# REFERENCE EVAPOTRANSPIRATION AND ACTUAL EVAPOTRANSPIRATION MEASUREMENTS IN SOUTHEASTERN NORTH DAKOTA

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**Title**

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

**MASTER OF SCIENCE**

SUPERVISORY COMMITTEE:

# ABSTRACT

Rijal, Ishara, M.S., Department of Agricultural and Biosystems Engineering, College of Engineering and Architecture, North Dakota State University, May 2011. Reference Evapotranspiration and Actual Evapotranspiration Measurements in Southeastern North Dakota. Major Professor: Dr. Xinhua Jia.

Subsurface drainage (SSD) has been used to remove excess water from fields in the United States upper Midwest for more than a century, but only since the last decade in the Red River Basin of the North in North Dakota (ND). The water leaving from a SSD system can affect both the quality and quantity of water that flows to a surface water system. Therefore, determination of the water balance components is the first step to study the impact of SSD on water quantity, while evapotranspiration (ET), one of the most important components in the water balance, needs to be accurately measured for SSD field.

A field experiment was conducted to study the water balance in SSD and undrained (having no artificial drainage system) fields in southeast ND. The field had three different water management systems: 22 ha undrained (UD), 11 ha subsurface drained, and the remaining 11 ha subsurface drained and subsurface irrigated. The ET rates were measured directly using an eddy covariance (EC) system for the SSD and UD fields. The changes in water table were monitored in 8 wells installed in both fields. Rainfall, SSD drainage volume, and soil moisture at six different depths at two locations were measured in both fields. The measurements were conducted in the growing seasons of 2009 and 2010. The ET rates were calculated for two different field crops: Corn (*Zea Mays*) in 2009 and soybean (*Glycine Max*) in 2010. Crop coefficient ($K_c$) value was also developed using the ET measured by the EC system and the reference ET ($ET_{ref}$)

estimated using the American Society of Civil Engineers Environmental and Water Resources Institute (ASCE-EWRI, alfalfa) method. The $ET_{ref}$ was also estimated using the ASCE-EWRI grass and the Jensen Haise (JH) methods.

The results indicated that the water table in the SSD field was lower during spring and fall than that in the UD field. The shallow water table and high soil moisture content in the spring and fall have resulted in higher ET rates in the UD field. In the summer, SSD field has favorable soil moisture at the root zone depth; the ET in the SSD field was 30% and 13% higher than that in UD field in summer 2009 and 2010, respectively. For the entire growing season, the ET in the SSD field was 15% higher compared to UD field and the difference was minimal in 2010. Though there were differences in the ET values, they were not statistically different. However, difference in magnitude of ET during summer 2009 yielded a statistical difference. During the peak growing season in July and August, the $K_c$ values were greater in the SSD field due to healthy crops.

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| **Abbreviations** | **Explanation** |
|---|---|
| ASCE-EWRI | American Society of Civil Engineers, Environmental and Water Resources Institute |
| AW | Available soil moisture |
| EC | Eddy covariance |
| ET | Evapotranspiration/ Actual evapotranspiration |
| $ET_{ref}$ | Reference evapotranspiration |
| FAO | Food and Agriculture Organization |
| G | Soil heat flux |
| H | Sensible heat flux |
| H/LE | Bowen ratio |
| JH | Jensen Haise |
| $K_c$ | Crop coefficient |
| LE | Latent heat flux |
| $LE/(R_n\text{-}G)$ | Evaporative flux |
| ND | North Dakota |
| NDAWN | North Dakota Agricultural Weather Network |
| NP | Neutron probe |
| PWP | Permanent wilting point |
| RH | Relative humidity |
| $R_n$ | Net radiation |
| SSD | Subsurface drained |
| SWB | Soil water balance |

|  |  |
|---|---|
| $T_{avg}$ | Average temperature |
| TAW | Total available soil moisture |
| $T_{max}$ | Maximum temperature |
| $T_{min}$ | Minimum temperature |
| UD | Undrained |

# 1. INTRODUCTION

## 1.1 Background

The presence of excess water in the crop root zone is always problematic as it disturbs the field operation and reduces the crop yield. Subsurface drainage (SSD) systems help to improve the field condition and trafficability of the field and support easy planting and harvesting of the crops. SSD is a process to remove excess water from the crop root zone at some depth below the soil surface via perforated conduits. The SSD maintains optimal soil moisture condition, lowers the water table depth, and enhances the nutrient and the water uptake by the plants (Ayars et al., 2006; Skaggs et al., 1999). Over time, SSD could decrease soil hardness and change soil chemical properties (Baker et al., 2004). However, the SSD flow can contain several elements like nitrogen, salt, pesticides and trace metals (Skaggs et al., 2005), which could affect the surface flow and surface water quality.

Both controlled and conventional modes of subsurface drainage system are useful to maintain the water level in the field. The water level during growing season is maintained at the desired depth using controlled drainage mode. The SSD system is becoming popular in the Red River Valley in the last two decades though it has been practiced in upper Midwest for more than 150 years. According to Schuh (2008), total permitted SSD area in ND was 9,293 ha. However, many agricultural lands that have the SSD system installed without the permit (Schuh, 2008); there could be more areas with SSD system.

Water leaving the SSD system affects the quality and quantity of water in the SSD field as well as the surface water system that it drains to (Skaggs et al., 1994). The surface runoff, evapotranspiration (ET), deep percolation and soil moisture content are all affected by the SSD system. The ET is always higher if optimal soil moisture is present in the field. If the available soil moisture is not sufficient to meet the crop water requirement, ET decreases and the crops undergo stress (Allen et al., 1998).

The ET of a particular area depends on the change in the water table (Cooper et al., 2006; Nachabe et al., 2005) and ET is high when water table is near the surface. Cooper et al. (2006) observed certain rise in ET due to a rise in water table. The ET of the field increases with the optimal soil moisture content (Payero et al., 2008). The ET of the particular crop directly depends on both the soil moisture content and water table depth of the area. The SSD system could be the proper way to maintain the water table and the soil moisture of the agricultural field during the growing season.

## 1.2 Rationale

The actual ET can be directly measured via soil water balance (SWB) or energy balance approaches. Lysimeter, soil water balance and eddy covariance (EC) systems are commonly used direct methods to measure the actual ET. Both the lysimeter and EC are the standard methods to measure ET (Farahani et al., 2007; Prueger et al., 1997; Sumner, 2001). The ET can also be estimated indirectly utilizing crop coefficient ($K_c$) and reference evapotranspiration ($ET_{ref}$). The estimation of the $ET_{ref}$ is highly dependent on the various weather parameters such as temperature, rainfall, and solar radiation (Allen et al., 1998; Doorenbos and Pruitt, 1977). Among all the methods, the American Society of Civil Engineers, Environmental and Water Resources Institute (ASCE-EWRI) method is a standardized and widely accepted method for $ET_{ref}$ calculation (Allen and Pereira, 2009; Farahani et al., 2007).

A lysimeter is a tank placed in the field to measure ET by growing crops inside the tank by maintaining growing conditions similar to the surrounding natural field conditions (Jensen et al., 1990). All components of the water balance (rainfall, irrigation, drainage and change in soil moisture content) over a certain time interval are measured to estimate the ET. Though lysimeter is a widely used and standard method, measuring ET by lysimeter is not a feasible method in humid regions and in area with shallow water table (Jia et al., 2006). Among the direct methods to estimate the ET, soil water balance is a popular method in ND. In ND, crop coefficients ($K_c$) for several crops (corn, soybean, potato, sorghum, etc.) have been developed using the ET estimated by soil water balance and $ET_{ref}$ by Jensen Haise (1963) method (Jensen and Haise, 1963). Several instruments like time domain reflectometry (TDR), Hydraprobe, tensiometer, and neutron probe (NP) are available to measure the soil moisture content. Among those methods, NP has been considered as the accurate instrument to measure soil moisture content (Gaze et al., 2002) and is in practice to measure soil moisture content in ND. Stegman et al. (1977) and Steele et al. (1996) used NP to measure the soil moisture content and used soil water balance method to estimate the ET. However, the use of NP is complicated as it requires in-situ calibration for the particular soil before installation (Gaze et al., 2002), contains a radioactive source and therefore, creates potential health hazard to the user (Mwale et al., 2005). Besides that, the measurement of all the components of water cycle becomes challenging in the areas with capillary rise, fluctuating water table, and subsurface drainage (Nachabe et al., 2005).

The EC system uses modern, precise and high frequency instruments to measure wind speed, temperature, humidity and air density, and computes ET electronically

(Campbell and Norman, 1998). This system has been used to measure the ET over several types of vegetations in the U.S. (Castellvi and Snyder, 2010; Jia et al., 2007, 2009; Sumner, 2001) and around the world (Li et al., 2008; Gong et al., 2004; Testi et al., 2004). The EC system measures the ET above the crop canopy, thus overcoming the site disturbance and limiting the need to measure individual components of the water balance, and is independent of the soil surface condition (Sumner, 2001; Twine et al., 2000). The EC system also covers a large area of measurement to account for the upwind distance of about 100 times the sensor height above the crop canopy (Campbell and Norman, 1998). The ET measured by the EC system shows good agreement with the ones from Bowen ratio method ($R^2$= 0.89) (Pauwels and Samsons, 2006) and is comparable to ET measured by lysimeter ($R^2$= 0.97) (Ding et al., 2010).

The majority of research in the SSD fields has been focused on water quality, including nutrient management and salinity (Kahlown and Azam, 2002; Skaggs et al., 2005). Tan et al. (2002) compared the ET between SSD and undrained (UD) fields and found difference in ET, surface runoff and soil water content when water level was controlled at different depths. The SSD system affected the surface and subsurface runoff, water balance of the field and ultimately the surface hydrology. The total SSD area and the total SSD volume need to be identified in order to address its effect in surface flow. If the ET of the area is measured, the water balance of the field could be identified. ET of the area depends on different environmental parameters, such as soil moisture content, water table depth and solar radiation. The EC system avoids site disturbance, does not require the measurement of other component of water balance and measures the ET of a larger area, so it could be the preferable method to measure ET in the SSD and UD fields. In the past, all ET related research in ND was to address the need of irrigation or water requirement of the crops (Steele et al., 1996; Stegmen et al., 1977). None of the research has been done to evaluate the ET and water balance between the SSD and UD fields. According to Schuh (2008), the amount of drainage during the growing season depends on the precipitation, ET, ground water table, water uptake capacity of crop and change in water table by snow melting in spring. Thus, the artificial modification of water table by SSD system can lead to ET variations.

## 1.3 Objectives

The general objective of this study was to determine the evapotranspiration of SSD and UD fields during the growing season. The specific objectives of the study were to 1) measure and compare ET of SSD and UD field using eddy covariance systems, 2) compare the reference ET estimated by the ASCE-EWRI (2005), and Jensen-Haise (1963), and 3) develop the crop coefficient ($K_c$) of corn and soybean crops in the SSD and UD fields grown in the Red River Basin.

## 1.4 Thesis Organization

This thesis is organized into one paper prefaced by general abstract, introduction, and literature review and followed by general conclusions and appendix. The paper covers all the objectives discussed above. The paper is written such that it could be submitted to a journal as a manuscript.

# 2. LITERATURE REVIEW

## 2.1 Evapotranspiration and its History

Evapotranspiration is the amount of water removed to atmosphere via evaporation and transpiration. Evaporation accounts for the loss of water from the soil surface, water surface and intercepted area, such as leaf surface. Transpiration is the diffusion of water from the plant, especially from the stomata to the atmosphere to equilibrate the water vapor. A plant basically absorbs water for their activities, such as photosynthesis, and removes part of the absorbed water to the atmosphere by transpiration. About 99% of water absorbed by the plant is released to the atmosphere by transpiration (Noggle and Fritz, 1983). The contact of the soil surface and the root zone make the transfer of water from soil to root zone. When there is less water in soil, plants cannot absorb enough water and wilts, so that the transpiration is stopped (Watson and Burnett, 1993).

In the past, ET was simply considered as the exchange of surface energy which is highly dependent on the vegetation cover (Farahani et al., 2007). During the late 1990s, Allen et al. (1998) defined actual evapotranspiration (ET) as "the evapotranspiration from disease-free, well-fertilized crops, grown in large fields, under optimum soil water conditions, and achieving full production under the given climatic conditions." Cropping practices, root zone water management, and tilling practices may directly influence crop water requirements. With the availability of water, ET reaches its maximum value depending upon the energy fluxes and vegetation. As the available soil water decreases, transpiration in the plants also decreases.

Potential evapotranspiration (PET) is defined as the loss of water from the surface to the atmosphere when unlimited water supply is available in the soil and vegetation

(Watson and Burnett, 1993). PET assumes transpiration is suppressed by the physiology of plant, but not by water.

ET measured with a reference crop is termed as reference ET ($ET_{ref}$). Generally, alfalfa and clipped grass surfaces are used as the reference crops. The $ET_{ref}$ is the evapotranspiration from a field with uniform cover of at least 100 m span of same or similar dense growing plants having specific height and surface resistance grown in well watered condition (Allen et al., 2005). Both PET and $ET_{ref}$ are highly dependent on climatic parameters such as air temperature, wind speed, solar radiation, and relative humidity.

Transpiration, one of the two processes in ET, is the removal of water from the crop canopy to the atmosphere. The physical appearance of vegetation, like the shape of leaf, leaf albedo, growth stage, crop height and soil factors are very important to understand crop water use. These physical appearances along with soil water uptake by the roots are major factors affecting transpiration (Allen et al., 1998; Allen et al, 2005) and ultimately ET. All these together are included into the reference ET equation (Allen et al., 1998).

Basically, ET depends on the aerodynamic roughness and albedo, which varies from crop to crop. It is different at different locations due to difference in transformation of sensible and latent heat flux. On the other hand, the evaporation is also affected by ground water table, capillary rise, soil moisture content, soil heat capacity and soil type. The ET is the major factor governing the crop water use since transpiration accounts 99% of water uptake by plants. In Florida, ET accounted for 70% rainfall (Sumner, 2001).

## 2.2 Factors Influencing ET

The rate of evapotranspiration depends on several factors like climate, hydraulic conductivity, depth of water table, salinity of soil, ground water and soil moisture content (Kahlown et al., 2005). Each of those factors is described separately in the sections below.

### 2.2.1 Crop factor

The ET for each crop is different from the other crops. In other words, ET for corn and wheat are different even though the growing conditions are similar. That difference is due to difference in plant physiology. The plant absorbs water from soil via roots. The root hairs which are spread to the deeper depth are responsible for water absorption or suction (Taiz and Zeiger, 1991). The water absorbed by the plant roots is taken up to the plant leaf via xylem, the plant tissue. The transpiration disperses that equivalent energy and cools the leaf. Transpiration depends on the water diffused from the stomata to the atmosphere to equilibrate the water vapor of the atmosphere. It also depends on the diffusional resistance of the stomata pore. The transpirational flux is given by the ratio of magnitude of driving force and the resistance in the pathway. This can also be written as

$$Transpirational\ \ flux = \frac{C_l - C_a}{r_s + r_b} \tag{2.1}$$

where $C_l$-$C_a$ is the vapor pressure concentration between the stomatal pores and air outside the leaf; $r_s$ is the resistance of stomata and $r_b$ is the resistance of boundary layer at the surface of the leaf (Noggle and Fritz, 1983; Taiz and Zeiger, 1991).

The volume of air space inside the leaf is small compared to wet surface from which water evaporates and the volume of air space varies from plant to plant. The air space volume is 5% of the total leaf area for pine needles, 10% for corn and 30 % for barley. Also, the internal area from which the water evaporates differs among plants (Taiz and Zeiger, 1991). The plant having higher air space has a lower rate of transpiration compared to the one having lower air space area. The larger difference between surface area and volume might be the main reason to support the vapor equilibrium inside the leaf and transpiration process.

The difference in transpiration between certain crops could be explained as the ET difference among those crops. The ET differs from crop to crop due to difference in their root zone depth, water absorption capacity, and length of growing season, water resistant capacity and stage of crops (Kahlown et al., 2005). The evapotranspiration is high in the peak growing season which can result the drawdown of the water table (Omary and Izunu, 1994). Crops require maximum water during their fruiting and reproductive stage. If the water supplied or soil moisture content does not meet the demand of crop, the rate of evapotranspiration decreases. Villagra et al. (1994) observed similar condition in corn, and they noticed a decrease in the ET rate due to high demand of water in silking and tesseling stage of corn development. For any agronomical and cereal crop planted during late spring (April-May), the middle of July is the peak growing period, when the crop attains maximum crop height and initiates the reproductive stages of its life cycle. The soybean transpiration during the peak growing season represents the 89-96% of the total ET (Singer et al., 2010).

Both the transpiration and ET of crop also differ according to location. The difference in ET according to location, crop type and variety and development stages could be best explained by crop coefficient ($K_c$). The ET could be estimated using $K_c$ and $ET_{ref}$, using equation 2.2 (Allen et al., 2005).

$$K_c = \frac{ET}{ET_{ref}} \tag{2.2}$$

The $K_c$ is used because ET of field crop differs from reference crops (grass and alfalfa) as they have different leaf area, ground cover, and canopy height and features (Fangmeier et al., 2006). The $K_c$ value was observed to be varying from crop to crop and at the different developmental stage. Allen et al. (1998) also explained the variation in $K_c$ value within the same crop during the different stage of growing period and location of the crop. For example, the $K_c$ during initial, mid and end period is 0.3, 1.2 and 0.6 for corn and 0.4, 1.15 and 0.5 for soybean respectively, for non stressed well-managed crops in sub humid climates. The above written $K_c$ value for the particular crop explains that the ET is higher during mid growing season. This could also be explained as the rise in the ET when the crop reaches its maximum height with dense area coverage.

### 2.2.2 Soil moisture

Soil moisture content at the root zone is another factor influencing the ET that decreases with the reduction in soil water content, especially in the root zone. Sometimes, ET goes high after the rainfall event because of high evaporation on a wet soil surface.

The water content in the soil depends on the type of soil. According to Hillel (1998), sandy soil has higher particle diameter >200 μm while clayey soil has <2 μm. Therefore, sandy soils form large pores in between their particles. In other words, sandy soils have higher hydraulic conductivity, whereas, clayey soils have high water holding capacity and lower hydraulic conductivity. Due to these reasons, sandy soils drain water more quickly as compared to clay soils which drain very slowly. Organic matter content in both these soils helps improve water holding capacity. Loamy soils, which falls in between these two soils drains faster than clayey soil and retains more water than sandy soil. Loamy soil support plant uptake of water as they remain at field capacity mostly.

If the soil moisture does not meet the water requirement of the crop, the ET decreases and the crop undergo stress (Allen et al., 1998). It could be because the transpiration of the plant decreases when soil moisture is limited.

Irrigation and drainage influence the status of soil moisture content. Irrigation provides the enough water to plants and maintains the proper water in the root zone. Drainage removes the excess water from the root zone to maintain the optimal soil moisture in the root zone. High soil moisture in the irrigated field was also reported by Garcia et al. (2010). In their research, irrigation water was supplied from the surface using the sprinkler system; therefore higher surface moisture was recorded in the irrigated field compared to other field. In both the cases, soil moisture content for the top 30 cm was lower than that of deeper depth. According to them, corn absorbed the water from the first 30 cm depth to meet the ET requirement. This phenomenon explains the decrease in soil moisture content with the increase in ET rates.

A strong linear relationship was observed between cumulative corn evapotranspiration and fraction of season in an experiment that studied the effect of irrigation on evapotranspiration (Payero et al., 2008). Additionally, they noticed increased evapotranspiration with irrigation until irrigation became excessive. ET was greater in the plot with higher soil moisture content. The drop in ET was due to water stress in the crop root zone. The soil moisture content of the field decreased as the ET rate exceeded the ground water discharge rate (Nachabe et al., 2005).

### 2.2.3 Water table

The ET of a particular area depends on the change in water table. The ET from the land includes evaporation from soil, transpiration from plants and evapotranspiration of ground water ($ET_g$) (Lautz, 2008). $ET_g$ is the direct/indirect use of water by the plant in the saturated zone or the one from capillary rise. In shallow water table, the capillary rise of water supports soil surface evaporation and hence ET. In contrast, if the capillary rise of water is less than the ET requirement, it leads to a drier soil surface, less water uptake to plants, subsequently lower evaporation and transpiration and hence ET (Kahlown et al., 2005). Capillary rise of water is not always favorable for the ET. It might bring some dissolved salt and other unnecessary nutrient present in soil and water to the soil surface. Presence of salt on the soil surface might decrease the ET as the season progresses (Pang et al., 2010). It might be because the salt content in the soil prevents the water uptake from the root zone.

The shallow water table or the water table at some centimeters below the root depth of agricultural crops maintains the proper soil moisture conditions and meets the water uptake of the plant. Good soil moisture and desirable water table depth supports the water consumption of plants. In addition, the water table should be near the root system of the plant that is within the depth from which the plant can absorb the required water. If the water table is deep, the plant cannot uptake enough water and suffers from stress. A similar case is discussed by Gardner and Firemen (1958), who found that the reduction in

ET at the water table depth was below 1.8 m for pachappa sandy loam soil. Likewise, when the water table depth was between 1.8 m to 3.6 m, ET dropped from 0.123 cm/day to 0.016 cm/day and finally reached to zero at 3.6 m water table depth (Raats and Gardner, 1972). As the water table depth and ET rate have a direct relationship, significant rise in the ET might be seen following a summer rain. Cooper et al. (2006) observed the rise in the ET during summer rains due to the rise of water table up to the soil surface. They also observed a 32% decrease in the annual ET when the water table drew down from 0.92 m to 2.5 m depth. Omary and Izuno (1994) monitored the rate of water table drop over a period of 4 months and found that the ET drop was related to water table drop. The authors observed a diurnal variation in the water table position where water table was the deepest shortly after noon, and shallowest around midnight. A similar pattern was found by Skaggs et al. (1972) and Nachabe et al. (2005). The water table recharge rate was higher after the sunset to the morning and lower during the day time, due to the higher rate of ET during day. In a similar way, the drop in water table with the presence of ET was noticed in subsurface drained (SSD) field by Skaggs et al. (1999).

## 2.3 Methods of Estimating Evapotranspiration

Though ET is very difficult to measure, several methods have been developed for its measurement. Generally, there are two different methods, namely direct and indirect methods. The direct method measures the ET directly. The direct method includes either water balance or the energy balance approaches. Lysimeter, eddy covariance, soil water balance and Bowen ratio methods are some of the direct methods. Lysimeter and eddy covariance (EC) system are widely used direct methods to measure the actual ET

(Farahani et al., 2007). The indirect method refers to estimating the ET from the $ET_{ref}$ and crop coefficient ($K_c$) value. There are different ways to estimate the $ET_{ref}$, namely combination, temperature, radiation, and pan evaporation based methods. The combination methods include the FAO Penman-Monteith (Allen et al., 1998), and the American Society of Civil Engineers, Environmental and Water Resources Institute (ASCE-EWRI) Penman-Monteith (Allen et al., 2005). The Priestley-Taylor (Priestley and Taylor, 1972) and FAO24 radiation methods (Doorenbos and Pruitt, 1977) are some of the radiation based methods. Some of the temperature based methods includes Jensen-Haise (Jensen and Haise, 1963) and FAO24 Blaney-Criddle (Doorenbos and Pruitt, 1977) methods. Among all those methods, this section includes some of the direct methods like lysimeter, EC, soil water balance and some indirect such as ASCE-EWRI, 2005 and Jensen-Haise method.

### 2.3.1 Lysimeter

Lysimeters are a widely used and accurate method to measure ET using the water balance equation. Lysimeters are also used as a standard method to calibrate other ET models (Jensen and Haise, 1963; Allen et al., 1998). According to Jensen et al. (1990) a lysimeter is a "tank filled with soil in which crops are grown under natural conditions to measure the amount of water lost by evaporation and transpiration." The crops grown in the lysimeter and surrounding field should be of same variety. Soil conditions inside the lysimeter should match with that of outer environment. All the components of water balance like rainfall, irrigation and drainage along with change in water storage is monitored in lysimeter to estimate the ET rate over a certain time interval (Jia et al., 2006).

The accuracy of the lysimeter, ET values also depends on the type of lysimeters. Mechanical lysimeter has the accuracy of about 0.05-0.02 mm (Howell et al., 1985). Generally, the shape, size and depth of the lysimeter design depend on its purpose and soil profile characteristics. The lysimeter can be of different types like weighing and non-weighing.

In the weighing lysimeter, the change in water storage could be monitored by weighing the lysimeter. The lysimeter can be weighed using counter balance, or load cells, or hydraulic scales (Farahani et al., 2007). Load cells are considered as the most accurate way to weigh the lysimeter. There are two tanks; an outer and inner tank, the load cell is installed between two tanks such that the weight of the inner tank could be taken (Jia et al., 2006). On the other hand, various soil moisture measuring devices like neutron probe, tensiometer, Hydraprobe, time domain reflectometry area used to monitor the change in soil water storage in nonweighing lysimeter.

Measuring ET by lysimeters is not feasible method in humid regions and in area with shallow water table (Jia et al., 2006) because pumping of water should be done frequently to remove the excess water from the tank. It is a closed system and does not allow for vertical and horizontal movement of water. Sometimes, the design of lysimeters is critical for ET estimates. Heating of the lysimeter rim by solar radiation may lead to micro-advection of sensible heat into the lysimeter plant canopy (Allen and Fisher, 1990; Farahani et al., 2007), generally when the lysimeter rim is made of steel. Lysimeters also have long measurement periods and relatively small fetch area compared with eddy covariance systems (Rana and Keterji, 2000).

### 2.3.2 Eddy covariance

The eddy covariance (EC) system is an advanced method and is considered to be more accurate than other methods for determining actual evapotranspiration (Farahani et al., 2007). Modern, precise and high speed instruments are used in the system. Sensors for measuring vertical wind speed (~ 10 Hz), temperature and humidity enable the EC system to compute ET electronically (Campbell and Norman, 1998). The EC system measures the ET of a large area, covering an upwind distance of about 100 times the sensor height above the canopy surface, where as lysimeter is useful only for a point measurement (Farahani et al., 2007).

This method offers more advantages over other methods. The EC system overcomes the site disturbance, no need to measure any components of the water balance, and measures the ET above the plant canopy (Twine et al., 2000; Sumner, 2001). Moreover, the ET measured by the EC is independent of the soil surface.

This system is also considered to be highly reliable to estimate energy fluxes (Baldocchi, 2003). It had been used to measure the temporal and spatial inconsistency of carbon dioxide, water vapor and energy fluxes in different vegetations by Moreo et al. (2007) and Baldocchi et al. (2001).

The EC system is used to measure the ET directly. This system draws a statistical covariance between vertical fluxes of vapor within the upward and the downward legs of turbulent eddies (Sumner, 2001). The measurement is made at a high speed for temperature and wind speed. The amount and direction of water vapor in the atmosphere is dependent on wind movement. Vertical wind speed is measured and compared with vapor density. The CSAT3 3D sonic anemometer measures the turbulent fluctuation of wind in horizontal and vertical direction. Latent heat flux (LE), which is equivalent to ET, can be determined using equation 2.3.

$$LE = \lambda \overline{w'\rho_v'} \qquad (2.3)$$

where $\rho_v$' is the fluctuation of water vapor density in kg/m$^3$; w' is the fluctuation of vertical wind speed in m/s; and $\lambda$ is the latent heat of vaporization in J/kg. The overbar represents the average of the period and primes indicate the deviation from the mean values during the averaging period (Sumner, 2001).The equation 2.3 directly gives LE, which is the energy released from the plant canopy when water changes its state from liquid to vapor phase (Sumner, 2001). LE is the function of heat of vaporization of water ($\lambda$) and ET. A Krypton Hygrometer, which is used to measure vapor density, is a very sensitive instrument and stops functioning when wet. The data recorded during night and early morning may not be good, because of the sensor's sensitivity. Jia et al. (2007) used day time reading for data analysis because the readings were not available at night and early morning. The Krypton Hygrometer is generally mounted about 10-15 cm from the centre of the CSAT3 sonic anemometer. It is installed in such a way that the source tube (longer tube) faces down and the detector tube faces up (Campbell Scientific Inc., 2007). Sensible heat flux (H) can be obtained from equation 2.4.

$$H = \rho C_P \overline{w'T'} \qquad (2.4)$$

where H is sensible heat flux in W/m$^2$; $\rho$ is the density of air in kg/m$^3$; $C_p$ is the specific heat in J/g $^o$C; and T' is the fluctuation of air temperature in $^o$C (Sumner, 2001). Wind speed and temperature can be measured by a sonic anemometer and a thermometer (Campbell Scientific Inc., 2007). Sonic anemometer and hygrometer are sensitive to water droplets. They both stop functioning when transducer is totally wet and start functioning when water is evaporated or manually wiped away. Though this system might stop, it is more accurate and helps to get the ET over a large area (Campbell Scientific Inc., 2007; Sumner, 2001).

The LE in the EC system is obtained by the difference between the water vapor in upward and downward moving eddies. This method has been used to measure the ET in wide range of vegetation around the world. It is widely used to measure the ET of forest areas. The dense vegetation in the forest area might be the obstacle to measure the ET by any other method. In Spain, ET for the olive tree was estimated by an EC system. ET from the EC and soil water balance method was observed within the 10% range for no precipitation (Testi et al., 2004). The EC system was used to estimate the ET of the boreal forest by Amiro and Wuschke, (1987) and both the boreal and temperate by Matsumoto et al. (2008). It was also adopted to estimate ET of non irrigated pasture land in Florida, USA, where the ET was measured in every 30 minutes for 19 months (28 September 2000 to 23 April 2002 (Sumner and Jacobs, 2004).

The EC system was used in Florida to measure the ET of the citrus crop (Jia et al., 2007). Two different sites with a water table deeper than 2 m and different soil characteristic (highly drained and poorly drained) were selected. Available energy was observed to be higher in the summer and lower in the winter. They noticed comparatively higher LE than H during summer and fall. Similar, seasonal pattern was found for LE and H by Matsumoto et al. (2008).

The EC system was not only used in forest areas or areas with tall trees, it was also proved good in the low height grasslands. The eddy system was used to measure the ET and energy fluxes of Bahiagrass in Florida by Jia et al. (2009). Pauwels and Samsons (2006) also estimated the grass ET of wet and sloping land surface. They compared energy fluxes measured by the Bowen ratio and EC system and found underestimation in the dirunal value of LE measured by the EC method. However, for the observation period (March 2002– June 2003), the ET estimated by both the methods was comparable with as $R^2$ value of 0.89. Twine et al. (2000) also observed 30-min closure of all energy balance in grasslands between 70-90% and used two methods: (i) LE flux calculation and (ii) Bowen ratio method for forced closure. The authors concluded that using Bowen ratio to conserve energy by adjusting LE and H gave better results than using LE flux method, as ignoring LE change was unjustifiable.

The use of advanced instrument and large fetch distance made the EC system popular in other crops field to measure ET. Ding et al. (2010) adopted the use of the EC system to measure the ET of corn in Wuwei, Gansu, China. They also observed the underestimation in the LE or ET value especially during the day time compared to large scale weighing lysimeter. They used the Bowen ratio method to close the energy balance for 30 minute periods and got good agreement with the ET measured by the EC system and lysimeter ($R^2$= 0.97). The EC system is good to get the measurement of LE and H for short duration like half hourly, hourly and daily time period. For most of the research mentioned above, the system was adopted to get the half hourly ET and energy which was later on summed to calculate the daily values. Zhang et al. (2010) made the comparison of H measured by the large aperture scintillometer (LAS) and EC system in the corn field of south east North Dakota, USA and found the overestimation of the H value measured by the LAS system when the values of daylight hours were only used.

### 2.3.3 Soil water balance

Evapotranspiration can be estimated from soil water budget equation:

$$ET = P + I - R - \Delta S - D \qquad (2.5)$$

where P is precipitation; D is deep percolation; R is runoff; I is irrigation; and ΔS is the change in water storage. In equation 2.5, the only remaining variable ET can be determined once all other variables are measured or estimated. Soil moisture content can be measured by different instruments such as time domain reflectometry (TDR), Hydraprobe, tensiometer, and neutron probe (NP) (Farahani et al., 2007). NP has been considered as the standard instrument to measure soil moisture (Gaze et al., 2002). However, using NP requires calibration for a particular site's soil before using (Gaze et al., 2002). Also, NP contains the radioactive source, potential health hazard to the user (Mwale et al., 2005). Deep percolation is difficult to measure when the measured depth is less than the wetting front. The capillary rise, fluctuating water table, and subsurface drainage are obstacles of this method (Nachabe et al., 2005). Though this method is only suitable for small area, it is a widely accepted method and can be used for irrigation scheduling (Nachabe et al., 2005).

If the ET rate exceeds the ground water discharge rate, the soil moisture content of the field will decrease (Nachabe et al., 2005). In soil water balance method, ET is estimated independently if rests of the water balance components are known. This system was successfully adopted in the large Imperial Valley in CA (Oster et al., 1984).

According to ASCE (1996) soil moisture content of soil below the root zone should be considered. The period for soil saturation near the root zone and rainfall event were avoided most of the time to overcome the error due to deep percolation and runoff (Nachabe et al., 2005; Stegmen et al., 1977). Stegmen et al. (1977) estimated the ET in south eastern part of North Dakota using soil water balance method only by considering the time without deep percolation and runoff. The water balance method of determining the ET in natural condition is by soil moisture method and lysimeter (Jensen, 1968). Using lysimeter all the parameters of the SWB can be measured, in the control system.

### 2.3.4 Reference evapotranspiration

The ET can be estimated indirectly from an $ET_{ref}$ value and a crop coefficient. Different weather parameters, like temperature, rainfall, and solar radiation are used to estimate $ET_{ref}$ using combination, temperature, radiation and pan evaporation methods (Allen et al., 1998; Doorenbos and Pruitt, 1977). Among all the methods, the ASCE-EWRI 2005 is the standardized and widely accepted method for reference ET calculation (Allen and Pereira, 2009; Farahani et al., 2007).

The combination methods include 1948 Penman, 1963 Penman, 1972 Kimberly-Penman, 1982 Kimberly Penman, 1977 FAO 24, and 1974 Hprcc Penman. All these methods use the weather parameters, such as temperature, radiation, wind and humidity for calculating the $ET_{ref}$ taking grass or alfalfa as the reference crops (Allen et al., 2005; Irmak et al., 2008). The 1963 Jensen-Haise, FAO 24 Blaney-Criddle, 1985 Hargreaves and Samani belong to the temperature method (Allen at al., 2005; Irmak et al., 2008). These methods use temperature and solar radiation as the main input parameter. The temperature method underestimates the $ET_{ref}$ during windy and sunny days (Irmak et al., 2008; Trajkovic and Kolakovic, 2009). Radiation method, like 1972 Priestley-Taylor and FAO 24 Radiation, are used widely for $ET_{ref}$ calculations. Though reasonable estimates of $ET_{ref}$ can be done from these methods, its accuracy is in doubt during windy, dry and hot days (Farahani et al., 2007; Irmak et al., 2008).The $ET_{ref}$ can also be measured by the Pan Evaporation method. It uses a metal pan of about 1 m diameter, placed in a desired environmental condition. Water is kept in the pan and loss of water is measured by the scale or read from the scale in pan (Allen et al., 1998). This method only measures the evaporation of surface, but not transpiration. So, the measured evaporation is multiplied using a pan coefficient to get the $ET_{ref}$. The amount of $ET_{ref}$ depends on the pan diameter and pan type (Allen et al., 1998). Pan evaporation method might sometime mislead the result due to the heat stored with in the pan and the reflection of solar radiation from the pan.

$ET_{ref}$ can also be directly measured using an atmometer (ET gage). Atmometer is an instrument for estimating $ET_{ref}$ in an easy way because it does not require any of the weather parameters and calculations. Two types of atmometers are available: manual and electronic models. The atmometer is mounted on a post at a certain height from the ground surface, parallel above the crop canopy. It is generally placed to the end of irrigated field where temperature and humidity is in the same range as that in the irrigated area. It should be free of any obstacle so that it can get a good sunlight. Only distilled water is used in the tube of the atmometer to avoid contamination in the ceramic plate and tubes (Irmak et al., 2005). The $ET_{ref}$ measured from the atmometer is multiplied by a respective crop coefficient to calculate the actual crop ET (Irmak et al., 2005). The atmometer could estimate ET under both grass and alfalfa crops depending on the type of canvas cover used. Different type of canvas covers are used for different purposes, for alfalfa reference crops, green canvas cover (No. 54) is used; No 30 is used for grass reference crop.

## 2.4 Evapotranspiration in Drainage Field

The ET of the field depends on the water table, soil moisture, precipitation, and the water availability of the crops. Presence of excess water in the crop root zone is always problematic. Excess water not only disturbs the field operation but also reduces the crop yield. During the rainy season, the field might have more water whereas in the peak growing season when the crop requires more water the soil moisture deficit is likely to occur. Agricultural drainage helps in drying the land in the early season, preparing the soil for planting. It also improves the trafficability of the field and makes field operation easier during planting and harvesting season. Throughout the growing season the drainage system improves the soil aeration, supports root development and enhances the nutrient and water absorption (Ayars et al., 2006; Skaggs et al., 1999). There are two different modes of the subsurface drainage systems based on the control mechanism namely, conventional and controlled drainage systems. According to Skaggs et al. (1999) the subsurface drainage rate could be changed by changing the position of the control structure. In the conventional drainage system the free drainage of water in the drain tube occurs by gravity flow (Fangmeier et al., 2006; Skaggs et al., 1999). On the other hand, controlled drainage systems consist of control mechanisms to control the drainage rate. The height of the control structure is maintained above the outlets or laterals. Water is prevented from draining through the drainage line until it overcomes the level of the control structure. The controlled drainage system prevents the drainage volume during peak growing season to support the upward water flux and replenish the ET rate (Ayars et al., 2006; Skaggs et al., 1999). In the peak growing season, the ET exceeds the rainfall and the crop requires more water. Drainage volume during those periods could be controlled or reduced using the control mechanism. It maintains the proper soil moisture condition. However, a gradual drop of the water table occurs due to the presence of ET (Skaggs et al., 1999). Rainfall during different periods of the growing season accounts for the rise of the water table. When rainfall exceeds the ET rates it leads to the rises in the water table. The controlled drainage mode of water table management is then operated as the conventional drainage system by lowering the height of the control structure (Fangmeier et al., 2006) to remove the excess water of the field. According to Schuh (2008) the amount of drainage during the growing season depends on the precipitation, ET, ground water table, water uptake capacity of crop and change in water table by snow melting in spring.

The removal of the excess water through the drainage and loss by the ET could be identified by the nature of the water table in the SSD field. When the water is drained out from the outlet the water table between the two drainage lines shows a parabolic shape (Skaggs et al., 1999).

The subsurface drainage has the good control over the soil moisture compared to the undrained (having no artificial subsurface drainage system) field. In the undrained (UD) field, water is removed either by the surface and subsurface runoff or percolation. Thus it is hard to maintain the proper soil moisture and water table depth within the required limit, and soil water deficit is likely to occur. However, the controlled drainage mode applied during the peak growing season can improve the soil moisture condition.

The soil moisture content of controlled drained and sub-irrigated areas was higher compared to the UD area (Tan et al., 2002). Tan et al. (2002) found a difference in soil moisture of free drainage and control drainage system up to the depth of 80 cm. That difference was especially observed in the dry periods whereas in wet or rainy reason, the difference was small or negligible. That supports sufficient uptake of water by the root resulting in the higher ET. Higher ET means more water used by plant and higher yield. Tan et al. (2002) observed higher corn ET in controlled drainage field along with increased crop yield compared to the UD field. Likewise, Mejia et al. (2000) also observed higher corn yield in subirrigated/water table controlled field compared to UD field.

### 2.5 Methods Used in North Dakota

In North Dakota, crop water related studies have been conducted at Oakes, ND. Most of the research has focused on the determination of ET for irrigation scheduling. Crop coefficient curves for seven different types of crops (sugarbeet, corn, spring wheat, soybean, potatoes and alfalfa) have been developed (Stegman et al., 1977). The Jensen-Haise (JH) method was used to calculate the $ET_{ref}$ and actual ET was estimated using soil water budget equation for small plots in Oakes, ND. Soil moisture changes were measured using neutron probe soil moisture sensor, after 2-3 days of irrigation and rainfall. Irrigation was done by center pivot system and rainfall amounts were measured using catch cans. The $K_c$ curve was developed as a function of "days past emergence" (Stegman et al., 1977). The $K_c$ was then used for irrigation scheduling.

Stegmen (1988) compared the crop coefficients curves of corn developed in Nebraska, North Dakota, and Kansas with that in eastern Colorado and found that the combined growing degree days from the time of emergence to maturity of corn was the best variable for difference in $K_c$. Steele et al. (1996) determined ET using water balance equation, and $ET_{ref}$ using Jensen-Haise and Penman equations for the south eastern part of ND. Lysimeters were used to measure water stored in the field. Data during the growing season for all 11 years (1981-1991) were used to develop the $K_c$, curves, based on "Days past planting." These $K_c$ curves are used highly for irrigation scheduling. According to Steele et al. (1997) seasonal soil moisture content correction should be done at least for every month to avoid overestimation of ET. This was highly recommended before using them for irrigation scheduling. Steele et al. (1997) monitored the soil water content of land near Oakes, ND and used the information in irrigation scheduling model to determine the irrigation requirement of crops.

All these studies are useful for estimating the irrigation requirement of the crop. Moreover, the ET is estimated using soil water balance method and $ET_{ref}$ by JH method. None of the past research uses the complete EC system to estimate the ET and ASCE-EWRI method to estimate $ET_{ref}$. Besides that, there is the need to study the effect of SSD in the water balance of the agricultural field. The emerging use of SSD might lead to the change in surface and subsurface hydrology of agricultural field in ND, which is yet to be studied.

# 3. PAPER: REFERENCE EVAPOTRANSPIRATION AND ACTUAL EVAPOTRANSPIRATION MEASUREMENTS IN SOUTHEASTERN NORTH DAKOTA

## 3.1 Abstract

A field experiment was conducted on the growing season of 2009 and 2010 to study the water balance in a farm field at Fairmount, ND. The total area of the field was 44 ha, half of which had subsurface drainage (SSD) installed in fall 2002 at approximately 1.1 m depth, and 18.2 m drain spacing. Corn (*Zea Mays*) was planted in 2009 and soybean (*Glycine Max*) in 2010. Evapotranspiration (ET) rates were measured in both the subsurface drained (SSD) and undrained (UD) fields using eddy covariance (EC) systems. The changes in water table and soil moisture content were measured continuously in both the SSD and UD portions of the field. Additionally, the crop coefficient ($K_c$) value was developed using the ET measured by the EC system and the reference ET ($ET_{ref}$) estimated using the American Society of Civil Engineers Environmental and Water Resources Institute (ASCE-EWRI) alfalfa method. Results showed that shallow water table and high soil moisture content in the spring and fall resulted in a higher ET in the UD field. However, in the summer, the ET in the SSD field was higher than that in UD field by 30 % in 2009 and by 13 % in 2010. Over the entire growing season, the ET in the SSD field was higher by 15 % in 2009 and the difference was minimal in 2010, respectively, as compared to that in the UD field. In the peak growing season (Jul-Aug), the $K_c$ was greater in the SSD field.

## 3.2 Introduction

Evapotranspiration (ET) is the combined process of evaporation from the soil surface and transpiration from plants, and is a major component of the water balance. It is affected by the available soil water content and water table change in the soil root zone (Kahlown and Azam, 2002). ET is the major factor governing crop water use since transpiration accounts for 99% of water uptake by plants. Sumner (2001) reported that ET accounted for 70% of rainfall in Florida.

The ET can be directly measured via soil water balance (SWB) or energy balance approaches. Lysimeter, soil water balance and eddy covariance (EC) are widely used direct methods to measure the actual ET. Lysimeter and EC methods have been considered as the standard methods to measure ET compared to all other methods (Farahani et al., 2007). ET can also be estimated indirectly utilizing crop coefficient ($K_c$) and reference ET ($ET_{ref}$). The $ET_{ref}$ is defined as the ET from a field with uniform cover of at least 100 m span of same or similar dense growing reference plants such as grass and alfalfa, having specific height and surface resistance and grown in sufficient moisture condition (Allen et al., 2005). Different weather parameters like temperature, rainfall, wind speed and solar radiation are used to estimate the $ET_{ref}$ (Allen et al., 1998; Doorenbos and Pruitt, 1977). Among all the methods, the American Society of Civil Engineers, Environmental and Water Resources Institute (ASCE-EWRI) method by Allen et al. (2005) is the standardized and widely accepted method for $ET_{ref}$ calculation (Allen and Pereira, 2009; Farahani et al., 2007).

A lysimeter is a tank placed in the field to measure ET by growing crops inside the tank while maintaining its conditions similar to its surrounding natural field conditions (Jensen et al., 1990). All components of water balance (rainfall, irrigation, drainage, soil moisture change etc.) over a certain time interval are measured and the residual is considered as ET. Measurement of all those components of water balance and maintaining the natural condition inside the lysimeter makes the operation more complicated. The accuracy of lysimeter depends on the measurement duration, shape, size and the construction material of the lysimeter, weighing mechanism and the environmental conditions (Howell et al., 1991). Measuring ET by lysimeter could be very difficult in humid regions and in area with shallow water table (Jia et al., 2006). Heating of lysimeter rim by solar radiation may also lead to micro advection of sensible heat in the planted crop (Allen and Fisher, 1990; Farahani et al., 2007), especially when the rim is made of steel.

Soil water balance is a widely used method in North Dakota to estimate the ET. In ND, crop coefficients for several crops (corn, soybean, potato, sorghum, etc.) were developed using ET estimated by soil water balance and $ET_{ref}$ by Jensen Haise method (Jensen and Haise, 1963). Soil moisture content can be measured by different instruments, such as time domain reflectometry (TDR), Hydraprobe, tensiometer, and neutron probe (NP). Stegman et al. ( 1977) used the NP to measure the soil moisture content and used soil water balance method to estimate the ET. NP has been considered as the standard instrument to measure soil moisture (Gaze et al., 2002); however, using NP requires periodical calibration for the soil before installation (Gaze et al., 2002). In addition, NP contains radioactive source and potential health hazard to the user (Mwale et al., 2005). The measurement of all components becomes challenging in areas which have capillary rise, fluctuating water table and subsurface drainage (Nachabe et al., 2005).

Moreover, both the lysimeter and soil water balance methods undergo site disturbance and can provide only a point ET measurement.

The EC system uses modern, precise and high frequency instruments to measure wind speed, temperature, humidity and air density and computes ET electronically (Campbell and Norman, 1998). It is an advanced method and has been considered to be an accurate method to determine ET (Farahani et al., 2007; Prueger et al., 1997; Sumner, 2001) compared with lysimeter and SWB methods. This system has been used to measure the ET of several types of vegetation in the U.S (Castellvi and Snyder, 2010; Jia et al., 2007, 2009; Sumner, 2001) and around the world (Li et al., 2008; Testi et al., 2004; Zermeno-Gonzalez et al., 2010). The EC system measures the ET above the crop canopy, overcomes the site disturbance and the need of measuring individual component of water balance, and is independent of the soil surface condition (Sumner, 2001; Twine et al., 2000). The EC system also covers large area of measurement to account for the upwind distance of about 100 times the sensor height above the crop canopy (Campbell and Norman, 1998).The ET measured by the EC system shows good agreement with the ones from Bowen ratio method ($R^2$= 0.89) (Pauwels and Samson, 2006) and is comparable to ET measured by lysimeter ($R^2$= 0.97) (Ding et al., 2010). More importantly, the ET determined by the EC method is often used to calibrate and validate remote sensing ET at a large spatial scale (Gowda et al., 2008; Lu and Zhuang, 2010; Yuan et al., 2010).

The ET of a particular area depends on the change in the water table (Cooper et al., 2006; Nachabe et al., 2005). Though the subsurface water contributes to ET, it is difficult to directly measure the precise amount going to ET (Nachabe et al., 2005). A shallow ground water table results in a higher ET. Coupling rise in water table and ET was observed after summer rains (Cooper et al., 2006). In general, water table drops shortly after noon, and becomes the shallowest around midnight. This might be because of the water table recharge rate being higher after the sunset and before the morning and lower during the day time due to the higher ET rate during the day (Nachabe et al., 2005). Similar pattern of drop in water table with the presence of ET was observed in subsurface drained field (Skaggs et al., 1999). Under optimum soil moisture content, the ET is high (Payero et al., 2008). Thus, ET of the particular crop depends on the soil moisture content and the depth of water table.

SSD is a process to remove excess water from the root zone at some depth below the soil surface via perforated conduits (Skaggs et al., 1999). The SSD can maintain the optimum soil moisture condition, lower water table depth and enhance the nutrient and the water uptake by the plants (Ayars et al., 2006; Skaggs et al., 1999). The presence of excess water in the crop root zone is always problematic as it disturbs the field operation and reduces the crop yield. The SSD can help improve the field condition and traction of the field, and support easy planting and harvesting of the crops. Application of the SSD system affects the quantity of water in the SSD field as well as the surface water system that it drains to (Skaggs et al., 1994).

The majority of the research conducted in a SSD fields has focused on field hydrology and water quality (Kahlown and Azam, 2002; Skaggs et al., 1994). A comparison of ET between controlled drainage and UD (having no artificial subsurface drainage system) field yielded the higher ET in the SSD field in summer and lower in spring and fall than that of UD field (Tan et al., 2002). The amount of drainage during the growing season depends on the precipitation, ET, ground water table, water uptake capacity of crop and change in water table by snow melting in spring (Schuh, 2008). The artificial modification of the water table by SSD can cause ET variations, and reversely, crop ET can affect the drainage water amount that alters the surface water hydrology and a regional water balance.

Therefore, it is important to accurately measure the ET and compare its difference between two agricultural water management practices, SSD and UD system. The objective of this paper is to develop crop coefficients ($K_c$) for corn and soybean using the ET measured by the EC system and the $ET_{ref}$ estimated by ASCE-EWRI equation such that the results can be transferred and used to estimate ET of similar fields.

## 3.3 Materials and Methods

### 3.3.1 Study area

The experimental site (46°00'45" N and 96°35'47" W) was located in the southeastern part of North Dakota near Fairmount, Richland County and to the northwestern part of Minnesota along the Red River Valley (Figure 3.1). The total area of the experimental site was 44 ha, which is divided into two treatments: SSD field (≈22 ha), and UD field (22 ha). Among the 22 ha of the SSD field, 50% of the field (11 ha) also had the subirrigation treatment (Figure 3.2). The SSD system was installed in August 2002 at an approximate depth of 1.1 m and a spacing of 18.2 m (Jia et al., 2008). The main drainage pipe was located at the east side of the field extending to the outlet buried at the depth of 1.8 m. According to Scherer and Jia (2010), number of pump cycles in the study area varied from 12 to 20 pump cycles per hour depending on the rainfall amount. This value was higher than the recommended 10 pump cycles/hr at peak flow (ASABE standards, 2009). The main drainage pipe was overdesigned as it was designed for entire 44 ha of field and SSD was installed later on only half of the area (22 ha).

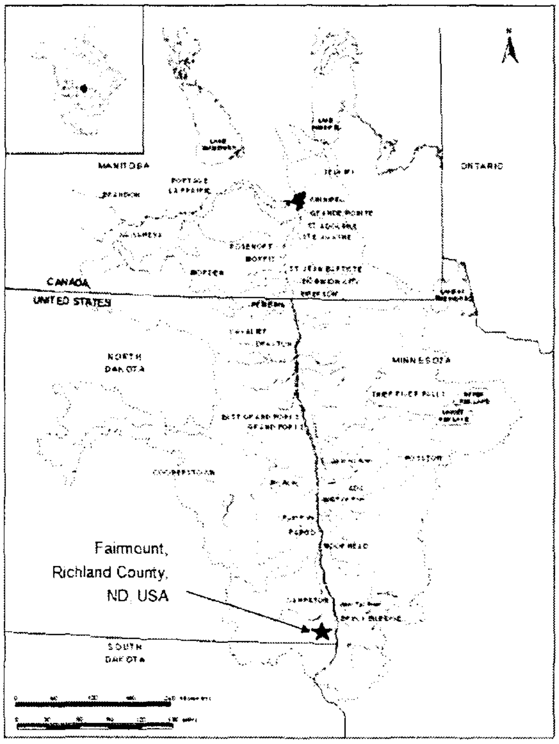

Figure 3.1. Location of experimental site, from Historical and Cultural Society, Clay County, ND.

### 3.3.2 Experimental layout

Figure 3.2 shows the field layout. The total width of the field was 806 m and the length 546 m. Two alleys, each 3 m wide, were made in the field 366 m apart from each other. All the field instruments were installed within those alleys. The alleys were also used for transportation and movement in the field. A lift pump was located to the north-eastern corner of the field. The drainage and subirrigated water volumes were measured at the pump lift station and irrigation wells, respectively. A standard national weather service manual rain gage and an automatic rain gage were installed at the northeastern edge of field. A weather station with a complete EC system was installed in both the UD and SSD fields. In 2009, the EC stations were operated from June 2 to November 18, 2009, while corn was planted on May 17, emerged on May 27and harvested on November 18, 2009. In 2010, the EC stations were operated from May 8, to September 29, 2010; soybeans were planted on May 22, emerged on June 1 and harvested on September 30, 2010. The ET measurement instruments were set up after planting and taken off before harvesting to avoid interference with field operations. The height of the EC station was determined such that the source area (footprint) of the measurements was confined within the extent of each sub-field (Zhang et al., 2010). Meteorological data were scanned every 50 msec (20 Hz) and were recorded at 30 minute intervals.

In fall 2007, 24 piezometers (shallow wells) were installed along the two alleys that ran north to south in the field. Each alley ran through the SSD and UD portions of the field (Jia et al., 2008). Along each alley, four piezometers were installed in the UD portion and eight piezometers in the SSD portion. Piezometers in the SSD field were in the horizontal distance of 1, 4, 7, and 10 m from the SSD tubes (Figure 3.2). Water level transducers (Model U 20-001-01, Onset Computer, PocA11asset, MA, USA) were installed in each piezometer. Water level changes were automatically recorded at 30-minutes intervals.

Six sets of Hydraprobe II (Stevens Water Monitoring Systems, Portland, OR) soil moisture sensors were installed at different depths across the field in the SSD and UD fields. Twelve soil moisture sensors were installed at two locations at six different depths; 15, 30, 45, 60, 90 and 120 cm from the soil surface. The horizontal spacing in the SSD field was set at 4 m and 7 m from the SSD line, whereas, in the UD field, the two sets were 3 m apart from each other.

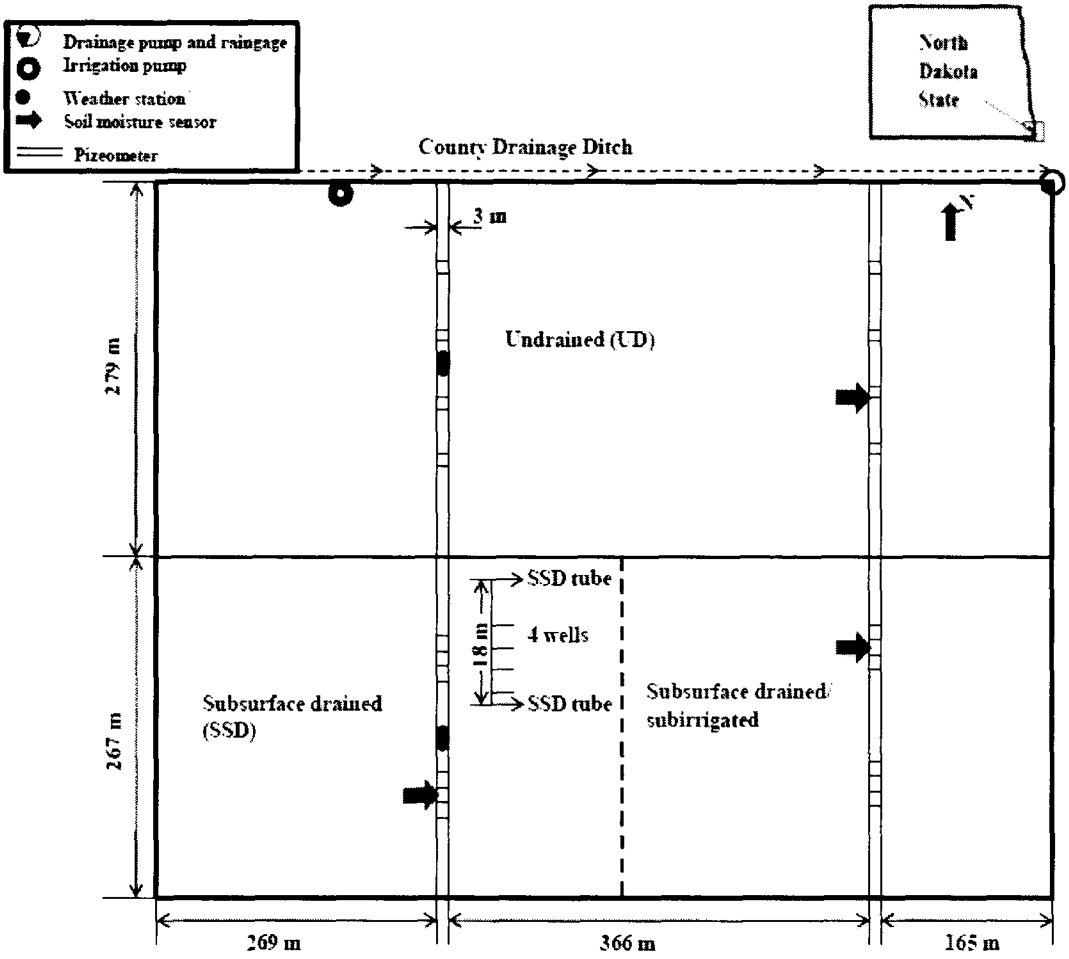

Figure 3.2. Field layout and instruments location.

### 3.3.3 Climate and vegetation of the study area

The experimental site has a typical continental climate. Average monthly air temperature of the study area varies from -14°C to 22°C. The air temperature during the summer months is high with the maximum temperature in July. The area is covered by snow for 4-5 months (Nov-Mar). During that period, it has freezing air temperature, with the minimum temperature recorded in January (Table 3.1). The average annual precipitation of the study area is 557 mm, with the major rainfall events observed from June to September (NDAWN, 2010). The average growing season rainfall of the area is

451 mm (May- November). The monthly average air temperature and the precipitation are shown in Table 3.1. The major crops grown in the study area are soybean and corn. They are normally grown in rotation at the site.

Table 3.1. Monthly average weather parameters near the experimental site at North Dakota Agricultural Weather Network, Wahpeton station from 2001 to 2009 (NDAWN, 2010).

| **Month** | **$T_{max}$ (°C)** | **$T_{min}$ (°C)** | **$T_{avg}$ (°C)** | **Precipitation (mm)** |
|---|---|---|---|---|
| Jan | -9 | -19 | -14 | 16 |
| Feb | -4 | -15 | -10 | 10 |
| Mar | 2 | -7 | -2 | 26 |
| Apr | 13 | 1 | 7 | 45 |
| May | 21 | 8 | 15 | 75 |
| Jun | 26 | 13 | 19 | 85 |
| Jul | 29 | 15 | 22 | 90 |
| Aug | 28 | 14 | 21 | 68 |
| Sep | 22 | 8 | 15 | 62 |
| Oct | 14 | 2 | 8 | 52 |
| Nov | 2 | -7 | -2 | 19 |
| Dec | -6 | -15 | -10 | 9 |
| **Averages/Sum** | **11.5** | **-0.2** | **5.75** | **557** |

### 3.3.4 Soil type

The field is dominated by four different soil series. The west half excluding a small longitudinal section in the northwest is Clearwater- Reis silty clay (map unit 1236 A, Figure A8). Antler-Mustinka silty clay loam (1397 A) extends from the eastern part of Clearwater- Reis silty clay and lies in the southern portion of the field, excluding small a strip on the far east side of the field. Antler silty clay loam (1396 A) occupies the most eastern part of the field extending from north to south. Doran clay (1243 A) lies to the north extending from northcentral to northwest part of the field (Jia et al., 2008; Web Soil Survey, 2010). All these soil series have poor drainage characteristics, low runoff rate and low permeability. These soils are common in the relatively flat, level (≤ 2% slope) land along the lake plains (NRCS, 2010).

### 3.3.5 Instrumentation

#### 3.3.5.1 Eddy covariance system

Two weather stations with complete EC systems were installed in the UD and SSD portion of the field. Instruments or sensors used in this project were either newly purchased or calibrated before installation. The figure A4 in the appendix shows the complete instrument set up of the EC system. The EC system consisted of CSAT3 sonic anemometer, CSI KH20 Krypton hygrometer, and other setup as shown in Table 3.2. The CSAT3 3D sonic anemometer measures wind speed and the speed of sound using three pairs of non- orthogonal sonic transducers. This sensor detects changes in wind fluctuations and has very high resolution. The sensor readings were used to calculate sensible and latent heat fluxes, two important components of the energy balance. The latent heat flux (LE) estimated from the EC system is equivalent to the ET of the area. The sonic anemometer was set up facing the prevailing wind direction, north-west. It was adjusted to keep it parallel to the crop canopy and to the height of at least 1 m from the top of the crop canopy. The KH20 Krypton hygrometer was mounted in between the CSAT3 transducers. The tubes were tilted to reduce the chances of water accumulation in the lenses. The tubes and detector lenses were cleaned periodically with distillated water. The fluctuation in vapor density estimated by KH20 depends on the ultraviolet radiation emitted from the source tube to the detector tube along the distance of 1 m. A REBS Q 7.1 net radiometer was used to measure net radiation. The sensor was placed higher than the crop canopy. The Vaisala HMP45 C temperature and relative humidity probe was used to measure relative humidity (RH) and air temperature. The probe was sheltered in a radiation shield in order to eliminate the error due to sunlight and to protect the probe from radiation. Two HFP01SC Hukseflux self-calibrating soil heat flux plates were buried in each station at the depth of 8 cm. The sensors consist of a thermopile and the film heater. The thermopile measures temperature gradients across the plate below the surface. The TCAV averaging soil thermocouple probe was buried along with the soil heat flux at the depth of 2 and 6 cm. It is needed to measure the temperature change of the soil layer above the soil heat flux. A CS616 TDR was buried to the depth of 5 and 15 cm. This sensor measured the time of propagation of electromagnetic waves, which was then converted to volumetric water content using the calibration curve provided by the manufacturer. A Texas Electronics TE525WS tipping bucket rain gage was installed at the weather stations. Every tip of the bucket was equivalent to 0.254 mm of rainfall. Along with all these instruments, the weather station consisted of a battery to run the system and a 70 watt solar panel to charge the battery. The CR3000 data logger was used to store the readings from all the sensors in the EC system (Figure A5). The scan interval of the sensors was 50 msec (20 Hz) and the recording was averaged to every 30-minute values.

Table 3.2. The height of instruments of complete eddy covariance weather stations at Fairmount, ND in 2009 and 2010. Negative height values indicate depth below the soil surface.

| | **Height of instruments (m)** | | | |
|---|---|---|---|---|
| | **2009** | | **2010** | |
| **Instruments** | **SSD** | **UD** | **SSD** | **UD** |
| CSI CSAT3 3D Sonic Anemometer | 2.92 | 2.97 | 2.49 | 1.85 |
| CSI KH20 Krypton Hygrometer | 2.92 | 2.97 | 2.49 | 1.85 |
| R.M. Young Wind Sentry Set | 3.3 | 3.3 | 2.88 | 2.09 |
| Texas Elec. TE525WS Tipping Bucket | 3.12 | 2.42 | 3.12 | 3.12 |
| REBS Q7.1 Net Radiometer | 3.05 | 3.18 | 1.75 | 1.46 |
| Vaisala HMP45C Temp/RH Sensor | 2.23 | 2.14 | 2.58 | 2.14 |
| HFP01SC Hukseflux Self-Calibrating Soil Heat Flux Plate (1) | -0.08 | -0.08 | -0.08 | -0.08 |
| HFP01SC Hukseflux Self-Calibrating Soil Heat Flux Plate (2) | -0.08 | -0.08 | -0.08 | -0.08 |
| TCAV Averaging Soil Thermocouple Probe (1) | -0.02 | -0.02 | -0.02 | -0.02 |
| TCAV Averaging Soil Thermocouple Probe (2) | -0.06 | -0.06 | -0.06 | -0.06 |
| CS616 Water Content Reflectometer (1) | -0.05 | -0.05 | -0.05 | -0.05 |
| CS616 Water Content Reflectometer (2) | -0.15 | -0.15 | -0.15 | -0.15 |

### 3.3.5.2 Soil moisture sensor

Soil moisture content was measured by Hydraprobe II (Stevens Water Monitoring Systems, Portland, OR). Each field conditions had 12 soil moisture sensors, buried at six different depths. The spacing of the sensors was 3 m from each other. In the SSD portion, the soil moisture sensors were located at the distance of 4 and 7 m from the SSD drain line.

The data were stored in a CR1000 data logger. Soil moisture was recorded every 15 minutes for all depths. Soil moisture measurement was conducted from June 11 to November 18 in 2009 and from May 26 to October 20 in 2010. The soil moisture were cross checked so that the largest value did not exceed the porosity and the lowest value did not fall below permanent wilting point (PWP) (Table A4). The readings outside of that range were linearly corrected using the porosity and PWP. The porosity of the field was measured in 2008 and the PWP was obtained from the web soil survey (Web Soil Survey, 2010).

### 3.3.5.3 Water table depth

The water table depth was measured in the 24 wells and the sump of the pump station both manually and automatically. Manual readings were taken weekly using a Temperature Level Conductivity (TLC) meter (Solinst, Georgetown, Ontario Canada). Automatic water level reading of each well was measured with the HOBO water level transducers (Model U 20-001-01, Onset Computer, Pocasset, MA, USA). The water level was calculated using barometric pressure, reference water level, temperature and the absolute pressure measured by the instrument every 30 minutes using equation (3.1) given below (Model U 20-001-01, Onset Computer, Pocasset, MA, US).

$$D = \frac{61.94 * Phy\_d}{\rho} \tag{3.1}$$

where D is the depth of water table in m from the bottom of the sensor to the water level, Phy_d is the difference of absolute and barometric pressure in Kpa; and ρ is the density of water in kg/m$^3$.

The water level transducer was hung in each piezometer with a steel cable. A small hole was drilled in the cap of the piezometer to vent the well in order to equilibrate with the atmospheric pressure. The barometric pressure measured at the NDAWN Wahpeton station, located within 16.1 km from the experimental site, was used to process the raw data obtained from the water level transducer. The water level measured by the TLC from the top of the well to the water level was taken as the reference water level. The fluid density was corrected using the measured water temperature from the same transducer (Model U 20-001-01, Onset Computer, Pocasset, MA, US). The depth from the soil surface to the top of water level can be calculated using equation 3.2.

$$d = X - D \tag{3.2}$$

where d is depth from soil surface to the top of water table (m), X is the depth from the soil surface to the bottom of the transducers (m) and D is the depth obtained in equation 1 in m.

#### 3.3.5.4 Drainage water amount

As mentioned earlier, out of the total 44 ha area, SSD was installed in the 22 ha of the field. Water from the SSD field was drained out from the automated pump station (Figure A3). The pump station was turned on in the spring, early summer and fall. The pumping rate from the lift station was recorded using a HOBO state data logger (Model H-06, Onset Computer, Pocasset, MA, USA) and measured with a split-core current switch (Scherer and Jia, 2010). The data was downloaded every week and the pumped water volume was calculated based on the on and off time and the pump curve (Scherer and Jia, 2010). The water level change in the sump pump was also verified by a water level transducer (Model U 20-001-01, Onset Computer, Pocasset, MA, USA). During the active growing season, the water was conserved in the SSD tubes to replenish the water requirement of the crop. Also the irrigated water from the subirrigated portion could flow into the part of the SSD area because there were no isolation devices between the two plots (Figure 3.2).

### 3.3.6 Methods

#### 3.3.6.1 Eddy covariance system

Sensible heat (H) and LE fluxes were measured using the CSAT3 sonic anemometer and the CSI KH20 hygrometer, respectively. The anemometer measured the wind speed in three orthogonal directions and the hygrometer measured the vapor density above the crop canopy. The fluctuation of wind speed, vapor density and virtual air temperature were recorded at 20 Hz and the covariance was calculated every half hour. The fluctuation of vapor density and vertical wind speed was used to estimate LE (equation 3.3) (Sumner, 2001). Similarly, H was calculated using the fluctuation of vertical wind speed and fluctuation of air temperature (equation 3.4) (Sumner, 2001).

$$LE = \lambda \overline{w'\rho_v'} \qquad (3.3)$$

$$H = \rho C_p \overline{w'T'} \qquad (3.4)$$

where $\rho_v$' is the fluctuation of water vapor density in kg/m$^3$; w' is the fluctuation of vertical wind speed in m/s; and $\lambda$ is the latent heat of vaporization in J/kg. The overbar represents average over the sampling period and prime is the deviation from the mean values during the averaging period. H is sensible heat flux in W/m$^2$; $\rho$ is the density of air in kg/m$^3$; $C_p$ is the specific heat in J/g °C; and T' is the fluctuation of air temperature in °C.

Data analysis was performed using only daytime values. At night, the energy fluxes were considered to be zero. Data from KH20 hygrometer might not be available in the early morning and after rainfall due to the vapor in its lens. The night time LE value was not used in the ET calculations.

The LE recorded every half hour was corrected for temperature induced fluctuations in air density (Webb et al., 1980). The sensible heat flux was corrected to account for the difference between the virtual and actual air temperature. Basically, for anemometer, the deflection of the sound path and the variation in air density caused by the fluctuation of water vapor resulted in the error of the sonic temperature (Schotanus et al., 1983). Both sensible heat flux and the latent heat flux were corrected for the error due to natural wind coordinate system (Baldocchi et al., 1988), and the average vertical wind speed was forced to zero. The Bowen ratio method was used to close the energy balance for each 30 minute period (Twine et al., 2000). This Bowen ratio closure method assumes that the EC system measures the Bowen ratio correctly. Moreover, it overcomes the underestimation of the LE flux measured by the EC system.

The modified Priestley Taylor (PT) approach was used to fill in the missing 30-minute LE values (Priestley and Taylor, 1972). The required empirical coefficient ($\alpha$) in the PT equation was determined from the available LE, H, $R_n$, G and temperature data using equation 3.5. The monthly value of $\alpha$ ranging from 0.74 to 1.23 was used to estimate the 30 minute LE in that month instead of a constant $\alpha$ 1.26 for all season (Priestley and Taylor, 1972).

$$\alpha = \frac{\lambda E(\Delta + \gamma)}{\Delta(R_n - G)} \qquad (3.5)$$

where $\alpha$ is the PT constant, $\lambda E$ is latent heat flux in $W/m^2$, $R_n$ is the solar radiation in $W/m^2$, G is soil heat flux in $W/m^2$, $\Delta$ is slope of the saturation vapor pressure curve, in $Pa/^oC$ , and $\gamma$ is psychrometric constant, in $Pa/^oC$.

### 3.3.6.2 Estimating stored energy and soil heat flux

The soil heat flux (G) is the combined term that represents the measurement of the HFP01SC soil heat flux plate at the 8 cm ($G_{8cm}$) from the soil surface and stored soil energy (s). The soil temperature measured at a depth of 2 and 6 cm and the soil moisture content at a depth of 5 and 15 cm from the soil surface were used to estimate stored soil energy. The stored soil energy value was estimated using equation 3.6 following Campbell Scientific, Inc. (2007)

$$s = \frac{\Delta T_s C_s d}{t} \qquad (3.6)$$

where s is stored soil energy in $W/m^2$; $\Delta T_s$ is the difference in soil temperature recorded at two different time at the depth of 2 and 6 cm in $^oC$ (Equation 3.7); $C_s$ is the heat capacity of the moist soil (equation 3.8) in $J/^oC$; d is the required depth of measurement in m (0.08 m); t is the time interval between the measurement in seconds (1800 sec).The difference in soil temperature was calculated as

$$\Delta T_s = \frac{(T_{1t2} + T_{2t2} - T_{1t1} - T_{2t1})}{2} \tag{3.7}$$

where $T_1$ is the soil temperature at 2 cm depth in °C; $T_2$ is the temperature of soil for 6 cm depth in °C; and t1 and t2 is time for which the temperature is recorded. The heat capacity of the moist soil was calculated as

$$C_s = \rho_b * C_d + \Theta_v * \rho_w * C_w \tag{3.8}$$

where $\rho_b$ is the bulk density, which is 1120 kg/m$^3$ and 1310 kg/m$^3$ for the soil in the SSD and UD field respectively; $C_d$ is the heat capacity of dry mineral soil (840 J kg$^{-1}$°C$^{-1}$); $\Theta_v$ is the soil moisture content in volumetric basis; $\rho_w$ is the density of water (1000 kg/m$^3$); and $C_w$ is the heat capacity of water (4910 J kg$^{-1}$°C$^{-1}$). Finally, G was calculated as

$$G = G_{8cm} + S \tag{3.9}$$

In 2010, the soil heat flux sensors were not functioning properly. However, the soil temperature and soil moisture were measured. Using the measured data in 2009, a relationship was developed based on soil moisture at the depths of 5 and 15 cm and soil temperature between 2 and 6 cm from the soil surface. New equations 3.10 and 3.11were developed for May to September and equations 3.13 and 3.14 were developed for October to November to calculate G when $G_{8cm}$ was not measured. In 2010, only the equations 3.10 and 3.11 were used.

The day time G value from May to September was estimated using,

$$G = 26.8 * \frac{(T_{1t2} + T_{2t2} - T_{1t1} - T_{2t1}) * K * SWC}{d * 2} \qquad (3.10)$$

The night time G value from May to September was estimated using,

$$G = 21 * \frac{(T_{1t2} + T_{2t2} - T_{1t1} - T_{2t1}) * K * SWC}{d * 2} \qquad (3.11)$$

The day time G value for October and November was estimated using,

$$G = 57 * \frac{(T_{1t2} + T_{2t2} - T_{1t1} - T_{2t1}) * K * SWC}{d * 2} \qquad (3.12)$$

The night time G value for October and November was estimated using,

$$G = 8 * \frac{(T_{1t2} + T_{2t2} - T_{1t1} - T_{2t1}) * K * SWC}{d * 2} \qquad (3.13)$$

where G is the soil heat flux in $W/m^2$;$T_1$ is the temperature of soil at 2 cm depth in $^oC$; $T_2$ is the temperature of soil for 6 cm depth $^oC$; t is time for which the temperature is recorded; d is the depth of soil for which the soil heat flux is to be calculated, m; SWC is the soil water content of the soil at that depth; K is the thermal conductivity, 1.6 $Wm^{-1}K^{-1}$ for that type of soil having soil moisture around 0.4 $cm^3/cm^3$ (Hillel, 1998); 26.8, 21, 57 and 8 are the constants. The G value estimated using the equation (3.10-3.13) and the one estimated using equation (3.6-3.9) showed a good agreement with $R^2$ greater than 0.7 when the data of growing season 2009 were used. Thus the equations (3.10-3.13) were used to estimate G value during the growing season in 2010.

### 3.3.6.3 Reference evapotranspiration

$ET_{ref}$ was estimated using the weather parameters recorded in Wahpeton weather station of NDAWN. Required weather parameters like minimum, maximum, average and dew point temperatures, solar radiation, wind speed, location and altitude of the station were downloaded from the NDAWN website for the 2009 and 2010 growing seasons. The $ET_{ref}$ was estimated using three different methods, ASCE-EWRI (2005) for grass and alfalfa reference crop and Jensen- Haise (1963) methods.

### 3.3.7 Development of crop coefficient value

The crop coefficient value for corn and soybean were developed for the SSD and UD fields using the $ET_{ref}$ methods ASCE-EWRI (alfalfa and grass) and JH and the ET by the EC system. The $K_c$ developed at the experimental site can be used to determine ET of corn and soybean field in other field with similar water management practices. The $K_c$ value was estimated following FAO 56 (Allen et al., 1998),

$$K_c = \frac{ET}{ET_{ref}} \tag{3.14}$$

Where $K_c$ is the crop coefficient; ET is the actual evapotranspiration estimated by the EC system and $ET_{ref}$ is the reference evapotranspiration estimated using ASCE-EWRI equation.

### 3.3.8 Statistical analysis

One way ANalysis Of VAriance (ANOVA) was conducted using Sigma Plot (11.0) (Systat Software Inc., Chicago, IL) to compare the daily ET of the SSD and UD field. The data were tested for normality using the Shapiro Wilk test. If the normality test failed, Kruskal-Wallis one way ANOVA was conducted, otherwise, a regular ANOVA test was performed. Similarly, $ET_{ref}$ value obtained from the ASCE-EWRI and the JH method, the soil moisture values between the SSD and UD field and $K_c$ values (ET from the EC system and $ET_{ref}$ from ASCE-EWRI, alfalfa) between the SSD and UD field were compared.

## 3.4 Results and Discussion

### 3.4.1 Distribution of soil moisture

The soil moisture distribution is affected by water management practices, soil properties, and soil textures. As expected, soil moisture values were different at different depths at a particular field condition. For both the SSD and UD fields, the available soil moisture (AW) in the root zone, down to 135 cm depth, exceeded 50% of the total available soil moisture (TAW) most of the time during the growing season of 2009 and 2010. When AW, the amount of water between field capacity and permanent wilting point, is greater than 50%, it indicates that there was adequate soil moisture available for crop water consumption or to meet ET requirement (Allen et al., 1998).

In both years, surface soil moisture content in UD field was higher than that in the SSD field (Figure A9-A10). In summer 2009, soil moisture content at the deeper depth (52.5-135 cm) was greater in the SSD field compared to that in the UD field (Figure A12-A14). In the SSD field, water entered the perforated SSD tubes and maintained higher soil moisture in the deeper depth. Also such variation could be due to spatial difference in soil texture. However, in 2010, both the fields had almost the same soil moisture content at deeper depths. At the depth of 75-135 cm from soil surface, the soil moisture in the UD field was greater compared to that in the SSD field (Figure A13-A14). In the growing season 2010, the rainfall in July was higher compared to that in 2009, which might have helped to maintain the optimal soil moisture content in entire depth at both fields. Similar, result was observed by Tan et al. (2002) during the cool growing season. Otherwise they recorded higher soil moisture in the control drained field compared to that in the freely drained one. By preventing the drainage water outflow during the summer 2009 and 2010 the optimum soil moisture was maintained at the root depth. Also, it was possible that the water from the subirrigated portion had moved to the SSD field through the SSD tubes. The soil moisture content (0-135 cm) yielded significant statistical difference in 2009 and the difference was insignificant in 2010 (P value greater than 0.05).

### 3.4.2 Variation in water table depth

The water table in spring and late fall was close to the soil surface in the UD, and was shallower compared to that in the SSD field. The deeper water table in the SSD area was due to the pumping of water out of the field via the SSD system. However, from July to September, water table in the SSD field was shallower than that in the UD field by about 0.2 m (Figure 3.3). During that period of the season, the wells in the UD field were dry. The water table was below 1.5 m, and reached up to 1.8 m during the first week of September. The dry well period in the UD field was corresponding to the time when corn and soybean demanded more water for their growth. Corn needs maximum water during tessling and silking stages (about 65-75 days after planting) and throughout the reproductive stage. The lower water tables from late July to early October in 2009 were likely due to the high water demand by corn (Figure 3.3). Likewise, soybean demands maximum water during the pod filling period (60-70 days after planting) and throughout maturity. Therefore, the drop in water table from late July to early September is likely due to the higher water demand of the soybean (Figure 3.4). During that higher water demand period, the water conserved in the soil and SSD line played vital role in supporting the water uptake by plants roots because controlled drainage system maintains the water table to the required depth by controlling or decreasing the drainage volume during peak growing season (Tan et al., 2002). In addition, the irrigation water from the subirrigation section might have flowed via SSD tube to the SSD field. There is no isolation device installed between the two fields. A rise in the water table was noticed after each rainfall event. The water table in the SSD field was maintained below the SSD line (1.1 m) during most of the period in the growing season.

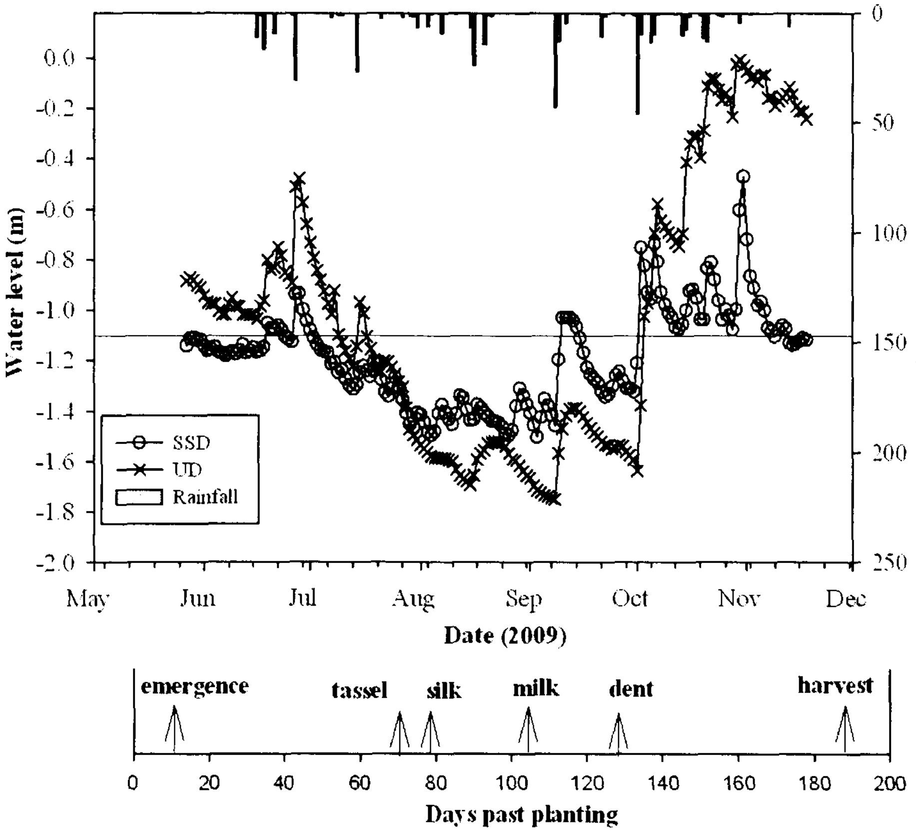

Figure 3.3. Water level in SSD and UD field during the growing season, 2009 along with the daily rainfall and different stages of corn development.

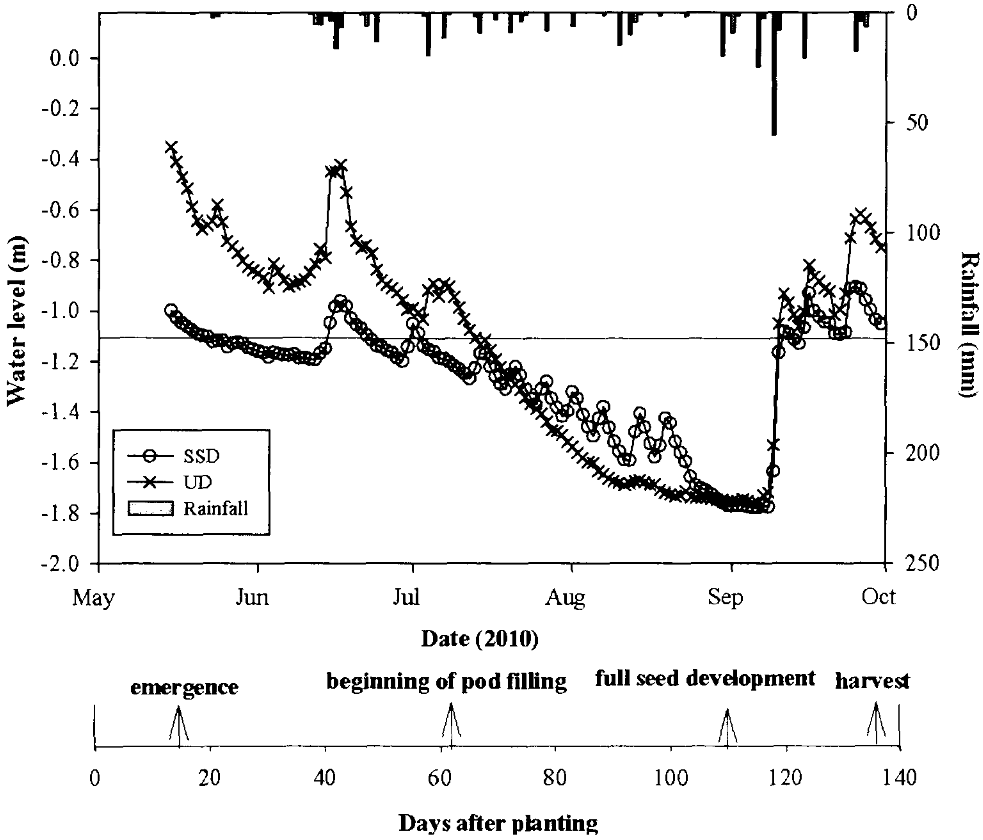

Figure 3.4. Water level in SSD and UD field during the growing season, 2010 along with the daily rainfall and different stages of soybean development.

### 3.4.3 Temperature and precipitation

The daily average air temperature of the experimental area in peak growing season 2009 was lower than the daily normal air temperature of that area (Table 3.1 and 3.3). However, the average daily and monthly temperature of experimental area was more by few degrees in peak growing season 2010 (July- August) than the average normal temperature of the Wahpeton station. The evapotranspiration would be higher in sunny and bright days than on cool and cloudy days.

Table 3.3. Average monthly air temperature and monthly rainfall amount of experimental site in growing season 2009 and 2010.

| | **Temperature, $^0$C** | | **Rainfall, mm** | |
|---|---|---|---|---|
| **Month** | **2009** | **2010** | **2009** | **2010** |
| May | - | 18 | 20 | 15 |
| Jun | 19 | 21 | 70 | 62 |
| Jul | 20 | 24 | 45 | 72 |
| Aug | 20 | 23 | 64 | 64 |
| Sept | 18 | 15 | 74 | 152 |
| Oct | 5 | - | 131 | - |
| **Average/Total** | **16** | **20** | **404** | **365** |

Rainfall was lower in the summer and higher in the fall in 2009 and 2010. Total rainfall observed during the growing season 2009 (May-Oct) and 2010 (May-Sept) was 404 and 365 mm (Table 3.3) respectively. Rainfall received in the growing season of 2009 and 2010 was greater than the normal rainfall of the area. Frequent rainfall events during the active growing season contributed to the water requirement of crops in both fields. The rainfall of 72 mm received in July 2010, might have met the water requirement of soybean in both the SSD and UD field.

### 3.4.4 Energy fluxes

The monthly average LE, H, $R_n$, and G for both fields under field conditions observed in both years is listed in Table 3.4. In 2009, the magnitudes of $R_n$ was higher in the SSD field most of the time. The higher amount of soil moisture in the SSD field could have reduced reflectivity (albedo) of shortwave radiation from both soil and leaves and resulted in the higher net radiation during summer, similar to that reported by Rosset et al. (1997). In 2010, the magnitude of $R_n$ was higher in UD field throughout the growing season except in the month of July. The soil moisture was more in the UD field which might have reduced the reflected energy and resulted in higher net radiation. The $R_n$ was high when soil moisture was optimum. The $R_n$ decreased with the drop in soil moisture because dry soil enhanced the reflectance and less energy was stored in the soil. According to Small and Kurc (2003), the reflected longwave radiation is lower when the soil is wet, and the highest difference occurred at the middle of the day, -45 W/$m^2$ difference whether with grass or shrub surface. However, they found minimal difference in incoming and outgoing shortwave radiation between a wet and dry surface. The surface albedo was lower when the soil was wet, and they found a strong relationship between albedo and soil moisture content. The $R_n$ measured between the SSD and UD field yielded dissimilar result in 2009 and 2010. The sensors were checked for the instrumental error, which showed that the instruments were functioning properly (error less than 1.5%). Thus the variation could be due to difference in soil moisture content in two water managed fields at several depths (Figure A9-A14).

In 2009, the LE was higher in the SSD field in July and August compared to that in the UD field. The optimum soil moisture content in the SSD field supported the higher LE. The highest monthly average LE in 2009 was in July, 220 W/$m^2$ and 169 W/$m^2$ in the SSD and UD fields respectively. In 2010, the LE in SSD field was higher in July, August and September (Table 3.4), but the difference was minimal. The soybean requires more water during flowering and pod filling periods. The frequent rainfall in July 2010 supplied the water requirement of both fields. In 2010, the highest LE was observed in July, 243 W/$m^2$ and 227 W/$m^2$ in the SSD and UD fields respectively. The LE in both the field during both years was higher in July and was in descending pattern in later growing season.

The transpiration of the crop is higher during the reproductive stage, so a higher LE is expected. Irmak (2010) found a high LE for corn at 75-80 days after planting and a maximum LE in soybean field at about 56 days after planting. The pattern observed at our experimental field was similar to the study. The H and LE values were inversely related throughout the growing season. The difference was highest in the summer (July-August), indicating a larger fraction of energy available for the ET process.

Table 3.4. Average monthly energy fluxes (W/m$^2$) in the subsurface drained (SSD) and undrained (UD) fields during the growing season 2009 and 2010.

| | | **Energy Fluxes (W/m$^2$)** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | **SSD** | | | | **UD** | | | |
| **Year** | **Month** | **$R_n$** | **G** | **LE** | **H** | **$R_n$** | **G** | **LE** | **H** |
| 2009 | Jun | 294 | 71 | 124 | 99 | 285 | 49 | 126 | 110 |
| | Jul | 328 | 46 | 220 | 63 | 320 | 31 | 169 | 120 |
| | Aug | 281 | 34 | 188 | 59 | 279 | 22 | 144 | 113 |
| | Sept | 220 | 32 | 97 | 91 | 220 | 24 | 99 | 97 |
| | Oct | 132 | -4 | 58 | 77 | 128 | -8 | 68 | 68 |
| | Nov | 98 | 9 | 40 | 49 | 90 | 13 | 38 | 38 |
| 2010 | May | 330 | 51 | 131 | 148 | 343 | 41 | 171 | 131 |
| | Jun | 296 | 36 | 127 | 134 | 324 | 35 | 144 | 145 |
| | Jul | 303 | 20 | 243 | 40 | 280 | 14 | 227 | 39 |
| | Aug | 264 | 18 | 211 | 34 | 287 | 17 | 208 | 62 |
| | Sept | 200 | 17 | 123 | 60 | 213 | 23 | 112 | 77 |

The evaporative ratio, LE/($R_n$.G) value, represents the available energy used in ET process. It increased greatly in the SSD field during summer 2009, representing higher mass transfer in the SSD field (Table A3). The highest LE/($R_n$-G) ratio was observed in July. During summer days, increase in LE/($R_n$-G) was observed after the rainfall events, likely due to increase in soil moisture. The rise in soil moisture enhanced the water uptake of plant leading to higher transpiration and LE/($R_n$-G). A similar result concerning the temporal LE/($R_n$-G) pattern was found and discussed by Tan and Black (1976). However, the LE/($R_n$-G) ratios were almost similar between the SSD and UD field in summer 2010.

Slightly higher Bowen ratio (H/LE) was noticed in the UD field than in the SSD field during the summer of 2009. The Bowen ratio was greater in the UD field compared to the SSD in July and August, 2009. The Bowen ratio in 2010 followed the similar pattern as in 2009. The lower Bowen ratio in the field during summer days ensured that the soil moisture content in field was enough to meet the water requirement of the plant (ASCE,1996).

### 3.4.5 Daily actual evapotranspiration

Higher ET was observed during the summer and early fall. In the SSD field, higher ET was observed during peak growing season, especially from late June to the end of August. The ET values observed in spring and fall were higher in the UD compared to SSD field. In 2009, the daily ET in the UD and SSD field (September-November) were comparable. In May-June 2010, ET in the UD field was greater than that in the SSD field. In September, 2010 ET in both UD and SSD fields were comparable. Figures 3.5 and 3.6 show the daily ET values in the SSD and UD fields in 2009 and 2010 respectively. The higher ET in the UD field during spring and late fall might be due to excess water in the soil near the surface. Also, during the spring, the evaporative ratio was higher in the UD field along with the low Bowen ratio. The higher ET during that period is probably due to higher evaporation in the UD field compared to the SSD field. In the UD field, water is either infiltrated into the soil, disappeared as runoff from the field, or evaporated back into the atmosphere. The higher evaporation rate might have resulted in the higher ET.

The ET was higher in the SSD field during July and August in response to the actual water consumed by crops. The total ET in summer (July-August) 2009 was greater in the SSD field than that of the UD field by 30%. Similarly, during July-August 2010, the total seasonal ET in the SSD field was greater by 13% compared to that in UD field. That difference is due to higher value of LE and LE/($R_n$-G) in the SSD field during summer. Also, the shallower water table in the SSD field might have supported the water uptake of the plant. Considering the entire growing season, the ET in the SSD field was 15% higher in 2009 compared to the UD field and in 2010 the difference was minimal. This difference in ET might have been due to the difference in soil moisture content and water table depth. The optimal amount of soil moisture content in the root zone in the SSD field might have enhanced the transpiration rate of the plant in the summer.

The ET of corn and soybean was found dependent on water table depth. During the summer (July-September), the water table became lower when ET started to increase, probably because corn and soybean absorbed water from the root zone and caused lowering of water table from the soil surface. The drop in water table with the rise in ET rate was also observed by Skaggs et al. (1999) and Nachabe et al. (2005). After 45 to 110 days past planting, ET was higher in the SSD field than that in the UD field. This was the period when crops demanded more water for their vegetative and reproductive growth. During that period, water was supplied from the conserved water in the SSD line, and the influence or flow of subirrigated water might have also maintained the water level depth. That water supported the capillary rise and maintained the good soil moisture in the root zone of the SSD field.

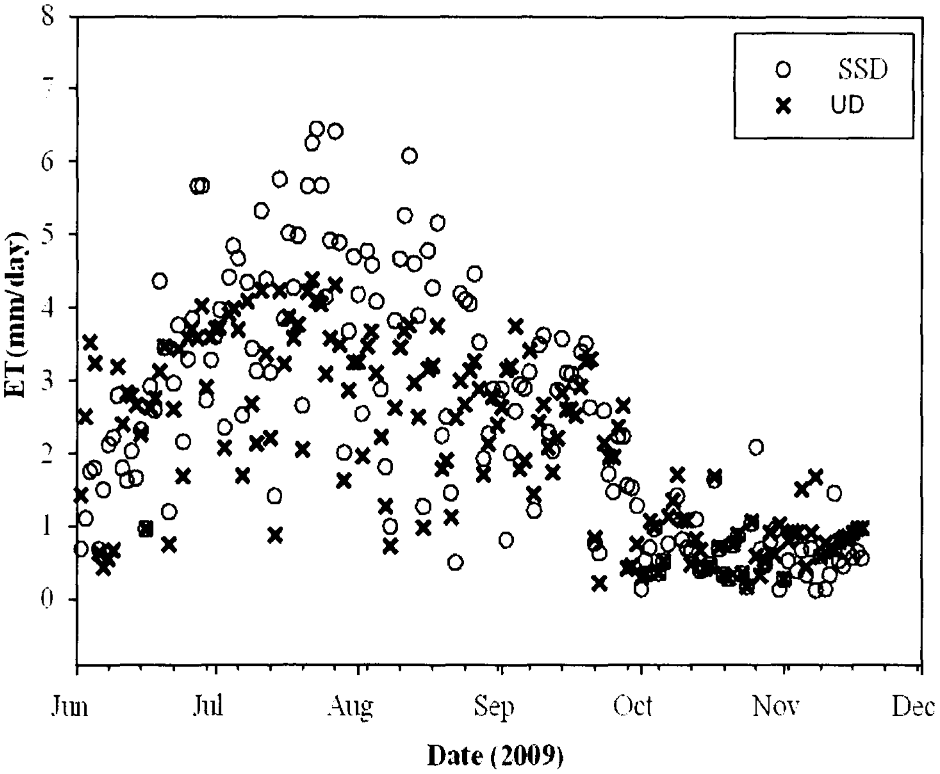

Figure 3.5. The daily average evapotranspiration observed in SSD and UD field during the growing season 2009.

However, in 2010, frequent rainfall in active growing period maintained the optimal soil moisture in both the SSD and UD fields, resulting in small variation in available energy and ET. In 2009, comparatively higher value of ET was noticed in July and lower in November in both the SSD and UD field (Table A1). Also in 2010 the ET value peaked during July and was lower in September. In 2009 the maximum value of ET in SSD and UD field was 6.44 mm/day on July 23 and 4.38 mm/day on July 23 respectively. Likewise in 2010 the maximum ET in SSD and UD field was 6.44 mm/day in July 18 and 5.37 mm/day on July 26 respectively.

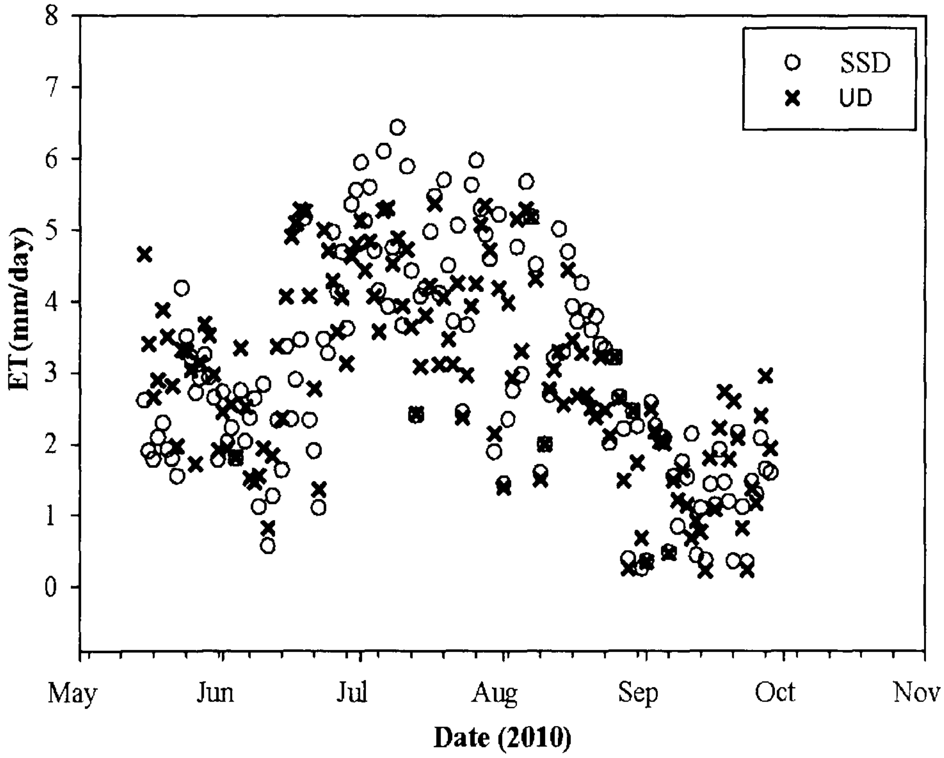

Figure 3.6. The daily average evapotranspiration observed in SSD and UD field during the growing season 2010.

The ET in the summer (July-August) 2009 was higher in the SSD field compared to that in the UD field with a significant statistical difference ($P < 0.001$). However, the daily average ET values in the SSD and UD fields throughout the growing season 2009 did not yield any significant difference ($P=0.216$). In summer (July –Aug) 2010, ET in the SSD and UD fields were comparable and did not show any statistical difference ($P = 0.067$). Also, there was not much variation in the soil moisture at the root zone, probably due to frequent rainfall events in July 2010 (Table 3.3). Likewise, no significant difference (P=0.879) was obtained between the daily ET values in the UD and SSD field during the growing season of 2010.

The summer 2009 showed some variation in soil moisture in the root zone, while soil moisture for corn was higher in the SSD field, possibly due to the influence of subirrigation water and also the water in the SSD field was prevented within the field and SSD tubes throughout the summer using control mechanism. The subirrigated water from the subirrigated field might have moved to the SSD field through the SSD tube.

Cooler and wetter climate conditions have resulted in the cool and wet summer in 2009 and 2010. Almost throughout the growing season the available soil moisture was more than 50% of total available soil moisture content to meet the crop water requirement. Though there was 0.2 m difference in the water table depth between the SSD and UD fields in summers (July-September) of 2009 and 2010, the difference was not large enough to cause large ET difference.

### 3.4.6 Reference evapotranspiration

The $ET_{ref}$ estimated by the ASCE-EWRI method for both grass and alfalfa reference crops were higher than the $ET_{ref}$ estimated by the JH method during the growing seasons 2009 and 2010 (Table A2). During the entire growing season 2009 (15 May- 18 November), the $ET_{ref}$ estimated by the ASCE-EWRI using alfalfa as the reference crops was 917 mm and the grass reference was 723 mm. Likewise, in growing season 2010 (20 May-30 September), the $ET_{ref}$ for alfalfa and grass were 846 mm and 665 mm respectively. The $ET_{ref}$ value estimated by JH method was 623 mm and 625 mm in 2009 and 2010 respectively. The growing season $ET_{ref}$ estimated by the ASCE-EWRI for alfalfa reference surface was more than the $ET_{ref}$ estimated by the JH method.

The JH method estimated lower $ET_{ref}$ value compared to ASCE-EWRI method throughout the growing season. However, during mild wind conditions, the $ET_{ref}$ values were comparable to that by the ASCE-EWRI methods. The monthly $ET_{ref}$ values were different depending on the type of method used. The ASCE-EWRI method showed the highest daily average $ET_{ref}$ in May when wind was the highest in the year for this location. The JH method estimated the highest $ET_{ref}$ in July because of highest temperature and solar radiation observed in those periods. The JH method was found to underestimate $ET_{ref}$ values during the windy conditions. The underestimation of the $ET_{ref}$ by the JH method during May-June and September-November was attributed to the presence of high wind during those days (Table A3). Similar result had been reported by Irmak et al. (2008), and Trajkovic and Kolakovic (2009). The underestimation of $ET_{ref}$ will yield underestimation of actual ET, which could lead to errors in water balance estimation and water management practices.

The $ET_{ref}$ estimated by the ASCE-EWRI grass and alfalfa references and JH methods showed a statistical difference ($P < 0.001$) throughout the experimental period. $ET_{ref}$ estimated by the ASCE-EWRI alfalfa and ASCE-EWRI grass references when plotted against JH methods yielded a $R^2$ (coefficient of determination) of 0.77 and 0.88 for ASCE-EWRI alfalfa and grass, respectively, indicating that 77% of total variation in $ET_{ref}$ ASCE-EWRI (alfalfa) and 88% of total variation in $ET_{ref}$ ASCE-EWRI (grass) is explained. The regression line between the JH and ASCE-EWRI (alfalfa) falls above 1:1 slope line (Figure 3.7), indicating that the $ET_{ref}$ estimated by ASCE-EWRI (alfalfa) was greater than the $ET_{ref}$ estimated by the JH method. The slope of regression line between the JH and ASCE-EWRI (grass) was less than one.

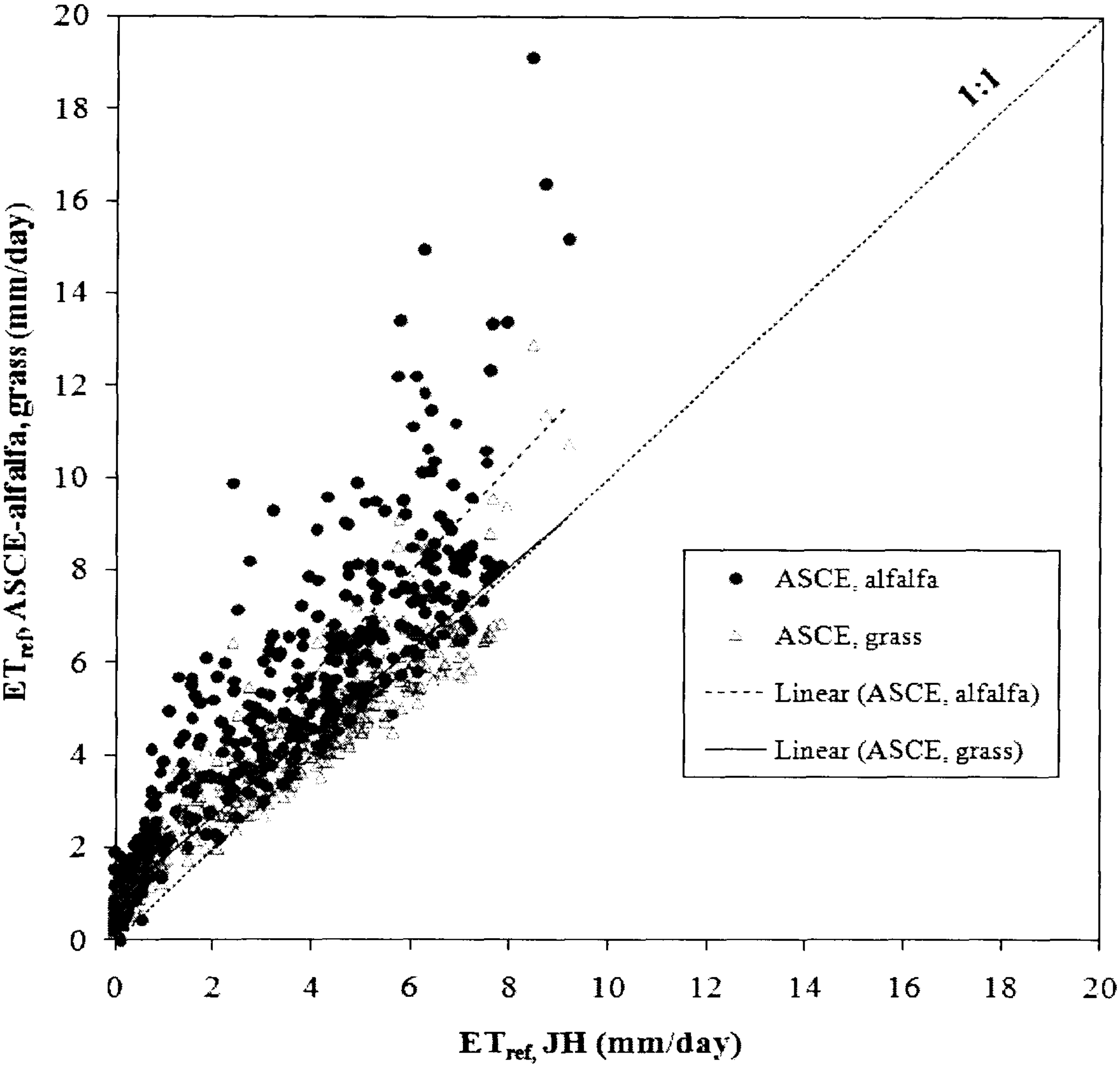

Figure 3.7. Regression analysis between reference evapotranspiration estimated by ASCE-EWRI, 2005 and Jensen Haise method using the weather parameters recorded in 2009 and 2010 at Wahpeton station of NDAWN (NDAWN, 2010).

ASCE-EWRI (alfalfa) and JH: $y= 1.130x+1.208$ ($R^2= 0.77$)
ASCE-EWRI (grass) and JH: $y= 0.902x+0.868$ ($R^2= 0.88$)

### 3.4.7 Crop coefficient ($K_c$)

The $K_c$ in the study area was developed using the ET estimated from the EC system and the $ET_{ref}$ from ASCE-EWRI (alfalfa). The $K_c$ values for both corn and soybean in the UD and SSD fields followed a similar pattern; reached the peak in July and dropped down when the crop was fully matured. In 2009, the drop in $K_c$ value was seen after the 3rd week of September (120 days after planting or 55 days before harvest) and in 2010, the drop in $K_c$ was observed from the middle of August (about 40 days before the harvest). Figure 3.8 and 3.9 shows the monthly crop coefficient for both corn and soybean in the SSD and UD fields.

The higher $K_c$ in the SSD field might be due to optimal soil moisture condition in the field. In the peak growing season (July-August), crops demand maximum amount of water for their reproductive and vegetative growth. The water conserved in the soil and SSD tubes of SSD field and the flow of irrigation water from subsurface drained/subirrigated field supported the water requirement of the SSD field. The snow melting in spring and rainfall in fall raised the water level. During planting and harvesting, crops require less water, so the more water in the SSD field was removed by the subsurface drainage. On the other hand, in the UD field, excess water can only be removed by surface runoff and evaporation. Thus, the higher $K_c$ in the UD field during spring and fall was the result of the higher evaporation rates.

#### 3.4.7.1 Corn crop coefficient

The monthly corn crop coefficient in the SSD field in June, July and August was higher than that in the UD field (Table 3.5). Using the ASCE-EWRI, alfalfa reference surface, the highest monthly corn $K_c$ in the SSD field was observed in August (0.70) followed by July (0.63). Likewise, the monthly corn $K_c$ was at its peak in August (0.54) in the UD field. The corn $K_c$ in the UD field was nearly to its peak in October, and it was higher than that of the SSD field. In October, the removal of excess water from the field reduced the evaporation, and thus the ET in the SSD field, while excess water in the UD field either increased the soil moisture content or evaporation and hence ET. The increase in ET could yield the difference in the $K_c$ values. However, the $K_c$ values (ET from EC and $ET_{ref}$ from ASCE- EWRI, alfalfa) between SSD and UD field did not yield any statistical difference.

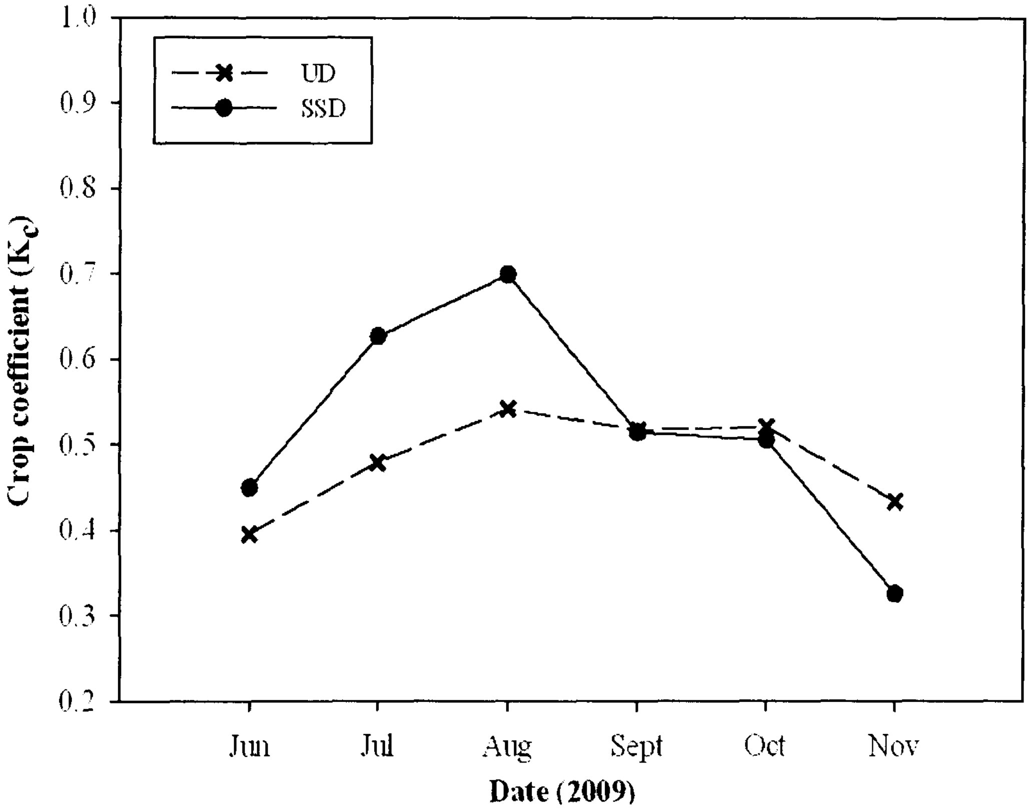

Figure 3.8. Corn crop coefficient developed for SSD and UD field, using $ET_{ref}$ estimated from ASCE-EWRI and ET measured by the EC system.

The corn crop coefficient developed in the experimental site had the similar trend as developed by Stegman et al., (1977), Steele et al., (1996) and FAO 56 (Allen et al., 1998); maximum during active growing period and lower during the early and late stage of corn development (Figure 3.8). However, the $K_c$ values were different among different methods.

The difference in $K_c$ value could be due to the different water management practices, varieties of corn and methods used to estimate ET and $ET_{ref}$. The corn variety in 2009 was Pioneer 38F33. Stegmen et al. (1977) used soil water balance method to estimate the ET and considered only the days without deep percolation and runoff. Steele et al. (1996) measured the ET using non-weighing lysimeter. Both of them used the $ET_{ref}$ estimated by JH method to develop corn coefficient. However, their experiments were conducted at Oakes, 120 Km west of our experimental site; the growing conditions were very different from our site. The soil type at Oakes was mainly coarse sand comparing to clayey soil at Fairmount site and the irrigation type was center pivot at Oakes. Most importantly, the weather in 2009 and 2010 was cool and wet, but during research period for Stegman et al. (1977), the weather was dry. The corn $K_c$ in the experimental site (Figure 3.8) was developed using ET estimated from the EC system and the $ET_{ref}$ estimated using ASCE-EWRI method taking alfalfa as the reference crop. The $K_c$ developed in the experimental site using the JH method was higher than the $K_c$ value developed from ASCE-EWRI method (Table 3.5). The $ET_{ref}$ estimated by the JH method was lower than the one estimated by ASCE-EWRI (grass and alfalfa) which might have resulted in different values of $K_c$. As the JH method does not consider the wind function, this could give misleading result during windy periods. Also, the $K_c$ estimated using the ASCE-EWRI (grass reference) was higher than the $K_c$ by alfalfa.

Table 3.5. The corn crop coefficient ($K_c$) value developed in the SSD and UD fields using the ET measured by the EC system and $ET_{ref}$ (JH and ASCE-EWRI, both grass and alfalfa) along with the standard deviation in parenthesis and $K_c$ developed by FAO 56, Stegmen et al. (1977) and Steele et al. (1996) with the reference ET method they used. Stegmen et al. (1977) and Steele et al. (1996) estimated ET using SWB methods.

| **Crop coefficient ($K_c$) of corn** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | SSD | | | UD | | |
| Month | FAO 56 | Stegmen et al. (1977) JH | Steele et al. (1996) JH | JH | ASCE-EWRI, grass | ASCE-EWRI, alfalfa | JH | ASCE-EWRI, grass | ASCE-EWRI, alfalfa |
| Jun | 0.35 | 0.40<br>(0.14 | 0.32<br>(0.10) | 0.63<br>(0.32) | 0.55<br>(0.26) | 0.45<br>(0.22) | 0.56<br>(0.19) | 0.49<br>(0.15) | 0.40<br>(0.13) |
| Jul | 0.46 | 0.93<br>(0.13) | 0.79<br>(0.16) | 0.83<br>(0.17) | 0.78<br>(0.16) | 0.63<br>(0.14) | 0.63<br>(0.11) | 0.59<br>(0.11) | 0.48<br>(0.09) |
| Aug | 1.2 | 1.1<br>(0.05) | 1.03<br>(0.06) | 0.84<br>(0.21) | 0.83<br>(0.21) | 0.70<br>(0.18) | 0.65<br>(0.12) | 0.64<br>(0.12) | 0.54<br>(0.11) |
| Sep | 0.9 | 0.69<br>(0.18) | 0.57<br>(0.18) | 0.75<br>(0.22) | 0.65<br>(0.15) | 0.51<br>(0.12) | 0.54<br>(0.27 | 0.75<br>(0.66) | 0.52<br>(0.30) |
| Oct | 0.6 | 0.21<br>(0.09) | 0.34<br>(0.01) | - | 0.61<br>(0.19) | 0.51<br>(0.19) | - | 0.66<br>(0.22) | 0.52<br>(0.20) |

### 3.4.7.2 Soybean crop coefficient

The soybean $K_c$ (from ET from EC system and $ET_{ref}$ ASCE, alfalfa) obtained was higher in the SSD field in June, July and August compared to that in the UD field. The highest monthly $K_c$ value in the SSD field was obtained in July ($K_c = 0.76$). The average monthly soybean $K_c$ was higher in the UD field in May (Table 3.6 and Figure 3.9) compared to that in the SSD field. The monthly average $K_c$ was the same in both the fields in September. The higher $K_c$ value indicated higher crop water use in the SSD field during the peak growing season. However, the $K_c$ values (ET from EC and $ET_{ref}$ from ASCE- EWRI, alfalfa) between SSD and UD field did not yield any statistical difference.

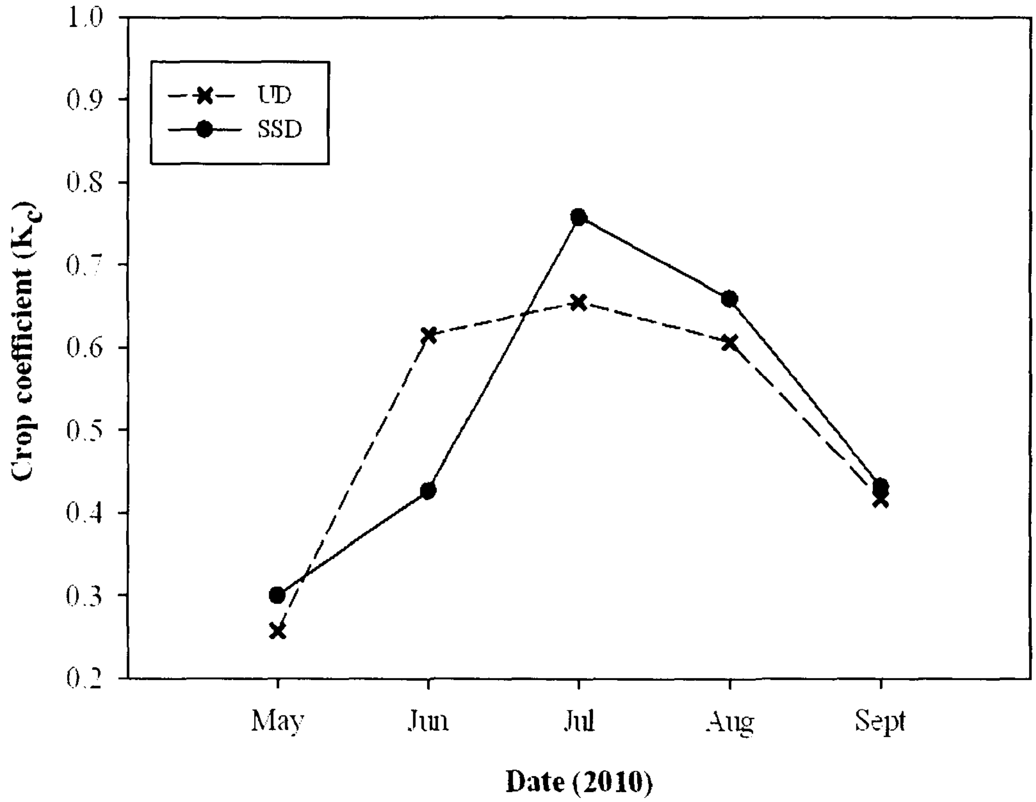

Figure 3.9. Soybean crop coefficient developed for SSD and UD field, using $ET_{ref}$ estimated from ASCE-EWRI and ET measured by the EC system.

Stegmen et al. (1977) obtained maximum monthly $K_c$ (1.08) in August. The FAO 56 showed the maximum $K_c$ for soybean in August (Table 3.6). The delay in peak $K_c$ from July to August implied a difference in soybean variety. The soybean variety planted in the experimental field, Pioneer Hi-Bred 90M60, was a special high protein soybean variety, typically grown in South Dakota and Iowa. The delay in peak indicated a late maturity and late harvesting of soybean in the past. The difference in $K_c$ value (Table 3.6) may be due to the difference in the methods used to estimate the actual ET and $ET_{ref}$. Stegmen et al. (1977) used the SWB method to estimate ET and JH method to estimate the $ET_{ref}$. As they ignored the deep percolation in the SWB method, it could equivocate both the ET and $K_c$ values. In contrast, the soybean $K_c$ in experimental site (Figure 3.9) was developed using ET estimated from the EC system and the $ET_{ref}$ estimated using ASCE-EWRI (alfalfa reference) method (Table 3.6) which could have yielded different results. The differences in the $ET_{ref}$ estimated between ASCE-EWRI references methods produce difference in $K_c$ values. The same principle applies when comparing ASCE-EWRI (grass and alfalfa) and JH method.

Table 3.6. The soybean crop coefficient ($K_c$) value developed in the SSD and UD fields using the ET measured by the EC system and $ET_{ref}$ (JH and ASCE-EWRI, both grass and alfalfa) along with the standard deviation and $K_c$ developed by FAO 56, Stegmen et al. (1977) with the reference ET method they used. Stegmen et al. (1977) estimated ET using SWB methods.

**Crop coefficient ($K_c$) of soybean**

| | | | SSD | | | UD | | |
|---|---|---|---|---|---|---|---|---|
| Month | FAO 56 | Stegmen et al. (1977) JH | JH | ASCE-EWRI, grass | ASCE-EWRI, alfalfa | JH | ASCE-EWRI, grass | ASCE-EWRI, alfalfa |
| May | 0.4 | 0.18<br>(0.003) | 0.44<br>(0.13) | 0.37<br>(0.10) | 0.30<br>(0.08) | 0.54<br>(0.21) | 0.45<br>(0.20) | 0.35<br>(0.17) |
| Jun | 0.4 | 0.38<br>(0.14) | 0.6<br>(0.18) | 0.54<br>(0.17) | 0.43<br>(0.15) | 0.88<br>(0.75) | 0.75<br>(0.60) | 0.61<br>(0.52) |
| Jul | 0.88 | 0.90<br>(0.13) | 0.82<br>(0.14) | 0.89<br>(0.13) | 0.76<br>(0.12) | 0.72<br>(0.28) | 0.78<br>(0.26) | 0.65<br>(0.22) |
| Aug | 1.15 | 1.08<br>(0.05) | 0.80<br>(0.18) | 0.80<br>(0.18) | 0.66<br>(0.16) | 0.75<br>(0.22) | 0.74<br>(0.23) | 0.61<br>(0.21) |
| Sept | 0.71 | 0.63<br>(0.21) | 0.70<br>(0.29) | 0.52<br>(0.24) | 0.43<br>(0.19) | 0.73<br>(0.18) | 0.53<br>(0.21) | 0.42<br>(0.17) |

## 3.5 Conclusions

The corn and soybean ET rates were measured in the growing season 2009 and 2010 respectively in the SSD and UD fields in the southeastern part of ND. Though some difference in magnitude between the daily ET rates of the SSD and UD field was observed it did not yield any statistical difference in the ET among two fields. Statistical difference in the ET value between the SSD and UD field was observed in summer (July-August) 2009. The SSD system showed a good control over the water table depth and water requirement of the crop throughout the growing season. The optimal soil moisture content and the required water table depth in the SSD field yielded a higher ET during active growing season. The ET values between SSD and UD fields did not yield any statistical difference in summer 2010. In 2010, little variation was observed in the soil moisture at the root zone due to frequent rainfall events in July. The $K_c$ was derived using the ET measured from the EC system and the $ET_{ref}$ from ASCE-EWRI (alfalfa) methods. The corn $K_c$ was the highest (0.70 for SSD and 0.54 for UD) in August, representing more water used by corn. On the other hand, soybean $K_c$ was highest in July; 0.76 and 0.65 in the SSD and UD field respectively. In early and late growing season, $K_c$ was comparable in both the fields. The higher corn $K_c$ in October and higher soybean $K_c$ in May in the UD could be due to higher ET in the UD field during that period.

## 3.6 Acknowledgements

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# 4. GENERAL CONCLUSIONS

In 2009 and 2010, corn and soybean ET rates were measured in the growing season in the SSD and UD fields in the southeastern part of ND. The daily ET rates were observed higher in the SSD field during summer (July-August) compared to UD field. The ET rates between the SSD and UD fields were statistically different in the summer of 2009. An optimal soil moisture content and deeper water table depth in the SSD field have yielded a higher ET during active growing season. The corn $K_c$ curve derived from the ET by the EC method and the $ET_{ref}$ by the ASCE-EWRI (alfalfa) method had its highest values 0.70 for the SSD and 0.54 for the UD in August, representing the highest water demand by corn during that period. On the other hand, soybean $K_c$ curve derived from the ET by the EC system and the $ET_{ref}$ by the ASCE-EWRI (alfalfa) had its highest value in July, which was 0.76 and 0.65 in the SSD and UD field, respectively. During the early and late growing seasons, the $K_c$ values were comparable in both fields.

The continuous recording of data of energy fluxes and other weather parameters were disturbed by the battery power. Through the battery was incessantly charged with the solar panel, the battery was out of power during gloomy and rainy days. In future while conducting such a field experiment some other alternative source of power such as wind energy should be used.

A year of study in the particular crop may not be sufficient to study the ET of certain crop and field. The study should be continued for some more years at least to catch the two growing season for a particular crop.

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# APPENDIX

## Actual evapotranspiration

The ET in the SSD field was higher during the peak growing season compared to that of SSD field. In fall and spring the ET was higher in the UD or comparable in both the fields. Monthly average evapotranspiration was maximum in July and August and lowest during the fall.

Table A1. Monthly average actual ET in SSD and UD field measured in growing season 2009 (June 2- November 17) and 2010 (May 15- September 29).

| | | **ET (mm/day)** | |
|---|---|---|---|
| **Year** | **Month** | **SSD** | **UD** |
| 2009 | Jun | 2.51 | 2.48 |
| | Jul | 4.28 | 3.29 |
| | Aug | 3.43 | 2.61 |
| | Sept | 2.36 | 2.20 |
| | Oct | 0.73 | 0.73 |
| | Nov | 0.53 | 0.84 |
| 2010 | May | 2.53 | 3.08 |
| | Jun | 2.40 | 3.00 |
| | Jul | 4.76 | 3.00 |
| | Aug | 3.82 | 3.43 |
| | Sept | 1.60 | 1.63 |

### Reference evapotranspiration

Reference ET of the experimental site was estimated using ASCE-EWRI and JH method. The $ET_{ref}$ estimated by ASCE-EWRI (alfalfa) was higher than the by JH method.

Table A2. Monthly average reference ET in SSD and UD field estimated in 2009 and 2010 (May 15- Nov 30).

| | | $ET_{ref}$ (mm/day) | | |
|---|---|---|---|---|
| **Year** | **Month** | **ASCE, alfalfa** | **ASCE, grass** | **JH** |
| 2009 | May | 8.94 | 6.40 | 4.32 |
| | Jun | 6.26 | 4.94 | 4.49 |
| | Jul | 6.81 | 5.49 | 5.28 |
| | Aug | 4.82 | 4.04 | 4.03 |
| | Sept | 4.52 | 3.65 | 3.38 |
| | Oct | 1.49 | 1.13 | 0.45 |
| | Nov | 1.70 | 1.24 | 0.50 |
| 2010 | May | 9.61 | 7.17 | 5.97 |
| | Jun | 6.85 | 5.34 | 4.95 |
| | Jul | 6.95 | 5.67 | 5.96 |
| | Aug | 5.99 | 4.83 | 4.88 |
| | Sept | 3.87 | 2.99 | 2.25 |
| | Oct | 4.08 | 2.85 | 1.45 |
| | Nov | 1.54 | 1.06 | 0.33 |

**Bowen ratio, evaporative flux, relative humidity and wind speed**

The ET of the particular field is lower when the Bowen ratio was high and vice versa. In the other hand higher the evaporative flux higher is the ET as explained in section 3.4.4 previously. Likewise, $ET_{ref}$ depends on the different weather parameters like wind speed, temperature, solar radiation. As explained earlier in section 3.4.6, JH method was lower than the $ET_{ref}$ compared to ASCE-EWRI. JH method does not consider the wind function resulting in lower ET compared to ASCE-EWRI method during high wind periods.

Table A3. Monthly average of Bowen ratio (H/LE) and evaporative flux ($LE/((R_n-G))$) in SSD and UD field along with relative humidity and wind speed in growing season 2009 and 2010.

| | | **SSD** | | **UD** | | | |
|---|---|---|---|---|---|---|---|
| **Year** | **Month** | **H/LE** | **$LE/(R_n-G)$** | **H/LE** | **$LE/(R_n-G)$** | **RH (%)** | **Wind Speed (m/s)** |
| 2009 | Jun | 0.99 | 0.57 | 0.91 | 0.53 | 66 | 3.18 |
| | Jul | 0.30 | 0.78 | 0.72 | 0.58 | 70 | 2.08 |
| | Aug | 0.34 | 0.76 | 0.78 | 0.56 | 79 | 1.52 |
| | Sept | 0.94 | 0.56 | 0.96 | 0.51 | 75 | 1.82 |
| | Oct | 1.24 | 0.45 | 1.03 | 0.49 | 81 | 1.88 |
| | Nov | 0.98 | 0.54 | 0.92 | 0.53 | 79 | 1.95 |
| 2010 | May | 1.18 | 0.47 | 0.85 | 0.57 | 68 | 3.36 |
| | Jun | 1.16 | 0.49 | 1.13 | 0.50 | 75 | 3.08 |
| | Jul | 0.17 | 0.86 | 0.18 | 0.85 | 78 | 1.76 |
| | Aug | 0.17 | 0.86 | 0.35 | 0.78 | 81 | 2.27 |
| | Sept | 0.61 | 0.65 | 0.73 | 0.59 | 83 | 2.27 |

## Porosity, field saturation and permanent wilting point

The porosity of the field was measured in 2008 and the PWP was obtained from the web soil survey (Web Soil Survey, 2010). Both the porosity and the PWP were used to cross check the soil moisture data obtained by the soil moisture sensor.

Table A4. Porosity, field saturation and permanent wilting point (PWP) of the field at different depth, and field conditions.

| Water management practices | Depth (cm) | Porosity (%) | PWP (%) |
|---|---|---|---|
| UD | 15 | 58 | 21 |
| | 30 | 50 | 21 |
| | 45 | 45 | 19 |
| | 60 | 48 | 18 |
| | 90 | 47 | 17 |
| | 120 | 45 | 17 |
| SSD | 15 | 51 | 29 |
| | 30 | 43 | 25 |
| | 45 | 50 | 23 |
| | 60 | 47 | 23 |
| | 90 | 51 | 22 |
| | 120 | 45 | 17 |

## Water pumped out

In the growing season 2009 and 2010 excess water from the SSD field was pumped out during spring and fall. Pumping water out of the field made the subsequent field operation easier. Figure A1 and A2 shows the daily volume of water pumped out along with the cumulative volume. Total volume of 30,697cubic meters of water was pumped out in 2009 and 32,358 cubic meters was pumped out in growing season 2010. Figure A3 shows the lift pump station located to the north east corner of the field.

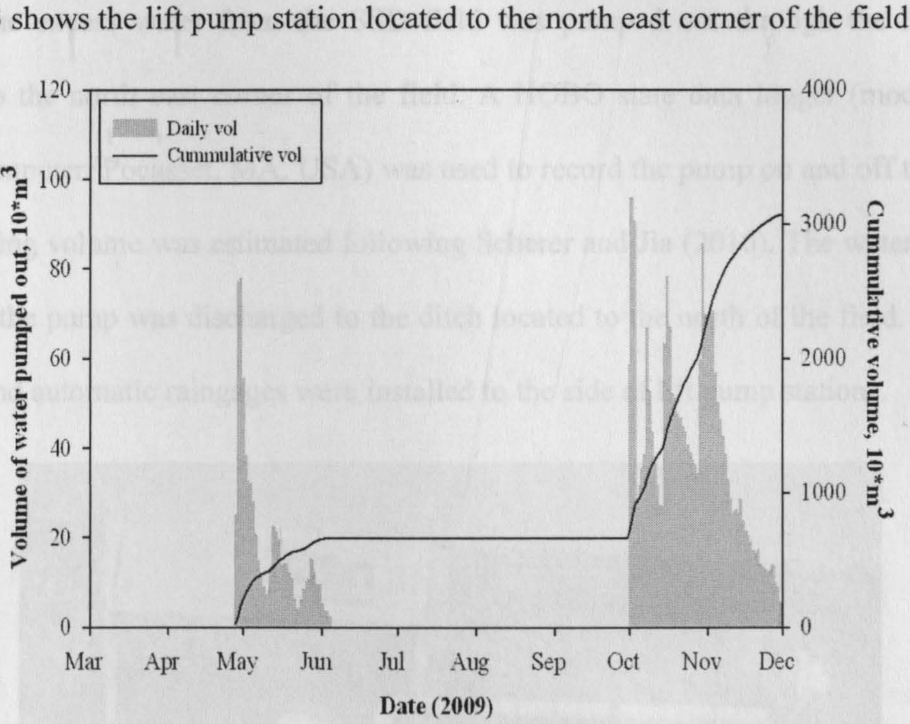

Figure A1. Daily volume of water pumped out along with cumulative volume in 2009.

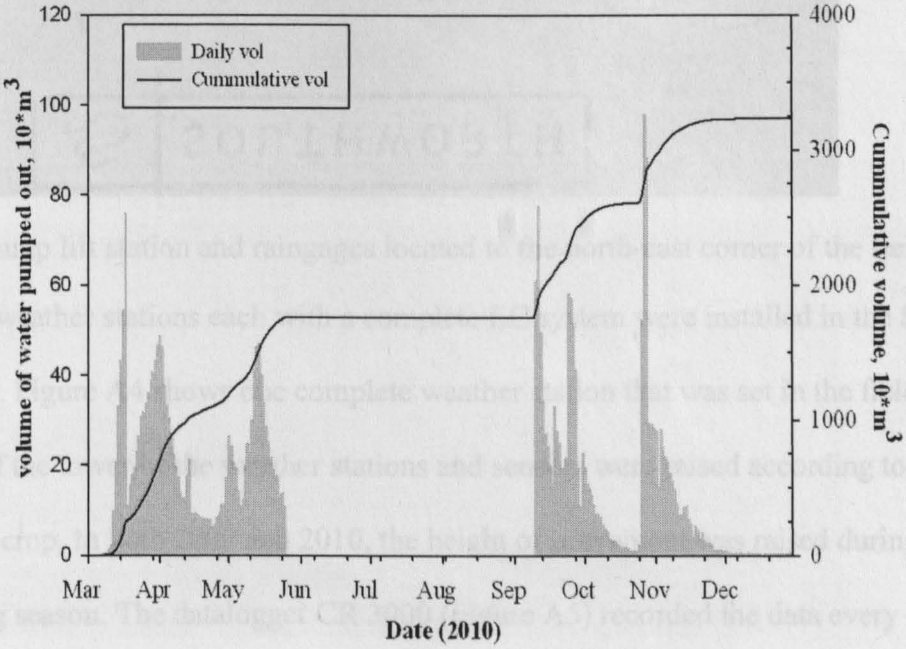

Figure A2. Daily volume of water pumped out along with cumulative volume in 2010.

**Instrumentation**

The excess water from the SSD field was pumped out through the lift pump located to the north east corner of the field. A HOBO state data logger (model H-06, Onset Computer, Pocasset, MA, USA) was used to record the pump on and off times and the pumping volume was estimated following Scherer and Jia (2010). The water pumped out from the pump was discharged to the ditch located to the north of the field. Both the manual and automatic raingages were installed to the side of lift pump stations.

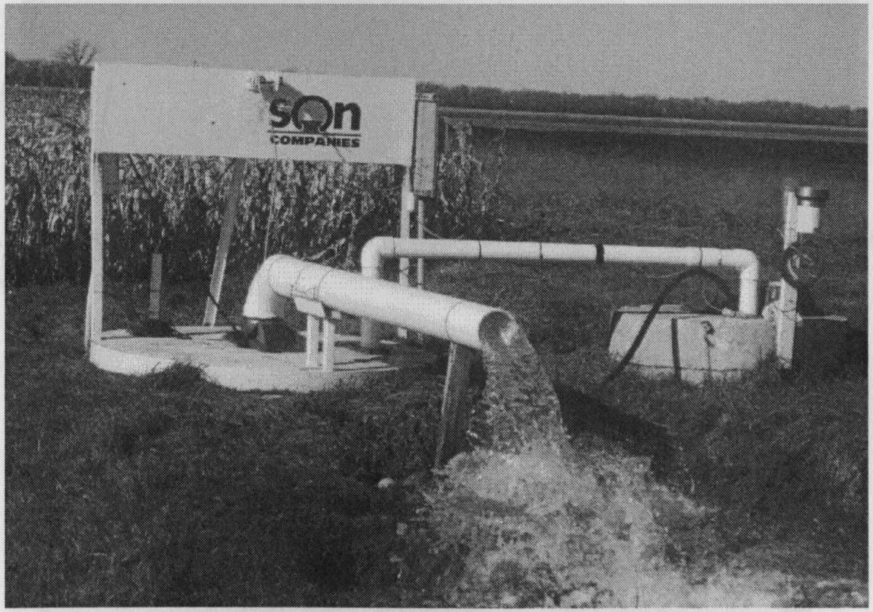

Figure A3. Pump lift station and raingages located to the north-east corner of the field.

Two weather stations each with a complete EC system were installed in the SSD and UD field. Figure A4 shows one complete weather station that was set in the field. The height of the tower of the weather stations and sensors were raised according to the height of the crop. In both 2009 and 2010, the height of instrument was raised during peak growing season. The datalogger CR 3000 (Figure A5) recorded the data every 30 minutes.

Figure A4. Weather station with complete eddy covariance system, in experimental site, Fairmount, ND.

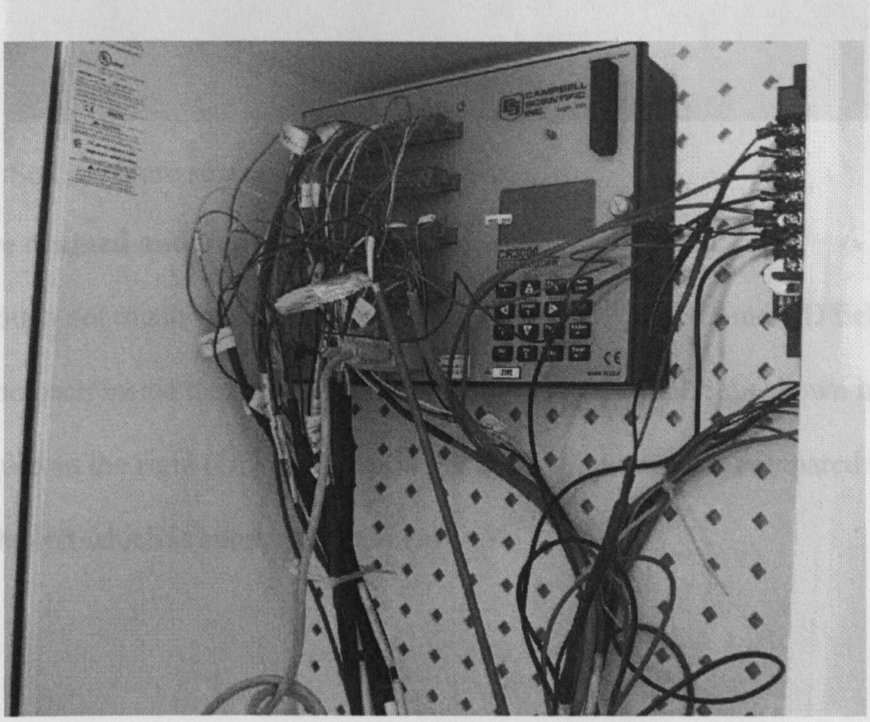

Figure A5. CR 3000 datalogger for weather station.

Twelve soil moisture sensors were installed at six different depths (15, 30, 45, 60, 90, 120 cm) from soil surface in both the SSD and UD field. Soil moisture was recorded every 15 minutes interval using datalogger CR 1000. The datalogger was sheltered inside the accessory box to protect it from external damage (Figure A6).

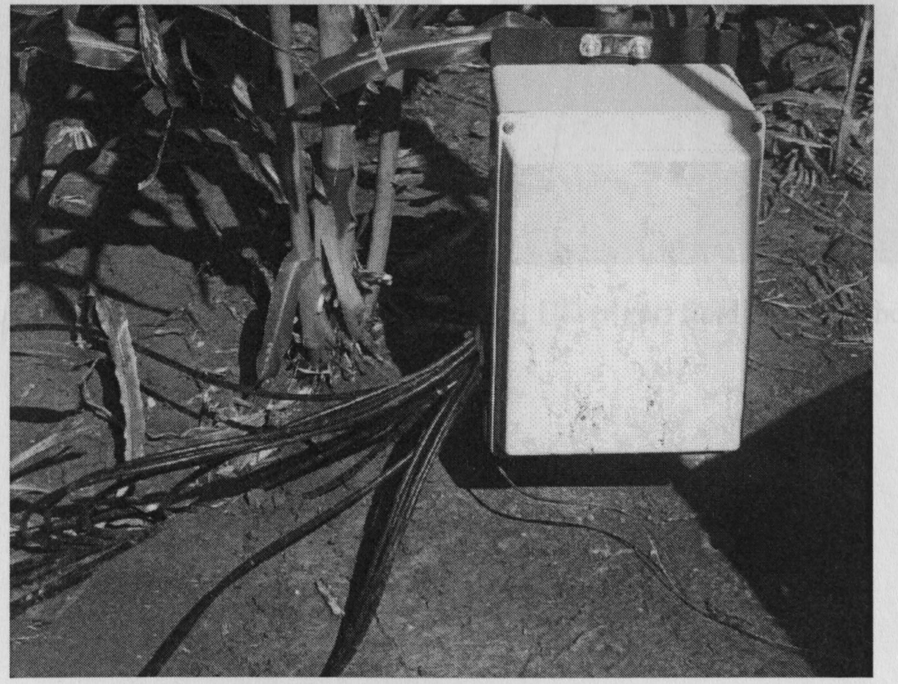

Figure A6. Soil moisture sensor and accessory box.

**Subsurface drained and undrained field**

Though not much variation was observed in the ET of SSD and UD field, it was easier to encroach inside the SSD field during spring and late fall.  As shown in figure A7, the figure on the right (UD field) has water at its soil surface as compared to the figure on the left which is subsurface drained field.

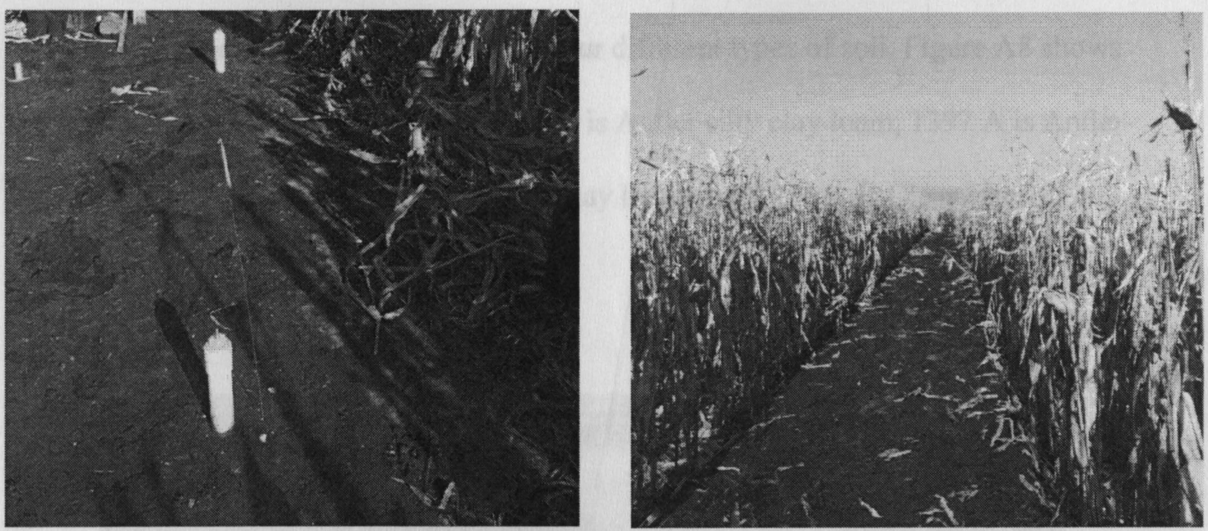

Figure A7. Visual observation of the SSD (left) and UD (right) field in November, 2009.

**Soil type**

As mentioned earlier, the field has four different types of soil. Figure A8 shows the soil map units of the field, where 1396 A is Antler silty clay loam, 1397 A is Antler-Mustinka silty clay loam, 1243 A is Doran clay loam, and 1236 A is Clearwater-Reis (Web Soil Survey, 2010).

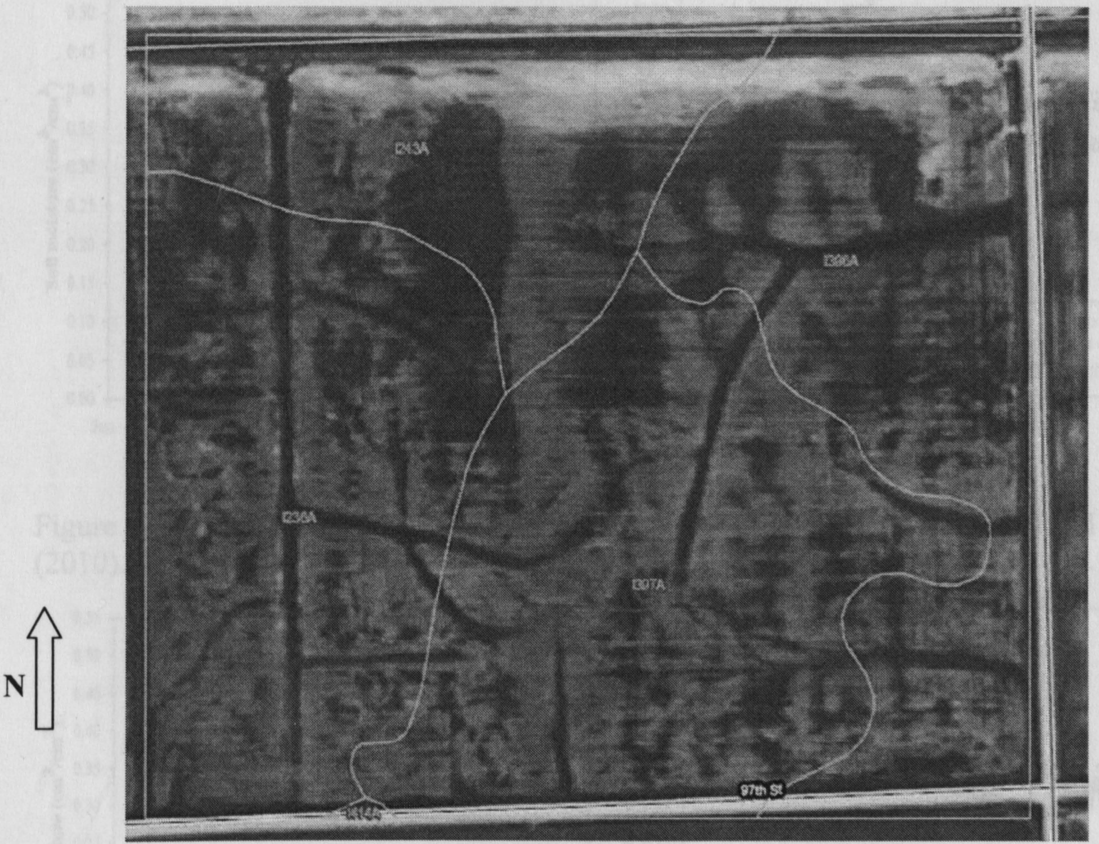

Figure A8. Soil distribution in different side of the field, where 1396 A is Antler silty clay loam, 1397 A is Antler-Mustinka silty clay loam, 1243 A is Doran clay loam, and 1236 A is Clearwater-Reis, from NRCS, Web Soil Survey.

## Soil moisture at different depth

The soil moisture at different depth was different. Two different water management fields experienced different soil moisture content at each depth. In 2009, the soil moisture content of the SSD and UD field showed more difference compared to that in 2010.

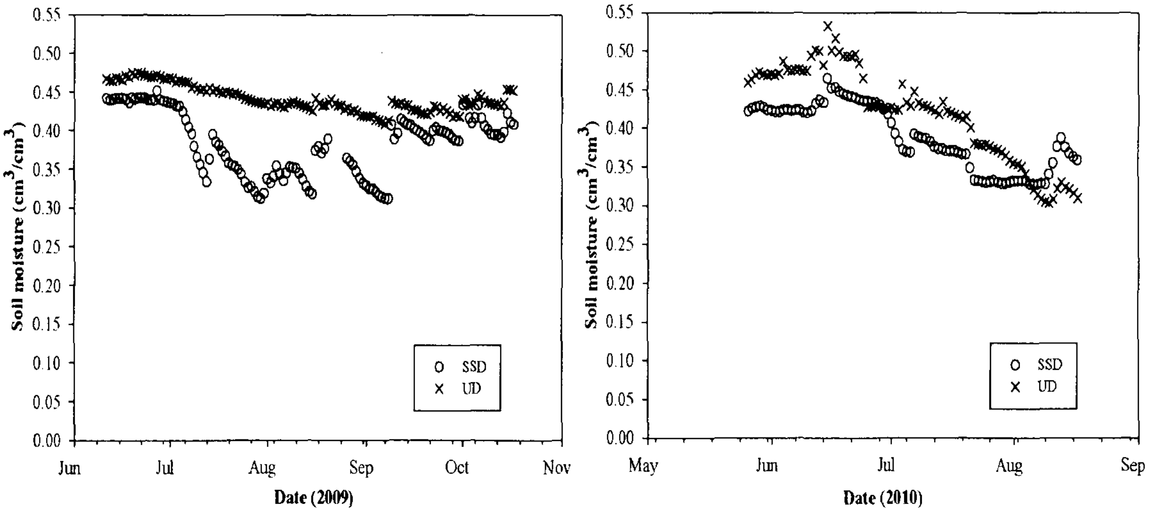

Figure A9. Soil moisture at the depth 0- 22.5 cm from soil surface: Left (2009) and Right (2010).

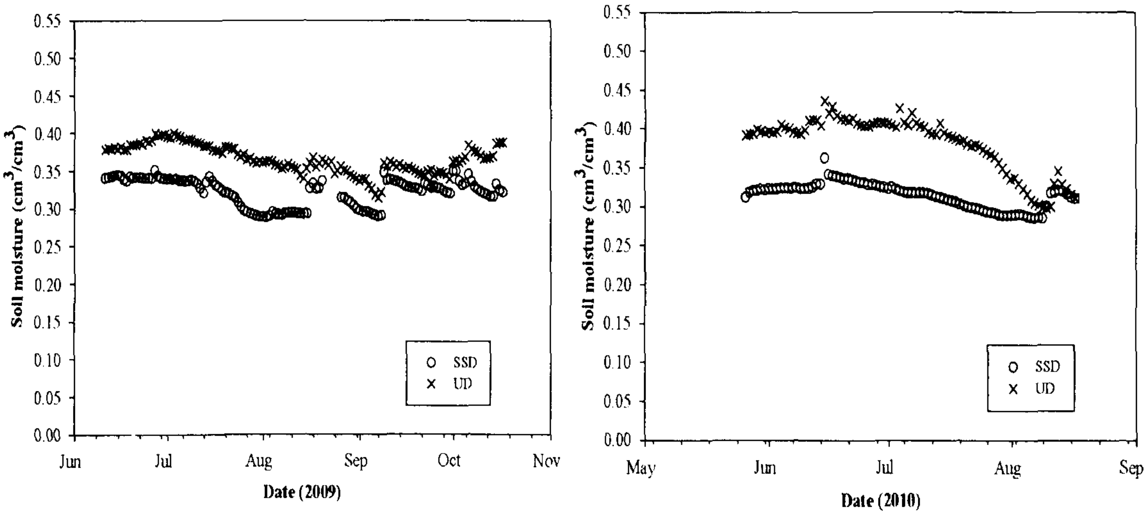

Figure A10. Soil moisture at the depth 22.5-37.5 cm below the soil surface: Left (2009) and Right (2010).

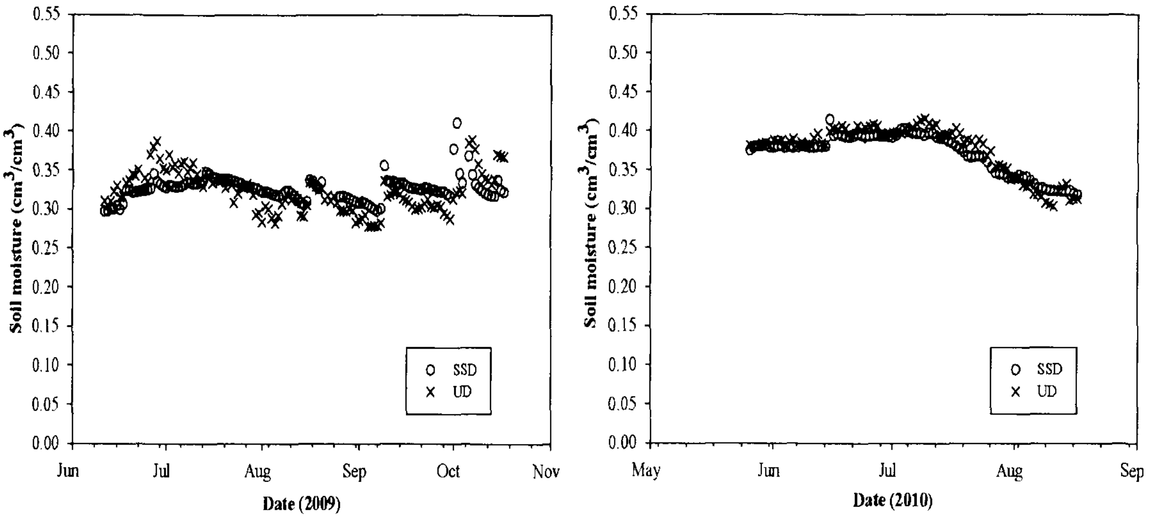

Figure A11. Soil moisture at the depth 37.5-52.5 cm below the soil surface: Left (2009) and Right (2010).

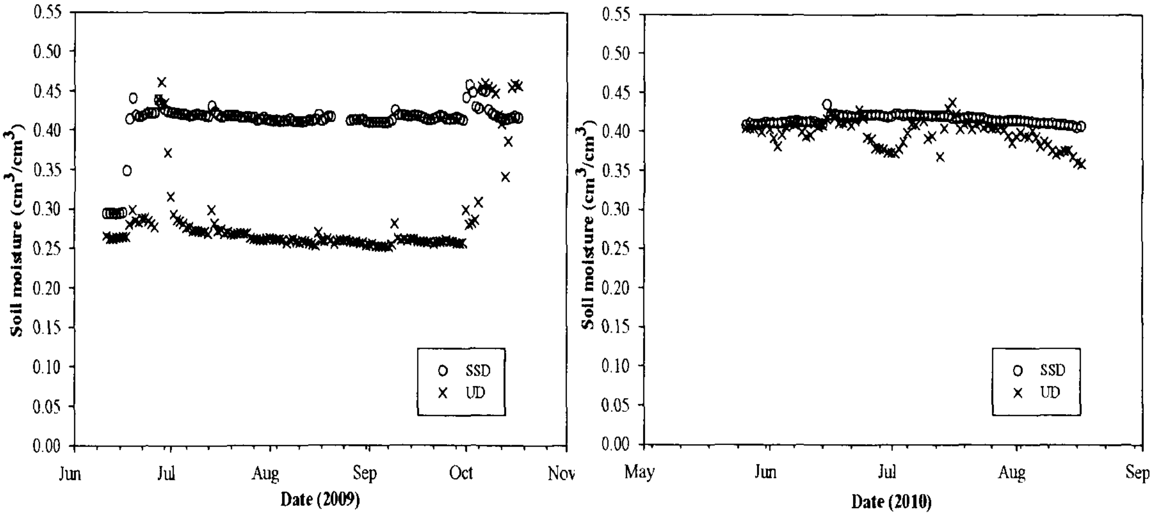

Figure A12. Soil moisture at the depth 52.5-75 cm below the soil surface: Left (2009) and Right (2010).

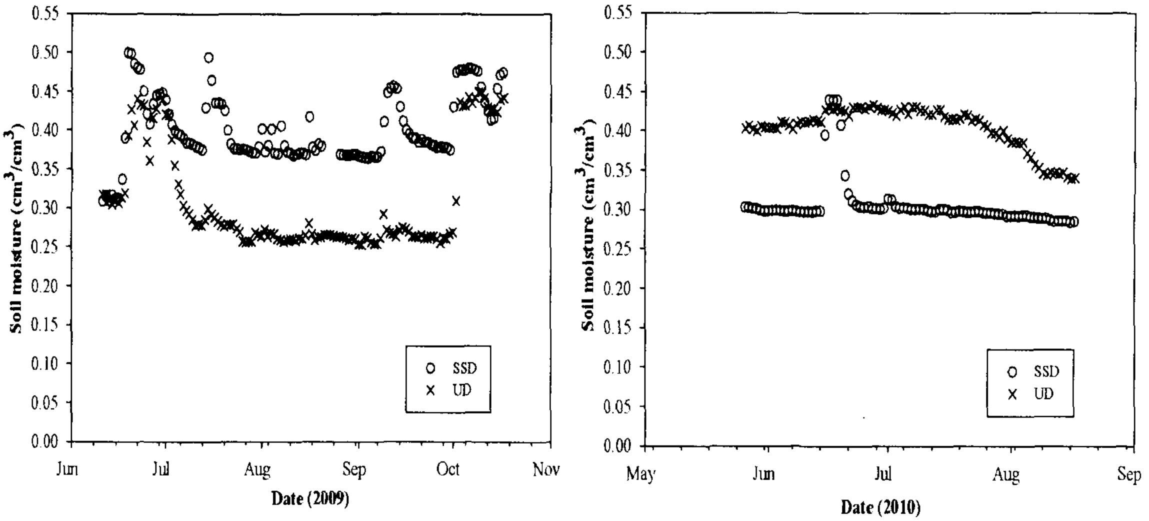

Figure A13. Soil moisture at the depth 75-105 cm below the soil surface: Left (2009) and Right (2010).

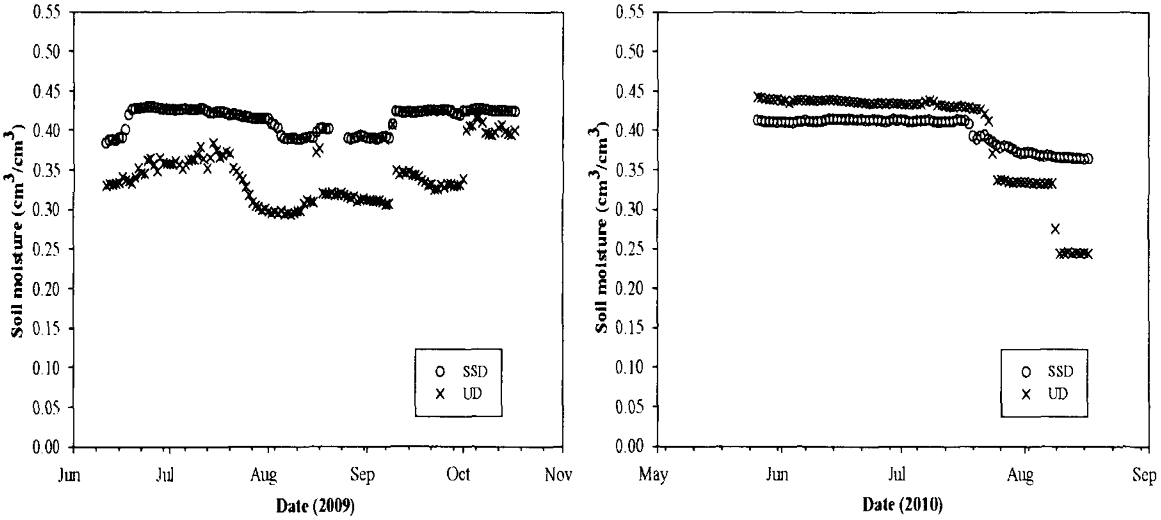

Figure A14. Soil moisture at the depth 105-135 cm below the soil surface: Left (2009) and Right (2010).