PHYSICAL CHARACTERISTICS OF A SEEPAGE IRRIGATED SOIL PROFILE IN THE TRI-COUNTY AGRICULTURAL AREA, NORTHEAST FLORIDA

By

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A THESIS PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
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To my wife, my parents, and my sisters

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Abstract of Thesis Presented to the Graduate School
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Physical properties significantly influence hydraulic characteristics of soils, which in turn determine the water and nutrient management practices and efficiencies of an agricultural field. In the Tri-County Agricultural Area of northeast Florida (TCAA), the sandy nature of surface soil overlying an impervious shallow hardpan has allowed controlled fluctuations of the perched water table levels for successfully irrigating crops. The irrigation system, referred to as 'seepage irrigation', however, is inherently inefficient in terms of water use despite its popularity and manageability. The potential loss of nutrients from the agricultural areas of northeast Florida and the consequent nonpoint source (NPS) pollution in the Lower St. Johns River (LSJR) are attributed to the inefficient irrigation system. Potato best management practices (BMPs) in the area have been developed and implemented in order to increase the nutrient use efficiency and reduce environmental losses. However, potential nutrient loss from agricultural fields is determined to a great extent by physical characteristics of the soil profile. The data on physical properties of the soil profile and the water restrictive hardpan layer in the TCAA, on the other hand, is limited. Seventy soil core samples were collected at 22.5cm, 45cm, 67.5cm, 90cm and 120cm depths from a 4.2ha seepage irrigated field in 26m×26m grids. Particle-size distribution (PSD), saturated hydraulic conductivity (K_s), and bulk density (D_b) at

the five depths and moisture retention capacity at the first three depths were determined with the respective standard protocols. Horizontal and vertical variations in soil properties were analyzed with statistical and geostatistical techniques. The PSD showed >90% of sand in most of the soil samples. Clay content (%clay) and D_b increased with depth, the highest values being at 120cm depth. The first three sampling depths showed little change in K_s while it decreased sharply at 120cm depth, indicating the beginning of the hardpan. Moisture release curves determined for the first three soil depths indicated a low capacity for moisture retention as the soils progressively dried out.

Variability of D_b and K_s was least in the soil samples collected from the hardpan (120cm depth). Percentage clay on the other hand, was least variable at 22.5cm followed by 120cm depth. Highest variation of K_s and %clay was observed at 90cm while for D_b, highest variation was found at 67.5cm followed by 90cm. The spatial variation in soil properties differed greatly with depth at the sampling interval of 26meters. A large *nugget* effect was prevalent in most of the cases while pure *nugget* effect was also observed in some of the property-depth combinations. The D_b values were significantly higher and the K_s values were significantly lower within the hardpan with little variability, indicating that vertical movement of water and solute below this compact layer was minimal. An evaluation of potential water loss from the experimental field under seepage irrigation showed that as high as 87% of water received by the field as irrigation and/or rainfall could be lost by surface and subsurface drainage. Overall results of the study indicated that the nature of the soil profile in the field could encourage a steady state subsurface lateral flow of water (SLFW) through the soil profile thereby increasing the potential of substantial amounts of water and nutrient loss from the field.

CHAPTER 1
INTRODUCTION

Tri- County Agricultural Area

Tri-County Agricultural Area (TCAA) located along the northeastern coastline of Florida covers approximately 15,000ha cropland of St. Johns, Putnam and Flagler counties. The TCAA is the most important potato producing area in the state, accounting approximately 60% of total potato production (USDA, 2008). In 2007, the total production of spring potato in Florida was approximately 354,120 metric tons harvested from 11,000ha. Approximately 59% (209,420 metric tons) of the total production was contributed by Hastings area of the TCAA alone (USDA, 2008). Both area and production were higher in 2008 than in the previous year with approximately 223,620 metric tons (61%) production from 6880ha Hastings area potato farms. Besides potato, other important crops in the TCAA are cabbage and cole crops. A typical one year crop rotation in the TCAA includes spring potato followed by a cover crop in the summer. Sorghum and corn are the most common cover crops in the area. Due to sandy nature of the soil, nutrient and water holding capacities are generally low. This area is characterized by a naturally occurring shallow hardpan at approximately one meter depth, with low K_s and high D_b. The subsurface hardpan restricts vertical movement of water and a resultant perched water table is built up, as the influx of water through surface irrigation and/or rainfall typically far exceeds the K_s of the hardpan. The level of the perched water table can be appropriately altered by controlling the lateral drainage through adjusting the riser boards in the discharge channels at the edges of the fields.

Current Management Practices in the TCAA

Much of the area in TCAA is planted with chipping variety of potato (var. *Atlantic*) during the spring season (February to May) followed by summer cover-crops such as corn or sorghum. A typical crop field in TCAA is divided into several crop beds separated by water furrows. Each crop bed is further divided into 16-20 crop rows with 101cm center-to-center distance from one another and raised approximately 25cm above the alleys.

Fertilizer Management

Successful potato production in TCAA has been accomplished for several years by the application of large amount of fertilizers. Nitrogen, being the most limiting nutrient, is typically applied in excess of the recommended amount. Average nitrogen application rate by producers in TCAA potato fields is 285 kg/ha (Hutchinson, 2005) whereas the recommended rates of fertilization in the area are 224:168:67 kg N: P_2O_5:K_2O per ha under soil test results of medium soil phosphorus content (Hutchinson et al., 2007). Although P_2O_5 is recommended only when the soil test value is 'Medium' or 'Low', growers may prefer to apply additional amount of phosphorus to their crop as an insurance against crop failure. Fertilizer applications are typically in two installments. Complete dose of P_2O_5 and half the recommended dose of N and K_2O are applied at the time of planting. The remaining N and K_2O amounts are applied 35-40 days after planting (Hutchinson et al., 2007). Due the low nutrient holding capacity of the soil, soluble N can leach into the perched water table and become unavailable to the crops. Application of fertilizers in split doses increases the bioavailability of N and K_2O by decreasing leaching and ensures better production even under the conditions of leaching.

Irrigation Management

In seepage irrigation, the water table is maintained at 20-25cm below the furrows between crop rows (Campbell et al., 1978) during the entire cropping period. Water is supplied to the water furrows instead of applying to individual crop rows. As the water flows along the furrows, it infiltrates down and raises the perched water table. Water then moves into crop root zone by capillarity and subsurface lateral flow (Smajstrla et al., 2000). Any undesirable rise in the perched water table is controlled by means of a check-gate constructed at end of the ditch.

The subsurface seepage irrigation practiced in TCAA is inherently an inefficient system because a large quantity of water is needed to maintain the water table at desired depth. According to Sjmastrla (1991), efficiency of seepage irrigation system can vary from 20-70%. The magnitude of water-loss from the system is both time- and site-specific because it depends on the permeability and continuity of the restrictive layer, and the management practices of the surrounding fields.

Environmental Impacts

Successful agricultural production requires abundant use of fertilizers coupled with adequate supply of water to the crops. On the other hand, these two important management considerations increase the potential of nutrient loss, especially in high rainfall areas. The average annual precipitation in the area is approximately 125cm (FAWN, 2008). Summer rainfall is predominantly through short duration thunderstorms due to which a high potential for leaching exists. Application of N fertilizer can often exceed the recommended amounts as insurance against farmers' perceived risk of crop failure (Munoz et al., 2008). Due to fluctuating shallow water table, fertilizers can be lost rapidly from crop root zone (Bonczek and McNeal, 1996). Nutrient loading into surface water bodies promotes rapid algal growth and accelerates the process of eutrophication (SJRWMD, 1996). Nitrogen contamination of LSJR has been increased rapidly in recent years and it is estimated that 5 to 20% of the total nutrient pollution in LSJR can be attributed to the row crops of TCAA (SJRWMD, 1996). With a goal to increase fertilizer application efficiency and reduce leaching loss, BMPs have been implemented in the

TCAA to comply with the Total Daily Maximum Load (TMDL) set under the Clean Water Act (WCA).

Physical characteristics determine how much water soils can hold and can supply to crop roots, affecting the efficiency of a water management system. Permeability of underlying soil horizons has a significant effect on soil hydraulic properties (Blume et al., 1987). According to Ezeaku et al (2006), the potential for ground water contamination and the use of perched water for agricultural production in an area depends largely on the physical properties of the soil profile and the underlying hardpan layer. It is therefore important to characterize the soil profile with respect to its physical properties. The knowledge on soil properties is also important for the assessment of alternative water and nutrient management practices in the area. Soil properties vary significantly both in horizontal and vertical direction. Field scale spatial variability study in these properties is therefore important in developing site specific farming practices which can reduce the potential of NPS pollution in LSJR.

Objectives

The objectives of this study were to-

1. determine the physical and hydraulic properties of soils in the TCAA
2. study the field scale variation in soil physical properties both horizontally and vertically
3. evaluate the potential of water loss from the agricultural fields of TCAA under the conventional seepage irrigation system

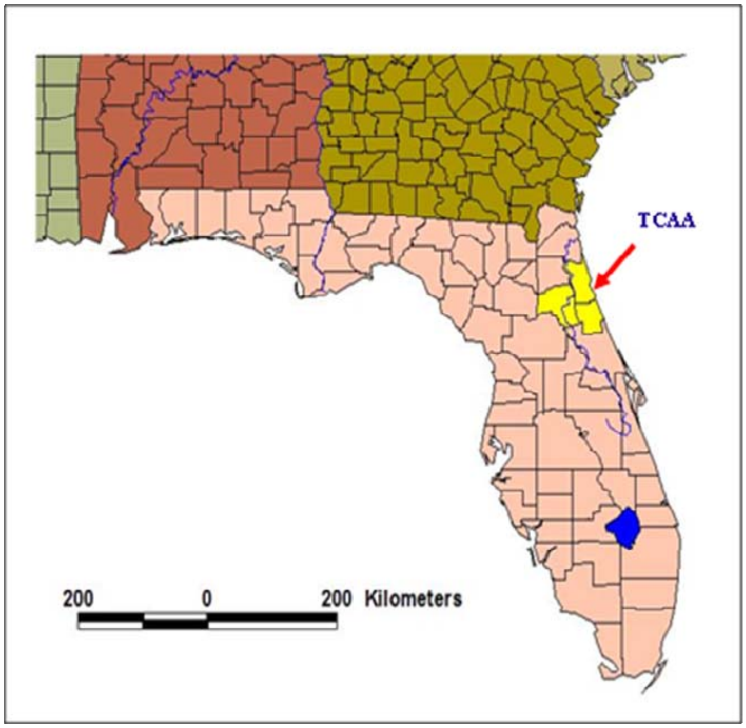


Figure 1-1. Tri-county agricultural area

Figure 1-2. Water table control/drainage channel

CHAPTER 2
LITERATURE REVIEW

Seepage Irrigation

Most of the gravity-flow irrigated farms in Florida are under seepage irrigation system, as surface irrigation is rarely used in the state (Sjmastrla and Haman, 1998). Seepage irrigation or simply subirrigation is preferred because of its cost effectiveness and low maintenance requirement (Haman et al., 1989) while being simple to operate and effective for crop production (Bonczek and McNeal, 1996). Seepage irrigation system also has another advantage; the open ditches commonly used for irrigation also function as drainage systems (Sjmastrla et al., 1984). Due to a significant increase in the use of water resource as well as the cost of installation and operation of irrigation systems, the design of efficient water management system has become more critical than before (Rosa, 2000). Under such a situation, conventional seepage irrigation may not be sustainable as it consumes a large amount of water. Clark and Stanley (1992) compared the conventional ditch conveyance seepage irrigation with a fully enclosed subirrigation system and reported that the fully enclosed system was more efficient in uniform water distribution as well as drainage in subirrigated fields. Sjmastrla et al (1984) studied whether the water use and energy consumption efficiency of conventional seepage irrigation could be increased by controlled water applications using an automatic float controller. Although their study showed only a small increase (8%) in the efficiency, it was pointed out that a proper and timely water table control system could have had better efficiency over the conventional system.

Sjmastrla et al (2000) conducted another experiment to study the feasibility of using automatic subsurface drip irrigation (SDI) system in a potato field in the TCAA. They reported that SDI system controlled the water table more accurately at the desired level and used approximately 36% less water than the conventional seepage system, but consumed 70% more energy, producing a similar yield as the seepage system. Cost effectiveness of the conventional seepage system and the lack of significant increase in the yield under SDI system therefore did not provide an economic incentive to growers towards changing the irrigation method to SDI.

Subsurface Lateral Water Flow

Subsurface lateral flow of water (SLFW) is a process by which water is transmitted laterally through the soil profile. This flow is usually ignored or misinterpreted while studying the water balance of an area (Styles and Burt, 1999). However, SLFW from fertilized agricultural lands is a major mechanism for moving nitrates and other agrochemicals to ground and surface water (Starr et al., 2005). Shaw et al (2001), from a tracer study in the upper coastal plain of Georgia, reported the lateral movement of an applied tracer, which had occurred due to reduced hydraulic conductivity of lower horizons. Subsurface horizons having reduced hydraulic conductivity impeded the downward flow thus encouraging lateral movement.

Occurrence of lateral flow though the permeable horizons overlying such water restrictive horizons has been reported in different studies (e.g. Blume et al., 1987; Bosch et al., 1999). According to Reuter et al (1998), rapid solute transport via perched water table occurs in the permeable horizons overlying hydraulically restrictive fragipan or argillic horizon. This may hasten the offsite carriage of agrochemicals thereby impairing the water quality of surface and subsurface water bodies. In a recent tracer study performed in the TCAA (Mylavarapu et al., 2008), it was revealed that a tracer injected into a 4.7ha field was quickly removed by subsurface lateral pathways. In a typical seepage irrigated field of TCAA, where a constant depth of perched water table was maintained throughout the crop seasons, the SLFW is typically governed by a steady state darcian flow given as follows.

$$Q = K_s \, i \, A \qquad (2\text{-}1)$$

where,

Q = Rate of subsurface lateral flow,

K_s = Saturated hydraulic conductivity of the soil

i = Hydraulic gradient of the field given as

$$i = \frac{dh}{dl} = \frac{h1 - h2}{dl} \qquad (2\text{-}2)$$

where,

h1 and *h2* are the observed head at the start and end points of the fields respectively. The head is the column of perched water above the impervious layer.

A = Cross-sectional area perpendicular to the direction of the flow

The application of Darcy's equation implies that K_s of the soil profile and hydraulic gradient of the field have a great influence on the total amount of SLFW from a field. According to Wilson et al (2002), the subsurface water movement is highly variable and site specific. Water moves rapidly form certain areas while little or no subsurface flow occurs in other areas, which is primarily due to the high variability in K_s of the soil profile.

Nutrient Problem in LSJR

Irrigated agriculture notably increases crop productivity, but consumes high volumes of water and may induce off-site pollution of receiving water bodies (Causapé et al, 2004). According to USEPA (2004), agricultural NPS pollution is the leading source of water quality impacts to surveyed rivers and lakes, the third largest source of impairments to surveyed estuaries and a major contributor to ground water contamination and wetlands degradation. According to the St. Johns River Water Management District (SJRWMD) (1996), approximately 5 to 20% of the nutrient pollution in LSJR is attributed to the row crop agriculture of TCAA. The most severe algal blooms in the LSJR have been observed in the freshwater reach near Palatka which coincides with the peak runoffs from the potato fields in the TCAA (SJRWMD, 1996).

In the past, there have been a few studies regarding nutrient leaching from the subsurface seepage irrigated fields of TCAA. With the growing concerns of NPS pollution due to agricultural activities in the area, researches have been directed towards reducing the leaching losses and consequent NPS pollution. The main goals of these studies have been to develop the BMPs for seepage irrigated vegetable and potatoes in TCAA thereby reducing potential of nutrient losses. These BMPs are promoted in the area through a cost share program developed by SJRWMD (Livingston-Way, 2000), which provides the growers an economic incentive to voluntarily adopt BMPs without incurring any loss (Hutchinson et al., 2002). The BMPs implemented in the area include a defined set of fertilizer and water management practices aimed in increasing nutrient application efficiency while reducing leaching losses. Other practices such as monitoring water table depth through observation wells and proper crop rotation are also parts of the BMPs.

Soil Physical Properties

Moisture Retention Characteristics

Determination of soil moisture release characteristic curves is one of the most important measurements for characterizing soil hydraulic properties as it will allow for assessment of water storage capacity of soils (Townend et al., 2001). According to Pachepsky et al (2001), soil moisture retention data is used in simulations of water and chemical transport in soil, estimations of water holding capacity and irrigation requirements, and assessment of water sorptivity to predict infiltration rates. Unger (1975) indicated that soil moisture storage capacity had a great influence in the management of irrigation water and precipitation for crop production. According to Hanks (1992) soil moisture characteristic curves are very nonlinear in nature. This means that for a given change of water content (θ) at one value, the change of matric potential (ψ_m) will be different than at another value. According to Hillel (1971), the amount of water retained at low tensions depends primarily on the pore-size distribution and soil structure whereas water retention at the higher pressures is due to adsorption and is influenced by soil texture and the surface area of clay fraction. Sandy soils contain large pores therefore most of the water is retained at low suctions. Clayey soils, on the other hand, release small amount of water at low suctions and retain a large proportion of water even at higher suctions. Jamison and Kroth (1958) indicated that, the order of available moisture storage capacity of particle-size fractions should be 'coarse silt>fine silt>clay>fine sand>coarse sand' from theoretical considerations. Hence, an increase or decrease in any textural components tends to change available storage capacity by its influence upon pore size distribution.

Compaction of a soil reduces the total pore spaces, particularly macropore spaces that retain water at low suctions. According to Hillel (1998), saturated water content and the initial decrease of water content with the application of low suction are diminished due to compaction. Reeve et al (1973) reported that D_b exerted a profound influence on water retention properties of soils but the effect varied between texture groups and horizons.

Saturated Hydraulic Conductivity (K_s)

Saturated hydraulic conductivity of soils is the ability to transmit water (Klute and Dirksen, 1986) when all the soil pores are filled with water. This is a very important soil water property from the standpoint of irrigation and drainage as well as environmental pollution. Information on K_s of surface soils is critical for agronomic and water management strategies including the design of irrigation systems. On the other hand, the knowledge on K_s of the shallow hardpan present in a soil profile is important from both agronomic and environmental perspectives as it influences the extent of solute and chemical movement through the soils. Surface water run-off, erosion, and deep percolation are directly affected by K_s of the soil (Suleiman and Ritchie, 2001).

Although K_s is a soil property that is difficult to obtain (Ahuja et al., 1993), it is needed to run the water balance of many crop simulation models (Suleiman and Ritchie, 2001). Saturated hydraulic conductivity of soils is determined by the PSD and the level of compaction. Soils dominated by sand particles have high K_s due to the presence of large number of macropores while in clay dominated soils, the opposite is usually true. According to Nakano and Miyazaki (2005), K_s is intrinsically related to the macropores in the soils and not necessarily related to the average soil porosity or average D_b. Because of the influence of macropores, the variation of K_s is mostly higher than other physical properties. Mohanty et al (1994) observed different variability for the K_s values measured with different methods and indicated that such variability had occurred due to the presence and absence of open ended macropores in the soil as well as due to variable soil compaction during core extraction. Some scientists have also indicated that the variability of K_s tends to decrease as the sampling volume increases (e.g. Anderson and Bouma, 1973; Bouma 1982). The number of continuous macropores in large samples is likely to be less than in small samples which can produce uniform K_s observations.

Spatial Variation in Soil Properties

Physical properties of the soils such as PSD, K_s, D_b and, water retention vary from one location to another within an area which tends to be correlated in space, both horizontally and vertically (Warrick et al, 1986). According to Iqbal et al (2005), spatial variability of soil physical properties within or among agricultural fields is inherent in nature due to geologic and pedologic soil forming processes but some of the variability may be induced by tillage and other management practices. Due to within field variation, uniform management of fields may often result in overapplication of inputs in low yielding areas and underapplication of inputs in high-yielding areas (Ferguson et al., 2002). Fine scale information on the spatial variability of soil is therefore necessary for implementing site specific management approaches (McBratney and Pringle, 1999). Spatial distributions of soil properties at field and watershed scales may affect yield potential, hydrologic processes, and transport of nutrients and chemicals to surface or ground water (Cambardella et al., 1994). According to Russo (1986), it is important to analyze the spatial distribution of soil properties in the field in order to suggest improved irrigation management schemes. Gupta et al (2006) indicated that an understanding of spatial and temporal variation in hydraulic properties of soils was crucial for characterizing the rate of water flow and solute transport through the soil profile. According to Mulla (1988), field scale modeling of attributes like infiltration and solute transport requires the knowledge of spatial patterns in soil water content, K_s and evaporation.

Camberdella et al (1994) studied the spatial variability of important soil properties and classified their spatial dependence as weak, moderate, and strong based on the ratio of *nugget* to *sill* expressed as the percentage. They found a moderate spatial dependence of the D_b along with several other soil properties. Gaston et al (2001) reported that the clay content of a surface soil in Mississippi delta was described by spherical semivariogram model. The *range* of the %clay was 220m and the *nugget* variance was approximately 30% of the total semivariance.

Study of the spatial variation of soil properties over a large area many not always be feasible due to various constraints. Due to this reason, several experiments have been conducted in field scales to study the spatial variation of soil properties. For example, Jung et al (2006) studied the spatial variability of soil properties in a 4ha field using 30m× 30m grid sampling and reported that clay and silt contents at 15-30cm depth of the soil profile were spatially autocorrelated at a separation distance of 40m. Duffera et al (2006) studied the spatial variation of texture, SWC at different pressures, K_s, and D_b in a 12ha field in North Carolina. They found moderate to strong spatial autocorrelation in the soil properties sampled in 60m grid intervals at five depths up to 72cm. The *range*s of clay content and D_b varied from 63m to 411m while the *range* was not obtained for the K_s at 60m sampling distance. Spatial dependence was strong at the first 4 depths while it was moderate at the last sampling depth (72m). Sahandeh et al (2005) studied the spatial and temporal variation of various soil nitrogen parameters including clay content with the help of 63 samples collected at 8m ×13m from a 2.5ha corn field. They reported that the spatial characteristics of soil texture and other related properties varied greatly with depth and landscape position.

Mulla (1988) intensively sampled two 660m long transects at 20cm spacing and analyzed the spatial variability of texture, SWC, and surface soil temperature using spherical semivariograms. Although different *ranges* of spatial variation in sand, clay, and SWC were obtained in the two transects, all the values were between 60m and 100m. No *nugget* effect was obtained for the water content in both transects. However, the *nugget* effects for clay and sand contents ranged from <3% to 26% and 11% to 13% respectively, indicating that the strength of spatial association in the properties was variable in the two transects. Cemek et al (2007) studied the K_s, P^H, exchangeable sodium percentage (ESP), and cation exchange capacity (CEC) of soil samples collected from 60 sampling sites at four depths. They reported that K_s had the strongest spatial dependence while it was more variable at the top soil layer

These literatures indicate that the information on physical properties of soil profile characterized by high water table and a shallow hardpan layer is still lacking. Therefore, the objective of this experiment was to study the spatial variation in soil texture, D_b, and K_s of the soil profile and the shallow hardpan of a typical seepage irrigated field in the TCAA.

CHAPTER 3
MATERIALS AND METHODS

Site Description

The study was performed in a 4.7ha (approx.260m × 182m) seepage irrigated field of UF/IFAS' Research and Demonstration Site located at Hastings, Florida. The soil at the experiment site is classified as Ellzey fine sand (sandy, siliceous, hyperthermic, arenic ochraqualf; 90-95% sand, <2.5 % clay, <5% silt) (USDA, 1983). The field is planted to spring potato, which is the main crop, followed by sorghum or corn during summer as the cover crops. The field resembled typical TCAA agricultural fields and consisted 14 crop beds each approximately 17.2m wide. Each crop bed was further divided into 16 rows raised approximately 25cm above the alleys (furrows between each crop row). The irrigation furrow separating each crop bed was approximately 1.01m wide. The distance from the first crop row of one bed and the last row of the adjacent bed was approximately 3m which allowed for the movement of farm vehicles, particularly during the cropping season.

The irrigation of the experimental field was through seepage system as described previously. During crop seasons, the water furrows continuously conveyed water along the bed-rows towards a drainage ditch constructed perpendicular to the field in the east-west direction. A check gate installed at the western end of the ditch controlled the level of water. The level of water in the drainage ditch in turn controlled the perched water table depth under the crop beds as determined. A few inches below the crop root zone, the soil profile was saturated throughout the cropping season and water was supplied to the root zone by upward capillary movement.

Sampling Design

Representative soil sampling is critical to the success of any field scale study. According to Petersen and Calvin (1986), the purpose of sampling is to estimate the various parameters of a population with accuracy. A sampling plan that fails to resemble the entire population in any one of the attributes of interest will result in inconsistent results. Therefore, a best suited sampling design that falls within the research bounds should always be employed, depending on the nature and variability of the attributes. Since soils are highly heterogeneous and characterized by high variation, it is necessary to consider the nature of the variation during sample collection for the proper representation of a particular soil population (Petersen and Calvin, 1986).

Soil samples can be collected either randomly from the study area or in a systematic way. Random sampling is the easiest method in which soil samples are collected at randomly selected locations throughout the study area. Random sampling is unbiased and hence every point within the study area has an equal chance of being sampled. However, in several studies random sampling may not be appropriate especially when some of the soil properties under consideration are not distributed uniformly over the entire study area. Under such a condition, random sampling is likely to miss the true variation of soil properties and therefore a different sampling schemes needs to be adopted in order to address the issue.

In our case, regular grid sampling scheme was used to collect soil samples from the soil profile. Grid sampling is usually used when intensive sampling is necessary from a relatively smaller area so that the extent of spatial variation in the properties can be represented in the field. The experimental field was first divided into 70 square grids of size 26m × 26m followed by locating the sample spots at the center of each grid. The width of the crop beds in the TCAA fields vary from 18 to 24m (16-20 crop rows). Therefore, the sampling scale of 26m was considered suitable to analyze whether any spatial autocorrelation in soil properties existed among the crop beds.

The sampling points in the field were determined with the help of measuring tapes. In order to locate the sampling spots, first a point at the southeast corner of the field was selected as the reference point. The boundary lines of the field were then determined by the right-angled triangle method using measuring tapes. On both the boundary lines, a point at 13m from the corner was flagged since the first set of sampling-points was located at 13m from the boundaries (Figure 3-3). Using the measuring tapes, a perpendicular line passing through the flagged point on one of the boundary line was located. The sample spots on the line were then located by stretching the tape along this perpendicular line. The process was repeated for all other sampling locations at every 26m.

Sample Collection

Soil samples were collected from the soil profile up to 1.2m at five different depths: 22.5cm, 45cm, 67.5cm, 90cm, and 120cm. At the first three depths, undisturbed soil cores were collected using a core sampler along with bulk soil samples. However, undisturbed soil samples could not be collected at the last two depths due to excessive moisture content in the soil profile. Only disturbed soil samples were therefore collected at these two depths. In order to collect the bulk soil samples from 90cm and 120cm depths, first a hole was drilled down to the sampling depth in the soil profile with the help of a tractor-mounted augur and the sample was taken using a hand augur. After sample collection, the actual coordinates of the sampling- points in the field were recorded using a GPS device (Trimble Inc.). The recorded coordinates were then differentially corrected in order to achieve high precision.

Sample Analyses

The soil samples were analyzed for their physical properties at the Soil Moisture Laboratory of Soil and Water Science Department, University of Florida. The measured physical properties included the texture, D_b, K_s and soil moisture characteristic curves.

Particle-Size Analysis

The PSD of the soil samples was determined for all the five depths using the hydrometer method (Gee and Bauder, 1986).Dry and sieved soil samples were first saturated with water in beakers and 27% hydrogen peroxide solution was added to the soils for digestion of organic matter, which took approximately 2-3 days. After digestion, the samples were oven dried and subject to dispersion by adding sodium hexametaphosphate solution. The content of the cylinder was then stirred for 3 minutes to disperse the soil particles. The final volume of the suspension was brought to one liter by adding water. The cylinder was then closed and shaken with hands to ensure proper dispersion. A hydrometer was dropped gently into the suspension and the particles were allowed to settle down for 40 seconds. This was the time when all the particles >5 mm were settled down at the bottom of the cylinder. The density of the suspension at 40 seconds was measured from which the combined silt and clay content was obtained.

After 40 seconds the cylinders were shaken again, hydrometers were dropped into each suspension, and left for two hours. By this time most of the silt particles present in the soil would be settled down at the bottom and the density of the suspension would solely be due to the clay particles suspended in water. From this hydrometer reading, %clay was calculated. Sand content (%sand) and silt content (%silt) were then obtained by using the two observations.

Bulk Density (D_b) and Saturated Hydraulic Conductivity (K_s)

Bulk density of the intact soil cores collected at the first three depths was determined as described in (Blake and Hartge, 1986). The cylinders containing intact soil cores were oven dried after recording the combined weight of the cylinder and the soil. The oven dried cylinders with soil were weighed in order to calculate the mass of oven dry soil, which was then used to calculate D_b.

Saturated hydraulic conductivity was determined by constant head method (Klute and Dirksen, 1986) which is described in the Darcy's equation. The cylinders with soil were covered by cheese cloth at one of the ends and saturated overnight. A constant head 3cm was maintained for 5 minutes at the top of each saturated soil core and the volume of discharge from the lower end was measured. The K_s values were calculated using the following expression as given in Klute and Dirksen (1986).

$$K_s = \frac{QL}{At\,\Delta H} \tag{3-1}$$

where,

Q = volume of discharge collected
L = length of the soil core
A = cross-sectional area of the core
t = time
ΔH = hydraulic head difference across the soil core

The D_b and K_s of the soil samples at 90cm and 120cm depth were determined from the reconstructed samples as undisturbed cores could not be collected due to field conditions. The bulk samples were reconstructed by careful trampling with hands in the laboratory. In order to achieve high structural integrity, the bulk samples collected in the field were maintained as intact as possible. While reconstructing a core was inserted into the soil and pressed gently from both the sides to maintain the integrity of the core. Care was taken not to apply very high pressure so that the total porosity of the samples would not decrease significantly.

Moisture Retention

The soil moisture retention by the undisturbed soil cores at different pressures ranging from 0kPa to -1500kPa were determined by using tempe cells for low pressures (0kPa to -33kPa) and, pressure chambers for high pressures (-500kPa and -1500kPa). The method comprised of repetitive weighing of the tempe cell assembly (which included the soil core with the cylinder, a porous ceramic plate, two rubber rings and the two tempe cell caps) before and after applying a particular pressure to the soil.

Tempe cell method used to determine the moisture retention is based on the principle that when the pressure inside the tempe cell is increased above the atmospheric level, it forces the soil water to move out through the pores present in the ceramic plate. The ceramic plate was boiled for several minutes to expel any air remaining in the pores prior to assembling the tempe cells. After assembling the cells, they were saturated over night in order to bring the soil water potential to zero. As the positive pressure was applied, water was extracted from the pores. Larger pores release water earlier than the smaller pores as micropores hold water with greater tenacity. Continuity of the pores between the soil sample and the ceramic plate was maintained as the pressures are increased gradually starting at saturation point.

Positive pressures were created by increasing the water level in the columns as appropriately as required. After a through extraction of moisture and reaching equilibrium at each pressure, the soil sample assembly was weighed and then exposed to next higher pressure. After reaching the equilibrium at -33kPa pressure, the assembly was weighed and then disassembled in order to record the combined weight of the soil core and cylinder. The rings were then resaturated and exposed to higher pressures in the pressure chamber followed by weighing in the end of each step. Finally, all the samples were oven dried in order to get the weight of the oven dry soil. Bulk density and the volumetric water content (θ_v) at respective pressures were determined from the data collected.

Soil moisture release curves were determined only for the first three depths (22.5cm, 45cm, and 67cm). Due to shallow water table depths maintained during potato season, undisturbed samples could not be collected from 90cm and 120cm depths. Twenty one soil cores were randomly selected from each set of samples at each depth for a total of 63 samples for determination of moisture retention characteristics.

Statistical Analysis

Comparison of depth wise measurements of PSD, D_b, K_s and moisture retention was performed using SAS (SAS Inc., 2005) and R (R Development Core Team, 2008) statistical software. The distribution and variation in the soil properties was evaluated using general statistical tools. Depth wise comparison of the %clay, D_b, and K_s was performed by ANOVA followed by Tukey's test.

Geostatistical Analysis

Classical statistical approaches assume that the measurements of soil properties are independent of space, that is, they are randomly distributed. Since the soil properties are spatially autocorrelated, these techniques may not be able to explain the underlying variation in the attributes. Spatial autocorrelation of soil properties renders classical statistical tools inadequate to explain the variation in those properties. The variation of soil properties with respect to space can be better explained by geostatistical techniques. Geostatistical study of an attribute assumes that the observations in space have some connection or continuity among themselves (Gutjahr, 1985). Geostatistical techniques are based on the theory of regionalized variables and stationarity which provide theoretical basis for analysis of spatial dependence of the attribute under study using spatial autocorrelation or semivariograms (Trangmar et al., 1985).

Spatial dependence of physical properties of the soil profile including hardpan was studied using geostatistical methods. Spatial dependence in the soil properties are commonly described with a semivariogram, which study spatial structure in the data distribution (Kravchenko, 2003). Semivariogram is the plot of semivariance against the separation distance between the samples, also called separation distance or Lag. Semivariance is defined as the half of the estimated squared differences between the sample observations at a given *Lag* (Trangmar et al., 1985). The estimated semivariance at a given *lag* is given by the following equation.

$$\gamma(h) = \frac{1}{2N(h)}\sum[A(Xi) - A(xi+h)]^2 \tag{3-2}$$

where,

> *A(Xi) and A(Xi+ h)* are the observations of the regionalized variable *A* at locations *X* and *X+h* respectively, *h* is the *lag* and *N* is the number of pair of observations separated by the *lag h*.

Semivariograms, thus, illustrate the change in the semivariance of the soil property data with changing *lag* distance thus giving an idea of the extent of spatial autocorrelation in the measurements.

Experimental semivariograms were created at all the five depths for D_b and K_s while for %clay, semivariograms were created only at 90cm and 120cm. Semivariograms of %clay at 22.6cm, 45cm and 67.5cm could not be created due to severe skewness in the data. Prior to producing the semivariograms, the datasets were tested for normality using Shapiro and Wilk Test (Shapiro and Wilk, 1965). Any variable that deviated significantly from normality was log-transformed in order to bring the variable close to normality.

The experimental semivariograms produced for each property were fitted with a best fitting model using wherever possible using Gamma Design Software in order to obtain the semivariogram parameters *nugget, sill and range*.

Potential Water Loss from the Soil Profile

Due to the nature of the water management system, a large amount of water applied to the fields of TCAA is lost without being utilized. A significant portion of drainage is contributed by subsurface lateral flow because there is no vertical movement due to the occurrence of the hardpan and the shallow water table. Since system reaches a steady state soon after initiating water application to the crop, the total amount of water applied is equal to the total amount drained plus the total amount lost by evapotranspiration (ET). Potential loss of water from the experimental field during potato seasons was therefore calculated using the ET, total rainfall (RF) and the total amount of irrigation applied during the seasons. Rainfall data of Hastings area was obtained from Florida Automated Weather Network (FAWN, 2008) for the required time periods. The data was then used to calculate average daily rainfall for approximately four months time period. Evapotranspiration rates for potato was calculated using the potato crop-coefficient (K_c) reported by Singleton (1990) where different K_c values for February, March, April, and May months corresponding to potato growth stages were reported. The ET values for the four months crop growth period were therefore calculated using the corresponding K_c and ET_0 values which were then used to calculate the average daily ET rates in mm per day (mmd^{-1}).

At steady state, there is no vertical movement of water which implies that the drainage is only in the lateral direction. Under seepage irrigation drainage is considered to be predominated by subsurface lateral flow. Therefore the total amount of drainage from the field can be expressed as follows-

$$Q_d = Q_i - [ET - RF] \qquad (3\text{-}3)$$

where,

Q_d = Rate of drainage (mm d^{-1})
Q_i = Rate of irrigation (mm d^{-1})
ET – RF = Net rainfall (+/-, mm d^{-1})

Average daily loss of water calculated for the experimental field therefore included the average daily precipitation received during the potato seasons.

Figure 3-1. Potato crop planted in beds separated by a water furrow

Figure 3-2. Experimental field

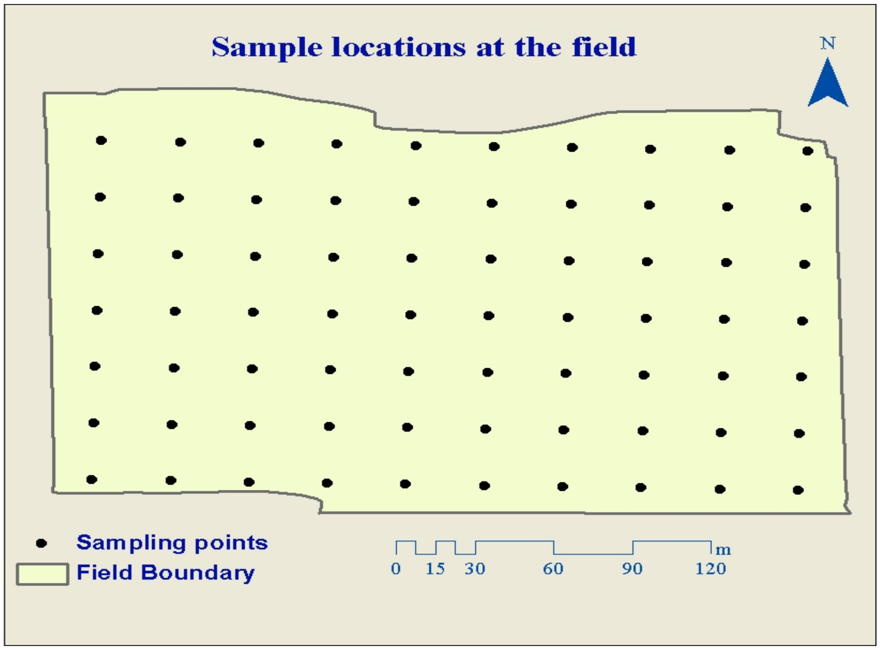


Figure 3-3. Soil sampling locations in the field

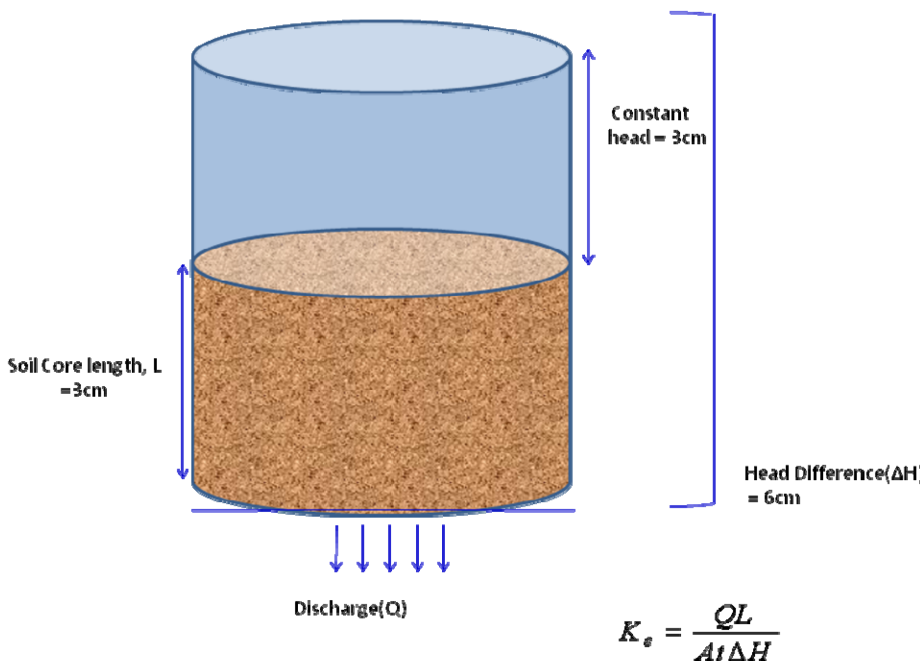


Figure 3-4. Schematic presentation of K_s determination in the lab

CHAPTER 4
RESULTS AND DISCUSSION

Statistical Analysis

Particle-Size Distribution

The summary statistics (average, variance, maximum and minimum, and coefficient of variation) of the PSD at the five depths are presented in Table 4-1. At all sampling depths, the average sand content was >90%. However, the average %sand content decreased by 6% from 22.5cm to 120cm depth while the average clay content increased by >5%. The maximum amount of clay recorded was 11.64% at 120cm depth. The average %silt was low (<2%) at all sampling depths with most of the samples having 0-1%. Higher clay content in subsurface soil layers was also reported by Bosch et al (1999) in a sandy loam profile of Georgia, where a prominent layer of clay was found in the soil profile from 1 to 4m depth which was responsible for low K_s and high D_b. Increased clay content of subsurface soil layers was possibly due to gradual translocation and deposition of the clay particles caused by fluctuating water table. Deposition of fine clay particles tends to decrease K_s of a soil horizon because fine clay particles can occupy void spaces between coarse soil particles thus reducing the permeability of the horizon.

Although the maximum variation of %clay was observed at 120cm depth, the coefficient of variation (CV) was highest in the three intervening depths between 22.5cm and 120cm. The magnitude of CVs decreased in the following order- 90cm>67.5cm>45cm>120cm>22.5cm. The least CV and the least average %clay at 22.5cm depth indicated that the soil at the surface was predominantly sandy throughout the field. On the other hand, higher average %clay and low CV at 120cm suggested a uniform distribution of clay at the hardpan layer. High CVs of the intervening soil layers was probably because of the entrapment of clay particles during vertical translocation.

The frequency distributions of %clay at the first four depths were highly skewed to the right, showing a maximum frequency in the range 1 to 4%. On the other hand, the distribution at 120cm was relatively symmetrical. The frequency of %clay observations at 120cm was highest in the range 6 to 11%, which further affirmed that the clay particles were uniformly distributed at the hardpan layer.

Analysis of variance of PSD data showed that the average %clay at upper three sampling depths were similar while the values at 90cm and 120cm were significantly higher than the first three depths (P-value < 0.001). At the same time, the average %clay values at 120cm depth were significantly higher than the values at 90cm.

Bulk Density

The summary statistics for D_b is presented in Table 4-2. Bulk density increased significantly with increasing depth (P-value < 0.05). However, the increase was highest at 120cm depth supporting the results of observed PSD data. Variation in D_b values was relatively lower in the horizontal direction (CV = 3-7%) than in the vertical direction (CV = 10%). These values were similar to the CV values reported by Warrick and Nielsen (1980). Similar to %clay, D_b exhibited highest variation in the two intervening soil layers (67.5cm and 90cm) while the least variation was observed in the 22.5cm and 120cm samples. Although the CV values of %clay and D_b differed significantly, depth wise change in variability was similar in both properties (Figure 4-2 and Figure 4-5).

Saturated Hydraulic Conductivity

Summary statistics for K_s is presented in Table 4-2. Saturated hydraulic conductivity showed a relatively larger variation at the first four sampling depths while it was slightly lower at 120cm depth. The CV for the K_s ranged from 61 to 77%. Saturated hydraulic conductivity of the soils is regarded as a highly variable soil property with possible CV at >100% (Warrick and Nielsen, 1980). Relatively lower CV for observed K_s values in the soil profile therefore indicated that the number of samples was adequate to provide a good estimation of the K_s of the whole population.

Despite the higher variation in K_s values within each of the first four sampling depths, the average K_s among the depths was similar. At 120cm depth however the average K_s value was significantly lower. Lower K_s values at 22.5cm depth were possibly because of temporary compaction tractor wheels or because of the organic matter content present in the soil.

Average K_s for 120cm was 3.8 $cmhr^{-1}$ although several values ranged from 0.13$cmhr^{-}$1 to 2$cmhr^{-1}$. In contrast, samples at 90cm and above had significantly higher K_s values. The sudden increase in %clay, D_b, combined with a decrease in K_s values at 120cm depth suggested that the hardpan layer in the soil profile began at a depth between 90cm - 120cm from the surface.

Moisture Retention

Average θ_v at field capacity (-33kPa) was approximately 15% while at permanent wilting point (-1500kPa), it was close to 5% or less at all three depths. There was no significant difference among the three depths with respect to average θ_v values at 0kPa, -33kPa, -500kPa and -1500kPa pressures. At 0kPa (saturation), θ_v increased with depth while at higher pressures (-500kPa and -1500kPa), the water content decreased. At -33kPa (field capacity), on the other hand, the distribution of θ_v at 67.5cm depth was quite dissimilar from the distribution at other three pressure levels. Although the median θ_v at that depth was close to the median value at 22.5cm, greater number of observations lied within the lower 50 percentile of the distribution, indicating that despite the observed difference in θ_v distribution, the values tended to decrease in the subsurface at higher pressures. This phenomenon not only supported the notion of the presence of macropores in subsurface layers but also suggested that the plough layer of the soil profile contained relatively higher amount of organic matter which helped to retain more water at higher pressures. At higher pressure, the water retained in the soil is mostly in the micropores, which is either due to %clay, %silt or organic matter content. However, as revealed by the texture data, the soil at 22.5cm depth was very low in %clay. Moisture holding capacity of the surface soil layer was enhanced possibly due to organic matter presence but at the subsequent two depths, lack of organic matter and increased bulk density without a corresponding increase in silt or clay content resulted in low microporosity. Therefore, water retention by the soil samples at 22.5cm could be attributed to the organic matter content which was routinely incorporated in the field every year.

Volumetric water content exhibited a high variability at all depths. The CV of θ_v was highest at -1500kPa (permanent wilting point) while the CV was lowest at 0kPa (saturation). This high variability could be due to either a small number of samples or due to the differences among soil samples in the number of macropores caused by small sample-size.

Moisture release curves for the three depths were characterized with the gradual decline in θ_v at lower pressures (0kPa to -33kPa) followed by a steep fall between -33kPa and -500kPa, confirming the low water holding capacity of the soils in the field. Moisture release curves at all the three depths were in close agreement with typical curves for highly sandy soils.

Spatial Analysis

Spatial variation analysis of the soil properties at each sampling depth was studied with semivariograms. Experimental semivariograms produced from the %clay, D_b and K_s data were fitted with a best-fit model in order to determine the parameters of the semivariograms. Semivariogram parameters were calculated by fitting the three common models which are given by the following formulae (Clark, 1979).

1. **Linear model**: This model fits a straight line through semivariogram points The linear model is given by

$$\gamma(h) = C_0 + m\,h \qquad \text{for } 0 \leq h \leq a \tag{4-1}$$

$$\gamma(h) = \gamma(h) = C_0 + C_1 \qquad \text{for } h \geq a \tag{4-2}$$

where,

m = slope of the best fit line
h = *lag* distance
C_0 = *nugget* C_1= *sill*
a = *range*

2. **Spherical Model**: This model is given by the formula

$$\gamma(h) = C_0 + C_1\left[\frac{3h}{2a} - \frac{1}{2}\left(\frac{h}{a}\right)^3\right] \qquad \text{for } 0 \leq h \leq a \tag{4-3}$$

$$\gamma(h) = \gamma(h) = C_0 + C_1 \qquad \text{for } h \geq a$$

3. **Exponential model**: This model is given by the formula

$$\gamma(h) = C_0 + C_1\left[1 - \exp\left(\frac{h}{a_0}\right)\right] \qquad \text{for } 0 \leq h \leq d \tag{4-4}$$

where,

d is the maximum distance over which the variogram is defined and $a_0 = a/3$

Semivariogram parameters *nugget, sill and range* provide valuable information on the spatial dependence of soil properties. The *Nugget*-to-*sill* ratio can be used as a measure of the strength of spatial dependence while the *range* is helpful in designing sampling schemes for future studies.

Experimental and fitted semivariograms for the log transformed %clay, D_b, and K_s are presented in figures 4-13, 4-14, and 4-15 respectively. The parameters, *nugget*, *sill* and *range*, of the semivariograms are presented in Table 4-4. The semivariograms of the %clay were calculated only for the 90cm and 120cm depth as the distribution of %clay in the upper three depths was severely skewed. More than 90% of the samples in the upper three depths had 3% or less of clay. The spatial variation of %clay at 90cm and 120cm was described by exponential and spherical models respectively. The *range* and *nugget* of the semivariograms were higher at 120cm than at 90cm depth whereas the *sill* was approximately equal at both sampling depths. On the other hand, the semivariogram was smoother at 120cm (R2 = 0.99) than at 90cm (R^2 = 0.82). Values of *nugget* and *range* of %clay were similar to those obtained by Iqbal et al (2005) in a deep soil horizon (1m depth) in Mississippi delta. Spatial variation of %clay at 90cm and 120cm depth could be attributed to the varying rates of illuviation in the profile. However, presence of large nugget effect at 120cm (44%) suggested that a denser sampling was necessary for explaining all the variation in %clay at 120cm.

Saturated hydraulic conductivity did not show any spatial autocorrelation at the sampling interval of 26m except at the 22.5cm depth (Figure 4-14). Even at 22.5cm, a high nugget effect was found while the range of spatial variation could not be defined. Semivariograms of the K_s values of lower sampling depths were hard to fit to any model and could be described as *pure nugget effects*. The K_s at these sampling depths behaved more randomly instead of showing any spatial autocorrelation. High nugget variance of K_s had also been reported in various the literatures (e.g., Gupta et al., 2006; Mallants et al., 1997; Bosch and

West, 1998). It was thus found in our case that, for the K_s values, classical statistical tools were more suitable than the spatial statistical techniques at the sampling interval of 26m. Sample collection at distance closer than 26m would probably be necessary to obtain the spatial association in K_s values

Semivariograms of D_b for the five sampling depths are presented in Figure 4-15. There was no spatial association observed in D_b at 22.5cm depth while a relatively better autocorrelation was observed at the subsequent three depths. Linear, exponential and linear semivariograms models were fitted, respectively, at 45cm, 67.5cm and 90cm sampling depths. The best correlation of the fitted model was found at 67.5cm depth (R^2> 95%) with *nugget* and *range* values of 0.005 (35%) and 135m respectively. However, at 45cm and 90cm depths, *nugget* variances were approximately 54% and 62% respectively indicating the existence of a weak spatial autocorrelation. Also, the *range* of spatial dependence was larger than the length of the field at 45cm and 90cm depths. At 120cm, D_b values exhibited a pure *nugget* effect or a random variation possibly because of coarser sampling resolution.

In summary, spatial dependence of soil properties differed based on the depth of sampling. At 120cm, there was no spatial autocorrelation in both the K_s and D_b values but the spatial variation of %clay was well described by a spherical model. The *range* of spatial autocorrelation was larger than the length of the field for some properties while the *range* was well defined for others. The *nugget* effect was prevalent in the semivariograms showing that the sampling interval of 26m was not adequate to explain the total spatial variation present in the properties. Sampling at a higher intensity was required for adequately explaining the field scale spatial variations in the soil properties.

Potential Water Loss from the Soil Profile

Above results confirmed that the soil profile of a typical field in TCAA was characterized by highly permeable sandy layers overlying an impermeable hardpan. The results also indicated that K_s was higher and more variable in the surface layers than in the hardpan suggesting the possibility of occurrence of macropore flow through the soil profile during storm events.

Subsurface hardpan layer present in the soil profile of the TCAA is being used advantageously for crop irrigation by creating a perched water table for several decades. Although the occurrence of shallow hardpan has been beneficial for easy and cost effective water management for crop production, the water management system itself however exposes a high potential of NPS pollution into nearby water bodies. In seepage irrigation, soil profile immediately below the root zone is saturated with the perched water and the root-zone is wetted through capillary rise from the perched water table. Continuous application of water into the water furrows allows for raising the perched water table level, which in turn is controlled by a riser board installed in the drainage channel. The height of the riser board is adjusted to facilitate precise controls on the water table level based on the water flowing from the spigots at the north-end of the field. Excess water will drain over the riser board, thus creating a steady state lateral subsurface water flow between the NE the SW edges of the field. Subsurface lateral flow is therefore the single most significant mechanism of water loss from TCAA fields during a cropping season.

In a recent study performed in the area by Mylavarapu et al (2008), the movement of an injected tracer was monitored in a seepage irrigated with a network of 90 wells over a six weeks period. It was reported that the tracer injected at NE-corner of the experimental field was quickly removed from the field by lateral subsurface flow. The distribution of tracer in the field and its subsequent removal by subsurface lateral flow was more rapid during the summer seasons when there was frequent rainfall, suggesting that the subsurface lateral movement was hastened by precipitation.

High precipitation that occurs in TCAA during the crop seasons can raise the perched water table up to the crop root zone, which potentially can flush a large amount of nutrient out of the crop root zone. Figure 4-16 shows the average water table depth in a typical TCAA potato field during the spring and summer seasons of 2006 and 2007 respectively. Due to shallow water table, even a relatively small amount of rainfall can raise the perched water table up to the crop root-zone, which dissolves the nutrients applied to the crop. When the water table settles down, the nutrients are transported below the root-zone and subsequently removed from the field by lateral transport.

Inefficient use of irrigation water and potential nutrient leaching are therefore the two most important disadvantages of seepage irrigation. In a typical spring potato season of approximately 100 days, the total amount of water applied to a seepage irrigated field is approximately 58.32 million L or 583,200 L daily.

Average daily ET (mmd^{-1}), average RF (mmd^{-1}), and average daily net-rainfall (ET-RF) (mmd^{-1}) during the potato seasons of 2006 and 2007 are presented in table 4-5. Approximate amount of water drainage (surface and subsurface) for the two years (2006 and 2007) is presented in table 4-6.

The crop coefficient for potato crop ranged from 0.41 in February to a high of 1.35 in April (flowering and tubering stage) before reducing to 1.28 in May before harvest stage. The calculated ET based on the K_c values during the crop growth period ranged from 1.028 to 5.635 mm d^{-1}. The average amount of water that was lost through lateral drainage (surface and subsurface) was 509,184 L d^{-1} or 50.9 million L in 100 days of a typical potato crop produced under seepage irrigation system in the TCAA.

Although a portion of drainage occurs as a surface flow, a significant amount of water drains as a lateral subsurface flow. The amount of water being lost through surface flow can possibly be determined by setting up measuring devices at the drainage end of each of the water furrows which can then be used to estimate the extent of subsurface lateral flow. Based on the above results, approximately 87% of applied water was lost via lateral flow (surface and subsurface), after meeting the ET demands during a typical potato season. This massive water loss from the fields also has the potential to remove plant nutrients from the crop root-zone. Because of the macroporous nature of surface soil layers, frequent storm events during the crop seasons can generate macropore flow thus hastening the leaching process. Therefore, such losses may likely result in lowered nutrient use efficiencies and crop deficiencies rather than water quality concerns due to significant dilution effect caused by the continuous application of large volume of irrigation water.

Table 4-1. Summary statistics of PSD at the five sampling depths

Soil Properties	Depth of Sampling(cm)	Average (%)	Variance	Max	Min	CV (%)
%clay	22.5	2.08	0.35	5.64	1.64	28.4
	45	2.09	0.903	9.00	1.64	45.5
	67.5	2.25	1.74	10.00	1.64	58.6
	90	4.04	6.34	11.00	1.64	62.3
	120	7.51	7.63	11.64	1.64	36.8
%sand	22.5	97.22	1.45	98.36	92.03	1.2
	45	96.88	2.59	98.36	88.00	1.7
	67.5	97.05	3.66	98.36	87.00	2.0
	90	94.33	10.05	98.36	86	3.4
	120	91.66	7.59	98.36	87.36	3.0
%silt	22.5	0.64	0.72	4.00	0.00	132.6
	45	1.01	1.28	4.66	0.00	112.0
	67.5	0.71	1.18	4.67	0.00	153.0
	90	1.61	1.63	6.00	0.00	79.3
	120	0.81	0.62	3.67	0.00	97.2

Table 4-2. Summary statistics of the θ_v, D_b, and K_s at the five sampling depths

Soil Properties	Depth of Sampling (cm)	Average	Variance	Max	Min	CV (%)
θ_v 0kPa ($cm3cm^{-3}$)	22.5	0.365	0.01512	0.6350	0.154	33.69
	45	0.360	0.00365	0.5011	0.259	16.78
	67.5	0.395	0.00485	0.5839	0.321	17.63
θ_v -33kPa ($cm3cm^{-3}$)	22.5	0.176	0.00955	0.3139	0.012	55.54
	45	0.155	0.00715	0.3041	0.0256	54.56
	67.5	0.157	0.01362	0.3325	0.0014	74.34
θ_v -500kPa ($cm3cm^{-3}$)	22.5	0.064	0.00044	0.1094	0.0333	32.78
	45	0.0482	0.00063	0.1247	0.0102	51.99
	67.5	0.056	0.00288	0.2158	0.0185	95.90
θ_v 1500kPa ($cm3cm^{-3}$)	22.5	0.047	0.00059	0.0907	0.0041	51.55
	45	0.036	0.00074	0.1136	0.0025	75.31
	67.5	0.047	0.00234	0.1845	0.0125	102.90
K_s ($cmhr^{-1}$)	22.5	13.099	103.68	52.920	1.05	77.73
	45	13.41	107.67	57.110	3.410	77.38
	67.5	15.288	104.49	36.680	1.05	66.86
	90	10.953	87.21	31.23	0.140	85.26
	120	3.833	5.586	14.670	0.130	61.66
D_b ($gmcm^{-3}$)	22.5	1.37	0.007	1.66	1.21	6.11
	45	1.42	0.0092	1.69	1.22	6.75
	67.5	1.52	0.0129	1.76	1.28	7.47
	90	1.60	0.0122	1.81	1.41	6.90
	120	1.78	0.0032	1.94	1.62	3.18

Table 4-3. ANOVA and mean comparison results for %clay, D_b and K_s

Soil properties	Sampling depth(cm)	Average	F-value	P-value (ANOVA)
%clay	22.5	2.08*	76.00	<.0001
	45	2.09*		
	67.5	2.25*		
	90	4.04**		
	120	7.51**		
D_b	22.5	1.37**	170.33	<.0001
	45	1.42**		
	67.5	1.52**		
	90	1.60**		
	120	1.78**		
K_s	22.5	13.09*	9.65	<.0001
	45	13.41*		
	67.5	15.28*		
	90	10.95*		
	120	3.833**		

* Not significantly different; ** significantly different

Table 4-4. Semivariogram parameters of the soil properties at different sampling depths

Soil Properties	Depth (cm)	Model	R^2	*Lag* (m)	*Nugget*	*Sill*	*% Nugget*	*Range* (m)
%clay	90	Exponential	0.82	36	0.009	0.346	2.601	78
	120	Spherical	0.99	36	0.135	0.304	44.57	164.5
D_b	45	Linear	0.84	31	0.0066	0.011	59.72	
	67.5	Exponential	0.98	29	0.0052	0.0145	35.58	135
	90	Linear	0.96	30	0.0094	0.0145	64.82	
K_s	22.5	Linear	0.88	33	0.356	0.746		

Table 4-5. Calculated ET and net rainfall (ET – RF) values for years 2006 and 2006 potato seasons

	2006					**2007**				
	RF*	K_c	ET_0*	ET*	ET-RF*	RF	K_c	ET_0	ET	ET-RF
Feb	5.4	0.41	2.28	1.03	-4.37	0.06	0.41	2.43	1.10	1.04
Mar	0.5	0.99	2.82	2.80	2.30	3.4	0.99	2.65	2.62	-0.73
Apr	0.8	1.35	3.86	5.21	4.40	1.04	1.35	3.44	4.64	3.60
May	0.3	1.28	4.4	5.63	5.37	1.02	1.28	3.92	5.01	1.10

*. Daily average values; unit: mmd^{-1}.

Table 4-6. Calculated amounts of irrigation and drainage from a 4.7ha field during the potato seasons of 2006 and 2007

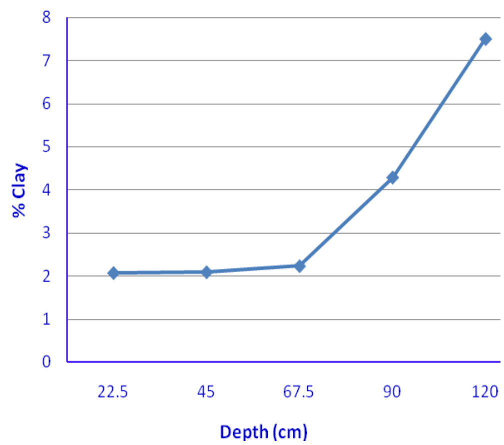
	2006					**2007**				
	Q_i ($100Ld^{-1}$)	Q_i (mmd^{-1})	ET-RF (mmd^{-1})	Q_d* (mmd^{-1})	Q_d ($100Ld^{-1}$)	Q_i ($100Ld^{-1}$)	Q_i (mmd^{-1})	ET-RF (mmd^{-1})	Q_d* (mmd^{-1})	Q_d ($100Ld^{-1}$)
Feb	5832	12.46	-4.37	16.9	7899.8	5832	12.46	1.04	11.4	5344.6
Mar	5832	12.46	2.30	10.2	4754.9	5832	12.46	-0.73	13.2	6172.9
Apr	5832	12.46	4.40	8.1	3772.1	5832	12.46	3.60	8.9	4146.5
May	5832	12.46	5.37	7.1	3318.1	5832	12.46	1.10	11.4	5316.5
Avg.	5832	12.46	-4.42	10.6	4937.4	5832	12.46	1.04	11.21	5246.3

*. Total drainage that also accounts for the net rainfall (net rainfall = ET – RF). Ld^{-1} = Liters per day

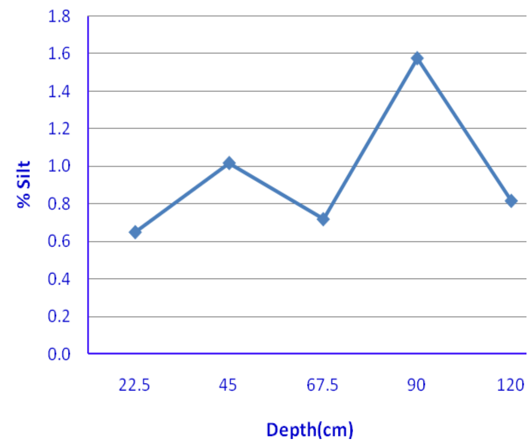
Table 4-7. Average water discharge and irrigation rate into the field

Reading	Spigot 1 (Ls^{-1})	Spigot 9 (Ls^{-1})	Spigot 13 (Ls^{-1})	Spigot 15 (Ls^{-1})	Pump Meter (Ls^{-1})	Qi (Ld^{-1})	Qi (mmd^{-1})
1	0.48	0.31	0.48	0.53	7.14		
2	0.45	0.3	0.5	0.53	7.28	583,200	12.46
3	0.43	0.31	0.5	0.56	7.28		
AVG	0.46	0.31	0.49	0.54	7.23		

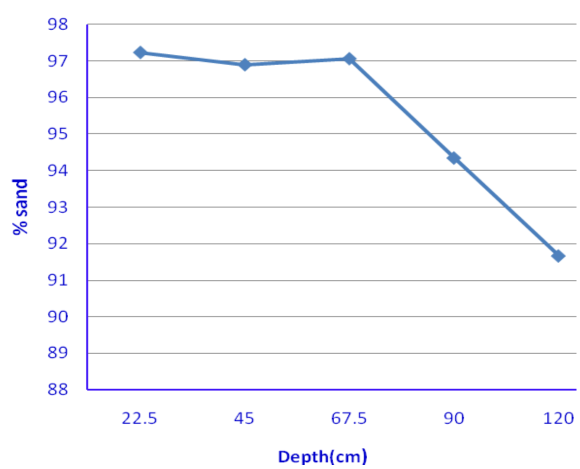
Ls^{-1} = Liters per second



(a)



(b)



(c)

Figure 4-1. Average PSD as a function of depth: (a) %clay; (b) %silt; (c) % sand

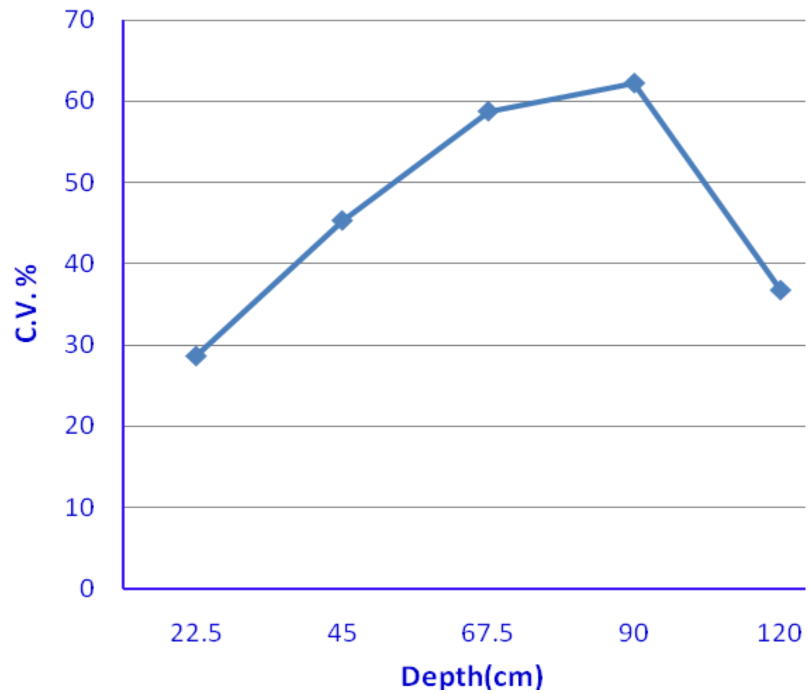


Figure 4-2. Coefficient variation of %clay at the five sampling depths

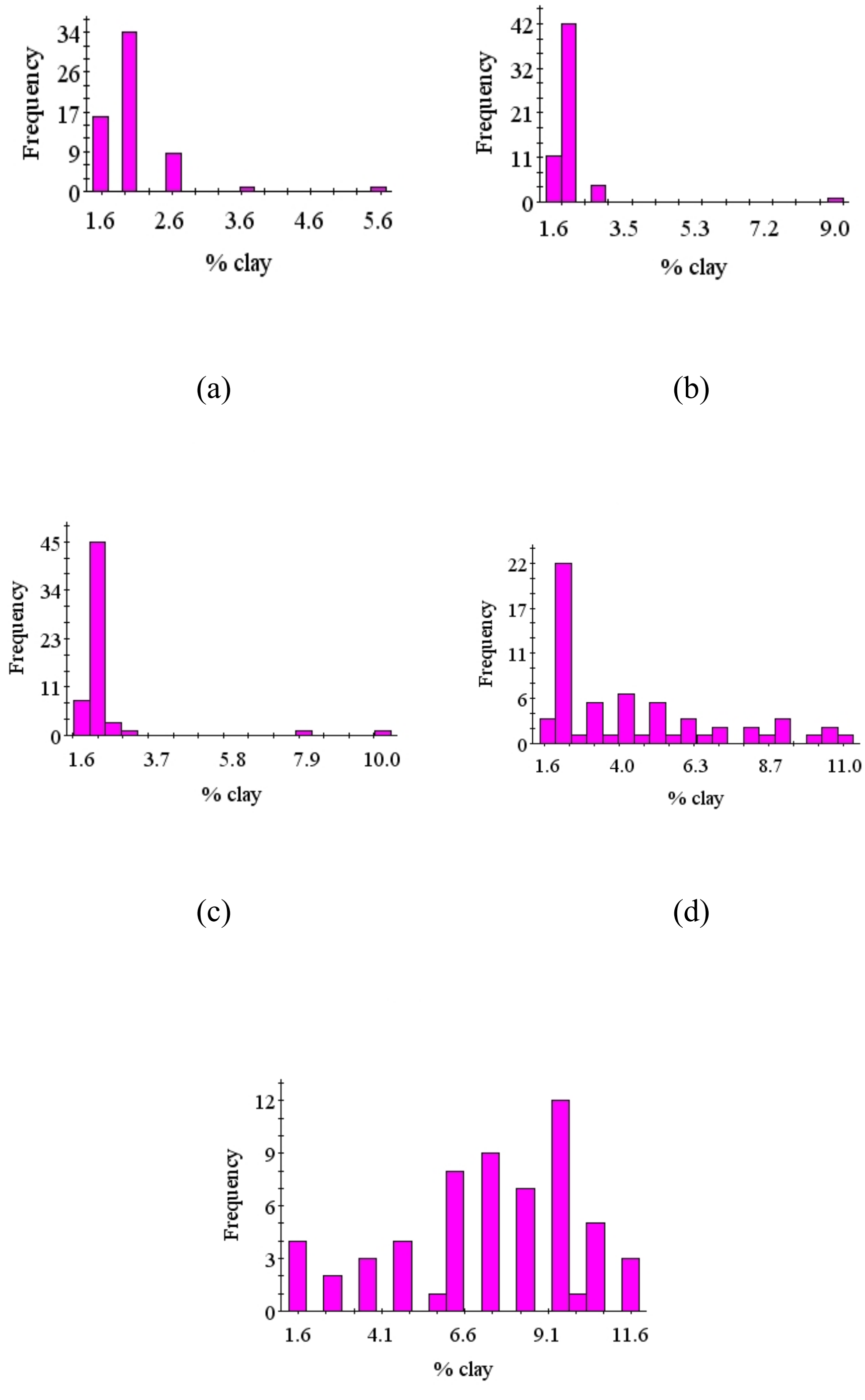


Figure 4-3. Frequency distributions of %clay at the five sampling depths: (a) 22.5cm; (b) 45cm; (c) 67.5cm; (d) 90cm; (e) 120cm

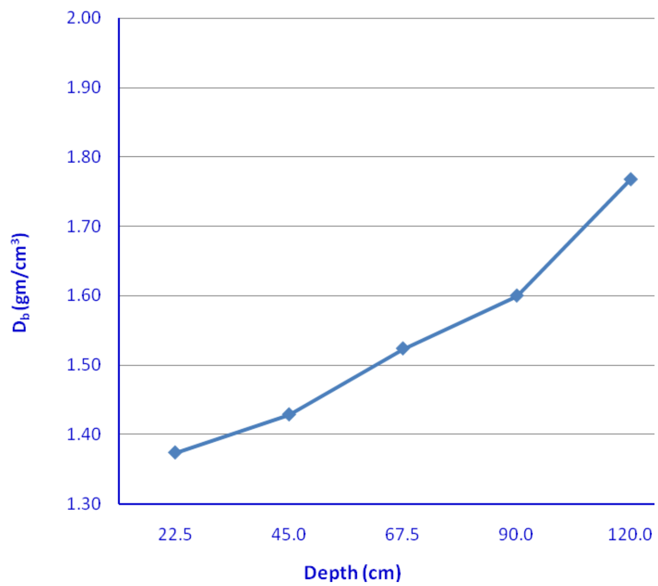


Figure 4-4. Bulk density as a function of depth

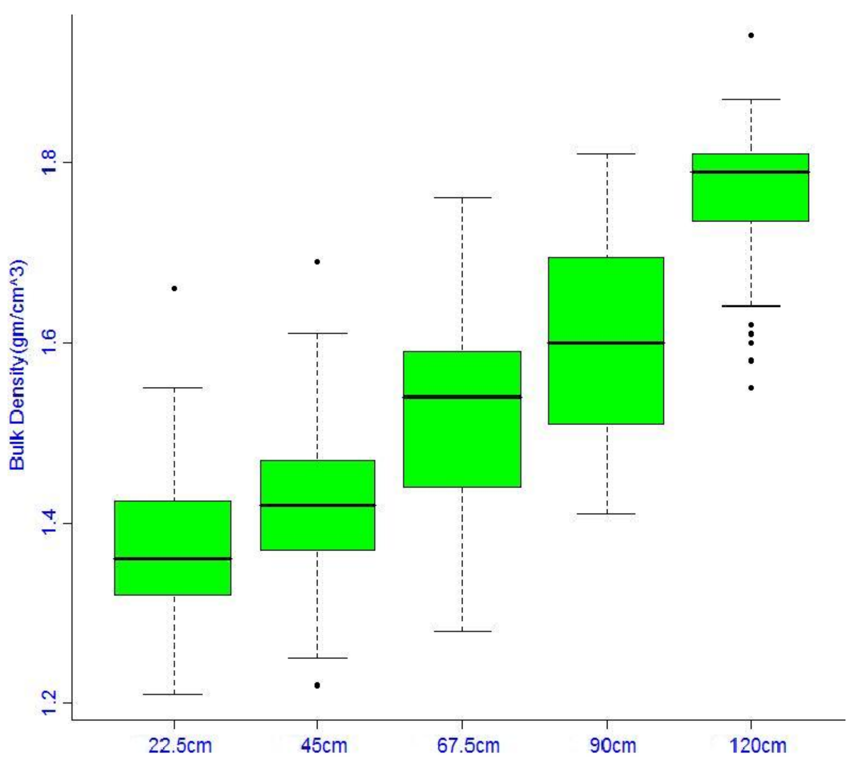


Figure 4-5. Distribution of D_b at the five sampling depths

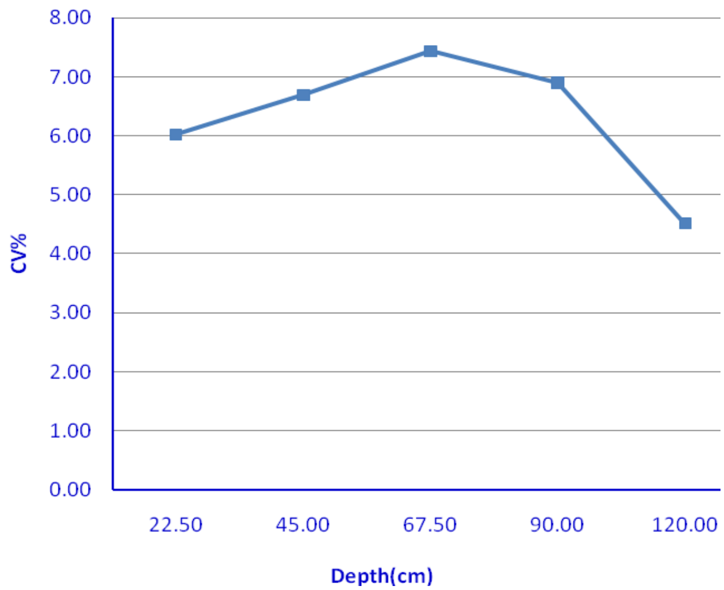


Figure 4-6. Coefficient of Variation of D_b as a function of depth

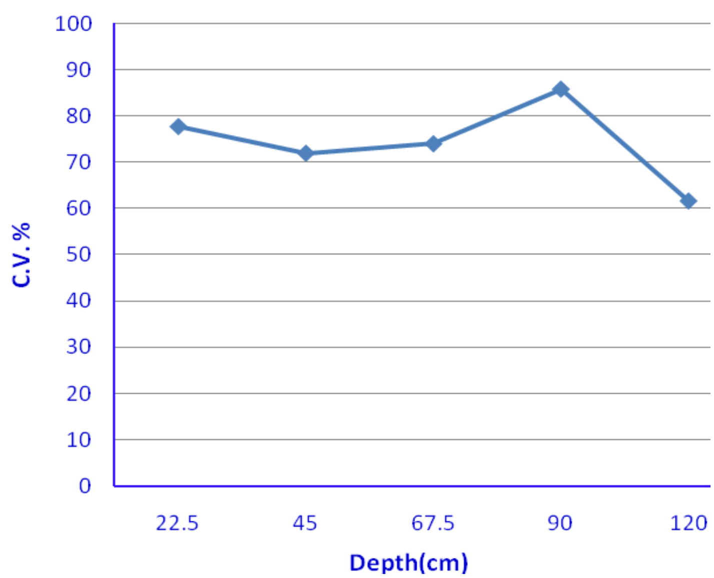


Figure 4-7. Coefficient of Variation of K_s at the five sampling depths

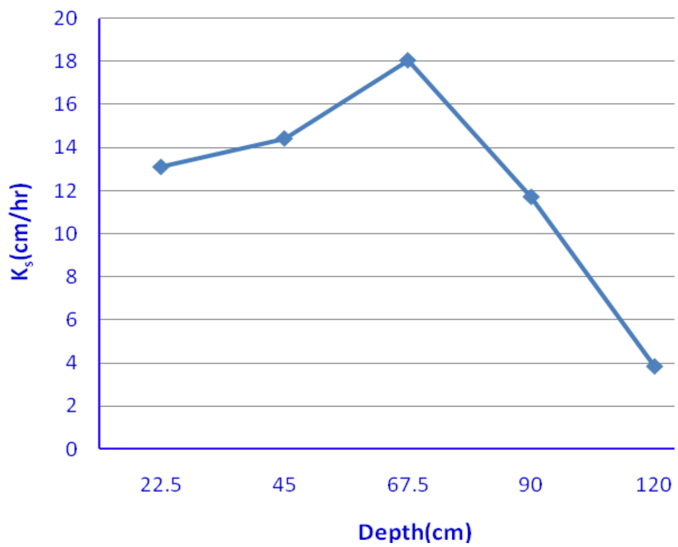


Figure 4-8. Saturated hydraulic conductivity (K_s) as a function of depth

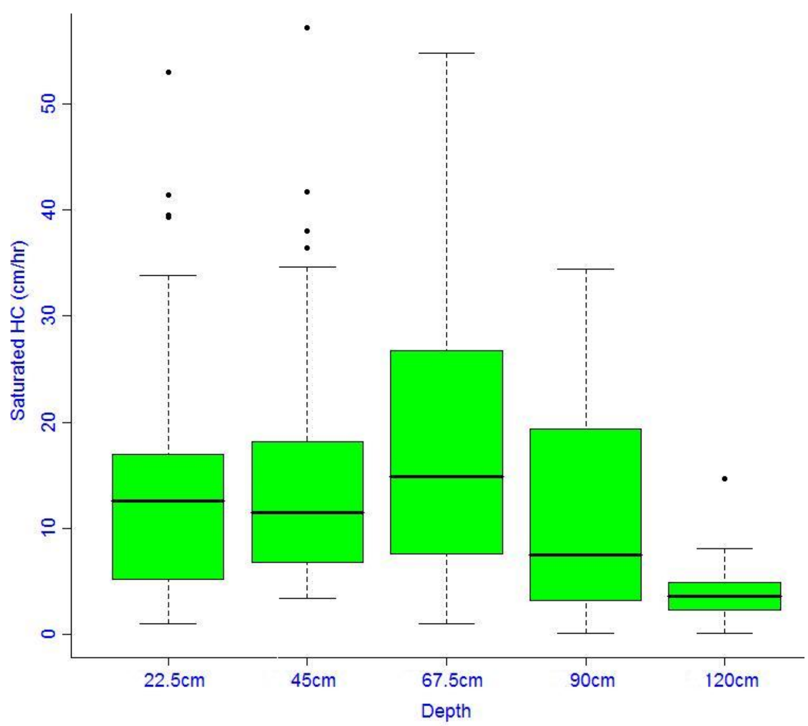
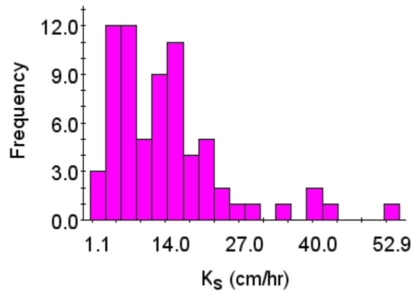
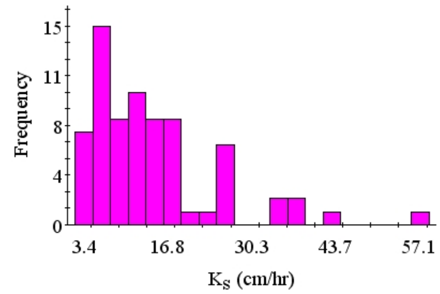


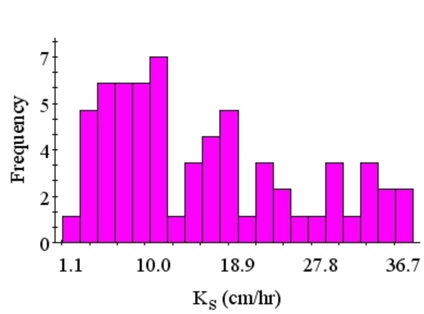
Figure 4-9. Distribution of K_s values at the five sampling depths



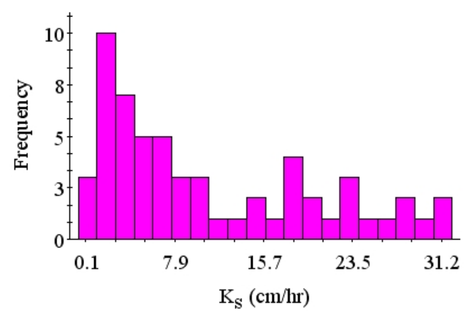
(a)



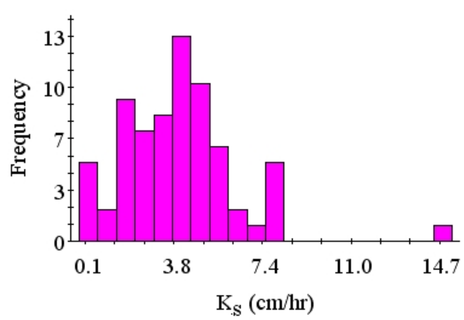
(b)



(c)

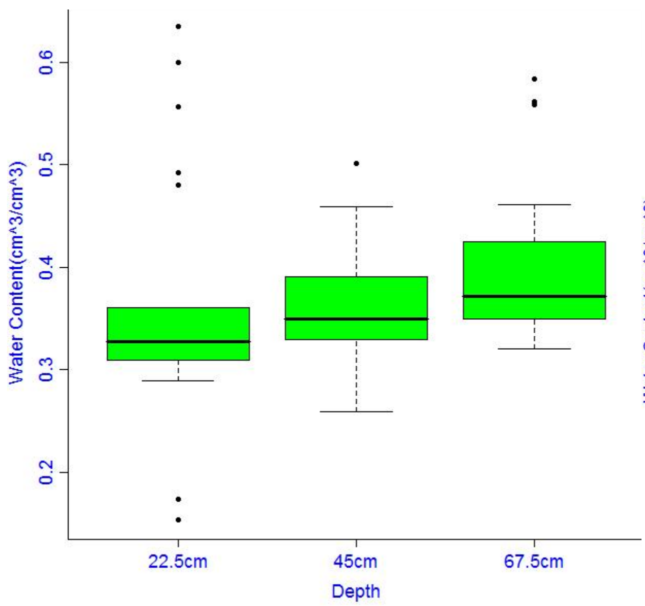


(d)

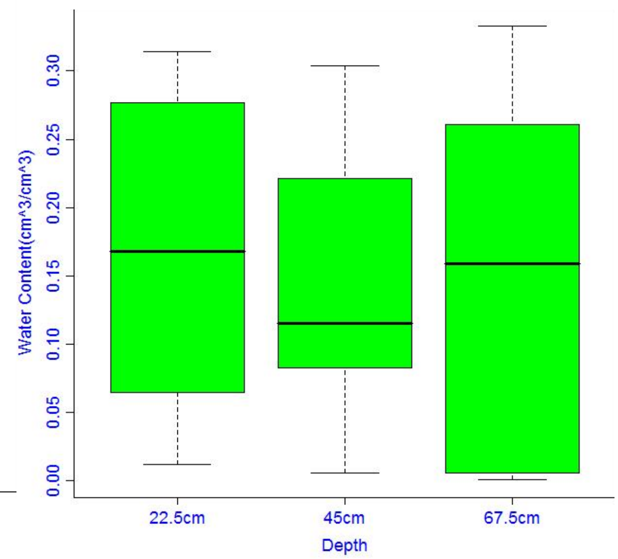


(e)

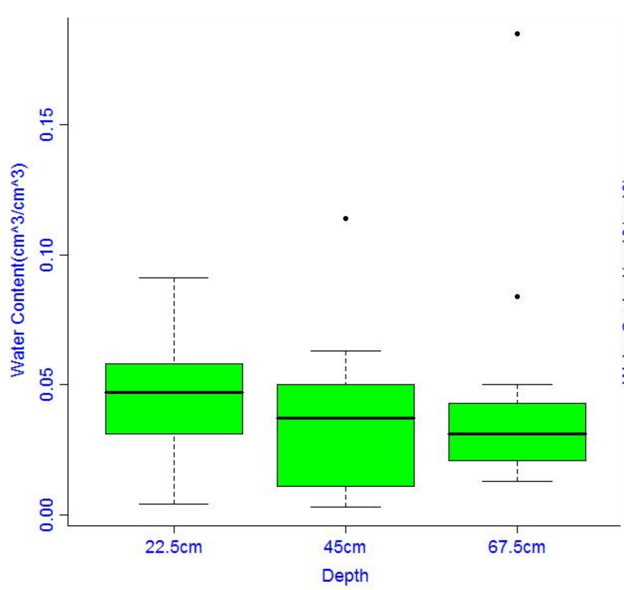
Figure 4-10. Frequency distributions of K_s (cmhr-1) at the five sampling depths. (a) 22.5cm; (b) 45cm; (c) 67.5cm; (d) 90cm; (e) 120cm



(a)



(b)



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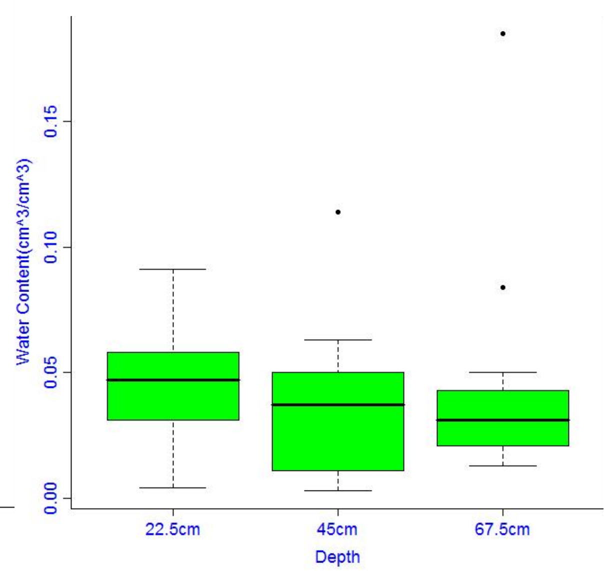


(d)

Figure 4-11. Distributions of θ_v in the soil samples at four different pressure levels. (a) 0kPa; (b) -33kPa; (c) -500kPa; (d) -1500kPa

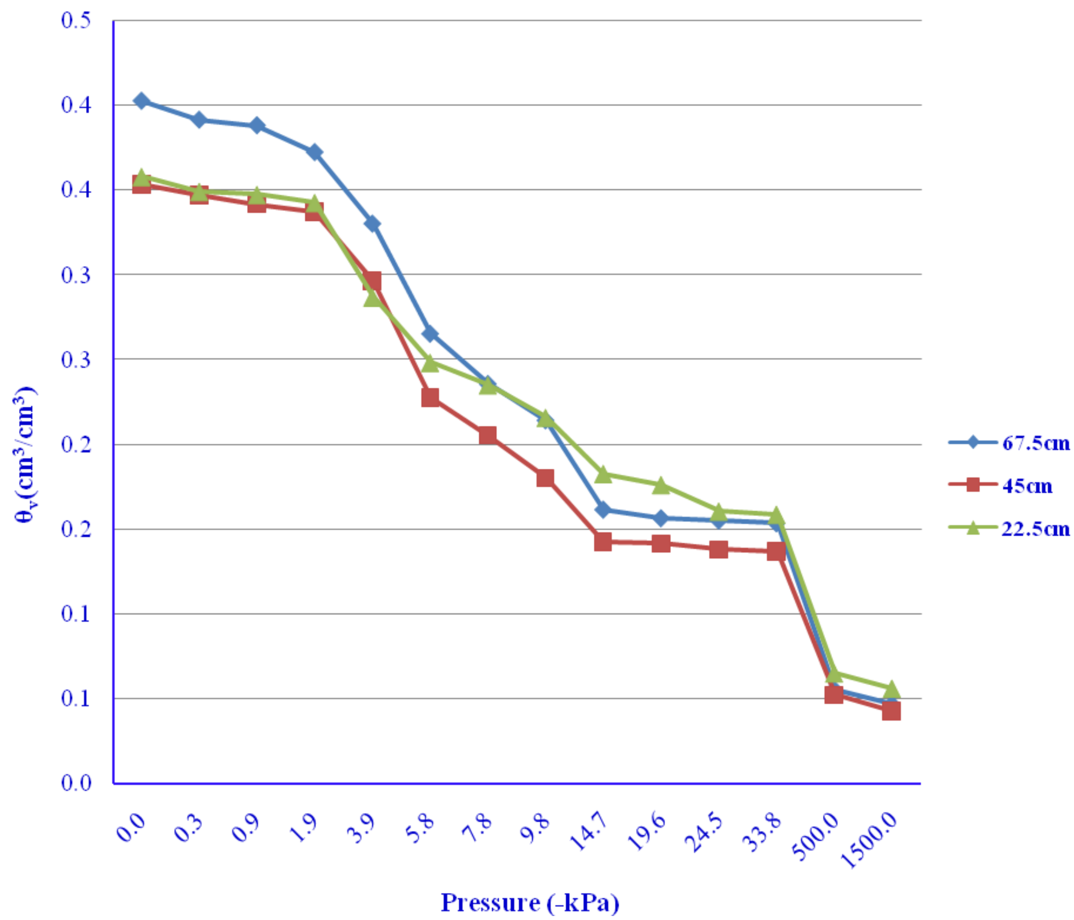
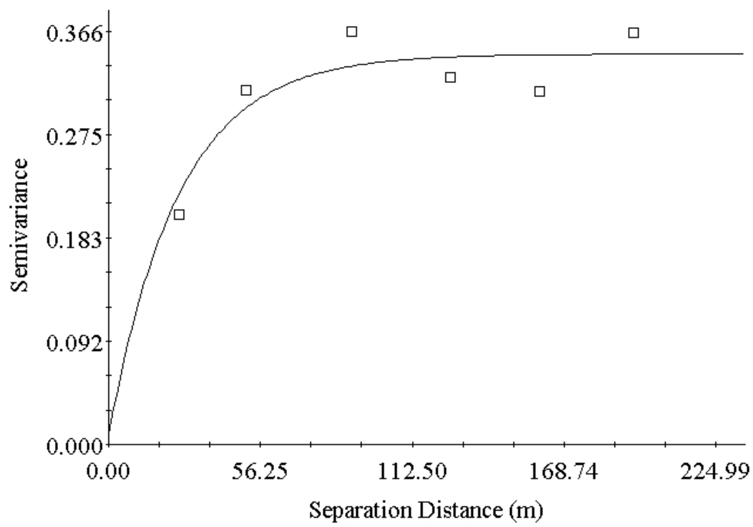
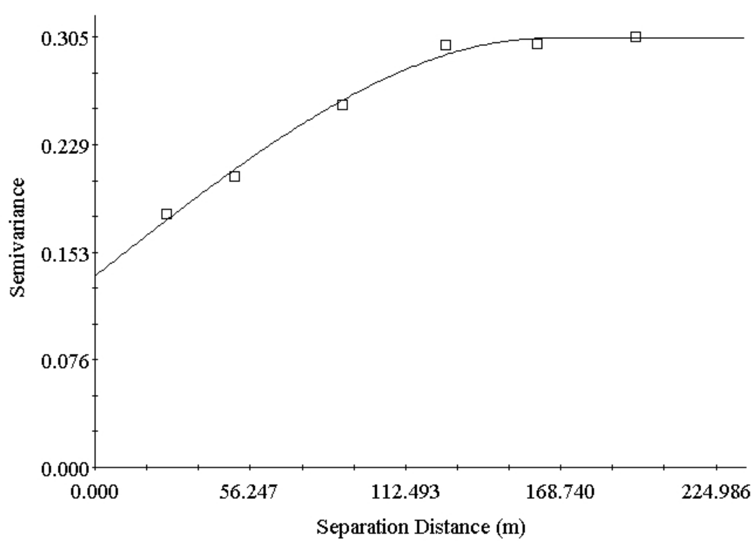


Figure 4-12. Soil moisture release curves of the soil samples at three depths

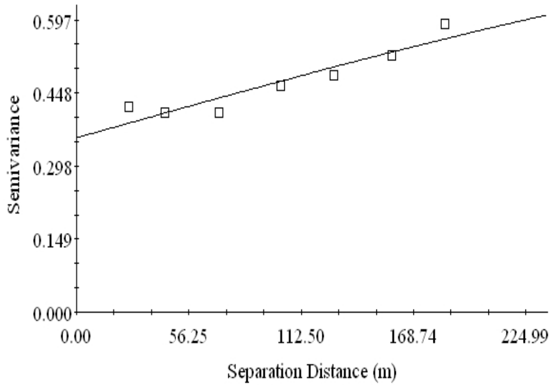


(a)

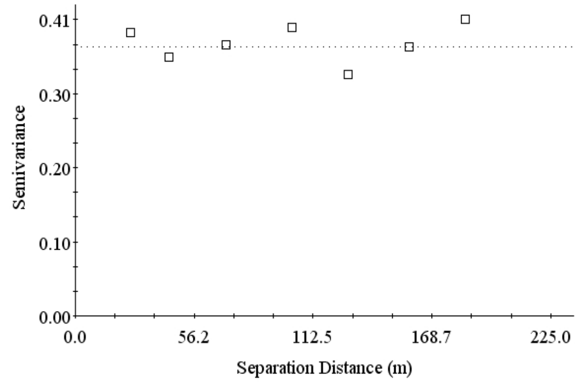


(b)

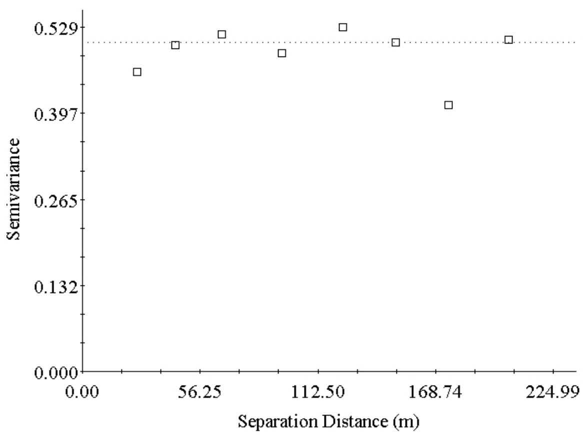
Figure 4-13. Semivariogram of the log-transformed %clay. (a) 90cm; (b) 120cm



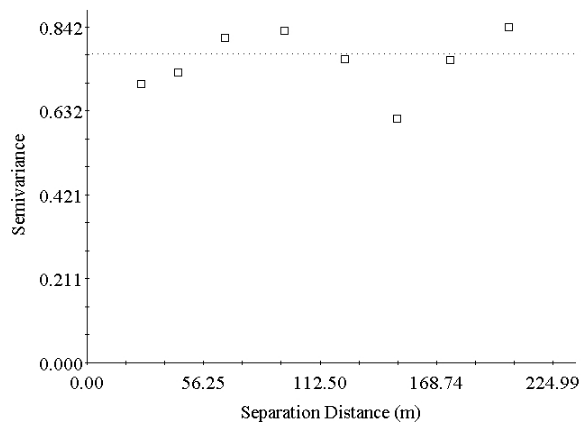
(a)



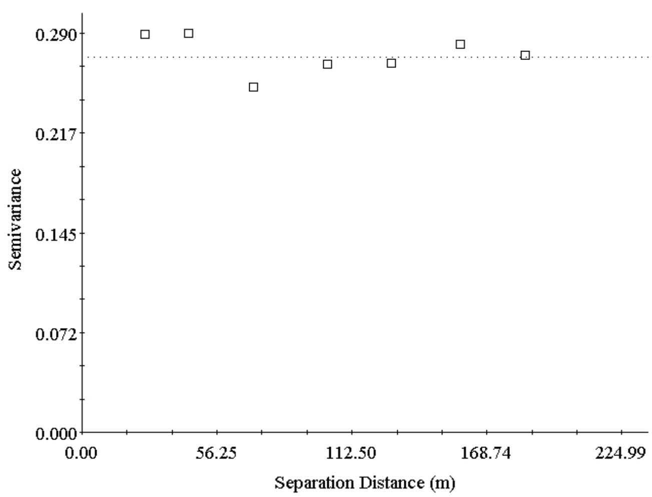
(b)



(c)



(d)



(e)

Figure 4-14. Semivariograms of the log-transformed K_s values at the five sampling depths. (a) 22.5cm; (b) 45cm; (c) 67.5cm; (d) 90cm; (e) 120cm

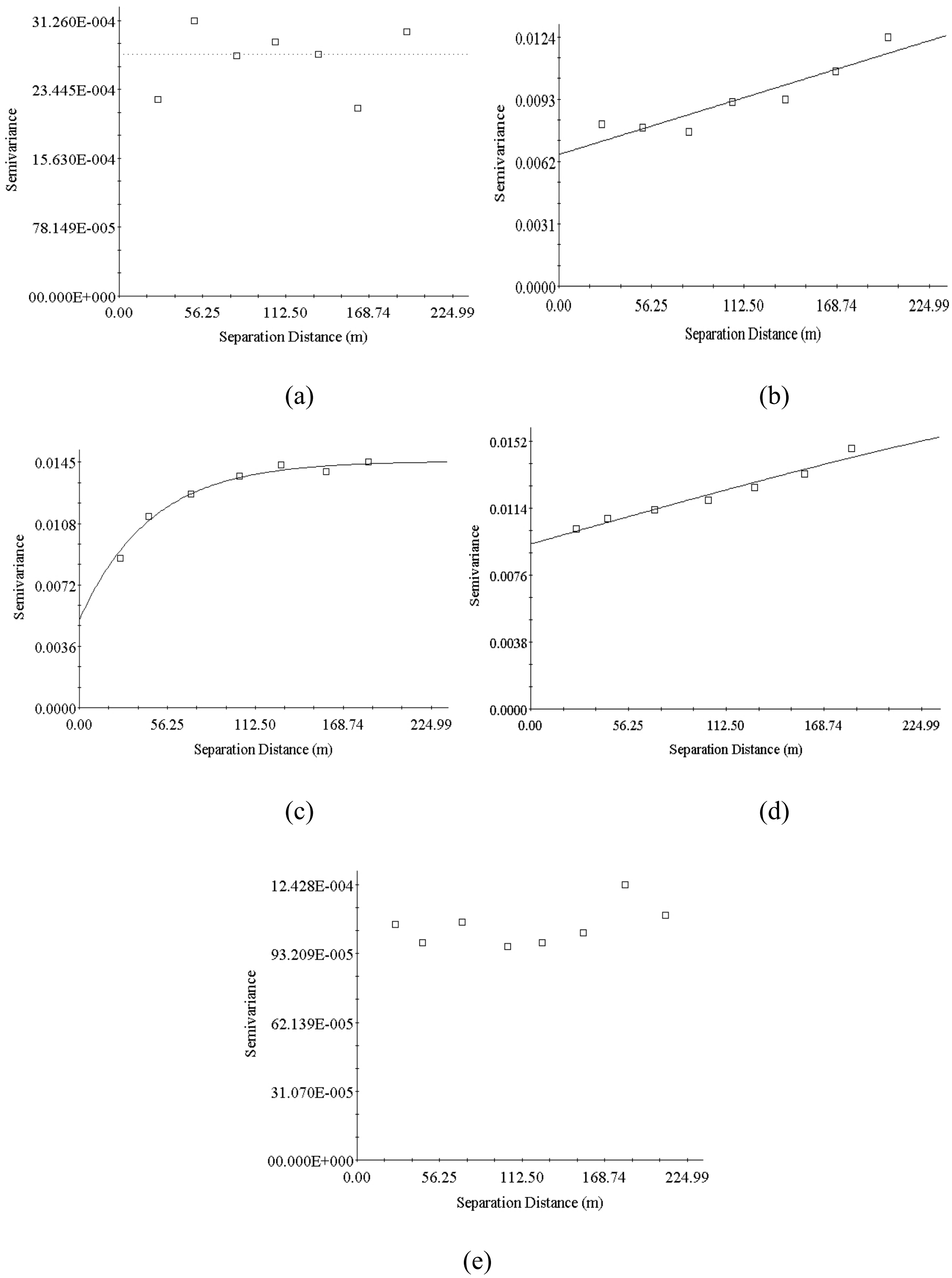


Figure 4-15. Semivariograms of the log-transformed D_b at the five sampling depths. (a) 22.5cm; (b) 45cm; (c) 67.5cm; (d) 90cm; (e) 120cm

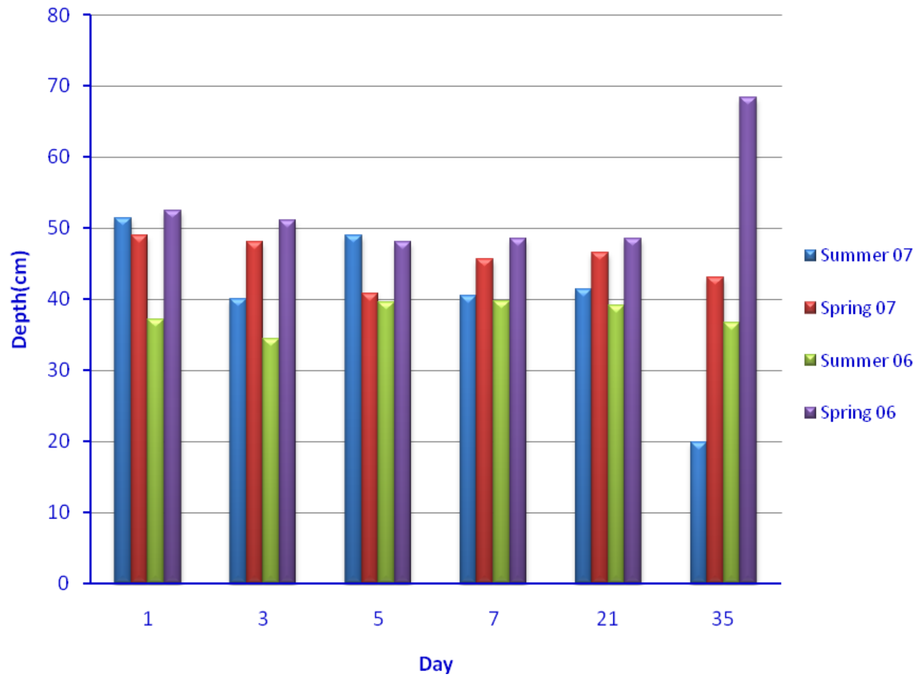


Figure 4-16. Average water table depth in the experimental field during six-week crop periods of 2006 and 2007

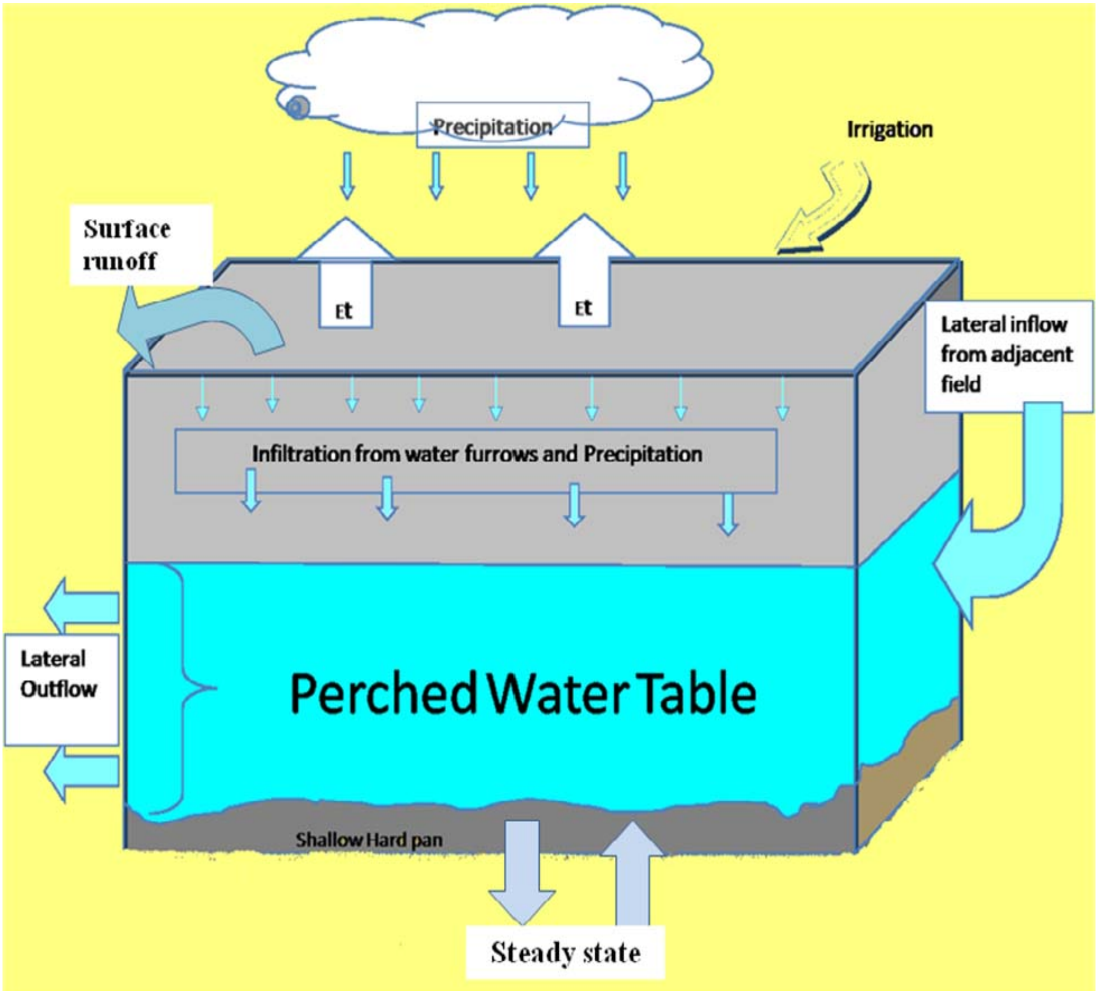


Figure 4-17. Water balance in a typical agricultural field in the TCAA

CHAPTER 5
SUMMARY AND CONCLUSION

Result of this soil profile study thus provided valuable information on the characteristics of soil properties at different depths in a seepage irrigated field in the TCAA. Clay content of the soil profile increased with depth, while the %sand decreased. The difference in clay percent was insignificant at the first four depths but was significant at 120cm indicating deposition of clay particles in the hardpan. Vertical translocation of fine clay particles and their deposition in the lower horizons is common in the high water table soils. The TCAA soils are continuously wetted by the perched water table at an average depth of 40-50cm during most parts of the year. Continuous flushing of the profile by fluctuating water table enhanced illuviation process and deposition of clay particles in the hardpan. The average silt percentage in the soil was very low at all sampling depths. Bulk density also exhibited a similar increase pattern with the sampling depth; the increase was abrupt and steep in the impervious zone. Saturated hydraulic conductivity was not significantly different at the first three depths but it dropped significantly at 90cm and further reduced at 120cm thus confirming the results of %clay and D_b. Results indicated that creation of perched water table above the hardpan occurred rapidly after the field received water from irrigation and/or rainfall, as the infiltration rate of overlying layers is very high. However as the hardpan was not completely impervious, it was indicated that some amount of water also moved vertically down through the hardpan.

Moisture retention characteristics determined through sequential increase in pressures from 0kPa to -1500kPa indicated low water retention in the soil profile, particularly at higher pressures. Average water content at 0kPa was found to be near 37% which dropped to about 16% at -33kPa. This implied that >50% of the total water retained in the soil at saturation was contributed by macropores. The average percentage of water held at -1500kPa was 4% or less.

Variability in measured soil properties was observed in both horizontal and vertical direction. The CV was high for %clay, %silt, K_s, and θ_v, while it was low for D_b and %sand, which supported the variations reported in literature (Warrick and Nielsen, 1985). Overall variation in the vertical direction was high in %clay, %silt, θ_v at -1500kPa, and K_s while the variation was comparatively lower in D_b, %sand, and θ_v at 0kPa and -33kPa.

Spatial variation analysis performed with the semivariograms indicated the prevalence of large *nugget* effects in all the soil properties studied. The variation of %clay, which was studied only in 90cm and 120cm, was well described by exponential ($R^2 = 0.82$) and spherical ($R^2 = 0.99$) models respectively. The *nugget* variance in 90cm was only 2.6% of the total semivariance while it was 44% at 120cm. The *range* was 78m and 164m respectively in the two depths thus indicating strong and moderate spatial variation of clay percentage.

Variation in K_s did not show any spatial autocorrelation at depths below 22.5cm (pure *nugget* effect). At 22.5cm the variation was best described by a linear model ($R^2 = 0.88$) with a *nugget* of 47%, while the *range was* greater than the total length of the experimental field, indicating a weak spatial autocorrelation in K_s at the sampling distance of 26m. The *nugget* effect, which occurred either due to measurement error or due to spatial autocorrelation at distance shorter than the sampling interval, most likely would be reduced if the sampling resolution could be increased.

Unlike K_s, D_b did not show any spatial autocorrelation at 22.5cm depth while the autocorrelation could be described by linear, exponential and linear models at 45cm, 67.5cm and 90cm respectively. The *Nugget* variance ranged from 35% to 63% indicating moderate to weak spatial variation at these depths. At the hardpan layer, however, pure *nugget* effect was observed in the semivariograms of D_b as well.

Potential water loss from the experiment field was calculated using the ET and RF data which showed that at steady state, as high as 87% of the total water received by the field (including total rainfall) was lost in the potato seasons years 2006 and 2007. The result indicated the potential of a substantial loss of not only the irrigation water but also the nutrients applied to the crops

In conclusion, the soil profile of the experiment field was characterized with increased %clay, increased D_b and reduced K_s at the water restrictive horizon (120cm) indicating the effect of continuously standing high water table in the area. The crop root-zone had very high and variable K_s and a low moisture holding capacity showing the possible existence of vertical macropore flow during precipitation. There was moderate to very weak spatial variation in the measured soil properties. Occurrence of high *nugget* effects suggested that the sampling distance was higher than that would be required for capturing the total spatial variability. The results, in conclusion, indicated that the nature of the soil profile in the TCAA could encourage subsurface lateral transport which could further be intensified by the nature of irrigation system and high rainfall. Massive water loss from the profile thus suggested that the seepage irrigated fields of the TCAA were also prone to reduced nutrient use efficiencies while potentially increasing nonpoint source pollution in the Lower St. Johns River. Therefore, there is an immediate need for developing alternate ways of water management in the TCAA that can effectively reduce water and nutrient loss while maintaining the level of production.

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BIOGRAPHICAL SKETCH

I was born in Kavrepalanchok district, Nepal, on January 25, 1980. In 1996, I finished my high school from the Kavre Secondary School at Banepa. I completed my undergraduate in Agriculture (B. Sc. Ag.) from the Institute of Agricultural and Animal Sciences at the Tribhuvan University, Nepal. In August 2006, I was matriculated to the Soil and Water Science Department at the University of Florida as a Master's student. After completing my Master's Degree, I plan to pursue the Degree of Doctor of Philosophy at the same department.