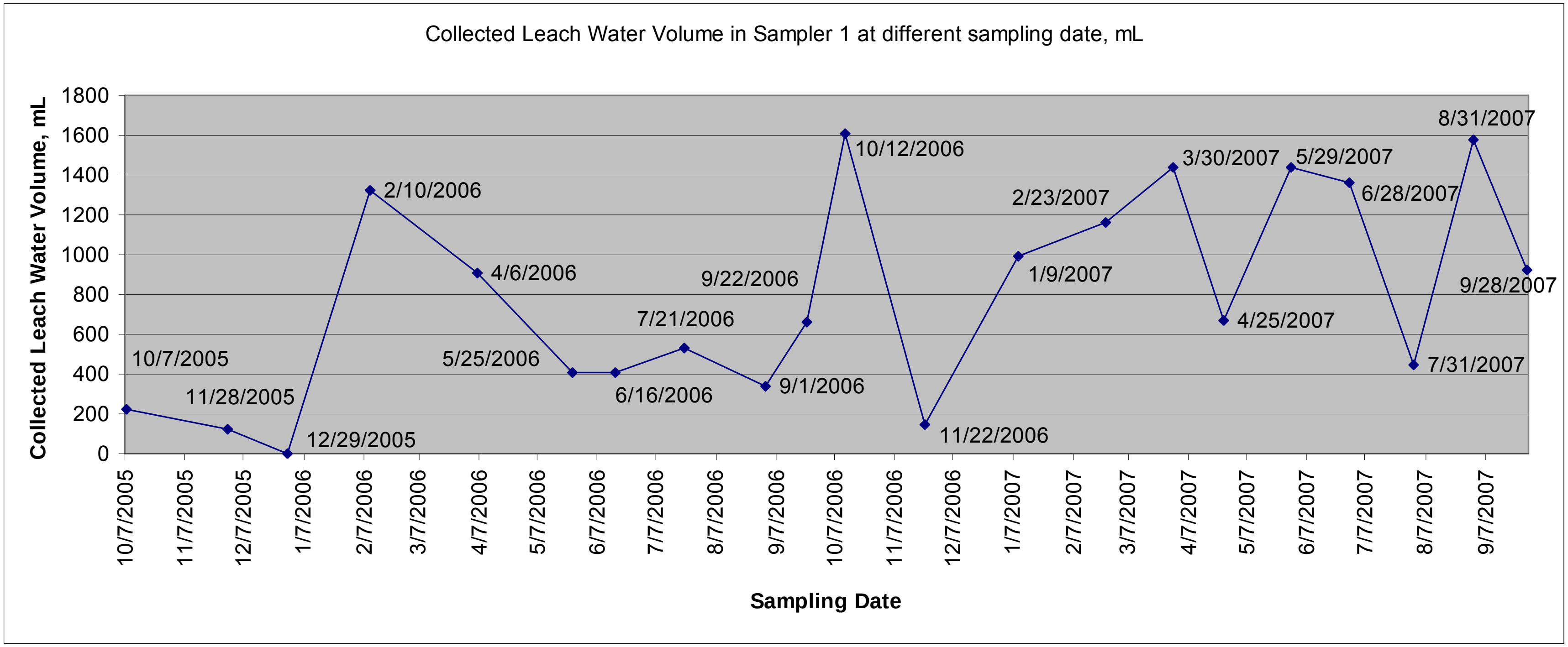

Figure C. 1 Collected leach water volume in sampler 1 at different sampling dates, mL

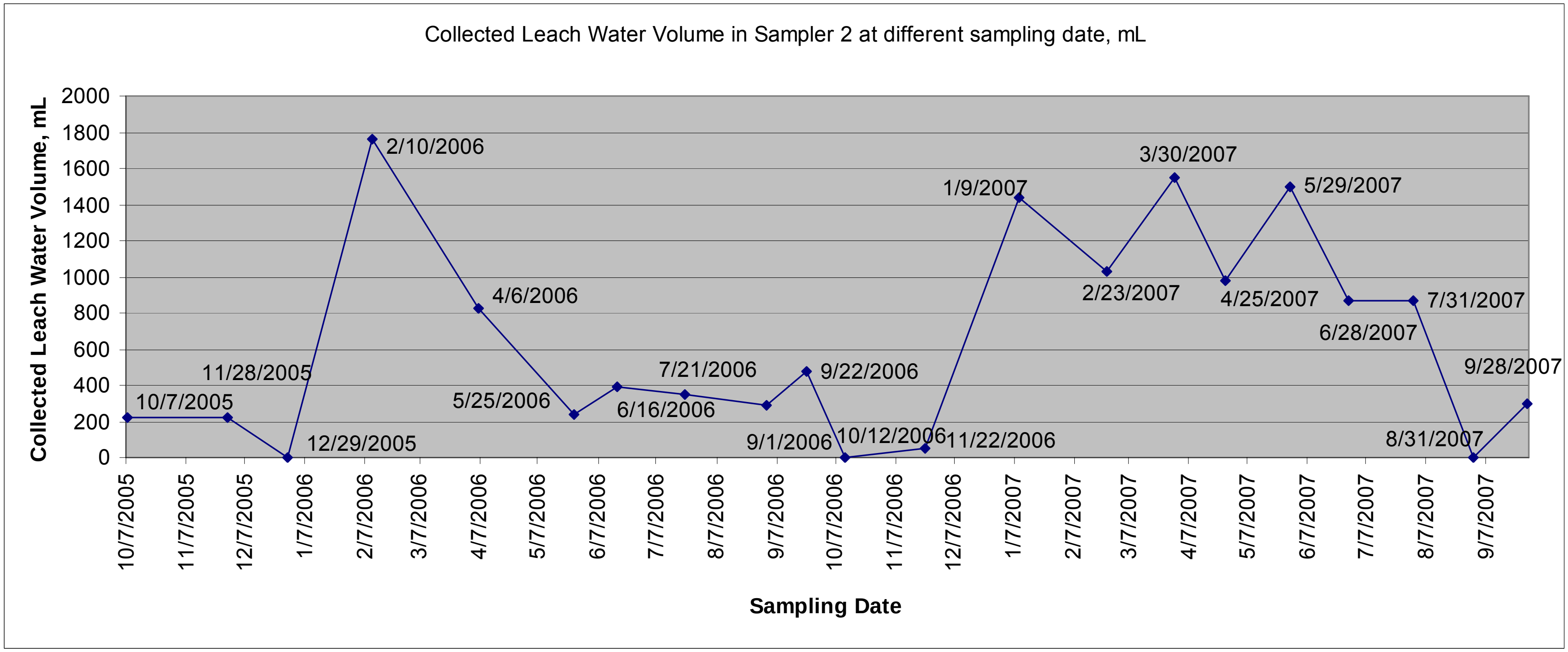

Figure C. 2 Collected leach water volume in sampler 2 at different sampling dates, mL

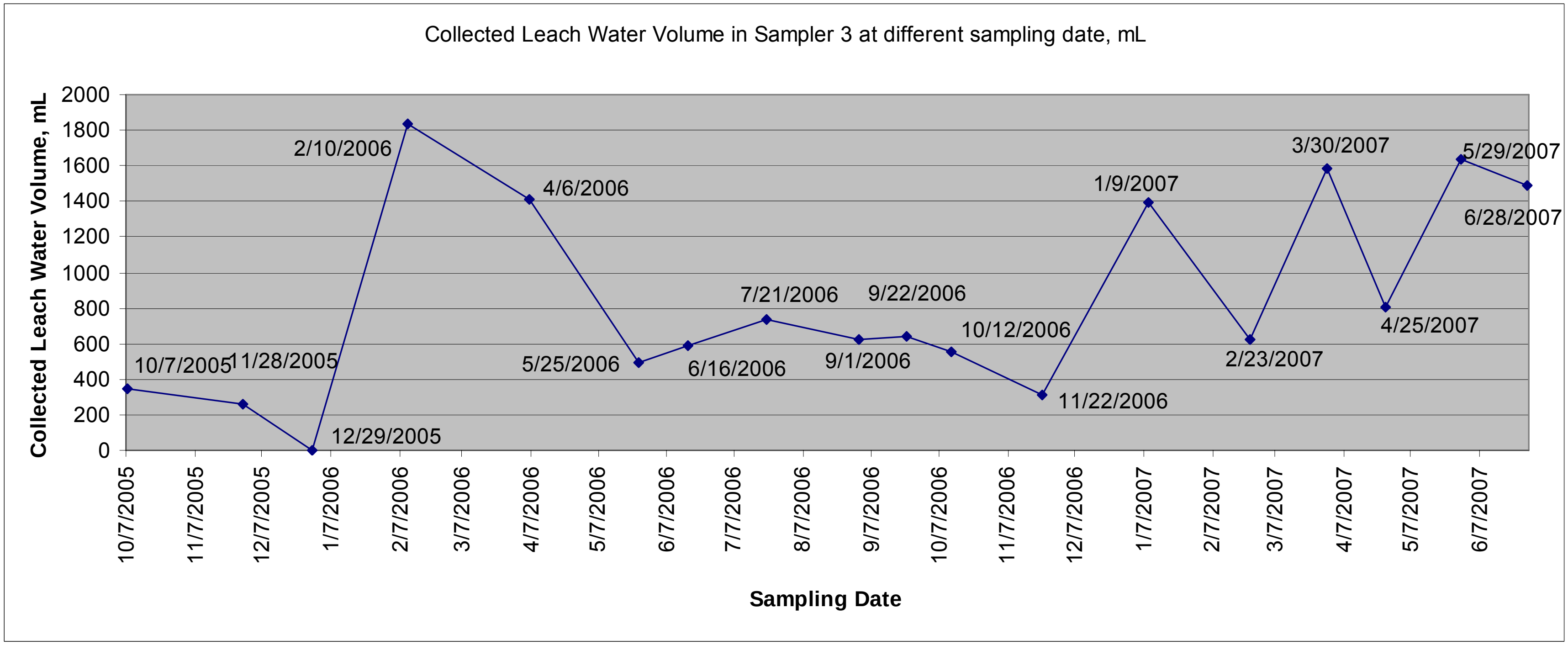

Figure C. 3 Collected leach water volume in sampler 3 at different sampling dates, mL

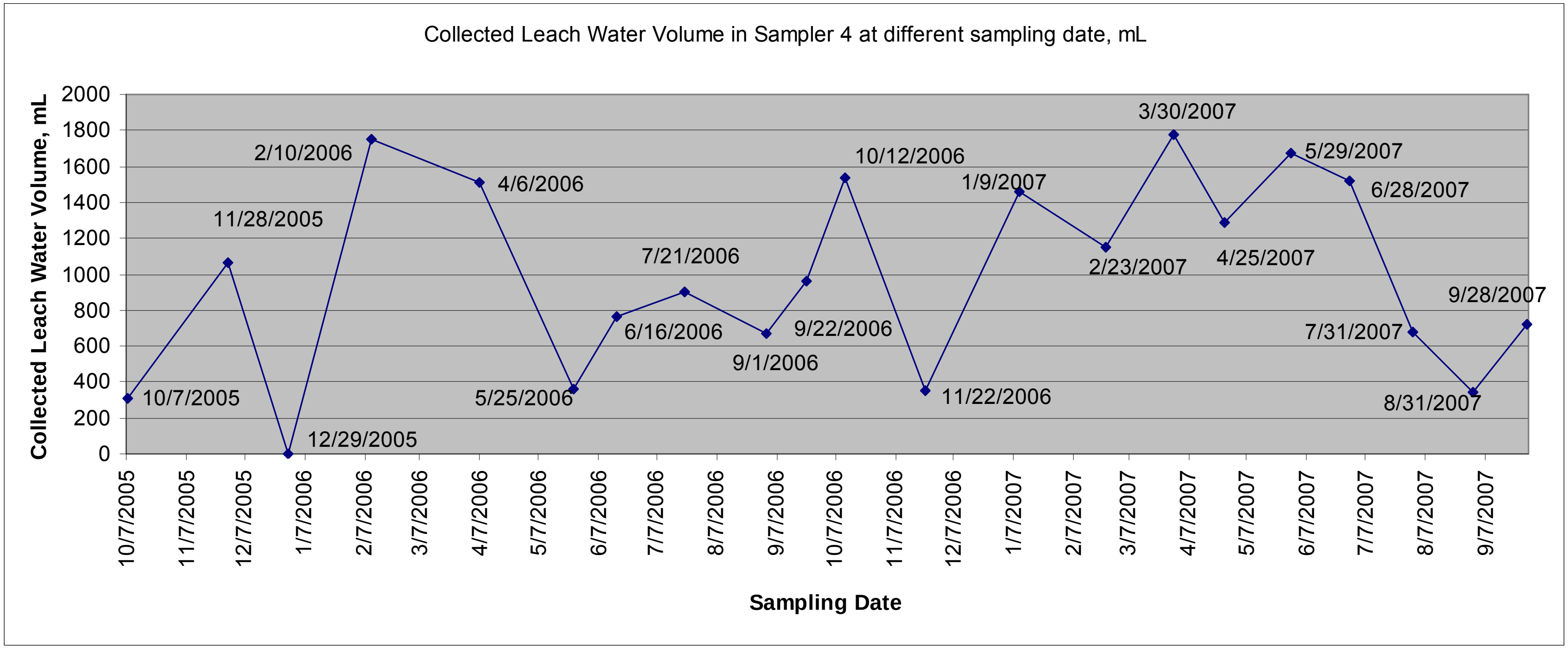

Figure C. 4 Collected leach water volume in sampler 4 at different sampling dates, mL

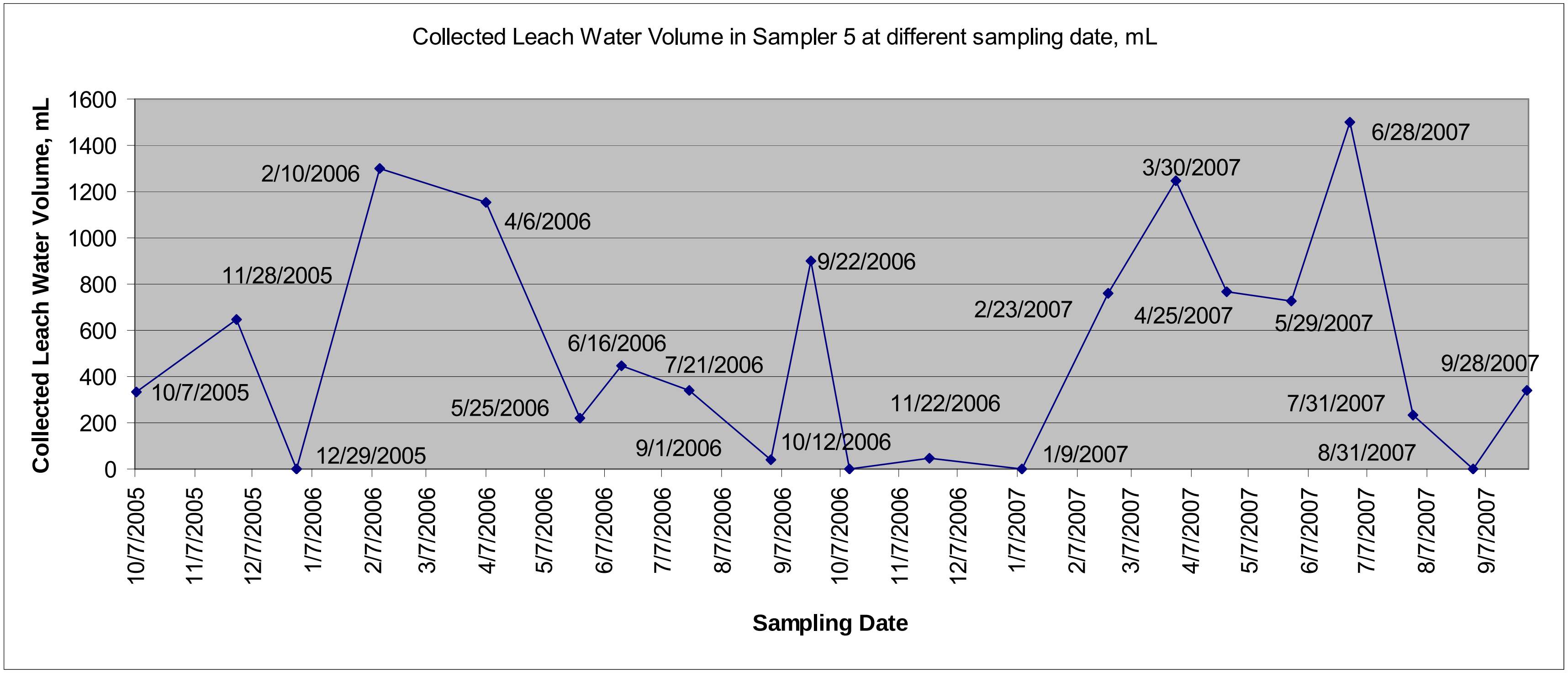

Figure C. 5 Collected leach water volume in sampler 5 at different sampling dates, mL

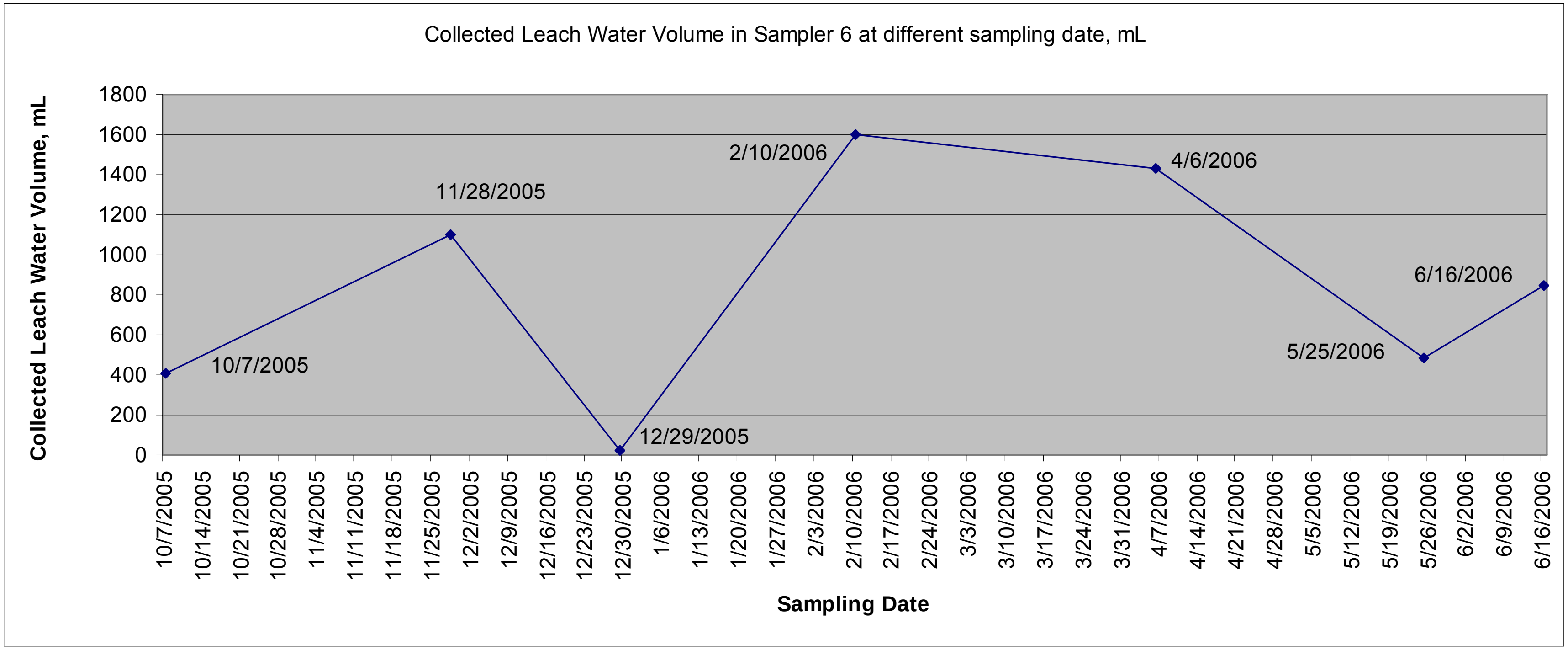

Figure C. 6 Collected leach water volume in sampler 6 at different sampling dates, mL

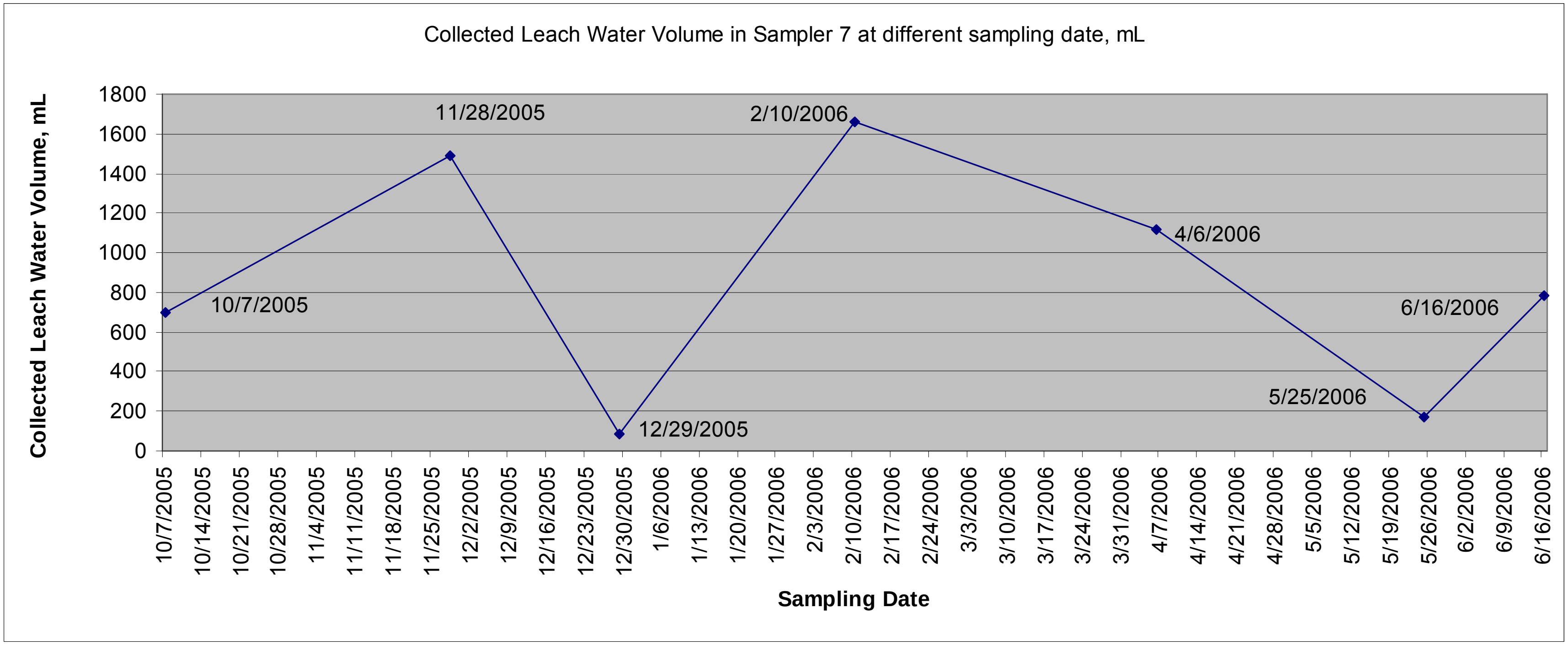

Figure C. 7 Collected leach water volume in sampler 7 at different sampling dates, mL

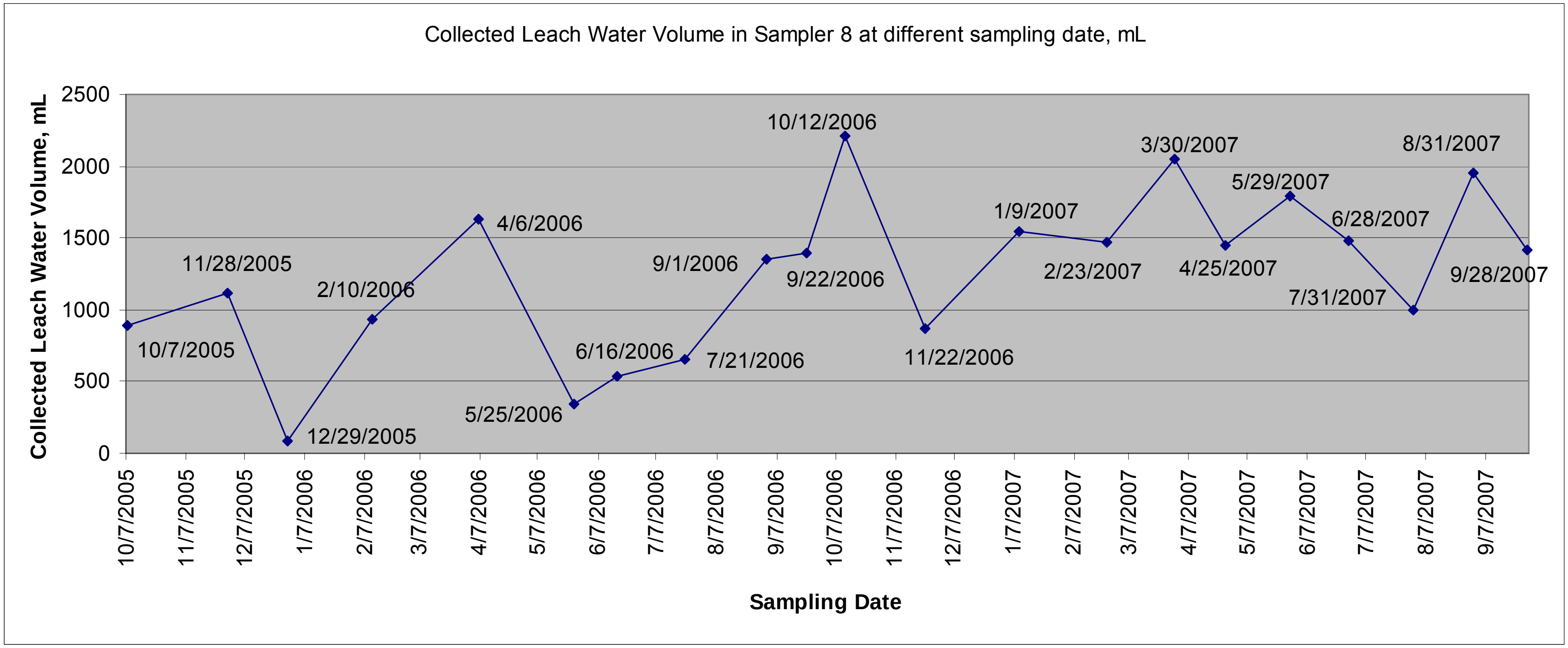

Figure C. 8 Collected leach water volume in sampler 8 at different sampling dates, mL

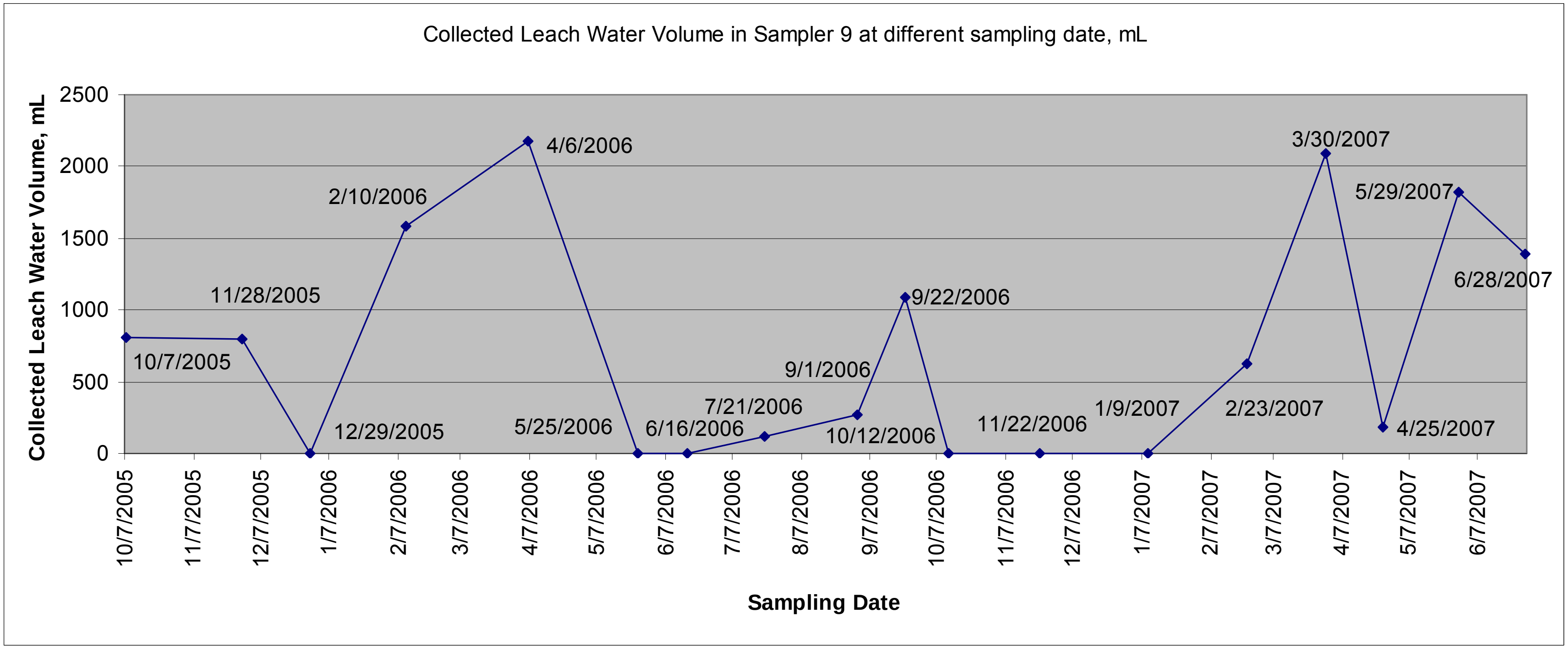

Figure C. 9 Collected leach water volume in sampler 9 at different sampling dates, mL

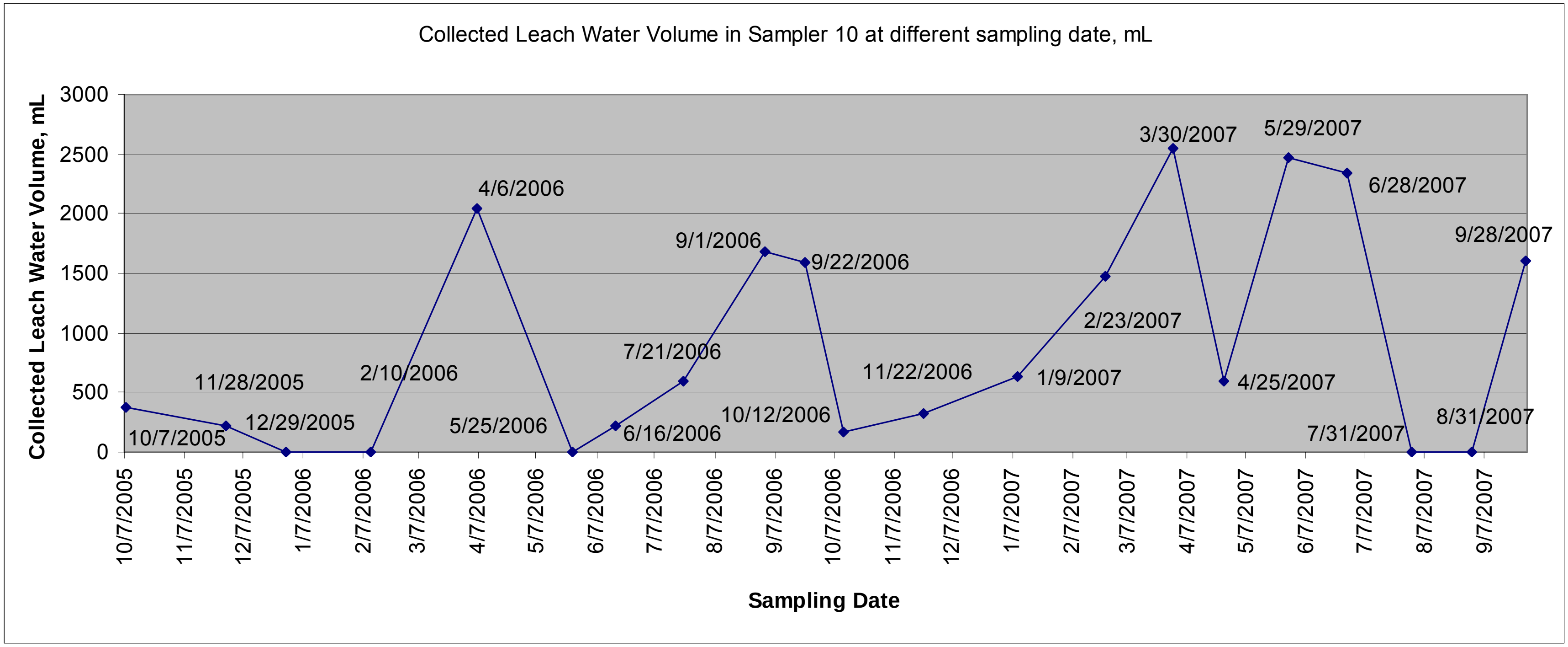

Figure C. 10 Collected leach water volume in sampler 10 at different sampling dates, mL

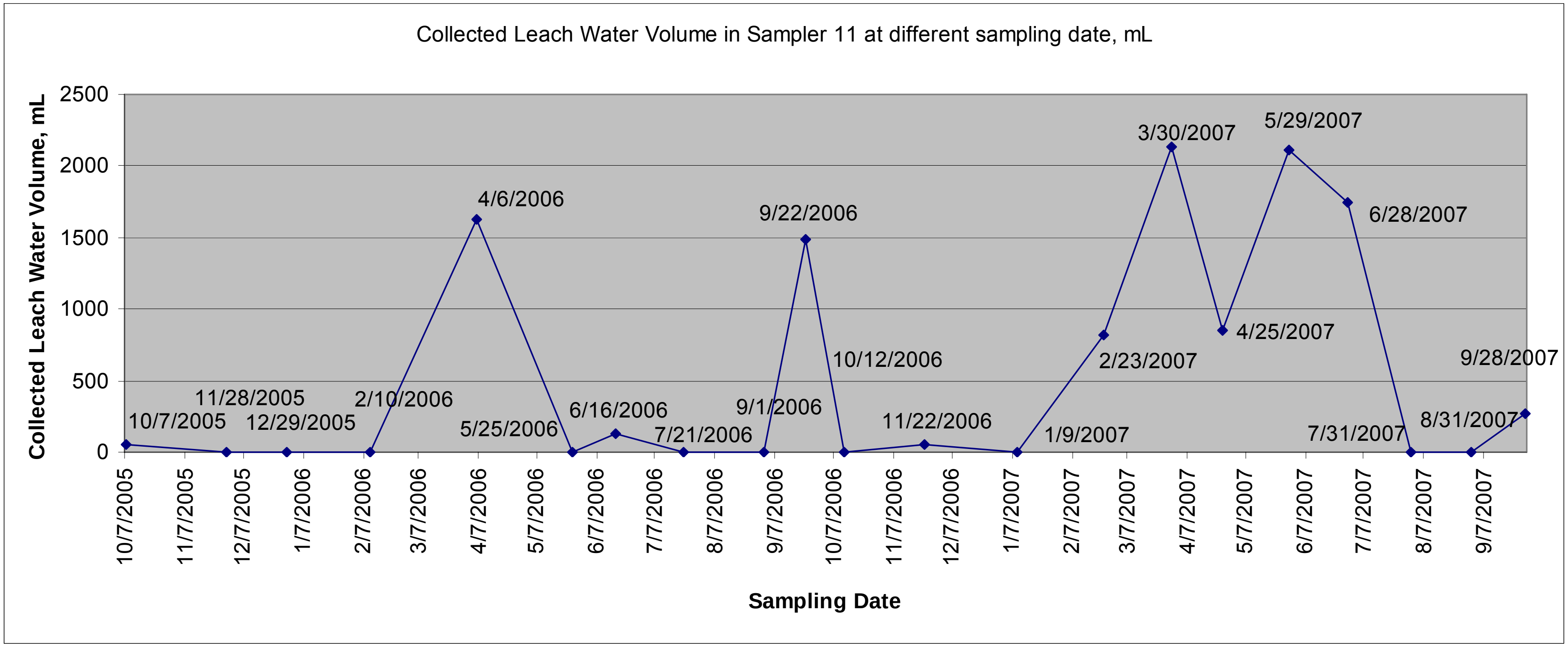

Figure C. 11 Collected leach water volume in sampler 11 at different sampling dates, mL

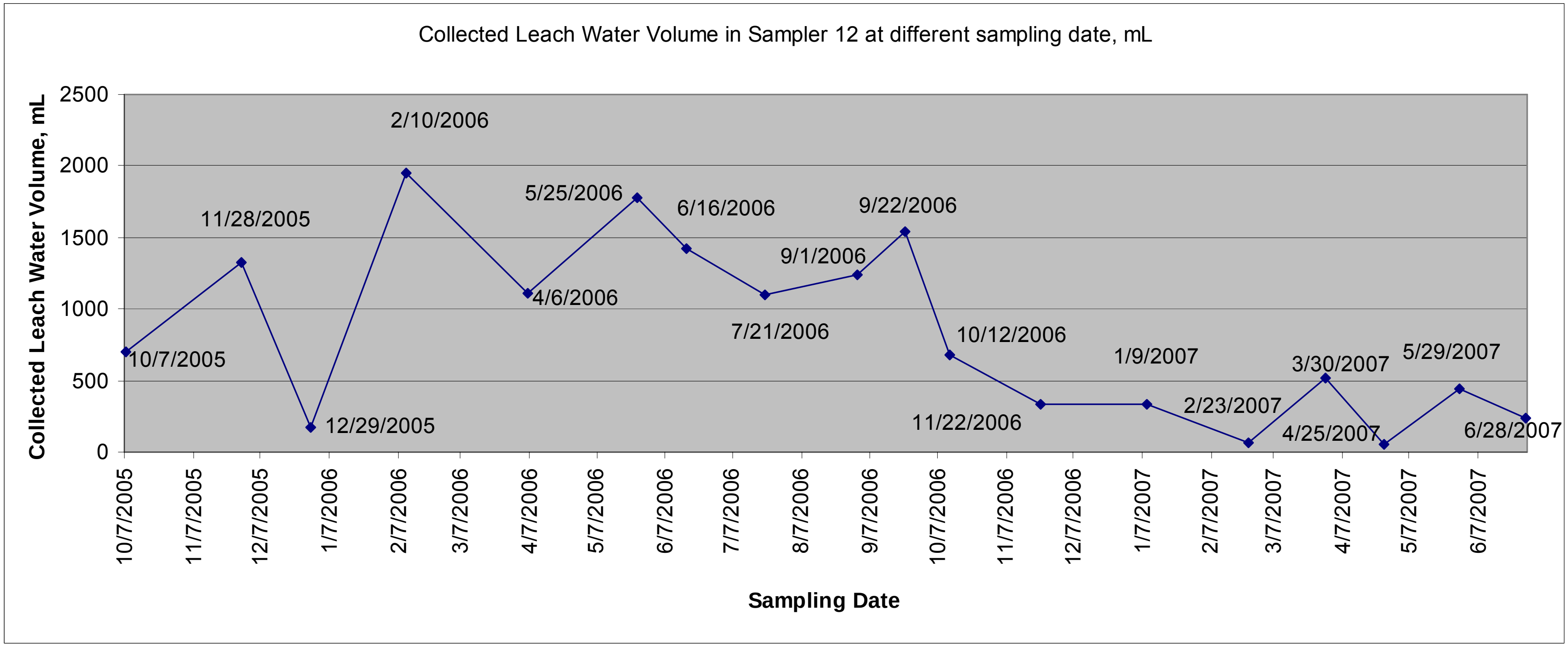

Figure C. 12 Collected leach water volume in sampler 12 at different sampling dates, mL

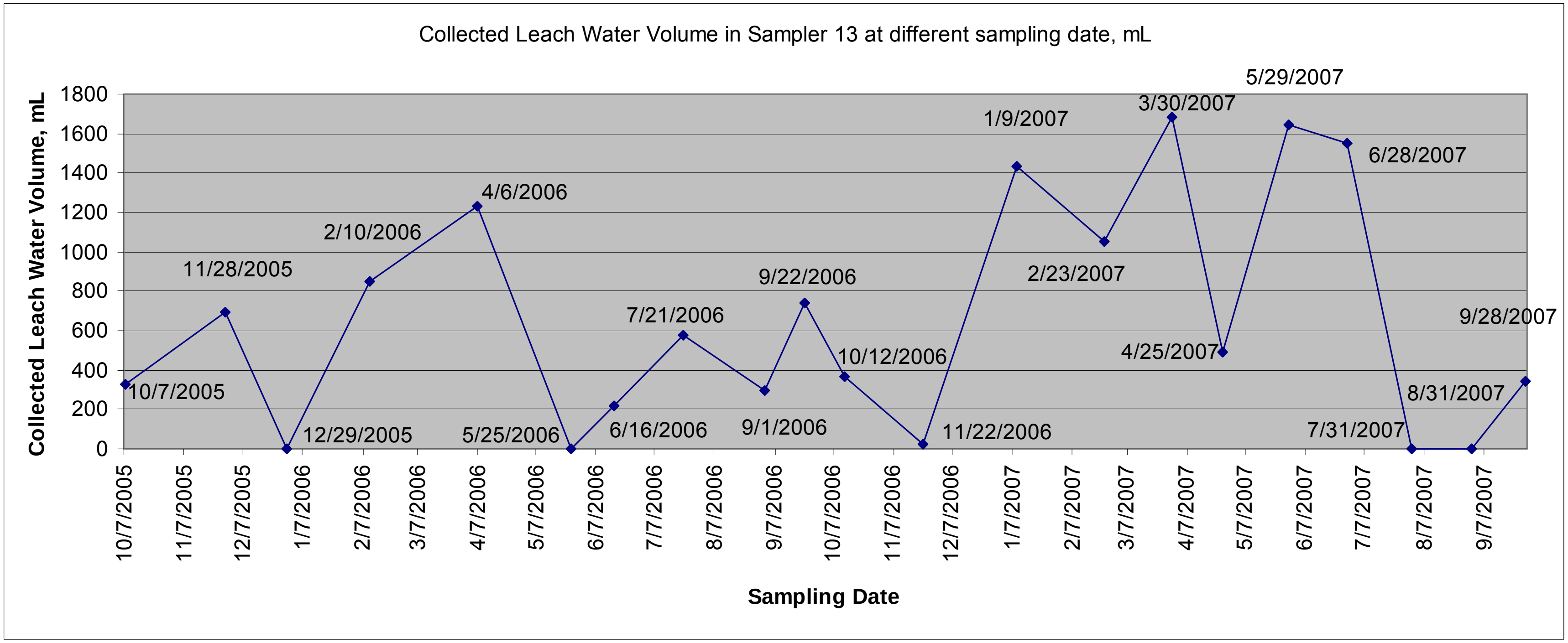

Figure C. 13 Collected leach water volume in sampler 13 at different sampling dates, mL

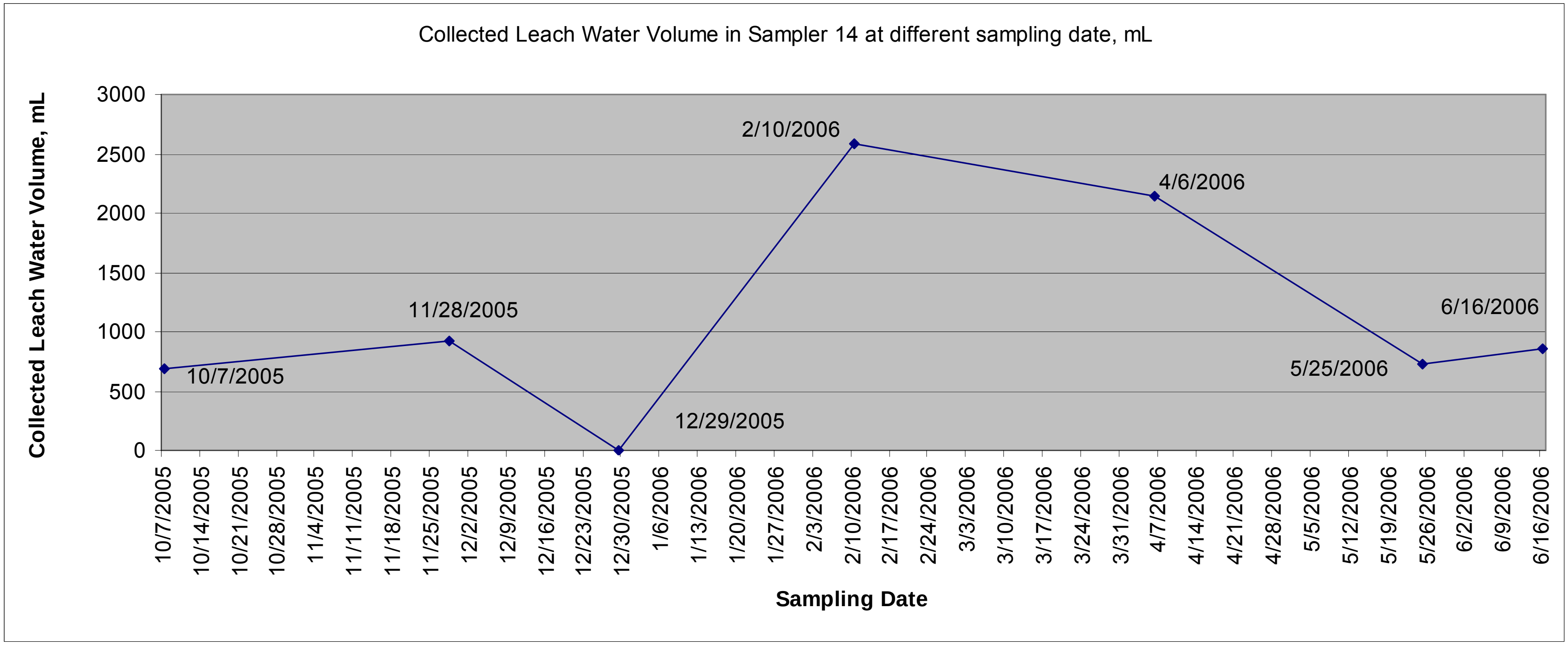

Figure C. 14 Collected leach water volume in sampler 14 at different sampling dates, mL

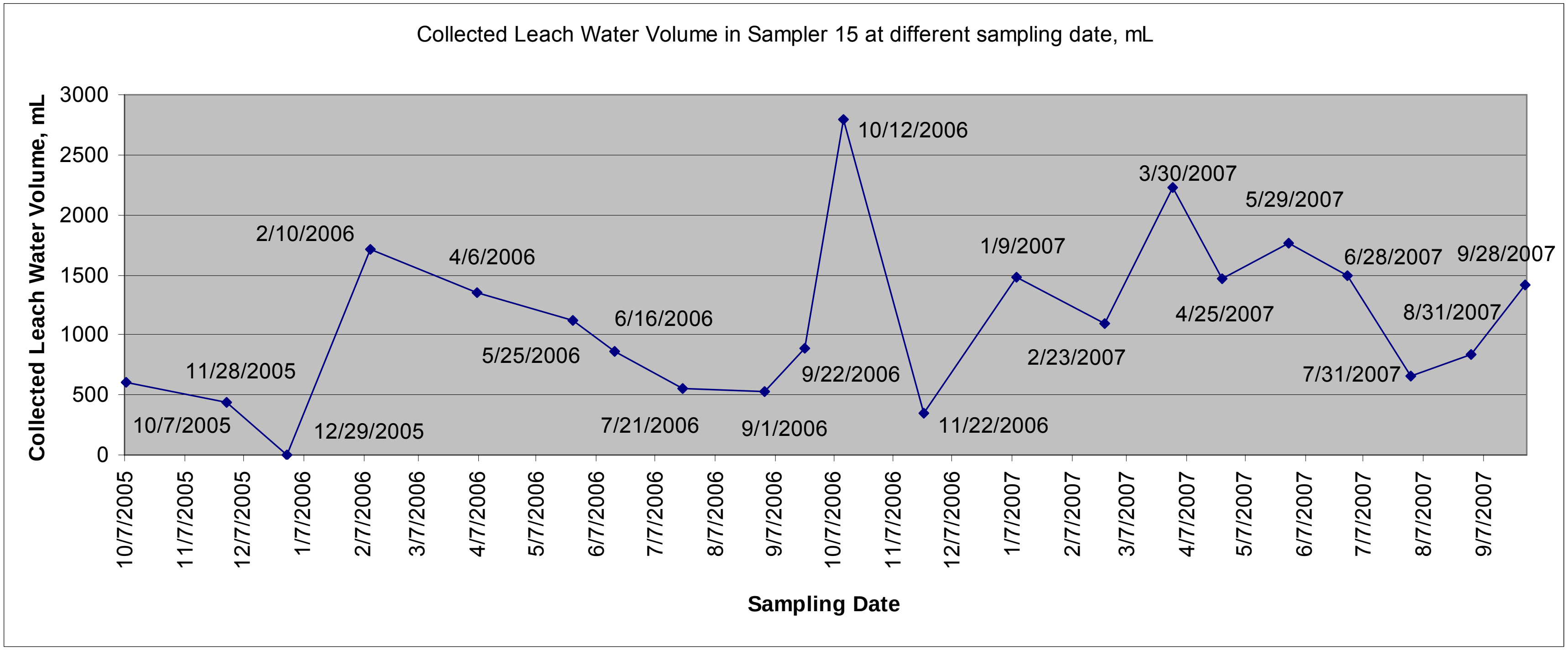

Figure C. 15 Collected leach water volume in sampler 15 at different sampling dates, mL

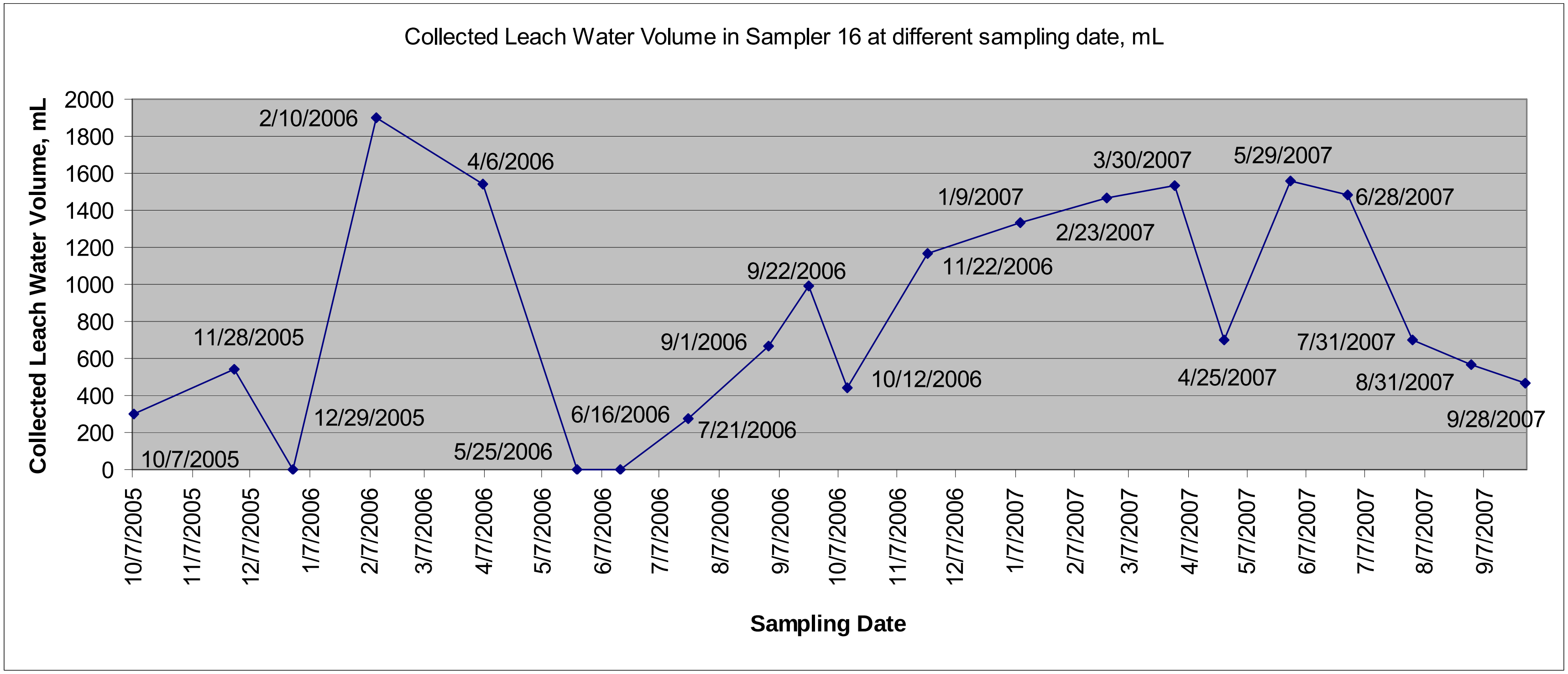

Figure C. 16 Collected leach water volume in sampler 16 at different sampling dates, mL

APPENDIX D

THE PLOTS OF SPATIAL DISTRIBUTION OF LEACHED TOTAL NITROGEN MASS

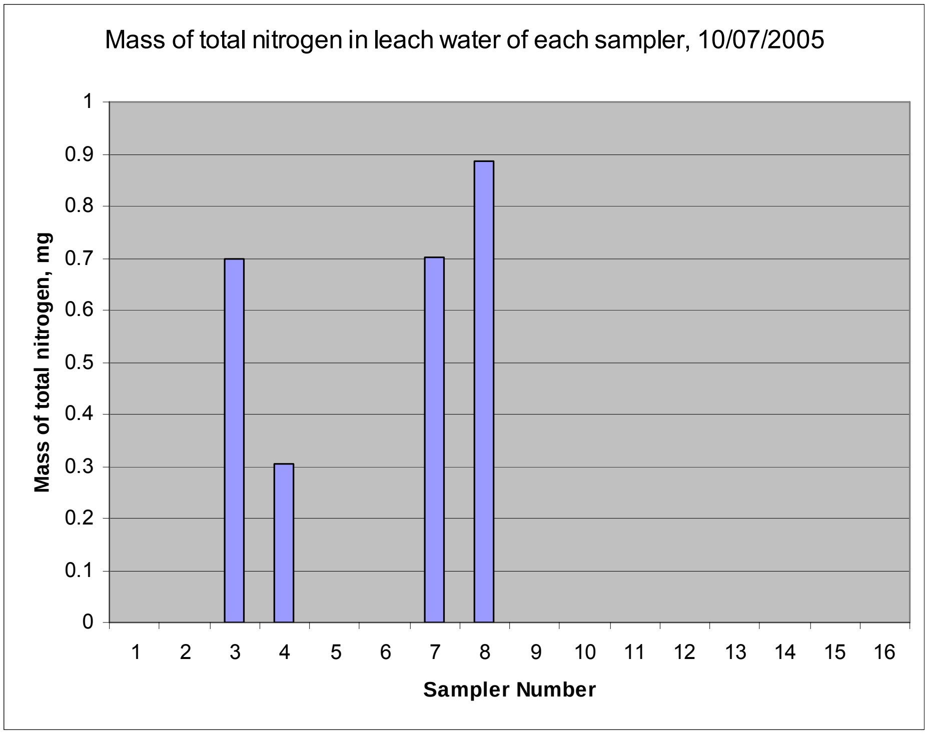

Figure D. 1. Mass of total nitrogen in the leach water of each sampler, 10/07/2005.

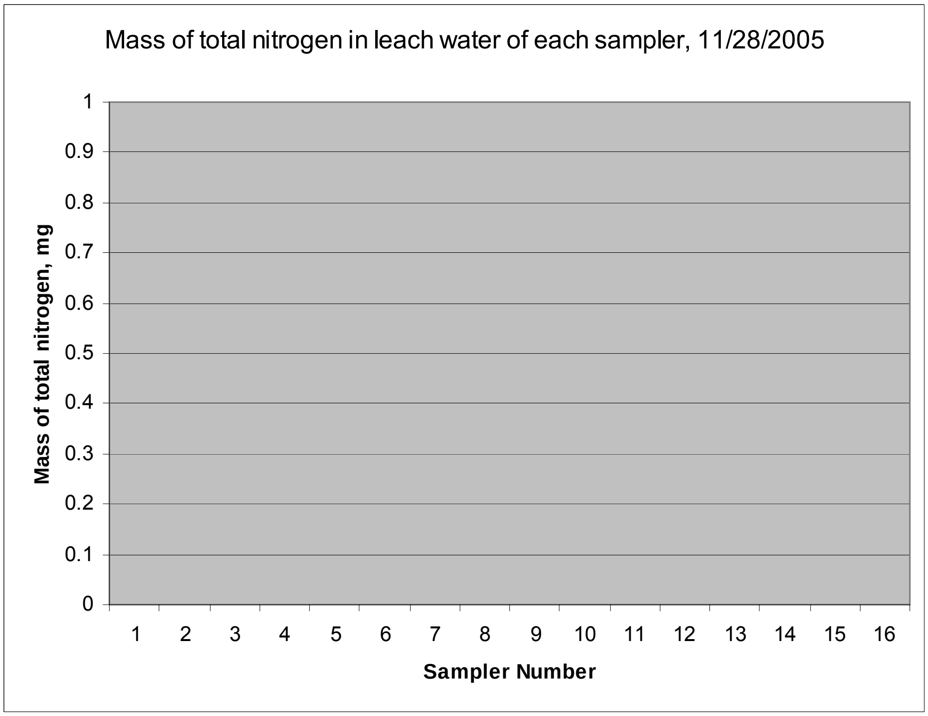

Figure D. 2. Mass of total nitrogen in the leach water of each sampler, 11/28/2005.

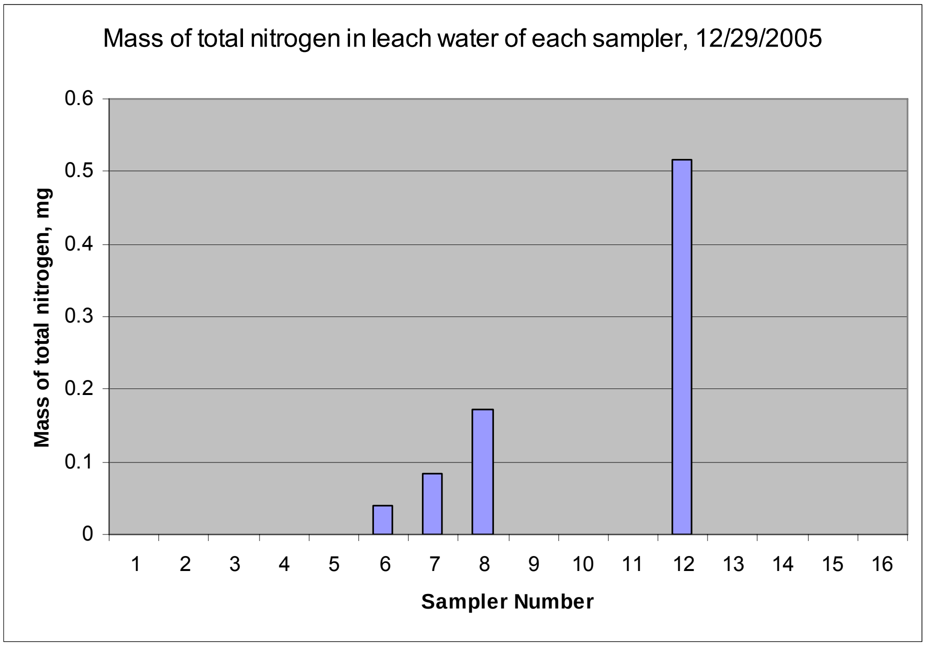

Figure D. 3. Mass of total nitrogen in the leach water of each sampler, 12/29/2005.

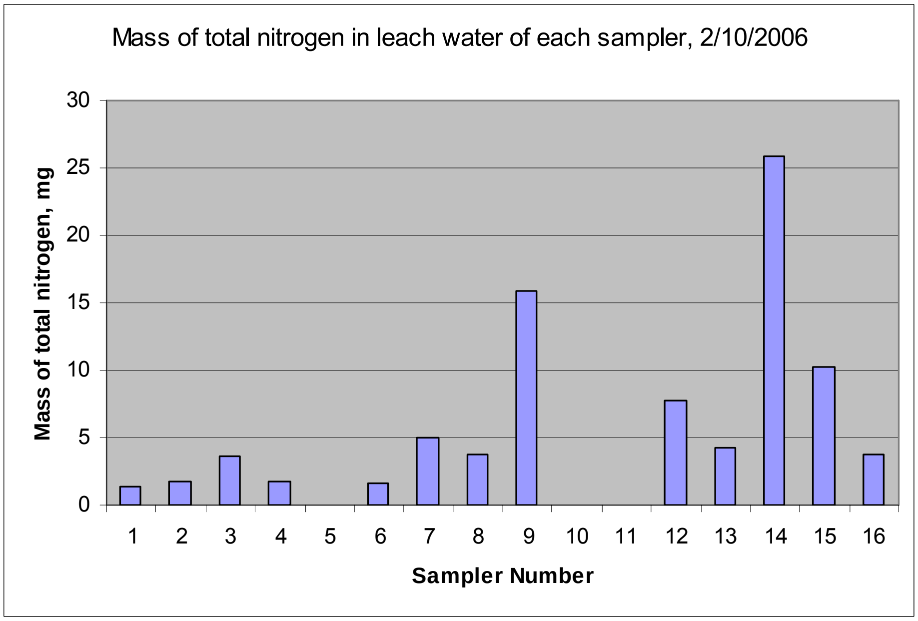

Figure D. 4. Mass of total nitrogen in the leach water of each sampler, 2/10/2006.

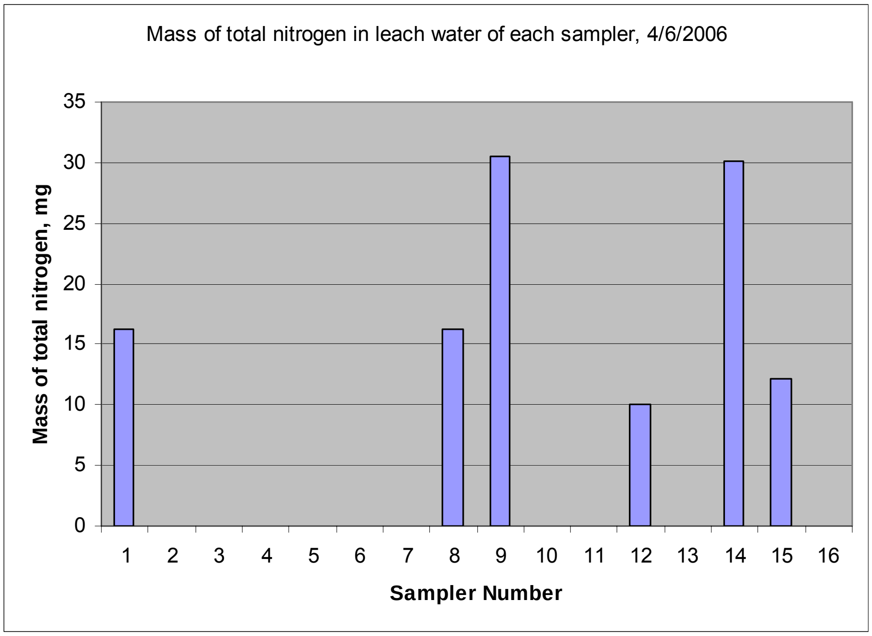

Figure D. 5. Mass of total nitrogen in the leach water of each sampler, 4/6/2006.

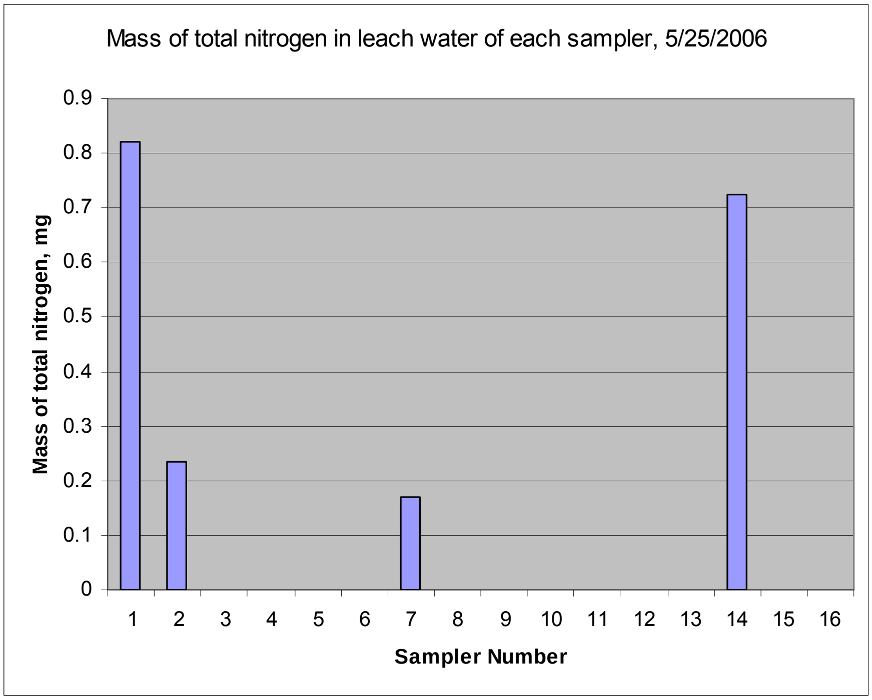

Figure D. 6. Mass of total nitrogen in the leach water of each sampler, 5/25/2006.

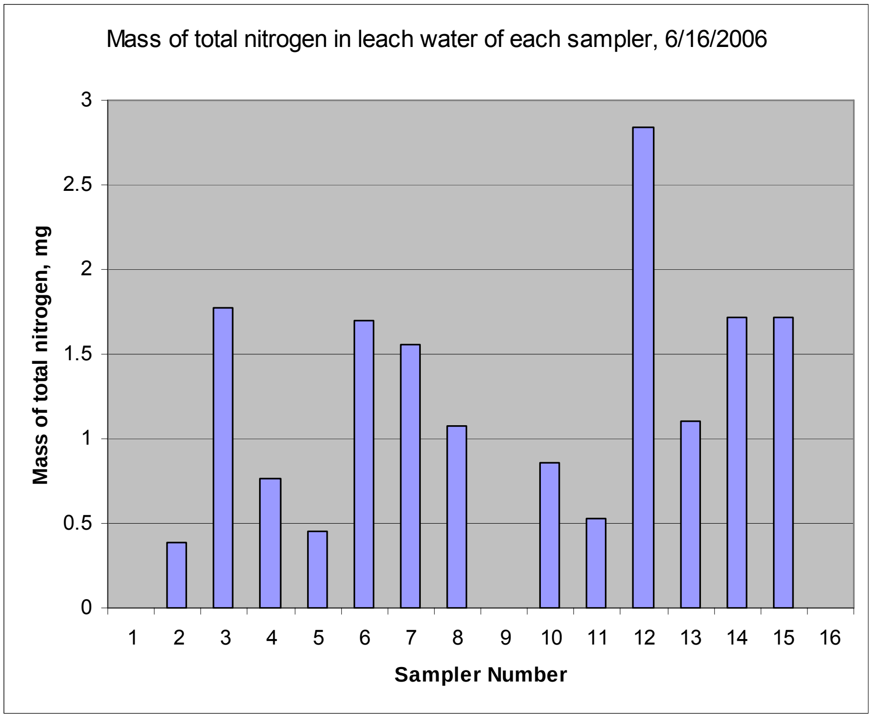

Figure D. 7. Mass of total nitrogen in the leach water of each sampler, 6/16/2006.

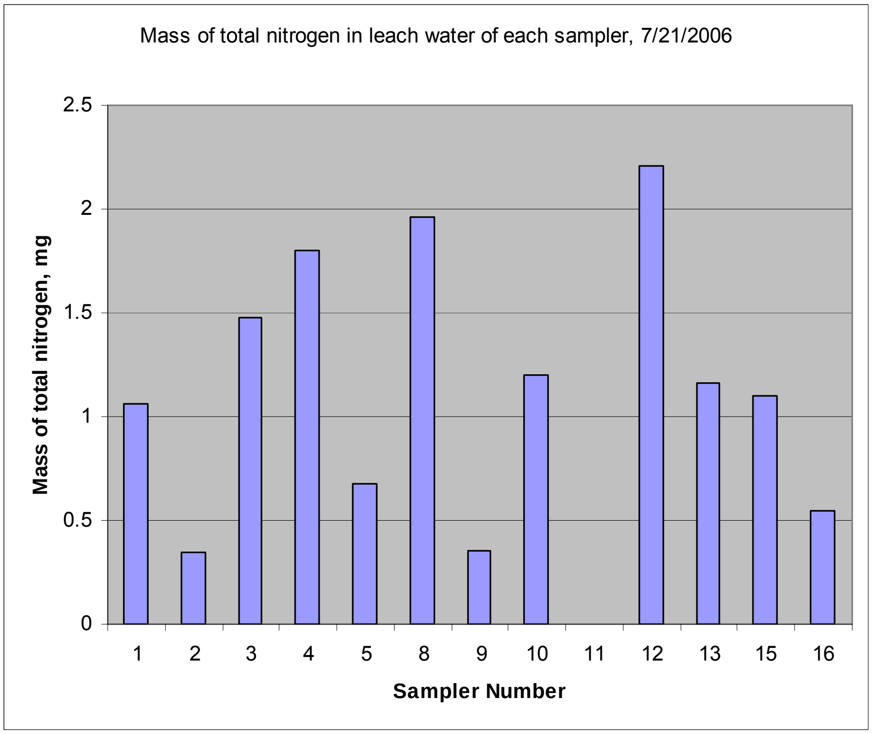

Figure D. 8. Mass of total nitrogen in the leach water of each sampler, 7/21/2006.

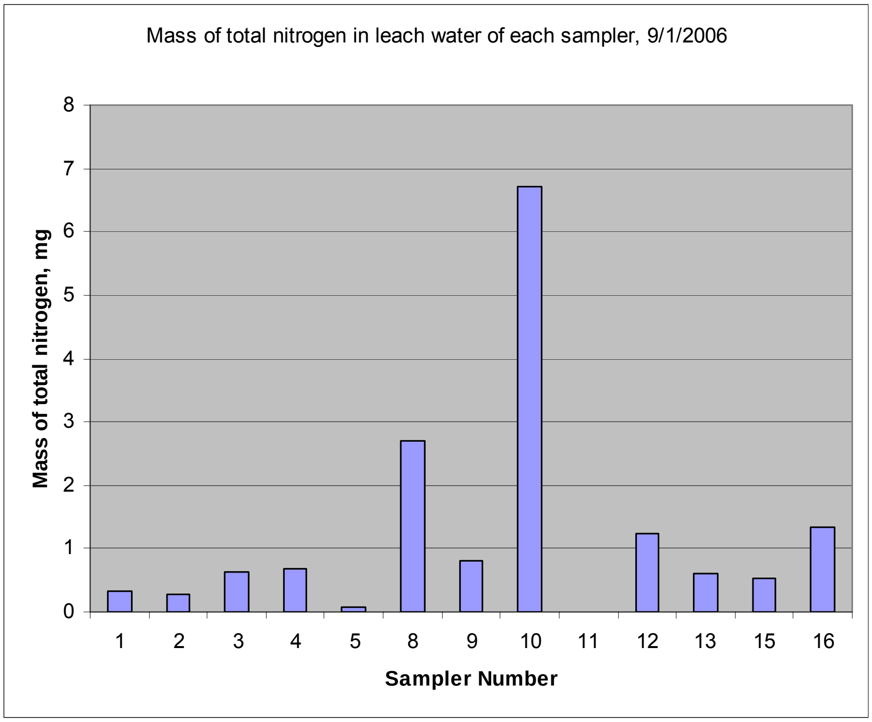

Figure D. 9. Mass of total nitrogen in the leach water of each sampler, 9/1/2006.

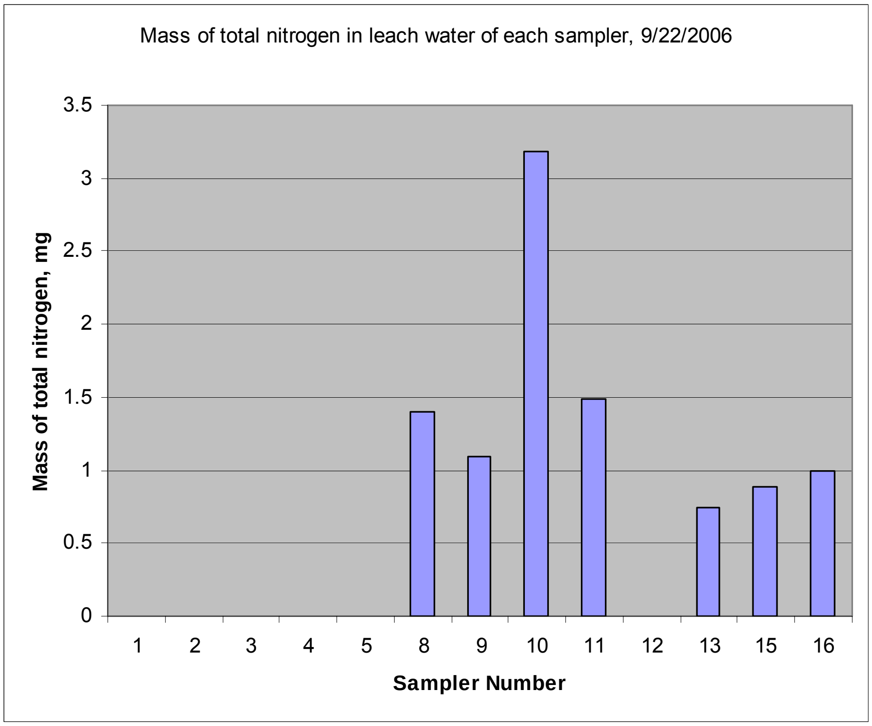

Figure D. 10. Mass of total nitrogen in the leach water of each sampler, 9/22/2006.

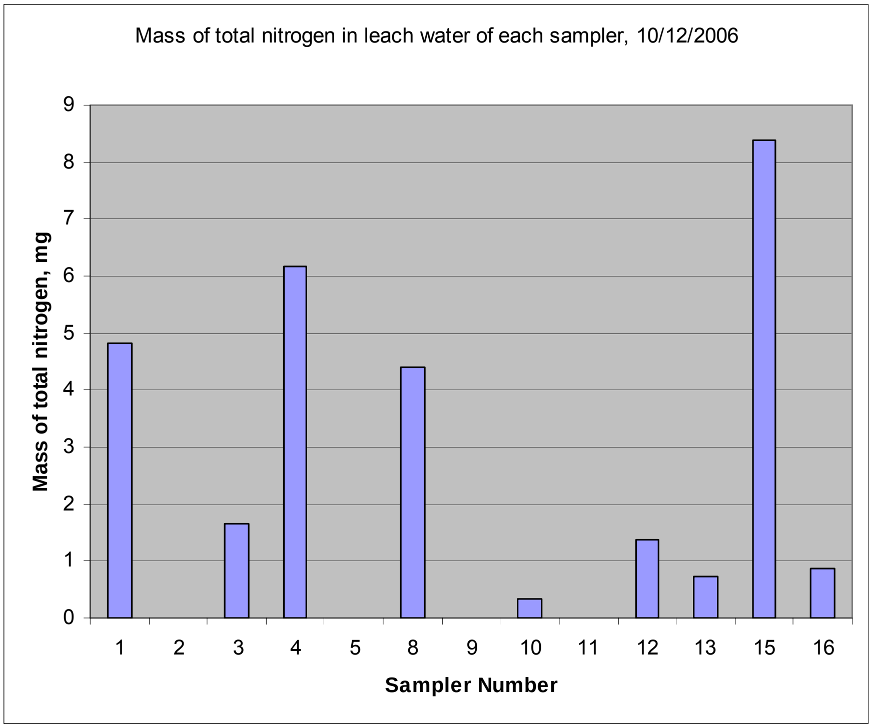

Figure D. 11. Mass of total nitrogen in the leach water of each sampler, 10/12/2006.

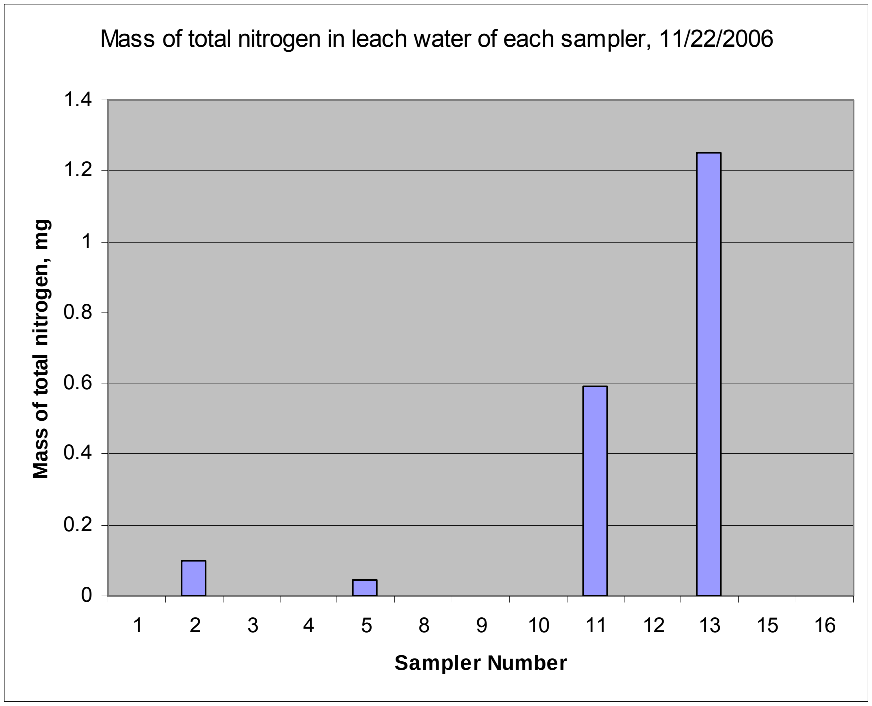

Figure D. 12. Mass of total nitrogen in the leach water of each sampler, 11/22/2006.

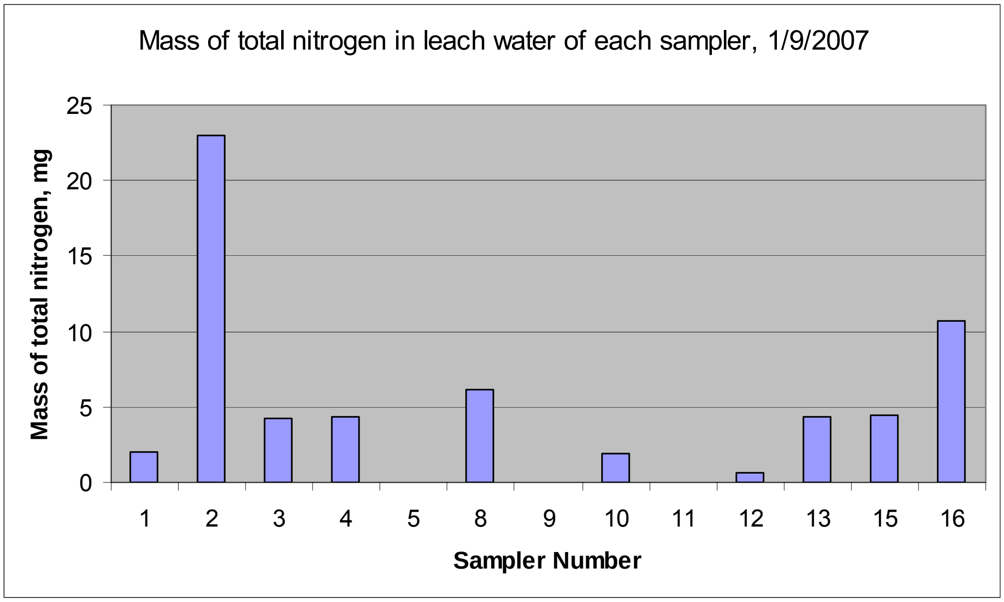

Figure D. 13. Mass of total nitrogen in the leach water of each sampler, 1/9/2007.

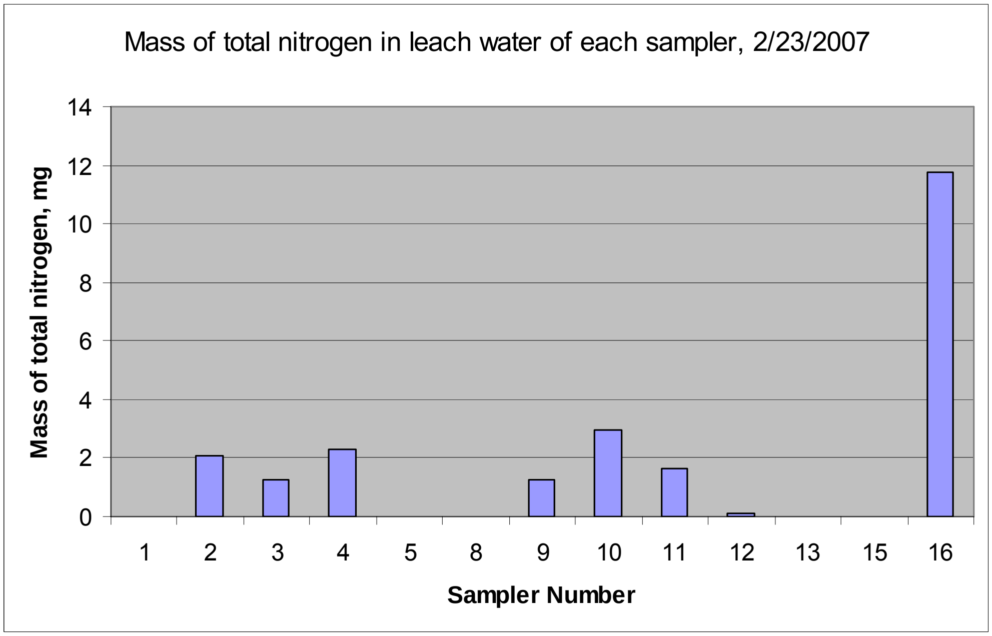

Figure D. 14. Mass of total nitrogen in the leach water of each sampler, 2/23/2007.

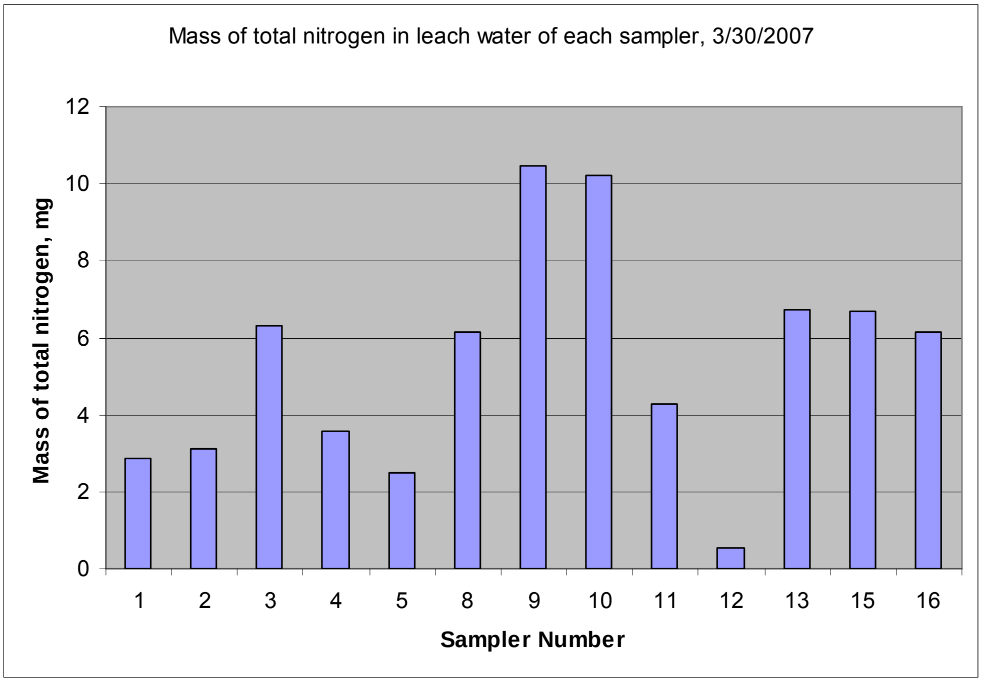

Figure D. 15. Mass of total nitrogen in the leach water of each sampler, 3/30/2007.

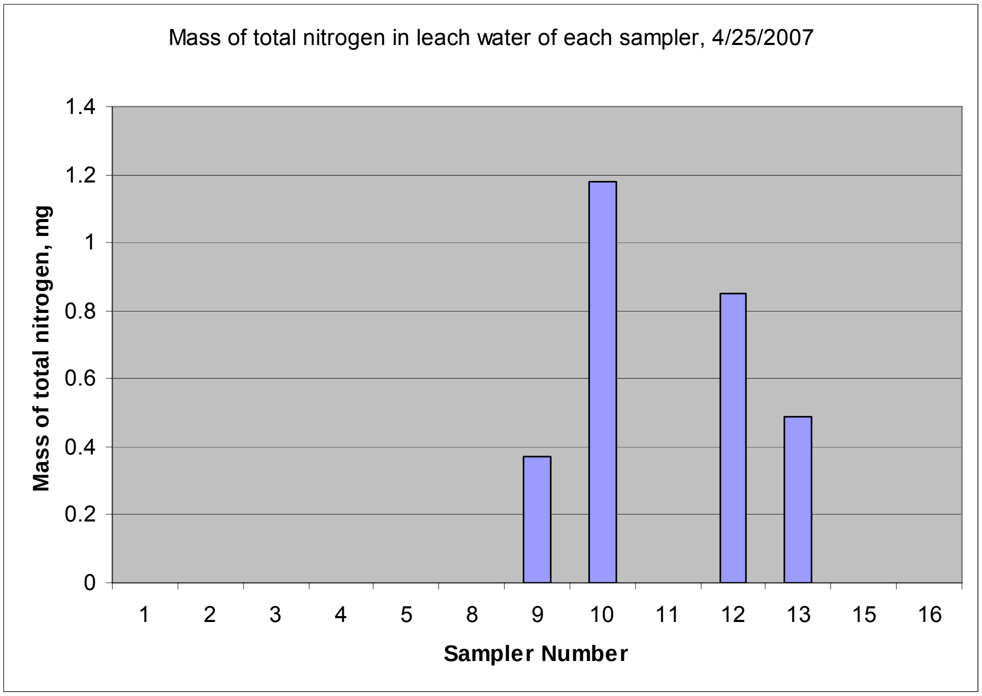

Figure D. 16. Mass of total nitrogen in the leach water of each sampler, 4/25/2007.

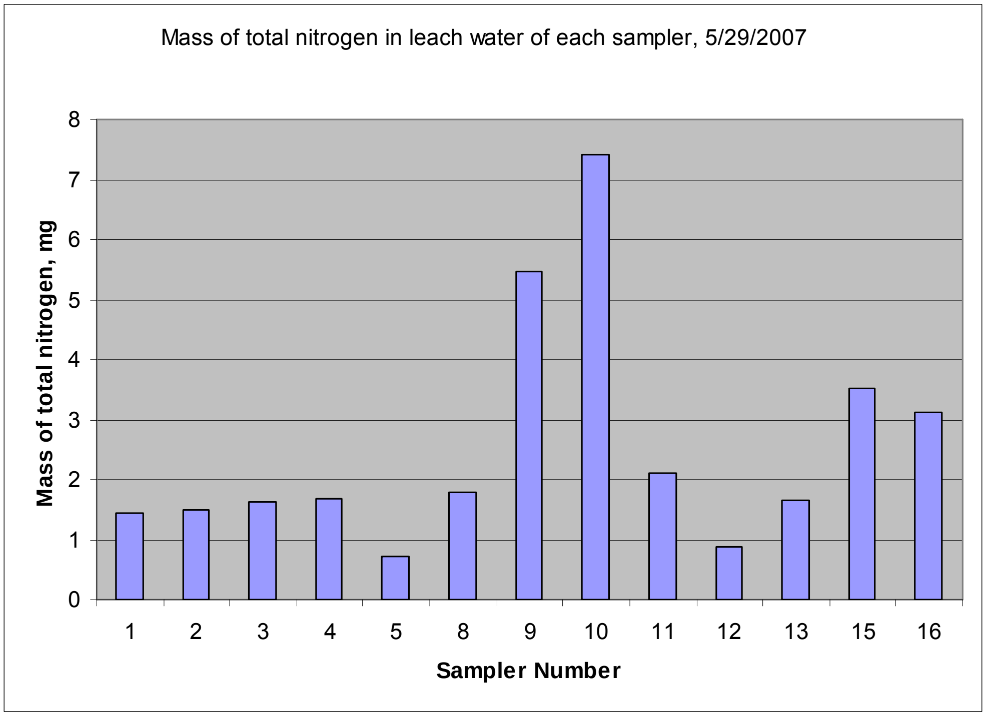

Figure D. 17. Mass of total nitrogen in the leach water of each sampler, 5/29/2007.

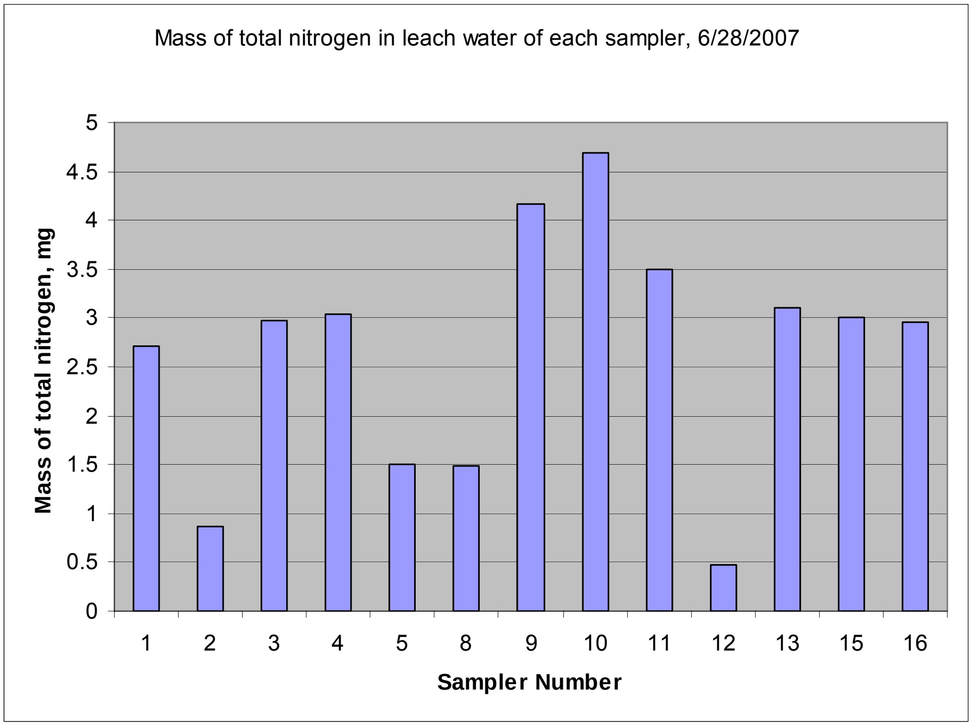

Figure D. 18. Mass of total nitrogen in the leach water of each sampler, 6/28/2007.

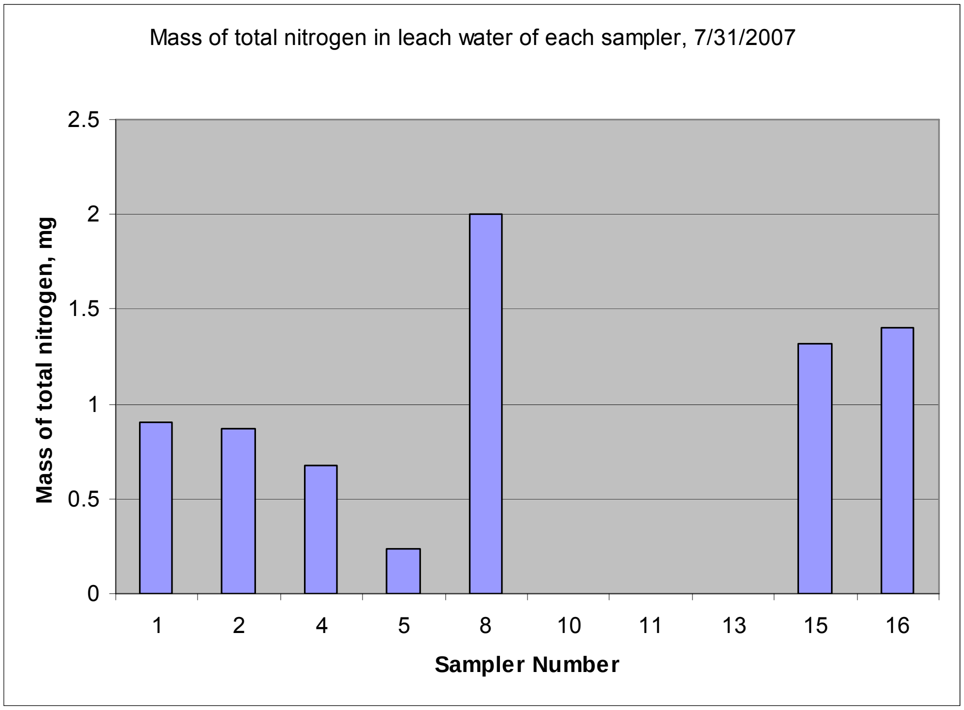

Figure D. 19. Mass of total nitrogen in the leach water of each sampler, 7/31/2007.

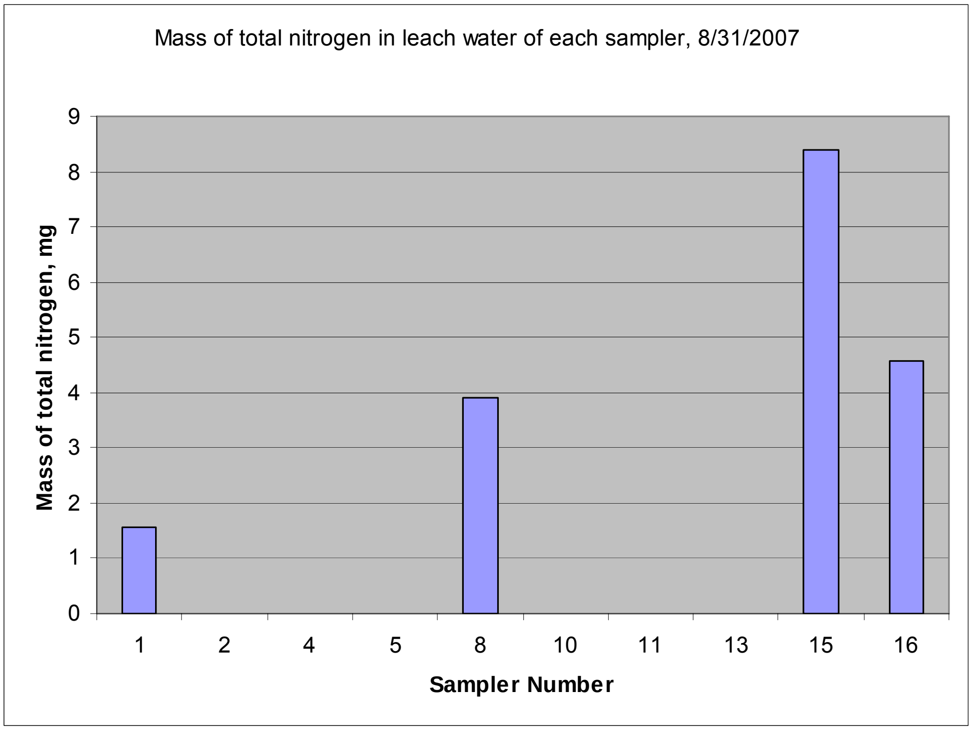

Figure D. 20. Mass of total nitrogen in the leach water of each sampler, 8/31/2007.

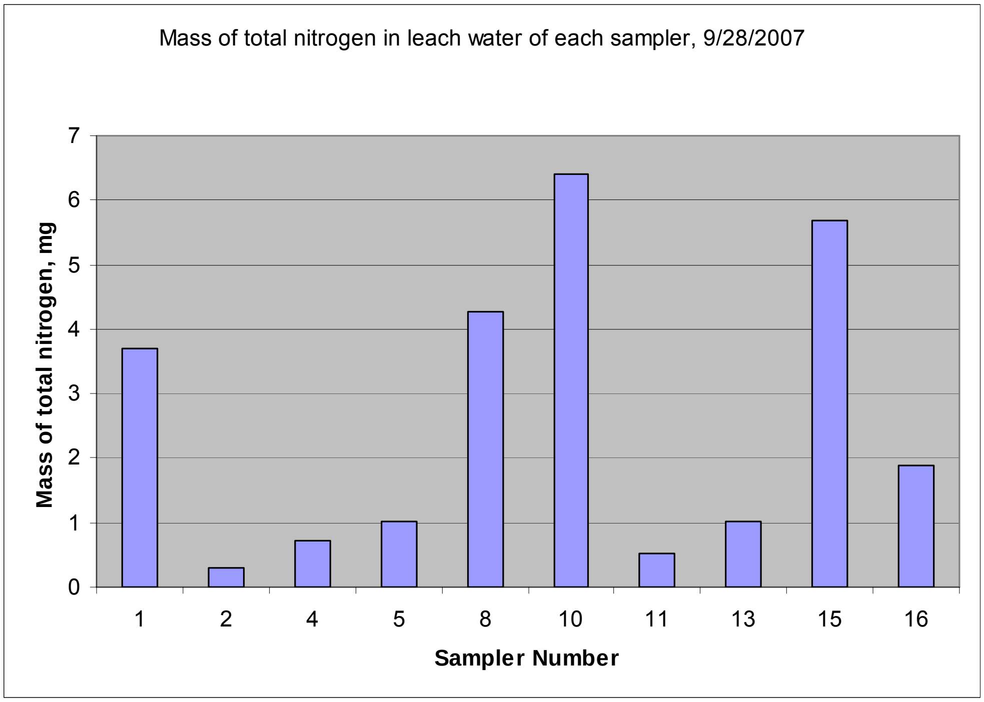

Figure D. 21. Mass of total nitrogen in the leach water of each sampler, 9/28/2007.

APPENDIX E

THE PLOTS OF SPATIAL DISTRIBUTION OF LEACHED SALT MASS

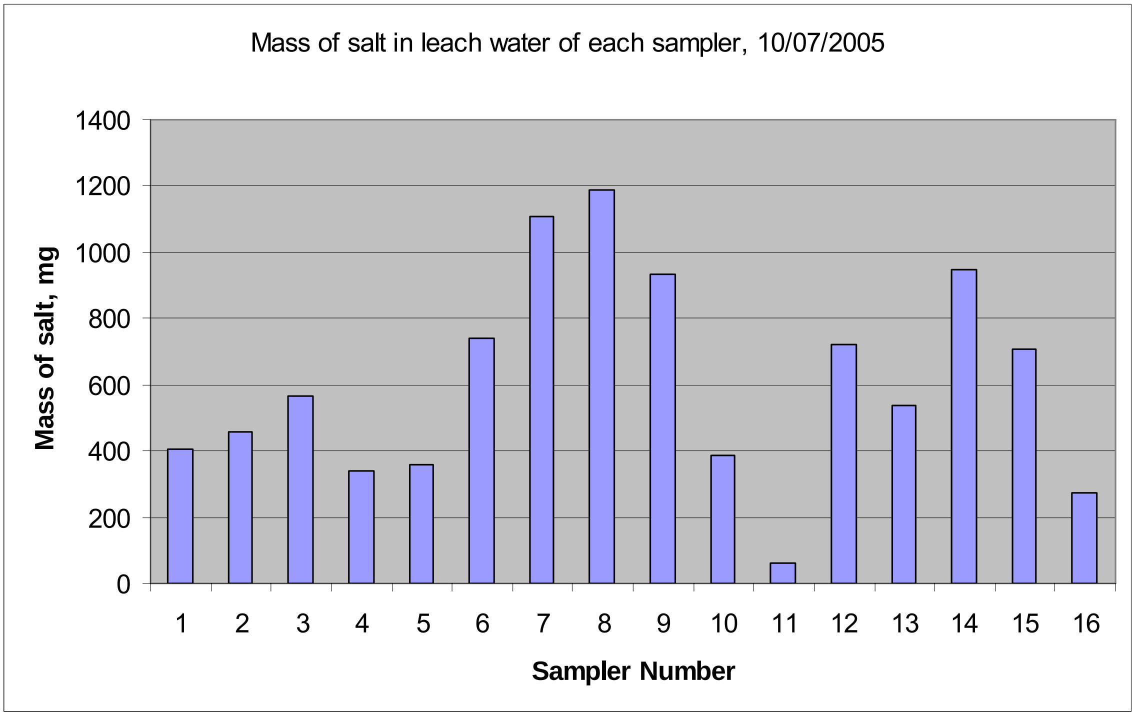

Figure E. 1. Mass of salt in the leach water of each sampler, 10/07/2005.

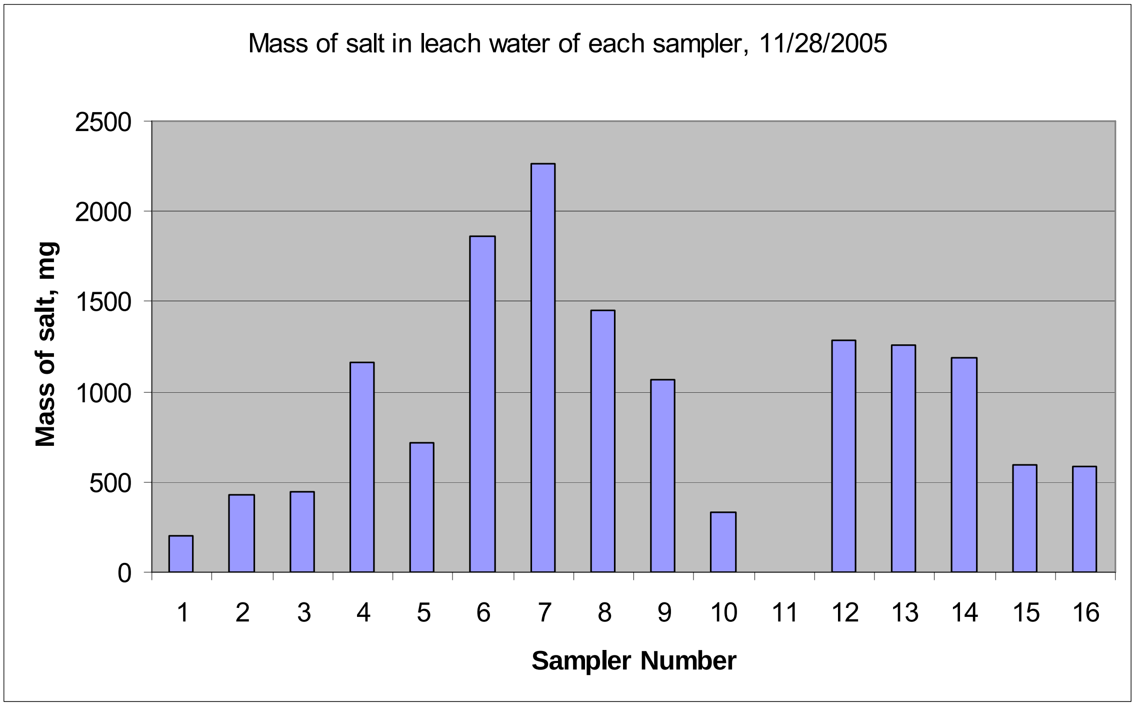

Figure E. 2. Mass of salt in the leach water of each sampler, 11/28/2005.

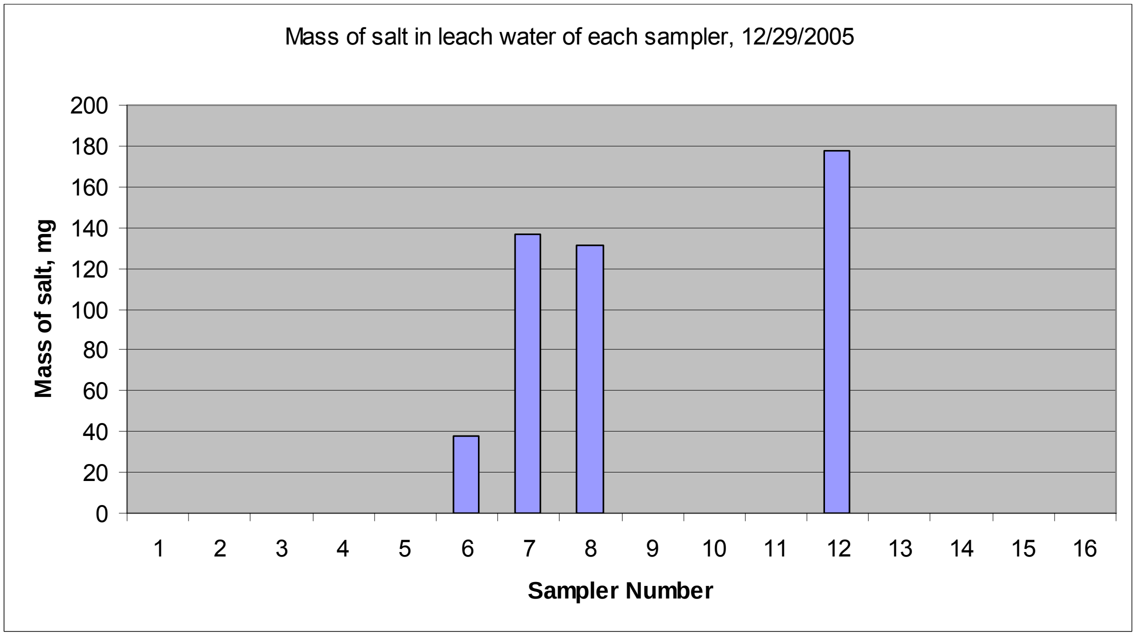

Figure E. 3. Mass of salt in the leach water of each sampler, 12/29/2005.

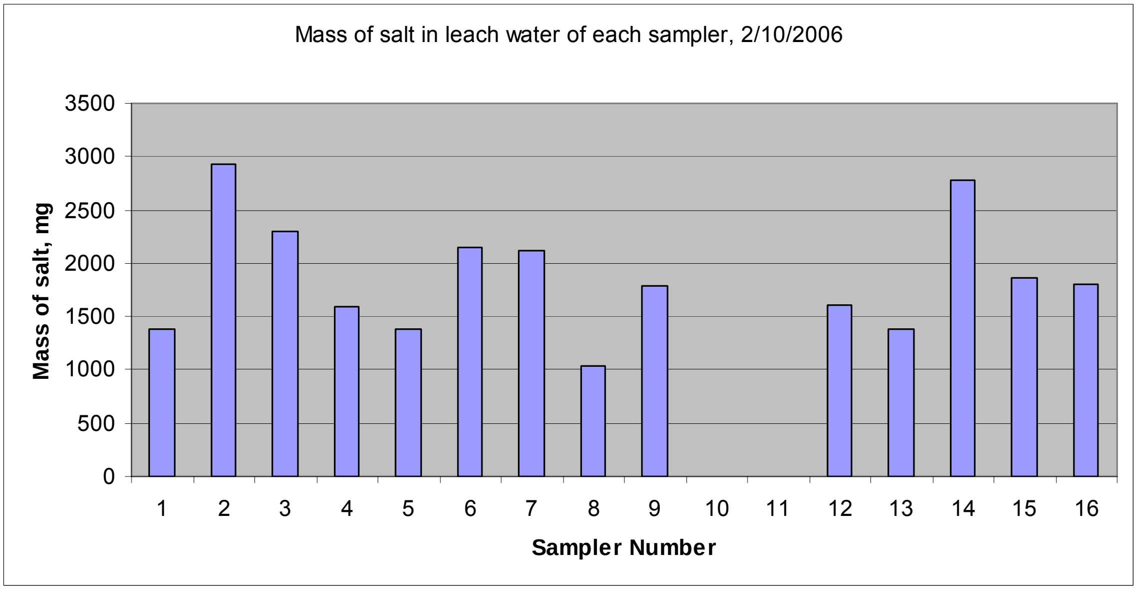

Figure E. 4. Mass of salt in the leach water of each sampler, 2/10/2006.

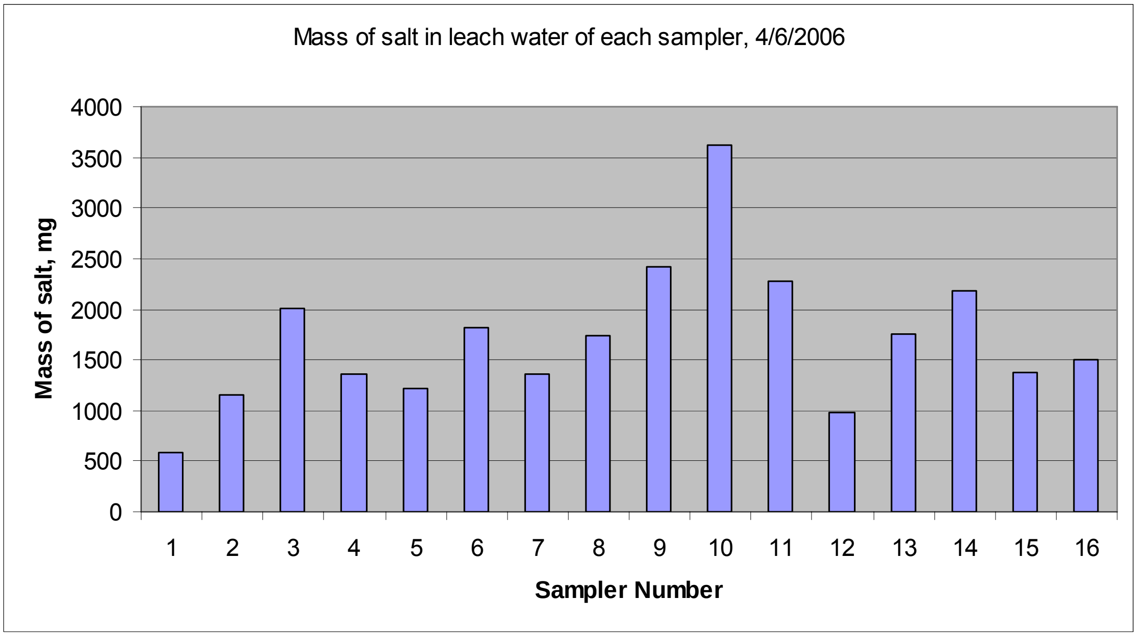

Figure E. 5. Mass of salt in the leach water of each sampler, 4/6/2006.

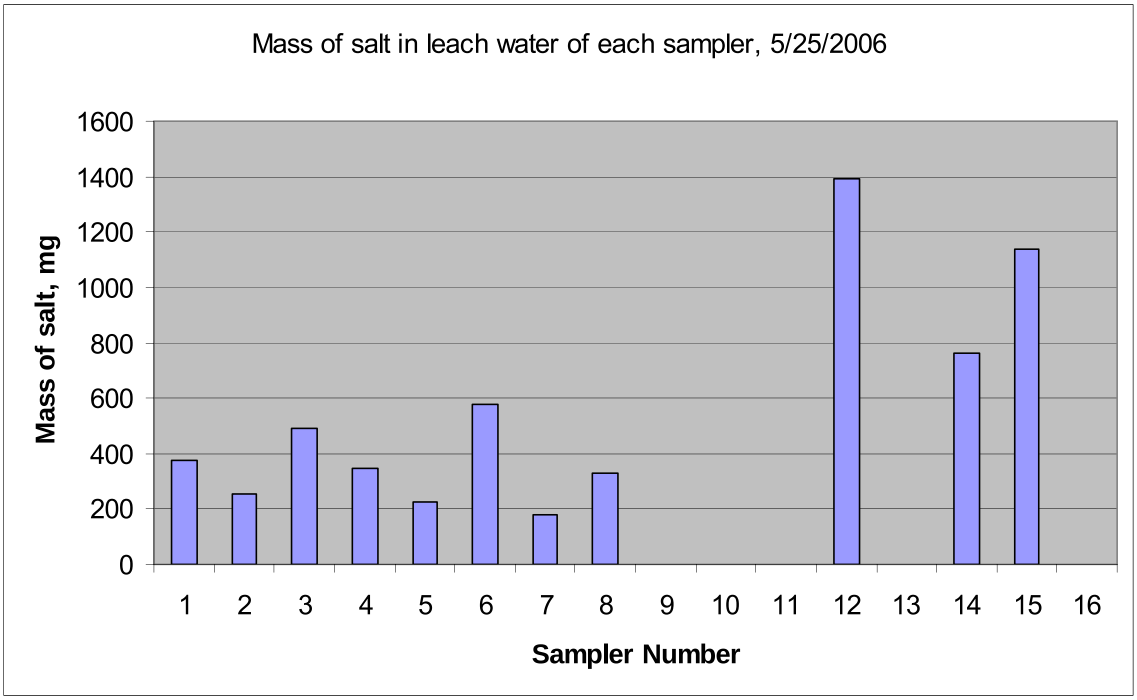

Figure E. 6. Mass of salt in the leach water of each sampler, 5/25/2006.

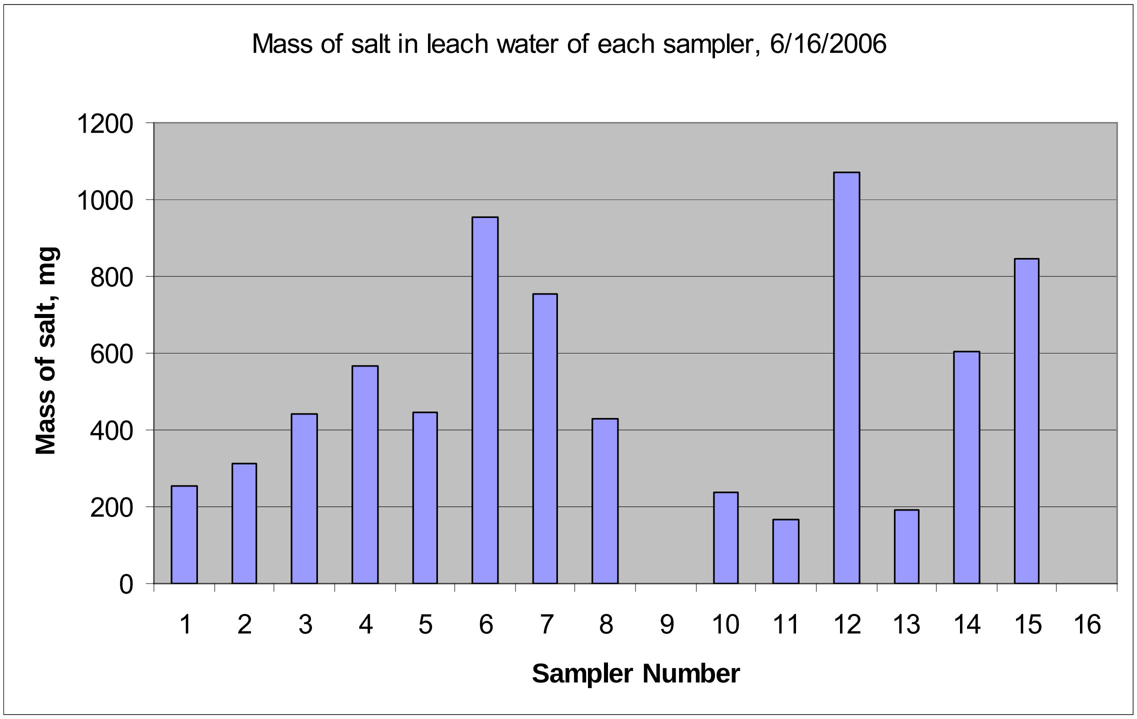

Figure E. 7. Mass of salt in the leach water of each sampler, 6/16/2006.

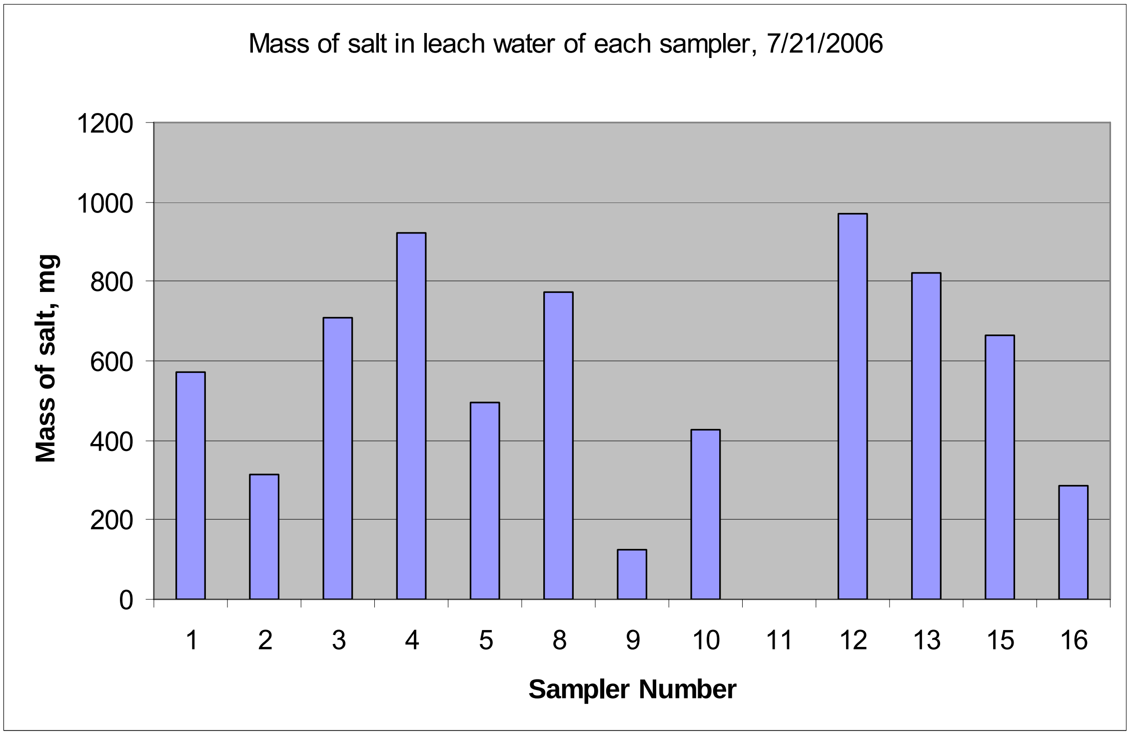

Figure E. 8. Mass of salt in the leach water of each sampler, 7/21/2006.

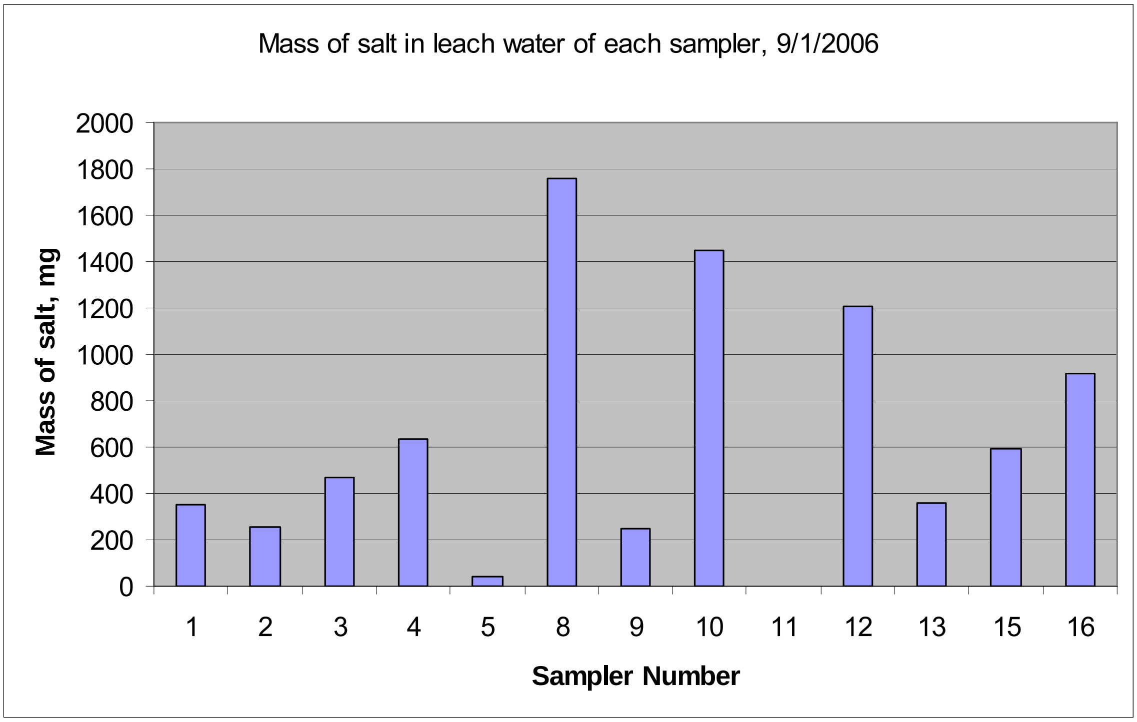

Figure E. 9. Mass of salt in the leach water of each sampler, 9/1/2006.

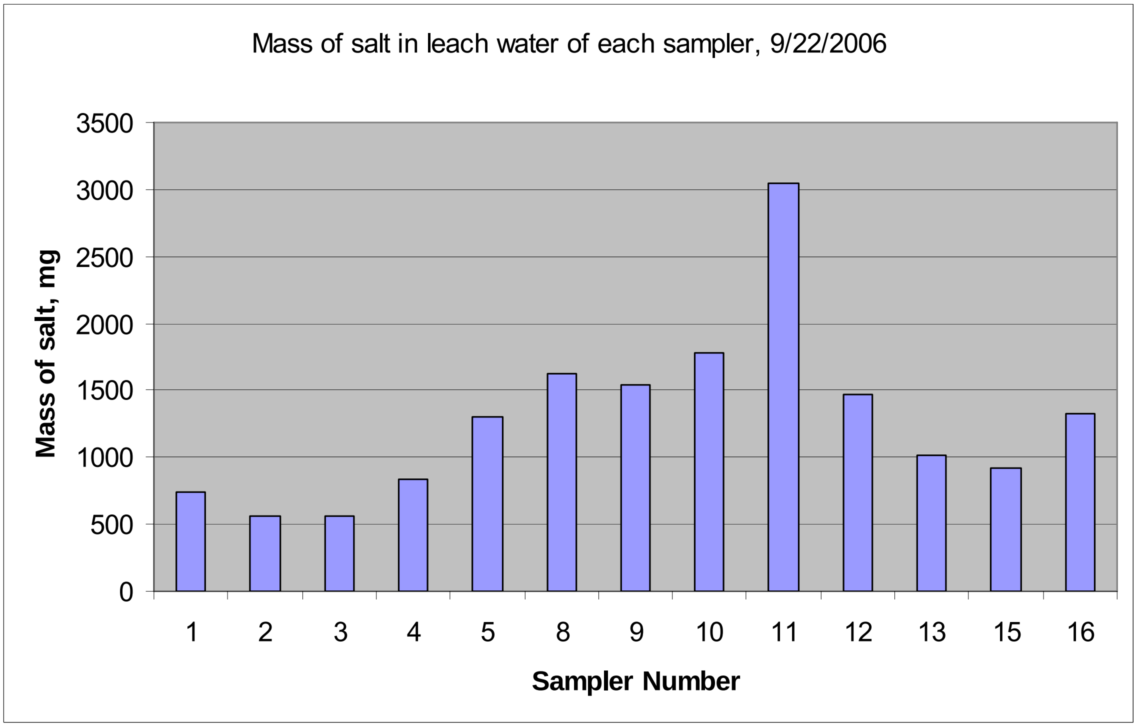

Figure E. 10. Mass of salt in the leach water of each sampler, 9/22/2006.

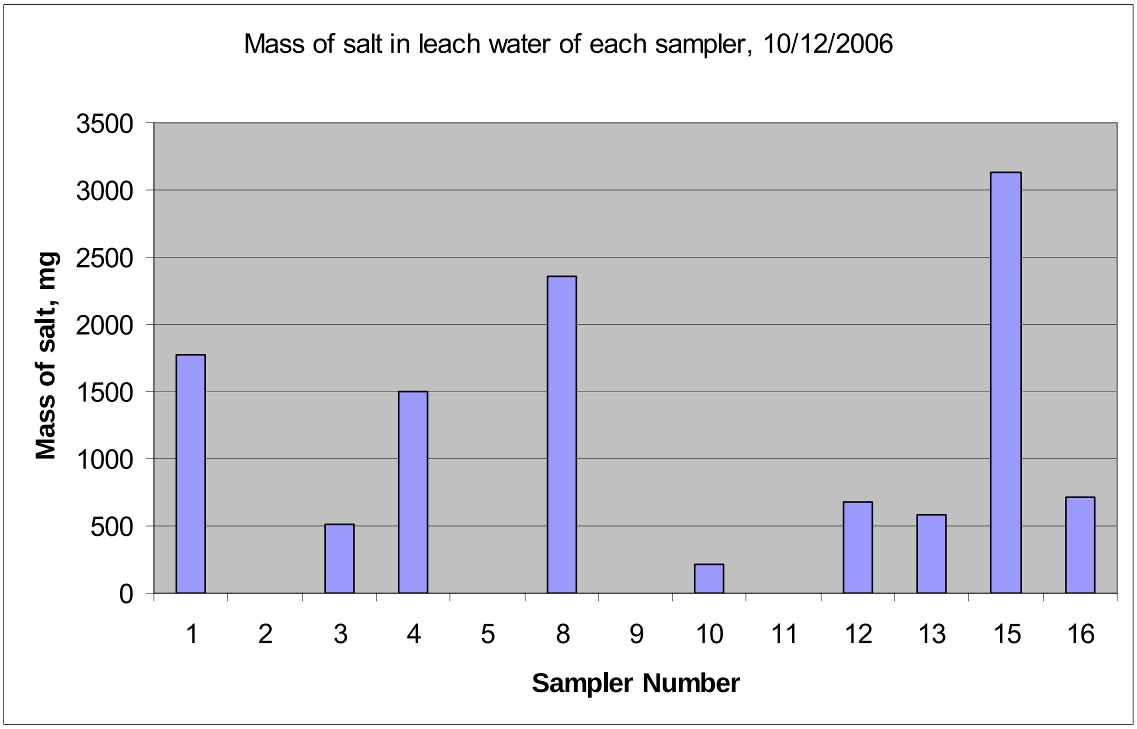

Figure E. 11. Mass of salt in the leach water of each sampler, 10/12/2006.

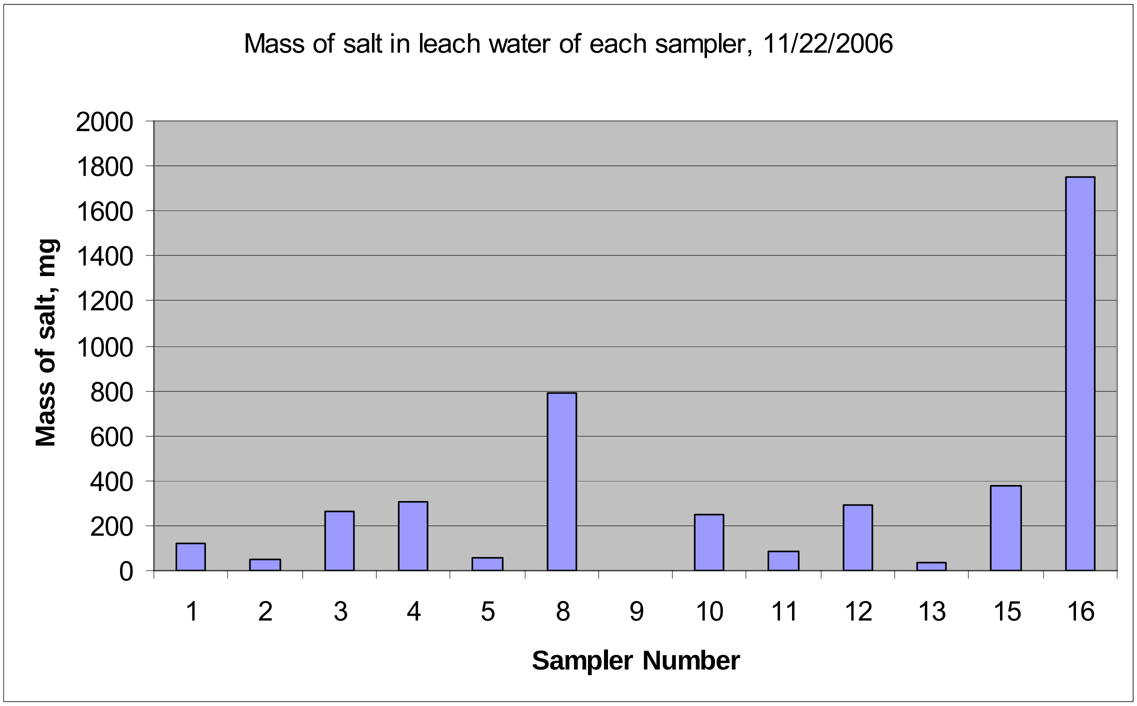

Figure E. 12. Mass of salt in the leach water of each sampler, 11/22/2006

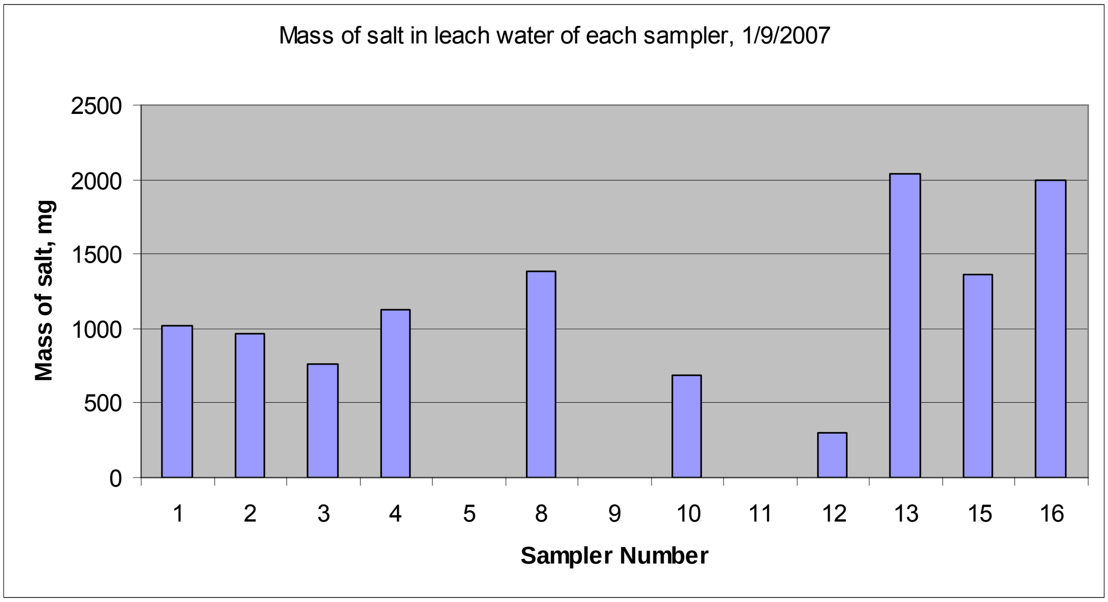

Figure E. 13. Mass of salt in the leach water of each sampler, 1/9/2007.

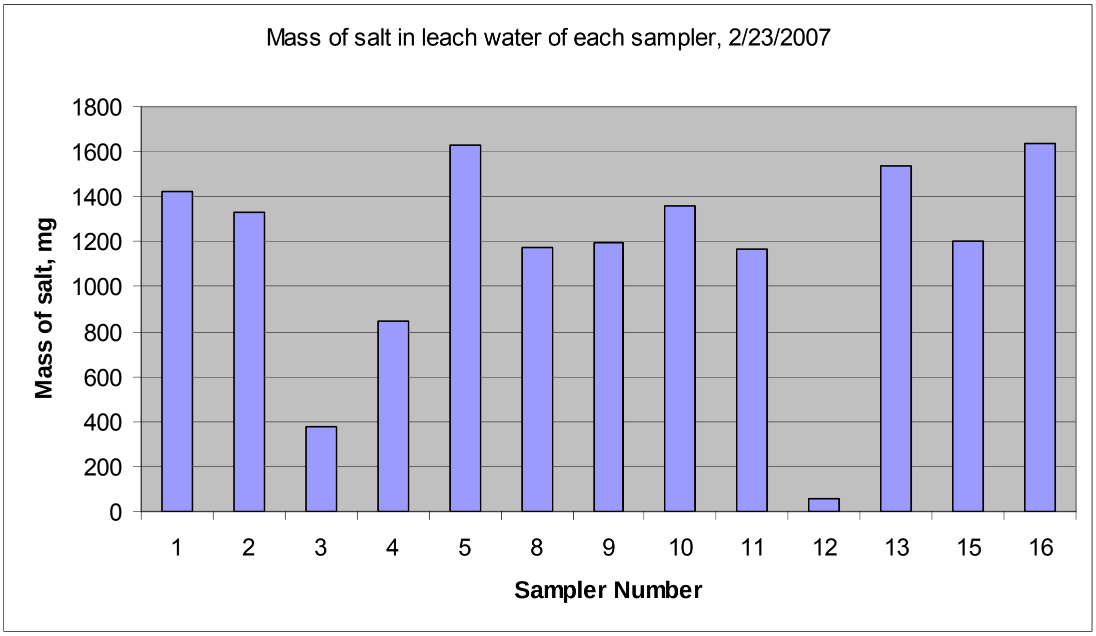

Figure E. 14. Mass of salt in the leach water of each sampler, 2/23/2007.

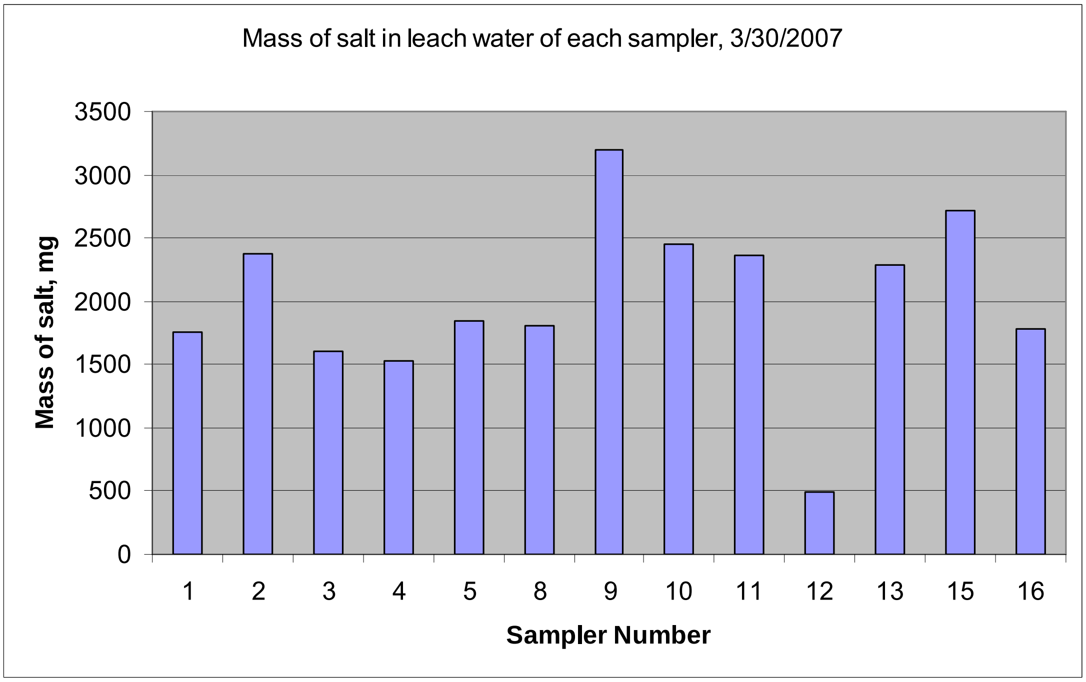

Figure E. 15. Mass of salt in the leach water of each sampler, 3/30/2007.

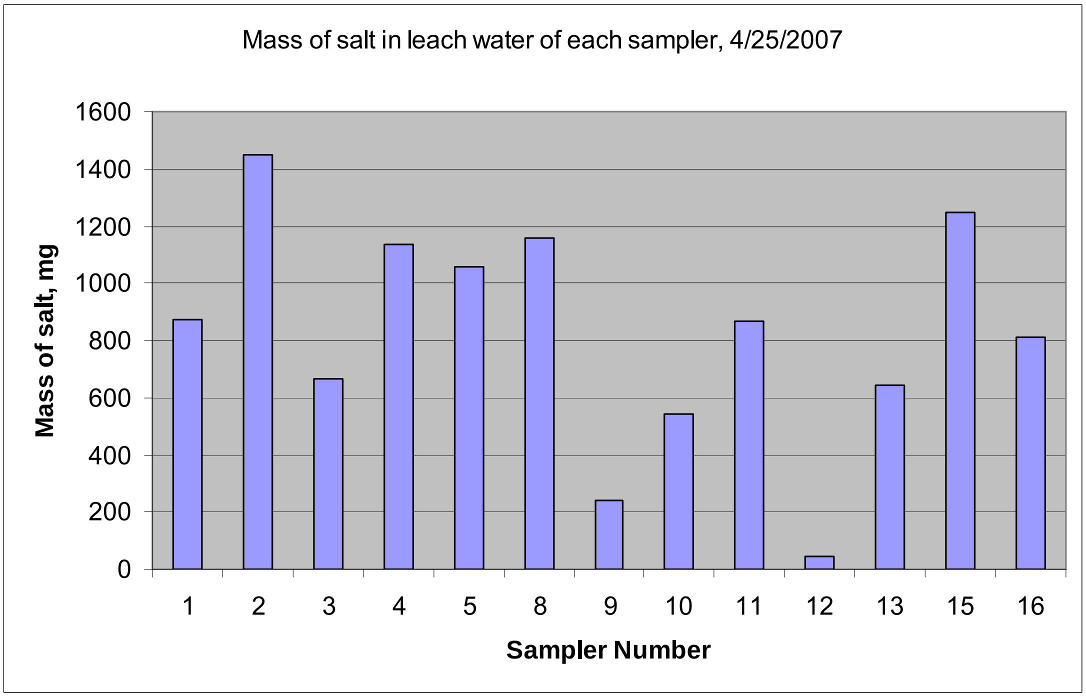

Figure E. 16. Mass of salt in the leach water of each sampler, 4/25/2007.

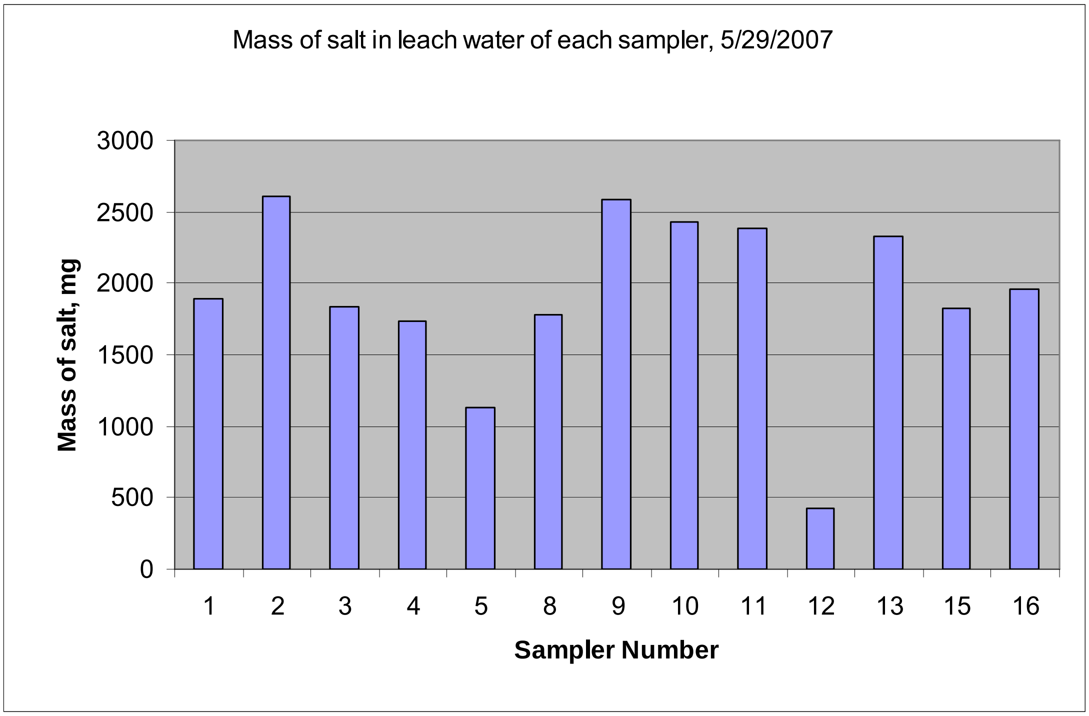

Figure E. 17. Mass of salt in the leach water of each sampler, 5/29/2007.

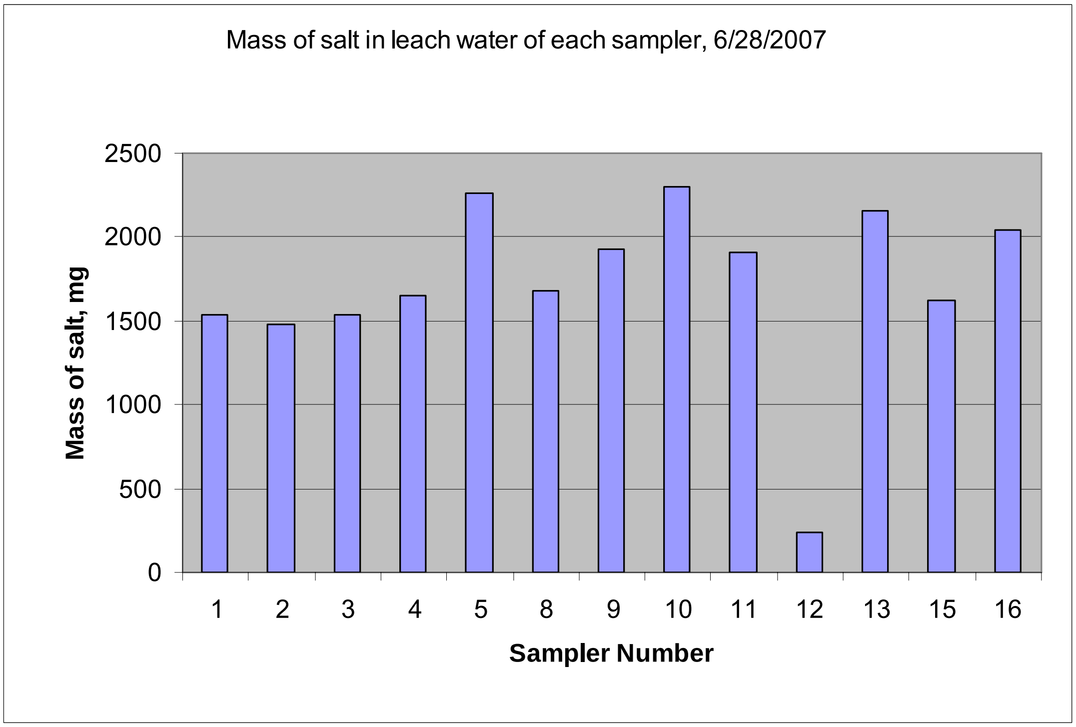

Figure E. 18. Mass of salt in the leach water of each sampler, 6/28/2007.

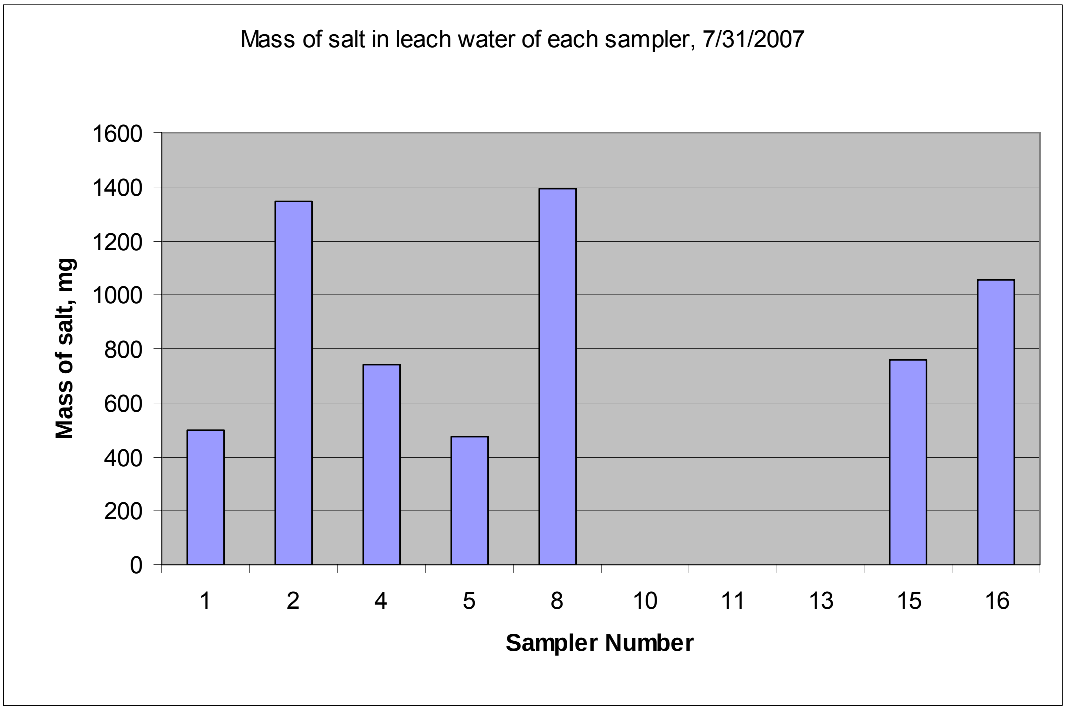

Figure E. 19. Mass of salt in the leach water of each sampler, 7/31/2007.

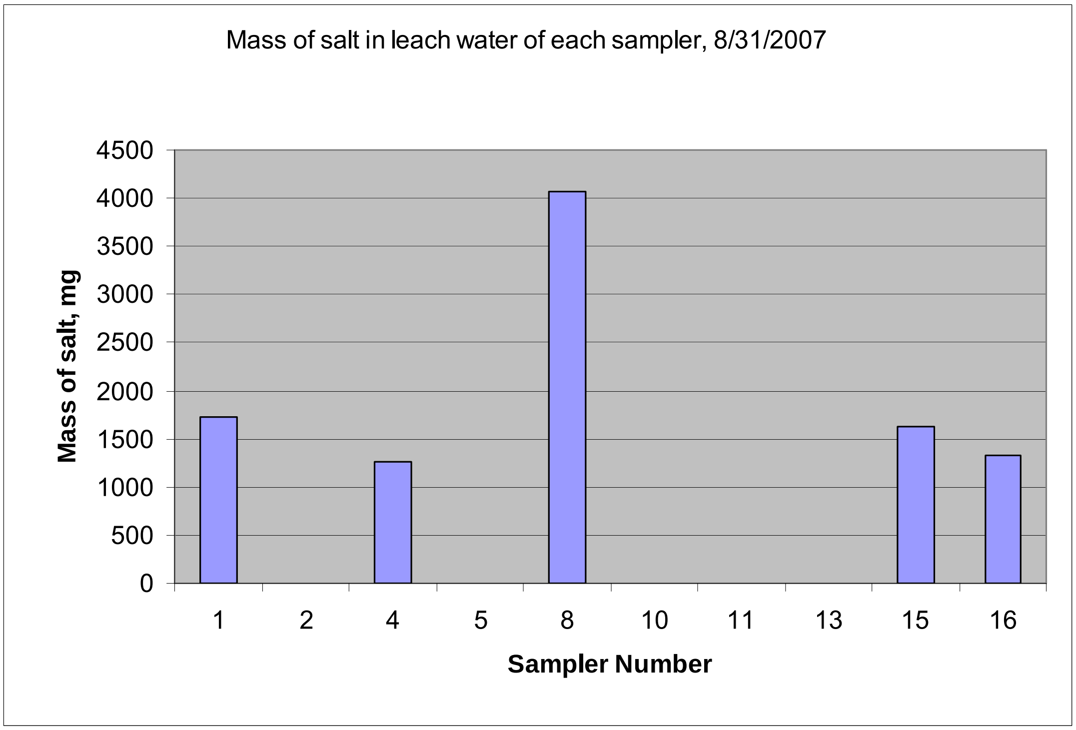

Figure E. 20. Mass of salt in the leach water of each sampler, 8/31/2007.

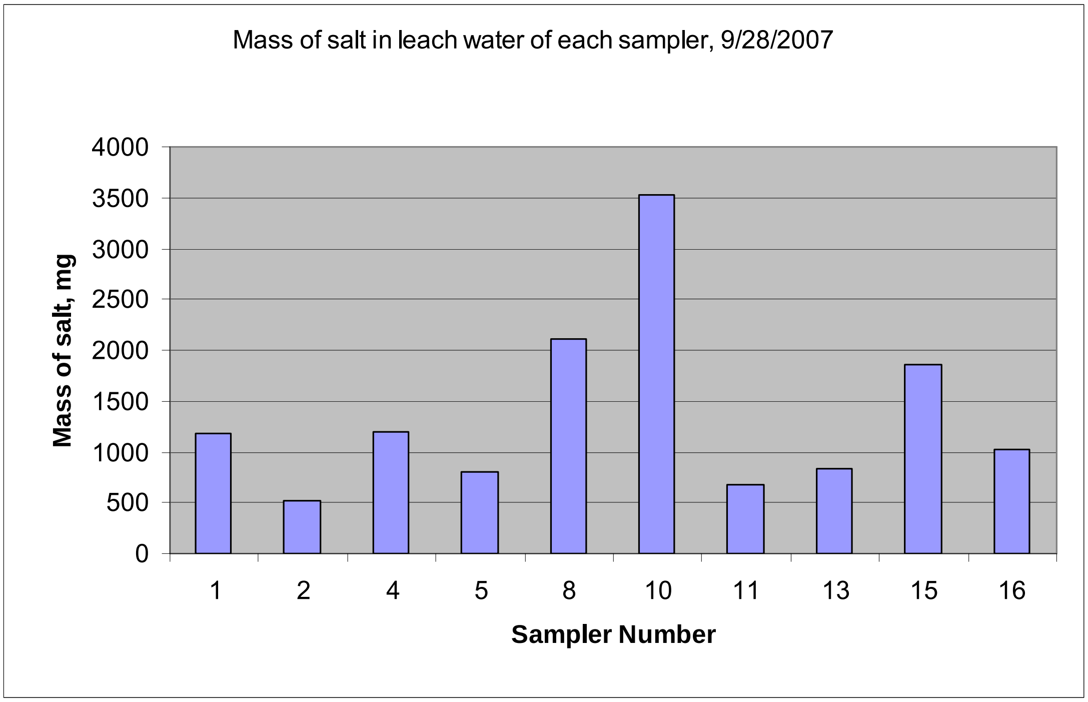

Figure E. 21. Mass of salt in the leach water of each sampler, 9/28/2007.