Potential for Nitrogen Losses from On-Site Wastewater Treatment Systems on Poorly Drained Soils to Curtain Drains

THESIS

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By

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Abstract

The poor internal drainage characteristics of the soils in Ohio pose a challenge to proper treatment of domestic wastewater in an On-Site Wastewater Treatment System, OSWTS. Seasonal high water tables in saturated soil cause only partial removal of pollutants from the wastewater, due to minimal time and space for proper natural processes. Most Ohio soils are not suitable for the safe operation of an OSWTS with a leach field system. To reduce the potential for OSWTS failure resulting from seasonal high water table conditions, Curtain drains are proposed to reduce or eliminate the potential for nitrogen leaching to surface waters from onsite wastewater treatment systems, OSWTS. The risk in the use of curtain drains is in their contribution to nonpoint source pollution by directly carrying pollutants into surrounding water bodies. Nutrients are not the only pollutants of concern from wastewater. Pathogenic parasites, bacteria, viruses, toxic organic compounds and metals impose high risks to public health.

DRAINMOD is a tool specifically designed for use with poorly drainage soils to model shallow water tables and the hydrology in many of the Ohio soils classified as poorly drained and somewhat poorly drained. An improved version of the hydrologic model, DRAINMOD-N II has the capability to assess the nitrogen balance in agricultural subsurface drainage systems. The proposed study will model and analyze a designed

matrix of drain depths, drain spacing, impeding depth and loading rate for the Blount Silt Loam soil at the Noland site to predict nitrogen drainage loss concentrations.

The modeling study will be conducted for 31 years over the period 1982 to 2012. The model generates a daily output of drainage loss concentrations of NO_3-N and NH_4-N in kg/ha. These losses are predicted to be those of the curtain drains. Statistical analyses of the modeling results will be used to test the significance of nitrogen loss differences between the drain depths, drain spacings, impeding depths, and loading rates, in order to predict which factor has the strongest effect on the output.

DRAIMOD N-II daily outputs of NO_3-N and NH_4-N drainage loss concentrations were prearranged and analyzed using Microsoft Excel, and Minitab. The statistical analysis conducted for this study were: Fit General Linear Model, Tukey's Comparison of Means, Paired T-test, and Probability Plot.

The differences in drain depth, drain spacing, and effluent loading rate resulted in significantly different exports of NO3-N into curtain drains. The drain spacings 183, 244, 488 cm were all significantly different from the rest of the spacings, except for drain spacings 305 cm and 366 cm they were not significantly different from each other but significantly different from the other treatment combinations. The drain depths 102, 117, and 147 cm were all significantly different in their effect on the nitrogen drainage loss. The combination of a DS of 183 cm and a DD of 147 cm was significantly different than the rest of the treatment combinations, with the highest nitrogen export into the curtain

drains. The combination of a DS of 148 cm and a DD of 102 cm yielded the lowest nitrogen loss when the means were compared.

Dedication

This document is first dedicated to my family. I dedicate this document for my Father, Jamal Ghumrawi, and Mother, Houda Ghumrawi for raising me to be a strong woman who pursuits her goals and never gives up on achieving them regardless of the obstacles. I dedicate this document to my grandparents, Abdullah Hilfawi; Rabeeha Kojok; Amneh Chehadeh, and Khalil Ghumrawi, whom I wish were present to see me achieve this degree because I know they would have been proud to see me further my education. I dedicate this to my aunt Ilham Hilfawi for all her love and prayers for my success. I dedicate this to my uncle Haissam Ghumrawi for all his love and support. I dedicate this document to my siblings, Safa, Baacr, Amneh, Reem and Sarah Ghumrawi, whom I hope to utilize this degree to provide them with the education and opportunities they seek. I dedicate this to my friends Dima Najjar, Jana; Banan, and Amr Al-Akhras, Fairuz Ali, Enas Azzazi, Nadine; Zaid; and Yazan Abunijim, who became my second family as I was far away from my own to pursue this degree. I dedicate this document to all my loved ones who have stood by me, supported me, encouraged me and believed in me.

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Chapter 1: Introduction

Over 25% of the U.S. population lives in non-sewered areas and depends on On-Site Wastewater Treatment Systems, OSWTS (USEPA, 2002). According to the Bureau of Census (1990), there is currently over one million homes in Ohio, alone, operating an OSWTS. OSWTS are often preferred to municipal sewage treatment systems for their low cost, low maintenance, low emissions and high energy efficiency, and are sometimes the most appropriate means for wastewater treatment when municipal systems are not available (USEPA, 2002). Among many types of OSWTS in use in rural and suburban areas are Subsurface Soil Absorption Systems (SSAS) also known as leach fields or leach lines, which is a typical type of system in Ohio (Figure 1). SSAS filter domestic wastewater through the soil column for proper treatment to remove excess nutrients and pollutants, but are often limited by the physical and chemical characteristics of the soil (USEPA, 2002). Bulletin 896 (Mancl & Slater, 2002) lists three types of OSWTS that could be used in poorly drained soils: septic system leach field, mound system, and wastewater irrigation system. If the requirements of the Ohio Administrative Code (Anon., 1997) are not met for a traditional leach field, a mound system can now be used. A mound system requires a 2-foot deep soil layer between the soil surface and the limiting soil condition. In some cases, the alternative is a wastewater irrigation system assuming proper management to prevent excessive soil wetness (Mancl & Slater, 2002).

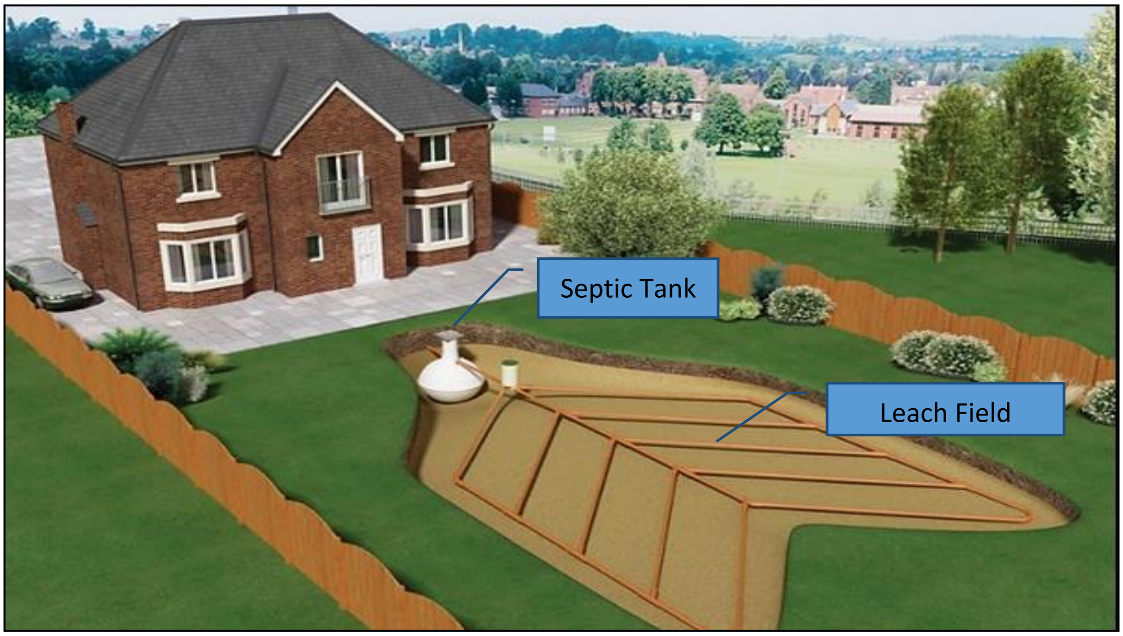

Figure 1- Sketch of an On-Site Wastewater Treatment System (OSWTS) (Source: http://selfbuild.ie/)

1.1 Pollution Potential

Domestic wastewater contains settleable and suspended solids, gasses, oils, and floatable matter. A large range of pathogenic agents, such as bacteria, viruses, protozoa, and helminths (Burge & Marsh, 1978) harmful to humans and in some cases the environment, are potentially present in domestic wastewater. Studies have indicated that one-third of all water-borne diseases in the United States resulted in the contamination of ground water between 1971-1976 (Craun et al., 1976). Other studies have indicated that contamination of surface water on a watershed basis can frequently occur from improper functioning conventional septic systems in unsuitable conditions (Reneau et al., 1974; Rahe et al., 1978).

The movement of pollutants in the soil column is dependent on many variables, such as; soil physical and chemical characteristics, underlying geology, topography, and rainfall (USEPA, 2002). Studies have found that nitrate levels resulting from soil-based treatment exceeded the drinking water standard of 10 mg/L (Robertson, 1991). According to Scheible (1993), untreated domestic sewage contains an average of 2085 mg/L of total nitrogen, of which 60 % is ammonium and 40 % organic nitrogen and traces of nitrates. Scheible also notes that once the sludge is conventionally treated in the septic tank, the effluent contains on average 15-35 mg/L of total nitrogen. Most nitrogen found in septic tank effluent is a mixture of 75% charged species on N and 25% organic N (Nizeyimana et al., 1996).

On poorly drained soils, subsurface drainage as curtain drains are used to remove some excess soil water from around the treatment trench (Figure 2). In some cases, this creates potential for NO_3-N to discharge to receiving water bodies. This is a concern for water quality. In saturated soil conditions, ammonia is not properly consumed by plants and microorganisms, instead, it moves through the soil profile to potentially pollute receiving water bodies (Mancl & Slater, 2002). Movement of soluble nutrients in subsurface drained soils is mainly affected by rainfall amounts and intensity, soil physical characteristics such as hydraulic conductivity, and drain depth and spacing (Mansell et al., 1980). The USEPA has indicated that OSWTS failure contributes to public health concerns, and could be the source of human diseases. The states and tribes have reported that OSWTS are one of the many contributors to increased nutrient and pathogen pollution of surface and ground waters. Excess nitrate reaching water bodies may affect aquatic life (i.e., hypoxia) but also is a major cause of methemoglobinemia in infants (Knobeloch et al., 2000). Failing OSWTS also contribute to overgrowth of algae and other pest aquatic plants, such as the case in Lake Erie (USEPA, 2002).

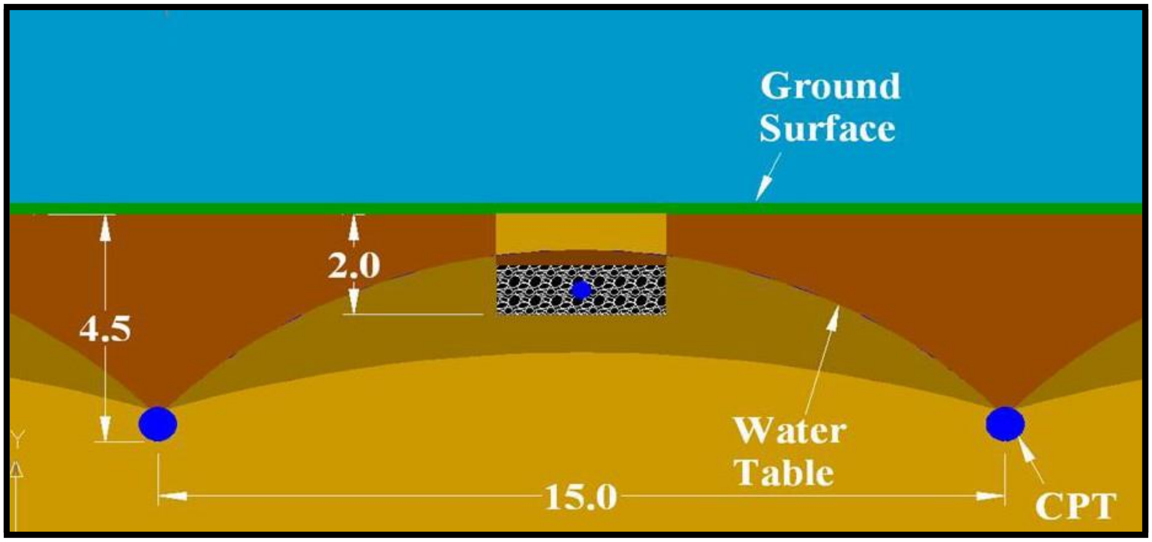

Figure 2- General case for a treatment trench and curtain drains (CPT is corrugated plastic tubing) (Source: Brown, 2008)

A study was conducted in Florida over five years to evaluate nitrate loading in a Surface Water Infiltration System (SWIS) in a subdivision, and determined mean effluent plume dispersion values of 18.3, 4.57 and 0.4 m (60, 15, and 1.2 ft) longitudinally, laterally, and vertically (USEPA, 2002). Such dispersion suggests that an effluent plume could travel into drainage systems since drainage depths and spacings for curtain drains would fall within the range of distances mentioned above. Fecal coliform in septic system effluent is another water quality concern. Studies have shown that fecal coliforms can move about 0.6 m (2 ft) vertically and 15 m (49.2 ft) longitudinally within one hour of entering the treatment trench in a saturated soil site with 14% slope, being studied in western Oregon (Cogger, 1995). Other researchers have linked the decline in water quality to untreated wastewater and improper septic system functions (Brooks & Cech, 1979; Maynard, 1969; Hackett, 1965). Therefore, it is essential to treat incoming wastewater properly to lower the risks of water resources pollution.

1.2 Description and Performance of OSWTS

As stated earlier, the main purpose of OSWTS is to remove excess nutrients and pollutants from domestic wastewater before reaching surrounding water bodies. Within the treatment system, the wastewater is subjected to several physical and biological processes, and hopefully, the treated wastewater is safe for the environment. A typical OSWTS often includes a septic tank, and a subsoil treatment trench or leach line. The trench is partially filled with gravel which encloses perforated corrugated plastic tubing (CPT) that helps with distribution of the wastewater along the treatment trench. During the first stage of wastewater treatment from the domestic source, a septic tank allows for suspended solids to settle. This material should not pass into the treatment trench, possibly causing clogging. The effluent from the septic tank is sent to the OSWTS treatment trench where it is distributed via perforated CPT onto the absorption bed (soil) of the trench. Treatment of the septic tank effluent occurs as the wastewater infiltrates the soil in the trench (Ringler & Slater, 2009).

In the treatment trench, anaerobic liquefication of collected organic solids is facilitated by a biomat that forms at the infiltrative surface of the unsaturated zone right below the infiltration field (USEPA, 2002). The biomat allows for physical and biological treatment to occur as the effluent moves through the soil profile. The biomat forms as particulate matter accumulate on the infiltrative surface and into the soil pores (Noland, 2014). The active biomat uses some of the carbon and nutrients from the treatment trench. The accumulation of suspended solids on the infiltrative soil surface and in soil pores reduces the infiltration rate, which leads to an increase in the resident time, and subsequently increased the time for the treatment processes (Noland, 2014). The biomat allows for optimal treatment of nitrogen because it provides an anaerobic environment for denitrification (USEPA, 2002). In the case that the biomat gets too thick, the system will be at risk of hydraulic failure because of ponding and spill onto the soil surface (Hagedorn et al., 1980).

A final refining of the discharge is performed in the unsaturated or vadose zone of the soil profile below the treatment trench before it reaches the saturated zone. Septic tanks function under anaerobic conditions, but only function to a limited extent in reducing bacterial populations and organic loads (Hagedorn et al., 1980). The main process of treatment occurs when the effluent percolates in the unsaturated zone below the treatment trench under aerobic conditions (Hagedorn et al., 1980).

Research has shown that in a properly functioning absorption field, pathogenic bacteria and fecal matter were almost completely eradicated within a short distance in unsaturated soil (Hagedorn et al., 1980). In one study, the unsaturated zone was most effective in treating the wastewater effluent in a 61 cm (24 in) distance (Lee & Franzmeier, 2004). Viraraghavan & Warnock (1976) showed that the removal of organisms, and the reduction of pollutants in sewage effluent, was highly efficient in the unsaturated soil. The lower the soil water content the longer the retention time of wastewater in the soil. The unsaturated zone has smaller pores, which allows for enhanced treatment by reducing the separation distance (USEPA, 2002). Water samples showed that that the fecal matter was always significantly reduced the further it percolated from the septic field. Another project done by (Bouma et al., 1972) determined that 30-90 cm (9.4-28.1 in) of unsaturated soil below the septic leach field were adequate to completely remove bacterial populations from the effluent, on the conditions that the soil is permeable for the effluent to flow through and another layer is restrictive enough to form a clogged zone.

1.3 Conditions and Causes of Failure

The rate of water movement in the soil profile and the availability of an unsaturated vadose zone in the soil profile determine the effectiveness of SSAS. On the one hand, in excessively drained soils wastewater moves rapidly through the soil columns which results in improper treatment (Parizek, 1973). Unsuitable soil conditions with restricted movement of effluent through the soil profile cause hydraulic overloads leading to a system failure. The ideal soil condition for proper treatment should provide a slow and steady movement of effluent within the system. However, the majority of soil series in Ohio create a strong restriction to the movement of water through the soil profile because of their high silt and clay content. Therefore, the poor internal drainage characteristics of the soils in Ohio present a challenge for proper treatment of domestic wastewater. Additionally, hydraulic overload could also be caused by seasonal high water tables, which impacts are intensified by multiple soil characteristics such as porosity, permeability, thickness, recharge, discharge from surface waters and evapotranspiration (Brown, 2008). Saturated soil does not allow for the removal of pollutants from wastewater, instead, the pollutants will travel with the water into surrounding water resources (Mancl & Slater, 2002). With a high water table, the effluents are only partially treated or a discharge of untreated wastewater can occur (Brown, 2008), due to minimal time and space for proper natural processes (biological, chemical, and physical).

Previous studies indicated that 93.8% of soils in Ohio are not suitable for proper onsite treatment (Mancl & Slater, 2001). Therefore, on-site wastewater treatment systems are ranked highest in total volume supply of wastewater discharged into ground water systems, and are frequently reported for groundwater contamination (Allen & Geldreich, 1975).

1.4 Engineered Curtain Drains as a Remedy

As noted earlier (Mancl & Slater, 2001), most Ohio soils are not suitable for the safe operation of an OSWTS with a leach field system. For that reason, alternatives are being studied to minimize or eliminate pollution from the failure of the OSWTS because of seasonally high water tables (Brown, 2008; Lowe & Siegrist, 2008). One technique proposed to help improve drainage performance of Ohio soils and to enhance the on-site system's ability to treat wastewater is curtain drains (Brown, 2008). To reduce the potential for OSWTS failure resulting from seasonal high water table conditions, curtain drains can be installed below the leach field. The risk in the use of curtain drains is in their contribution to nonpoint source pollution by directly carrying pollutants into surrounding water resources (Mancl & Slater, 2002).

The Ohio Department of Health's Household Sewage Rules, Chapter 3: 701-29-16 section D of the Ohio Administrative code (Anon., 1997) permits the installation of curtain drains in poorly drained soils to control the high seasonal water table. The code specifies that there should be at least 15.2 cm (6 in) of unsaturated soil below the bottom of the leach field and should have a spacing of at least 2.4 m (8 ft) from the center of the treatment trench. The unsaturated zone is specified to meet the requirement of 1000 CFU/100 mL before it is distributed into the soil. If used properly curtain drains could improve the performance of OSWTS. Leachate from OSWTS has potential to carry bacteria, such as E. coli and other fecal bacteria, further than 0.60 m (2 ft) of soil, which is the set guideline (Kephart et al., 2004). Studies by Kephart concluded that bacteria carried by leachate was very likely to be intercepted and transported through curtain drains, but on the other hand, bacteria originated in the septic tank were not detected within the perimeters of the curtain drains.

The efficiency of an OSWTS system is dependent on several soil properties and hydrological characteristics such as land slope, high seasonal water table, soil permeability, soil structure, depth to limiting layer (Cunningham, 1984). Wilson et al. (1982) conducted studies on the field performance of OSWTS to determine the efficiency of artificially draining wet soils in allowing for proper operation of septic leach fields. The study found that Nitrate-N concentrations in agricultural (tile) drain discharges were all below the drinking water standard of 10 mg/L (Table 3) set by the Federal Water Quality Regulations (USEPA, 1976). The Wilson et al. (1982) study also found that fecal coliform concentrations were within 200 mg/ 100 mL, the minimum required by the Water Quality Standards. This study also showed that OSWTS were more successful when they were surrounded by agricultural (tile) drains. Water quality was not adversely affected by the usage of drains around OSWTS, when compared to other environmental issues, such as urban runoff, and point-source discharges (Wilson et al., 1982). Other studies showed that organisms moved rapidly through the soil Macropores via saturated flow (Rahe et al., 1978).

The results of the experiment conducted by Wolf et al. (1998) on poorly drained soils; and the effect of drains connected to a low-pressure distribution septic system on the treatment of septic tank effluent are summarized in tables (1,2,3,4).

Parameter	**Number of samples**	**Mean**	**Median**	**Minimum**	**Maximum**
			mg/L		
NH_4-N	3	41.7	41.2	24.1	76.7
NO_3-N	3	0.8	0.1	0.0	3.9
Cl^-	3	48.4	48.5	29.1	73.0
E.C. (dS/m)	3	0.82	0.83	0.48	1.15
TOC (unfiltered)	2	58.6	51.9	28.6	109.8
TOC (filtered)	1	15.7	37.4	14.6	71.4
Ortho-P	1	15.7	15.5	8.4	25.4

Table 1- Concentrations of selected chemical and biological parameters from septic tank effluent *(Wolf et al., 1998)*

Year	**Background**	**Filter Field**	**Mean**
		mg NH_4-N/L	
1	0.0	1.0	0.5
2	0.1	0.8	0.4
3	0.8	1.3	1.0
Mean	0.3	1.0	

Table 2- Mean NH_4-N concentrations in background and filter field agricultural (tile) drains for three years *(Wolf et al., 1998)*

		Year	
Tile Drain	1	2	3
		mg NO_3-N/L	
Background	0.4	2.5	0.6
Filter Field	2.5	5.8	1.4

Table 3- The NO_3-N concentration in background and filter field agricultural (tile) drains for three years *(Wolf et al., 1998)*

Tile Drain	**Cl^-**	**Ortho-P**	**TOC**	
			Unfiltered	Filtered
		mg/L		
Background	8.7	0.03	3.4	2.8
Filter Field	31.5	0.86	5.2	4.2

Table 4-Concentrations of three chemical parameters in water from background and filter field agricultural (tile) drains *(Wolf et al., 1998)*

The data in Table 5 shows that in the septic tank effluent, the 5-day biological oxygen demand (BODs), total dissolved solids (TDS) and ammonium (NH_4^+) all decreased substantially as depth increased (Wolf et al., 1998). On the contrary, nitrite (NO), nitrate (NO_3) and sulfates increased with depth (Table 5) (Wolf et al., 1998). The soil was effective in removing the phosphate and TOC from the effluent in 68 cm of soil (Table 4) (Wolf et al., 1998). However, the detected measurements of all pollutants in Table 5 were between 0.15 m (6 in) and 0.3 m (12 in), indicating the possibility of reaching the drains (Wolf et al., 1998).

Contaminants	**Concentration mg/L**
Pollutants	2.32
BODs	1.3
Sulfates	33.5-39.2
Nitrite	0.51-0.30
Nitrate	17.0-19.1
Ammonia	0.34-1.68

Table 5- Detected measurements of all pollutants between 15 cm (6 in) and 30 cm (12 in) of soil *(Wolf et al., 1998)*

In 2013, a research project was initiated in Union County, Ohio to study the influence of different curtain drain geometries on OSWTS (Burgess & Niple, 2013; Noland, 2014). When the installation is completed in 2017, this research will be evaluating engineered curtain drains (Burgess & Niple, 2013; Noland, 2014) used to lower the seasonal water table around OSWTS. This field study site hereafter will be referred to as the Noland Site, named after the land owner. The goal is to minimize interaction between wastewater and adjacent water bodies. Engineered (curtain) drains are being studied for promoting removal of excess soil water from precipitation, snowmelt, overland flow, underground seepage and ground water, from around the leach field without producing excessive loading of nitrogen or other potential pollutants.

Curtain drains or engineered drains are a practice used to drain soils with seasonal high water tables and to try to maintain an unsaturated zone below the treatment trench. In this study curtain drains are installed parallel along each side of each treatment trench. Figure 3 illustrates the engineered drain concept.

1.5 Overall Purpose

Associated with the field study at the Noland site are two modeling studies using DRAINMOD to evaluate the hydrologic performance of curtain drains installed near OSWTS. These studies include that by (Toledo De-Leon, 2014) and the current study. While some research has been conducted on field evaluation of curtain drains adjacent to OSWTS, there is a lack of real-world data associated with OSWTS in Ohio (Noland, 2014). Little to no research has been published on using DRAINMIOD-N to predict and evaluate nitrogen losses from OSWTS into curtain drains.

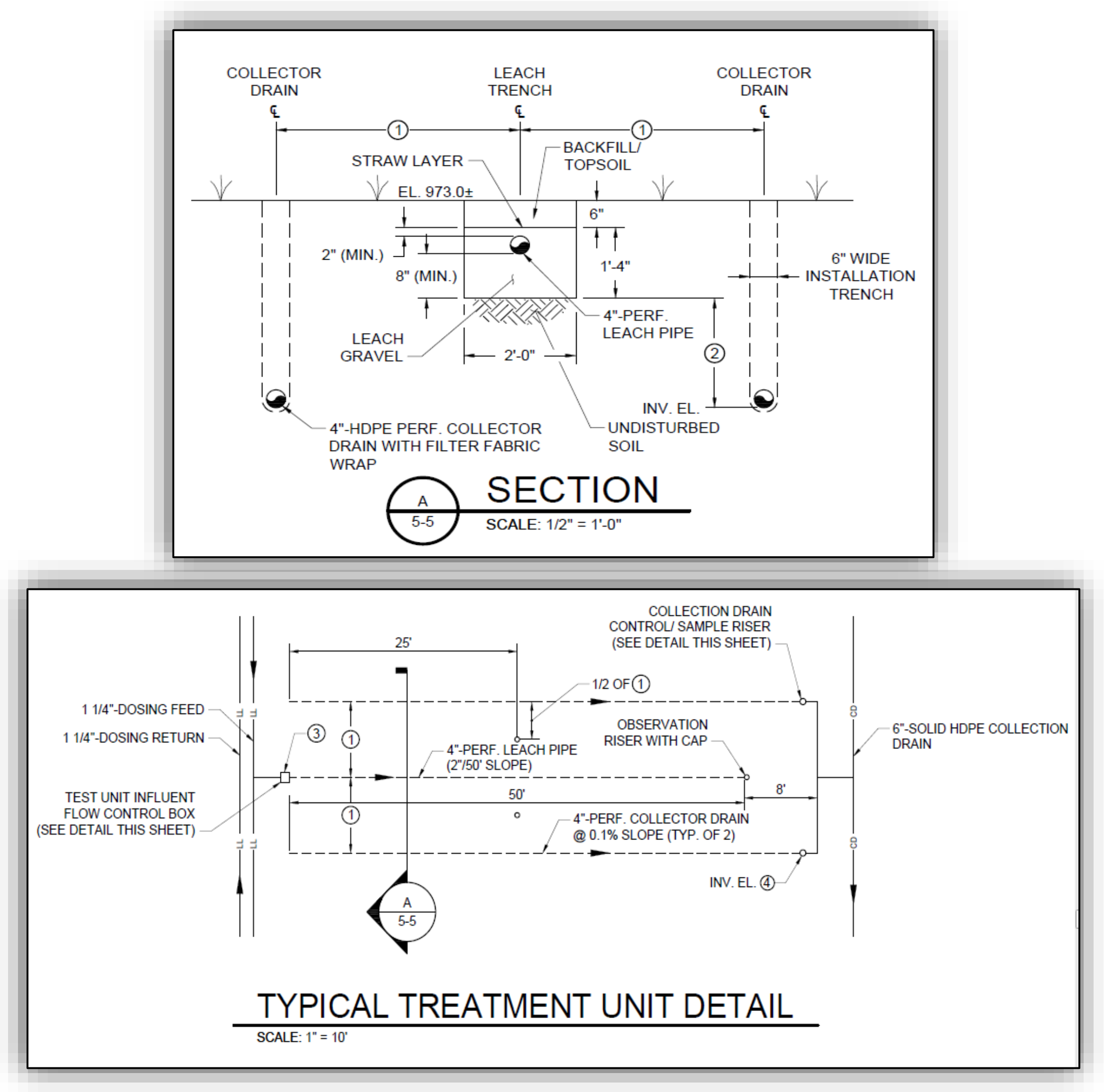

Figure 3- Illustration of proposed Engineered Drains for evaluating the hydrological performance of On-Site Wastewater Treatment System (OSWTS) installed in poorly drained soils *(Burgess & Niple, 2013)*

For the current study, curtain drains were proposed to reduce or eliminate the potential for nitrogen leaching to surface waters from onsite treatment systems using the agricultural water management model DRAINMOD (Skaggs, 1978; Skaggs, 1980). DRAINMOD is a tool specifically designed for use with poorly drainage soils that have a shallow water table (Skaggs, 1978; Skaggs, 1980), and has been used to model the hydrology in many of the Ohio soils classified as poorly drained and somewhat poorly drained (Brown, 2008). An improved version of the hydrologic model, DRAINMOD-N (Youssef et al., 2005), has the capability to assess the nitrogen balance in agricultural subsurface drainage systems. DRAINMOD-N simulates the nitrogen cycle and the changes in concentration in the soil (Youssef et al., 2005). DRAINMOD-N considers both NO_3-N and NH_x-N to simulate the nitrification process. The model also includes a fertilizer submodule that simulates the application of NH_4 and NH_4 forming fertilizers like Urea and anhydrous NH_3 (Youssef et al., 2005). DRAINMOD-N takes into consideration short-term processes such as fertilizer dissolution, urea hydrolysis, temporal changes in pH, and NH_3 volatilization. DRAINMOD-N II also simulates the carbon cycle to better simulate the mobilization and immobilization of nitrogen (Youssef et al., 2005). The Noland Site is being constructed to study the performance of eleven combinations of drain depth, spacing, and effluent loading rate.

1.6 Hypotheses and Organization

In this study I hypothesized that: 1) differences in drain spacing, drain depth, depth of the impeding layer and influent nitrogen loading rate will result in significantly different exports of nitrogen in the curtain drains, and 2) drain spacing (treatment area) will have the greatest effect on nitrogen losses to the curtain drains. The study was performed with DRAINMOD and the thesis is organized as follows:

- Chapter 2: A literature review of nitrogen, constituents of wastewater
- Chapter 3: An introduction to the research site, description of DRAINMOD, model parameters, the experimental design, the statistical analysis used to test the hypotheses.
- Chapter 4: The modeling results and discussion.
- Chapter 5 presents a summary, conclusions, and recommendations for future research.

Chapter 2: Literature Review

To better understand the risks posed by discharges from an OSWTS, it is necessary to understand the pollutants found in the effluent and their pollution risks. The processes of pollution and purification are essential in understanding the processes that take place in an OSWTS, and understanding how to prevent environmental risks.

2.1 Nitrogen Forms in the Environment

Nitrogen is an essential gas for life on earth. Although an abundance of it in the atmosphere and the soil are beneficial, an abundance of it in water can be detrimental to forms of life. To understand the way nitrogen functions in the environment, it is necessary to understand its cycle and its different physical and chemical forms. Nitrogen assumes about 79 percent of the atmosphere (Scheible, 1993). Nitrogen goes through several oxidation forms, according to the environment, the most important forms of soil and water science are described in (Table 6).

Nitrogen Compound	**Formula**	**Oxidation State**
Ammonia	NH3	-3
Ammonium Ion	NH4+	-3
Nitrogen Gas	N2	0
Nitrite Ion	NO2-	+3
Nitrate Ion	NO3-	+5

Table 6 - Nitrogen Forms of interest in the Environment *(Scheible, 1993)*

Nitrogen assumes different forms and compounds through several mechanisms, the most important ones are fixation, ammonification, synthesis, nitrification, and denitrification (Scheible, 1993). Each process will be discussed separately to indicate its significance in the Nitrogen Cycle in the environment. Nitrogen in wastewater exists in the form of organic matter and ammonia. After the effluent goes through the septic tanks, 85 % of N is in the form of Ammonia (USEPA, 2002). Once the effluent is past the infiltrative surface the anaerobic bacteria in the biomat and the vadose zone converts ammonia into nitrite followed by nitrate. Nitrate is a major concern because it is an underground water pollutant, and once it is in water it moves freely (USEPA, 2002).

For nitrogen to be used by plants and animals it must be fixated from an inert gas into a chemical compound. The process of fixation is mainly a biological one done by microorganisms. Ammonification is the process of hydrolysis of urea, in an organic form, into the ammonium form. Ammonification occurs when plants and animal tissues and animal fecal matter decompose. Synthesis which is also known as assimilation is a biochemical process that transforms ammonium or any nitrate compounds into plant protein. Animals, on the other hand, cannot transform inorganic nitrogen, and they require plant and animal protein to form their own protein. (Scheible, 1993)

Nitrification is a biological oxidation process that requires two steps. The first step transforms ammonium into nitrite then the second step transforms nitrite into nitrate. The mechanism requires chemoautotrophic bacteria to carry on the reaction, with inorganic carbon as its energy sources. Nitrate is then possibly used in synthesis and plant growth or it is denitrified (Scheible, 1993). Denitrification is another essential mechanism that transforms nitrate back into nitrogen gas. With the presence of organic carbon, many heterotrophic bacteria can carry on the reaction (Scheible, 1993).

All the previously named processes are essential to the treatment of wastewater and for nitrogen control. There are many environmental factors that play an important role in the previous processes, such as temperature, pH, microbiology, oxidation-reduction potential, nutrients, and availability of oxygen (Scheible, 1993).

Nitrogen can reach surface and ground water in several ways and forms. Nitrogen can deposit through rainfall and dustfall, it could also reach water from direct discharge of wastewater or cross contamination of water with effluents. Nitrogen gas can also be fixed by photosynthetic blue-green algae and other microbes (Scheible, 1993).

Ammonification, nitrification, synthesis and denitrification can all occur in aquatic environments (Scheible, 1993). Microorganisms process organic matter through ammonification and ammonium and nitrate are formed which are then synthesized by algae and aquatic plants, which leads to many water quality issues (Scheible, 1993). Denitrification is another process that requires anoxic conditions to occur, thus a low-oxygen aquatic environment is very suitable to reduce nitrate into nitrogen gas which mostly escapes into the atmosphere (Scheible, 1993).

Aside from the previously mentioned way of nitrogen depositing into surface and ground water, humans play a role in introducing excess nitrogen into the environment. Fertilizer application is a major nitrogen source; wastewater effluent, plant and animal matter, and artificial fertilizers. Nitrogen is present in an organic form in the soil, either as plants or, animal matter, or humus which is a result of residual decomposition (Scheible, 1993). Nitrate is the lowest found form because it is usually taken up for synthesis by plants, but if it leaches into the ground water it could cause major water quality issues.

The main sources of nitrogen in the septic tank effluent are a human waste and food from the kitchen sinks and dishwashers (USEPA, 2002). According to the USEPA (2002), a 1991 study found that conventional waste treatment systems accounted for 74% of nitrogen entering the Buttermilk Bay in Massachusetts. This input of nitrogen waste products in household wastewater results in total N concentrations of 30 – 170 mg/L (average = 60 mg/L) in the septic tank effluent (Lowe et al., 2009).

2.2 Nitrogen and Water Quality

High inputs of nutrients in surface water bodies can have adverse effects on biota. Biota change is evident in the decrease of the diversity of species and the change of dominant biota (Mason, 1996). There is a correlation between the increase in nutrient inputs and the increase in phytoplankton, microflora and non-rooted macrophyte populations (Laws, 1993). Algal species are the main concern of pollution of fresh water bodies, causing low diversity due to the sensitivity of species to the algal blooms. Algal blooms out-compete other plant species in the water bodies due to reduced levels of oxygen (Nartker & Mancl, 2002). Low levels of oxygen in the water column, affects fish species present as well. Algal blooms tend to produce toxins which are not only harmful to fish and invertebrates but are also harmful to humans if contact is established (Nartker & Mancl, 2002). Algal blooms are formed by cyanobacteria which prosper in the presence of excess phosphorous. Aquatic plants will die due to reduced oxygen level, which in turn will make the habitat unsuitable for aquatic animals and organisms (Illinois Department of Natural Resources, 1998). Excess of carbon dioxide is caused by the reduced levels of oxygen, which can increase the fish ventilation volume, leading to a reduced cardiac output, until the fish is no longer able to function due to oxygen tension in the blood (Mason, 1996).

Nitrate-N density is closely related to septic system density. As the latter increases Nitrate-N in stream water increases. The closer the septic systems are to surrounding surface water bodies the higher the Nitrate-N concentration (Nartker & Mancl, 2002). Septic systems built before 1970 contribute to higher concentrations to surrounding water bodies than those built in the 1980s and the 1990s (Nartker & Mancl, 2002). In the Gulf of Mexico, large concentrations of nitrate have led to major fish kills and hypoxia. When nitrate concentrations are high, fish hemoglobin is converted to methemoglobin which renders ability of blood to carry oxygen (Nartker & Mancl, 2002). This is also the case for infants and Blue Baby Syndrome when children consume drinking water with high levels of Nitrate-N. Otherwise known as methemoglobinemia, Blue Baby Syndrome is the inability of hemoglobin to release oxygen to the blood tissues (Chen, 2014).

Nitrogen and phosphorous are essential for plant growth and are in most cases deficient (Ringler & Slater, 2009). Amino acids, which are building blocks of life, are assimilated using NH_4^+ and NO_3^-. Another essential nutrient for amino acids is phosphorous. H_2PO^{4-} or HPO_4^{2-} (ortho-p) are essential for root growth, DNA, RNA, energy storage and transfer (Ringler & Slater, 2009). Aerobic microorganisms also depend on nutrients such as ammonia, phosphorous, and oxygen for oxidation of organic compounds into humus, carbon dioxide, and water (Tchobanoglous et al., 2003). The presence of some plants in an OSWTS leach field, in particular grasses, can be beneficial in promoting biological activity for to enhance purification (Ringler & Slater, 2009).

2.3 Unsaturated Zone below OSWTS

As mentioned previously the unsaturated zone is an important component of the treatment process (Bitton & Gerba, 1994; Mancl & Slater, 2002). Unsaturated flow provides higher retention time, which allows longer time for adsorption onto soil particles in addition to proximity to soil particles (Ausland et al., 2002). Clay is an ideal soil for adsorption of bacteria and viruses (Gerba et al., 1975). Nutrient removal by adsorption onto the soil CEC is increased as well as adsorption of viruses to dry soil (Lance et al., 1976). Mechanical straining is also increased, because when the pores are unsaturated the water can move in any direction with no restriction (Watson et al., 1994). When the soil is unsaturated the conditions for aerobic processes are available. Oxygen is constantly diffusing into the soil pores from the atmosphere allowing for rapid decomposition by aerobic microorganisms (Ringler & Slater, 2009). During the flow of water through the unsaturated zone, 10%-50% of the total nitrogen is either absorbed or removed before the effluent can reach groundwater (Hazen and Sawyer, 2009). After the process of nitrification, ammonia is converted to nitrate if there is not sufficient time and space for denitrification the nitrate will most likely leach into the underground water.

2.4 Soil Absorption and Treatment of Effluent

There are several properties that determine performance and treatment potential of the wastewater, such as; depth of the soil column, soil permeability, and the extent of the vadose zone (unsaturated zone) (Mancl & Slater, 2001). The absorption and treatment of untreated or partially untreated wastewater are mainly dependent on the soil's physical and hydrological properties (Lowe & Siegrist, 2008). According to the previous description water movement through the soil profile is driven by the effects of its saturated hydraulic conductivity. The saturated hydraulic conductivity of the soil determines the retention time of the wastewater in the soil profile for proper treatment (Noland, 2014). The dominance of the exchangeable Ca or Mg over Na concentrations, CEC or ECEC, plays an essential role in the function of the soil profile. Low CEC or ECEC define a poor soil in treating effluent due to soil structure and dispersion of soil particles. The movement through the soil profile is dependent on the textural classification of the soil profile. To achieve effective treatment of the effluent, a distance of 61 cm (24 in) of aerated, permeable soil between the treatment trench and the water table is recommended (Lee & Franzmeier, 2004). Poorly drained soils are not able to absorb effluent at the rate it is applied (Lee & Franzmeier, 2004), which makes the soil unsuitable for subsurface treatment and disposal of wastewater (Sobsey, et al., 1980). Although clay is great and efficient in adsorption and removal of viruses due to their high CEC or ECEC, they require artificial drainage to maximize their performance in treating wastewater in an OSWTS (Meschke & Sobsey, 1998).

2.5 Constituents in Wastewater

Nutrients are not the only pollutants of concern from wastewater. Pathogenic parasites, bacteria, viruses, toxic organic compounds and metals impose high risks to public health. Also, the movement and fate of endocrine disruptors from pharmaceuticals are a rising concern (USEPA, 2002). The lack of oxygen in the infiltration field encourages the survival of the pathogens which poses a risk to groundwater or surface waters (Lee & Franzmeier, 2004).

Water polluted with sewage is a serious public health issue. When sewage water comes in contact with drinking water, many health issues can arise, such as diarrhea, nausea, cramps, dysentery, and hepatitis (Schultheis, 2015). A failing system is easily detectable due to the smell of the seeping effluent before it is properly treated from harmful pathogens (Schultheis, 2015) (Table 7). Septic tanks function under anaerobic conditions, but they only function to a limited extent in reducing bacterial populations and organic loads (Hagedorn et al., 1980).

2.5.1 Bacteria, Viruses, and other Pathogens

Bacteria (Table 7) and viruses found in septic effluent are prominent public health concerns because they cause intestinal diseases which are known as enteric diseases such typhoid, diarrhea, and dysenth (Nartker & Mancl, 2002). Human feces can contain harmful bacteria such as Salmonella and Shigella, as well as harmless bacteria naturally found in human G.I. tract (Nartker & Mancl, 2002). The main indicators of pathogens present in fecal effluent are fecal streptococci and fecal coliform, mainly because they exist in huge numbers in the human system and are able to survive without a host body (Nartker & Mancl, 2002). The soil is typically a great medium for filtering the effluents as the soil pores are able to block bacteria from going through, in addition to the chemical, biological and physical processes the bacteria is subjected to as it moves down the soil column. The absence of nutrients and oxygen can also cause the death of bacteria (Nartker & Mancl, 2002). On the other hand, viruses act more like chemicals because they can survive and reproduce without nutrients and without being in a host cell. Since viruses are too small to be filtered through the soil profile, physical-chemical absorption onto soil particles is the only possible way to remove them (Nartker & Mancl, 2002). Pathogenic organisms are divided into bacteria, viruses, and parasites, which can cause 4 classes of water-borne diseases to those who consume it. Class 1 is water-borne disease, caused by contact with drinking water polluted with such pathogens, such as cholera, typhoid, and hepatitis (Mason, 1996). Class 2 are diseases caused by low hygiene on a personal basis, such as hand washing. Diseases include but are not limited to class 1 diseases in addition to diarrhea and eye and skin infections (Mason, 1996). Class 3 are diseases caused by flukes and flatworms since they can survive in the water cycle (Nartker & Mancl, 2002). Lastly, class 4 diseases are transported by water-related vectors such as mosquitoes transporting yellow-fever and river blindness (Mason, 1996).

Nature of Pollution	Organisms	Medium	Maximum distance traveled	Time of travel
Sewage trenches intersecting ground water	Bacillus Coli	Fine sand	19.8 m (65 ft)	27 weeks
Sewage trenches intersecting ground water	Coliforms	--	70.7 m (232 ft)	--
Sewage in pit latrine intersecting ground water	Bacillus Coli	Fine and coarse sand	24.4 m (80 ft)	--
Sewage in bored latrine intersecting ground water	Bacillus Coli	Sand and sandy clay	10.7 m (35 ft)	8 weeks
Sewage in pit latrine intersecting ground water	Bacillus Coli	Fine and medium sand	3.1 m (10 ft)	--
Primary and treated sewage in infiltration basins	Coliforms	Fine sandy loam	0.6- 4 m (2-13 ft)	--
Diluted primary sewage injected subsurface	Coliforms	Aquifer	30 m (98 ft)	33 hours
Canal water in infiltration basins	Escherichia coli	Sand dunes	3.1 m (10 ft)	--
Subsurface injection	Enterococci	--	15 m (44 ft)	--
Secondary sewage in infiltration basins	Coliforms	Sandy gravels	0.9 m (3 ft)	--
Tertiary treated wastewater in percolation beds	Fecal coliforms and fecal streptococci	Coarse gravels	457.2 m (1500 ft)	15 days
Primary sewage injected subsurface	Coliforms	Sand and pea gravel aquifer	30.5 m (100 ft)	35 hours
Secondary sewage injected subsurface	Fecal coliforms	Fine to coarse sand aquifer	30.5 m (100 ft)	--
Tertiary treated wastewater in percolation beds	Coliforms	Sand and gravel	830 m (2723 ft)	--
Inoculated water and diluted sewage injected subsurface	Bacillus Stearothermophilis	Crystalline bedrock	28.7 m (94 ft)	24- 30 hours
Tertiary treated wastewater in infiltration basins	Coliforms	Fine to medium sand	6.1 m (20 ft)	--
Secondary sewage in infiltration basins	Fecal coliforms	Fine loamy sand to gravel	9.1 m (30 ft)	--
Primary sewage in infiltration basins	Fecal streptococci	Silty sand and gravel	183 m (600 ft	--

Table 7- A summation of the results of selected studies on the transport of bacteria through the column in relation to land application of domestic wastewater *(Hagedorn et al., 1980)*

2.5.2 Phosphorous

Phosphorus is a major source of pollution, that has contributed to many water quality issues in the Lake Erie basin. Phosphorous is found usually in household detergents. Phosphorous is converted to orthophosphate in the septic tank, but once it leaches into the soil it either precipitates or is absorbed onto the soil particles (Nartker & Mancl, 2002). Several forms of phosphorous $–PO_4^{3-}$, orthophosphates, and polyphosphates, contribute to the eutrophication which is a major water quality issue (Tchobanoglous et al., 2003). Eutrophication is caused by increased nutrient loading, especially phosphorous and nitrogen, into pristine water bodies (Cloern, 2001). Increased nitrogen and phosphorus in water bodies, such as Lake Erie, causes increased plant and root growth (Cloern, 2001). This might not only choke the aquatic environment but also promotes the growth of algal blooms which release toxins harmful to the aquatic environment and cause oxygen depletion (Cloern, 2001).

2.5.3 Chemicals and Toxic Substances

Volatile organic compounds, which are toxic, are also commonly found in household effluents. Samples from the scum and the sludge reveal the presence of dichloromethane, toluene, benzene, bromomethane, and ethylbenzene (Nartker & Mancl, 2002). Metals are also found in household effluents, such as aluminum, iron, and copper. Copper is naturally found in soil but excessive amounts in the soil can cause copper to make its way into the waterways (Hall, Jr. et al., 1998). Motor vehicle waste fluids being dumped down drains has also contributed to the presence of additional heavy metals and VOCs in septic tank effluent (Nartker & Mancl, 2002). When a septic system is properly designed and managed, treatment of wastewater pollutants can be achieved by removing suspended solids through filtration, and absorption of phosphorous, nitrification of ammonium, biodegradation of organic matter, and destruction of bacteria and inactivation of viruses (Nartker & Mancl, 2002).

2.5.4 Organic Matter and Suspended Solids

Organic matter is a major source of pollution in waterways and it is attributed to on-site septic effluents (Mason, 1996). Organic matter that occurs naturally in water bodies is taken up by plants, detritivores, bacteria and fungi for natural processes (Abel, 1996). When discharged in high quantities, organic matter can cause a major drop in available oxygen levels in the water (Abel, 1996). Organic matter can make its way to water bodies due to human waste as they constitute proteins, carbohydrates, fats and nucleic acids, and pathogenic organisms (Mason, 1996). Suspended solids are another major pollutant that can cause turbidity which inflicts direct and indirect risks on aquatic life (Illinois Department of Natural Resources, 1998). Excess suspended solids can have many negative effects on fish, such as causing abrasions in their gills, interfering with feeding habits since it blocks vision in locating food, and causing mortality (Abel, 1996).

As far as aquatic plant life, turbidity can prevent photosynthesis which hinders plant growth and productivity. Suspended solids can also create stable weed beds which affect egg-laying sites on the plants (Abel, 1996).

2.5.5 Salts and Metals

Salts are another common pollutant of OSWTS, which comes from the common table salt consumed in food, and could also be found in brackish water, and water softeners (Illinois Department of Natural Resources, 1998). Biological systems seldom depend on salt in natural processes, so excess salt could congregate in wetlands which act as sinks. Salt can consequently induce the growth of cattails which replace essential wetland vegetation (Illinois Department of Natural Resources, 1998).

Copper naturally exists in the soil column, but an excess of it could be introduced through household septic effluent. One of the oxidation states of copper, Cu^{2-}, is rendered toxic to aquatic life (Hall, Jr. et al., 1998). Cu^{2-} inhibits enzymes of trophic groups of aquatic species, when found in concentrations 10 to 50 times higher than the needed amount for plant uptake (Hall, Jr. et al., 1998). Copper can induce health issues in fish species such as histological alterations in the gill, kidney, hematopoietic tissue, mechanoreceptors, chemoreceptors and other tissues (Hall, Jr. et al., 1998). Copper also has the ability to negatively impact egg production and causes abnormalities in fish which reduces their survival rate (Hall, Jr. et al., 1998). The biota is also affected by bioaccumulation of copper, which inhibits photosynthesis and disrupts growth (Hall, Jr. et al., 1998).

2.5.6 Pharmaceuticals, Hormones, and PCPs

According to the U.S. Geological Survey, pharmaceuticals, hormones and personal care products (PCPs), are major contaminants of ground water from septic systems in New York and New England (USGS, 2015). Studies have also identified high nitrates in ground water samples down gradient from OSWTS (USGS, 2015). OSWTS have been recognized for being a source of a variety of micro-pollutants in New York, due to minimal treatment of the effluent before it reaches shallow ground water reservoirs (USGS, 2015). In New York, studies have observed a decline in fisheries and shellfish and higher female to male ratios in surface waters, which is being attributed to high concentrations of hormones, detergent degradation products, galaxolides, fragrances, insect repellents, sunscreen additives, floor cleaners, carbamazepine, and mood stabilizing products found in surface water bodies.

Pollutants go through several phases of purification beginning in the septic tank. Aerobic microorganisms found in the septic tank begin by converting nitrogen into nitrogen gas. Solid organic matter is also broken down to soluble organic acids which produce CO_2 and methane in the process (James et al., 2006). Studies have shown that about 40 % of solids are decomposed in the septic tank before reaching the absorption field (Ringler & Slater, 2009).

Once the effluent passes through to the absorption field there are several mechanisms that process the effluent through the soil. The effluent is processed physically, biological and chemically (Mancl & Slater, 2002). Physically, soil acts as a filtration complex, where the bacteria and organic matter are adsorbed onto soil micropores (Gerba et al., 1975). Chemically, there are several factors playing a role in the chemical treatment of septic effluent, such as Cation Exchange Complex (CEC), iron and aluminum oxides, soil organic matter and soil pH (Gerba et al., 1975). Viruses are removed by CEC when they are charged, and when they are neutral the process will be pH dependent (Gerba et al., 1975). Bacteria are adsorbed onto clay particles which are negatively charged (Bitton & Gerba, 1994). On the other hand, organic compounds are non-polar in nature so they are easily adsorbed onto soil organic matter found on soil particles (Ringler & Slater, 2009).

Nutrients are also purified through chemical processes. Phosphorous is fixed onto iron and aluminum oxides found on clay particle surface (Ujang & Henze, 2006). Ammonia is removed by adsorption on the CEC. In the case that soluble nitrogen and phosphorous are not adsorbed by the soil CEC, they will be retained in the soil for biological removal by plant and microorganisms uptake so long soil water content does not exceed field capacity (Ringler & Slater, 2009).

Leach fields contribute to over 90% removal of fecal coliforms from wastewater effluent, in most soil types (Ringler & Slater, 2009). Only 20% of all soil types met the EPA standards by removing just enough fecal coliforms (Ringler & Slater, 2009).

2.6 Previous and Associated Studies Specific to the Current Study

To study the effectiveness of engineered drains, a matrix of depths and spacing combinations was created to study their effects on the hydrological performance and lowering the high seasonal water table (Brown, 2008). Brown (2008) modeled water table elevations to evaluate potential failure by considering three inputs in testing 58 soil series in Ohio, water table depth criteria, rainfall and wastewater application. Wastewater application was only considered for four soils; Blount, Crosby, Mahoning, and Hoytville.

The average water table depth midway between two parallel curtain drains was evaluated daily (Brown, 2008). Water table depth was defined as the number of days the water table depth was ≤ 30, 60 and 90 cm (12, 24, 36 in) from the ground surface. The drain depth was placed at 140 cm (4.5 ft) and drain spacings of 5, 10, 15 m (16, 33, 50 ft). A no drainage class was also studied as a 1000 m (3281 ft) drain spacing. Two loading rates of wastewater were tested one of 1.25 cm/day (0.5 in/day) and 0.33 cm/day (0.13 in/day) for water table ≤60 and 90 cm (24, 35 in). Drain depths were set at 0.6, 0.9, 1.4 m (2, 3, 4.6 ft) and drain spacings of 5, 10, 15 m (16, 33, 49 ft).

The study found that the number of days the water table criteria were equaled or exceeded, as the drain spacing increased (Brown, 2008). Also, as the wastewater application loading rate increased the number of days the water table depth criteria were equaled or exceeded increased (Brown, 2008). The preferred loading rate was 0.33 cm/day (0.13 in/day). Results have shown that the shallower the drain the lower the effect was on the water table depth. Engineered drains were shown to be efficient in lowering the high seasonal water table depth when compared to no drainage cases (Shedekar, et al., 2015).

The study was followed up by studying the different factors that affect the water table (Toledo De-Leon, 2014). Toledo's study showed a significant difference between the different treatment combinations of spacing and depth on the number of days that the water table depth criteria were equaled or exceeded. The study also indicated that drain depth had a significant effect on the water table versus drain spacing which did not have a significant effect, suggesting that drain depth had a higher effect on the response. Toledo's study also found that the drain depth combinations did have a significant effect on the water table criteria. The study highly recommended the use of installed engineered drains to lower high seasonal water tables in poorly drained soils. Toledo (2014) recommended further studying the nitrogen loss concentrations in curtain drains from OSWTS in order to improve the design criteria for curtain drains on a treatment trench

As introduced in an earlier section, the associated field research is being constructed on the Noland Site in Union County. The field site is located west of the northbound Industrial Pkwy, Union County, Ohio (US), as a part of the Union County Soil Research Laboratory (40.788, -83.2715). The land area of Union County is approximately 1130 Km^2, with most of the soils being classified as poorly to somewhat poorly drained. The research site is approximately 4047 m^2 and sits at 296 m above sea level. The mean annual temperature is between 42 and 55 ^oF, while the mean annual precipitation falls between 736.6 mm and 1066.8 mm. The land slope of the site is 0-2%.

Blount soil represents the majority of soil in Union County (Figure 4) and is classified as a silt loam. Blount soil, are located on 95% of the plot area. The drainage classification of the Blount series is poorly to somewhat poorly drained soil with a high seasonal water table reaching to up to 15 cm (6 in) below the soil surface. The Blount soil series profile consists of a silt loam layer (1-15 cm) (0.4-6 in), silty clay loam layer (15-56 cm) (6-22 in), and clay loam layer (56-152 cm) (22-60 in) (National Cooperative Soil Survey, 2013). Blount soil is not generally suitable for a traditional OSWTS in Ohio (Mancl & Slater, 2001), largely because of the dense clay loam till layer in the lower soil profile, which produces a seasonable high water table.

Figure 4- Image of Noland site and dominant soil series *(Toledo De-Leon, 2014)*

The Noland Site is divided into three sections, each with six test units. A secondary treatment unit is also available for further treatment of effluent, in accordance with OEPA standards (Figure 5). The main purpose of the system is to treat any collected water from the test units to reduce the potential discharge of partially treated or untreated wastewater into ground or surface waters. Additional information is available in the two project reports (Burgess & Niple, 2013; Noland, 2014).

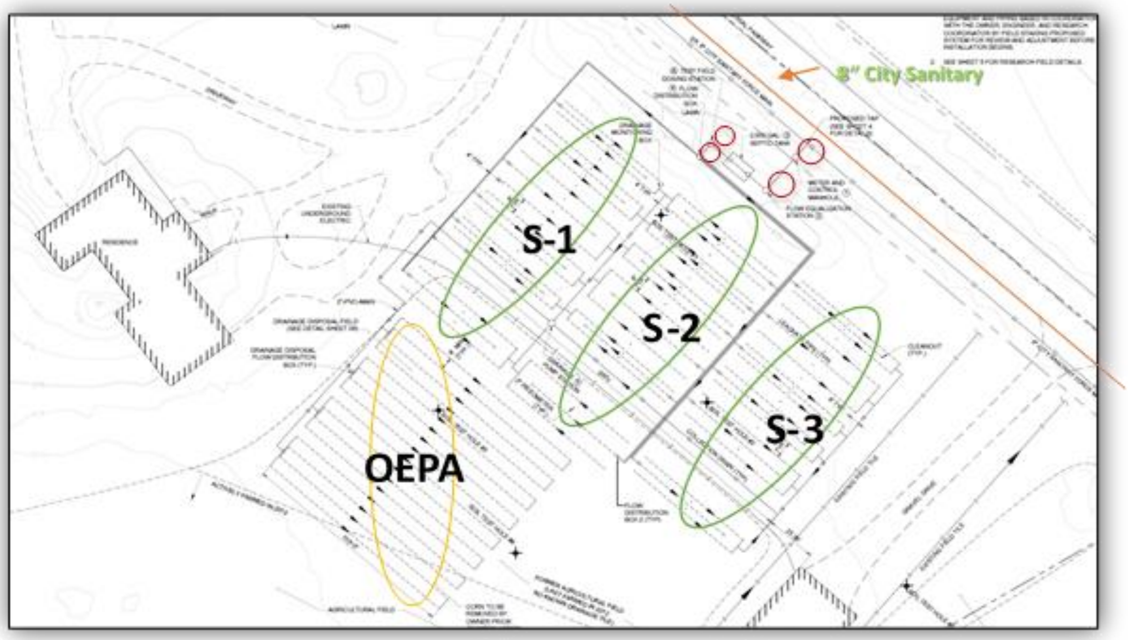

Figure 5 – Research plot set up of OSWTS *(Toledo De-Leon, 2014)*

Chapter 3: Materials and Methods

A description of DRAINMOD–N II, parameterization of the model, the experimental design and the statistical methods used to test the hypotheses for the study are presented in this chapter.

3.1 DRAINMOD Model Components, Parameters, and Simulations

A two-step process is required to simulate nitrogen in DRAINMOD. The first step is simulating the hydrology (Skaggs 1978; Skaggs et al., 2012), and the second one is simulating the nitrogen cycle with DRAINMOD-N II (Youssef et al., 2005). The modeling work by Toledo De-Leon (2014) was used as the basis of the hydrological modeling, but some modifications to certain model inputs related to the application water depth with wastewater irrigation were made by the current author to appropriately parameterize the nitrogen component. In the next two sections, both model components are briefly summarized in relation to the current study.

3.1.1 Water Management Model

The model approximates the hydrologic components of shallow water table soils. The model simulates the water balance on a daily basis to calculate the infiltration, evapotranspiration, subsurface drainage, runoff, subirrigation, deep seepage, water table depth, and soil water at every step (Youssef et al., 2006).

Soil water content is a primary driver of the model, and when the soil is completely saturated Kirkham's equations is used to estimate the drainage rate at ponded surface conditions. When the soil is not saturated, due to environmental effects such as evapotranspiration, the drainage rate is calculated using steady-state Hooghoudt equation since the water is not able to move from the surface to the drains (Bouwer & Van Schilfgaarde, 1963). Drainage rate is identified as the rate of water movement out of the soil into the drains at a given water table elevation. Drainage rate depends on several factors: depth and spacing combinations of the drains, hydraulic conductivity, and hydraulic capacity commonly known as drainage coefficient, DC (Skaggs et al., 2012).

3.1.2 The Nitrogen Model

DRAINMOD-N II (Youssef et al., 2005) is a field scale, process-based model, which simulates nitrogen and carbon dynamics in drained lands, for different soil series, under different climatic conditions and management practices. Model inputs are soil properties, management parameters, carbon and nitrogen processes and transformations parameters (Youssef et al., 2006). While the outputs include NO_3-N and NH_x-N concentrations in soil water and drain flow, the Organic Carbon content of the top 20 cm

(8 in) of the soil profile, and the rates if simulated N processes on the daily, monthly and annual basis (Youssef et al., 2006).

Knowledge of the soil water content is essential to study the properties and potential functions of an OSWTS. If the biological activity is not properly functioning the treatment of wastewater in the soil column is negatively affected, and could be non-existent. Other soil properties such as the saturated hydraulic conductivity influence both the hydrology and nitrogen cycling components of Drainmod. Typically, soil properties vary with depth so DRAINMOD requires information on the thickness of each soil layer and the soil properties associated with that layer.

3.1.3 Nitrogen cycle

The model studies three different nitrogen pools; NO_3-N, NH_3-N, ON (Youssef et al., 2005). NH_4-N dominates in soils with pH higher than 7.5 since they are pH dependent (Halvin et al., 1993). The multiple processes considered by DRAINMOD are; atmospheric disposition, application mineral N fertilizer (Urea and anhydrous NH_3), application of ON sources, plant uptake, mineralization, immobilization, denitrification, nitrification, NH_3 volatilization, NO_3-N and NH_x-N losses via subsurface drainage and surface runoff (Youssef et al., 2005). The Carbon Cycle plays an essential role in determining nitrogen dynamics. Organic carbon is a major factor in the denitrification process. DRAINMOD N II includes a sub-model that relies on three different soil organic matter pools to simulate the carbon cycle (Youssef et al., 2005). The three different pools are; active, slow and passive pool, metabolic and structural pool, and surface microbial pool. Each SOM pool provides OC content, potential rate of decomposition, and Carbon-to-nitrogen (C: N) ratio (Parton et al., 1993; Parton et al., 1987). Normal mode in DRAINMOD considers both forms of nitrogen NH_x-N and NO_3-N (Youssef et al., 2005).

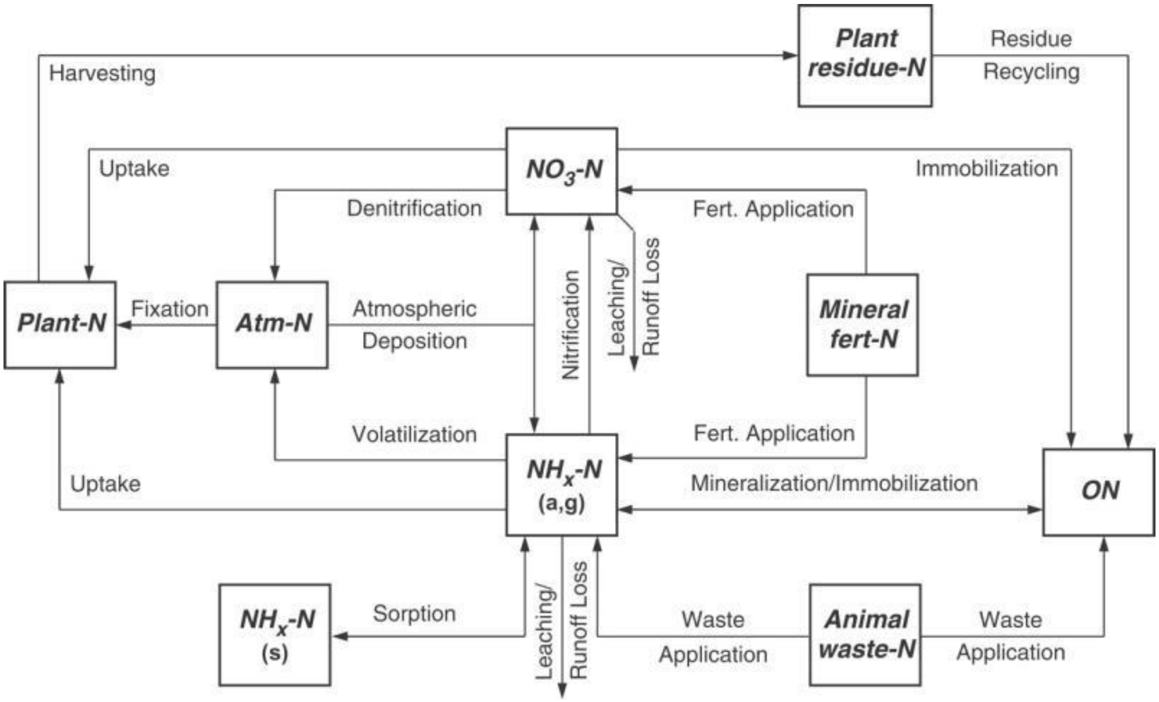

Figure 6- Nitrogen Cycle in the soil *(Youssef et al., 2005)*

3.1.4 Nitrification

Nitrification is the biological process of oxidizing NH_4^+ to NO_3^- , with the assistance of autotrophic bacteria such as Nitrosomonas and Nitrobacter. Nitrification is a multiple step process where Ammonium, NH_4^+, is oxidized to Nitrogen Dioxide, NO_2^-, which subsequently oxidizes to Nitrite, NO_3^- (Halvin et al., 1993). The following equations represent the nitrification reactions (Youssef et al., 2005):

This reaction occurs with the facilitation of Nitrosomonas

$$2\ NH_4^+ + 3\ O_2 \rightarrow 2\ NO_2^- + 2H_2O + 4\ H^+ \qquad (3.1)$$

This reaction occurs with the facilitation of Nitrobacter

$$2\ NO_2^- + O_2 \rightarrow 2NO_3^- \qquad (3.2)$$

The presence of hydrogen ions indicates soil acidity. DRAINMOD also assumes the presence of nitrifying bacteria in the soil when the pH is appropriate for microbial activity (Skaggs et al., 2012). DRAINMOD uses the Michaelis-Menten function to simulate the nitrification reactions in the soil (Mahli & McGill, 1982). When proper soil conditions are present, the nitrification process proceeds rapidly which produces NO_3^-, leaving it vulnerable to leaching down the soil profile and denitrification losses. Such processes can leave Nitrogen unavailable for plant uptake, leaving crop yields and environmental quality at risk (Youssef et al., 2005). Best Management Practices recommend using nitrogen inhibitor- fertilizers to reduce the risks of nitrogen loss and to all nitrogen to be held longer in the soil for proper plant uptake and denitrification. DRAINMOD assumes that both forms of nitrogen, NO_3-N, and NH_4-N, are available for plant uptake equally, and the uptake of each form is proportional to the amount available in the mineral N pool (Johnsson et al., 1987).

3.1.5 Denitrification

Denitrification is the reaction describing the reduction of NO_3-N to Dinitrogen gasses, N_2O and N_2. Denitrification requires anaerobic conditions for the denitrifying bacteria, or the facultative anaerobes, to use NO_3-N as the electron acceptor rather than O_2 (Coyne, 1999). In addition, low O_2 availability and NO_3-N availability, availability of organic carbon, OC, is essential to the process as a source of energy for the denitrifying microorganisms (Barton et al., 1999). Studies have shown that denitrification rates are proportional to NO_3-N and OC concentrations and availability (Reddy et al., 1982). DRAINMOD N II uses the Michaelis-Menten Kinetics to model denitrification in the system relying on NO_3-N (Youssef et al., 2005; Kohl et al., 1976). Organic Carbon is modeled using an exponential depth function (Breve et al., 1997). In the end, denitrification rates are dependent on soil organic matter and soil texture, as well as agronomic practices (Youssef et al., 2005).

Soil pH is another quantity essential to processes in the soil. DRAINMOD N II can model pH change in the soil, according to the application, nitrification, and plant N uptake. Fertilizer application does not directly affect soil pH but the nitrification of NH_4 acidifies the soil due to the production of hydrogen ions. On the contrary, the addition of NO_3-N does not increase soil acidity when uptake by plants occurs (Youssef et al., 2005).

3.2 Model Input Parameters

3.2.1 Soil Input Data

In this study, the model was expected to project the nitrogen loss from the OSWTS into the curtain drains. For this specific site, field data was collected to create the soil input files (Toledo De-Leon, 2014). Data collected included soil texture, soil bulk density, water content at field capacity (FC) and at permanent wilting point (PWP). The Rosetta Model was then used to generate the soil files using the above inputs, for further instructions please refer to (Toledo De-Leon, 2014).

3.2.2 Climate Input Data

Records from Marysville City, Union County, and Ohio Weather Station (Location ID: FIPS: 39159), 8 miles north of the site, were collected for maximum and minimum temperature and daily total precipitation. Temperature data was also collected from National Climate Data Center and National Oceanic and Atmospheric Administration (NOAA), using the Global Historical Climatological Network- Daily Documentation (GHCN- Daily) (Toledo De-Leon, 2014). Records of 31 years of climate data records were used beginning on January 1, 1982, until December 31, 2012. Any missing values from the data were replaced using data from Delaware, Ohio and Ohio State University Airport, Columbus, OH stations. These stations are about 18 mi northeast of Union County and 22 miles Southeast of Marysville. Data replacement was very little since 99% of the initial data was available from Marysville weather station (Toledo De-Leon, 2014).

3.2.3 Evaporation and Evapotranspiration

The Potential Evapotranspiration daily and monthly factors and heat index are estimated using the temp-based Thornthwaite equations (Luo et al., 2010) in DRAINMOD when daily or monthly factors are unavailable. PET has an effect on many functions of DRAINMOD from crop yield to water table depth and drainage volume (Skaggs, 1978). The Ohio Agricultural Research Development Center (OARDC) provides monthly climate records that allow for determining the PET monthly values using the Penman-Monteith Equation (FAO, 2012). In this case, the values provided more accurate estimates of the monthly PET (Skaggs, et al., 2012). The "Monthly PET Factors" were set at 1 for every month (Amatya et al., 2014). For details please refer to (Toledo De-Leon, 2014).

3.2.4 System Drainage Design Parameters

For this study, parameters of the model were to a large extent dependent on the work of others and in particular the work of Toledo De-Leon (2014). Input parameters were selected according to observed data, and literature based data. Geometry inputs are summarized in (***Error! Reference source not found.***).

System Design Input Parameters	
Drain Depth (cm)	102, 117 and 147
Drain Spacing (cm)	183, 244, 305, 366, and 488
Effective Radius (cm)	0.51
Depth to Impermeable Layer (cm)	200
Drainage Coefficient (cm/day)	1.27
Maximum Surface Storage (cm)	2.5
Kirkham's Depth (cm)	1

Table 8-DRAINMOD system design parameters and wastewater irrigation rate (Toledo De-Leon, 2014)

Other input sources and/or values are described below:

- Drain depth and spacing- The selected values were in accordance with site set up by the Ohio Department of Health (ODH) and the Ohio Environmental Protection Agency (OEPA).
- Effective Radius (EFFRAD) 0.51 cm (0.06 in) (Skaggs, 1980). The radius of a completely open tube with the same resistance to inflow as the real drain. Since we were working with a standard 10.2-cm (4-in) corrugated drain the opening is 38 cm^2/m (1.8 in^2/ft).

- Depth from the surface to permeable layer (ADEPTH) 200 cm (80 in): based on USDA Web Soil Survey databases the depth was determined from the bottom of the soil profile to the surface.
- Equivalent Depth from Drain to the impermeable letter (HDRAIN) - this was calculated by the model, representing the actual depth from the drain to the impermeable layer.
- Drainage Coefficient (DC) 1.27 cm/day (0.5 in/day) (Schwab et al., 1982)- in Ohio, the chosen DC is recommended because it was less limiting and more commonly used.
- Minimum Surface Storage (STMAX) 2.5 cm (1 in) (Skaggs, 1980)- before runoff occurs there was a minimum storage level that must be met. The value chosen was in accordance with the sensitivity analysis done by Skaggs.
- Kirkham’s Depth for Flow to Drains (STORRO) 1.0 cm (0.4 in) (Workman & Fausey, 1985)- This value represented the storage in local depressions.

3.2.5 Soil Profile

Knowledge of the soil water content is essential to study the properties and potential functions of the OSWTS. If the soil water content is below 10% or higher than 25% by volume, the biological activity of the soil would be affected negatively. If the biological activity is not properly functioning the treatment of wastewater in the soil column would be negatively affected, and could be non-existent. When soil water content is between 10 and 25% by volume, the biological activity will be at its highest which will promote the biological processes and chemical reactions for the microbes to treat the wastewater (Lal & Shukla, 2004). Determination of soil texture is necessary for determining the potential of wastewater treatment. Soils properties at the site were evaluated for sewage treatment and disposal by Toledo De-Leon (2014). His results are summarized in Table 9 and were used in my study. The low permeability of the soil, like the Blount soil in my study, limits the proper transmission of the untreated wastewater through the soil profile, which in turn promotes the anaerobic conditions suitable for proper treatment.

“A” Horizon

Properties	Average	SD	Max	Min
Sand %	20.95	0.25	21.20	20.70
Silt %	55.03	0.12	55.15	54.91
Clay %	24.02	0.13	24.15	23.90
DBD (g/cm^3)	1.28	0.04	1.32	1.24
Ө at .33 Bar	0.32	0.01	0.32	0.31
Ө at 15 Bar	0.17	-	-	-

“B” Horizon

Properties	Average	SD	Max	Min
Sand %	15.90	10.71	39.55	8.35
Silt %	43.70	5.86	47.49	30.69
Clay %	40.40	5.27	45.94	29.76
DBD (g/cm^3)	1.42	0.04	1.47	1.36
Ө at .33 Bar	0.34	0.04	0.41	0.29
Ө at 15 Bar	0.22	-	-	-

“BC” Horizon

Properties	Average	SD	Max	Min
Sand %	18.33	13.27	47.75	9.45
Silt %	45.11	9.00	50.71	25.20
Clay %	36.56	4.51	40.72	27.05
DBD (g/cm^3)	1.44	0.04	1.50	1.38
Ө at .33 Bar	0.33	0.03	0.38	0.27
Ө at 15 Bar	0.23	-	-	-

“CD” Horizon

Properties	Average	SD	Max	Min
Sand %	17.38	11.61	42.45	6.10
Silt %	47.06	8.18	55.25	30.21
Clay %	35.56	4.67	41.26	27.34
DBD (g/cm^3)	1.45	0.07	1.51	1.31
Ө at .33 Bar	0.32	0.04	0.36	0.23
Ө at 15 Bar	0.20	-	-	-

Table 9- Laboratory results and statistics of soil physical and hydrological properties of site-specific samples (Toledo De-Leon, 2014)

3.2.6 Lateral Saturated Hydraulic Conductivity

Lateral saturated hydraulic conductivity is the measure of the soil's ability to transmit water and the ease with which a fluid a fluid can move through pore spaces or fractures (Lal & Shukla, 2004). The lateral saturated hydraulic conductivity is an essential DRAINMOD input for all the soil layers present in the soil sample (Skaggs, 1978).

Soil Layer	Depth to Bottom of Hole (in)	Depth to Bottom of Hole (cm)	Calculated Hydraulic Conductivity (in/h)	Calculated Hydraulic Conductivity (cm/h)	Permeability Class (USDA-NRCS)	Hole #
A[a]	-	-	1.30	3.30	Mod. High	-
B	30	76	0.035	0.089	Very Low	3
BC	40	102	0.129	0.330	Mod. Low	4
CD	48	122	0.086	0.220	Mod. Low	1
D	54	153	0.028	0.073	Very Low	2

Aa: Saturated Hydraulic Conductivity for Ap layer was not determined by Auger Hole Method. USDA-NRCS soils database was used in order to estimate Ap layer Values

Table 10-Average saturated hydraulic conductivity values determined by the Auger Hole Method, Kirkham and Van Bavel (1948) equations and Cisler's (1967) Nomogram. (Toledo De-Leon, 2014)

Data from Table 9 and Table 10 were inputs to DRAINMOD for the Noland site-specific Blount silt loam soil simulations.

3.2.7 Nitrogen Input Data

For the carbon/nitrogen cycle the daily, monthly and yearly simulations were observed, and most importantly the N concentration in drainage water. The DRN output file was the most necessary output file because it indicated the nitrogen discharge concentration in drained wastewater. For the management options, the plant shoots and plant roots were chosen as part of the plant residue recycling.

The Nitrogen cycle is mainly driven by the carbon cycle, which is supported by the organic matter present in the system. Plant residue is a major organic matter source for the system. In the case of this field study, Bermuda grass was chosen as the “crop” of the system. The dissolved organic matter from the plant residue going into the system was minimal compared to actual agricultural systems so the plant residue was estimated at 700 kg/ha (Gossen et al., 1993), but in order to minimize the effect of the plant residue on the N-cycle we chose a value of 0 kg/ha. The Harvest index was set at 0.5 and the rest of the parameters were left at default. For the transport inputs a uniform grid was chosen with a depth of 200 cm (80in) and an increment of 5 cm (2 in). The Nitrogen inputs were all extracted or calculated according to (Youssef et al., 2005). All inputs are summarized in Table 11.

Carbon/Nitrogen Input Description	Selected Input Parameter
Crops	
Yield Parameters	
Potential yield (Kg/ha)	0
Harvest index	0.5
Root-to-Shoot ratio	0.1
Plant Biochemical Composition	
Grain Nitrogen (%)	1.5
Shoot Nitrogen (%)	0.5
Root Nitrogen (%)	0.5
Shoot Carbon (%)	45.0
Root Carbon (%)	45.0
Shot Lignin (%)	8.0
Root Lignin (%)	8.3
Transport	
Grid	Uniform
Depth	200
Increment	5
Hydrodynamic Dispersion	
Longitudinal Dispersivity (cm)	25
Tortuosity	0.5
Accuracy Parameters	
Maximum allowable error	0.0001
Minimum time step (d)	0.001
Initial/boundary conditions	
Rain NO3-N conc. (mg/l)	0.32
Rain NH4-N conc. (mg/l)	0.34
Air NH3-N conc. (mg/l)	0
Depth	0, 200
NO3-N conc. (mg/l)	20, 0
NH4-N conc. (mg/l)	0.2, 0
Transformations	
Nitrification	
Michaelis-Menten Parameters	
Max. rate (ug N/g soil)	14

Continue Table 11- Carbon/Nitrogen DRAINMOD input descriptions

Continue Table 11- Carbon/Nitrogen DRAINMOD input descriptions	
Half-saturation constant (ug N/ g soil)	10
Effects of Environmental factors on process rate	
Soil temperature	
Optimum temperature (deg-C)	25
Empirical shape coefficient	0.4
Soil water	
Lower WFPS	0.5
Upper WFPS	0.6
Relative process **rate**s at wilting point	0
Relative process **rate**s at saturation	0
Empirical exponent	1
Soil pH	Consider pH effect
Lower range	6.7
Upper range	7.2
Min. pH	3.5
Max. pH	10
Relative process **rate**s at min. pH	0
Relative process **rate**s at max. pH	0
Empirical exponent	1
Denitrification	
Michaelis-Menten Parameters	
Max. rate (ugN/g soil d)	2
Half-saturation constant (mg/l)	40
Effects of environmental factors on process rate	
Soil temperature	
Optimum temperature (deg- C)	36.9
Empirical shape coefficient	0.186
Soil water	
Threshold WFPS	0.171
Empirical exponent	2
Effects of soil carbon on process rate	
Empirical exponent	0.04
Other processes	
Fertilizer Dissolution	
Zero-order rate coefficient (1/d)	1
Threshold soil water content (cm^3/cm^3)	0.18
pH change and NH3 volatilization	
Continue	

Continue Table 11 – Carbon/Nitrogen DRAINMOD input descriptions	
pH modeling option	Do not reset soil pH
Threshold soil pH	7.5
Max soil buffering capacity	10000
Empirical resistance factor (s/cm)	50
Organic Matter	
Added organic material	
Surface AOM Pools	
Microbial	
Decomposition rate (1/d)	0.0164384
C:N ratio	8
Min. C:N ratio	10
Max. C:N ratio	20
Structural	
Decomposition rate (1/d)	0.0106849
C:N ratio	150
Metabolic	
Decomposition rate (1/d)	0.0405479
C:N ratio	15
Max N content of OM for min C:N ratio of surface microbial pool (%)	2
Below ground AOM pools	
Structural	
Decomposition rate (1/d)	0.0134247
C:N ratio	150
Metabolic	
Decomposition rate (1/d)	0.0506849
C:N ratio	15
Initial added organic material	
AOM (Kg/ha)	2000, 500
%OC	40, 40
%Lignin	10, 10
C:N ratio	100,100
Depth	0, 20
Soil organic matter	
Soil organic matter pools	
Active	
Decomposition rate (1/d)	2.00000E-02
Min. C:N ratio	3
Max. C:N ratio	15
Continue	

Continue Table 11 – Carbon/Nitrogen DRAINMOD input descriptions	
Initial C:N ratio	8
Initial % of SOC	2
Slow	
Decomposition rate (1/d)	5.47945E-04
Min. C:N ratio	12
Max. C:N ratio	20
Initial C:N ratio	20
Initial % of SOC	38
Passive	
Decomposition rate (1/d)	1.23288E-05
Min. C:N ratio	7
Max. C:N ratio	10
Initial C:N ratio	10
Initial % of SOC	60
Max. mineral N for min. C:N ratio (ug N cm^3 soil)	10
Initial soil organic carbon	SOC content along soil profile
SOC resetting options	Do not reset SOC
Environmental factors	
Soil temperature	
Optimum temperature (deg-C)	36.9
Empirical shape coefficient	0.186
Soil water	
Lower WFPS range	0.5
Upper WFPS range	0.6
Relative process **rate**s at wilting point	0.3
Relative process **rate**s at saturation	0.8
Empirical exponent	1

3.3 Experimental Design

To evaluate the first hypothesis, I created a matrix of 3 drain depths (DD) (102, 117, 147 cm), 5 drain spacings (DS) (183, 244, 305, 366, 488 cm), and 3 impermeable depths (160, 200, 240 cm) to give a total of 45 treatments. The depths and spacings were selected to match those at the Noland Site. The two impermeable depth values of 160 cm and 240 cm are 80% and 120% of the 200 cm estimate reported by NRCS. In addition to adjusting these depth and spacing variable, where possible three loading rates were considered. A limitation of the model was that it gave errors for irrigation rates less than 0.04 cm/hr. The irrigation rates used for each combination of drainage pipe depths and drainage pipe spacings are shown in Table 12.

Each treatment trench was modeled to receive approximately 217.8 gal/day of wastewater. This value was selected to be representative of the wastewater from the Noland residence and gives a loading rate of about 0.73 gpd/ft^2 for a 6ft wide (DS) by 50ft long treatment area. The daily load was modeled as a daily irrigation depth. The loading rate was adjusted for each drain spacing using Equation 3.3:

$$LR_D = Q_D / A_T \tag{3.3}$$

Where LR_D is the daily loading rate in gallons/day/ft^2 (gpd/ft^2), Q_D is the daily influent discharge into the leach trench in gallons/day/ft of treatment width (gpd/ft), A_T is the treatment area in square feet (ft^2). The treatment area A_T is the length of the leach trench

(50 ft) times the curtain drain spacing DS in ft. Therefore, when DS was changed it was necessary to change Q_D to maintain the same loading rate. (Table 12). To convert the loading rate to an irrigation rate in cm/hr per meter width of the treatment area (DS), QD was multiplied by 0.101 and divided by the drainage spacing. For example, a load of 217.8 gallons/day was equivalent to a rate of 0.12 cm/hr per cm of drain spacing for drains 183 cm apart (217.8 * 0.101/183)

The loading rate was distributed over the width drain spacing at a uniform depth, to be modeled in DRAINMOD as a wastewater irrigation application with subsurface drainage (Brown, 2008). In the case of wastewater application, it is applied every day at a constant depth. The loading rates were converted to depth measurements based on the drain spacings (183, 244, 305, 366, 488 cm), the irrigation rates for each spacing were (0.12, 0.09, 0.07, 0.06, 0.04 cm/hr), respectively. To further study the effect of the loading rate on the design, and the quality of the discharge, 45 more simulations were performed to evaluate smaller loading rates. Units with drains spacings (183, 244, 305 cm) were modeled with 2/3 of the initial irrigation rates (0.08, 0.06, 0.047 cm/hr), respectively. Units with spacings (183, 244 cm) were also modeled with irrigation rates of (0.06, 0.04) respectively. The 31- year, daily drainage loss concentrations of NO_3-N and NH_4-N in Kg/ha were extracted from the DRAINMOD DNP output file to be analyzed.

Drain Depths and Spacings from Ground Surface		
Vertical Drain Depth (cm)	**Horizontal Drain Spacing (cm)**	Irrigation rates **(cm/hr)**
102	183	0.12, 0.08, 0.06
102	244	0.09, 0.06, 0.04
102	305	0.07, 0.047
102	366	0.06
102	488	0.04
117	183	0.12, 0.08, 0.06
117	244	0.09, 0.06, 0.04
117	305	0.07, 0.047
117	366	0.06
117	488	0.04
147	183	0.12, 0.08, 0.06
147	244	0.09, 0.06, 0.04
147	305	0.07, 0.047
147	366	0.06
147	488	0.04

Table 12– Irrigation rates and drain pipe depths and spacings that were evaluated.

Since the OSWTS is a functioning system year-round a value of 1 was chosen for the month and day to begin wastewater application and the interval between irrigation events in the irrigation set up. The hours of irrigation were chosen to be between 7 am- 8 pm. A value of 0 was chosen for all the no irrigation dates inputs since we are irrigating every day. The irrigation constraints were set as 0 cm (0 in) for minimum drained volume required for irrigation and 100 cm (39 in) for minimum rainfall to delay irrigation. For the hourly irrigation rates please refer to Table 12.

The soil physical and chemical properties were entered as provided in Table 13. Soil pH was left at the default value of 7 and distribution coefficient of 2.5. The general parameters for soil temperature were chosen from the ODH report for modeling with engineered drains with OSWTS in Ohio (Shedekar et al., 2015).

Input Description	Selected Input Parameter	Source
Soil temperature		
ZA coefficient	2.5	(Shedekar et al., 2015)
ZB coefficient	1.21	(Shedekar et al., 2015)
TKA coefficient	0.39	(Shedekar et al., 2015)
TKB coefficient	1.33	(Shedekar et al., 2015)
Avg air temperature below which precipitation is snow (deg C)	0	(Shedekar et al., 2015)
Avg air temperature above which snow starts to melt	1	(Shedekar et al., 2015)
Snow melt coefficient (mm/dd-deg C)	5	(Shedekar et al., 2015)
Critical ice content above infiltration stops (cm^3/cm^3)	0.2	(Shedekar et al., 2015)
Initial conditions	(0,0) (215,10) snow depth=0, snow density=100(kg/m^3)	
Phase lag for daily air temperature sine wave (hour)	8	(Shedekar et al., 2015)
Soil temperature at bottom of the profile (deg- C)	10	
Freezing Characteristics	(0,0.3), (-1,0.15) (-20,0)	

Table 13- General parameters for soil temperature

The crop inputs were chosen next. The cropping window was set between day 1 and day 365. Growing season was set between day 75 and day 270. The rest of the inputs were left at default values used by Toledo De-Leon. The excess and deficit water stress were left at default as well. The root depths parameters used are shown in Table 14.

For the SEW inputs the lower limit of water content in the root zone was set at 0.126 cm^3/cm^3.

Input Description	**DM code variable**	**Selected Input Parameter**	**Source**
Weather Data			
Station ID		From weather file	
Latitude		40 D 14 M	
Heat Index		50	(Shedekar et al., 2015)
PET Factors		1	
Crop Data			
Crop Inputs			
Root Depths (cm)		(1,1,20) (12,31,20)	
Lower limit of water content in root zone (cm^3/cm^3)		0.126	
Limiting water table depth (cm)	SEWX	30	(Shedekar et al., 2015)
Dates to begin counting Wet/Drought stress	ISEWMS	4/25	
Date to end counting wet/ drought stress	ISEWME	10/15	
Trafficability Inputs			
Input Description	DM code variable	Selected Input Parameter	Source

Continue Table 14– DRAINMOD weather and crop input parameters

Continue Table 14 - DRAINMOD weather and crop input parameters

Month number to begin counting work days (Period 1)	MOBW1	2 (FEB)
Day to begin counting work days (Period 1)	IDABW1	15
Month number to end counting work days (Period 1)	MOEW1	5 (MAY)
Day to end counting work days (Period 1)	IDAEW1	26
Start hour of work day (Period 1)	SWKHR1	7
Ending hour of work day (Period 1)	EWKHR1	20
Minimum air volume required to work land (Period 1) (cm)	AMIN1	0.56
Minimum rain to delay work (Period 1)(cm)	ROUTA1	2.5
Delay after rain to recommence work (Period 1) (cm)	ROUTT1	1
Month number to begin counting work days (Period 2)	MOBW2	10
Day to begin counting work days (Period 2)	IDABW2	21
Month number to end counting work days (Period 2)	MOEW2	12
Day to end counting work days (Period 2)	IDAEW2	31
Start hour of work day (Period 2)	SWKHR2	7
Ending hour of work day (Period 2)	EWKHR2	20
Minimum air volume required to work land (Period 2) (cm)	AMIN2	0.4
Minimum rain to delay work (Period 1)(cm)	ROUTA2	2.5
Delay after rain to recommence work (Period 2) (cm)	ROUTT2	1

3.4 Hypothesis Testing

DRAIMOD daily outputs of Drainage loss of NO_3-N and NH_4-N were analyzed using Microsoft Excel, and Minitab to test the hypotheses. The statistical analysis conducted for this study were: a Probability Plot, a General Linear Model with a Tukey Comparison and a Paired T-test Analysis. The normality of the distribution of the 31-year annual NO3-N and NH4-N drainage loss concentrations was tested with probability plots using Minitab. For normally distributed data, with multiple factors and data, the General Linear Model analysis was performed to determine whether the means of the different combinations of DD, DS, and Dimp differed. The General Linear Model tested how strong the effect of the factors DD, DS and Dimp was on the response (NO3-N drainage loss) for all treatment combinations. A Tukey's comparison method was used in ANOVA to create 95% confidence intervals for all pairwise differences between factor level means, in order to determine whether there was a difference between the levels of each of the factors, DD, DS, and Dimp.

The loading rates in the system were also analyzed for their effect on the system. The initial loading rate of 217 gals/day was analyzed against 2/3 of the amount, 144 gal/day, and half the amount 108 gal/day. To determine whether a significant difference between the loading rates in the system existed, a paired t-test was performed. The paired t-test calculated the difference within each before-and-after pair of measurements, which determined the mean of these changes, and reported whether the means of the differences were statistically significant.

A paired t-test is considered ideal for dependent observations such as the ones to be analyzed. Also, a paired t-test did not require both samples to have equal variance. Therefore, it was logical to address my question of whether the change in the loading rate without changing the drain spacing made a difference in the drainage loss on NO3-N with a paired design. The paired t-test determined whether the mean of the differences was significant using a 95% confidence interval.

Chapter 4: Results, Conclusion and Recommendations

4.1 Results and Discussion

The results of the normality testing of the distribution of the 31-year annual NO3-N drainage loss concentrations using probability plots are reported in Appendix B. The middle line in the plot represented the expected percentile from the distribution of the data. The closer the points were to the middle line the better the fit. The left and right lines in the plot represented the 95 percentile confidence lower and upper boundaries. When the data fell within the lines, it was considered to be a good fit. Each plot provided a Mean, Standard Deviation and a p-value for the ordered data. The p-values indicated that the NO3-N data was normally distributed, while the NH4-N data was not. For many years the NH4-N data had zero or very low values that skewed the data. For this study, I decided not to continue with the analysis of NH4-N and only study the hypotheses for NO3-N drainage loss concentrations.

4.1.1 Hypothesis 1

The General Linear Model (GLM) was performed to test whether the differences in drain spacing, drain depth, depth of the impeding layer and effluent nitrogen loading rate would result in significantly different exports of nitrogen in the curtain drains.

Minitab provides a table of factors (drainage spacing DS, drain depth DD, impeding layer depth Dimp) with the number of treatments (levels) for each, and the level values (Table 15, Appendix A). Other tables are the ANOVA table statistics (Table 16, Appendix A), a table of GLM coefficients, and a table of unusual observations (Appendix A).

Factor	**Type**	**Levels**	**Values (cm)**
DS	Fixed	5	183, 244, 305, 366, 488
DD	Fixed	3	102, 117, 147
Dimp	Fixed	3	160, 200, 240

Table 15- GLM Table of Factors

Source	**DF**	**Adj SS**	**Adj MS**	**F-value**	**p-value**
DS	4	27830	6957.5	35.45	0.000
DD	2	30422	15210.9	77.50	0.000
Dimp	2	203	101.6	0.52	0.596
DD*DS	8	3416	427.0	2.18	0.027
DS*Dimp	8	64	8.0	0.04	1.000
DD*Dimp	4	259	64.7	0.33	0.858
DS*DD*Dimp	16	154	9.6	0.05	1.000

Table 16 - Analysis of Variance

The Analysis of Variance table gave, for each term in the model, the degrees of freedom, DF, the adjusted (partial) sums of squares (Adj SS), the adjusted means squares (Adj MS), the F-statistic from the adjusted means squares, and its p-value. The p-values of DS, DD and DS*DD were each less than 0.0005 so for each of these variables the null hypothesis that the means were equal was rejected. An unexpected result was that changes in the impeding depth, Dimp, did not significantly impact the mean annual. The GLM model only explained 19.05% of the variance in the mean annual NO3-N discharges. This was not unexpected as the drainage volume in a curtain drain are a complex non-linear function of the drainage spacing and the drain depth.

The Tukey Pairwise Comparison compared DD, DS, Dimp, DS*DD, DS*Dimp, DD*Dimp, and DS*DD*Dimp to the annual NO3-N drainage loss with 95% confidence interval. Means that do not share a letter are significantly different. Results in Table 17 showed that drain spacings of 183, 244, and 488 cm gave significantly different exports of nitrogen into curtain Drains. The drain spacings of 305 cm and 366 cm were significantly different from the other spacings but not from each other. The comparison also indicated that the larger the spacing the smaller the nitrogen export into curtain drains, which could be a result of longer residence time in the soil and less drainage.

DS	N	Mean	Grouping
183	279	48.66	A
244	279	44.7	B
305	279	41.29	C
366	279	39.36	C
488	279	35.62	D

** Means that do not share a letter are significantly different. N is the number of the annual NO3-N drainage loss concentration values associated with the factor*

Table 17 - Tukey Pairwise Comparison: Influence of drain spacing (DS, cm) on the mean annual values (kg/ha). Results for the 305 cm and 366 cm spacings were not significantly different.

Table 18 displays the significant difference between the 3 levels of the drain depth, indicating that a DD of 102 cm gave the lowest contribution to NO3-N export into curtain drains. All the drainage depth treatments were significantly different from each other. N is the number of the yearly values of NO3-N drainage loss concentrations associated with the given factor.

DD	**N**	**Mean**	**Grouping**
147	465	48.39	A
117	465	39.87	B
102	465	37.52	C

** Means that do not share a letter are significantly different. N is the number of the annual NO3-N drainage loss concentration values associated with the factor*

Table 18- Tukey Pairwise Comparison: Influence of drain depth (DD, cm) on the mean annual values (kg/ha). Results for each drain depth were significantly different.

Table 19 displays that the different levels of Dimp showed no significant difference in their effect on the NO3-N drainage loss because they all shared the same letter grouping.

Dimp	**N**	**Mean**	**Grouping**
200	465	42.27	A
240	465	42.17	A
160	465	41.4	A

** Means that do not share a letter are significantly different. N is the number of the annual NO3-N drainage loss concentration values associated with the factor*

Table 19- Tukey Pairwise Comparison: Influence of depth to the impeding layer (Dimp, cm) on the mean annual values (kg/ha). Results for each impeding depth were not significantly different.

Table 20 displays the result of comparing the effects of the combinations of drain depths and spacings on the response. The combination of a DS of 183 cm and a DD of 147 cm was significantly different than the rest of the treatment combinations. This combination also yielded the highest nitrogen export into the curtain drains. Even though the rest of the combinations were not always significantly different from other treatments, on their effect on the nitrogen drainage loss, there were 8 distinct treatments. For example, Group B was significantly different from groups E, F, G, and H. The combination of a DS of 148 cm and a DD of 102 cm yielded the lowest nitrogen loss when the means were compared.

DS	DD	N	Mean	Grouping
183	147	93	58.98	A
244	147	93	51.64	B
305	147	93	47.29	B C
183	117	93	44.82	B C D
366	147	93	44.6	C D E
244	117	93	42.91	C D E F
183	102	93	42.19	C D E F G
244	102	93	39.54	D E F G H
488	147	93	39.4	D E F G H
305	117	93	39.29	D E F G H
366	117	93	37.76	E F G H
305	102	93	37.3	F G H
366	102	93	35.72	G H
488	117	93	34.58	H
488	102	93	32.87	H

** Means that do not share a letter are significantly different. N is the number of the annual NO3-N drainage loss concentration values associated with the factor*

Table 20- Tukey Pairwise Comparison: Combinations of DS and DD (cm) on mean annual nitrate discharges (kg/ha)

Tukey's comparison for DS*Dimp showed no significant difference between the effect of the combinations on NO3-N drainage loss. On the contrary, when pairing Dimp with a DD of 147 cm the NO3-N drainage loss was significantly higher than when paired with a DD of 117 cm or 102 cm (Appendix A). When pairing all three factors DD, DS, and Dimp against the response there was no significant difference in the NO3-N export into any combination of curtain drains (Appendix A).

The loading rate was a function of the drain spacing and due to that high correlation I used a paired t-test to analyze the difference between the means from the different loading rates used. Load 1 was 217 gal/ day, Load 2 was 144 gal/day and Load 3 was108 gal/day. Load 1 and 2 were compared for three drain spacings (183, 244, 205 cm), then load 1, 2 and 3 were compared for drain spacings (183, 244 cm).

Load	**N**	**Mean**
1	558	44.89
2	558	42.56
Difference	558	2.33
p-value=0.000		

**N is the number of the annual NO3-N drainage loss concentration values associated with the factor*

Table 21 - Paired T-test for Load 1 and Load 2 for DS of 183 cm, 244 cm, and 305 cm pooled together for each load. Mean are reported in (kg/ha)

Table 21 indicated a significant difference between the means of Load 1 (217 gal/day) and Load 2 (144 gal/day) with the matrix of three DD (102, 117, 147 cm), three Dimp (160, 200, 240 cm) and three DS (183, 244, and 305 cm). There was evidence that Load 2 contributes less to nitrogen export into curtain drains since it had a lower mean - refer to Appendix A for more details.

For a load of 108 gals/ day and a matrix of three DD (102,117, 147 cm), three Dimp (160, 200, 240 cm) and two DS (183, 244 cm) the following was observed

Load	**N**	**Mean**
1	558	46.68
2	558	43.87
Difference	558	2.811
p-value=0.000		

******N is the number of the annual NO3-N drainage loss concentration values associated with the factor*

Table 22- Paired T-test for Load 1 and Load 2 for DS of 183 cm and 244 cm pooled together. Mean are reported in (kg/ha)

Load	**N**	**Mean**
1	558	46.68
3	558	42.37
Difference	558	4.315
p-value=0.000		

**N is the number of the annual NO3-N drainage loss concentration values associated with the factor*

Table 23- Paired T-test for Load 1 and Load 3 for DS of 183 and 244 pooled together. Mean are reported in (kg/ha)

Load	**N**	**Mean**
2	558	43.87
3	558	42.37
Difference	558	1.50
p-value=0.000		

**N is the number of the annual NO3-N drainage loss concentration values associated with the factor*

Table 24- Paired T-test for Load 2 and Load 3 for DS of 183 and 244 pooled together. Mean are reported in (kg/ha)

Tables 22, 23, and 24 show, that at a 95% confidence interval, there was a significant difference in the nitrogen export into curtain drains between the three different loads, with load 2 yielding the lowest mean. However, it was surprising that the reductions in the mean annual NO3-N discharges were small compared to the large reductions in the loading rates.

In conclusion, we cannot reject the null hypothesis that differences in drain spacing, drain depth, and effluent nitrogen loading rate will result in no significant differences in exports of nitrogen in the curtain drains. However, we do reject the null hypothesis for changes in the depths of the impeding layer since changes in this variable did not result in significant changes in the mean annual NO3-N discharges.

4.1.2 Hypothesis 2

The regression equation in Appendix A shows that DS had the highest coefficient. This indicates that DS had the highest effect on nitrate as all DS values in cm were also greater than the DD values in cm. Unfortunately, R^2 value for the equation was small, so it is difficult to be confident in accepting the assumption that the drain spacing (treatment area) had the greatest effect on nitrogen losses to the curtain drains.

4.2 Discussion

For the location in this study, I concluded that the differences in drain depth, drain spacing, and effluent loading rate resulted in significantly different exports of NO3-N into curtain drains. The drain spacings 183, 244, 488 cm were all significantly different from the rest of the spacings. The drain depths 102, 117, and 147 cm were all significantly different in their effect on the nitrogen drainage loss. The loading rates 217 gals/day, 144 gals/ day, 108 gals/day each resulted in NO3-N into curtain drains that were significantly different but the differences were smaller than anticipated. The initial Nitrogen concentration entering the system was reported by the research site to be approximately 20 mg/l. This load was not adjusted for the different loading rates which could have affected the Nitrogen concentration output. In this case, I am not able to make a statement regarding the difference of effect between the loading rates. The different levels of Dimp showed no significant difference in their effect on the NO3-N drainage loss. The saturated hydraulic conductivities were not taken into account in DRAINMOD, which was an error in the modeling on my part. The model inputs included the hydraulic conductivity up to 153 cm of depth, anything beyond that layer the hydraulic conductivity was eithr assumed to be 0 or equal to that of the last layer. The model could have also taken the weighted average of Ksat of the whole soil profile in the model. Whichever the case may be, the saturated hydraulic conductivities must be obtained for those lower layers for more accurate comparison of the impeding depths.

Based on the analysis that was performed it was not possible to determine if the drain spacing (treatment area) was more significant than the drainage depth. Multiple limitations occurred in using DRAINMOD to simulate nitrogen exports to curtain drains. In this study, OSWTS was modeled in DRAINMOD as uniformly applied wastewater irrigation to the ground surface. However, the OSWTS actually occurs by discharging the wastewater from a pipe near the bottom of a trench located at the midpoint between the curtain drains. At the Noland site, the effluent enters the leaching system 16 in below the soil surface. Therefore, an approach similar to the effective depth might be needed to establish an effective ground surface for the system.

The effective ground surface could be estimated as the bottom or top of the wastewater pipe or some other depth. However, the zone above the wastewater pipe has some influence as suction forces can move the effluent upward. Also, precipitation enters the soil profile from the ground surface so artificially reducing the depth from the ground surface to the drainage pipe will influence the hydrology of the system. Another limitation to consider is the saturated hydraulic conductivity which changes with the deepening of the layers and plays a major role in the hydrology of the system overall. The saturated hydraulic conductivity is lower at the depth that the effluent is introduced, and since DRAINMOD assumes the application is at the surface it takes into consideration the hydraulic conductivity. This could really effect the nitrogen concentrations because there could be less treatment taking place in the soil profile. The seepage rate was ignored in this study due to lack of data. Seepage was another limitation that required more field data, and could have a significant effect on the hydrology of the system.

Uniformly applying the wastewater as irrigation to the ground water modifies nitrogen cycling in the system. With the loading midway between the curtain drains the lateral and vertical pathways of the nitrogen will be very different than surface applied wastewater. I anticipate that as the drain spacing increases, the loads to the curtain drains will decrease because the application location becomes more distant from the drains. However, with the surface application as irrigation water, a percentage of the load will always be simulated as being applied the same distance from the curtain drains regardless of their spacing. This artificially amplifies the importance of drain depth and reduces the importance of drain spacing.

There is an uncertainty of the way DRAINMOD represents the outputs. The NO3-N drainage loss was represented in kg/ha in the DNP output file. I am uncertain of the performance of DRAINMOD to conclude with such units. Regardless, the units do not affect the results compared relatively to each other.

4.3 Conclusions

Based on this study, I conclude that the differences in drain depth, drain spacing, and effluent loading rate resulted in significantly different exports of NO3-N into curtain drains. The drain spacings of 183, 244, 488 cm were all significantly different from the rest of the spacings, except for drain spacings 305 cm and 366 cm they were not significantly different from each other but significantly different from the rest. I am not able to make a statement on the differences of the loading rates 217 gals/day, 144 gals/ day, 108 gals/day due to the error mentioned earlier. The drain depths 102 cm, 117 cm, and 147 cm were all significantly different in their effect on the nitrogen drainage loss. The strength of the effect of drain spacing on the outcome was not adequately evaluated because of limitations in how I had to model the real system in DRAINMOD. However, the results show that the drain spacing is one of the most important factors that influence nitrate exports in the curtain drains.

4.4 Recommendations

Collecting nitrogen data at different layers of the soil, the effluent entering the system, and the water exiting the drains is necessary to compare to DRAINMOD predictions, and to measure the true environmental risks of the system. A collection of flow rate data for each treatment is recommended to calibrate DRAINMOD, in order to obtain more solid predictions. Finding the average drainage outflow from curtain drains in Ohio will be necessary to compare the nitrogen concentration in discharges, in the case that the drainage outflow of the system falls within the range of the state average. Using the year as a factor in the statistical analysis is recommended to assign variance to different factors which could make the testing more robust. While DRAIMOD is a model that predicts the hydrology and nitrogen discharge of curtain drains, further research is recommended on evaluating how to model a “point” wastewater load midway between the curtain drains and below the ground surface.

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APPENDIX A: Annual Nitrogen Discharges in the Curtain Drains

NO3-N Drainage Loss Concentrations, Drain Depth: 102 cm					
DS (cm)	D_{Imp} (cm)	Range (Kg/ha)	Mean (Kg/ha)	Standard Deviation (Kg/ha)	Median (Kg/ha)
183	160	20.67-75.82	42.17	14.44	41.99
183	200	20.76-75.82	42.17	14.44	41.99
183	240	20.68-75.82	42.22	14.4	41.99
244	160	19.55-68.84	39.56	13.27	39.08
244	200	19.53-68.89	39.53	13.28	39.15
244	240	19.53-68.89	39.53	13.28	39.15
305	160	19.41-63.52	37.29	12.47	36.9
305	200	19.32-63.19	37.29	12.41	35.94
305	240	19.32-63.19	37.33	12.37	35.94
366	160	18.09-62.58	35.86	12.17	35.13
366	200	18.15-61.16	35.64	12.12	34.98
366	240	18.14-61.51	35.66	12.17	34.99
488	160	16.48-56.97	32.94	10.87	32.08
488	200	16.38-56.54	32.85	11.08	32.39
488	240	16.58-56.18	32.82	10.98	32.48

Table 25- Annual NO3-N Drainage loss concentration means data compilation of 31 years for DD= 102 cm

NO3-N Drainage Loss Concentrations, Drain Depth: 117 cm					
DS (cm)	**D_{Imp} (cm)**	**Range (Kg/ha)**	**Mean (Kg/ha)**	**Standard Deviation (Kg/ha)**	**Median (Kg/ha)**
183	160	22.0-82.72	44.82	15.11	43.53
183	200	22.06-82.74	44.81	15.11	43.54
183	240	22.06-82.74	44.81	15.11	43.54
244	160	20.43-72.89	41.69	13.86	41.36
244	200	25.17-64	45.28	10.82	46.44
244	240	20.42-73.95	41.78	14.03	41.55
305	160	18.7-69.23	39.32	13.07	39.18
305	200	18.75-69.43	39.28	13.10	38.64
305	240	18.75-69.46	39.27	13.09	38.59
366	160	17.35-66.62	37.62	12.74	37.17
366	200	17.39-67.08	37.77	13.01	37.18
366	240	17.39-67.11	37.89	13.20	37.2
488	160	16.14-58.39	34.30	11.57	34.15
488	200	16-58.9	34.69	11.72	34.18
488	240	16.47-59.21	34.75	11.70	35.06

Table 26- Annual NO3-N Drainage loss concentration means data compilation of 31 years for DD= 117 cm

NO3-N Drainage Loss Concentrations, Drain Depth: 147 cm

DS (cm)	D_{Imp} (cm)	Range (kg/ha)	Mean (kg/ha)	Standard Deviation (kg/ha)	Median (kg/ha)
183	160	30.05-110.1	57.81	18.71	57.9
183	200	34.26-112.2	59.58	18.56	60.17
183	240	34.31-112.2	59.57	18.56	60.17
244	160	26.95-92.92	50.62	16.56	50.045
244	200	28.16-100.96	52.09	17.37	49.62
244	240	28.2-101.11	52.22	17.42	49.7
305	160	24.48-82.9	45.8	15.4	44.36
305	200	24.54-86.91	48.00	15.74	47.19
305	240	24.62-87.00	48.07	15.82	46.93
366	160	21.42-77.89	43.02	14.21	42.06
366	200	23.56-81.55	45.26	14.78	45.05
366	240	23.66-82.35	45.54	14.96	45.06
488	160	18.07-67.73	38.15	12.65	38.68
488	200	18.72-71.07	39.86	13.04	39.06
488	240	19.45-71.97	40.29	13.15	39.84

Table 27- Annual NO3-N Drainage loss concentration means data compilation of 31 years for DD= 147 cm

NO3-N Drainage Loss Concentrations, Impeding Depth: 160 cm

DS (cm)	DD (cm)	Range (kg/ha)	Mean (kg/ha)	Standard Deviation (kg/ha)	Median (kg/ha)
183	102	20.67-75.82	42.17	14.44	41.99
183	117	22.0-82.72	44.82	15.11	43.53
183	147	34.31-112.2	59.57	18.56	60.17
244	102	19.55-68.84	39.56	13.27	39.08
244	117	20.43-72.89	41.69	13.86	41.36
244	147	26.95-92.92	50.62	16.56	50.045
305	102	19.41-63.52	37.29	12.47	36.9
305	117	18.7-69.23	39.32	13.07	39.18
305	147	24.48-82.9	45.80	15.14	44.36
366	102	18.09-62.58	35.86	12.17	35.13
366	117	17.35-66.62	37.62	12.74	37.17
366	147	21.42-77.89	43.02	14.21	42.06
488	102	16.48-56.97	32.94	10.87	32.08
488	117	16.14-58.39	34.30	11.57	34.15
488	147	18.07-67.73	38.15	12.65	38.68

Table 28- Annual NO3-N Drainage loss concentration means data compilation of 31 years for Dimp= 160 cm

NO3-N Drainage Loss Concentrations, Impeding Depth: 200 cm

DS (cm)	DD (cm)	Range (kg/ha)	Mean (kg/ha)	Standard Deviation (kg/ha)	Median (kg/ha)
183	102	20.67-75.82	42.17	14.44	41.99
183	117	22.06-82.74	44.81	15.11	43.54
183	147	34.26 -112.2	59.58	18.56	60.17
244	102	19.53-68.89	39.53	13.28	39.15
244	117	25.17-64	45.28	10.82	46.44
244	147	28.16-100.96	52.09	17.37	49.62
305	102	19.32-63.19	37.29	12.41	35.94
305	117	18.75-69.43	39.28	13.10	38.64
305	147	24.54-86.91	48.0	15.74	47.19
366	102	18.15-61.16	35.64	12.12	34.98
366	117	17.39-67.08	37.77	13.01	37.18
366	147	23.66-8.55	45.26	14.78	45.05
488	102	16.38-56.54	32.85	11.08	32.39
488	117	16-58.9	34.69	11.72	34.18
488	240	19.45-71.97	40.29	13.15	39.84

Table 29- Annual NO3-N Drainage loss concentration means data compilation of 31 years for Dimp= 200 cm

NO3-N Drainage Loss Concentrations, Impeding Depth: 240 cm

DS (cm)	DD (cm)	Range (kg/ha)	Mean (kg/ha)	Standard Deviation (kg/ha)	Median (kg/ha)
183	102	20.68-75.82	42.22	14.4	41.99
183	117	22.06-82.74	44.81	15.11	43.54
183	147	34.31-112.2	59.57	18.56	60.17
244	102	19.53-68.89	39.53	13.28	39.15
244	117	20.42-73.95	41.78	14.03	41.55
244	147	28.2-101.11	52.22	17.42	49.7
305	102	19.32-63.19	37.33	12.37	25.94
305	117	18.75-69.46	39.27	13.09	38.59
305	147	24.62-87.00	48.07	15.82	46.93
366	102	18.14-61.51	35.66	12.17	34.99
366	117	17.39-67.11	37.89	13.20	37.2
366	147	23.66-82.35	45.54	14.96	45.06
488	102	16.58-56.18	32.82	10.98	32.48
488	117	16.47-59.21	34.75	11.70	35.06
488	240	19.45-71.97	40.29	13.15	39.84

Table 30- Annual NO3-N Drainage loss concentration means data compilation of 31 years for Dimp= 240 cm

NO3-N Drainage Loss Concentrations, Drain Spacing: 183 cm					
DD (cm)	**D_{Imp} (cm)**	**Range (kg/ha)**	**Mean (kg/ha)**	**Standard Deviation (kg/ha)**	**Median (kg/ha)**
102	160	20.67-75.82	42.17	14.44	41.99
102	200	20.76-75.82	42.17	14.44	41.99
102	240	20.68-75.82	42.22	14.4	41.99
117	160	22.0-82.72	44.82	15.11	43.53
117	200	22.06-82.74	44.81	15.11	43.54
117	240	22.06-82.74	44.81	15.11	43.54
147	160	30.05-110.1	57.81	18.71	57.9
147	200	34.26-112.2	59.58	18.56	60.17
147	240	34.31-112.2	59.57	18.56	60.17

Table 31- Annual NO3-N Drainage loss concentration means data compilation of 31 years for DS= 183 cm

NO3-N Drainage Loss Concentrations, Drain Spacing: 244 cm

DD (cm)	**D_{Imp} (cm)**	**Range (kg/ha)**	**Mean (kg/ha)**	**Standard Deviation (kg/ha)**	**Median (cm)**
102	160	19.55-68.84	39.56	13.27	39.08
102	200	19.53-68.89	39.53	13.28	39.15
102	240	19.53-68.89	39.53	13.28	39.15
117	160	20.43-72.89	41.69	13.86	41.36
117	200	25.17-64	45.28	10.82	46.44
117	240	20.42-73.95	41.78	14.03	41.55
147	160	26.95-92.92	50.62	16.56	50.045
147	200	28.16-100.96	52.09	17.37	49.62
147	240	28.2-101.11	52.22	17.42	49.7

Table 32- Annual NO3-N Drainage loss concentration means data compilation of 31 years for DS= 244 cm

NO3-N Drainage Loss Concentrations, Drain Spacing: 305 cm

DD (cm)	**D_{Imp} (cm)**	**Range (kg/ha)**	**Mean (kg/ha)**	**Standard Deviation (kg/ha)**	**Median (kg/ha)**
102	160	19.41-63.52	37.29	12.47	36.9
102	200	19.32-63.19	37.29	12.41	35.94
102	240	19.32-63.19	37.33	12.37	35.94
117	160	18.7-69.23	39.32	13.07	39.18
117	200	18.75-69.43	39.28	13.10	38.64
117	240	18.75-69.46	39.27	13.09	38.59
147	160	24.48-82.9	45.8	15.4	44.36
147	200	24.54-86.91	48.00	15.74	47.19
147	240	24.62-87.00	48.07	15.82	46.93

Table 33- Annual NO3-N Drainage loss concentration means data compilation of 31 years for DS= 305 cm

NO3-N Drainage Loss Concentrations, Drain Spacing: 366 cm

DD (cm)	D_{Imp} (cm)	Range (kg/ha)	Mean (kg/ha)	Standard Deviation (kg/ha)	Median (kg/ha)
102	160	18.09-62.58	35.86	12.17	35.13
102	200	18.15-61.16	35.64	12.12	34.98
102	240	18.14-61.51	35.66	12.17	34.99
117	160	17.35-66.62	37.62	12.74	37.17
117	200	17.39-67.08	37.77	13.01	37.18
117	240	17.39-67.11	37.89	13.20	37.2
147	160	21.42-77.89	43.02	14.21	42.06
147	200	23.56-81.55	45.26	14.78	45.05
147	240	23.66-82.35	45.54	14.96	45.06

Table 34- Annual NO3-N Drainage loss concentration means data compilation of 31 years for DS= 366 cm

NO3-N Drainage Loss Concentrations, Drain Spacing: 488 cm

DD (cm)	D_{Imp} (cm)	Range (kg/ha)	Mean (kg/ha)	Standard Deviation (kg/ha)	Median (kg/ha)
102	160	16.48-56.97	32.94	10.87	32.08
102	200	16.38-56.54	32.85	11.08	32.39
102	240	16.58-56.18	32.82	10.98	32.48
117	160	16.14-58.39	34.30	11.57	34.15
117	200	16-58.9	34.69	11.72	34.18
117	240	16.47-59.21	34.75	11.70	35.06
147	160	18.07-67.73	38.15	12.65	38.68
147	200	18.72-71.07	39.86	13.04	39.06
147	240	19.45-71.97	40.29	13.15	39.84

Table 35- Annual NO3-N Drainage loss concentration means data compilation of 31 years for DS= 488 cm

NO3-N Drainage Loss Concentrations, Load 1

(217 gal/day)

DD (cm)	**DS (cm)**	**D_{Imp} (cm)**	**Range (kg/ha)**	**Mean (kg/ha)**	**Standard Deviation (kg/ha)**	**Median (kg/ha)**
102	183	160	20.67-75.82	42.17	14.44	41.99
102	183	200	20.76-75.82	42.17	14.44	41.99
102	183	240	20.68-75.82	42.22	14.4	41.99
102	244	160	19.55-68.84	39.56	13.27	39.08
102	244	200	19.53-68.89	39.53	13.28	39.15
102	244	240	19.53-68.89	39.53	13.28	39.15
102	305	160	19.41-63.52	37.29	12.47	36.9
102	305	200	19.32-63.19	37.29	12.41	35.94
102	305	240	19.32-63.19	37.33	12.37	35.94
117	183	160	22.0-82.72	44.82	15.11	43.53
117	183	200	22.06-82.74	44.81	15.11	43.54
117	183	240	22.06-82.74	44.81	15.11	43.54
117	244	160	20.43-72.89	41.69	13.86	41.36
117	244	200	25.17-64	45.28	10.82	46.44
117	244	240	20.42-73.95	41.78	14.03	41.55
117	305	160	18.7-69.23	39.32	13.07	39.18
117	305	200	18.75-69.43	39.28	13.10	38.64
117	305	240	18.75-69.46	39.27	13.09	38.59
147	183	160	30.05-110.1	57.81	18.71	57.9
147	183	200	34.26-112.2	59.58	18.56	60.17
147	183	240	34.31-112.2	59.57	18.56	60.17
147	244	160	26.95-92.92	50.62	16.56	50.045
147	244	200	28.16-100.96	52.09	17.37	49.62
147	244	240	28.2-101.11	52.22	17.42	49.7
147	305	160	24.48-82.9	45.8	15.4	44.36
147	305	200	24.54-86.91	48.00	15.74	47.19
147	305	240	24.62-87.00	48.07	15.82	46.93

Table 36- Annual NO3-N Drainage loss concentration means data compilation of 31 years for Load 1= 217 gal/day

NO3-N Drainage Loss Concentrations, Load 2

(144 gal/day)

DD (cm)	DS (cm)	D_{Imp} (cm)	Range (kg/ha)	Mean (kg/ha)	Standard Deviation (kg/ha)	Median (kg/ha)
102	183	160	20.28-70.42	40.56	13.76	38.96
102	183	200	20.28-70.42	40.56	13.76	38.96
102	183	240	20.28-70.42	40.56	13.76	38.96
102	244	160	19.27-66.51	38.34	13.13	37.7
102	244	200	19.39-66.3	38.28	13.07	37.75
102	244	240	19.39-66.3	38.28	13.07	37.75
102	305	160	19.05-63.65	36.55	12.44	35.61
102	305	200	19.05-64.74	36.56	12.53	35.35
102	305	240	19.32-63.19	37.33	12.37	35.94
117	183	160	21.55-76.79	42.38	14.36	41.86
117	183	200	21.55-76.79	42.34	14.34	41.82
117	183	240	21.55-76.72	42.34	14.34	41.82
117	244	160	20.19-70.64	39.94	13.37	39.29
117	244	200	20.21-71.44	39.97	13.51	38.71
117	244	240	20.21-71.44	39.97	13.51	38.71
117	305	160	18.15-67.12	38.24	13.06	37.81
117	305	200	18.45-67.36	38.16	13.03	37.25
117	305	240	18.47-67.4	38.15	13.02	37.26
147	183	160	28.6-100.25	52.83	17.13	51.94
147	183	200	28.99-100.01	54.01	17.34	54.13
147	183	240	28.97-99.96	54.00	17.33	54.14
147	244	160	25.4-87.31	47.31	15.66	54.21
147	244	200	25.88-91.69	48.95	16.10	46.99
147	244	240	25.98-91.78	49.06	16.11	46.99
147	305	160	22.75-79.47	43.86	14.40	43.1
147	305	200	24.14-80.77	45.66	14.9	43.43
147	305	240	24.18-8.67	45.70	14.88	43.36

Table 37- Annual NO3-N Drainage loss concentration means data compilation of 31 years for Load 2= 144 gal/day

NO3-N Drainage Loss Concentrations, Load 3

(108 gal/day)

DD (cm)	DS (cm)	D_{Imp} (cm)	Range (cm)	Mean (cm)	Standard Deviation (cm)	Median (cm)
102	183	160	20-69.45	39.67	13.64	38.73
102	183	200	20-69.45	39.67	13.64	38.73
102	183	240	20-69.45	39.67	13.64	38.73
102	244	160	19.17-65.84	37.31	12.86	35.89
102	244	200	19.3-65.8	37.26	12.81	35.85
102	244	240	19.3-65.8	37.26	12.81	35.85
117	183	160	21.43-75.57	41.55	14.07	40.52
117	183	200	21.42-75.6	41.57	14.07	40.47
117	183	240	21.42-75.6	41.57	14.07	40.47
117	244	160	19.82-67.07	38.67	13.12	37.05
117	244	200	19.81-68.28	38.71	13.22	37.37
117	244	240	19.81-68.28	38.71	13.22	37.37
147	183	160	26.71-94.41	50.35	16.69	48.58
147	183	200	28.69-95.97	51.48	16.73	49.85
147	183	240	28.65-95.93	51.48	16.74	49.93
147	244	160	23.9-83.82	45.12	15.15	42.89
147	244	200	24.83-85.13	46.22	15.38	44.12
147	244	240	24.88-85.15	46.34	15.37	44.32

Table 38- Annual NO3-N Drainage loss concentration means data compilation of 31 years for Load 3= 108 gal/day

APPENDIX B: General Linear Model, Tukey Comparison, and Paired T-test Analysis and Results in Minitab

General Linear Model: Annual NO3 versus DS, DD, Dimp

```
Method

Factor coding  (-1, 0, +1)


Factor Information

Factor  Type   Levels  Values
DS      Fixed       5  183, 244, 305, 366, 488
DD      Fixed       3  102, 117, 147
Dimp    Fixed       3  160, 200, 240


Analysis of Variance

Source          DF  Adj SS   Adj MS  F-Value  P-Value
  DS             4   27830   6957.5    35.45    0.000
  DD             2   30422  15210.9    77.50    0.000
  Dimp           2     203    101.6     0.52    0.596
  DS*DD          8    3416    427.0     2.18    0.027
  DS*Dimp        8      64      8.0     0.04    1.000
  DD*Dimp        4     259     64.7     0.33    0.858
  DS*DD*Dimp    16     154      9.6     0.05    1.000
Error         1350  264963    196.3
Total         1394  327310


Model Summary

      S    R-sq  R-sq(adj)  R-sq(pred)
14.0096  19.05%     16.41%      13.56%


Coefficients

Term             Coef  SE Coef  T-Value  P-Value   VIF
Constant       41.929    0.375   111.78    0.000
DS
  183           6.734    0.750     8.98    0.000  1.60
  244           2.770    0.750     3.69    0.000  1.60
  305          -0.635    0.750    -0.85    0.398  1.60
  366          -2.566    0.750    -3.42    0.001  1.60
DD
  102          -4.406    0.530    -8.31    0.000  1.33
  117          -2.057    0.530    -3.88    0.000  1.33
Dimp
  160          -0.532    0.530    -1.00    0.316  1.33
```

```
  200           0.344    0.530     0.65    0.517  1.33
DS*DD
  183 102       -2.07     1.06    -1.95    0.051  2.13
  183 117       -1.79     1.06    -1.69    0.092  2.13
  244 102       -0.75     1.06    -0.71    0.477  2.13
  244 117        0.27     1.06     0.26    0.797  2.13
  305 102        0.41     1.06     0.39    0.698  2.13
  305 117        0.06     1.06     0.05    0.959  2.13
  366 102        0.76     1.06     0.72    0.472  2.13
  366 117        0.45     1.06     0.43    0.668  2.13
DS*Dimp
  183 160        0.14     1.06     0.13    0.899  2.13
  183 200       -0.15     1.06    -0.14    0.885  2.13
  244 160       -0.21     1.06    -0.20    0.841  2.13
  244 200        0.59     1.06     0.56    0.579  2.13
  305 160        0.04     1.06     0.04    0.969  2.13
  305 200       -0.12     1.06    -0.11    0.913  2.13
  366 160        0.00     1.06     0.00    0.998  2.13
  366 200       -0.15     1.06    -0.14    0.889  2.13
DD*Dimp
  102 160       0.572    0.750     0.76    0.446  1.78
  102 200      -0.372    0.750    -0.50    0.620  1.78
  117 160       0.209    0.750     0.28    0.781  1.78
  117 200       0.150    0.750     0.20    0.842  1.78
DS*DD*Dimp
  183 102 160   -0.19     1.50    -0.13    0.898  2.84
  183 102 200    0.16     1.50     0.11    0.913  2.84
  183 117 160    0.20     1.50     0.13    0.895  2.84
  183 117 200   -0.34     1.50    -0.23    0.818  2.84
  244 102 160    0.19     1.50     0.13    0.898  2.84
  244 102 200   -0.57     1.50    -0.38    0.704  2.84
  244 117 160   -0.69     1.50    -0.46    0.644  2.84
  244 117 200    1.28     1.50     0.85    0.394  2.84
  305 102 160   -0.09     1.50    -0.06    0.952  2.84
  305 102 200    0.13     1.50     0.09    0.932  2.84
  305 117 160    0.31     1.50     0.21    0.836  2.84
  305 117 200   -0.39     1.50    -0.26    0.796  2.84
  366 102 160    0.10     1.50     0.06    0.949  2.84
  366 102 200    0.10     1.50     0.07    0.947  2.84
  366 117 160    0.18     1.50     0.12    0.905  2.84
  366 117 200   -0.34     1.50    -0.22    0.823  2.84


Regression Equation

Annual NO3 = 41.929 + 6.734 DS_183 + 2.770 DS_244 - 0.635 DS_305 - 2.566 DS_366
             - 6.304 DS_488 - 4.406 DD_102 - 2.057 DD_117 + 6.463 DD_147
- 0.532 Dimp_160
             + 0.344 Dimp_200 + 0.188 Dimp_240 - 2.07 DS*DD_183 102
- 1.79 DS*DD_183 117
             + 3.86 DS*DD_183 147 - 0.75 DS*DD_244 102 + 0.27 DS*DD_244 117
+ 0.48 DS*DD_244
             147 + 0.41 DS*DD_305 102 + 0.06 DS*DD_305 117 - 0.47 DS*DD_305 147
```

```
             + 0.76 DS*DD_366 102 + 0.45 DS*DD_366 117 - 1.22 DS*DD_366 147
+ 1.65 DS*DD_488
             102 + 1.01 DS*DD_488 117 - 2.66 DS*DD_488 147 + 0.14 DS*Dimp_183
160
             - 0.15 DS*Dimp_183 200 + 0.02 DS*Dimp_183 240 - 0.21 DS*Dimp_244
160
             + 0.59 DS*Dimp_244 200 - 0.38 DS*Dimp_244 240 + 0.04 DS*Dimp_305
160
             - 0.12 DS*Dimp_305 200 + 0.07 DS*Dimp_305 240 + 0.00 DS*Dimp_366
160
             - 0.15 DS*Dimp_366 200 + 0.15 DS*Dimp_366 240 + 0.03 DS*Dimp_488
160
             - 0.17 DS*Dimp_488 200 + 0.14 DS*Dimp_488 240 + 0.572 DD*Dimp_102
160
             - 0.372 DD*Dimp_102 200 - 0.200 DD*Dimp_102 240
+ 0.209 DD*Dimp_117 160
             + 0.150 DD*Dimp_117 200 - 0.358 DD*Dimp_117 240
- 0.780 DD*Dimp_147 160
             + 0.222 DD*Dimp_147 200 + 0.558 DD*Dimp_147 240
- 0.19 DS*DD*Dimp_183 102 160
             + 0.16 DS*DD*Dimp_183 102 200 + 0.03 DS*DD*Dimp_183 102 240
             + 0.20 DS*DD*Dimp_183 117 160 - 0.34 DS*DD*Dimp_183 117 200
             + 0.15 DS*DD*Dimp_183 117 240 - 0.00 DS*DD*Dimp_183 147 160
             + 0.18 DS*DD*Dimp_183 147 200 - 0.18 DS*DD*Dimp_183 147 240
             + 0.19 DS*DD*Dimp_244 102 160 - 0.57 DS*DD*Dimp_244 102 200
             + 0.38 DS*DD*Dimp_244 102 240 - 0.69 DS*DD*Dimp_244 117 160
             + 1.28 DS*DD*Dimp_244 117 200 - 0.58 DS*DD*Dimp_244 117 240
             + 0.50 DS*DD*Dimp_244 147 160 - 0.71 DS*DD*Dimp_244 147 200
             + 0.21 DS*DD*Dimp_244 147 240 - 0.09 DS*DD*Dimp_305 102 160
             + 0.13 DS*DD*Dimp_305 102 200 - 0.04 DS*DD*Dimp_305 102 240
             + 0.31 DS*DD*Dimp_305 117 160 - 0.39 DS*DD*Dimp_305 117 200
             + 0.08 DS*DD*Dimp_305 117 240 - 0.22 DS*DD*Dimp_305 147 160
             + 0.26 DS*DD*Dimp_305 147 200 - 0.04 DS*DD*Dimp_305 147 240
             + 0.10 DS*DD*Dimp_366 102 160 + 0.10 DS*DD*Dimp_366 102 200
             - 0.20 DS*DD*Dimp_366 102 240 + 0.18 DS*DD*Dimp_366 117 160
             - 0.34 DS*DD*Dimp_366 117 200 + 0.16 DS*DD*Dimp_366 117 240
             - 0.27 DS*DD*Dimp_366 147 160 + 0.24 DS*DD*Dimp_366 147 200
             + 0.04 DS*DD*Dimp_366 147 240 - 0.00 DS*DD*Dimp_488 102 160
             + 0.18 DS*DD*Dimp_488 102 200 - 0.17 DS*DD*Dimp_488 102 240
             + 0.01 DS*DD*Dimp_488 117 160 - 0.21 DS*DD*Dimp_488 117 200
             + 0.20 DS*DD*Dimp_488 117 240 - 0.00 DS*DD*Dimp_488 147 160
             + 0.03 DS*DD*Dimp_488 147 200 - 0.03 DS*DD*Dimp_488 147 240
```

Comparisons for Annual NO3

Tukey Pairwise Comparisons: Response = Annual NO3, Term = DS

```
Grouping Information Using the Tukey Method and 95% Confidence

DS     N     Mean   Grouping
183  279  48.6634  A
244  279  44.6994     B
305  279  41.2943        C
366  279  39.3632        C
488  279  35.6254           D

Means that do not share a letter are significantly different.
```

Tukey Simultaneous 95% CIs

Tukey Pairwise Comparisons: Response = Annual NO3, Term = DD

```
Grouping Information Using the Tukey Method and 95% Confidence

DD     N     Mean  Grouping
147  465  48.3926  A
117  465  39.8720     B
102  465  37.5229        C

Means that do not share a letter are significantly different.
```

Tukey Simultaneous 95% CIs

Tukey Pairwise Comparisons: Response = Annual NO3, Term = Dimp

```
Grouping Information Using the Tukey Method and 95% Confidence

Dimp    N     Mean  Grouping
200   465  42.2733  A
240   465  42.1173  A
160   465  41.3969  A

Means that do not share a letter are significantly different.
```

Tukey Simultaneous 95% CIs

Tukey Pairwise Comparisons: Response = Annual NO3, Term = DS*DD

```
Grouping Information Using the Tukey Method and 95% Confidence

DS*DD     N     Mean         Grouping
183 147  93  58.9878  A
244 147  93  51.6437     B
305 147  93  47.2905     B  C
183 117  93  44.8151     B  C  D
366 147  93  44.6085        C  D  E
244 117  93  42.9154        C  D  E  F
183 102  93  42.1873        C  D  E  F  G
244 102  93  39.5392           D  E  F  G  H
488 147  93  39.4324           D  E  F  G  H
305 117  93  39.2923           D  E  F  G  H
366 117  93  37.7604              E  F  G  H
305 102  93  37.3001                 F  G  H
366 102  93  35.7205                    G  H
488 117  93  34.5769                       H
488 102  93  32.8671                       H

Means that do not share a letter are significantly different.

* NOTE * Cannot draw the interval plot for the Tukey procedure. Interval plots
for
         comparisons are illegible with more than 45 intervals.
```

Tukey Pairwise Comparisons: Response = Annual NO3, Term = DS*Dimp

```
Grouping Information Using the Tukey Method and 95% Confidence

DS*Dimp   N     Mean   Grouping
183 240  93  48.8695  A
183 200  93  48.8543  A
183 160  93  48.2665  A  B
244 200  93  45.6325  A  B  C
244 240  93  44.5116  A  B  C
244 160  93  43.9542  A  B  C
305 240  93  41.5572     B  C  D
305 200  93  41.5230     B  C  D
305 160  93  40.8027        C  D
366 240  93  39.6973        C  D
366 200  93  39.5588        C  D
366 160  93  38.8333        C  D
488 240  93  35.9508           D
488 200  93  35.7978           D
```

```
488 160  93  35.1277           D

Means that do not share a letter are significantly different.

* NOTE * Cannot draw the interval plot for the Tukey procedure. Interval plots
for
         comparisons are illegible with more than 45 intervals.
```

Tukey Pairwise Comparisons: Response = Annual NO3, Term = DD*Dimp

```
Grouping Information Using the Tukey Method and 95% Confidence

DD*Dimp    N     Mean  Grouping
147 240  155  49.1386  A
147 200  155  48.9591  A
147 160  155  47.0801  A
117 200  155  40.3657         B
117 240  155  39.7019         B
117 160  155  39.5483         B
102 160  155  37.5623         B
102 240  155  37.5113         B
102 200  155  37.4950         B

Means that do not share a letter are significantly different.
```

Tukey Simultaneous 95% CIs

Tukey Pairwise Comparisons: Response = Annual NO3, Term = DS*DD*Dimp

```
Grouping Information Using the Tukey Method and 95% Confidence

DS*DD*Dimp    N     Mean          Grouping
183 147 200  31  59.5829  A
183 147 240  31  59.5745  A  B
183 147 160  31  57.8061  A  B  C
244 147 240  31  52.2200  A  B  C  D
244 147 200  31  52.0906  A  B  C  D  E
244 147 160  31  50.6203  A  B  C  D  E  F
305 147 240  31  48.0713  A  B  C  D  E  F  G
305 147 200  31  48.0010  A  B  C  D  E  F  G
305 147 160  31  45.7994  A  B  C  D  E  F  G  H
366 147 240  31  45.5394     B  C  D  E  F  G  H
244 117 200  31  45.2765        C  D  E  F  G  H
366 147 200  31  45.2619        C  D  E  F  G  H
183 117 160  31  44.8239        C  D  E  F  G  H
183 117 200  31  44.8106        C  D  E  F  G  H
183 117 240  31  44.8106        C  D  E  F  G  H
```

```
366 147 160  31  43.0242           D  E  F  G  H
183 102 240  31  42.2232           D  E  F  G  H
183 102 200  31  42.1694           D  E  F  G  H
183 102 160  31  42.1694           D  E  F  G  H
244 117 240  31  41.7845           D  E  F  G  H
244 117 160  31  41.6852           D  E  F  G  H
488 147 240  31  40.2877           D  E  F  G  H
488 147 200  31  39.8590           D  E  F  G  H
244 102 160  31  39.5571           D  E  F  G  H
244 102 200  31  39.5303           D  E  F  G  H
244 102 240  31  39.5303           D  E  F  G  H
305 117 160  31  39.3197           D  E  F  G  H
305 117 200  31  39.2829           D  E  F  G  H
305 117 240  31  39.2742           D  E  F  G  H
488 147 160  31  38.1503              E  F  G  H
366 117 240  31  37.8942                 F  G  H
366 117 200  31  37.7697                 F  G  H
366 117 160  31  37.6174                 F  G  H
305 102 240  31  37.3261                 F  G  H
305 102 160  31  37.2890                 F  G  H
305 102 200  31  37.2852                 F  G  H
366 102 160  31  35.8584                    G  H
366 102 240  31  35.6584                    G  H
366 102 200  31  35.6448                    G  H
488 117 240  31  34.7461                    G  H
488 117 200  31  34.6890                    G  H
488 117 160  31  34.2955                    G  H
488 102 160  31  32.9374                       H
488 102 200  31  32.8455                       H
488 102 240  31  32.8184                       H

Means that do not share a letter are significantly different.

* NOTE * Cannot draw the interval plot for the Tukey procedure. Interval plots
for
         comparisons are illegible with more than 45 intervals.
```

Paired T-Test and CI: Load 1, Load 2 for 2/3 load

```
Paired T for Load 1 - Load 2

              N    Mean   StDev  SE Mean
Load 1      837  44.886  16.026    0.554
Load 2      837  42.560  15.039    0.520
Difference  837   2.326   3.314    0.115


95% CI for mean difference: (2.101, 2.551)
T-Test of mean difference = 0 (vs ≠ 0): T-Value = 20.30  P-Value = 0.000
```

Paired T-Test and CI: Load 1, Load 2 for ½ load

```
Paired T for Load 1 - Load 2

             N    Mean   StDev  SE Mean
Load 1      558  46.681  16.568    0.701
Load 2      558  43.871  15.478    0.655
Difference  558   2.811   3.893    0.165


95% CI for mean difference: (2.487, 3.134)
T-Test of mean difference = 0 (vs ≠ 0): T-Value = 17.05  P-Value = 0.000
```

Paired T-Test and CI: Load 1, Load 3 for ½ load

```
Paired T for Load 1 - Load 3

             N    Mean   StDev  SE Mean
Load 1      558  46.681  16.568    0.701
Load 3      558  42.366  14.919    0.632
Difference  558   4.315   4.262    0.180


95% CI for mean difference: (3.961, 4.670)
T-Test of mean difference = 0 (vs ≠ 0): T-Value = 23.92  P-Value = 0.000
```

Paired T-Test and CI: Load 2, Load 3 for ½ load

```
Paired T for Load 2 - Load 3

             N    Mean   StDev  SE Mean
Load 2      558  43.871  15.478    0.655
Load 3      558  42.366  14.919    0.632
Difference  558  1.5047  1.2085   0.0512


95% CI for mean difference: (1.4042, 1.6052)
T-Test of mean difference = 0 (vs ≠ 0): T-Value = 29.41  P-Value = 0.000
```

APPENDIX C: Results of Testing if the Data for Each Treatment were Normally Distributed

* NO_3-N and NH_4-N concentrations are in Kg/ha

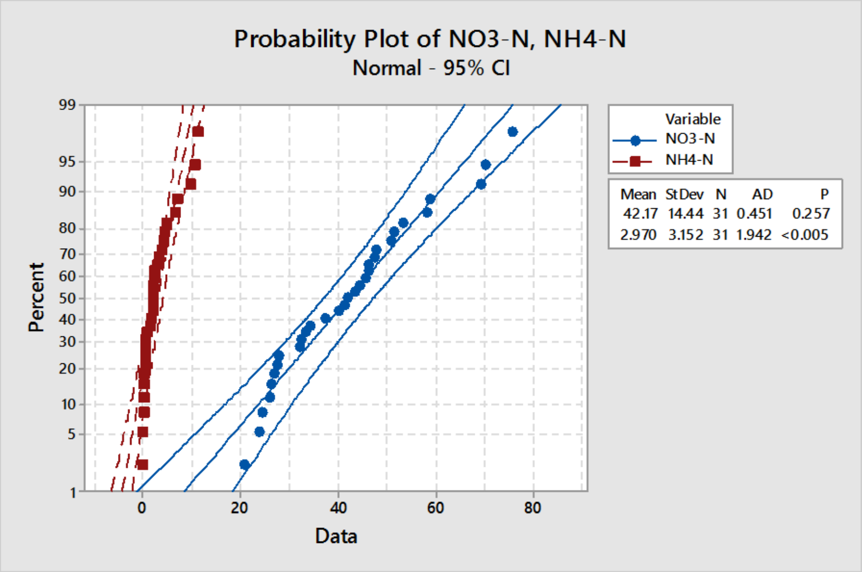


Figure 7 - Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss for DS= 183cm,

DD= 102 cm, Dimp= 160 cm

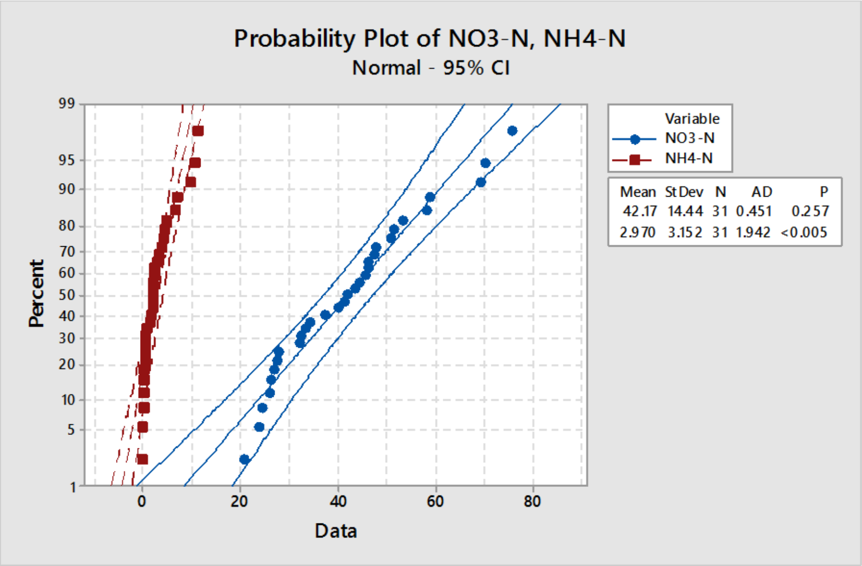


Figure 8- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss for DS= 183cm, DD= 102 cm, Dimp= 200cm

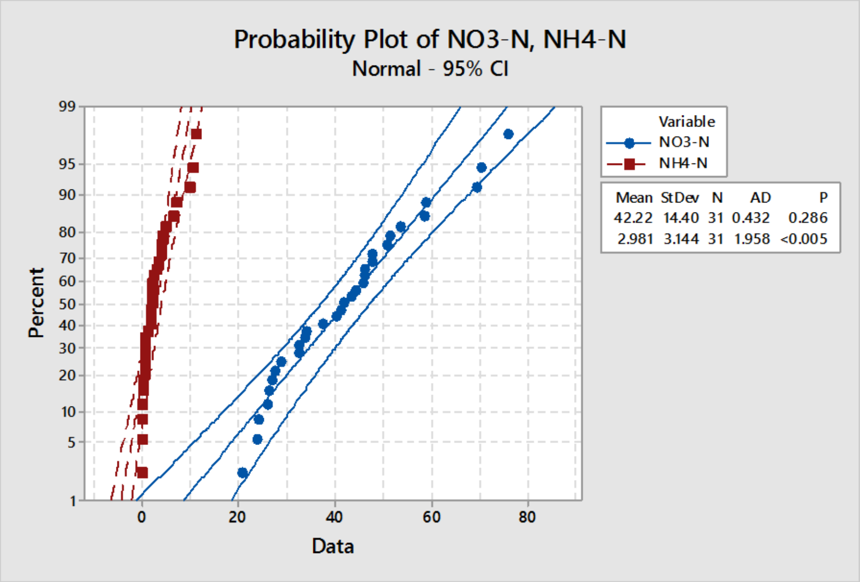


Figure 9- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss t for DS= 183cm, DD= 102 cm, Dimp= 240cm

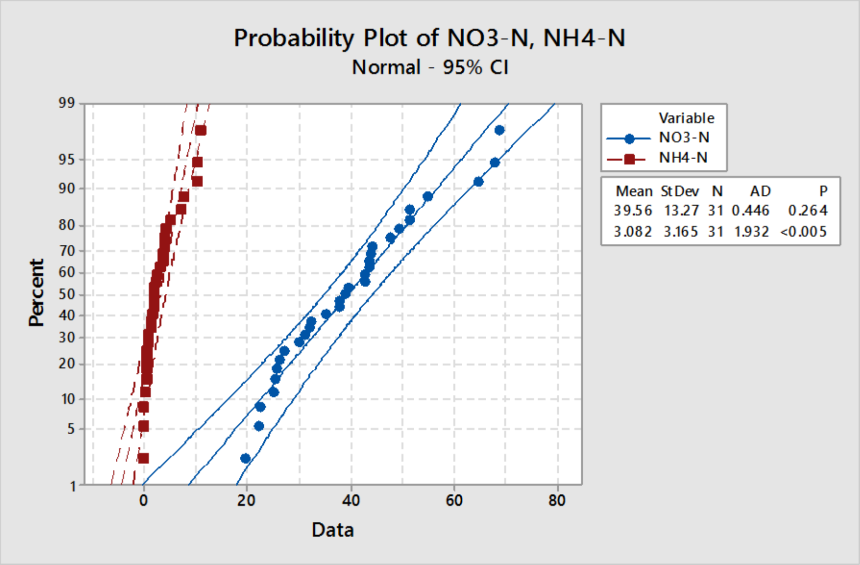


Figure 10- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss for DS= 244cm, DD= 102 cm, Dimp= 160 cm

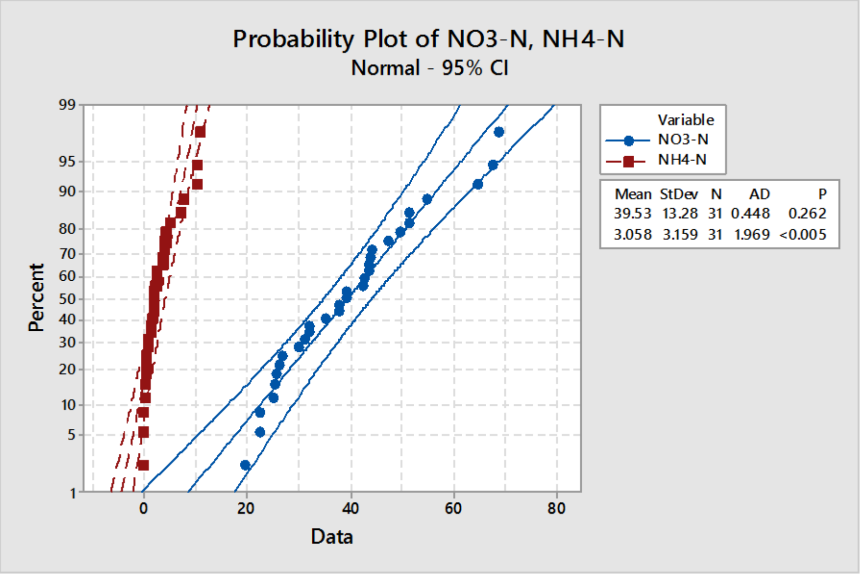


Figure 11- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss for DS= 244cm, DD= 102 cm, Dimp= 200 cm

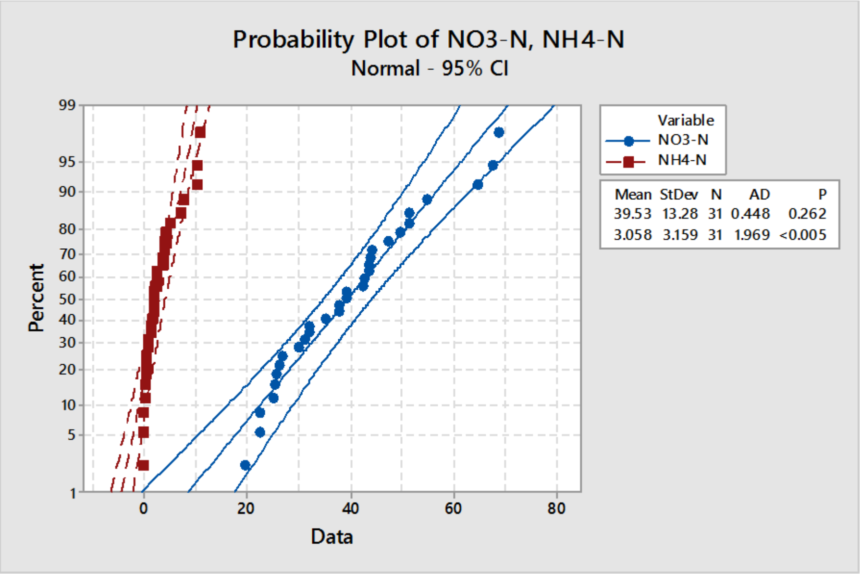


Figure 12- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss for DS= 244cm, DD= 102 cm, Dimp= 240 cm

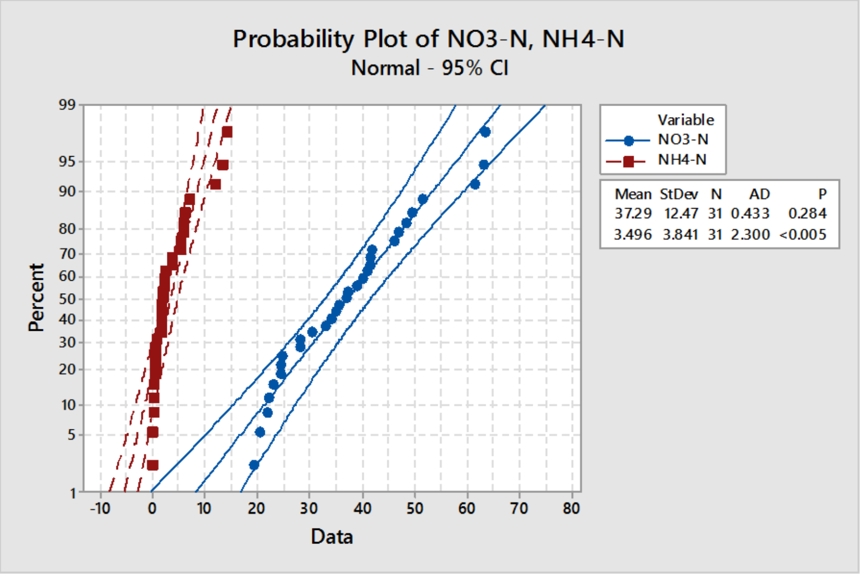


Figure 13- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss for DS= 305 cm, DD= 102 cm, Dimp= 160 cm

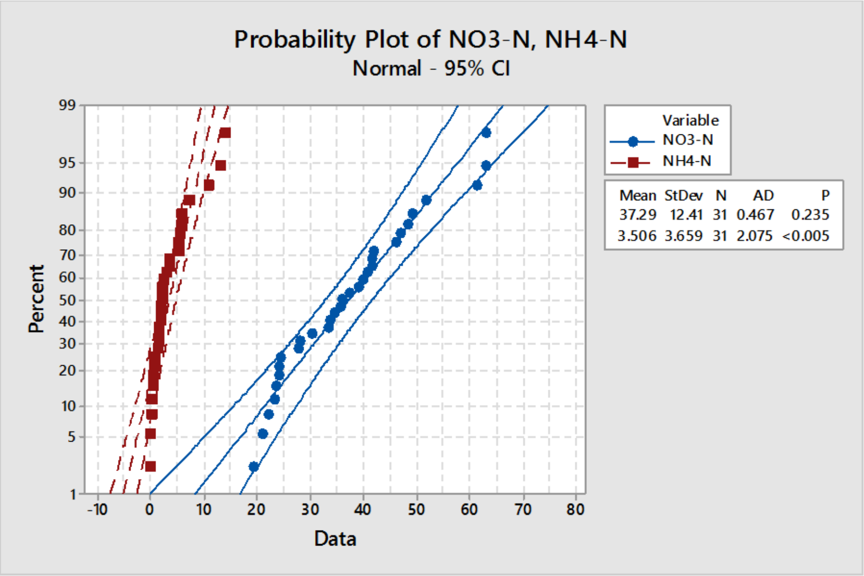


Figure 14- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss for DS= 305 cm, DD= 102 cm, Dimp= 200cm

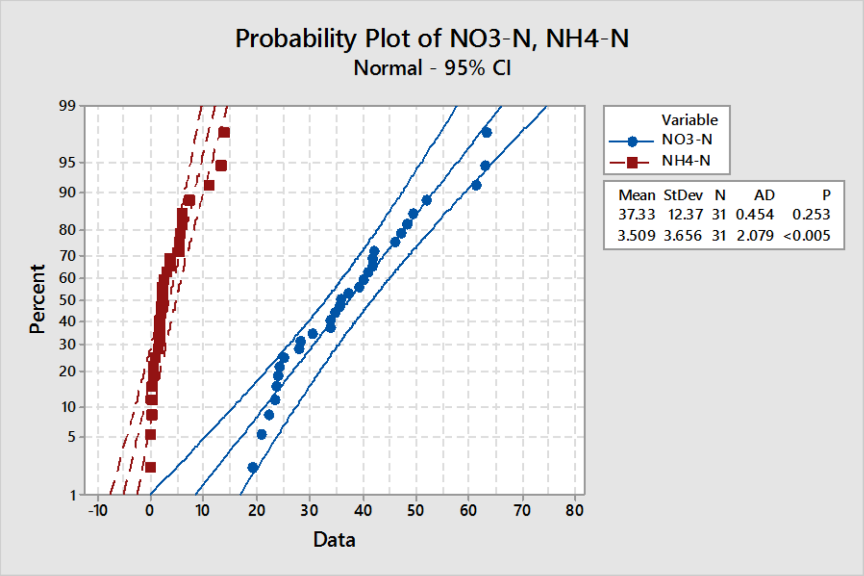


Figure 15- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 305 cm, DD= 102 cm, Dimp= 240cm

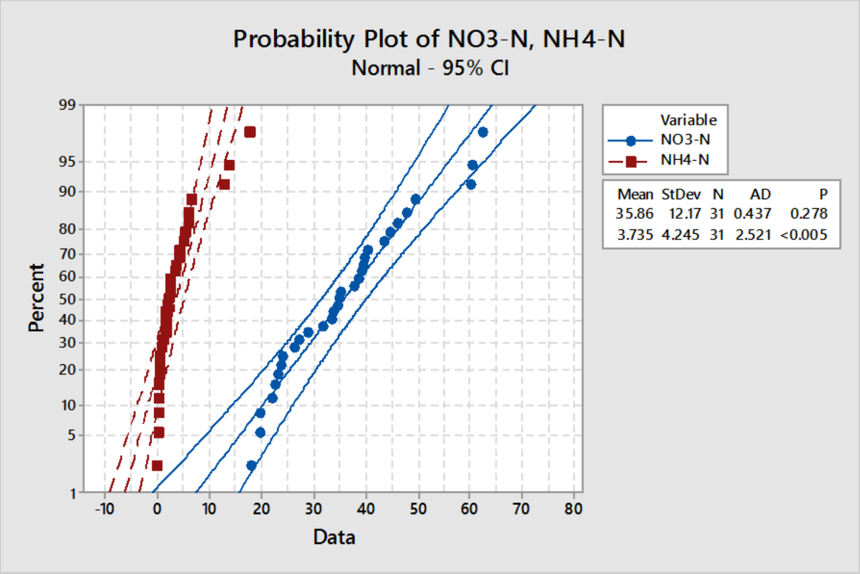


Figure 16- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 366 cm, DD= 102 cm, Dimp= 160cm

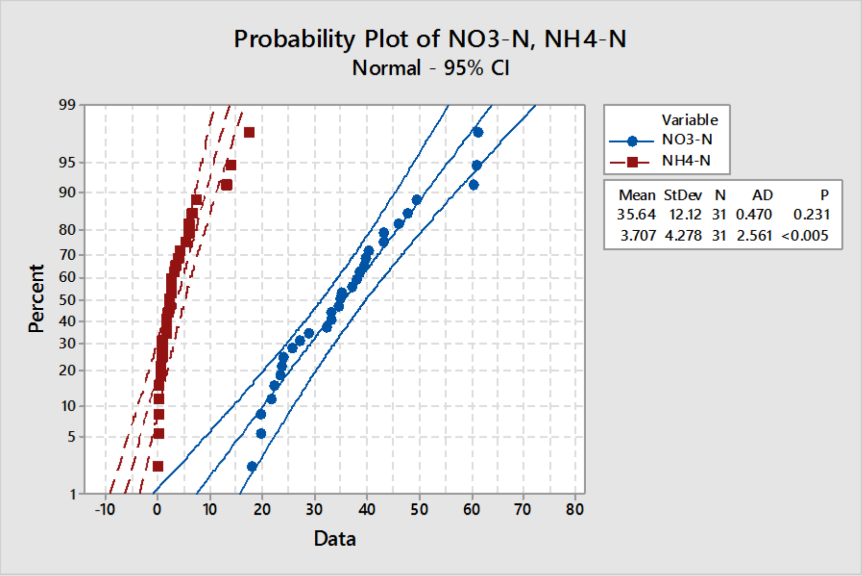


Figure 17- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 366 cm, DD= 102 cm, Dimp= 200 cm

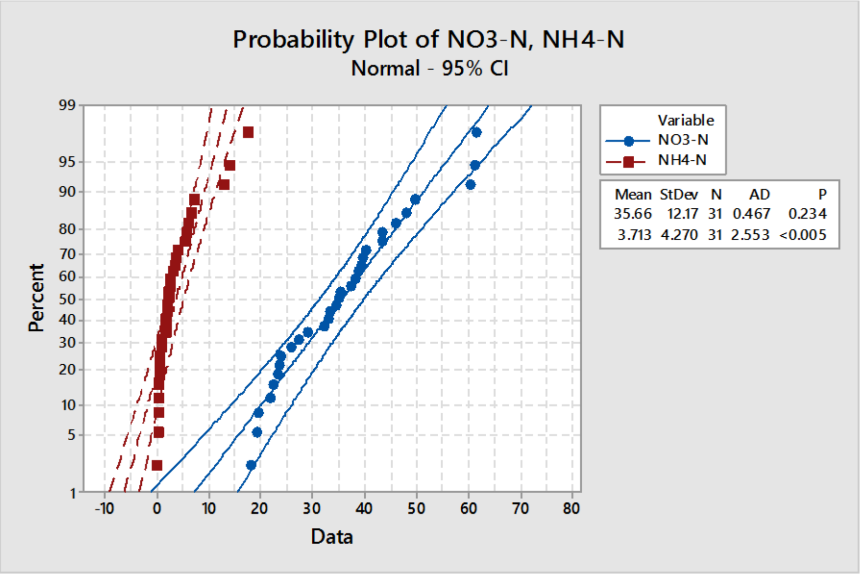


Figure 18- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 366 cm, DD= 102 cm, Dimp= 240 cm

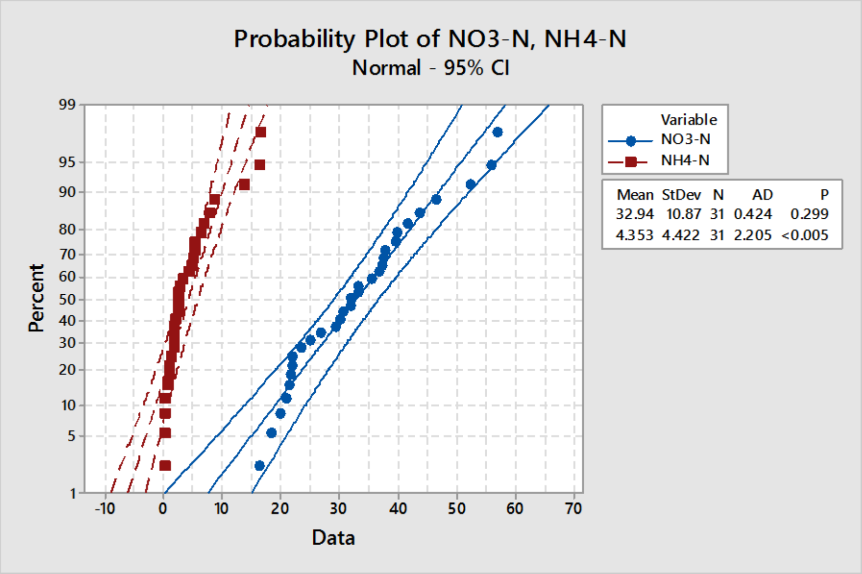


Figure 19- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 488 cm, DD= 102 cm, Dimp= 160 cm

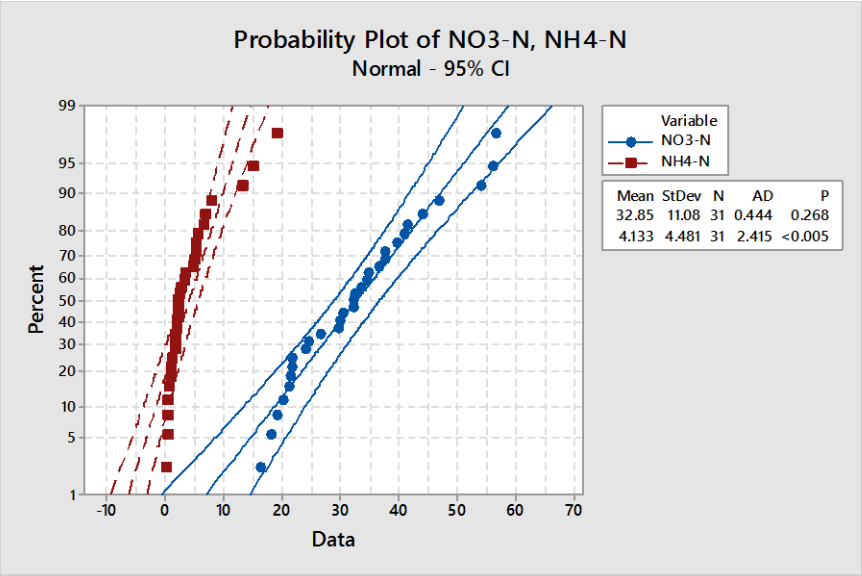


Figure 20- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 488 cm, DD= 102 cm, Dimp= 200 cm

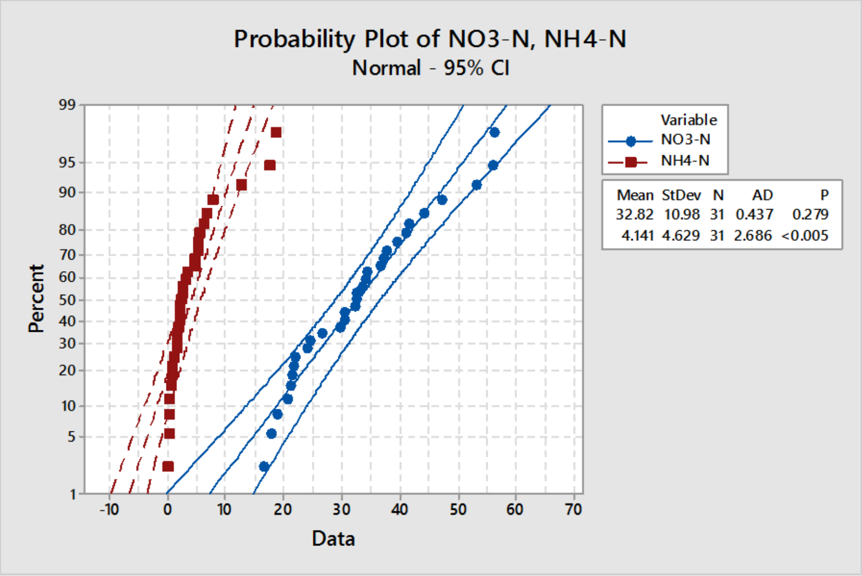


Figure 21- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 488 cm, DD= 102 cm, Dimp= 240 cm

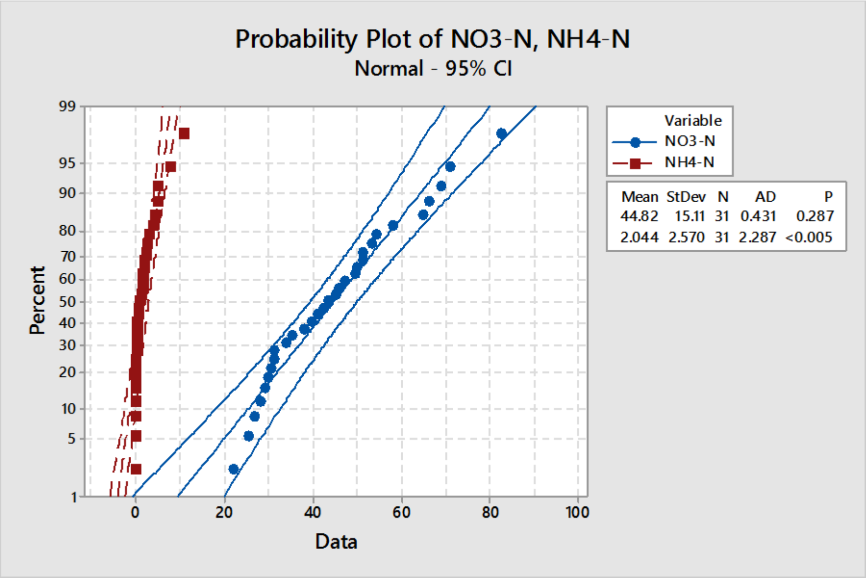


Figure 22- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 183 cm, DD= 117 cm, Dimp= 160 cm

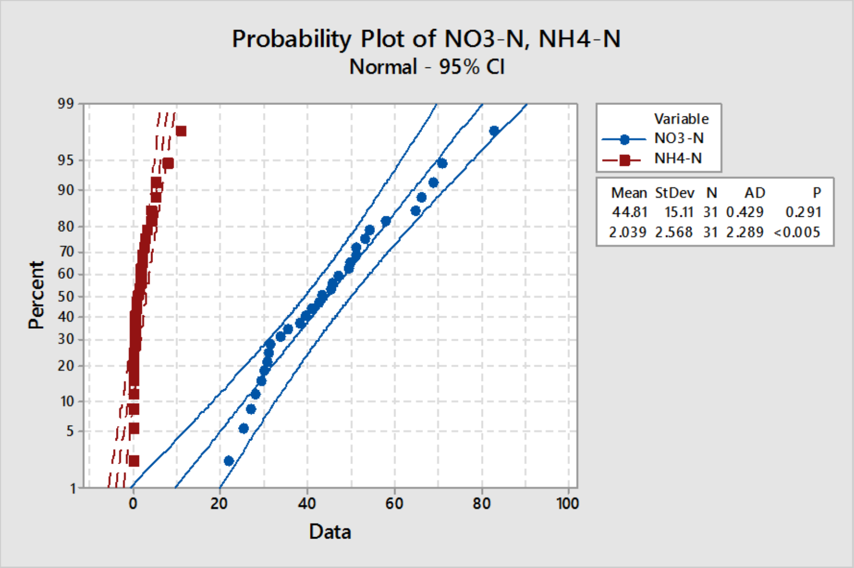


Figure 23- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 183 cm, DD= 117 cm, Dimp= 200 cm

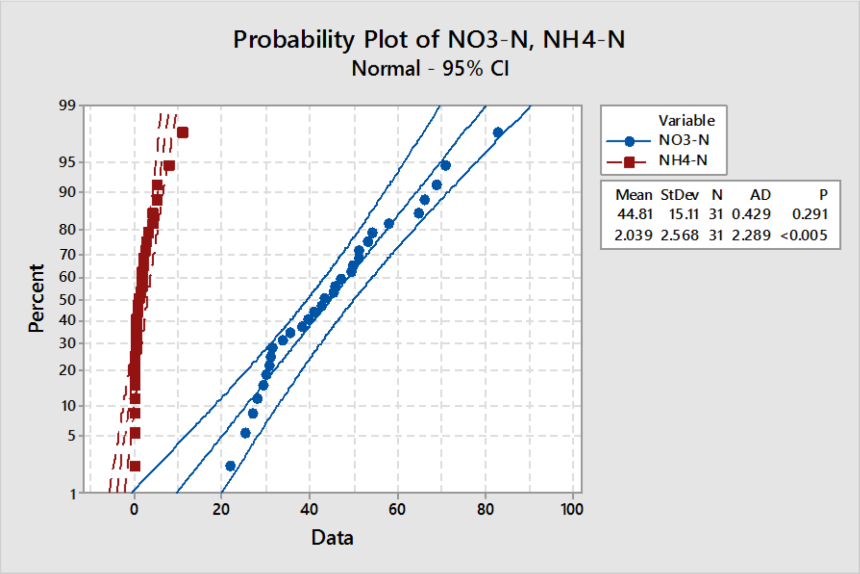


Figure 24- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 183 cm, DD= 117 cm, Dimp= 240 cm

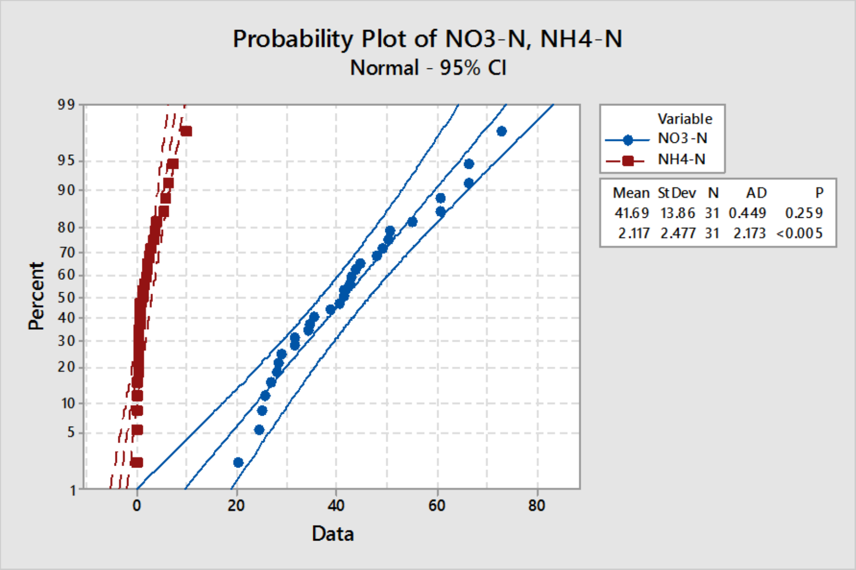


Figure 25- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 244 cm, DD= 117 cm, Dimp= 160 cm

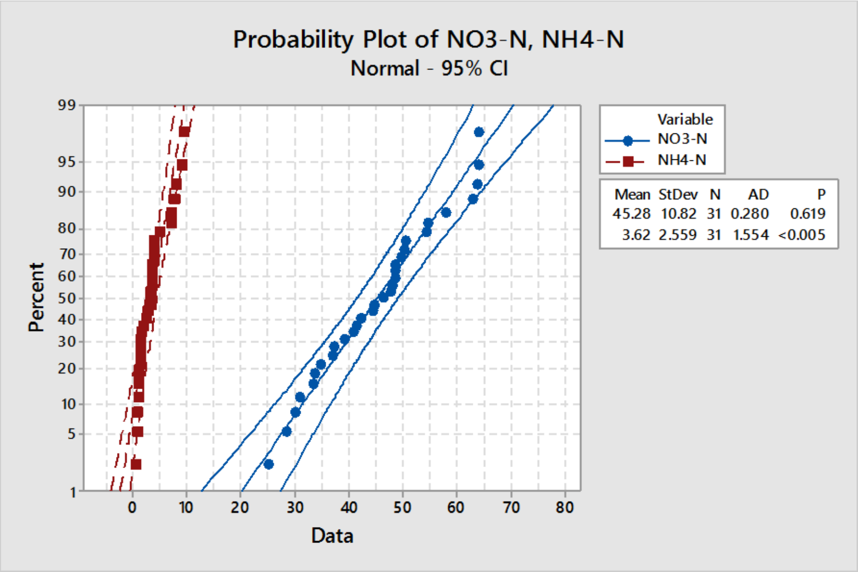


Figure 26- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 244 cm, DD= 117 cm, Dimp= 200 cm

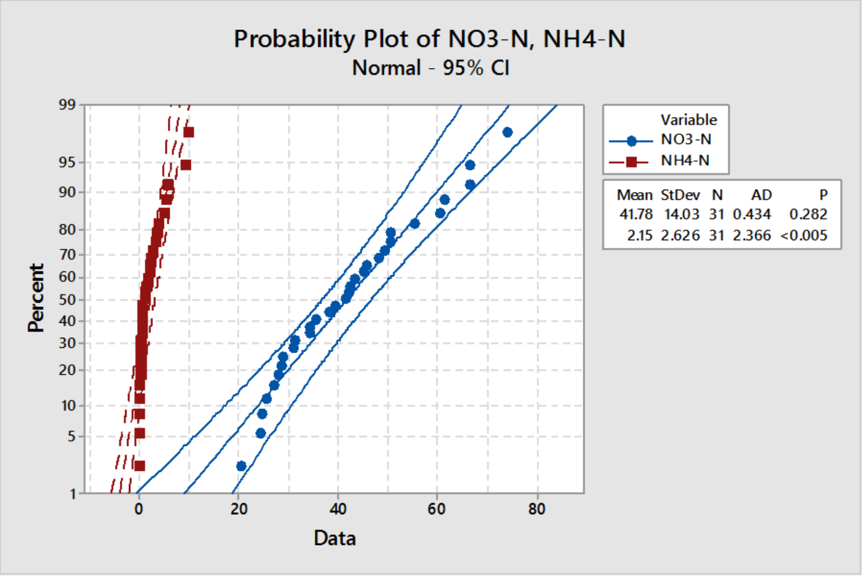


Figure 27- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 244 cm, DD= 117 cm, Dimp= 240 cm

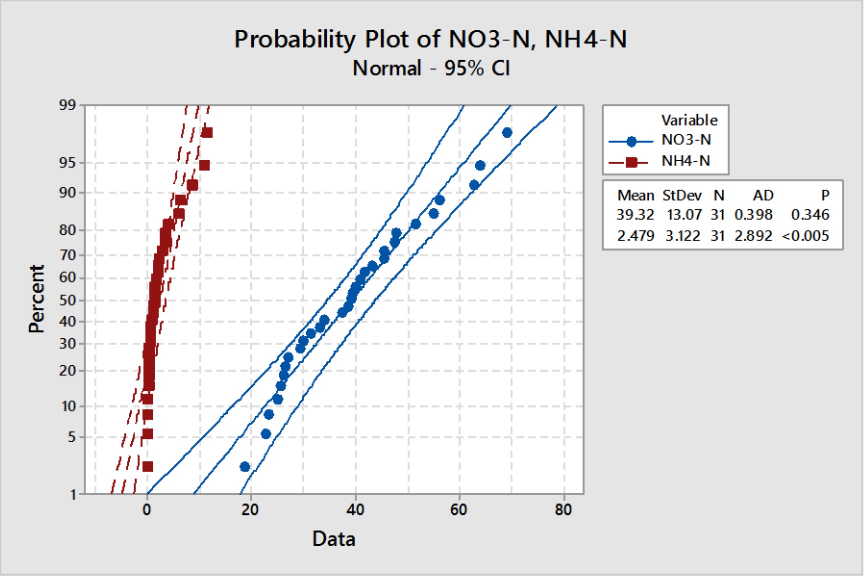


Figure 28- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 305 cm, DD= 117 cm, Dimp= 160 cm

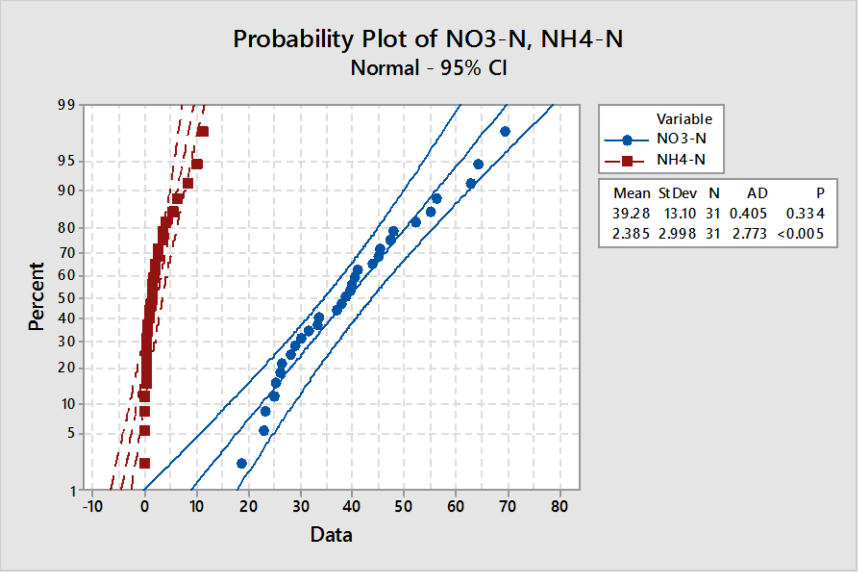


Figure 29- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 305 cm, DD= 117 cm, Dimp= 200 cm

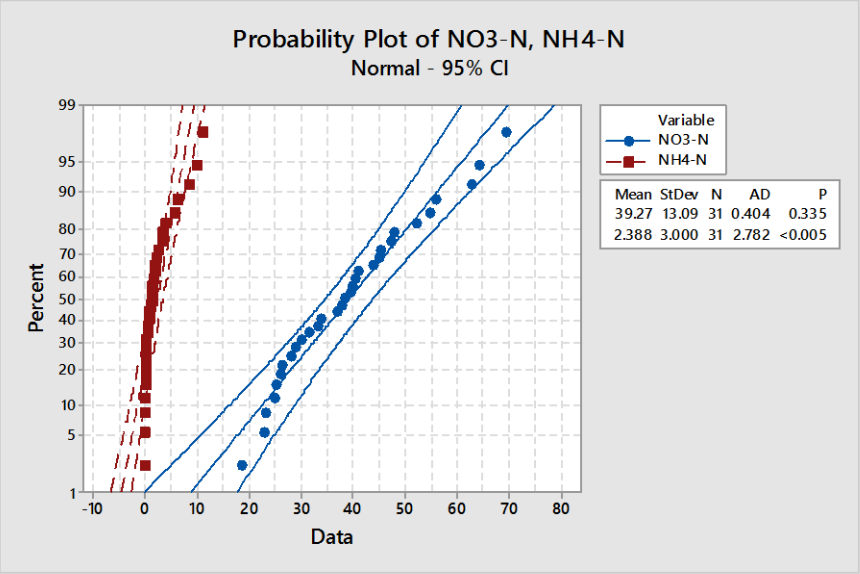


Figure 30- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 305 cm, DD= 117 cm, Dimp= 240 cm

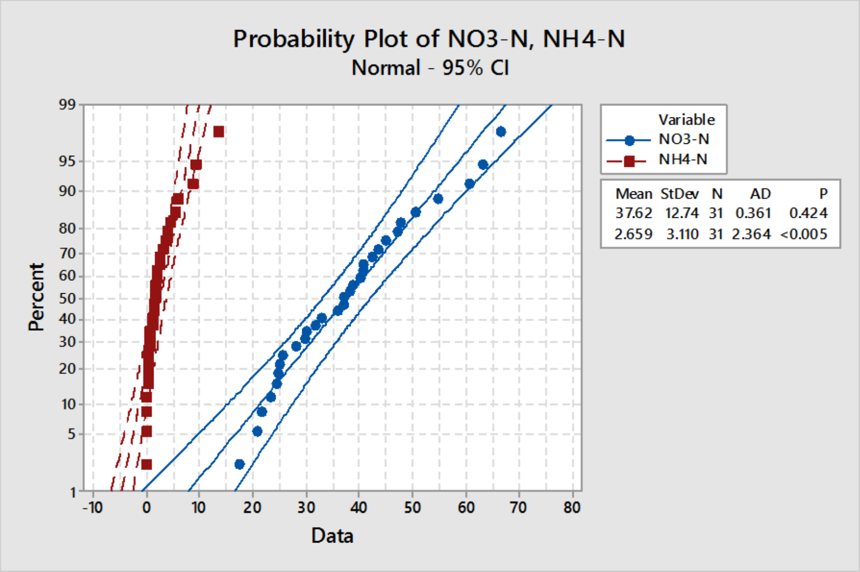


Figure 31- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 366 cm, DD= 117 cm, Dimp= 160 cm

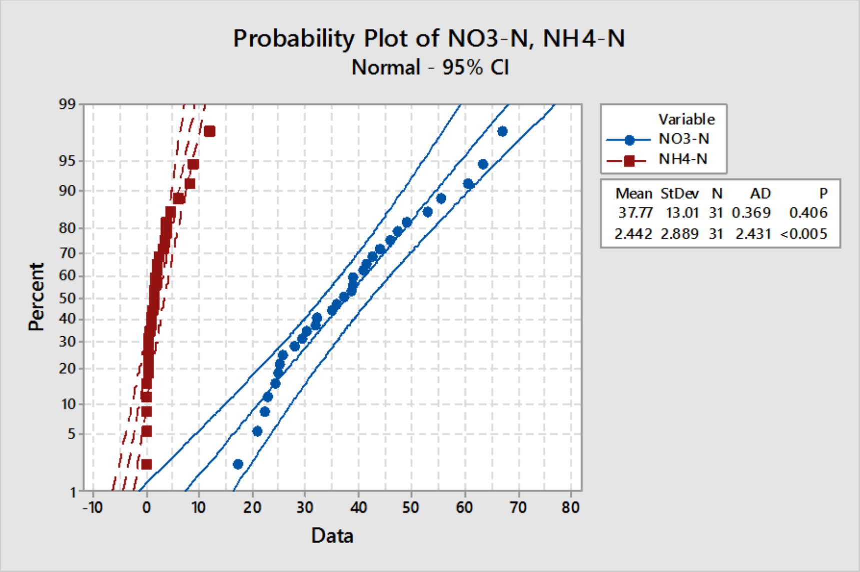


Figure 32- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 366 cm, DD= 117 cm, Dimp= 200 cm

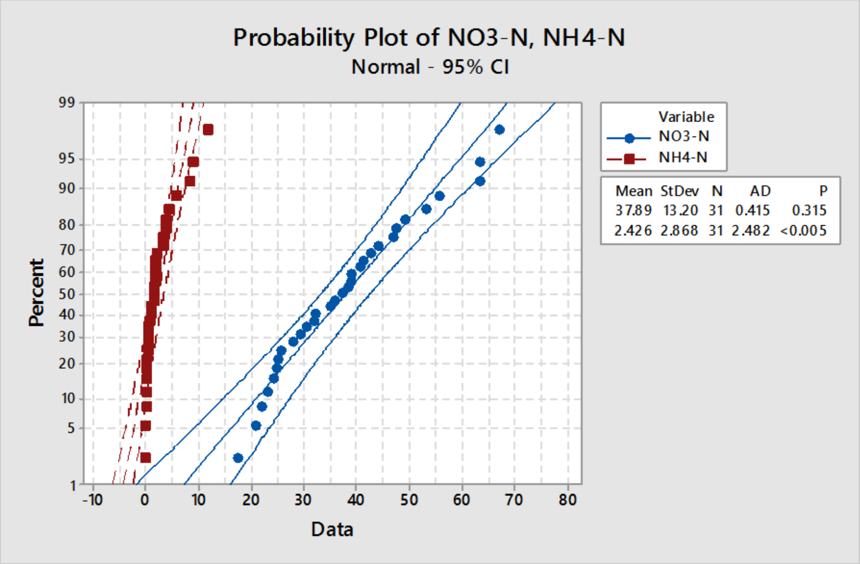


Figure 33- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 366 cm, DD= 117 cm, Dimp= 240 cm

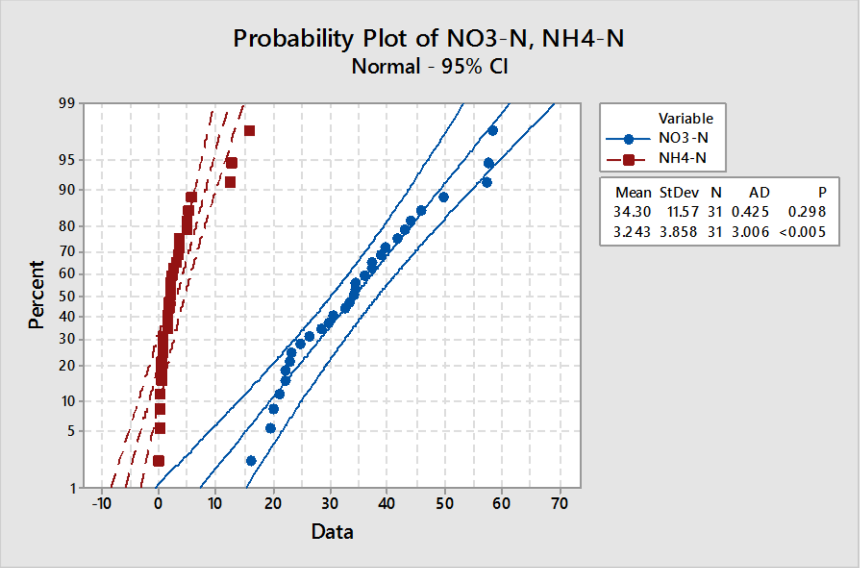
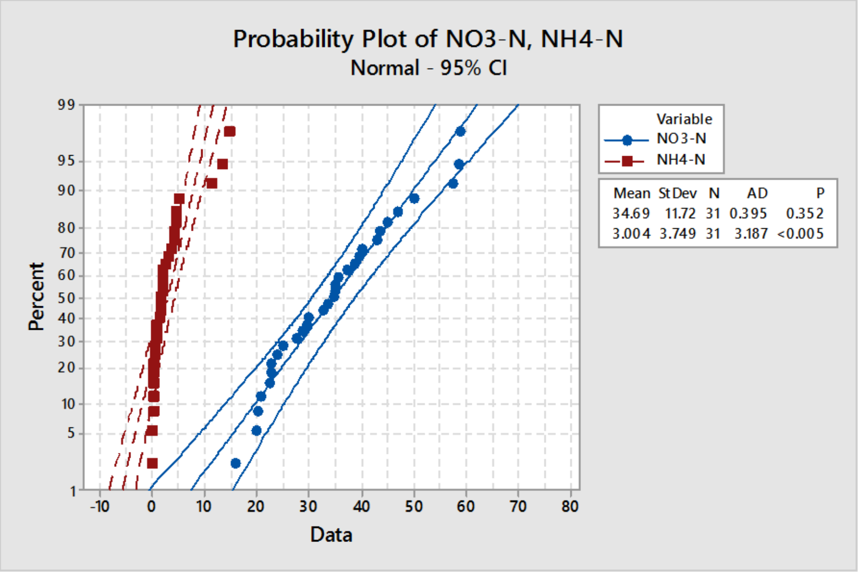
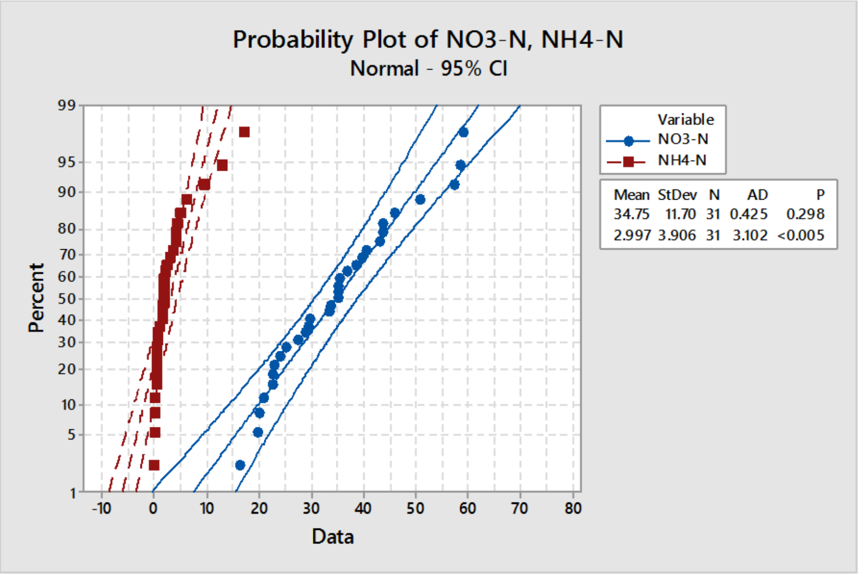


Figure 34- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 488 cm, DD= 117 cm, Dimp= 160 cm



Mean	StDev	N	AD	P
34.69	11.72	31	0.395	0.352
3.004	3.749	31	3.187	<0.005

Figure 35- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 488 cm, DD= 117 cm, Dimp= 200 cm



Mean	StDev	N	AD	P
34.75	11.70	31	0.425	0.298
2.997	3.906	31	3.102	<0.005

Figure 36- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 488 cm, DD= 117 cm, Dimp= 240 cm

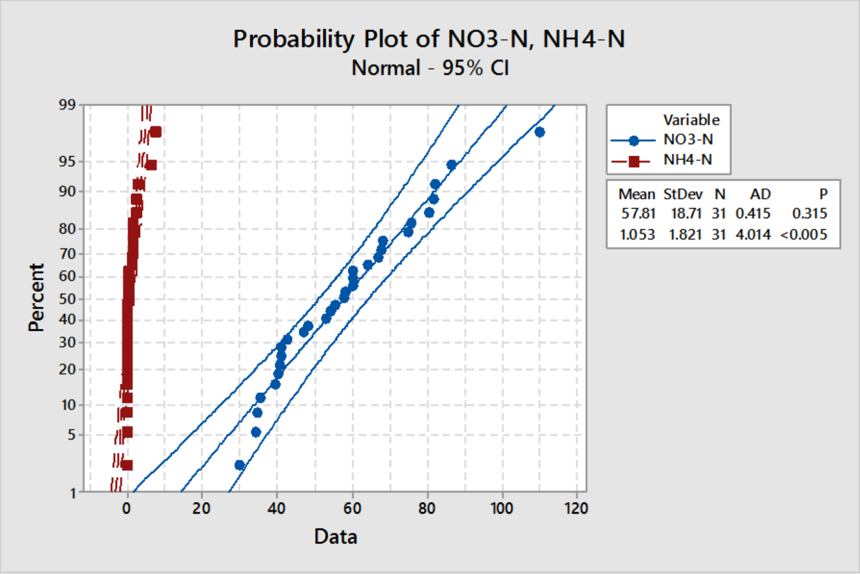


Figure 37- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 183 cm, DD= 147 cm, Dimp= 160 cm

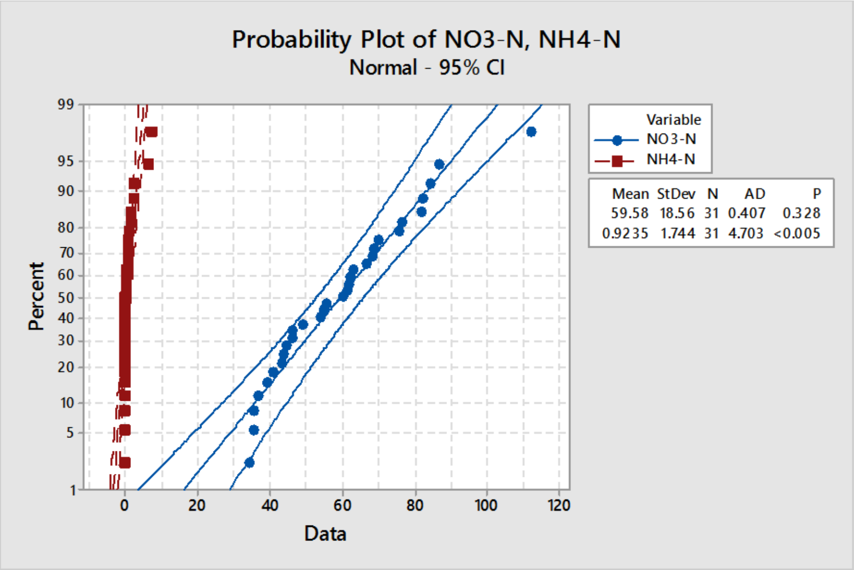


Figure 38- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 183 cm, DD= 147 cm, Dimp= 200 cm

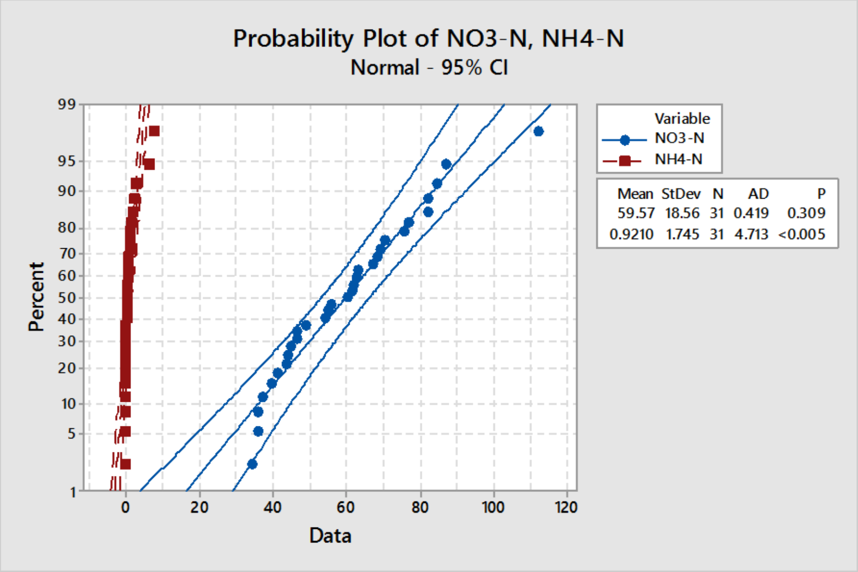


Figure 39- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 183 cm, DD= 147 cm, Dimp= 240 cm

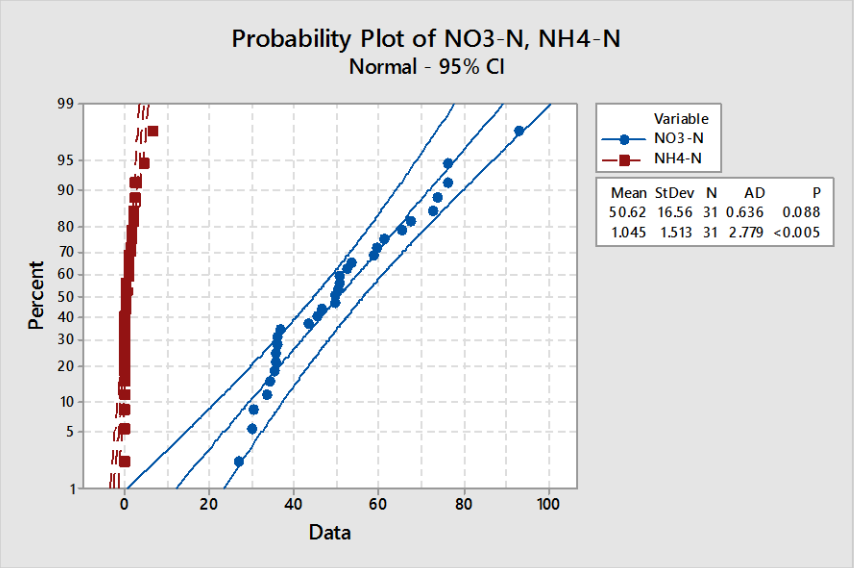


Figure 40- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 244 cm, DD= 147 cm, Dimp= 160 cm

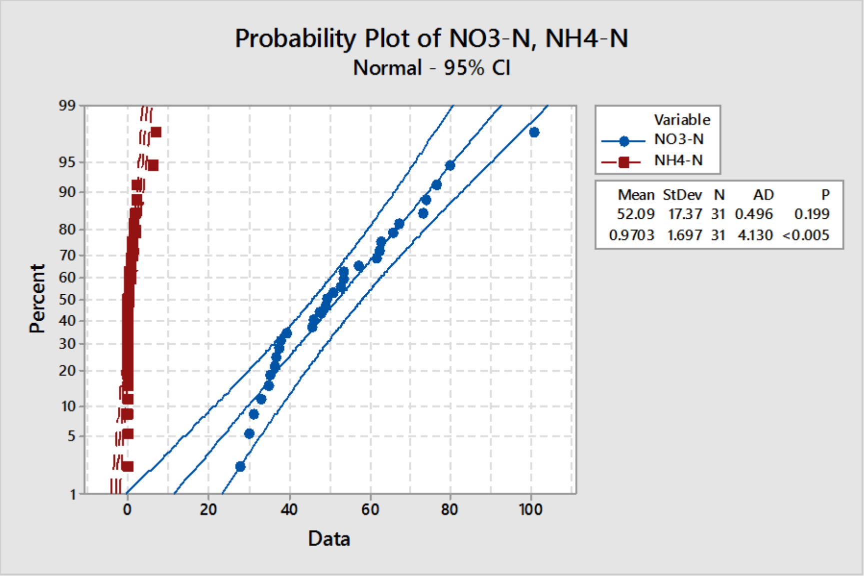


Figure 41- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 244 cm, DD= 147 cm, Dimp= 200 cm

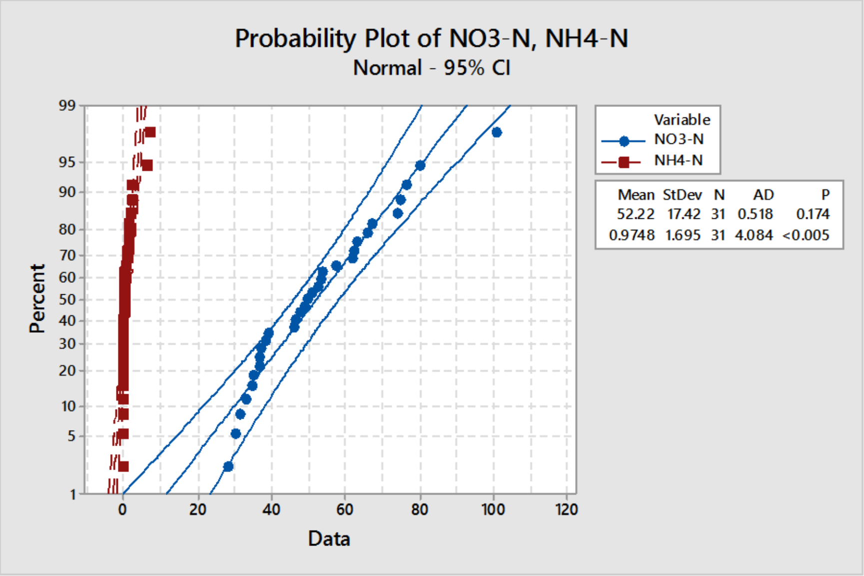


Figure 42- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 244 cm, DD= 147 cm, Dimp= 240 cm

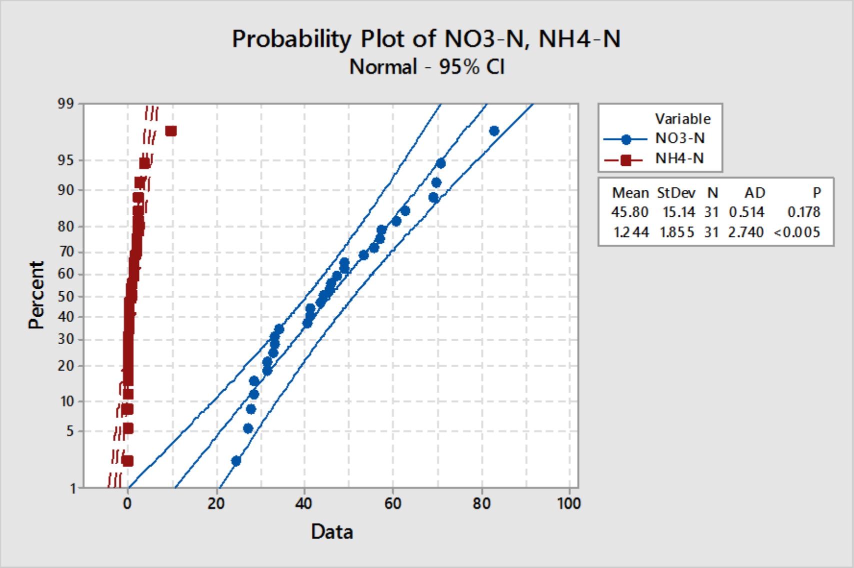


Figure 43- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 305 cm, DD= 147 cm, Dimp= 160 cm

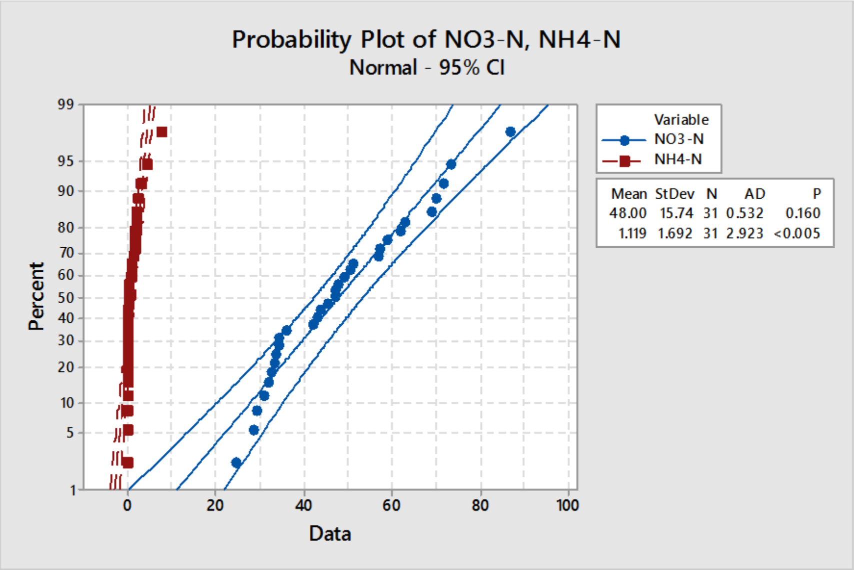


Figure 44- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 305 cm, DD= 147 cm, Dimp= 200 cm

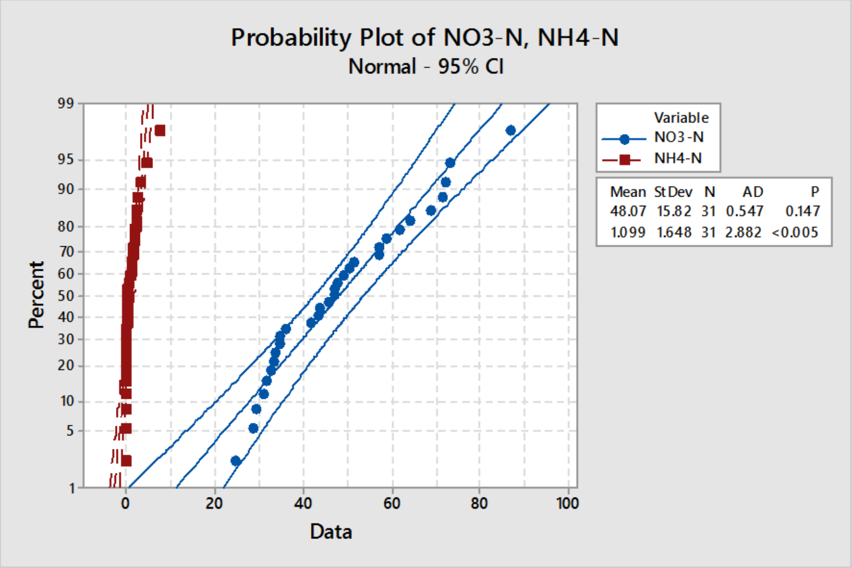


Figure 45- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 305 cm, DD= 147 cm, Dimp= 240 cm

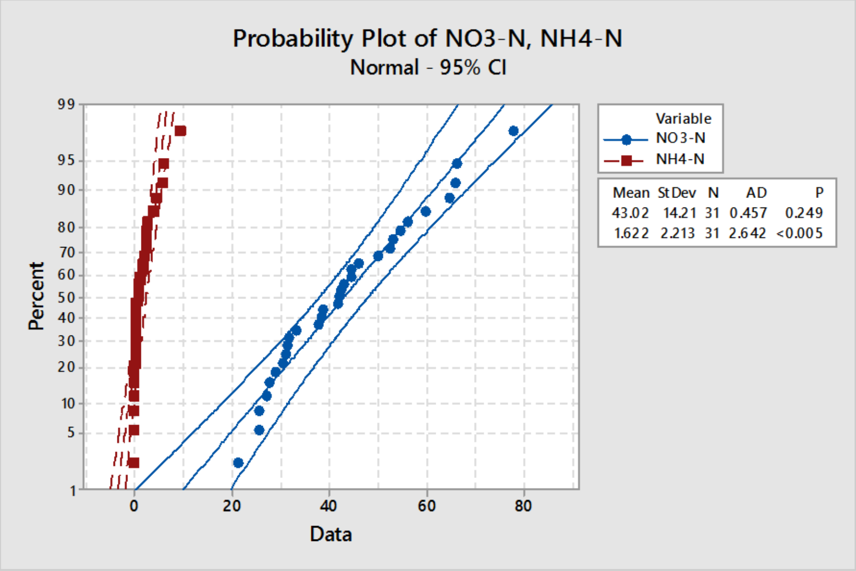
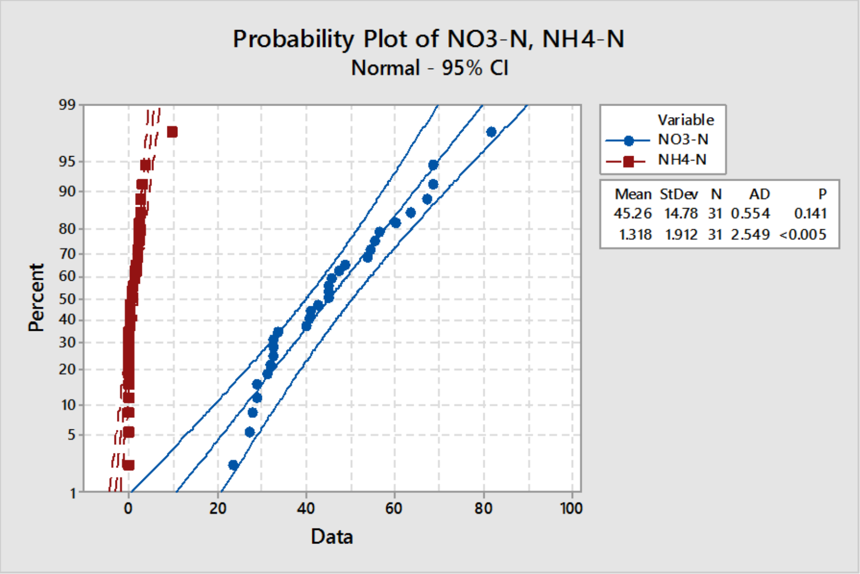
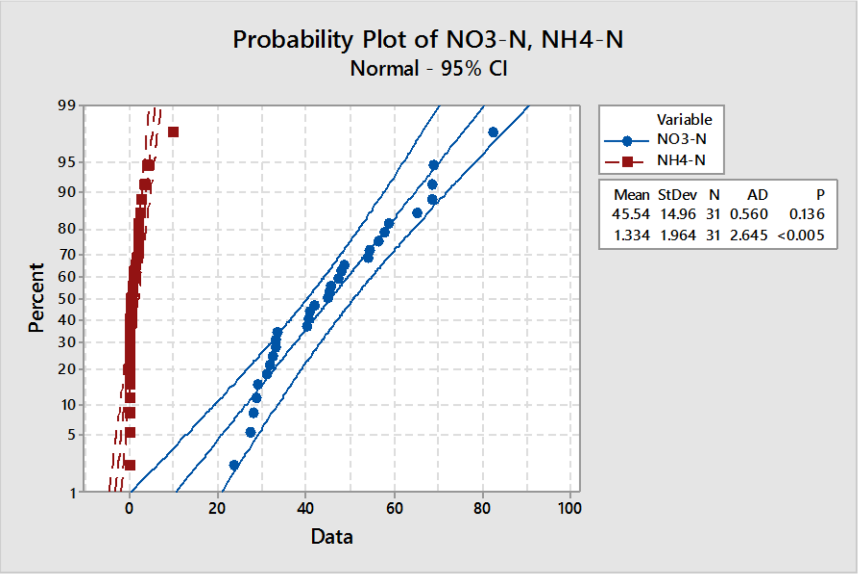


Figure 46- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 366 cm, DD= 147 cm, Dimp= 160 cm



Mean	StDev	N	AD	P
45.26	14.78	31	0.554	0.141
1.318	1.912	31	2.549	<0.005

Figure 47- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 366 cm, DD= 147 cm, Dimp= 200 cm



Mean	StDev	N	AD	P
45.54	14.96	31	0.560	0.136
1.334	1.964	31	2.645	<0.005

Figure 48- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 366 cm, DD= 147 cm, Dimp= 240 cm

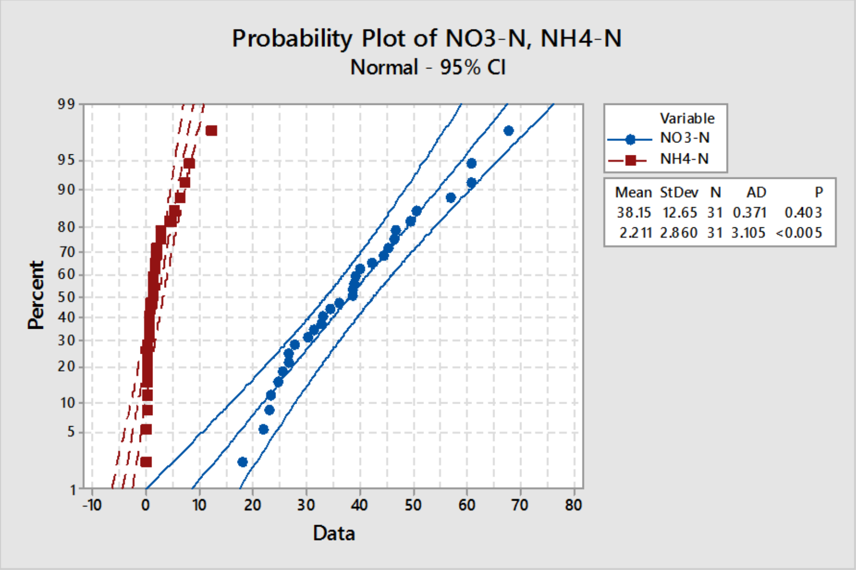


Figure 49- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 488 cm, DD= 147 cm, Dimp= 160 cm

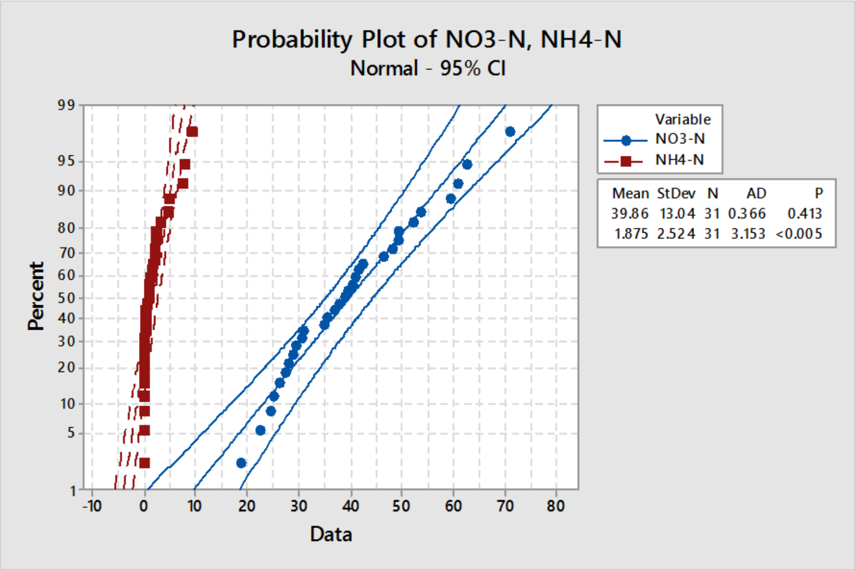


Figure 50- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 488 cm, DD= 147 cm, Dimp= 200cm

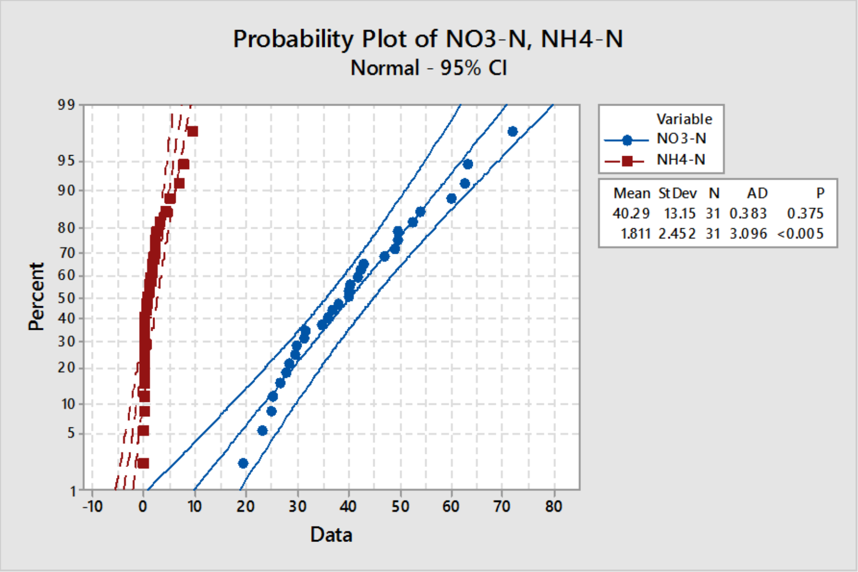


Figure 51- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 488 cm, DD= 147 cm, Dimp= 240 cm

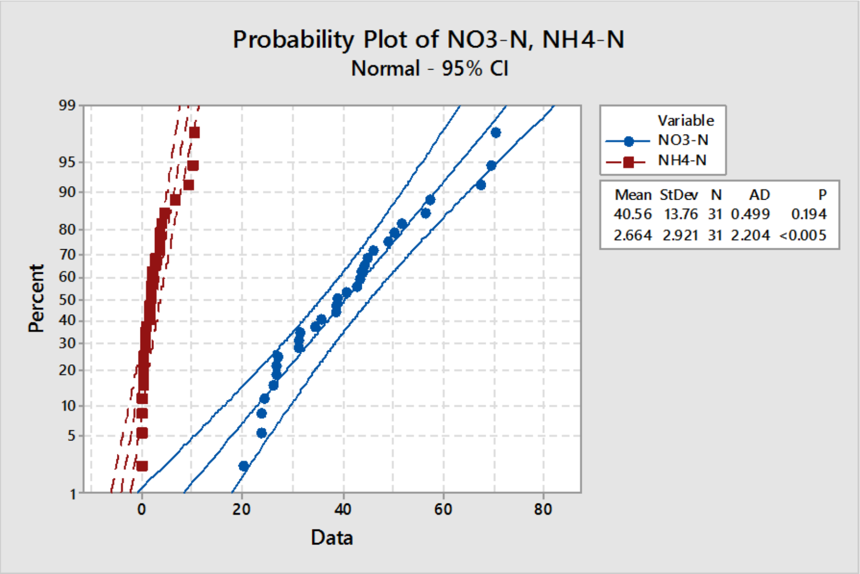


Figure 52- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 183 cm, DD= 102 cm, Dimp= 160 cm, Load 2

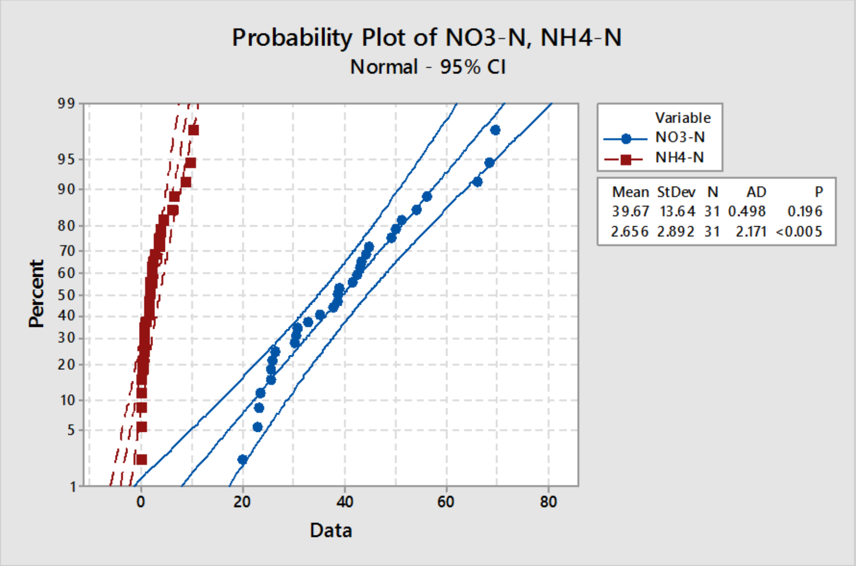


Figure 53- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 183 cm, DD= 102 cm, Dimp= 160 cm, Load 3.

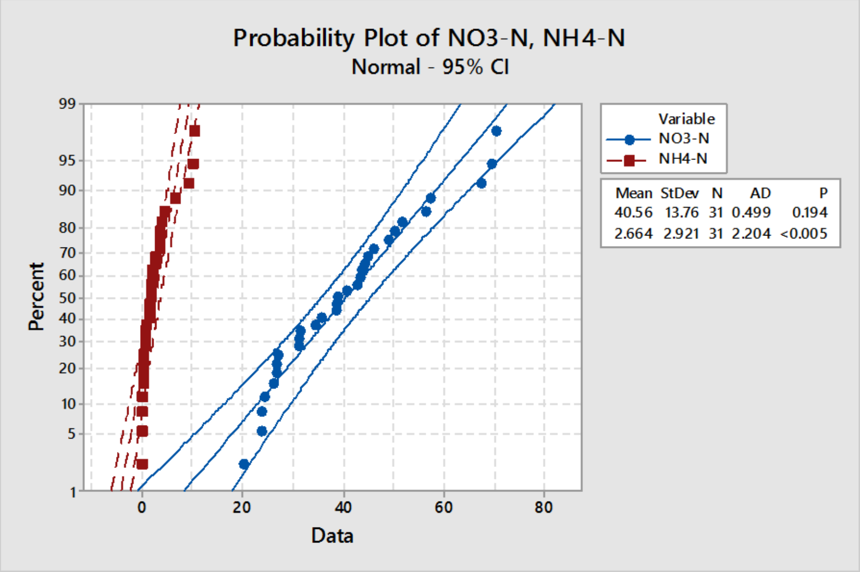


Figure 54- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 183 cm, DD= 102 cm, Dimp= 200 cm, Load 2.

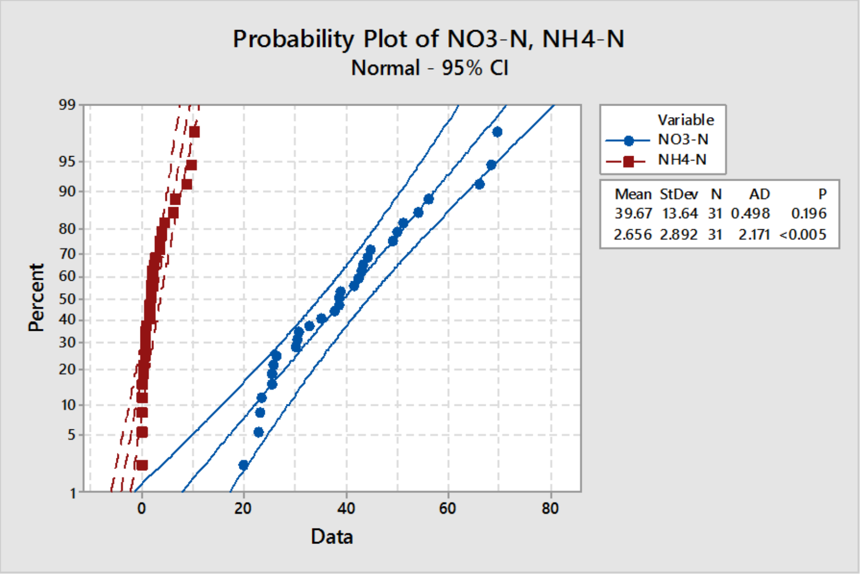


Figure 55- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 183 cm, DD= 102 cm, Dimp= 200 cm, Load 3.

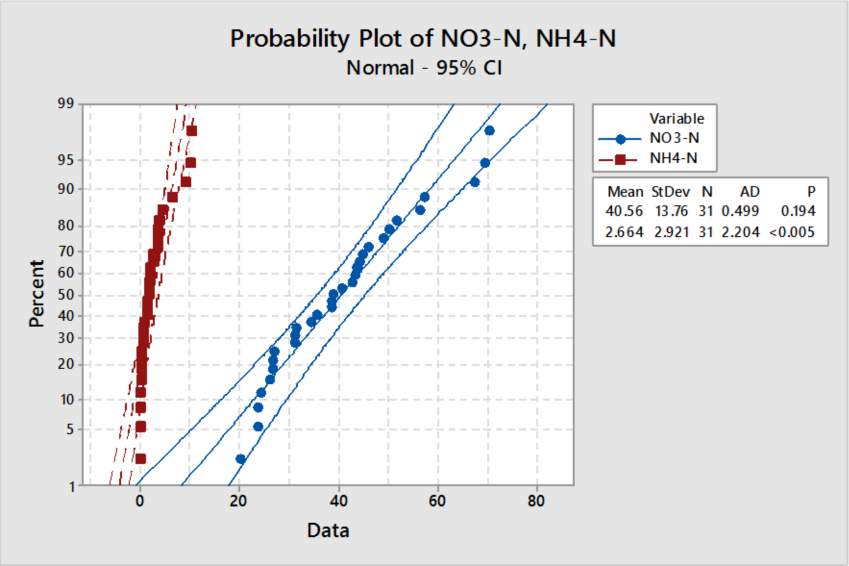


Figure 56- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 183 cm, DD= 102 cm, Dimp= 240 cm, Load 2.

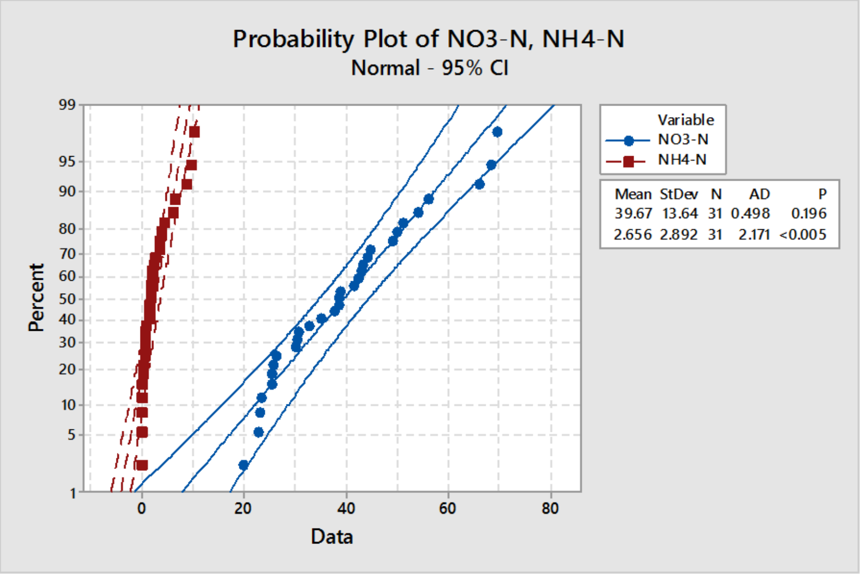


Figure 57- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 183 cm, DD= 102 cm, Dimp= 240 cm, Load 3

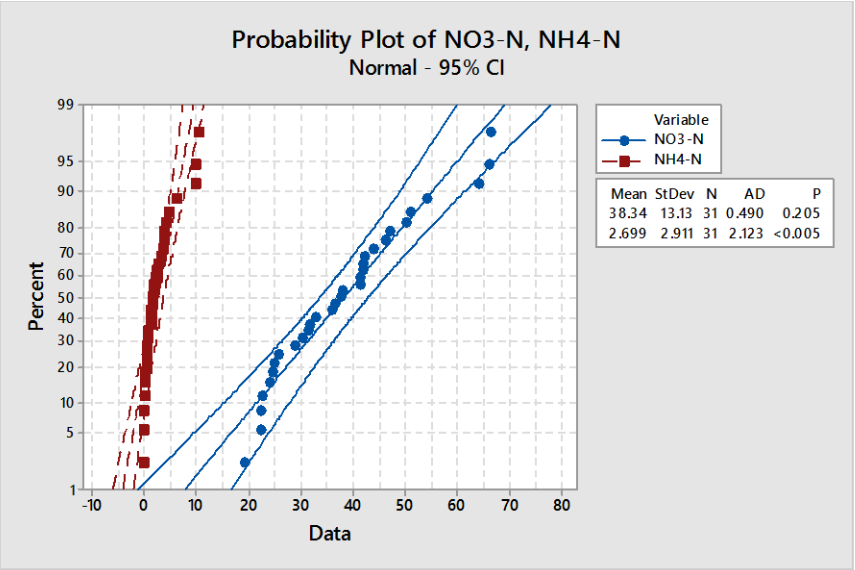


Figure 58- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 244 cm, DD= 102 cm, Dimp= 160 cm, Load 2

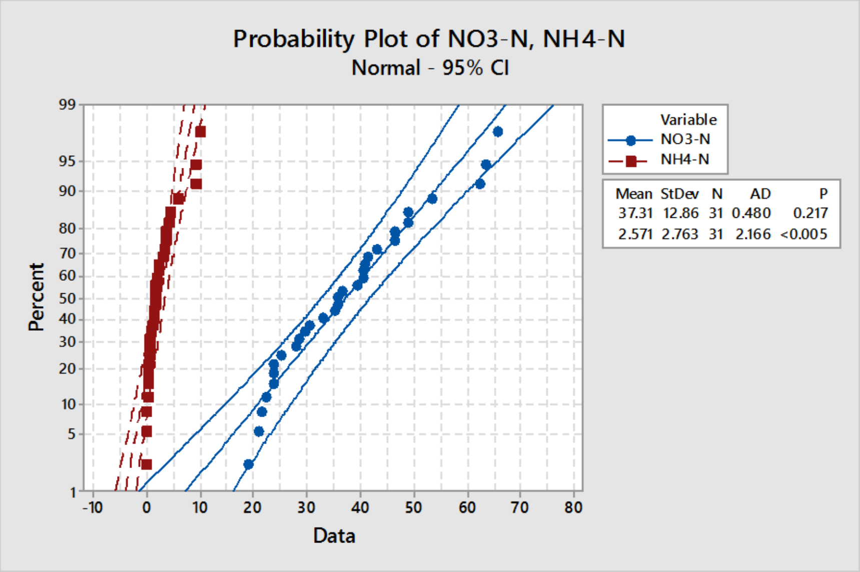


Figure 59- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 244 cm, DD= 102 cm, Dimp= 160 cm, Load 3

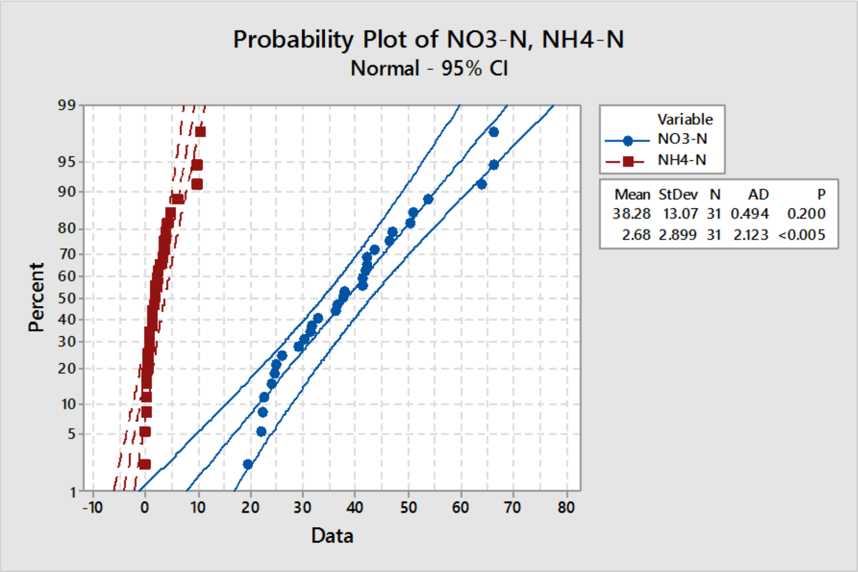


Figure 60- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 244 cm, DD= 102 cm, Dimp= 200 cm, Load 2

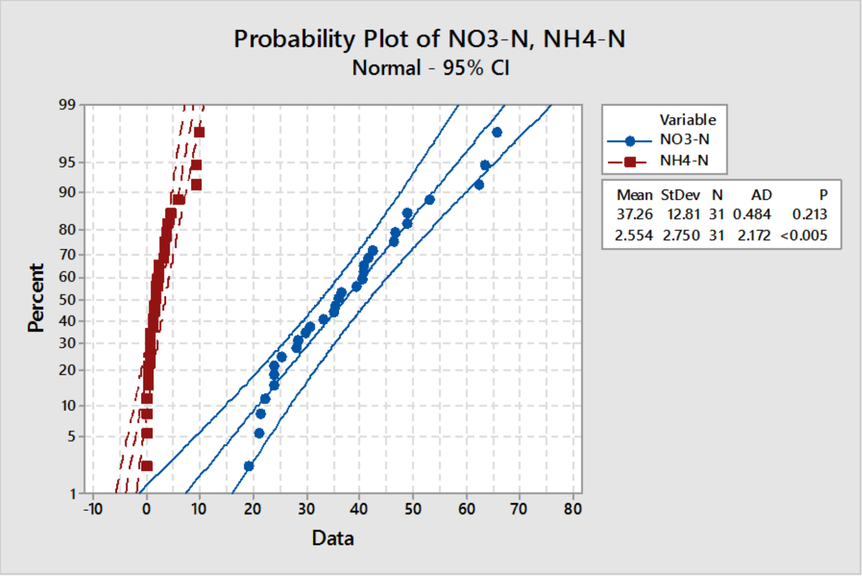


Figure 61- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 244 cm, DD= 102 cm, Dimp= 200 cm, Load 3

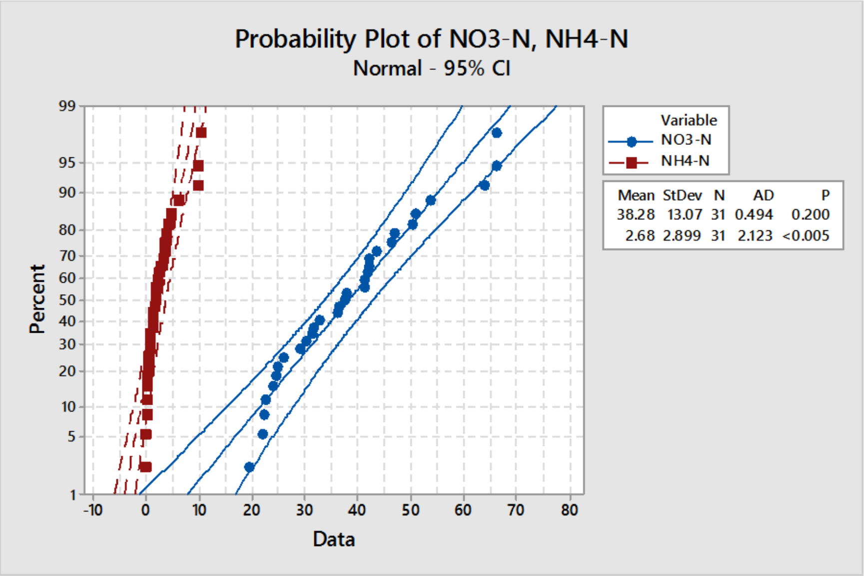


Figure 62- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 244 cm, DD= 102 cm, Dimp= 240 cm, Load 2

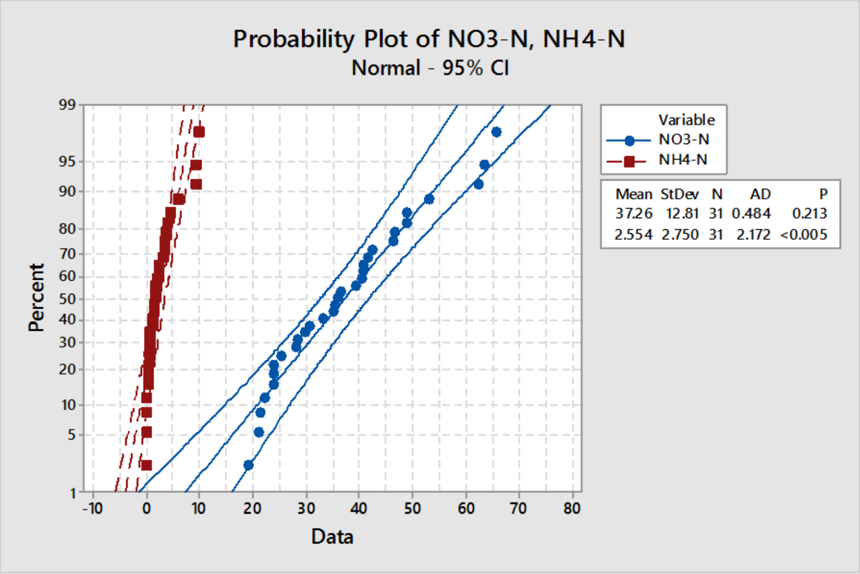


Figure 63- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 244 cm, DD= 102 cm, Dimp= 240 cm, Load 3

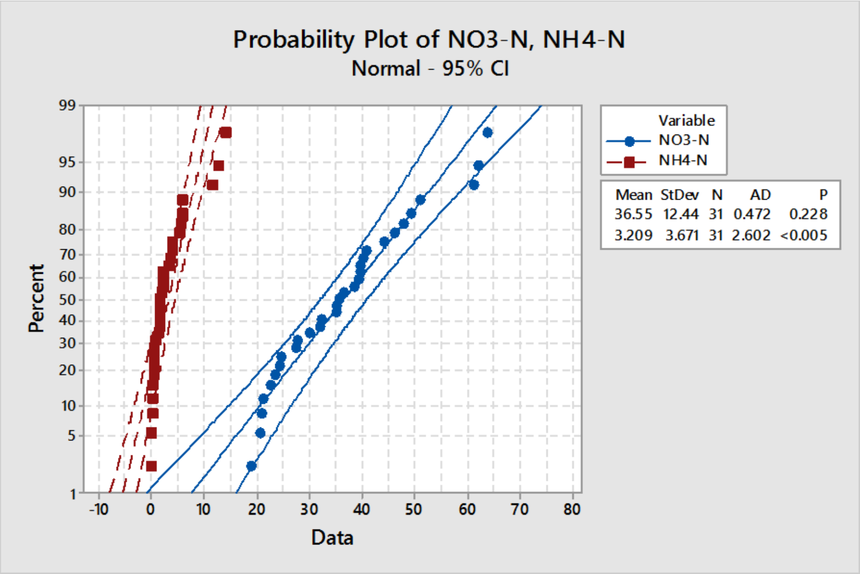


Figure 64- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 305 cm, DD= 102 cm, Dimp= 160 cm, Load 2

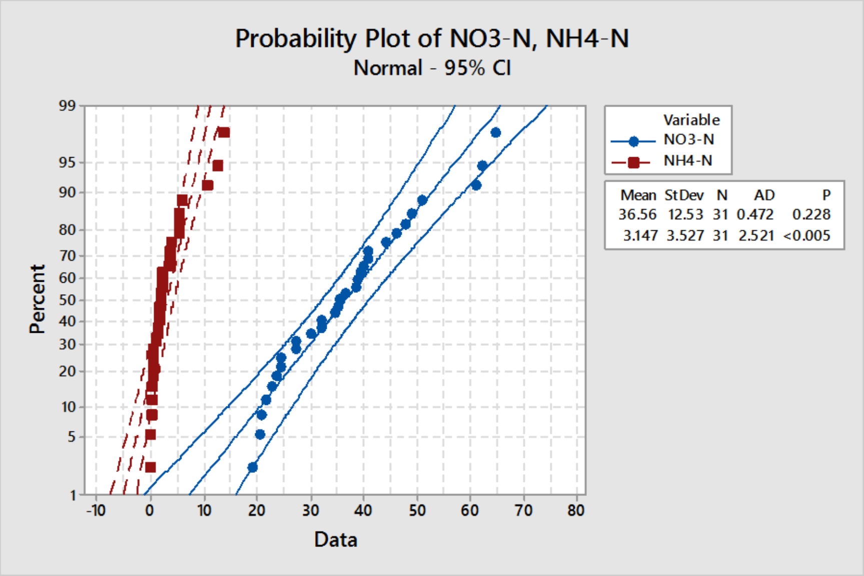


Figure 65- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 305 cm, DD= 102 cm, Dimp= 200 cm, Load 2

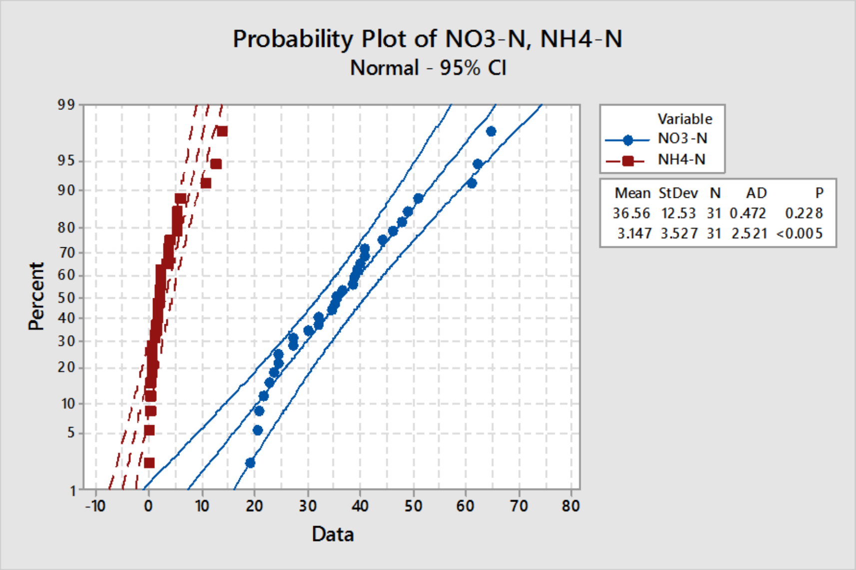


Figure 66- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS= 305 cm, DD= 102 cm, Dimp= 240 cm, Load 2

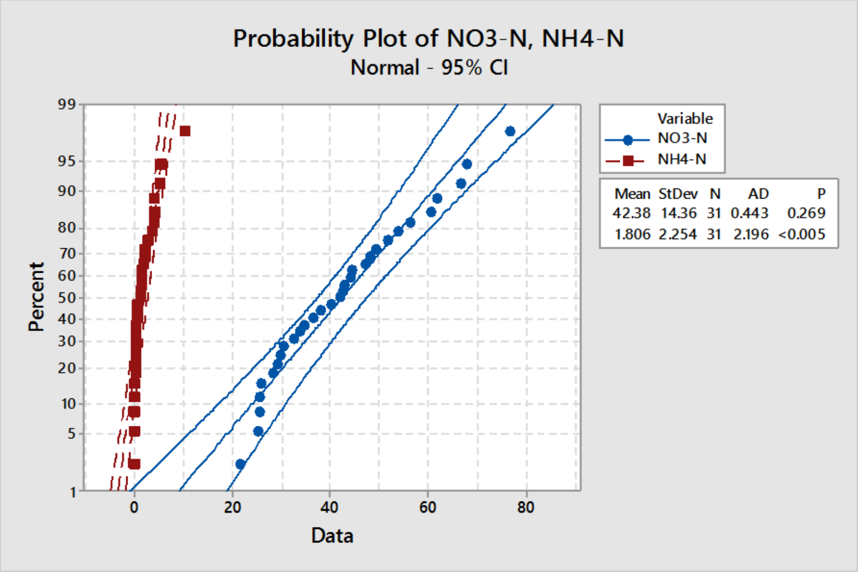


Figure 67- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS=183 cm, DD= 117 cm, Dimp= 160 cm, Load 2

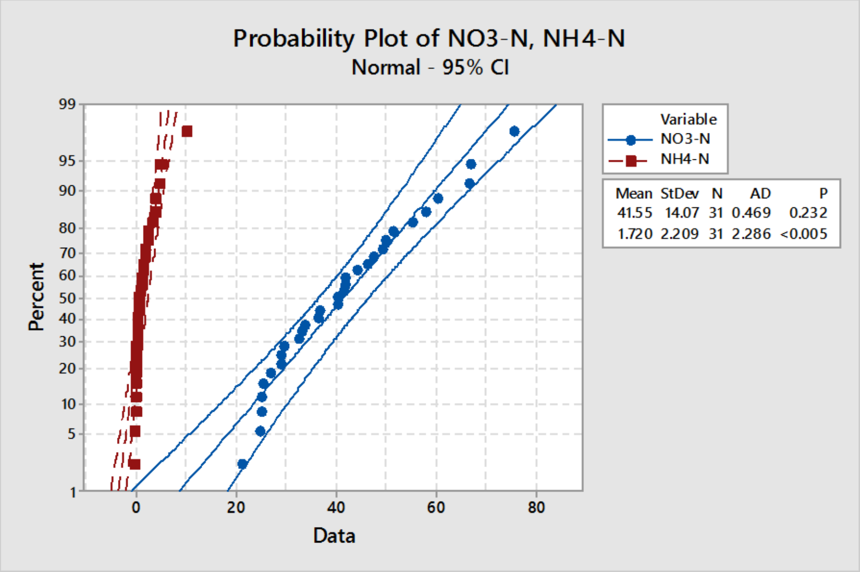


Figure 68- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS=183 cm, DD= 117 cm, Dimp= 160 cm, Load 3

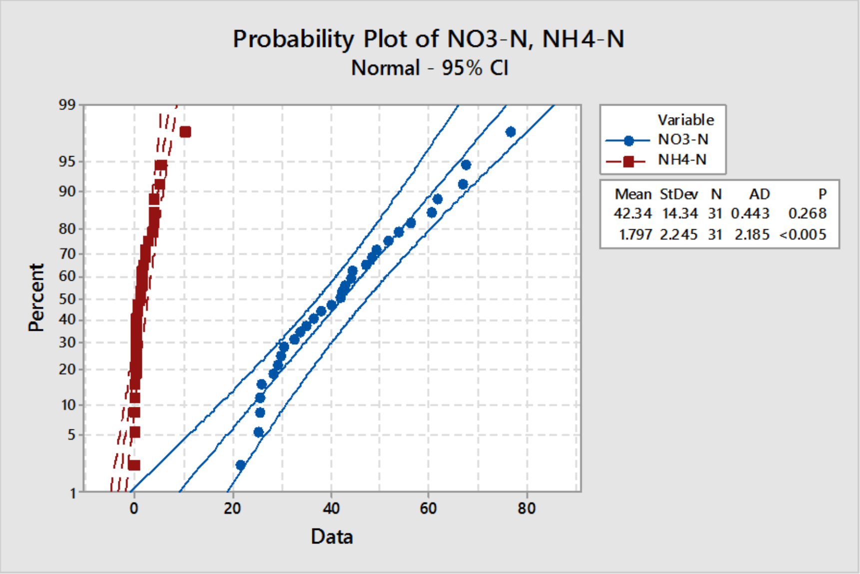


Figure 69- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS=183 cm, DD= 117 cm, Dimp= 200 cm, Load 2

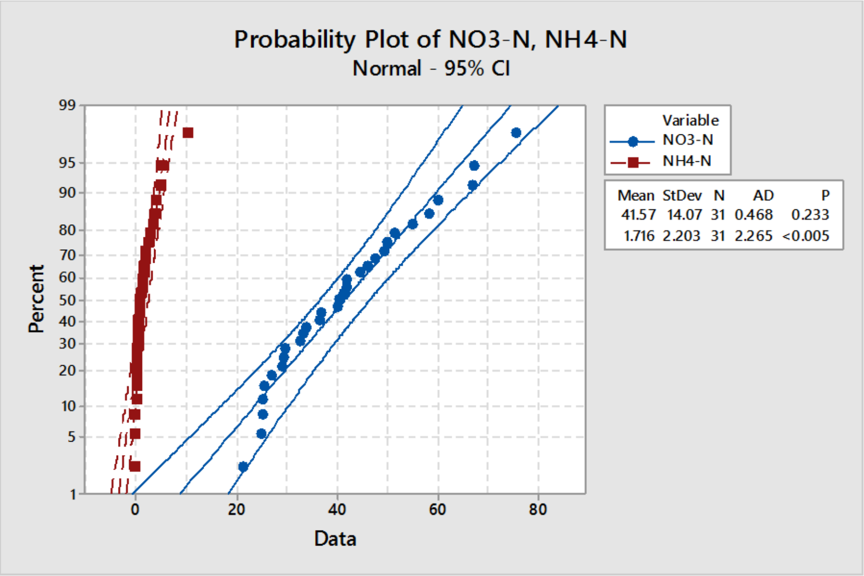


Figure 70- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS=183 cm, DD= 117 cm, Dimp= 200 cm, Load 3

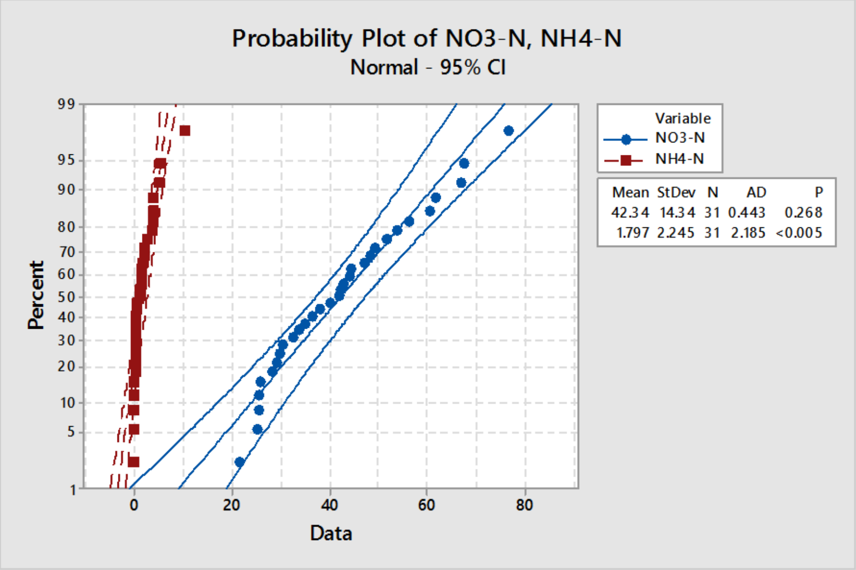


Figure 71- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS=183 cm, DD= 117 cm, Dimp= 240 cm, Load 2

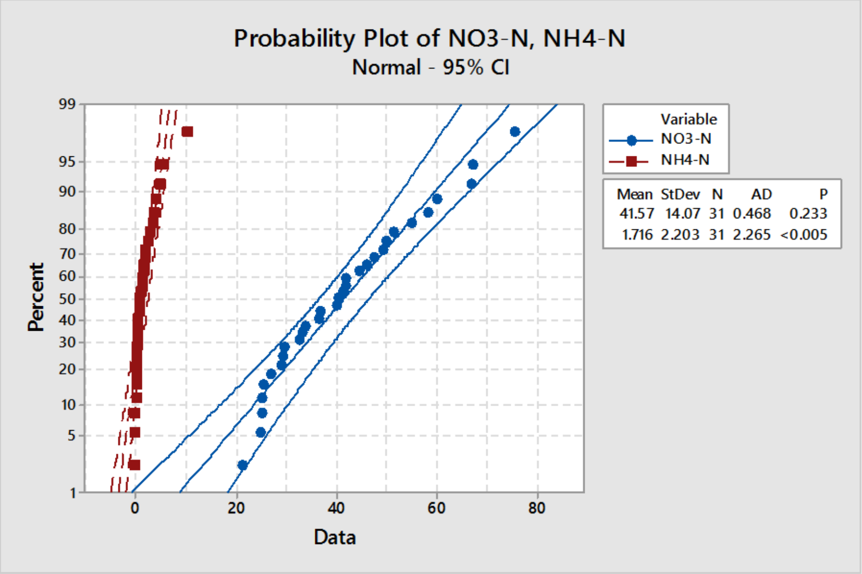


Figure 72- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS=183 cm, DD= 117 cm, Dimp= 240 cm, Load 3

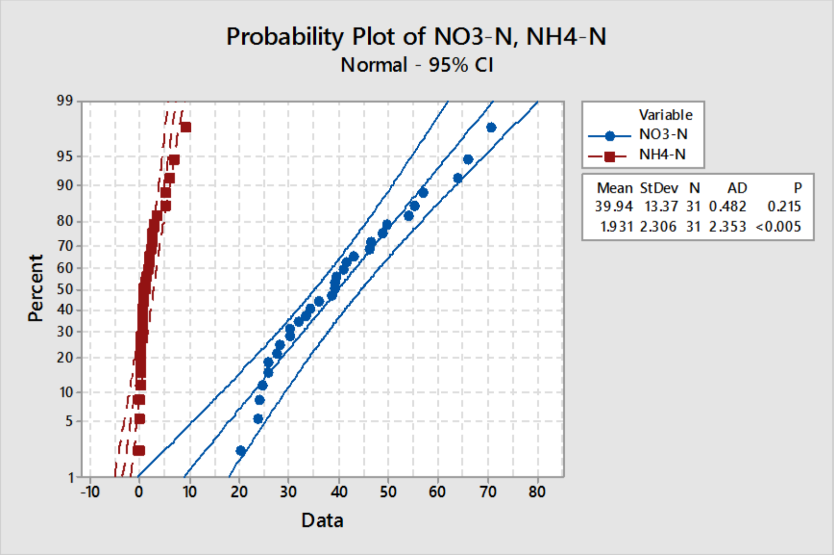


Figure 73- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS=244 cm, DD= 117 cm, Dimp= 160 cm, Load 2

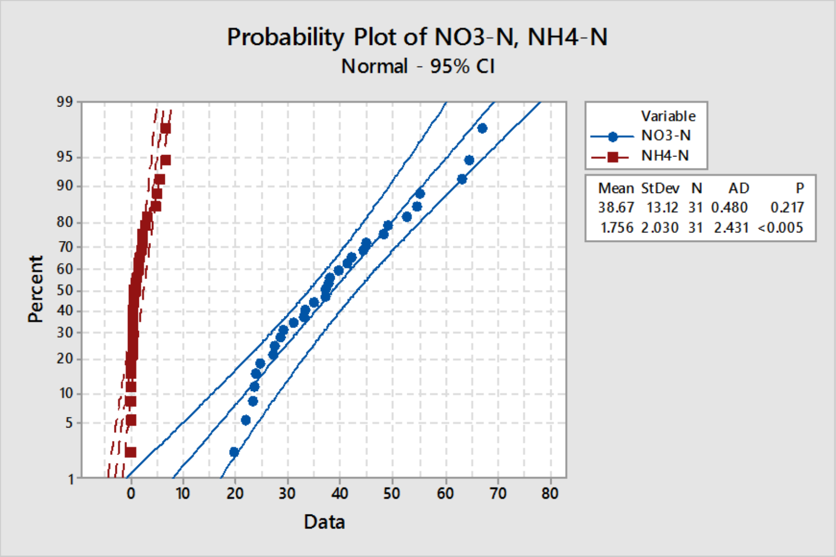


Figure 74- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS=244 cm, DD= 117 cm, Dimp= 160 cm, Load 3

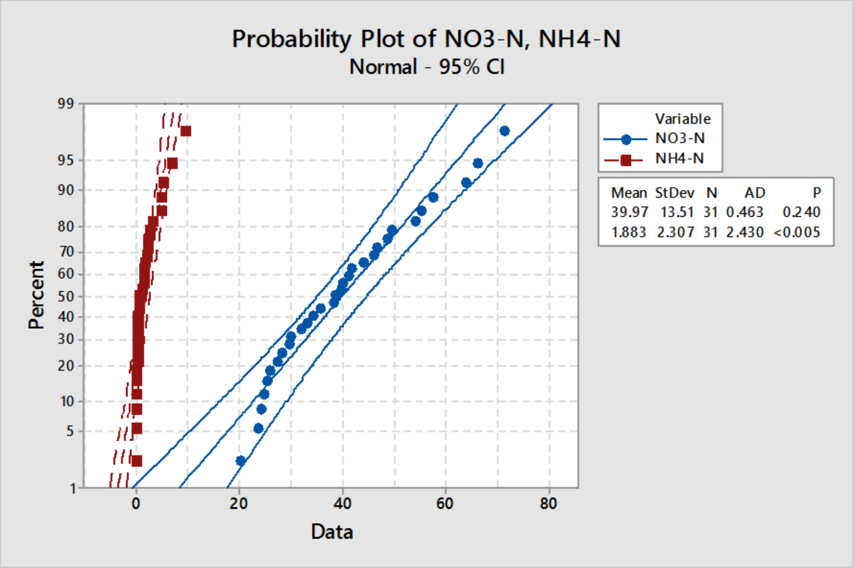


Figure 75- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS=244 cm, DD= 117 cm, Dimp= 200 cm, Load 2

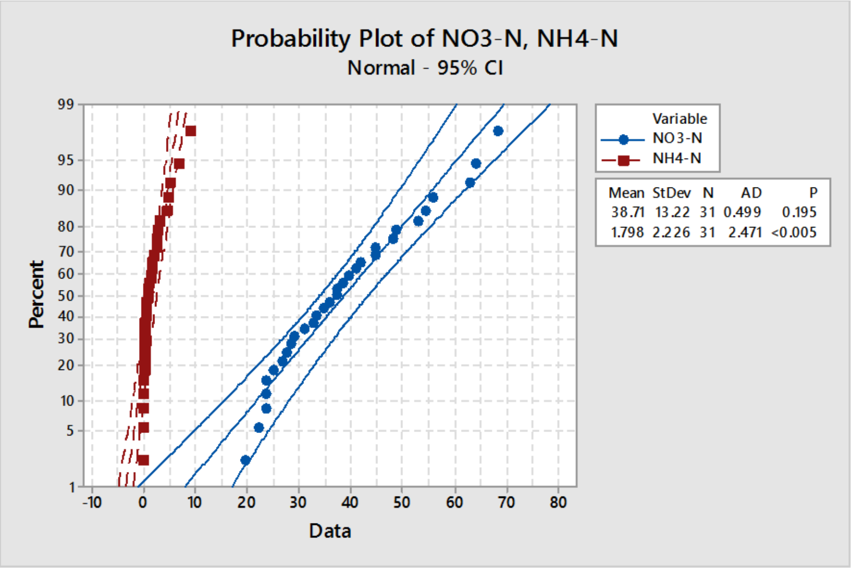


Figure 76- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS=244 cm, DD= 117 cm, Dimp= 200 cm, Load 3

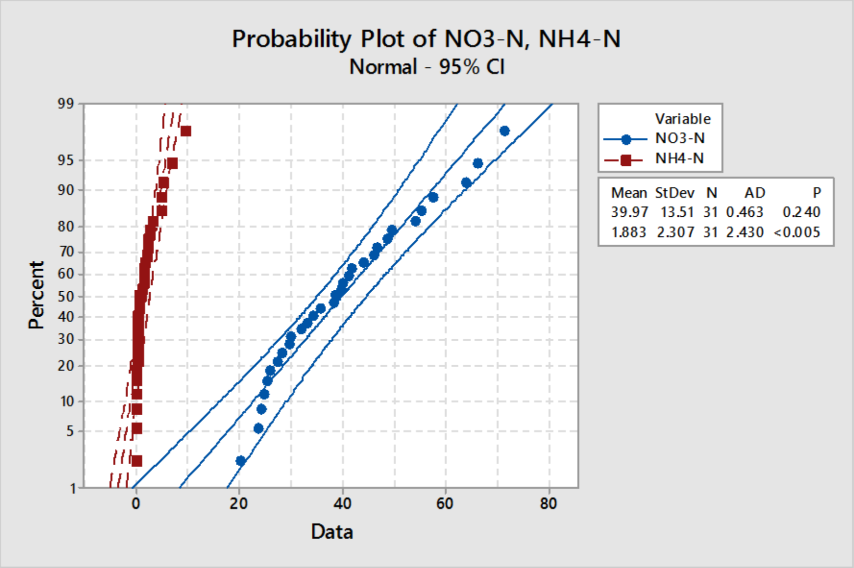


Figure 77- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS=244 cm, DD= 117 cm, Dimp= 240 cm, Load 2

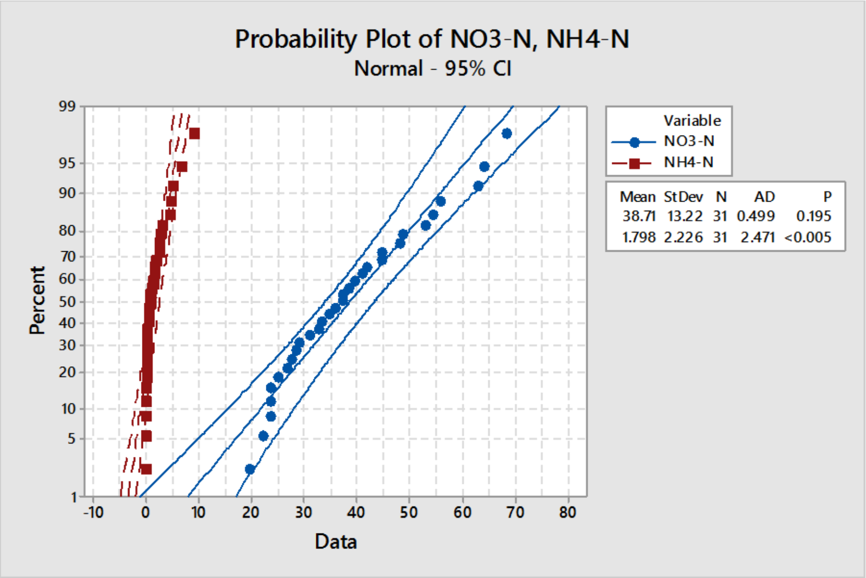


Figure 78- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS=244 cm, DD= 117 cm, Dimp= 240 cm, Load 3

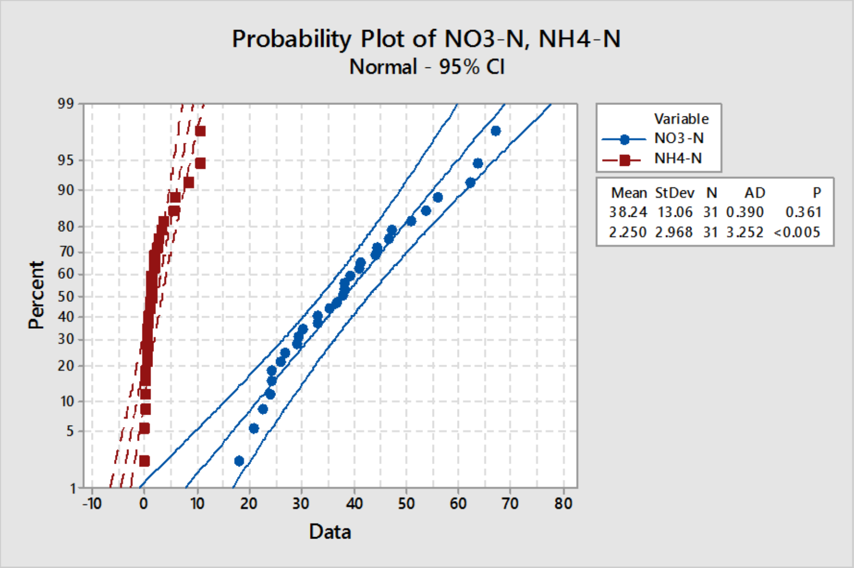


Figure 79- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS=305 cm, DD= 117 cm, Dimp= 160 cm, Load 2

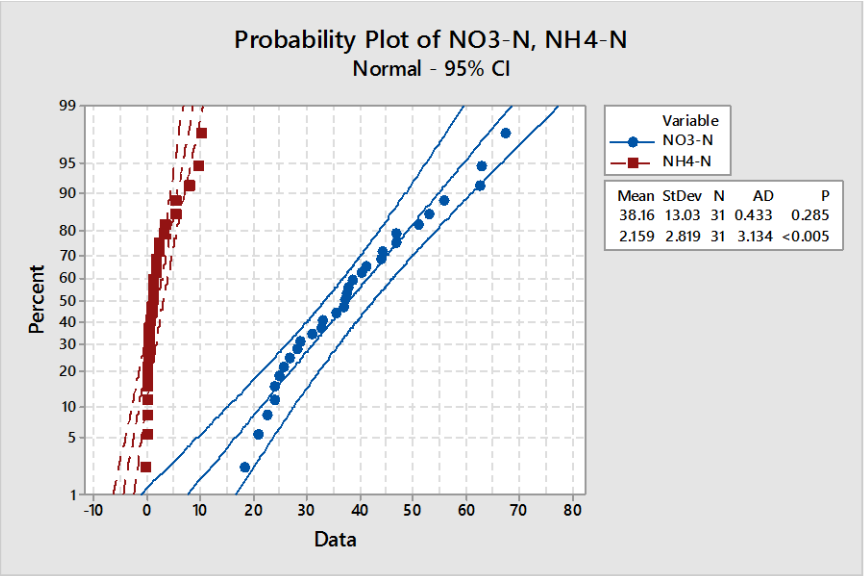


Figure 80- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS=305 cm, DD= 117 cm, Dimp= 200 cm, Load 2

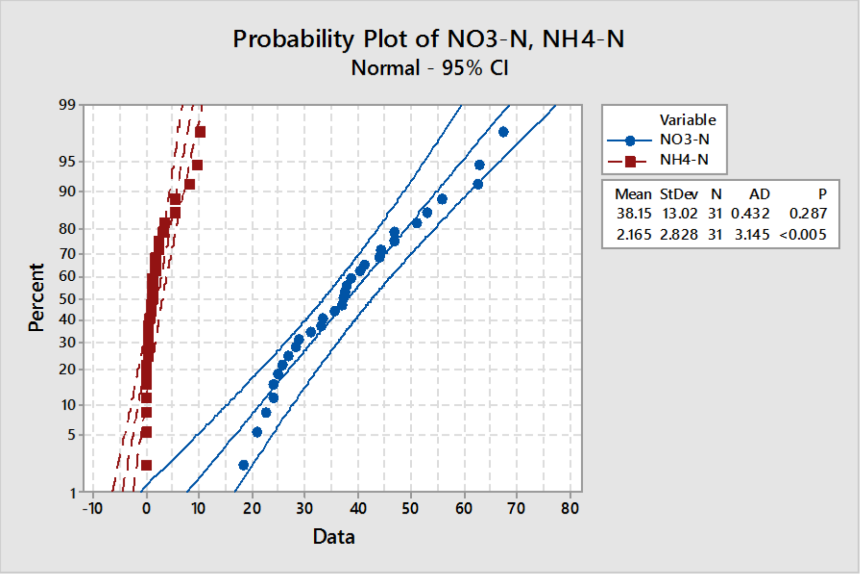


Figure 81- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS=305 cm, DD= 117 cm, Dimp= 200 cm, Load 2

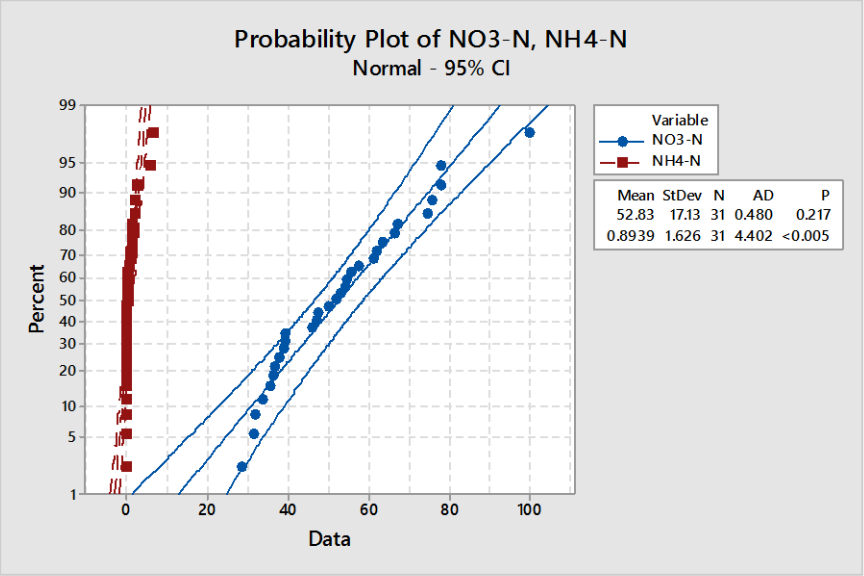


Figure 82- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS=183 cm, DD= 147 cm, Dimp= 160 cm, Load 2

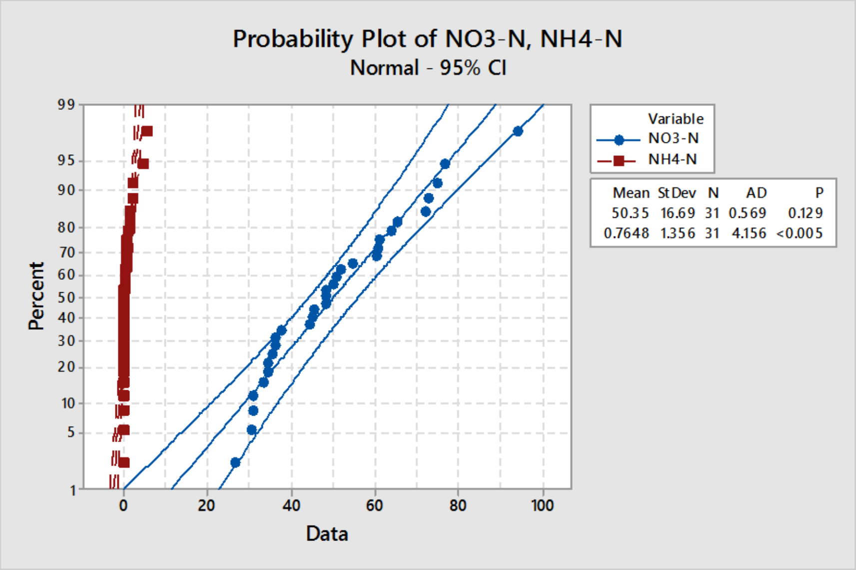


Figure 83- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS=183 cm, DD= 147 cm, Dimp= 160 cm, Load 3

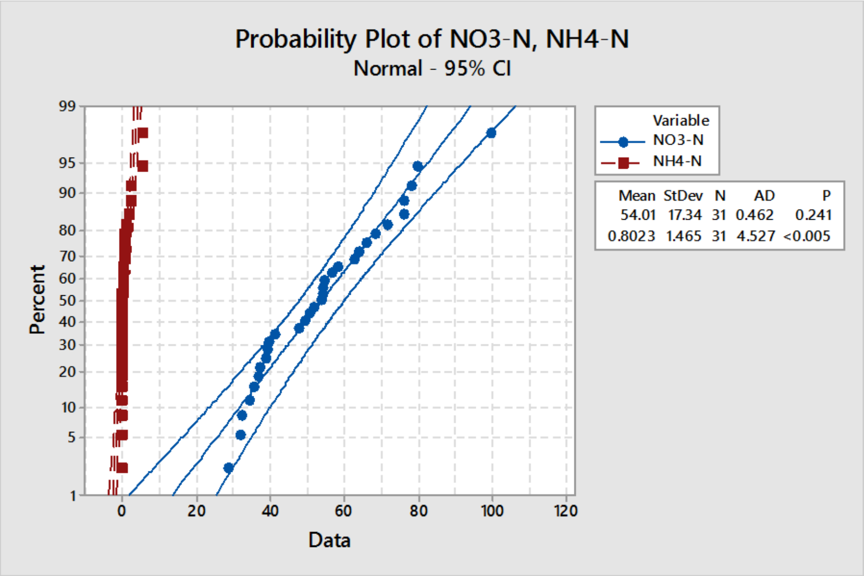


Figure 84- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS=183 cm, DD= 147 cm, Dimp= 200 cm, Load 2

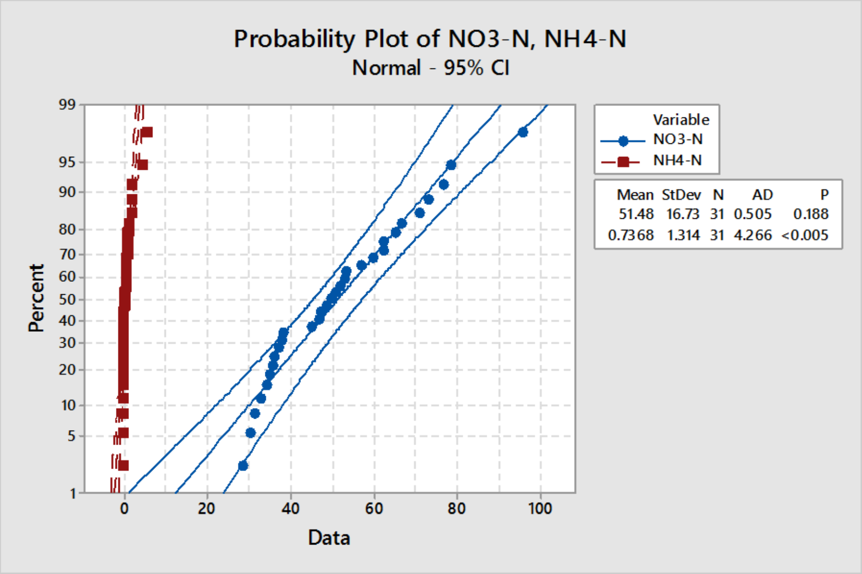


Figure 85- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS=183 cm, DD= 147 cm, Dimp= 200 cm, Load 3

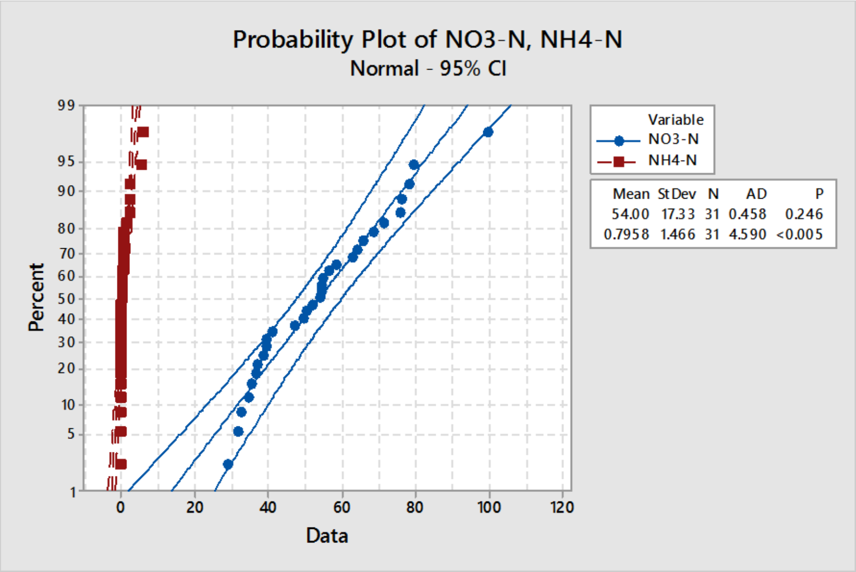


Figure 86- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS=183 cm, DD= 147 cm, Dimp= 240 cm, Load 2

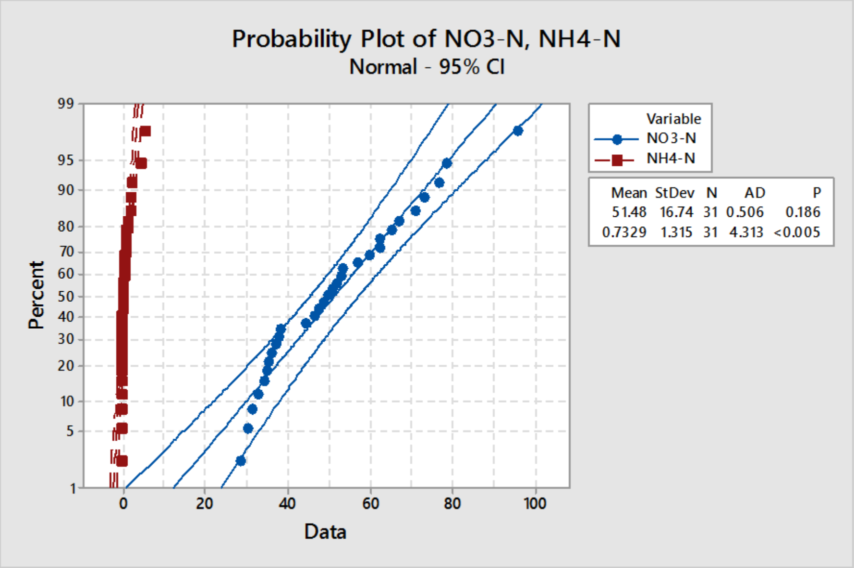


Figure 87- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS=183 cm, DD= 147 cm, Dimp= 240 cm, Load 3

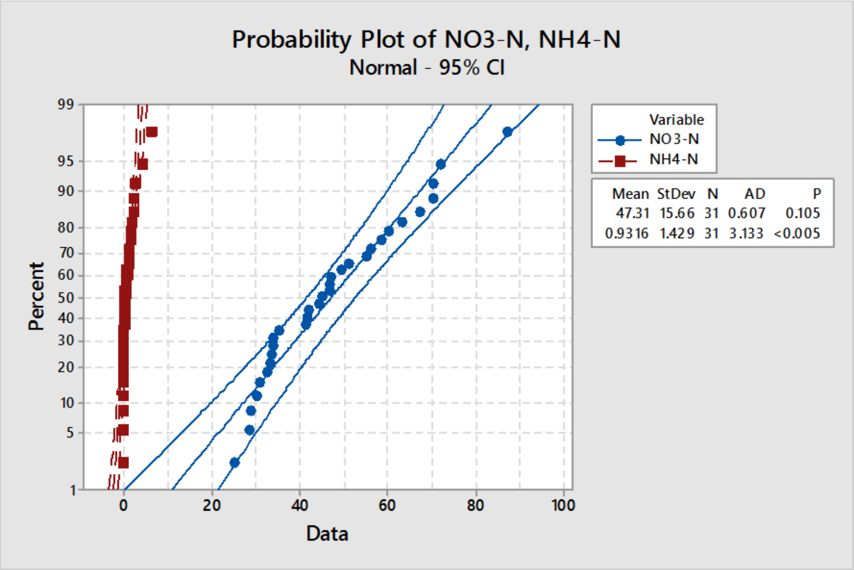


Figure 88- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS=244 cm, DD= 147 cm, Dimp= 160 cm, Load 2

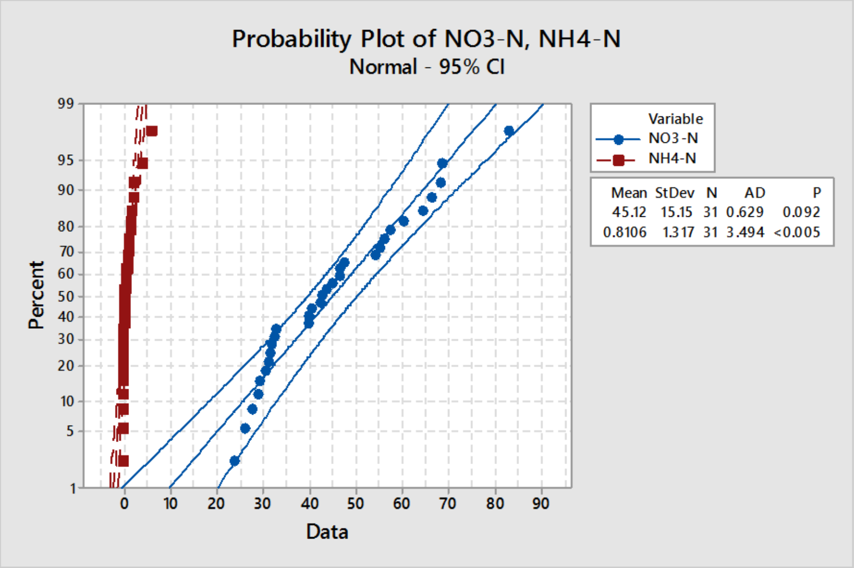


Figure 89- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS=244 cm, DD= 147 cm, Dimp= 160 cm, Load 3

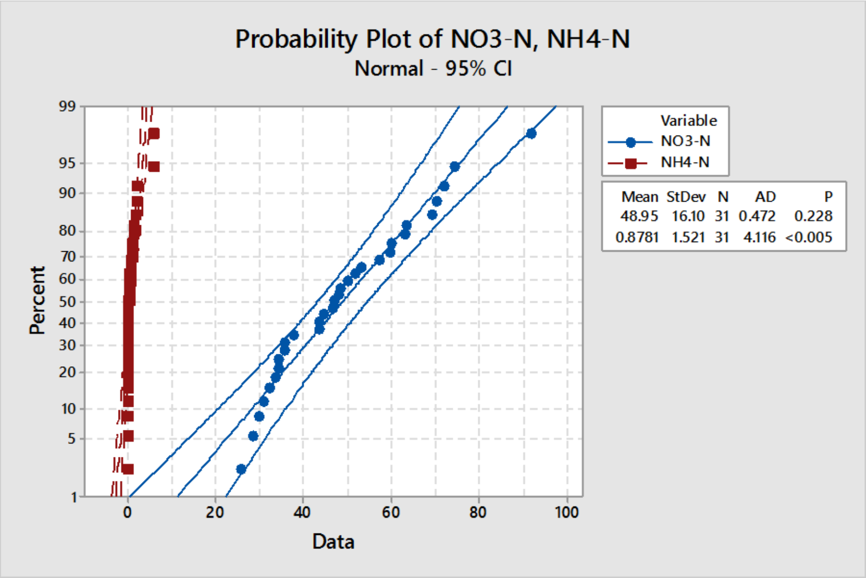


Figure 90- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS=244 cm, DD= 147 cm, Dimp= 200 cm, Load 2

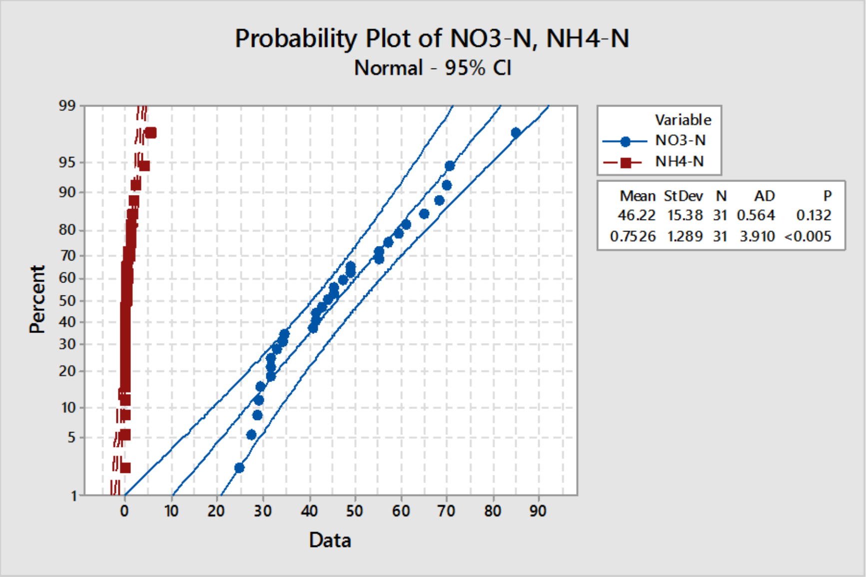


Figure 91- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS=244 cm, DD= 147 cm, Dimp= 200 cm, Load 3

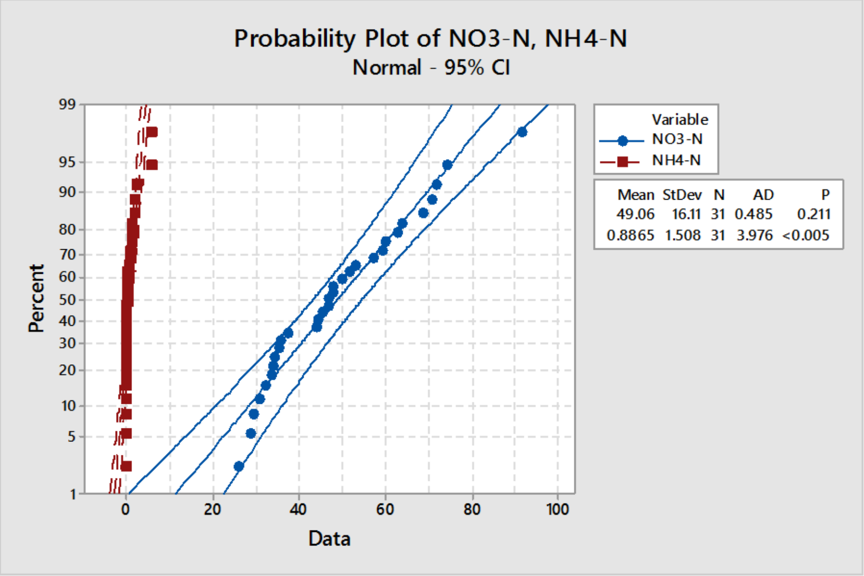


Figure 92- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS=244 cm, DD= 147 cm, Dimp= 240 cm, Load 2

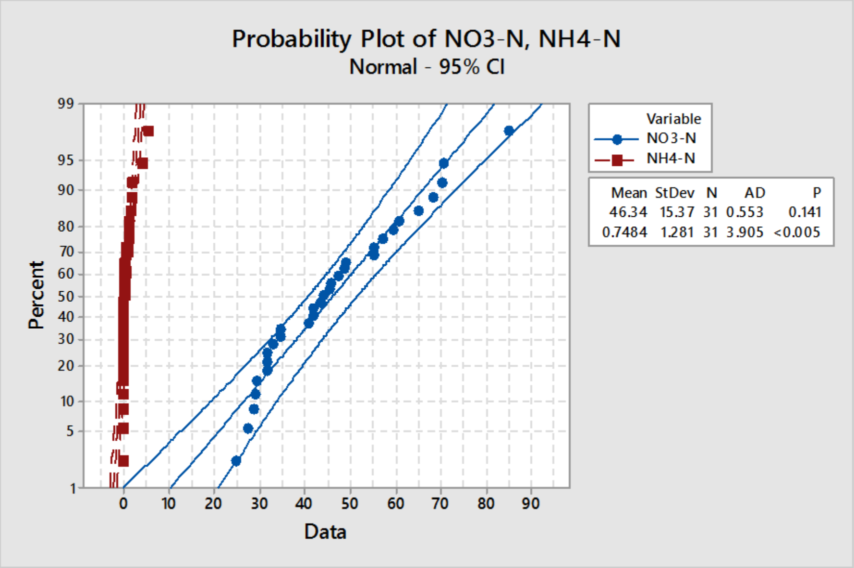


Figure 93- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS=244 cm, DD= 147 cm, Dimp= 240 cm, Load 3

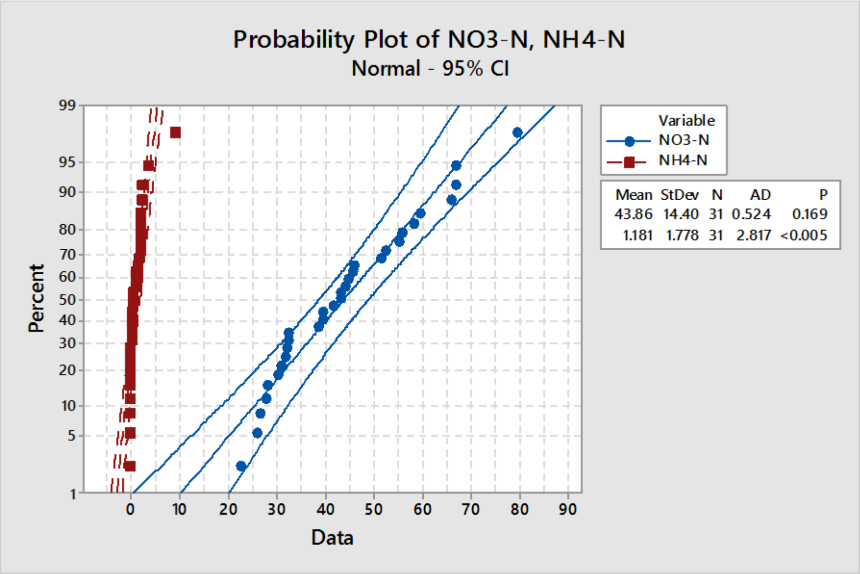


Figure 94- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS=305 cm, DD= 147 cm, Dimp= 160 cm, Load 2

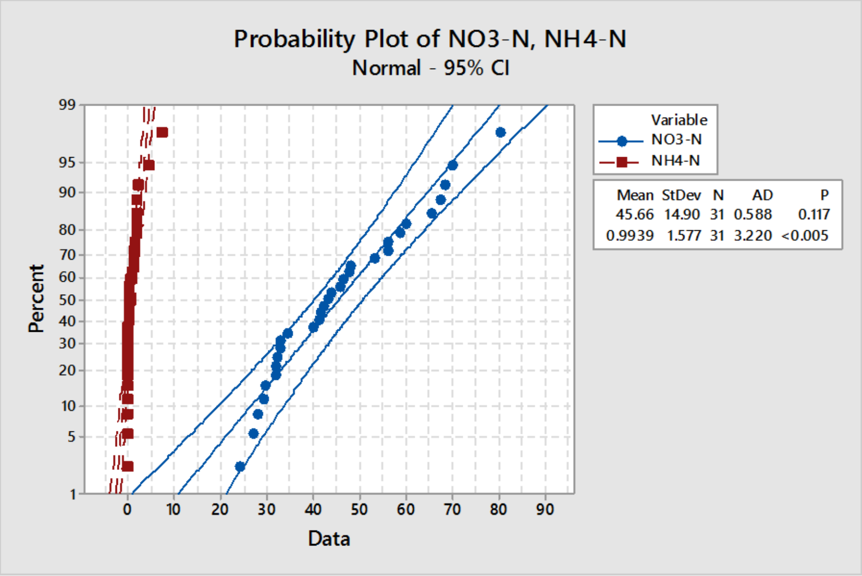


Figure 95- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS=305 cm, DD= 147 cm, Dimp= 200 cm, Load 2

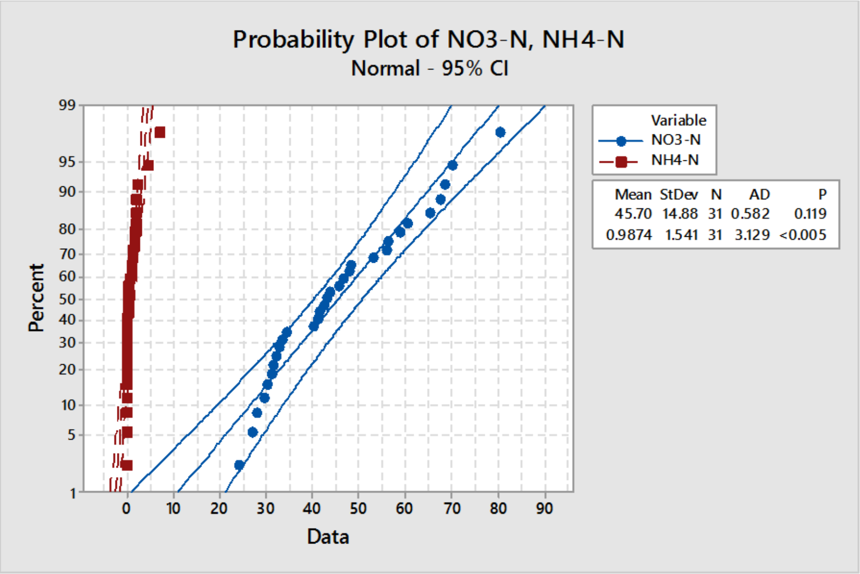


Figure 96- Probability Plot of 31- year Annual NO3-N and NH4-N drainage loss concentrations for DS=305 cm, DD= 147 cm, Dimp= 240 cm, Load 2