THESIS

QUANTIFYING GROUNDWATER RECHARGE BENEATH FURROW IRRIGATED CORN USING LYSIMETRY, AN UNSATURATED ZONE WATER BALANCE AND NUMERICAL MODELING

Submitted by

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ABSTRACT

QUANTIFYING GROUNDWATER RECHARGE BENEATH FURROW IRRIGATED CORN USING LYSIMETRY, AN UNSATURATED ZONE WATER BALANCE AND NUMERICAL MODELING

Understanding the effects of new irrigation methods on groundwater recharge rates in semi-arid regions is becoming more important as the demand for water in these areas increases. Predicting groundwater recharge under furrow irrigated agricultural land can be a difficult task due to spatial variability of infiltration down a furrow, as well as the heterogeneity of hydraulic properties throughout the vadose zone. There are few methods currently being used to estimate the amount of recharge under these conditions. Each method has its own set of assumptions that create varying degrees of uncertainty in the results. The objective of this study is to quantify the amount of groundwater recharge beneath various irrigation methods and to evaluate the ability of a 2D unsaturated zone model to predict these results. The study will compare the results of two field water balance methods conducted at an experimental furrow irrigated agricultural site with those obtained using a 2D unsaturated zone model. For this experiment, a 15-acre corn field was sub-divided into three blocks with one block fully irrigated and two blocks under deficit irrigation. For each block, deep percolation (DP) was estimated at two to three locations using lysimetry and the unsaturated zone water balance (UZWB) method.

The HYDRUS (2D/3D) modeling software was used to create and calibrate a model that could effectively predict the quantity and timing of the drainage flux through the vadose zone. Two models were created for each site to test the effect of soil composition and layering on goodness-of-fit to the data collected during the two growing seasons. Model calibration was

performed for the 2011 season and validated with the 2012 data. The layered model calibrated to the lysimeter data performed most consistently during the validation process, although the layered model calibrated to the UZWB data showed the least bias in results and the lowest average root mean squared error (14.63 cm). Overall, this study has shown that a layered model is needed to most accurately represent water flow in this scenario, and the results of UZWB method can be used to calibrate a predictive model.

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CHAPTER ONE

1.1 THEORY AND BACKGROUND

1.1.1 Water Flow solutions for the unsaturated zone

Groundwater is a vital natural resource and a main component of the hydrologic cycle. In the past, water was often used with no regard to the impacts on future water availability and quality. This mismanagement has led to increasing threats of water scarcity for the 1.5 billion people worldwide that rely on groundwater as their main source of freshwater (Clarke et al. 1996). For this reason, a great effort has been directed towards improving the understanding of physical processes which affect unsaturated flow and transport.

Many relationships have been created in order to describe the physical process of water movement through unsaturated media. In order to choose the most appropriate solution, the size of the area of interest must be taken into consideration. Hendrickx and Flurry (2001) defined three scales at which water flow can be evaluated: pore scale, Darcian (local) scale, and areal scale. Each of these scales requires a different equation to adequately describe the behavior of flow. At the pore scale, water is considered by its movement through a single capillary-like tube and can be described by equations 1.1a and 1.1b, which describe laminar flow based on Poiseuille's Law.

$$q_f = -K_f \frac{dH}{dz} \tag{1.1a}$$

$$K_f = \frac{\rho g}{\mu} \frac{b^2}{12} \tag{1.1b}$$

In this case, q_f is water flux through a smooth walled opening with an aperture of b length, where dH/dz is the gradient of the total hydraulic head with respect to depth. The conductivity term, K_f, is a function of density (ρ), gravitational acceleration (g), dynamic viscosity (μ), and aperture width (Hendrickx and Flurry, 2001). This method of determining flow through a single pore is very simple, but it only represents a porous material in which the pore extends continuously and is filled with water (Witherspoon et al., 1980; Bear et al., 1993)

The next scale, in terms of size, is the Darcian or local scale. The conditions of this division require that the volume being taken into consideration is representative of the whole. In this case, the Darcy-Buckingham equation (equation 1.2) can be used to represent flux through a representative volume of unsaturated media.

$$q = -K(h)\frac{dH}{dz} \qquad (1.2)$$

This equation uses an unsaturated hydraulic conductivity that is dependent on the soil water pressure (h). The flux of water (q) is determined by multiplying $K(h)$ with the gradient of the total hydraulic head ($H= h+z$) in relation to depth. Although this equation appears similar in form to equation 1a, the difference lies in the unsaturated hydraulic conductivity value which can be described by the relationship shown in equation 3a and 3b.

$$K(\theta) = K_s\left[\frac{\theta-\theta_r}{\theta_s-\theta_r}\right]^{\lambda}\left[1-\left[1-\left(\frac{\theta-\theta_r}{\theta_s-\theta_r}\right)^{\frac{1}{m}}\right]^{m}\right]^2 \qquad (1.3a)$$

$$\frac{\theta-\theta_r}{\theta_s-\theta_r} = \frac{1}{[1+(\alpha h)^n]^m} \qquad m = 1-1/n \qquad (1.3b \;\&\; 1.3c)$$

This function, proposed by Van Genuchten (1980), uses the relationship between measured data to determine water retention parameters. These parameters include the saturated hydraulic conductivity (K_s), the residual water content (Θ_r), the saturated water content (Θ_s), and the empirical constants λ, n and α.

In 1931, some years after the presentation of the Darcy-Buckingham equation, a study was conducted that produced one of the most commonly used equations in the field of unsaturated zone flow. This equation is now referred to as the Richards equation. Richards was able to amend the potential term to include the effects of capillary pressure, which allowed the equation to more accurately represent a wider range of soil textures (Richards, 1931). Over the years, many successful studies have been conducted involving direct calculations and numerical modeling with both the Richards and Darcy-Buckingham equation, which shows the strength of these relationships (Geiger and Durnford, 2000; Maréchal et al., 2006; Ababou et al., 1998).

Although the Darcian scale methods have been shown to be quite reliable at the representative volume scale, applying these methods to a much larger area can become a very laborious task. In order to apply the Richards/Darcy-Buckingham equation to a large area, extensive characterization would have to be completed to determine the hydraulic properties of the media. For this reason, larger scale mass balance methods are commonly used for studies evaluating groundwater recharge at the areal scale. These larger scale methods generally rely on a traditional water budget, as described by equation 1.4 (Healy, 2010).

$$\Delta S = P - ET - R_{off} - D \tag{1.4}$$

Where, the change in storage (ΔS) is equal to the inputs (precipitation (P)) minus the outputs (evapotranspiration (ET), runoff (R_{off}), and drainage/recharge (D)).

Large scale water balances have been, and still are a commonly used tool for estimating groundwater recharge rates at a regional scale. But, some studies have suggested that spatially averaging areas with extensive subsurface heterogeneity and transient climatic conditions can introduce substantial amounts of error into long term calculations (Kim et al., 1997; Sharma and

Luxemore, 1979; Chen et al. 1994). Kim et al. showed that even when using formally derived "equivalent" parameters that are meant to include the effects of heterogeneity, the relationships did not hold true under transient conditions. In the 1994 Chen et al. study, results of two simplified analytical solutions were compared to those produced by a finite element model. For this study, the analytical solutions were preferred methods due to the minimal requirement for computing time and effort. Even though this study suggested that the analytical solutions were sufficient for calculating unsaturated flow, their use was limited to situations with small soil property contrasts and still produced results that were inferior to those of the numerical model.

1.1.2 Numerical models for predicting infiltration in heterogeneous soil

In recent years, with improved personal computing power, finite element modeling has become a staple of unsaturated zone studies. A growing number of codes for simulating non-equilibrium water flow and solute transport have become publically available. The HYDRUS code, based on the Richards equation, has become one of the most popular codes for simulating unsaturated zone flow and solute transport. This is due to its ability to model a large variety of scenarios and the availability of an open access version of the HYDRUS 1D code. The HYDRUS software package is able to deal with a wide range of flow and transport scenarios, from traditional uniform flow to more complex, dual permeability models that can take into account both physical and chemical non-equilibrium. Although HYDRUS is one of the more popular software packages, there are a number of other codes available for predicting infiltration in heterogeneous, unsaturated soils. One of these models is the UZF1 package developed as a way to include unsaturated zone flow in the popular groundwater modeling code, MODFLOW (Niswonger et al, 2006). Another one of these models is the TOUGHREACT multiphase, reactive transport model for variably saturated media, being developed at Lawrence Berkeley

National Laboratory, which focuses heavily on the geochemical processes that occur during unsaturated zone flow (Xu et al, 2008). The dual porosity MACRO model (Jarvis, 1994) is another recent option available that incorporates the effects of macropores into the water flow solution.

1.1.3 Model Calibration and Validation

In hydrogeology, numerical models are used to represent very complex natural systems that can be difficult to define. One way to address this problem is by including model calibration and validation into the modeling process (Abbasi et al. 2004). These steps are vital to a strong and defensible model, especially if it is to be used in water management applications. After an initial model is created, the process of model calibration comes in as a way to systematically improve a model with observed data. Model calibration can be defined as the practice of fine-tuning a model for an individual problem by adjusting the input parameters within reasonable ranges (Šimůnek et al. 2012). The goal of this process is to minimize the difference between the observed and simulated results until a "best-fit-model" is achieved.

The main steps of this process are outlined in Figure 1.1 and include defining a base model, running the model, comparing the observed vs. simulated values and repeating these steps. In between each iteration of this process, alternative models must be considered and model parameters adjusted accordingly (Hill and Tiedeman, 2007). Regression analysis is a commonly used tool for evaluating model performance. In the case of a perfect model, when simulated versus observed data are plotted against each other, the data points would fall on a line with a unit slope and a zero intercept (Flavelle, 1992). Since models are never perfect, a number of methods have been developed to quantify the degree of fit between the two data sets.

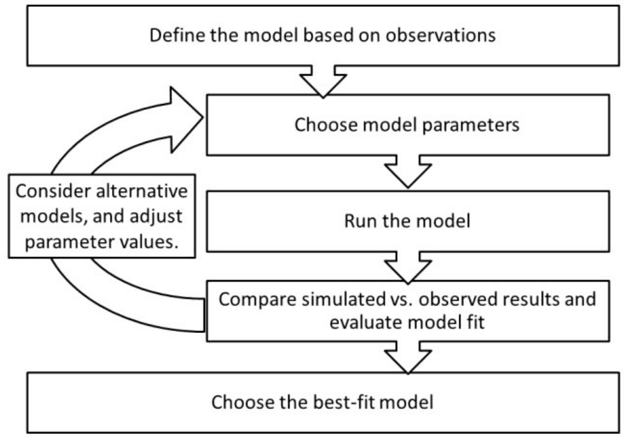

Figure 1.1: Model Calibration Flow Chart (adapted from Hill and Tiedman, 2007)

Many basic statistical concepts can be used to accomplish this task; the mean average error and root mean squared error are two common ways that error is reported. Although these two statistical measures can tell you about the degree of fit in a model, the bias of the results must also be taken into consideration. An unbiased model would be one that systematically under or over estimates the results (Hill and Tiedeman, 2007). Overall, both of these factors must be taken into consideration when performing a model calibration.

Once a best-fit-model is completed, a validation process is used to ensure that the model can truly represent the behavior of a system over time. Model validation can be defined as a process conducted by comparing model predictive results with actual experimental observations either at a later time or under new conditions (Flavelle, 1992). A model will be considered "validated" once an acceptable level of predictive accuracy is achieved. Although this seems like a simple task, model validation is a controversial issue due to the suggestive nature of the term. Some modelers believe that the word – valid – suggests a level of legitimacy that is unjustified (Anderson and Woessner, 1992; Oreskes and Kenneth, 2001). Nevertheless, some form of predictive model performance evaluation should be conducted for any model being used for water management purposes.

1.2 MOTIVATION

1.2.1 Agriculture

Water is scarce in the semi-arid regions of the west, which includes much of the State of Colorado. The water law in these areas is based on the doctrine of prior appropriations. This doctrine has led to the development of a complex water market in which water is bought, sold and traded as a commodity. Since many of the current senior water rights lie in the hands of agricultural water users, municipalities and industries in need of freshwater supply have been looking to the agricultural sector for help (Rowan et al., 2010). Starting as early as the 1950's, entities in need of water have been buying up irrigated land in order to obtain the water rights associated with it. This has led to a 7.4 million acre reduction in cropped land in the last 60 years (Colorado Conservation Trust, 2012). In that same time period, the population of the state of Colorado has seen an 830% increase and is predicted to grow by an additional three million people by 2050 (Colorado Conservation Trust, 2012). As the population grows, the demand for both water and food will also increase, creating a dilemma in regards to current water acquisition approaches.

In order to address this looming problem, many alternative approaches to the complete buying and drying a farm are currently being researched and tested in Colorado. Some of these alternatives include interruptible water supply agreements, rotational fallowing, water banking, and conservative irrigation techniques (Smith and Smith, 2013). The idea behind these ideas is that farmers can reduce their water consumption through more efficient management techniques.

By doing this, they can just replace the historic return flows through a flow augmentation program and then lease the saved consumptive water to municipalities and others during times of need (Cech, 2010). This process would allow for farmers to still produce food and maintain their farms to pass on to future generations.

1.2.2 SWIIM System

The more direct motivation of the projects lies in the need to provide a means of verification for the surface-based methods currently used in the monitoring program for the farm management software created by Regenesis Management Group. This software, the Sustainable and Innovative Irrigation Management (SWIIM) system, is used by agricultural water users to enable them to optimize their water rights, conserve water and increase net income for farming operations (Regenesis Management Group, 2013). As described above, the demand for water is continually increasing and agricultural water transfers are becoming the major way for municipalities and industry to meet their needs in the state of Colorado. The main goals of the SWIIM system involve using a monitoring program to verify consumptive water use and return flows for farmers. This information can then be used to lease their saved water to other beneficial uses without harming the water rights of the downstream users and at the same time, allow them to retain those rights to use for future growing seasons.

1.3 OBJECTIVE

Hydrogeologic techniques were utilized to monitor subsurface water fluxes through the vadose zone in order to provide an estimate of deep percolation at the SWIIM systems experimental field site. The unsaturated zone water balance method, lysimetry, and numerical modeling were used to accomplish this goal. The data collection, methods and analysis for this project were organized into a scientific paper to be submitted to a professional journal, and are presented in Chapter 2. Chapter 3 includes additional work that was done for a predictive scenario for the SWIIM field site, as well as recommendations for future work at the site or for similar studies elsewhere.

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CHAPTER TWO

2.1 INTRODUCTION

2.1.1 Background

With over 80% of the water use in Colorado going to agricultural purposes, it is becoming important to explore and understand new conservation irrigation techniques. As the demand for municipal water increases, new programs are being investigated that will allow a farm to temporarily lease a portion of its water rights to municipalities while still maintaining a portion to use for growing crops (Stephens, 2006). In Colorado, agricultural water falls into two categories, return flow and consumptive use. Return flows qualify as any water that passes through the root zone without evaporating or being used by the plant. Consumptive use is the water that is either taken up by the plant roots, or evaporated at the surface, and this is the only type of water that farmers can legally sell or lease (Denatale, 2008). Many farms in northeastern Colorado have chosen to follow the “buy and dry” practice, which requires fallowing large areas of field and replacing historical deep percolation (DP) by building recharge ponds, although this method has proven to have negative impacts on the local communities and economies (Pritchett et al., 2008). For new water leasing programs to comply with the laws of the State of Colorado, the farmers must show that their new, non-traditional practices are not reducing their return flows. To prove this, a standard method must be developed and tested that will allow farmers to report current and historical deep percolation values under any previous or current irrigation methods.

2.1.2 Purpose

The aim of this project is to determine the amount of deep percolation (DP) beneath a deficit furrow irrigated corn field. Three methods were used (the unsaturated zone water balance, lysimetery and a numerical model) and evaluated for their reliability and ease of employment in the estimation of DP. The results of this project will build a better understanding of the processes and inputs that affect deep percolation under furrow irrigated agriculture, which will help verify estimates of groundwater return flows required by Colorado State law. There are a number of uncertainties in the currently used methodology that relate to surface measurements of evapotranspiration (ET) and rough calculations of surface water inputs that are required to calculate DP as a residual (Stephens et al., 2006). The subsurface methods used for calculating DP in this study will help to limit the number of assumptions being made and supply a direct measurement of water draining from the soil profile. Also, by using these results to create a numerical model, this study will test an alternative way to estimate DP which could be used in future seasons, requiring much less time and resources.

This study focuses on differences in method performance in relation to degree of soil heterogeneity and irrigation styles. The irrigation methods used include a fully irrigated control treatment (treatment #1); a low frequency, high volume limited irrigation treatment (treatment #2); and a high frequency, low volume limited irrigation treatment (treatment #3). The two subsurface water balance methods include the unsaturated zone water balance method (UZWB), also known as the zero-flux plane method, and lysimetry. The third method is a 2D unsaturated zone numerical model created using the HYDRUS (2D/3D) software.

2.2 PREVIOUS WORK

2.2.1 Water Balance Methods

Many studies have been conducted that look at movement of water through the vadose zone under irrigated agriculture. Recently, a United States Geological Survey (USGS) study (Arnold, 2011) was conducted to evaluate deep percolation beneath both furrow and sprinkler-irrigated corn in Weld County, CO using the unsaturated zone water balance (UZWB) and the water table fluctuation (WTF) method. The results showed that the UZWB method and the WTF method only differed by 10% for the flood-irrigated site, but by over 100% for the sprinkler irrigated site. For the Arnold study, standard irrigation methods were applied, and only one site was used in each field. Therefore, the effects of spatial variability and various furrow flood irrigation styles were not evaluated in this study. In two other studies conducted in 2009, water balance methods using lysimeters and neutron probes for measurement were compared. In both studies, drip irrigation methods were used and yielded consistent water balance values between the two water balance methods (Tolk et al. 2009; Vera et al. 2009).

Other studies have been conducted that look at various ways to obtain direct measurements of deep percolation through lysimetery. There are two main types of drainage lysimeters that have been used: zero-tension lysimeters and tension lysimeters. Zero-tension lysimeters rely on gravitational force to drain water from the soil profile once it has reached saturation (Brye, 1999). Tension lysimeters combine the effects of gravity with soil water potential gradients, which help encourage flow without complete saturation. One study showed that zero-tension lysimeters have the potential for underestimating flow, if there is not sufficient surface area, by missing macropores and allowing for flow bypass (Jemison and Fox, 1992). In the Brye et al. (1999) study, a lysimeter experiment was conducted under three different land uses (prairie, no tillage, and chisel plow), in which tension was used with soil water potential sensors in order to maintain equilibrium at the soil drainage boundary to allow for free drainage. The results of this study showed that this method was most consistent under the prairie system, and showed the highest variability under the no tillage agroecosystem (Brye et al., 1999).

Additionally, some studies have been conducted that look at water movement through the vadose zone, but also look at the variability of drainage values in relation to soil type. Ochoa et al. (2009) conducted a study in an irrigated valley in New Mexico, in which water movement through the vadose zone was evaluated at six different plots all within ~200 meters of each other. This study showed that surface soil type had a large effect on the water flux through the vadose zone. Nimmo et al. (2002) looked at water fluxes in alluvium in the Mojave River Basin. In this study it is shown that the basic Darcian method for determining water fluxes does not hold true in cases of heterogeneous material. The study used core samples to determine the unsaturated conductivity on a two-dimensional grid in order to accurately determine the flux through the heterogeneous material. The time and cost of the Mojave study method would not be feasible in most cases.

Although many vadose zone studies have been conducted, when combining issues such as soil type and non-traditional irrigation methods, there are still a number of unanswered questions when it comes to confidently determining DP. The experiment presented in this paper addresses these issues by combining new management strategies with extensive subsurface monitoring techniques. The subsurface water balance methods used for calculating deep percolation are not dependent on soil types or surface inputs, and are able to sample the spatial variability that occurs during furrow flood irrigation. Also, it is always beneficial to compare the results of multiple methods when attempting to accurately determine a value as spatially and temporally variable as groundwater recharge.

As has been shown in many studies before, the actual amount of recharge at any given location is never known with 100% certainty (Delin et al. 2007, Healy 2010). For example, in the 2007 Delin study, both the UZWB and WTF methods were used and results between two nearby sites varied by nearly 47%, and there was up to 62% variance between the different methods. For this study, the UZWB was considered most accurate at a scale of one square meter, whereas the WTF method was considered most accurate at a scale of hundreds of square meters. Overall, every method has inherent limitations and is accurate on varying spatial and temporal scales. Therefore, it is important to understand these factors when evaluating method results.

2.2.2 Unsaturated Zone Numerical Models

There are many methods for calculating DP, but many require continuous data collection and time consuming field work. The creation of a calibrated and validated numerical model for a field site allows for a reliable prediction of DP in settings where continuous field work is not practical (Šimůnek et al. 2008). Having a working model also allows for predictions based on proposed irrigation management schemes. The HYDRUS 2D modeling package has been used as a method for simulating drainage beneath furrow irrigated agriculture in a number of studies (e.g., Abbasi et al., 2004; Crevoisier et al., 2008), and is considered a standard method for modeling water flow in soils with mixed and variable boundary conditions by the Cooperative Research Centre for Irrigation Futures (Cook et al. 2006).

2.3 MATERIALS AND METHODS

2.3.1 Site Description

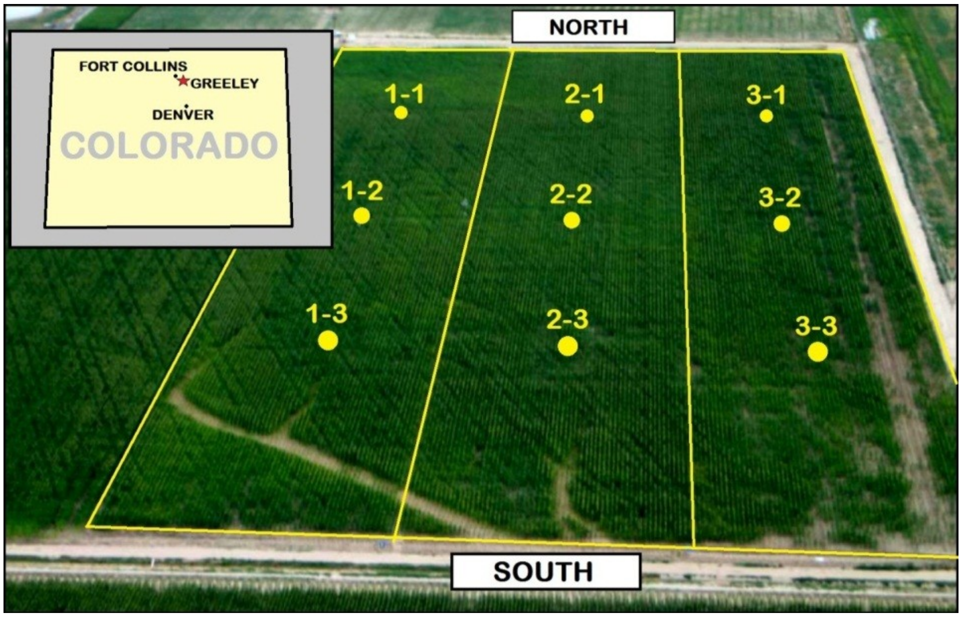

Figure 2.1: Field map showing instrumentation locations and site numbers.

The research site is located near the city of Greeley in Weld County, Colorado (Figure 2.1). The climate of this area is characterized as semiarid with large seasonal temperature variation. The average high throughout the 2011-2012 field seasons was 29℃ with an average low of 11℃. During the 2011 and 2012 field seasons, the site received 184 mm and 142 mm of precipitation respectively (collected from the Colorado Agricultural Meteorological Network). The soil on approximately 90% of the field is characterized by the USDA Soil Survey as Nunn clay loam with 0-1% slopes, which has a parent material of mixed alluvium and aeolian deposits (Soil Survey Staff). The northwestern side of the field is comprised of a coarser material that is classified as the Olney fine sandy loam, which is from a mixed deposit outwash parent material. The site consists of one 5.7 hectare corn field that is divided into three adjacent blocks. Each block is 45 meters wide and 395 meters long with instrumentation sites at ¼, ½, and ¾ length of the field (Figure 2.1).

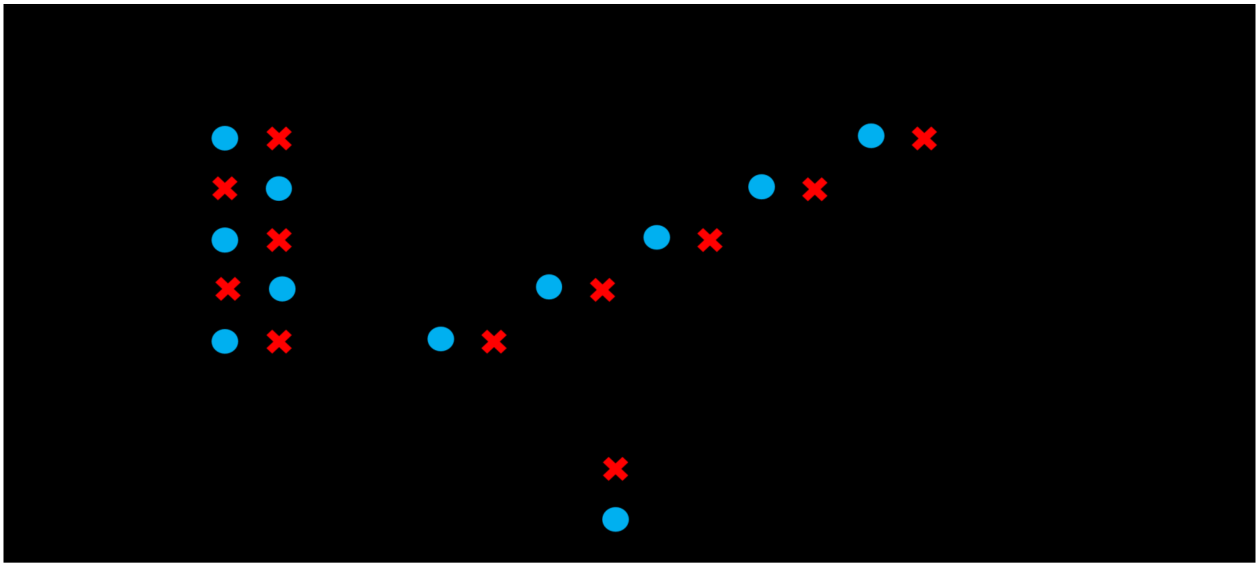

Figure 2.2 Cross-sectional diagram of a typical instrumentation site in the north and south ends of the field (not to scale).

All sites are instrumented with a neutron probe access tube, water content sensors and piezometers (for water table elevation and neutron probe access), with drainage lysimeters at ¼ and ¾ of the way down the field (King and Sanford, 2011). A cross section of the typical site design is shown in Figure 2.2. Three different irrigation treatments were used throughout the field; each was applied to one block and rotated to a different block the next season.

2.3.2 Irrigation Applications

In order to evaluate the effects of multiple irrigation management schemes, the field was divided into three separate blocks. Each block was approximately 45 meters wide and 395 meters long. An irrigation well with 0.04 m^3/s flow capacity was used with a gated pipe delivery system to supply water to the north end of the furrows during each irrigation event. Flow into the furrows was measured using magnetic flow meters, and flow at three sites down the furrows and at the end was measured by monitoring furrow flume water levels. Applied water values for each site were calculated using the difference in flow rates of adjacent flumes over the irrigation period.

The three irrigation treatments each used a unique water application scheme that involved different amounts and frequencies of applied water. The fully irrigated treatment was used as a control plot, and was based on the standard management practices for the region. There were six irrigation events in 2011 and ten in 2012 with average applications of 220 mm and 54 mm, respectively. The second treatment was the low frequency, high volume scheme, which aimed to wet the entire soil profile with a large irrigation event in the beginning of the season, and to meet DP requirements with a late irrigation. This treatment used two applications in 2011 and three in 2012, with an average application of 465 mm and 252 mm. The third treatment used a high frequency, low volume irrigation approach, which sought to minimize the amount of DP. This treatment used seven irrigations in 2011 and six in 2012, with average water applications of 129 mm and 42 mm.

Even though more water was applied, irrigation furrow advance was typically less than 100% for the 2011 season. A number of factors contributed to this, including the breakthrough of irrigation water via a cross furrow flow paths and patches of soil with unusually high infiltration rates. In 2012, tillage practices were changed from standard to conservation tillage methods. These changes involved delaying the till until the spring, leaving all excess organic matter from harvest at the surface to prevent winter erosion, and only furrowing every other row, to prevent irrigation water breakthrough. These management practices led to almost 100% furrow water advance for every treatment and every irrigation event for the 2012 season.

2.3.3 Lysimeter

Deep Percolation values were collected using drainage lysimeters installed in the north and south ends of the field (King and Sanford, 2011). The drainage lysimeters have been in operation since the 2010 field season, and are emptied before any irrigation event and a minimum of three to four more times. These lysimeters were designed with walls that extend up to approximately one meter below the pre-furrowed ground surface in order to capture any water that makes it past the root zone. Water percolates through the lysimeter soil column and drains freely into a reservoir at a depth of approximately two meters below the pre furrowed ground surface.

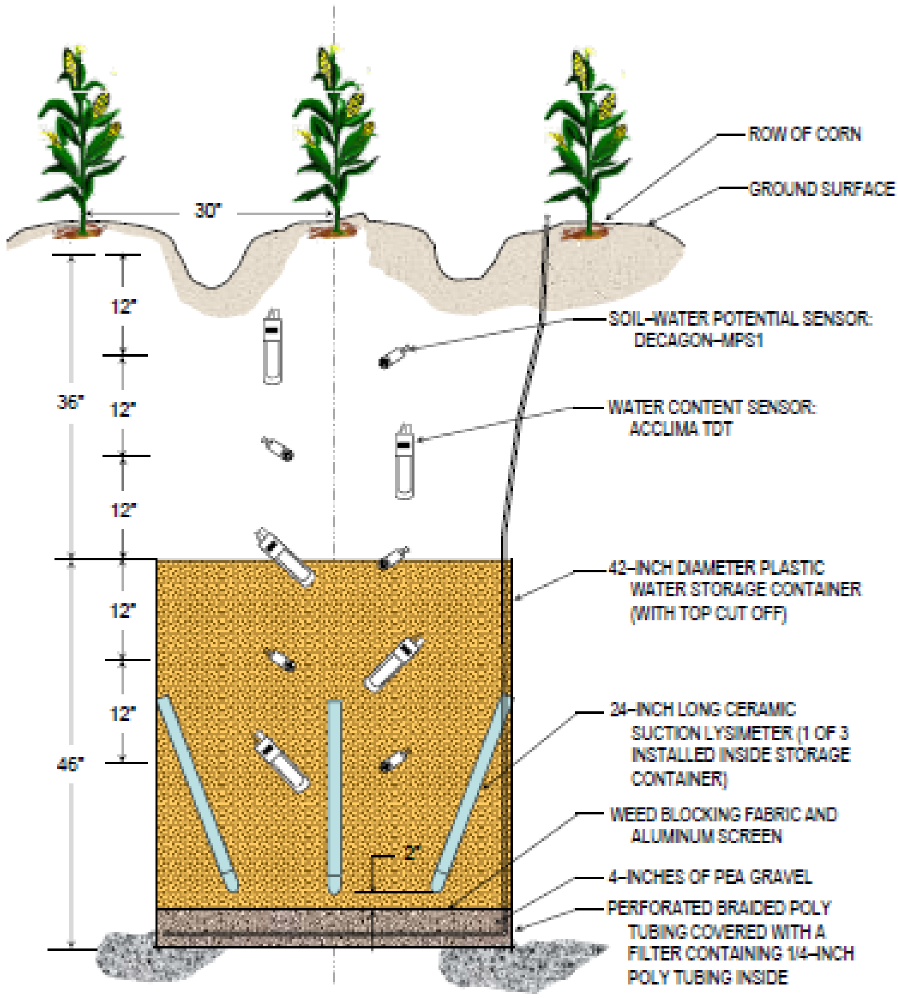

Figure 2.3: Cross-sectional diagram of the lysimeter construction. (Adapted from King and Sanford, 2011)

The lysimeters are constructed from 1.2 meter tall plastic cylinders with open tops, and were installed using a 107 cm diameter auger. Figure 2.3 shows a cross section of the drainage lysimeters which are 86 cm in diameter on the south end and 106 cm in diameter on the north end. The difference in diameters is due to availability of materials and limited amount of time for installation. Soil was excavated carefully so that the material remained separated into piles by depth, which would allow the backfilled soil profile to resemble the native conditions. The reservoir extraction system was then installed at the bottom of the lysimeter. This system (Figure 2.3) consists of five 6.5 mm diameter polyethylene tubes that are used to extract water from the 10 cm thick pea gravel reservoir at the bottom of the lysimeter, with the use of a peristaltic pump at the surface. This is done three to four times after every irrigation application. Before back filling the lysimeter, a metal screen and weed blocking fabric were installed above the gravel to prevent the leaching of the soil into the reservoir. At approximately five centimeters above the reservoir, three tension lysimeters were installed in order to remove water above the reservoir where the air-entry value has not yet been overcome (Derby et al., 2002). This small amount of tension helps to maintain equilibrium conditions by removing any excess water that may be retained in the porosity directly above the drainage boundary.

2.3.4 Unsaturated zone water balance

In order to obtain the soil moisture data needed for the unsaturated zone water balance, neutron probe measurements were taken throughout the growing season, most frequently directly following an irrigation event. Eight wells were installed, three in the north quarter, two in the center and three in the south quarter of the field, to be used as neutron probe access sites.

The neutron probe access wells were installed using a push point drilling method, which minimized formation damage and allowed for good contact between the drilled hole and the outer walls of the well. The wells were drilled to depths sufficient to intersect the local water table, and are comprised of two, five centimeter ID metal pipe with a 91 centimeter screened interval at the bottom to allow for water table measurement readings. The metal piping continued up to approximately 50 cm below the soil surface and was joined with a small section of PVC pipe that would allow for temporary burial during standard agricultural practices, such as plowing. The CPN 503DR Hydroprobe was used to collect soil moisture readings from approximately 1.5-5 five meters below the surface at approximately 50 cm intervals. Each measurement represents bulk water content of a sphere with approximately a 15 cm radius from the middle of the radiation source (Ward and Wittman 2009).

The soil moisture data obtained from the neutron probe readings were used to estimate deep percolation via the UZWB method. This method is based on the idea that at some point beneath the soil surface, the hydraulic gradient will shift from up to down, meaning all water beneath that point will eventually become deep percolation. This point, referred to as the zero-flux plane, occurs just below the zone of root water uptake, where the upward movement of water due to ET is no longer occurring (Delin et al. 2000, Healy 2010). The calculation of deep percolation via this method relies on the simplification of a basic water-budget equation

$$DP = P - ET - \Delta S - R_{off} \tag{2.1}$$

where DP is deep percolation, P is precipitation or any other surface applied water, ΔS is change in storage, and R_{off} is surface runoff (Healy, 2010). For the UZWB method, which only applies to the zone between the zero flux plane and the capillary fringe zone, all surface components of the water-budget can be ignored, leaving:

$$DP = -\Delta S \quad (2.2)$$

Deep percolation was determined for each irrigation event by calculating ΔS (equations 2.3 and 2.4). Water content measurements were taken directly before irrigation events and daily for at least two days post irrigation and approximately three times per week after that in order to determine soil water storage values (Healy 2010).

$$S = \int_{z_{wt}}^{z_{zfp}} \theta dz \quad (2.3)$$

$$\Delta S = S_t - S_{t-1} \quad (2.4)$$

Where S is soil water storage per unit area z_{zfp} is the depth of the zero-flux plane, z_{wt} is the depth of the water table, Θ is the volumetric water content at each depth, and dz is the depth increment between measurements. The maximum post irrigation soil water storage value was then subtracted from the initial storage value to calculate the ΔS value for that particular event. This was repeated for every irrigation event, and then ΔS values were summed to obtain the seasonal DP value for each measurement site.

2.3.5 Soil Core Analysis

Soil cores were collected from each site during the instrumentation installation and analyzed using both the USDA hand texturing method. The hand texturing was performed as described in a previous work (King, 2013 unpublished). Soil textures for each site are shown in Figure 2.4.

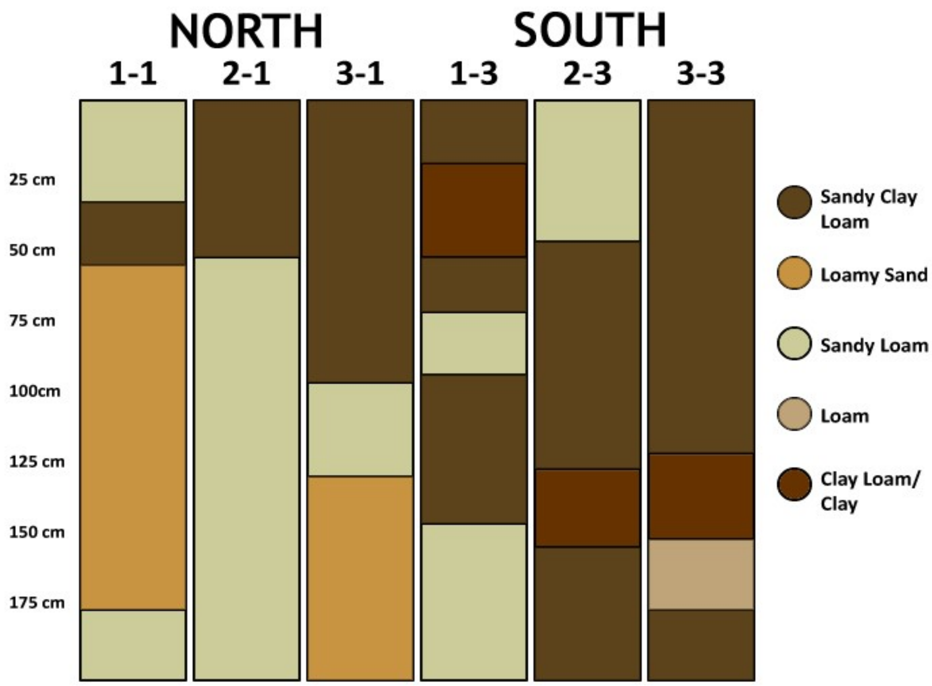

Figure 2.4: Diagram of soil textural classifications based on hand texturing and particle size analysis.

2.3.6 HYDRUS Model

The third part of this study includes the development and verification of a numerical model using the HYDRUS (2D/3D) software. This model simulates unsaturated flow using the finite element method with a governing equation as the 2D Richards equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[K(h)\frac{\partial \theta}{\partial x}\right] + \frac{\partial}{\partial z}\left[K(h)\frac{\partial \theta}{\partial z} + K(h)\right] \quad (4)$$

Where θ=volumetric water content; h=soil water pressure head; t=time; x=horizontal space coordinate; z=vertical space coordinate and K= hydraulic conductivity (Šimůnek et al. 2006).

For this experiment, each site had identical model domains (shown in Figure 2.5), and boundary/initial conditions were adjusted for each scenario and site. The basic model design was a 210 cm x 600 cm rectangle with half circle depressions at 60 cm spacing to represent the furrows. The model was built to the depth of 210 cm to represent the surface where the lysimeter collection point would be. This depth allowed for calculation of water flux below the zero-flux plane (a point where root water uptake was no longer occurring), without over complicating the model or unnecessarily extending the computation time. Both a single-layer and multi-layer model domain was created for each site. For the layered models, three to four layers were built into the domain with 2-3 different materials. The model was automatically discretized using a target finite element size of 10 cm. On average, each model consisted of approximately 2,300 nodes and 4,500 2D-elements.

For each soil profile type, soil textures from the core data were used to determine the hydraulic parameters for the model based on the built-in Rosetta database. Rosetta is a pedotransfer software package that predicts soil hydraulic parameters using a neural network model and soil texture as input (Schapp et al., 2001; Skaggs et al., 2004). For the homogeneous profile, an effective hydraulic conductivity value (a harmonic mean), was used to determine which set of hydraulic parameters would represent the whole profile. For the heterogeneous profile, layers were built into each site model to uniquely match the layers determined by the core analysis (Figure 2.5).

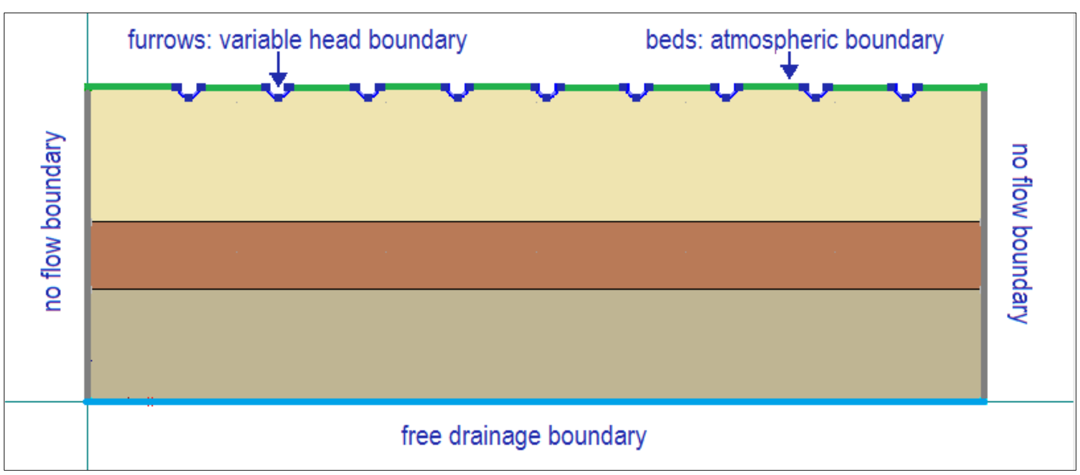

Figure 2.5: Shows the boundary conditions and geometry for a typical heterogeneous model in the HYDRUS 2D model domain.

The irrigation applications were applied using a variable pressure head boundary condition based on furrow flume irrigation data. Height of water in the furrows was monitored throughout each irrigation event at a flume near each instrumentation site. These data were used to determine the timing of the pressure head boundaries. The total application times were different for each event and with position down the field due to variations in furrow water advance. A pressure head of one centimeter was applied to the entire surface of the furrow in order to allow for continuous supply of water throughout the designated "wet" period and to avoid creating too large of a gradient at the soil surface. Due to the size of the model, the reasonable discretization level does not allow for convergence under very high hydraulic gradients, which often occur when a sudden irrigation application is applied to the extremely dry soil surface.

The root zone was distributed within the top meter of the domain, and root water uptake was determined based on the built-in Feddes model, which included water stress response function parameters specific to corn (Šimůnek et al. 2006). An atmospheric boundary condition was applied to all nodes except the ones inside of the furrows. Daily rates of precipitation and ET were manually input based on values from an on-site weather station. Initial conditions at the site were set to approximate field capacity based on soil type and referencing shallow soil moisture sensors.

Four irrigation scenarios were applied to each site: 1) full season, homogeneous soil profile; 2) full season, heterogeneous soil profile; 3) single irrigation event, homogeneous profile, 4) single irrigation event, heterogeneous profile. The full season models were run for the field season of 180 days, and the single event run times were varied, starting two days pre-irrigation and ending the day before the following irrigation.

2.3.7 Model Calibration

Each of the models was run based on the original hydraulic properties assigned, using the built in Rosetta database feature, and cumulative DP modeled results were calibrated to the DP values obtained using the UZWB method. After the initial models were run, a second model was then created in order to run a trial-and-error calibration. For this calibration process, the saturated hydraulic conductivity (K_s) was adjusted by a maximum of ±50% in order to obtain the best fit to the measured data, while staying within a reasonable range for the documented soil type of the given profile. The layered model was calibrated in a similar manner to the homogeneous model, beginning with hydraulic parameters from the Rosetta database and adjusting each layer until a best fit value was reached. After all models were completed, the model cumulative DP values were compared with each method separately to evaluate the relationships and consistency between methods. Statistical data and visual fit for the modeled vs. observed DP values were then used to determine whether the homogeneous model was strong enough to represent the system or if the heterogeneous model was needed. The chosen model was then used in a predictive fashion to produce results for the 2012 season. This predictive model run was used as a way to verify that the model was capable of producing accurate results under different conditions.

2.4 RESULTS AND DISCUSSION

2.4.1 Unsaturated Zone Water Balance

Throughout the 2011 and 2012 seasons, soil moisture data were collected using the neutron probe, approximately three times per week, sometimes more often directly following an irrigation event (complete data set can be found in the appendix). Water content profiles were compiled for the UZWB at each data collection date, allowing for the times of minimum and maximum soil water storage to be determined. An example of these profiles can be seen in Figure 2.6. The zero-flux plane was defined to be at approximately 1.2 meters. This was determined using a combination of matric potential sensors (located at approximately 30 cm intervals to a depth of 2 meters) to evaluate hydraulic gradient, as well as knowledge of crop rooting depths. Deep percolation was determined for each of the irrigations with equations 2.2 and 2.3 using measurements from approximately 1.5 to 5.5 meters depth, and summed to get the season totals, which are shown in table 2.1. These data are also presented as percent deep percolation (%DP) as a way to standardize the results of the three methods. Percent deep percolation was calculated by dividing the calculated deep percolation by the applied water for each site.

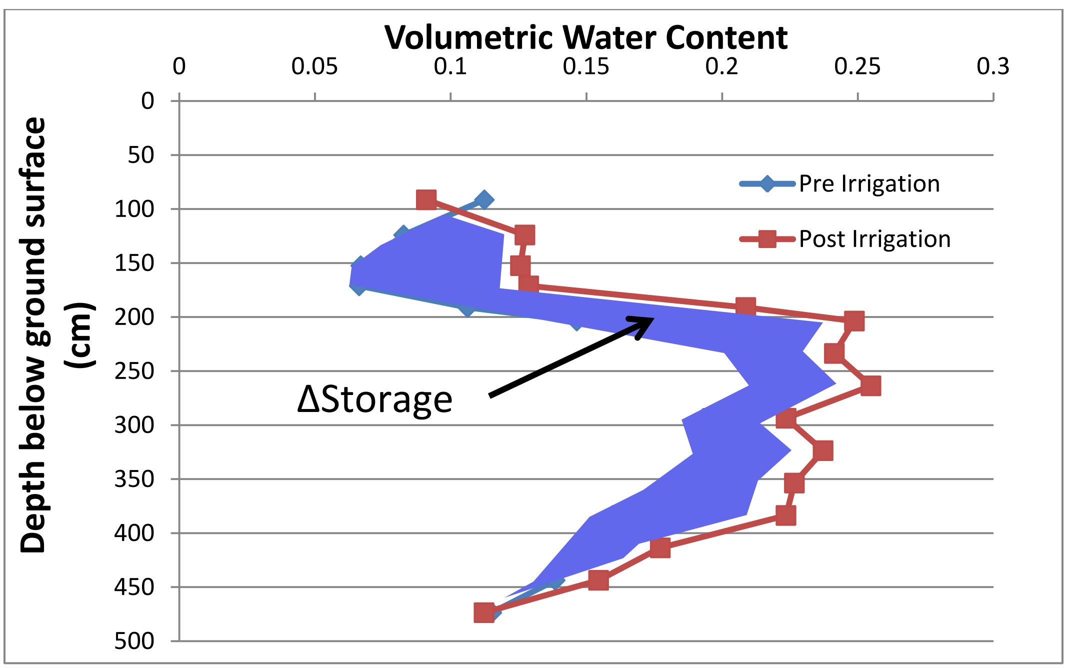

Figure 2.6: UZWB Profiles- An example of data from site 2-1 is shown here. The blue line is water content with depth before an irrigation event and the red line shows the post irrigation maximum storage reading. The shaded area in the middle represents the area calculated as ΔS.

Table 2.1: Seasonal Totals of Deep Percolation and Applied Water per Site.

Fully Irrigated Seasonal Deep Percolation (% DP)						
	2011			2012		
	North	Middle	South	North	Middle	South
UZWB (cm)	30.2 (19%)		40.5 (62%)	13.2 (23%)	7.1 (13%)	16.0 (32%)
Lysimeter (cm)	28.3 (18%)		38.7 (59%)	27.6 (48%)		43.2 (82%)
Water Applied (cm)	159.5	54.7	65.4	57.5	54.7	50.7

High Frequency, Low Volume Deficit Seasonal Deep Percolation (% DP)						
	2011			2012		
	North	Middle	South	North	Middle	South
UZWB (cm)	15.3 (16%)	11.9 (22%)	15.6 (99%)	14.3 (44%)		16.9 (65%)
Lysimeter (cm)	5.4 (6%)		6.9 (44%)	16.4 (50%)		31.1 (120%)
Water Applied (cm)	95.5	55.0	15.7	32.8	29.9	25.9

Low Frequency, High Volume Deficit Seasonal Deep Percolation (% DP)						
	2011			2012		
	North	Middle	South	North	Middle	South
UZWB (cm)	50.4 (46%)	40.2 (45%)	36.0 (71%)	4.0 (5%)	8.7 (11%)	8.0 (11%)
Lysimeter (cm)	30.1 (27%)		18.1 (36%)	27.9 (35%)		25.2 (35%)
Water Applied (cm)	110.1	90.2	50.8	78.7	76.4	72.7

There was a distinct shift in trends between the two growing seasons. As a whole, deep percolation values ranged from 11.9- 50.4 cm (16-99 %DP) in 2011, and 4.0- 16.9 cm (5-65 %DP) in 2012. The highest %DP values occurred, as predicted, in the low frequency, high volume treatment (#2) in 2011, while they occurred in the fully irrigated treatment (#1) in 2012. There was one outlier to this general trend which occurred at site 1-3 in 2011, where %DP was calculated to be 99% for the UZWB method. This data point suggests that almost all water applied to south end of the high frequency deficit treatment (#3) would have percolated down through the soil profile. This is highly unlikely due to the slow movement of water at the south end of the field and the clay rich soil texture. The most likely explanation of this outlier is cracking of clay rich soils at the site, which can lead to preferential flow paths down to the more permeable, lower layers (Greve et al., 2010). The shift in trends is also apparent when looking at the sites with the lowest deep percolation values. In 2011, as expected, the high frequency, low volume treatment (#3) showed the lowest %DP, except for at site 1-3 (for reasons mentioned above). For the 2012 season, the low frequency deficit (#2) showed the lowest values of %DP, which was an unexpected result.

This change in trends between seasons could be related to a number of causes including soil type, plowing practices and water application uncertainties. By rotating the irrigation treatments to different locations every year, the effects of soil variability are difficult to separate from the effects of the irrigation treatments. A change from loamy soil to sandy or cracked soil could affect the rate of infiltration as well creating preferential pathways. Tillage practices were also changed from the 2011 to 2012 field seasons from conventional plowing to conservation, minimal tillage practices, which incorporates much more organic matter into the soil and can change the soil structure and hydraulic properties. Previous studies have shown that infiltration rates can be either increased or decreased when conservation tillage practices are used in place of conventional methods (Lipiec et al., 2006; Jones et al., 1994; Edwards et al., 1988). The resulting effect is dependent on antecedent soil properties as well as the length of time the practices had been implemented, meaning that it is difficult to understand the full effect that these practices have had on each site.

2.4.2 Lysimetry

Volumes of DP were directly collected from the lysimeters regularly throughout both seasons. The largest amounts of water were collected within a week of each irrigation event. Season totals for DP collected from the lysimeters are shown in table 2.1. In 2011, lysimeter DP values were consistently lower than those calculated using the UZWB method, while the opposite occurred in 2012. The range of % DP shifted upwards between 2011 and 2012, with values of 6-59% and 35-120%, respectively. This shift in trends is most likely due to the same factors listed above for the UZWB values. Since the lysimeter directly collects volumes of water, the effects of these potential factors vary in degree. For example, even though less water made it to the end of the field, higher values of DP were collected in the south end of the field for five out of the six cases. This is likely due to the fact that soils on the south end of the field consistently displayed surface soil cracks, which allowed for preferential flow. Since the lysimeters are located less than two meters below the surface and collect water from an approximately 0.6 square meter area, they are more susceptible to the effects of cracking than the soil moisture measurements used for the UZWB method. A 2010 lysimeter study by Greve et al. (2010) showed that during flood irrigation, water will first flow down the cracks at the surface before diffusing into the matrix. Greve et al. also showed multiple continuous soil cracks that extended 1.3 meters, which was the entire length of the lysimeter soil column. These surface level preferential pathways could also affect the accuracy of the water applied calculations which are dependent on known infiltration rates.

2.4.3 Model Calibration and Results

Nine models (one for each instrumentation location) were created using HYDRUS (2D/3D), the same domain geometry for each site (Figure 2.5) and soil properties specific to each location.

Each site model began as a single layered, homogeneous model or a layered model. Trial-and-error calibration was performed in order to minimize the residual between the models and the UZWB for the 2011 season data. An example of the visual model results is shown in Figure 2.7, where water movement in the heterogeneous profile is compared to that in the homogeneous model through time lapse water content maps. A predictive model run was then conducted for 2012 and results were used to verify the model calibration.

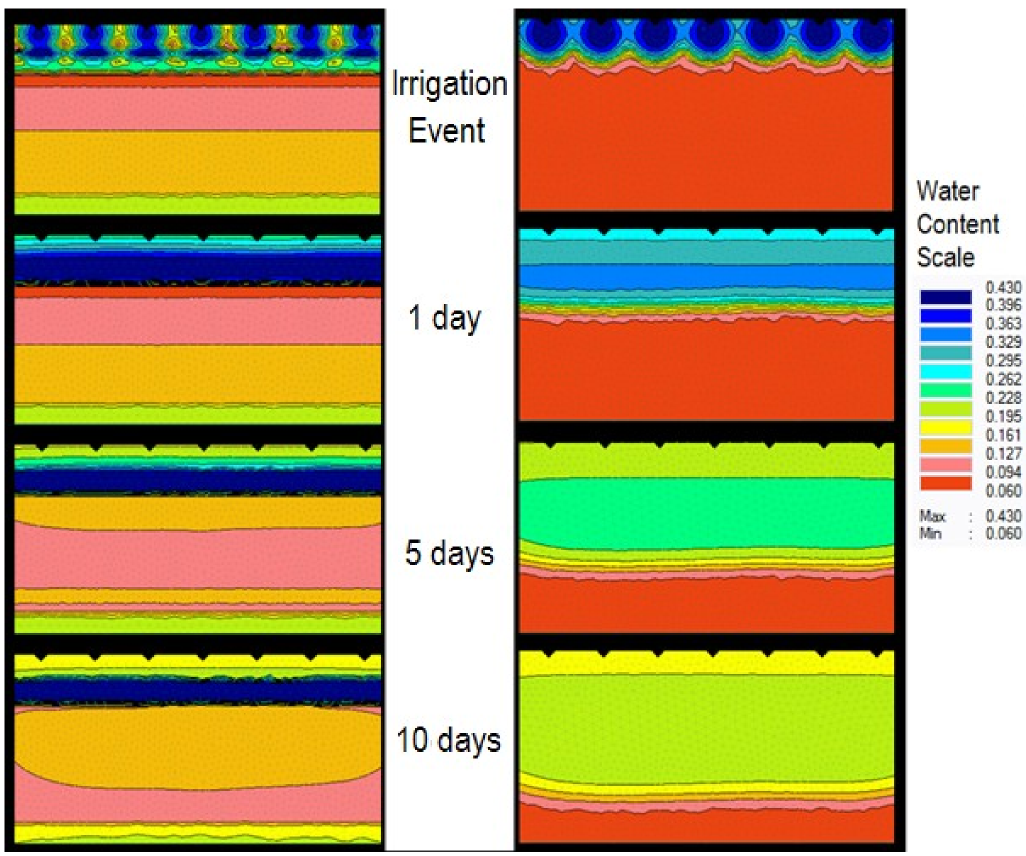

Figure 2.7: Modeling Results- Shows differences in soil moisture retention and behavoir between the heterogeneous (left) and homogeneous (right) profiles over one irrigation event.

The DP model results are shown in comparison with the UZWB and lysimeter values in Figure 2.8. The models were evaluated for goodness-of-fit based on the mean average error (MAE), MAE/range (normalized MAE), and root mean squared error (RMSE). In general, the statistical fit of the modeled versus measured values were better for the 2011 data than for 2012, with only one exception. The only error value that was smaller in the 2012 predictive model run was the normalized MAE for the lysimeter versus the heterogeneous model fit. This can be attributed to the fact that there was a larger range of data values for the 2012 season than for 2011, since the MAE values for the two seasons only varied by 0.15 cm. Figure 2.8 displays the results from the modeled versus observed relationships for both of the water balance methods and the homogeneous and heterogeneous models, and Table 2.2 shows the statistical analysis of the models' goodness-of-fit.

Table 2.2: Statistical Analysis Values for 2011 and 2012 HYDRUS models

UZWB vs Homogeneous			
	MAE (cm)	*MAE/Range*	*RMSE (cm)*
2011	8.15	0.16	9.88
2012	11.86	0.25	17.11
Lysimeter vs Homogeneous			
	MAE (cm)	*MAE/Range*	*RMSE (cm)*
2011	11.11	0.23	13.01
2012	16.64	0.35	20.50
UZWB vs Heterogeneous			
	MAE (cm)	*MAE/Range*	*RMSE (cm)*
2011	4.94	0.10	7.84
2012	14.76	0.26	21.42
Lysimeter vs Heterogeneous			
	MAE (cm)	*MAE/Range*	*RMSE (cm)*
2011	12.10	0.25	15.44
2012	12.25	0.22	17.72

The homogeneous models show a slight bias to the right of the 1:1 line. Therefore, even though the normalized MAE value for the UZWB vs. the homogeneous model is among the lowest, it would not be recommended as the most reliable estimate for future predictions. Both of the heterogeneous models show a more unbiased spread around the 1:1 line. Based on visual evaluation, the UZWB vs. the heterogeneous model has a narrower spread than when compared with the lysimeter data. This evaluation is confirmed by comparing the average statistical analysis values for the two seasons, which shows a 23% smaller MAE, 6% smaller normalized MAE, and 13% smaller RMSE for the UZWB comparison to the heterogeneous model than for the lysimeter data.

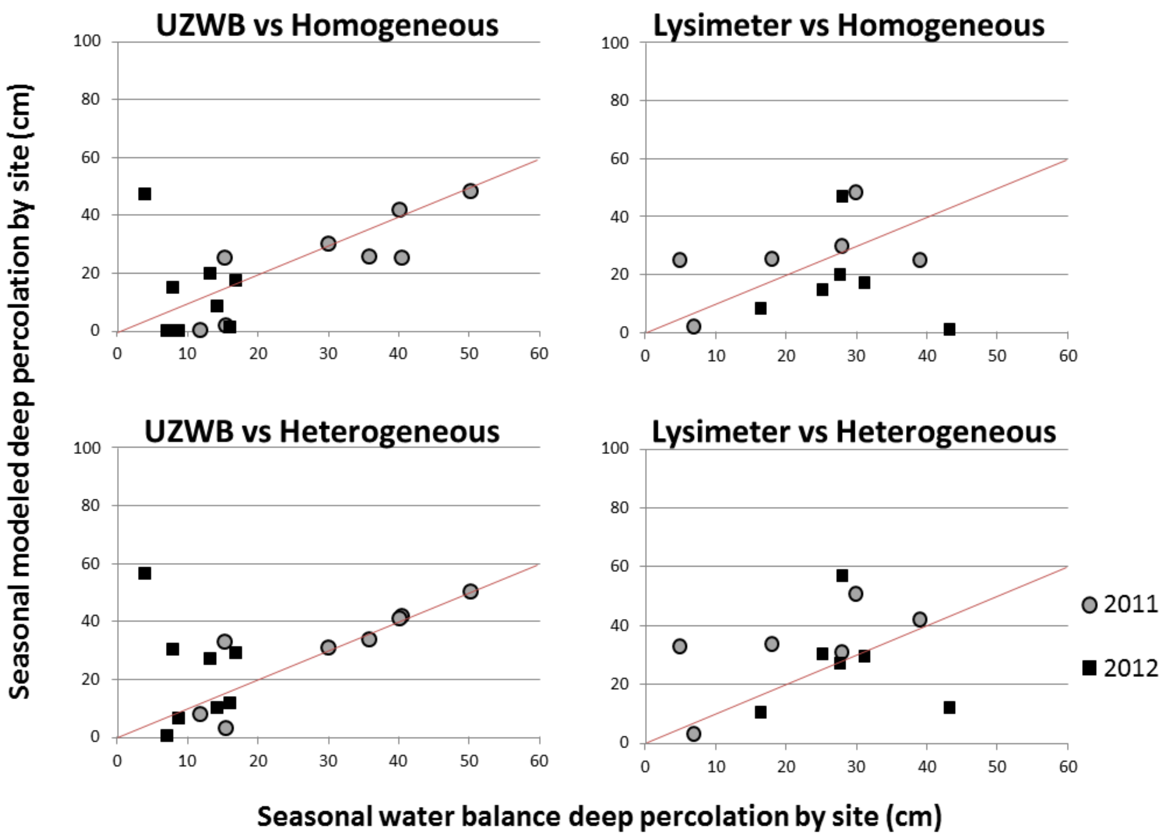

Figure 2.8: Modeled versus Observed Deep Percolation Values

These results suggest that it is difficult to determine a single set of hydraulic parameters within a reasonable range to accurately represent a soil column as homogeneous. One way that some of the single layered models could have improved their fit is by assigning very high conductivity values as a way to intrinsically include the increased infiltration from cracks. The main concern with this method would be the unreasonable values that would have to be used, as well as whether or not these values would hold true under a variety of soil moisture conditions (e.g. high moisture contents, when cracks might close). A dual porosity model is another option for modeling preferential pathways, but given the inconsistent nature of the soil cracking at this site, it would be difficult to assign parameters to define the nature and abundance of these pathways.

2.5 CONCLUSIONS

For this study, two subsurface water balance methods were used to calculate DP beneath a furrow irrigated field and create and calibrate a 2D numerical model. The two water balance methods were the UZWB method and lysimetry, which used a combination of water content data and direct water collection values. The results showed that the UZWB was able to calculate DP values with the least amount of influence from potential uncertainties such as soil heterogeneity and preferential pathways, which is due to the fact that this method integrates water content over a larger vertical scale. The lysimeter values varied more from year to year, which could potentially be caused by the dynamic effects of soil cracking.

The 2011 results from the water balance methods in combination with soil core data were used to create and calibrate both a homogeneous and heterogeneous numerical model for each instrumentation site. In general, the heterogeneous model was able to best replicate the timing and quantity of DP when calibrated to the UZWB. In order to use a single layer model, it was determined that unreasonable hydraulic parameters would have to be used. The model was then validated using the results from 2012. Small changes in normalized MAE values suggest that the model could reasonably predict the DP for the following year by just changing the water input boundary conditions.

Overall, this study has provided information on method performance for calculating DP beneath furrow irrigated agriculture. These results will provide evidence for the reliability of DP estimations provided to the State of Colorado in relation to water leasing applications. This study has also shown that as long as heterogeneity is taken into account, a calibrated numerical model can be used to help predict the potential outcomes of future irrigation schemes in a much less time and labor intensive manner.

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CHAPTER THREE

3.1 PREDICTIVE MODELING

After all models were verified with the second season of field data, predictive runs were conducted to test the effects of proposed management schemes for the 2013 field season. The issue of uncertainty in furrow water advance has led to the development of a new irrigation scheme that involves irrigating the field in two separate halves (Figure 3.1).

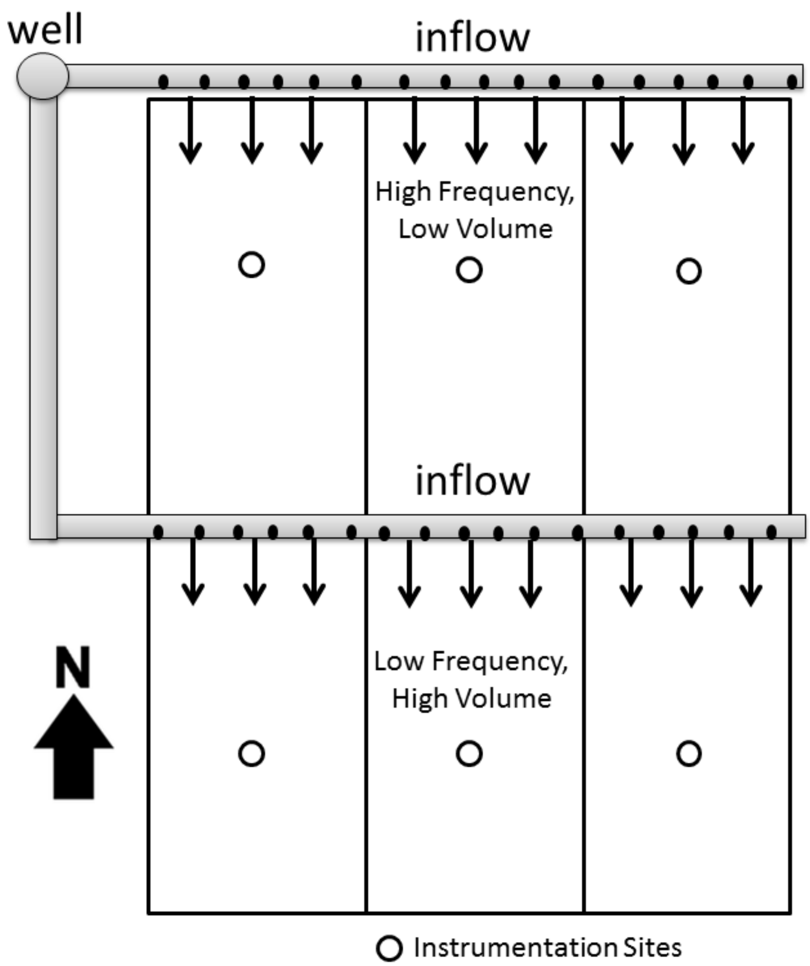

Figure 3.1: Irrigation Design for proposed 2013 irrigation treatments

By dividing the field into smaller sections, this will decrease the distance and time the water must spend traveling down the furrow, therefore reducing the uncertainty in quantity and timing of water applied. The proposed scheme involves using the same irrigation styles, but applying the high frequency, low volume treatment (#3) to the north end of the field and the low frequency, high volume treatment (#2) to the south.

In order to test the effects of these changes, water input boundary conditions from the north end of the field from 2012 were used as guidelines. The layered models, which were shown to produce the best fit for 2012, were used for these applications. A base case scenario was run for each site, in which the fully irrigated boundary conditions were applied to all six sites. This model run provides a deep percolation (DP) value that is able to represent “historical” conditions. A second model run was then conducted using the boundary conditions which would be representative of the proposed scheme. This meant applying time variable boundary conditions similar to those from site 2-1 in 2012, to all three sites in the north and those similar to site 1-1 to all sites in the south. To obtain base case values, the water application boundary conditions similar to site 3-1 were run for all six sites. The proposed irrigation plan is shown in table 3.1. As seen below, the proposed conservative irrigation schemes will reduce the total number of irrigation hours by approximately 40%, with the intended goal of reducing consumptive use.

Table 3.1: Irrigation Plan for Predictive Model

Management Scheme	Number of Irrigations	Duration of Irrigation Event
Base Case (Fully Irrigated)	10	7 hours
High Frequency, Low Volume (Deficit)	7	7 hours
Low Frequency, High Volume (Deficit)	3	14 hours

Table 3.2: Deep Percolation (DP) results for the Predictive Model

Proposed Management Scheme	Site	Base Case (cm)	Proposed Scheme (cm)	Percent Change in DP
High Frequency, Low Volume	1-1	45.8	35	-24%
	2-1	16.67	7.5	-55%
	3-1	32.5	23.42	-28%
Low Frequency, High Volume	1-3	29.58	15.16	-49%
	2-3	43.5	22.9	-47%
	3-3	21.5	7.67	-64%

The results of these predictive model runs are shown in table 3.2. The comparison of the base case scenario with the proposed management scheme shows that both of the treatments will reduce the total amount of DP that will occur throughout the season. In the north end, where the high frequency treatment would be applied, DP would decrease by an average of 36%. An even greater effect would be seen in the south end, where seasonal DP would be reduced by an average of 53%. When averaged together, the field total change in DP between the base case and the proposed scheme is a 41% decrease (a total of 78 cm). These results show that decrease in applied water is directly correlated with the decrease in deep percolation. Although the treatments did follow the same trend, there is a slight variation in the degree of response. For treatment #3 (high frequency), there was a 30% reduction in irrigated hours with respect to the base case, and a 35% reduction in DP. For treatment #2 (low frequency), there was a 40% reduction in irrigations and a 53% reduction in DP.

These results are an example of one way that this study can be used for future management decisions. It will enable water managers to make more informed decisions when planning future projects and help identify the need and potential scale of additional projects necessary to meet the requirements of Colorado water law (e.g. recharge ponds.).

3.2 RECOMMENDATIONS

This study as a whole has shown that deep percolation beneath furrow-irrigated agriculture can be estimated using a variety of methods. Although this study has produced acceptable evidence to support its results, there are still a number of uncertainties that warrant further investigation. Some approaches to further investigate these uncertainties could include:

- The use of a larger scale, integrated water balance method, such as the Water Table Fluctuation Method. This method would provide an additional subsurface based calculation of DP that would take into account a larger area and more heterogeneity. In order to execute this method at the current field site, an offsite monitoring well would need to be installed. This additional piezometer would need to be in a location where water table levels are not directly affected by nearby pumping wells, so that it could provide a representation of regional water table levels.
- Improve instrumentation set up so that reliable, automated water content data could be more easily and frequently collected during irrigation events. Current sensors in the field could potentially be removed, tested and reinstalled for these purposes.
- Development of a user friendly inverse process for determining soil properties for future investigations. Specific sites within a field, and one reliable method should be chosen as a guideline for repeating this at other sites in the future.
- Addition of a dual-porosity scenario into the numerical model. Further in-situ soil analysis could be conducted in order to more accurately constrain the aperture and extent of the cracks in the soils.

APPENDIX

Table A.1: Water Content Data used for Site 1-1 in 2011 in the Unsaturated Zone Water Balance

Site 1-1 2011												
depth (cm)	*18-Apr*	*24-Jul*	*30-Jul*	*5-Aug*	*9-Aug*	*13-Aug*	*19-Aug*	*22-Aug*	*26-Aug*	*27-Aug*	*8-Sep*	*16-Sep*
93.98	0.02	0.07	0.07	0.06	0.03	0.07	0.06	0.06	0.06	0.06	0.05	0.06
121.92	0.05	0.11	0.11	0.10	0.06	0.08	0.08	0.08	0.07	0.07	0.07	0.08
152.4	0.18	0.20	0.20	0.19	0.18	0.23	0.22	0.22	0.21	0.22	0.21	0.22
171.11	0.18	0.20	0.20	0.19	0.19	0.20	0.19	0.19	0.18	0.19	0.18	0.19
183.98	0.19	0.22	0.21	0.21	0.21	0.22	0.21	0.21	0.20	0.21	0.20	0.21
203.65	0.19	0.24	0.23	0.23	0.22	0.23	0.23	0.23	0.22	0.23	0.22	0.22
233.65	0.21	0.21	0.21	0.22	0.20	0.21	0.21	0.21	0.21	0.21	0.20	0.21
263.65	0.20	0.22	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.20
293.65	0.17	0.19	0.18	0.18	0.19	0.19	0.18	0.19	0.18	0.18	0.17	0.18
323.65	0.12	0.16	0.15	0.16	0.15	0.15	0.16	0.15	0.16	0.15	0.15	0.15
353.65	0.11	0.15	0.14	0.14	0.14	0.14	0.14	0.15	0.14	0.15	0.14	0.14
383.65	0.09	0.14	0.13	0.14	0.14	0.14	0.13	0.13	0.12	0.13	0.13	0.13
413.65	0.14	0.19	0.18	0.20	0.19	0.18	0.18	0.18	0.18	0.17	0.17	0.17
443.65	0.13	0.17	0.17	0.23	0.22	0.20	0.18	0.18	0.17	0.17	0.17	0.17
S (cm)	49.91	62.14	59.96	61.64	58.54	61.08	59.32	59.36	58.49	58.91	57.05	58.95
ΔS (cm)	12.23		1.68		2.54		0.04		0.42		1.89	

Table A.2: Water Content Data used for Site 2-1 in 2011 in the Unsaturated Zone Water Balance

Site 2-1 2011												
Depth (cm)	*6-Jun*	*4-Jul*	*10-Jul*	*17-Jul*	*30-Jul*	*5-Aug*	*9-Aug*	*12-Aug*	*22-Aug*	*27-Aug*	*7-Sep*	*13-Sep*
91.44	0.11	0.09	0.08	0.09	0.07	0.07	0.04	0.12	0.09	0.09	0.09	0.09
123.98	0.08	0.13	0.11	0.13	0.12	0.10	0.11	0.11	0.10	0.10	0.09	0.11
152.4	0.07	0.13	0.10	0.12	0.11	0.10	0.09	0.12	0.10	0.12	0.10	0.11
171.11	0.07	0.13	0.09	0.12	0.10	0.10	0.09	0.11	0.09	0.10	0.08	0.10
191.11	0.11	0.21	0.17	0.21	0.19	0.19	0.18	0.21	0.17	0.18	0.16	0.18
203.65	0.15	0.25	0.21	0.24	0.21	0.22	0.20	0.23	0.19	0.19	0.18	0.19
233.65	0.21	0.24	0.23	0.24	0.24	0.24	0.24	0.25	0.23	0.24	0.24	0.24
263.65	0.22	0.25	0.24	0.26	0.25	0.25	0.25	0.25	0.24	0.25	0.25	0.25
293.65	0.19	0.22	0.22	0.23	0.21	0.22	0.22	0.22	0.22	0.22	0.21	0.21
323.65	0.20	0.24	0.22	0.23	0.23	0.22	0.22	0.23	0.22	0.22	0.22	0.22
353.65	0.18	0.23	0.22	0.23	0.21	0.22	0.22	0.22	0.21	0.22	0.21	0.21
383.65	0.16	0.22	0.21	0.22	0.21	0.21	0.21	0.21	0.21	0.21	0.20	0.20
413.65	0.15	0.18	0.17	0.18	0.16	0.17	0.16	0.16	0.16	0.16	0.16	0.16
443.65	0.14	0.15	0.17	0.17	0.16	0.19	0.18	0.18	0.16	0.15	0.16	0.16
473.65	0.12	0.11	0.14	0.15	0.16	0.23	0.23	0.20	0.14	0.14	0.14	0.14
S (cm)	57.19	73.36	68.73	74.06	69.32	71.14	69.67	73.21	67.31	68.83	66.17	68.00
ΔS (cm)		16.18		5.33	1.81		3.54		1.52		1.83	

Table A.3: Water Content Data used for Site 3-1 in 2011 in the Unsaturated Zone Water Balance

Site 3-1 2011				
dates	*4-Jul*	*24-Jul*	*26-Aug*	*2-Sep*
91.44	0.066666	0.092216	0.073871	0.17533
121.92	0.118256	0.148055	0.099234	0.200129
152.4	0.068751	0.109915	0.062963	0.183122
171.11	0.063463	0.107023	0.063673	0.187907
191.11	0.073201	0.142378	0.09804	0.217848
203.65	0.07807	0.152803	0.10372	0.226473
233.65	0.098158	0.196673	0.120758	0.252347
263.65	0.175543	0.245724	0.196172	0.273138
293.65	0.194019	0.23355	0.211725	0.300492
323.65	0.198436	0.246889	0.213339	0.249696
353.65	0.189182	0.248378	0.214275	0.246236
383.65	0.21817	0.255793	0.2317	0.264052
413.65	0.177897	0.219758	0.200463	0.225511
443.65	0.174931	0.234683	0.194623	0.236666
473.65	0.150361	0.19363	0.169614	0.173325
503.65	0.181315	0.24595	0.200496	0.197801
S (cm)	60.41188	82.20104	66.32017	94.88512
ΔS (cm)	21.78915959		28.56494286	

TableA.4: Water Content Data used for Site 1-1 in 2012 in the Unsaturated Zone Water Balance

Site 1-1 2012						
depth	*07-01*	*07-08*	*07-30*	*08-02*	*08-10*	*08-14*
152.4	0.21	0.24	0.21	0.26	0.22	0.23
191.11	0.22	0.24	0.23	0.24	0.24	0.24
261.11	0.20	0.22	0.21	0.21	0.21	0.21
321.11	0.15	0.17	0.15	0.15	0.16	0.16
381.11	0.12	0.13	0.13	0.13	0.15	0.15
441.11	0.17	0.16	0.17	0.17	0.18	0.17
501.11	0.12	0.13	0.15	0.13	0.16	0.15
S (cm)	59.07	63.30	61.77	62.99	65.67	64.28
ΔS (cm)	4.23		1.21		0	

Table A.5: Water Content Data used for Site 2-1 in 2012 in the Unsaturated Zone Water Balance

Site 2-1 2012								
Dates	*05-27*	*06-17*	*06-21*	*06-27*	*07-25*	*07-30*	*08-14*	*08-17*
152.4	0.08	0.10	0.09	0.12	0.09	0.21	0.08	0.08
191.11	0.14	0.14	0.13	0.14	0.15	0.21	0.14	0.14
261.11	0.24	0.23	0.24	0.24	0.24	0.21	0.23	0.24
321.11	0.20	0.20	0.20	0.20	0.21	0.21	0.20	0.21
381.11	0.18	0.18	0.18	0.18	0.18	0.21	0.18	0.18
441.11	0.13	0.12	0.13	0.13	0.13	0.21	0.13	0.13
501.11	0.15	0.16	0.15	0.15	0.15	0.21	0.15	0.15
S (cm)	59.24	59.66	59.84	61.21	60.93	72.39	59.37	60.43
ΔS (cm)	0.42		1.37		11.46		1.06	

Table A.6: Water Content Data used for Site 3-1 in 2012 in the Unsaturated Zone Water Balance

Site 3-1																
depth (cm)	*05-27*	*06-10*	*06-21*	*06-24*	*06-27*	*07-08*	*07-13*	*07-17*	*07-22*	*07-25*	*08-02*	*08-03*	*08-10*	*08-17*	*09-04*	*09-06*
152.4	0.06	0.09	0.08	0.10	0.09	0.10	0.08	0.12	0.09	0.12	0.08	0.11	0.08	0.09	0.08	0.10
191.11	0.09	0.13	0.11	0.12	0.12	0.12	0.12	0.12	0.12	0.14	0.11	0.14	0.12	0.12	0.11	0.11
261.11	0.19	0.21	0.20	0.21	0.20	0.21	0.21	0.21	0.20	0.21	0.21	0.20	0.20	0.20	0.19	0.19
321.11	0.21	0.20	0.21	0.22	0.21	0.22	0.22	0.22	0.22	0.23	0.23	0.22	0.23	0.22	0.23	0.23
381.11	0.23	0.24	0.24	0.24	0.24	0.23	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24
441.11	0.18	0.18	0.18	0.19	0.18	0.19	0.19	0.19	0.19	0.19	0.19	0.18	0.19	0.19	0.19	0.19
501.11	0.19	0.19	0.19	0.19	0.18	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.20	0.19	0.19	0.19
S (cm)	60.42	65.51	64.33	66.29	65.42	65.84	65.47	66.88	66.21	68.95	66.04	67.25	65.88	66.20	65.57	64.42
ΔS (cm)	5.09		1.96		0.41		1.40		2.74		1.20		0.32		0	

Table A.7: 2012 Lysimeter Collection Volumes

2012 Lysimeter Volumes (mm)						
	Site Number					
Date	***1-1***	***1-3***	***2-1***	***2-3***	***3-1***	***3-3***
11-Apr	0.771726	0.290251	0.187637	2.509817	2.427022	4.729384
22-May	19.6846	3.261055	0	2.424449	2.516497	2.47567
27-May	35.00727	17.44921	0	1.929315	0	0
3-Jun	29.6723	23.22008	0	2.100051	0.894755	1.861021
10-Jun	7.191589	21.28223	0	1.963463	44.92786	70.29196
13-Jun	2.516497	0.990268	0.625458	27.82995	30.51113	14.29913
21-Jun	1.543452	2.117125	0	37.63872	23.16296	5.975756
26-Jun	16.10558	0.717091	3.252379	46.38894	2.203333	39.20096
30-Jun	0	0	2.50183	27.28359	5.883011	31.9959
3-Jul	1.409238	1.99761	1.438552	5.053782	4.484957	0
12-Jul	34.73325	24.84207	0.375275	5.446474	20.88693	54.85744
18-Jul	2.393468	2.526891	0.625458	12.90763	11.40812	41.18149
22-Jul	29.32558	25.43964	0	3.653748	13.5779	14.81987
30-Jul	7.504753	13.65887	na	na	na	na
3-Aug	34.29147	33.63497	na	2.697627	2.494128	3.6196
5-Aug	28.56504	25.32867	3.181077	20.69319	28.17358	20.69319
9-Aug	21.89912	15.07598	3.560104	30.96295	10.81535	20.04439
14-Aug	5.200761	6.778214	1.883878	10.51733	6.363941	37.06676
16-Aug	0	27.31774	0.005004	13.65887	11.31864	10.24415
27-Aug	1.118443	3.14154	0.381529	40.49855	20.27737	29.69097
30-Aug	0	0	0.187637	8.741677	4.675092	1.621991
6-Sep	0	0	0.062546	3.457401	2.326362	18.14922
10-Sep	0	0	0	0	3.48395	4.404985
30-Sep	0	2.441523	0.093819	2.66348	4.731014	4.831825

Table A.8: 2013 Lysimeter Collection Volumes

2011 Lysimeter Volumes (mm)						
Site Number						
DATE	***1-1***	***1-3***	***2-1***	***2-3***	***3-1***	***3-3***
21-Apr	0.000	0.236	0.030	0.113	0.220	0.075
23-Apr	0.066	0.118	0.013	0.065	0.240	0.024
26-Apr	0.079	0.174	0.003	0.155	0.218	0.044
30-Apr	0.086	0.174	0.010	0.162	0.237	0.050
6-May	0.070	0.106	0.008	0.089	0.161	0.024
14-May	0.094	0.271	0.031	0.230	0.227	0.094
16-May	0.050	0.096	0.009	0.055	0.113	0.022
21-May	0.092	0.224	0.000	0.125	0.171	0.063
25-May	0.076	0.172	0.020	0.080	0.115	0.058
28-May	0.089	0.142	0.093	0.058	0.084	0.048
30-May	0.081	0.109	0.034	0.041	0.060	0.036
1-Jun	0.059	0.094	0.013	0.032	0.044	0.034
5-Jun	0.051	0.157	0.091	0.060	0.086	0.061
7-Jun	0.031	0.108	0.026	0.032	0.051	0.031
9-Jun	0.038	0.109	0.022	0.034	0.041	0.034
12-Jun	0.056	0.159	0.011	0.051	0.070	0.050
17-Jun	0.078	0.218	0.089	0.068	0.061	0.093
20-Jun	0.054	0.159	0.027	0.044	0.092	0.080
22-Jun	0.040	0.100	0.015	0.022	0.034	0.031
24-Jun	0.035	0.094	0.013	0.029	0.034	0.033
26-Jun	0.003	0.067	0.016	0.032	0.038	0.036
30-Jun	0.035	0.109	0.089	0.058	0.000	0.000
1-Jul	0.000	0.000	5.964	0.017	0.083	0.075
2-Jul	0.040	0.099	2.626	0.015	0.000	0.000
3-Jul	0.200	0.063	1.879	0.017	0.038	0.034
6-Jul	1.073	0.137	0.983	0.041	0.045	0.044
9-Jul	0.072	0.145	0.310	0.044	0.047	0.046
11-Jul	0.049	0.102	0.214	0.031	0.032	0.032
14-Jul	0.065	0.138	3.450	4.333	0.048	0.048
16-Jul	0.665	0.111	2.006	2.139	0.032	0.032
17-Jul	0.019	0.043	0.367	0.319	0.011	0.014
19-Jul	0.050	0.109	0.464	0.411	0.028	0.031
23-Jul	0.081	0.181	0.424	0.253	7.086	6.050
24-Jul	0.039	0.058	0.375	0.289	1.210	0.823
25-Jul	0.053	0.050	0.040	0.079	0.547	0.171
28-Jul	0.123	0.147	0.661	4.005	0.122	0.077
29-Jul	0.034	0.065	0.753	1.577	0.729	0.369

3-Aug	0.081	0.196	0.564	0.736	0.410	0.191
7-Aug	0.002	0.178	0.420	0.277	0.314	0.172
8-Aug	0.028	0.050	0.039	0.077	0.000	0.000
10-Aug	0.046	0.096	1.752	4.224	0.177	0.059
11-Aug	0.025	0.049	0.939	1.809	0.081	0.024
14-Aug	0.064	0.130	0.756	0.936	0.198	0.126
16-Aug	0.042	0.090	0.329	0.405	0.134	0.042
18-Aug	0.046	0.089	0.073	0.140	0.119	0.027
20-Aug	0.046	0.096	0.356	0.225	0.103	0.042
21-Aug	0.023	0.038	0.037	0.061	0.036	0.012
24-Aug	0.374	0.137	0.087	4.218	0.138	0.060
26-Aug	0.037	0.073	0.067	1.728	0.075	0.019
29-Aug	0.057	0.113	0.277	0.591	0.129	0.040
1-Sep	0.055	0.104	0.079	0.219	4.646	4.927
3-Sep	0.000	0.000	0.000	0.000	4.036	1.764
4-Sep	0.056	0.097	0.311	0.186	2.798	0.364
7-Sep	0.050	0.090	0.304	3.987	1.789	0.224
9-Sep	0.033	0.015	0.069	1.504	0.441	0.213
12-Sep	0.049	0.043	0.084	0.535	0.394	0.142
15-Sep	0.046	0.077	0.082	0.241	0.162	0.058
19-Sep	0.054	0.060	0.084	0.219	0.195	0.084
24-Sep	0.058	0.087	0.083	0.246	0.321	0.136
28-Sep	0.049	0.063	0.084	0.215	0.225	0.097
4-Oct	0.040	0.079	0.082	0.236	0.246	0.067
23-Oct	0.086	0.133	0.087	0.256	0.258	0.191
8-Nov	0.081	0.073	0.081	0.265	0.262	0.164