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MODLEING THE FIELD WATER BALANCE ON IRRIGATED
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MODELING THE FIELD WATER BALANCE ON IRRIGATED CROP FIELDS USING ROOT ZONE WATER QUALITY MODEL

By

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ABSTRACT

MODELING THE FIELD WATER BALANCE ON IRRIGATED CROP FIELDS USING ROOT ZONE WATER QUALITY MODEL

By

Michael I. Gangwer

Managing the amount and timing of irrigation water and liquid manure applications on crop fields is a major requirement for optimizing crop yield and reducing the potential for soil and water resource degradation.

This study had two objectives. One, develop parameters for evaluating the performance of a comprehensive water budgeting model, and two, evaluate the performance of the model by comparing empirically derived field water balance (FWB) with model simulations.

Ten fields on four dairy farms in the Willamette Valley were instrumented with a soil moisture sensor, Irrometer Watermark. These sensors measure electrical resistance, thereby using conductivity as a measure of moisture content. Local rainfall amounts were obtained by installing a weather station on each of the four farms. Other climate data was obtained from AgriMet and National Weather Service weather stations.

Bulk soils from these ten fields were evaluated for particle size analysis and moist bulk density. Soil cores were analyzed for paired matric potential and volumetric water content. The paired data yielded the soil water characterization curve (SWCC).

The Root Zone Water Quality Model (RZWQM) was parameterized with three data sets. One, data obtained from NASIS (soil data mart) based upon the soil map unit

for that field. Two, a mix of RZWQM data, field, and laboratory data. And three, complete data sets for each field based upon the SWCC, and related field data.

The model simulations were evaluated using four statistical measurements, including Root Mean Square Error, Mean Error, and the Nash Sutcliffe Equation. Results show that using strictly NASIS data result in poor model performance. This is likely related to alluvial soils deposited from recent flood events.

Results were largely mixed comparing a combination of default, field, and laboratory data with the complete field and data set. This study suggests that the large investment deriving the SWCC in the laboratory did not improve model performance.

The model performed reasonably well with field determinations of particle size analysis, including sand, silt, and clay content. Once the clay content was known, the model assigned default values for volumetric water content at saturation and field capacity. Model performance could have been improved if saturated hydraulic conductivity was measured using some field technique. RZWQM does not have a robust crop growth component; FWB simulations could have been improved by knowing evapotranspiration (ET) from the crop based on growth.

Obtaining bulk soil from a field, then determining particle size analysis, coupled with field measurements of moist bulk density, volumetric water content at saturation and FC, saturated hydraulic conductivity and accurate ET for the growing crop could be used with RZWQM for the determination of the Field Water Balance over one or more years.

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Chapter One. Introduction

1.1 History

In what was to become a nine year odyssey, this research paper helps complete a journey begun in June 1996. During the summer of that year representatives from Oregon State University Extension Service (OSUE), Oregon Department of Agriculture (ODA), Oregon Department of Environmental Quality (DEQ), and several livestock commodity groups met and talked about research needs for the dairy industry in the Willamette Valley Oregon.

The charge was given to this researcher: develop a tool that would help landowners estimate the field water balance, utilize water for crop growth that would improve irrigation water management, and reduce the potential for surface runoff of manure into surface water. A working hypothesis was developed.

1.2 Hypothesis

Evaluating Root Zone Water Quality Model (RZWQM) using field, laboratory, and default input values, can lead to predicting the Field Water Balance for a crop field receiving irrigation water and liquid manure. Model output can provide technicians a new tool for estimating those periods during the year that may require greater attention to irrigation water management, therefore improving water utilization on fields, and reduce the potential for surface runoff, which meet recommended guidelines and enhance environmental management of the water resource.

1.3 Rationale for Objectives

The rationale for using a model was based upon limited resources (costs of field instrumentation, labor, and monitoring). The funding for this project, a DEQ 319 Grant (USEPA Region 10, Seattle, WA, and Oregon DEQ, Salem, OR) was sufficient for the installation of four weather stations and instrumenting ten fields with soil matric sensors. The farms and specific fields were carefully identified. Four relatively stable dairy farms were selected, and then on each farm specific fields were identified for instrumenting. Campbell Scientific instruments were used for the WS package. The Irrometer Watermark was selected for the matric potential measurements. The Watermark is a granular matrix resistance block that mimics the volumetric water content in the soil. A voltage is expressed across the block. The current flow results in a voltage drop, and the resistance is measured. The resistance is a measure of moisture content. The drier the block, the greater the resistance. After some period of data collection a FWB was determined at four incremental 30 cm depths to 1.2 m. The FWB or volumetric water content over time was the empirical data set used for this study.

The question for modeling was: what are the data input requirements for evaluating the modeled FWB with the empirical data obtained in the ten instrumented fields? Two objectives were proposed so that question could be answered:

1. Develop parameters for evaluating RZWQM, including three approaches:
    a. USDA National Soil Information System (NASIS) data, based upon selected Soil Map Unit identification for each field based on the Soil Survey.
    b. Particle size analysis, bulk density, and RZWQM default values.

c. Determination of the Soil Water Characterization Curve (SWCC) using full data input of paired volumetric water content and matric potential values, in addition to particle size analysis and bulk density (complete soil hydraulic and physical data).

2. Evaluate empirical FWB with Model FWB simulations using three methods of model parameterization in objective one.

   a. Empirical data are coupled data of field matric potential (Watermark) and lab derived SWCC.

   b. Model data are combinations of NASIS, RZWQM default, and complete soil hydraulic and physical data

In terms of developing the parameters for evaluating the model, the NASIS data is readily available on the internet for public use. A user could identify a field location, select the predominant soil map unit, and then use NASIS data for input soil hydraulic and physical values in RZWQM. One advantage is no field work is required.

The second approach was using a combination of model default values and some field measurements. The field measurements included particle size analysis (textural class), moist bulk density, and volumetric water content at saturation, each at 30 cm incremental depths. RZWQM default values included all other required hydraulic and physical data to run the model simulations.

The third approach required full parameterization. The user overrides all default values for hydraulic and physical properties with either field or laboratory data. In this study the SWCC was derived for each 30 cm depths (four per field) to 1.2 m. The model required volumetric water content at saturation, at 0.01 MPa, at 0.033 MPa (Field

Capacity), and 1.5 MPa (Permanent Wilting Point). The model requires horizon depth by textural class with defined sand, silt, and clay content by percentage.

Saturated hydraulic conductivity was not measured in this study. The NASIS data mean values were used for first approach; for the second and third approach the saturated hydraulic values that gave no runoff were used. Landowners do not purposely apply an amount of irrigation water or waste water that will cause a runoff event.

Once the model parameters were obtained or measured, the field simulations were conducted using RZWQM. The model output as volumetric water content over the study period were compared with the Watermark field data for the purpose of evaluating the three approaches at determining the FWB in the instrumented field.

Four statistical analyses were used for evaluating model performance. The goodness to fit analysis Root Mean Square Error and the model efficiency measure known as the Nash Sutcliffe Equation were particularly useful in evaluating RZWQM for these irrigated crop fields.

The basic research structure with chronological timeline is presented below. This list provides the reader with a list of field, laboratory, and modeling activities that are presented in this paper.

1.4 Research Structure

1. Select experimental study period: October 1997 – September 2002.
2. Identify four dairy farms in the Willamette Valley study area.

3. Instrument each field with Watermark soil moisture sensors at 30 cm depths to 1.2 m. Hard wire to data logger. Include weather instrumentation for a portion of the study period.
4. Record spatial and temporal water input volumes (manure and irrigation) on ten fields found on the four dairy farms (as supplied by the landowners). Evaluate delivery equipment in terms of volume flow per unit time.
5. Measure physical soil characteristics of typical soils in the study area. These include particle size distribution, bulk density, and SWCC at 30 cm depths to 1.2 m.
6. Obtain climate data for the study area. Use AgriMet, National Weather Station, and local weather data from instrumentation on each farm.
7. Parameterize RZWQM with climate, field, and management data based on the time period the farm had an operable weather station.
8. Determine FWB for all fields. [Completes Objective One.]
9. Evaluate RZWQM performance based on three methods of parameterization (Lab only, Lab and RZWQM combination, and USDA-NASIS data only). Rank scenarios using rainfall distribution as sensitivity analysis, then suggest input parameters required for model use in other non instruments fields. [Completes Objective Two.]

Finally, a discussion of why this research is necessary is presented below.

1.5 Research Benefit

This paper takes a step towards providing a list of input data for determining the FWB on irrigated crop fields using a model. One further step will help landowners implement irrigation water management practices during the growing season, and utilize liquid manure during all periods of the year, based on knowledge of the FWB over a time period. These improve water utilization and reduce the potential of groundwater and surface water pollution to acceptable levels. The work fills a part of the research gap by providing a model or tool for use in determining the volumetric water content over a period of time without instrumenting a specific field or farm. Further, this work offers a new approach at combining fragmentary data into a systems analysis in meeting the research objectives. The effort is based on systems thinking across the SPAC, including water, bridging the disciplines of soil physics, water flow, climate and environmental phenomenon, plant physiology, and a comprehensive deterministic research model. The key is the selection of RZWQM as the model of choice for this systems approach, and identifying which input parameters are required for model calibration on non-instrumented fields.

Chapter Two. Literature Review

2.1 Introduction

On Earth, life is dependent upon water. Democritus wrote in 400 B.C. that "plant growth involved the cycling of nutrients through water" (Tindall and Kunkel, 1999). Later, in the 16th Century Sir Francis Bacon believed that water was the source of nourishment for plants (Daumus, 1958). Jan Baptiste van Helmont confirmed Bacon's work in his famous experiment, which he concluded water was the sole nutrient for plant growth (Tindall and Kunkel, 1999). In the early 17th Century Robert Boyle stated that plant growth was a function of salts and other materials found in water (Tindall and Kunkel, 1999). Further work by Buckingham of England, Green and Ampt of Australia, Widstoe of Utah, Gardner, Martin, Bouyoucus, Richards, Kirkham, Keen, Penman, Bresler, and Hillel all made huge contributions to the understanding of water in soils (Tindall and Kunkel, 1999). Today, advances in plant physiology have linked water in the soil to water flow through plants. In photosynthesis, water is oxidized providing a source of electrons and protons. These drive carboxylation of CO_2 and ultimately organic carbon is made into plant tissue. Plants are cooled by water evaporation. The transpiration ratio of water used versus dry mass retained in plants is 500 to 1,500 (Mengel and Kirkby, 2001). Water carries solutes from the root zone into the plant, thereby transporting plant essential elements from soil to growing plant tissue.

Soil water is essential for plant growth. The evaporative process for cooling and nutrient uptake for growth occurs only when soil water is sufficiently moving into root tissue as a function of hydraulic suction, or negative pressure. In the plant rooting zone soil moisture moves by the inputs of rain, irrigation, or capillarity, and the outputs of evaporation, transpiration by plants, and the movement of soil water by gravimetric potential, or deep leaching. The status of soil water at any point in time is the Field Water Balance, FWB; it is dynamic both spatially and temporally.

For most of the Earth's surface, the FWB is largely weather driven. The land use will alter the FWB. Forests can consume large volumes of water given deep rooting zones of several meters. Perennial grasslands will consume water in a shallower rooting zone (no greater than one meter), thus timely rainfall is required to maintain the FWB. On the farm scale, crops are selected by climate zones and distribution of water throughout the growing season. In rainfed agronomic systems, crop yield is a function of timely rainfall, thereby maintaining the FWB.

2.2 Irrigation

Farmers can irrigate soils with supplemental water. This practice likely began when groups of people, or communities, settled in places where rain did not supply water to growing crops. Surface waters were diverted using hand-dug canals. Some form of energy was used to draw water from hand-dug wells, thus soil water at depths beyond any root zone were obtained.

With the development of machines and the movement of people to the Western United States, entire societies were located in places where rain rarely fell. The damming of rivers, the construction of canals and pumping stations and reservoirs supplied water to the desert. The FWB was maintained by diverted water, not rain. Irrigation turned barren land into productive farms.

Productive farms are usually profitable farms. As the need to produce food for humans and feed for livestock increases, the diversion of water to desert soils helps meet this need. Yet an important question looms: is irrigation sustainable?

At the farm level, the landowner attempts to optimize yield, derive profit, and do so efficiently. Some understanding of the FWB provides greater irrigation efficiency: the timing, the location, and the amount of water applied to a crop field are important decisions. For livestock farmers with animals in confinement, liquid manure may be irrigated on the field. For this practice, special care is given to avoiding applications when the FWB is sufficiently saturated. Irrigating water on soils at or greater than field capacity move liquid manure out of the rooting zone before sufficient treatment can take place. Surface runoff or deep leaching can occur. The livestock owner with a liquid manure system, therefore, uses two criteria, which guide irrigation decisions: timing and depth of application.

2.3 The History of irrigation in the Western United States

In a book dedicated to writing the reclamation history of the West, historian Michael Robinson (1979) describes the development of irrigation on arid lands. The manifestation of "agrarian ideals" by Thomas Jefferson set the stage for Federal Laws, construction, and settlement of a new society. One of the first to do so was the Mormons. They settled the Salt Lake Valley in 1847, digging irrigation canals by hand, and turning the "Great American Desert" (Thomas, 1948) into productive fields sustaining an entire farming community. The great trek West, including the Oregon and Californian Trails during the 1880's was brought about in part by the Mormon effort to reclaim the desert.

During this period of time, the reclamation effort was born. Congress sought to encourage pioneers settlement in the West; the Carey Act of 1894 granted one million acres to ten states if these lands were developed for agricultural irrigation.

The individual Western States, however, lacked the resources to fully develop the scope of irrigation projects. State's boundaries and water flow were different. The Federal Government, led by President Teddy Roosevelt's natural resources interest, passed the Federal Reclamation Act in 1902 (Gates, 1968). During the late 19th Century, an engineer, pioneer, and explorer, John Wesley Powell, trekked over much the West. He mapped, made inventory, and conducted crude water flow measurements. He did not like what he saw.

Powell's report to Congress in 1878, titled "The Lands of the Arid Regions of the United States (Smythe, 1911), advocated using science and a thorough inventory to utilize water and land while avoiding overuse, non sustainable farming practices, and monopolistic control. In what was to become known as a development plan for the West, Powell suggested three components: a topographical map, measuring the annual volume of water for each catchment or drainage areas, and conduct soil surveys (Robinson, 1979). Congress, however, largely ignored his foresight. His request for funding was almost completely denied.

During the first years of the 20th Century, three men joined in an effort to build support for Federal Reclamation in the West (Hodge, 1963). Frederick Newell, an engineer and first head of the Reclamation Service, Francis Newland, a Congressman from Nevada, and George Maxwell, a California Lawyer and founder of The National Irrigation Congress in 1987 pushed through Congress a bill which funded the first six reclamation projects in the West (Hollen, 1966). The second appropriations act supplied the funds for another 25 projects, largely the formation of reservoirs by building Federal Dams. The first, Roosevelt Dam (appropriately named after Teddy Roosevelt and his Reclamation Service bill in 1902), was built on the Salt River in Arizona (Robinson, 1979).

The rapid increase of people settling in the West spurred Congress to provide significant dollars towards reclaiming the West (Smith, 1950). Stegner (1954) coined the term "Beyond the Hundredth Meridian," as he described the efforts of the Federal Reclamation Service to "tame" the Western Rivers and develop irrigation infrastructure. He claimed the rationale was driven by an "engineering ethos" which simply stated that humans can conquer Nature if given enough resources, time, and most of all, public will. Engineers made up the upper hierarchy of the Federal Reclamation Service. They sold their philosophy to politicians in the Eastern U.S. in economic terms. The newly constructed dam would provide hydropower to new settlements in arid lands. The new reservoir behind the dam would provide flood control and irrigation water. With power and water, arid land would support agriculture and family farming (Robinson, 1979). The original Reclamation Act of 1902 had important language which sought to avoid monopolistic development of irrigated lands (Smith, 1950). The 160-acre farm or quarter section (one quarter mile by one quarter mile square) was deemed enough irrigated land to support one family unit.

In 1925 the Reclamation Service was renamed a branch service under the Department of Interior, called the Bureau of Reclamation. The second, third and fourth decade of the 20^{th} Century were heady days for dam, reservoir, and irrigation construction by the Bureau, including the Elephant Butte Dam in New Mexico (1920), the Hoover Dam on then Colorado River (1935) and the Grand Coulee Dam on the Columbia River (1941). All provided energy and power to rapidly growing settlements of city and farm people (Robinson, 1979).

After WWII, the emphasis of the Bureau changed. In what is largely thought to be a revisit of John Wesley Powell's concern for water management, the Bureau sought to place greater emphasis upon flood control, recreation, fish management, and improved irrigation efficiency (Coddington, et al., 1972). Some of the last dams built by the Bureau were on the Columbia River System. As a youngster in the late 1950's my father would take our family to a Columbia River bluff overlooking the construction site of the McNary Dam. We watched workers manage huge buckets of concrete, lay thousands of rebar rods, and install magnetic turbines in the bowels of this construction site. Fish ladders and ship locks were built too, and in the later days of the construction, erections of steel towers were set upon the expanse, thereby moving electricity hundreds of miles south across the Eastern Oregon Basin. Soon after hundreds of center pivot irrigation systems turned the flat brown desert into circles of potatoes, onions, corn, and alfalfa hay.

2.4 U.S Bureau of Reclamation today

The Bureau of Reclamation remade itself during the 50's, 60's and 70's but retained its theme, which according to Robinson (1979) is "To Conserve and Manage Water in the Public Interest." The changes, however, during these years up to the present are dramatic. Instead of attempting to tame the Western Rivers, the Bureau attempts to manage them efficiently, using water "more than once" (USBR, 2004). The Bureau attempts to address the complex issues of water use and management in the West, whereas in earlier years supplying water to reclaimed land was its emphasis. Today, the Bureau of Reclamation makes the following verbatim statement on their Website (USBR, 2004):

- Manages, develops, and protects water and related resources in an environmentally and economically sound manner in the interest of the American public.
- Serves as the fifth largest electric utility in the 17 Western States and the nation's largest wholesale water supplier, administering 348 reservoirs with a total storage capacity of 245 million acre-feet (an acre-foot, 325,851 gallons of water, supplies enough water for a family of four for one year).
- Provides 1 out of 5 Western farmers (140,000) with irrigation water for 10 million farmland acres that produce 60% of the nation's vegetables and 25% of its fruits and nuts.
- Operates 58 hydroelectric power plants averaging 42 billion kilowatt-hours annually.
- Delivers 10 trillion gallons of water to more than 31 million people each year.
- Manages in partnership 308 recreation sites visited by 90 million people a year.

The third bullet point, that of providing water for irrigation, is coupled with the water efficiency objective; both were responsible for the Bureau's development of weather stations (WS) scattered throughout 17 Western States. In 1983, the Bureau worked with Bonneville Power Administration (BPA) to develop a satellite based weather station (WS) system for capturing climate and field characteristics (USBR, 2004). The system is known as Agrimet, a word derived from Agriculture and Meteorology. Today there are 74 WS in the Pacific Northwest (PNW) including Washington, Oregon, Idaho, Montana, and parts of California, Nevada, Utah, and Wyoming. The AgriMet Network (USBR, 2004) is supported by a consortium of public and private resources, including the United States Department of Agriculture's Natural Resources Conservation Service (NRCS) and Agriculture Research Service (ARS), Land Grant Universities, the Cooperative Extension Service, and the Northwest Energy Efficiency Alliance (NWEEA).

2.5 USBR AgriMet weather stations

AgriMet WS are equipped with below and above ground instruments. Data is stored in a datalogger, and on five-minute intervals logged telemetry is relayed via satellite to a mainframe computer in Boise Idaho. Complied mainframe data is posted to USBR Website for each WS on the Network. A time delay of approximately four hours exists for field data and complied web posted data. One calculation provided is evapotranspiration, the sum of evaporation from the field surface and transpiration of water through the growing crop. The value is listed as mm or inches of water consumption daily for a reference crop (ET_r) that is well watered and growing. In the more arid locations, alfalfa is used for the reference crop; in the West side of the Cascade Mountain range, in Washington and Oregon, a grass crop is used. The calculation is based upon a Modified Penman Monteith equation (FAO, 1998).

Irrigators may make better irrigation decisions using these data. Specifically, the ET_r is multiplied by a crop coefficient, which provides the irrigator with a volume depth of water consumption on a daily basis. Irrigators can schedule a single irrigation volume depth based on resupplying the crop field with water that is consumed by the crop ET, or ET_c. The FWB is, therefore, maintained using a mass balance approach: input (irrigation) equals output (ET_c).

The USBR's AgriMet Network provides a valuable tool for irrigators where WS's are located. An estimate of water consumption for a particular crop must be known so greater efficiency can be obtained. However, the water consumed by a particular crop is just one component of the FWB.

2.6 Development of the FWB definition

Daniel Hillel, in his twentieth Chapter of Environmental Soil Physics, Water Balance and Energy Balance in the Field (Hillel, 1998), defined the FWB in these words: "The field water balance, like a financial statement of income and expenditures, is an account of all quantities of water added to, subtracted from, and stored within a given volume of soil during a specified amount of time." He used the Law of Conservation of Mass, which states matter (water in this case) cannot be created or destroyed but can only change from one form to another. Hillel went on to explain the FWB in terms of energy balance; that the Conservation of Matter and the Conservation of Energy are integrated since they are involved in the same processes (form change accountability) within the same physical volume (a volume of soil supporting plant growth). The root zone water balance can be expressed as follows (Hillel, 1998):

$S + V = (P + I + U) - (R + D + E + T_c)$

Where

S = change in soil water storage per unit time

V = change in volume or mass of water incorporated into plant biomass per unit time

P = precipitation volume depth per unit time

I = irrigation volume depth per unit time

U = upward capillary flow per unit time

R = runoff volume depth per unit time

D = downward drainage out of the root zone (leaching) per unit time

E = evaporation from the soil surface

T_c = transpiration of water from the crop per unit time

Evett and Lascano (1993) suggested a FWB (S_v, volumetric water) as follows:

$S_v = \Delta S + P + R - F - ET$

Where

ΔS = change in soil water storage

P = precipitation or irrigation volume depth

R = the sum of field runoff and runon

F = flux of water across the lower boundary of the profile

ET = water loss to the atmosphere including evaporation and transpiration

Both equations have commonalities. The S factor, the change in soil water is a volume concept. The difference over a time unit, i.e. 24 hours, is a volumetric change. The volume can be converted to a weight assuming soil water at 1.0 g cm^{-3}. In typical root zone profile, the volumetric water content of the soil is multiplied by the volume depth to yield a depth of water stored (Howell, 1995). For example, at a rooting depth of 60 cm, if the volumetric water content is 25%, or 0.25 cm water/cm soil depth, the depth of water stored is 15 cm. This volume depth constantly changes depending upon the other components of the FWB. Hillel (1998) refers to a change in water content for plants in this rooting depth. Canny (1998) described water transport and water retained over the growing season. He showed that water retention in a plant had several roles, including stem turgor, solute transfer, leaf extension, and cell wall maintenance. The whole plant water content of agronomic plants at the end of their vegetative growth period is at least 80% and can be as high as 95% (Boyer, 1985).

The P component is water added to the soil root zone profile by precipitation or irrigation. This value is measured and expressed as a volume depth, i.e. 7 mm of rain or 15 mm of irrigation water. The value is always zero or positive. The R component is runoff or runoff and runon. The likely case is runoff from fields after a rainfall event of some intensity. Runon can occur too, if surface flow from an adjacent field enters the surface the area of this study field. The U and the F terms are somewhat similar. The movement of water into the root zone from a layer at some depth below the zone occurs due to capillary potential, or from a wet soil into a dry soil, the result of decreasing negative matric potential (Ritchie, et al., 1999; Mandal, et al., 2002; Starks, et al., 2003). This value is negative (water inflow) or positive (water outflow, or deep leaching).

The E component in the first equation refers to the amount of thermal energy, which drives the evaporation of water from the soil. This is an energy term, expressed as some measure of thermal heat, as in MJ m^{-2} day^{-1}, the amount of energy entering the soil surface one m square in one day (Bowers, et al., 1965; Sepaskhah et al., 1979; Peart, et al., 1998. The E term in the second equation is the mass of water leaving the soil root zone, thereby it is positive when water is evaporating from the soil surface and transpiration is occurring.

The components of a FWB can be a derivative of a moment in time, or in integral form, which describes the FWB flux over a time period. For example, a 24 hour period in summer when no rain falls, but thermal input as radiant energy is significant, i.e. 26° C, and a crop is in its vegetative state fully transpiring water from a soil root zone at or near field capacity. In this case the change during the twenty-four hours is negative; the change in water storage is decreased by 7 mm. The FWB can be positive the next day, if 10 mm of rain falls. This rainfall depth is balanced against the amount of water leaving as evaporation and transpiration, and the amount gained in plant tissue. The FWB can be a combination of time steps, for one growing season, for one calendar year, or several calendar years.

2.7 Determining the FWB

2.7a Direct measurement

The FWB can be measured by installing monolithic weighing lysimeters in a field (Wright, 1991; Phene, et al., 1990). Large lysimeters (10 m diameter) can yield good results (Howell, et al., 1995). A lysimeter is described in detail in a review paper by Howell (1991). Work done by Grebet and Cuenka (1991) provided guidance methodology for installing and maintaining lysimeters, which minimized error. They report the largest error was differences between the lysimeters bulk soil in situ due to disturbance and the field soil in its normal state. Differences between tillage primarily and seed planting to some extent influences the error between lysimeters and field conditions. Other workers report heat flux errors in smaller (30 cm) lysimeters (Black, et al., 1968) and the high cost (Lourence and Moore, 1991), although Schneider et al. (1996) described a low cost 1.5 m diameter monolithic lysimeter, which gave nearly as accurate results. These low cost lysimeters were suggested for use in developing countries.

There are two principal designs. One design (Marek et al. 1988) offers access to lysimeters sides and bottom for installation and repair. The datalogger and related instruments are installed in the cavity beneath the lysimeters, including the load cells directly beneath the monolith soil container. The volumetric water content is recorded with Time Domain Reflectometry. The excess water is drained into a sump hole and removed from the cavity with a pump. A diameter of 3 m is common but the largest lysimeters are 10 m in diameter located at the University of California – Davis.

The second design (Schneider, 1998) is simplified and less costly. The monolith of soil (1.5 m diameter) is obtained from the field and installed in a hole slightly larger than the monolith diameter. Prior to installation, the cavity is dug 0.5 m deeper and filled with fine gravel. A volume of space is left for water to accumulate when the monolith drains. This volume is removed by using a hand driven vacuum pump. The scale is usually a platform beam unit resting on the gravel surface. The scale is wired to a datalogger at some point above ground from the lysimeter. The soil monolith, once installed, prohibits users from repairing the instruments and scales beneath the monolith.

Weighing lysimeters measure water mass, and over time, the change in water content in the soil monolith and plant tissue. Users may assume water bulk density is exactly 1 g cm^3, thereby converting mass to volume. The change in water mass, over time, and if negative, measures the water storage loss over that time. If negative, water has been lost as evaporation, transpiration, or out of the bottom of the monolith. If positive, a rainfall volume depth, or irrigation event, increase the mass, and therefore the soil water storage is increased. The soil water change is known, and can be plotted as time step (x) and storage status (y) (Evett, 1998).

The other components of a FWB are measured as well. Thermal energy provides a measure of energy influencing the crop and the surface of the soil monolith. Wind speed and relative humidity influence the rate of ET for the crop growing in the soil monolith. The physical characteristics of the soil mineral, the matric, osmotic, and gravimetric potentials are measured thereby providing knowledge of field capacity and permanent wilting point, the volumetric water content between these two points is available water capacity for crop consumption (Hillel, 1998). For example, if the FC is 44%, or 13.2 cm per 30 cm depth, and the PWP is 24%, or 7.2 cm 30 per cm depth, the AWC is 6 cm per 30 cm depth. Optimal crop growth occurs between these two points; the 6 cm or 60 mm of soil water storage is maintained by irrigation or rainfall.

Microlysimeters have been used at the field level (Lascano and Hatfield, 1992). These smaller devices have a 10 cm diameter, can be removed by hand, weighed, and then replaced in the field core. For a precision of 0.5 mm d^{-1}, only seven units were required at any soil wetness. The units are labor intensive, but offer the researcher a low cost measurement of the FWB.

2.7b Indirect FWB measurement

The measurement of FWB can be done indirectly. A methodology for measuring several of the components in any FWB equation can predict the change in soil water status over a time period. As early as 1802, John Dalton (Davenport, 1984) suggested a method for free water evaporation. The evaporation rate was calculated using the vapor pressure gradient, the difference between saturated vapor pressure and actual vapor pressure, and this factor was multiplied by an empirical coefficient to determine rate. The Dalton equation follows:

$$E = C(e_w - e_a)$$

Where

E = evaporation rate

C = empirical coefficient

e_w = saturation vapor pressure

e_a = actual vapor pressure

Dalton proposed the use of an empirical coefficient, C, to refine vapor pressure gradient ($e_w - e_a$). This gradient was influenced by air and water temperature, wind velocity, atmospheric pressure as a function of altitude, and the orientation and shape (slope) of the field surface (Tindall et al., 1999). Refinement of Dalton's Law, as it was known, and continued by Fitzgerald (1886), Meyer (1915), Horton (1917), Rohwer (1931), Harbeck, et al. (1958), Kohelker et al. (1955), and Dingman, et al. (1968). Tindall et al. (1999) provides a list of equations for each of these researchers. The newer equations suggest models for determining the empirical coefficient, C. For instance, Fitzgerald (1886) used wind velocity for C, Meyer (1915) suggested that E rates should be based upon depth of water, and Horton (1917) in his rather well known work modified C by incorporating the relationship of turbulent wind time and relative humidity over a large area, i.e. and field instead of a single location in that field. Harbeck et al. (1958) incorporated air temperature in his equation, and Kohler et al. (1955) began using pan evaporation data collected at some site in the field.

The efforts of these researchers yielded some knowledge of evaporation of water from a water surface and from the wet soil surface. Evaporation data like these were indirectly influenced by location: if the evaluation site was not vegetated, the values were truly evaporation estimates. If, however, the site was heavily vegetated, i.e. a forest, grass or actively growing crop, the estimate certainly was influenced by the presence of biomass.

Viehmeyer and Brooks (1954) suggested a near saturated soil surface will evaporate water approximately at the same rate as water from a water surface. Meyer (1915) assigned the E rate as a function of water depth, but included the corresponding mean monthly vapor pressure (in inches mercury) and the mean monthly air temperature. Thus the monthly evaporation rate was known. Meyer (1915) further refined his equation by fine-tuning the coefficient C, by measuring wind velocity. A monthly mean was determined using velocity as miles per hour at a height of 10 m above the evaluation site. In what was to become known as the Meyer Equation (Tindall et al., 1999), the monthly value could be divided by 30 to approximate daily evaporation assuming equation factors were daily mean values. Meyer was, therefore, one of the earliest researchers to use empirical data to calculate monthly and daily evaporation rates from a wet soil or water surface.

One additional note on evaporation should include the use of the U.S. National Weather Service's use of Class A Evaporation Pans (James, 1988; Jensen, 1980; Pair et al., 1983). The National Weather Bureau sought to know something about water flux, that of an evaporative flux, or the conversion of liquid water into water vapor. This is known as the latent evaporative flux; it is the amount of energy required to dissociate water molecules, which are bonded into a matrix, into water molecules, which escape the bonded matrix and enter the much less dense atmosphere. This reaction requires energy. For example, at 20° C, the latent heat of evaporation is 2.45 MJ kg^{-1}, or in other words 2.45 MJ of energy is required to vaporize 1 kg of water. The expression is usually expressed as energy per unit area: 2.45 MJ of energy is required to vaporize 0.001 m or 1 mm of water per square m, or m^2. The energy is supplied by sunlight through radiant solar energy.

Class A Evaporation Pans were placed in over five hundred sites in the U.S. with another several hundred in other countries (Cuenca, 1989). The pan is 1.2 m in diameter and 250 mm deep. The operating level is 175-200 mm. The pan sits 150 mm above the soil surface. Birds and debris are kept out of the water by placing a meshed screen on the pan's rim. Measurements are taken daily. Excess water from rain is removed from the pan (and recorded); water is added when evaporation over time exceeds rainfall. An automatic depth recorder can be used to automatic data collection.

The volume depth removed from a pan is combined with a coefficient, which estimates the amount of evapotranspiration for a particular crop. Sample crop coefficients are supplied by FAO (1998). For evaporation pans crop coefficients that are less than one, indicating that less water is removed from the field than that water from a water surface. The coefficient could be greater than one, however, if the soil was wet and the crop was transpiring more water (a function of rooting depth) than that water from a water surface (FAO. 1998).

2.8 Evapotranspiration

The idea that evapotranspiration could be more accurately calculated began in the 1940's and was examined by many researchers in the 1950's (Tindall et al., 1999). Jensen et al. (1990) reviewed this early research effort and discovered three methodologies: temperature methods, radiation methods, and combination methods.

The most commonly accepted temperature method is the Blaney-Criddle Method (Blaney and Criddle, 1950). This method assumes that ET is a function of mean monthly air temperatures and monthly percentage of daylight hours for an actively growing crop in a well-watered soil. The daylight hour component was determined by knowing the degrees of North Latitude, i.e., the further away from the equator (larger Latitude) the differences in daylight hour percentages in a 24-hour cycle. The percentages were determined monthly. Blaney and Criddle (1962) developed monthly crop coefficients, which served the same purpose as the pan evaporation coefficients. Three corrective factors were made to the original BC Method. Pochop et al., (1984) recommended an elevation factor, thereby in addition to the planimetric location, a vertical input was needed. They proposed reducing ET by 10% for every elevation gain of 1,000 m, which accounted for lower temperatures at higher elevations at a given level of solar radiation. Lastly, Doorenbos and Pruitt (1977) modified the BC Method by using a standard reference crop, or what is now known as ET_c. They used a well watered, actively growing grass crop as their ET_c. Their work was the basis for the FAO 24 publication, which during the 1970's and 1980's became the accepted method for determining ET_c using grass, and the development of crop coefficients for all other crops.

The radiation method was originally suggested by Jensen and Haise in the late 1950's (Jensen and Haise, 1963). The JH Method is based upon knowing solar radiation, and the term they used is Langley's, calories per square cm of field surface per day. They borrowed the planimetric component from the BC Method, and developed a chart of mean solar radiation in the listed units as a function of 5 degree increments both north and south of the equator. The values are lower as latitude increases, in approximately the same manner as daylight hour percentage (Tindall, 1999). Other components include saturated and actual vapor saturation or humidity, mean air temperature, and a temperature scale intercept when ET divided by R_s, defined as Langley's at that point when no evaporation (not ET) occurs. Richardson and Wright (1984) provided a method for determining solar radiation if local data were not available. One of the original JH method authors, Jensen and other workers (Jensen et al., 1971), would later define the crop coefficients, which would be used in almost all combination methods.

This early work by a group of scientists set the stage for development of what were as combination methods. That is, temperature and solar radiation, both direct measurements, were used together. In a well written review paper published in 1990, Jensen, Burman, and Allen (Jensen et al., 1990) would review the work to that time and suggest what would be called the FAO Penman Model, a combination model, based upon the previous effort at combining temperature and solar radiation into a more accurate model.

2.9 Combination models

Penman (1948) developed the first ET combination model. Known as the FAO Penman Model, it combined four primary climatic factors: solar radiation as energy or thermal input, wind speed in terms of turbulent intensity, vapor flux, as the difference between saturated vapor pressure, or 100% relative humidity, and actual vapor pressure, or relative humidity, and mean ambient air temperature. The thermal input term drives the energy into the soil-atmosphere system. Logically, the greater the thermal input and the longer the daylight hours (sunlight exposure), the greater the thermal input load per 24-hour period. Wind speed is required given the thermodynamic properties of turbulent flow. Increased wind velocity drives turbulent flow, thereby removing water vapor from the soil-atmosphere at a rate faster than still or calm air. The vapor flux, or what is known as the vapor pressure deficit (VPD), is an evaporative property of the air space above the soil surface and the soil atmosphere as well. The larger the VPD, the greater the difference between existing humidity and atmospheric water content at saturation. The VPD is a function of all climate terms, especially thermal input. The latent heat of evaporation requires energy; the evaporative capacity of the atmosphere is the VPD. Finally, ambient air temperature expressed as mean degrees per day is required to complete the FAO Penman model. Temperature is a measure of energy in a system, and the degrees to which energy increases or decreases per unit time.

Further refinements of Penman's original model occurred in the 1950's. 60's and 70's (George et al., 2002). Three modifications sought to incorporate stomatal resistance (Penman, 1963), modify wind function (Monteith, 1965) and VPD's (Doorenbos and Pruitt, 1977). A scientist in France, Perrier (1977) moved the calculation of reference ET towards more emphasis upon energy terms. His model used sensible heat and latent heat exchange functions to describe the available energy for the actively growing crop canopy. Bouchet (1963) added another perspective. He suggested that as a soil surface dries from an initially wet or saturated condition, the potential ET increases while the actual ET decreases. When the soil is nearly dry, there is no or little water to evaporate, even thought the potential to evaporate water is high. He suggested the following relationship:

$$dE_c + dET_p = 0$$

Where

dE_c = the change in ET caused by a change in soil water in the root zone

dET_p = the change in potential ET caused by a change in actual ET

The equation is set to zero, inferring that when one increases the other decreases. As a soil is rewet, for instance due to rain or irrigation, the actual ET increases due to greater water availability in the root zone. Because more water is evaporating, i.e., the latent heat flux is increasing, the increasing water vapor content of the atmosphere above the actively growing crop reduces the VPD. This work was known as the complimentary relationship between actual and potential evaporation. Many researchers shifted their focus towards developing models that referenced a specific crop, as described by ET_r.

The work in refining potential ET, ET_p was not done yet. Scientists were beginning to understand the necessity of refining crop characteristics (Pereira et al, 1999). Two components stood out that required definition. The first is crop canopy height, or vertical distance of the uppermost biomass leaf layer from the field soil surface. Certainly there are differences. Grass is less than one meter, soybeans, potatoes, and sugar beets are just less than one meter, corn is two to three meters, and then forest trees can be many meters high. The actual ET for any given crop, ET_c, would be larger as crop height increases due to a greater vertical resistance of water vapor movement. The second component is crop density. The term Leaf Area Index is defined as the one sided green leaf area per unit ground area in broadleaf canopies, or as the projected needleleaf area per unit ground area in needle canopies. As crops grow and biomass increases, the LAI increases, thereby increasing the resistance of water vapor flow to the uppermost distance in the canopy. Once these two components are established, aerodynamic resistance from wind speed and average surface resistance (stomatal regulation and canopy dimensional shape) can be measured for a particular crop. Two crops were selected: grass and alfalfa.

2.10 Penman Monteith model

The original FAO Penman Model, coupled with an understanding of field soil water status, and the aerodynamic relationships of crop vertical height and crop density, was modified by Monteith in 1965 into what was know as the Penman Monteith ET Model, or PM ET Model (Monteith, 1965). Almost 15 years would pass before the PM Model would be used as the reference ET_p model by the American Society of Civil Engineers, ASCE (Itenfisu et al., 2003). The PM Model was also adopted by the Food and Agriculture Organization of the United Nations in 1998 (FAO, 1998). The model would have two names: the ASCE Standardized Reference PM ET Model, and the FAO PM ET Model (Itenfisu et al., 2003). Two separate groups of scientists developed the reference crop measurements. Doorenbos and Pruitt (1977) earlier had developed grass crop ET calculations based upon a well-watered clipped cool season grass. Wright

(1982) worked at the Kimberly ARS Research Station in Idaho. The climate there is arid, thereby requiring additional calibration of the original PM ET Model. In fact much of the Western U.S. uses a modified PM ET model with alfalfa as a reference crop. The model was named after Wright's work (in location terms, not name): the Kimberly Penman ET Model.

The FAO PM ET Model reference equation for grass follows:

$$ET_r = [0.408\Delta(R_n - G) + \lambda(C_n/(T + 273)u_2(e_s - e_a)]/[\Delta + \lambda(1 + C_d u_2)]$$

Where

ET_r = daily reference (grass) ET (mm day^{-1})

R_n = net radiation at reference crop surface (MJ m^{-2} day^{-1})

G = soil heat flux density (MJ m^{-2} day^{-1})

T = mean daily temperature 1.5 m height above soil surface (^oC)

u_2 = mean daily wind speed at 1.5 m height above soil surface (m s^{-1})

e_s = mean daily saturated vapor pressure at 1.5 m above soil surface (kPa)

e_a = mean daily actual vapor pressure 1.5 m above the soil surface (kPa)

Δ = slope of saturation vapor pressure temperature curve (kPa $^oC^{-1}$)

λ = psychrometric constant (kPa $^oC^{-1}$)

C_n = numerator constant representing reference type and time step

C_d = denominator constant representing reference type and time step

Four assumptions are required for ET_r based on grass. They are:

- grass canopy height is 0.12 m, or 12 cm above the soil surface
- a fixed surface resistance of 70 s m^{-1}
- albedo (surface color) of 0.23

- LAI greater than one, crop is actively growing, and all fluxes are vertical

For alfalfa as a reference crop two assumptions are different. They are:

- alfalfa canopy height of 0.5 m, or 50 cm above the soil surface
- fixed surface resistance of 45 s m^{-1}

The FAO PM ET Model requires climate data (FAO, 1998). They are the same climate data proposed by Penman in his earlier 1948 work. A measurement of solar radiation is required as an input, R_n. Minimum and maximum ambient air temperatures are required as measure of energy status, T. Wind speed, u_2, provides a measure of turbulent flow, thereby air turnover of drier air replacing wetter air. Finally, the evaporative capacity of that air volume, $e_s - e_a$, or VPD, is measured. One component of the model, the heat flux density G, is assumed to be zero when the time step is one day. A measurement of actual temperature changes in the soil may be used to alter the model if the time step is many weeks or months.

If climate data were obtained in a field of grass or alfalfa, and the appropriate PM ET model parameters were used, an accurate estimation of ET would be made. There are two issues, however with these calculations. The first is the impact and accuracy of weather data (Itenfisu et al., 2003). The need to provide accurate climate data as near to the evaluation field is obvious. This is likely one reason why WS Networks are expanding in the PNW (as well as Midwestern States) (USBR, 2004). For each WS, the calibration of sensors is a necessity, to the extent that electronic sensors are exposed to climate extremes and must be monitored often.

The second challenge is born out of the word "estimate". In a review article by Itenfisu et al. (2003), a group of combination models were used to calculate ET_r for grass and alfalfa at 49 locations in the U.S. They found good agreement using the ASCE PM ET Model at locations across diverse climates in the U.S. However, given the differences of climate, with the use of several equations to model reference ET, the root mean square difference values comparing these models ranged from as low as 0.04 mm day^{-1} to a high of 0.76 mm day^{-1}. These results underscore the variations of models to estimate reference ET. The RMSD as a percentage of mean daily ET ranged from a low of 0.8% to a high of 22.2%. Of all models, the ASCE (and FAO) PM ET Model performed the best using grass as a reference crop. The importance of this work suggests that on a field basis, the calculation of reference ET is challenging and the results are estimates.

If the crop is something other than grass or alfalfa, another adjustment must be made. The challenge of making this adjustment is huge. For a user to know ET for corn when the equation is based upon a cool season grass, requires extensive crop physiological knowledge in terms of water consumption and biomass growth (from which TR can be modeled), as well as some understanding of the FWB. Recall that the PM ET Model requires a wet soil so water can be evaporated and water can be transpired (Bouchet, 1963).

Crop coefficients have been developed by workers in fields the world over (FAO, 1998). These are known as crop ET values, or ET_c, and specifically model particular crop water consumption over the growing season or some evaluation time period.

2.11 Crop coefficients

A crop coefficient is defined as a dimensionless number which is multiplied by the reference ET, ET_r, to obtain crop ET, ET_c (FAO, 1998). The formula takes on this from:

$$ET_c = ET_r * K_c$$

Where

ET_c = Evapotranspiration for a particular crop c (mm day^{-1})

ET_r = Evapotranspiration for a reference crop (alfalfa or cool season grass) (mm day^{-1})

K_c = crop coefficient (dimensionless)

The crop coefficient K_c integrates four crop characteristics that are, at any one point during crop growth, different from the reference crop, i.e. alfalfa or cool season grass (FAO, 1998). They are:

- Crop height, which influences the aerodynamic resistance term U_2 in the FAO PM ET model.
- Albedo, or the reflectance of the crop soil surface. A wet soil surface is darker, thereby absorbing more energy into the soil and reflecting less into the atmosphere. This term influences the $R_n - G$ terms in the FAO PM ET model.
- Canopy resistance, which influences the surface resistance term derived by $e_s - e_a$, and is affected by LAI, leaf area (stomatal density), and physiological degree of stomatal control (specifically, the location of the stomata in reference to the leaf surface i.e.).
- Evaporation from soil especially exposed when the crop canopy is minimal, as a LAI less that 0.5.

Crop coefficients are given as standard and non-standard numbers (FAO, 1998). Standard conditions include no limitations on crop growth. Soil water is moving through the plant in sufficient amounts to regulate leaf temperature as a function of solar radiation. Sufficient crop density, good weed control, minimal insect activity, and no soil fertility problems (macro or micro nutrient deficiencies, salinity, or soil pH) are apparent in the field. Non-standard conditions represent a limitation on optimal crop yield, including the presence of any environmental or characteristic that would limit or significantly the crop yield in relationship to the crop coefficient.

A good reference source for crop coefficients is found in FAO Irrigation and Drainage Paper No. 56. Researchers in all parts of the world have developed crop coefficients for food and feed crops. Other sources include Smith et al., 1991, and Allen et al., 1998. Pereira et al. (1999) discussed some fine-tuning efforts by workers (Allen et al., 1996) in adjusting crop coefficients during especially the mid growing season for agronomic crops. Wright (1982) sought to adopt what he called baseline crop coefficients by modifying the K_c value as a function of time period after an irrigation or rainfall event. He suggested the term soil water stress coefficient, K_s, which would account for a longer period of time after an irrigation or rainfall event. Logically this term, if higher, was the result of crop stress, and that stress was the result of soil water depletion in the root zone without replacing it with irrigation or timely rainfall. Allen (1996) suggested accounting for crop stress as a function of the relative evaporation from the soil surface as a layer. This approach was derived by knowing a fundamental property of soil water change over time using the Law of Conservation of Mass.

Work by Ritchie (1972) suggested a different approach. He proposed defining a crop coefficient by measuring crop density and water availability in the root zone. His formula is:

$$ET_c = f_1(\theta)f_2(\mathrm{LAI})ET_r$$

Where

ET_c = ET for a selected crop

$f_1(\theta)$ = volumetric water content in the crop root zone

$f_2(\mathrm{LAI})$ = LAI, as a function of crop density

ET_r = reference ET using alfalfa or cool season grass

Function f_1 and f_2 are soil specific and crop specific, and both are influenced by climate factors, farming practices, and crop density. One final approach is the concept of a composite crop coefficient. Pereira et al. (1999) suggested the following equation:

$$ET_c = \alpha_o\alpha_c ET_r$$

Where ET_c = ET for a selected crop

α_o = term expresses the influence of climate upon aerodynamic resistance

α_c = term explains the crop specificity when compared to the reference crop, or how similar or different is the selected crop with the reference crop of alfalfa or cool season grass. Therefore,

$$K_c = \alpha_o\alpha_c$$

Where

K_c = a selected crop coefficient

Pereira et al. (1999) state this final equation as the promise for future work. For now, the referenced source of crop coefficients is found in FAO Irrigation and Drainage Paper NO. 56 (FAO, 1998).

2.12 FWB and ET

At this point, the discussion of FWB has included direct measurement using some form of lysimeter equipment, and an indirect measurement using climate data. However, in both measurements, there is one unknown: the relative proportions of the solid and void space in the soil volume. A lysimeter measurement is based upon an understanding of soil particle size, mass of soil per unit volume, or bulk density, and the relative proportions of gravimetric, matric, and osmotic potential which can be used to derive the soil water characteristic curve. Two additional components are required: an understanding of infiltration as a function of water movement into the soil volume, and two, the conductivity of water through the soil volume during matric flow and during gravimetric flow.

The FWB, therefore, is influenced by the climate factors used in determining ET, but can only be known if the fundamental properties of the soil root zone are known. Farmers can have access to reference ET values, and based upon their crop can know something about the adjustments made to ET_r by using a crop coefficient. But to what extent does ET_c influence the volume of water in the crop root zone?

The FWB is known only when the parameters of the crop root zone are known; that volume of soil containing soil particles, void space, some volume of water, some root tissue, will have a volume of water which is capable of moving into the root tissue, into the vertical xylem canals, and through the stomata via evaporative flux. This volume of soil will also lose water due to surface evaporative flux, a function of solar radiation and the presence of crop biomass.

An example of the FWB inflows and outflows are presented in Figure 2.1.

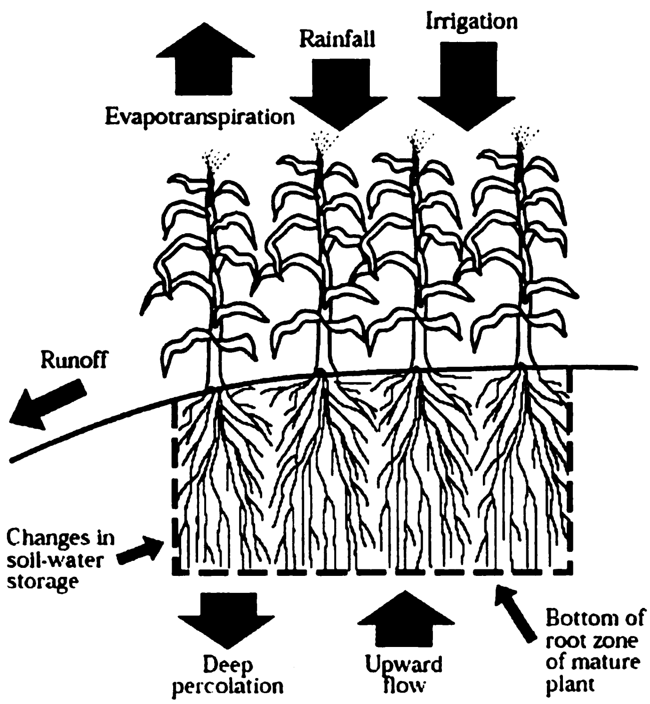

Figure 2.1 Field Water Balance illustrating water inputs and outputs for a crop system

In figure 2.1, the crop root zone is defined at some depth of soil from the soil surface. The FWB is known only when the change in soil water storage is quantified. The values of rainfall and irrigation can be measured with relative ease (in units of volume depth, or mm of water). Crop ET, ET_c is calculated from a reference ET, ET_r, and a crop coefficient, K_c. Runoff, or water on the soil surface which has not entered the soil void space, can be calculated by knowing infiltration rate and soil bulk density of the soil surface layer, and the rate of water as an input, i.e., a hydrograph of rainfall intensity or irrigation rate per unit time.

Below the crop root zone is a leaching zone, in which water may move upward against the gravimetric potential, or water may enter from the crop root zone in response to a lower hydraulic potential. The below ground component measurements are problematic. Defining changes in soil water storage, or volumetric water content per unit depth, are required, however, if the FWB is to be known. The above ground climate measurements will predict water moving out of the crop root zone, in units of volume depth, mm day^{-1}, but this value must be referenced to a unit of volume per volume depth of soil. If the crop root depth had units of measurement similar to water, i.e. 1 Mg m^{-3}, then the volume depth removal would be accurately known.

2.13 Soil water

Gravimetric water content of soil can be expressed as the ratio of the mass of water in the soil sample before drying to the mass of the soil sample after it has been dried to a static mass at 105°C (Topp et al., 2002). The soil sample must be taken in as undisturbed manner as possible, thereby minimizing sample compaction. The water volume is expressed as a percentage of total volume. The mass based gravimetric water content is related to the volume based water content by measuring the soil bulk density, ρ_b in units of Mg m^{-3}, and the density of water ρ_w, in units of Mg m^{-3} (Topp et al., 2002). The volumetric water content equation is:

$$\theta_v = (\rho_b / \rho_w)\theta_m$$

Where

θ_v = volumetric water content

θ_m = gravimetric water content

The bulk density of soil particles, ρ_b is given as 2.65 Mg m^{-3} (Zavattaro and Grignani, 2001; Logsdon and Cambardella, 2000; and Grossman and Reinsch, 2002). A recent paper by Flint and Flint (2002) described soil particle bulk density in detail. They provide a list of soil particle densities; selected materials are presented below:

Apatite	3.2 g cm^{-3} (or Mg m^{-3})
Montmorillonite	2.5
Kaolinite	2.65
Feldspar	2.5 – 2.8
Mica	2.6 – 3.2
Biotite	2.7 – 3.1
Quartz (sand)	2.65

The bulk density of water, ρ_w is given as 1 Mg m^{-3} at 4°C (Hillel, 1998), and decreases as temperature increases. For instance at a temperature of 25°C, the bulk density of water is 0.99708 Mg m^{-3}, and decrease of 2.92 kg m^{-3}, or about 0.29% less mass per cubic meter.

Soil bulk density is defined as the mass of soil per unit volume. Typical values ranges are 0.9 – 1.3 (top 20 mm) and 1.2 – 1.6 Mg m^{-3} for agricultural soils (Logsdon and Cambaredella, 2000), 1.4 to 1.52 (Ap Horizon) and 1.3 Mg m^{-3} (> 20 cm) for agricultural soils (Zavattaro and Crignani, 2001), 1.41 – 1.56 Mg m^{-3} on agricultural soils (Mandal, et al., 2002), and an average of 1.35 Mg m^{-3} on tilled Ap horizons (Rawls, et al., 1998). Soil bulk density was variable given the non-uniform spatial regularities of the soil volume (Grossman and Reinsch, 2002). The authors list a number of studies reporting variability but no clear range or coefficient of variation around the mean values. They do report, however, their own study of 5,000 samples moving through the USDA Soil Survey Laboratory. The standard deviation of duplicate soil samples was 0.04 g cm^{-3} (0.04 Mg m^{-3}).

Grossman and Reinsch (2002) discuss the shrinkage of soils as they undergo wetting and drying cycles. The shrinkage of sandy soils was negligible; clayey soils will have measurable shrinkage. Grossman (1990) presented a series of equations that convert bulk densities to a standard value at 33 kPa soil matric potential (field capacity). Grossman recommends that from a practical matter, soils should be sampled at or near field capacity, and the stated bulk density value referenced as such.

Once the bulk density of the soil particles is determined (or assumed to be 2.65 Mg m^{-3}) and the bulk density of the soil mass is determined, the void space or porosity, f is known using the following equation:

$$f \text{ (porosity)} = 1 - (\rho s/\rho b)$$

Where

f = porosity as a dimensionless value less than one

ρs = bulk density of soil volume (Mg m^{-3})

ρb = bulk density of soil particles (2.65 Mg m^{-3} f (porosity) = 1)

For example, if the soil volume bulk density is 1.35 Mg m^{-3}, then the porosity f is equal to:

$$f \text{ (porosity)} = 1 - (1.35/2.65) = 0.4906$$

The porosity value of 0.4906 may be used two ways. One, the soil volume is multiplied by 0.4906 to yield the void space, i.e. a cubic meter of soil has a void space of 490.6 L, equivalent to 49.06 % of the total volume. Two, this value is a hypothetical value of the volume of water, which can replace the void space. The value is never attainable in the field given the entrapment of air particles as the soil volume is rewet (Hillel, 1998). From a practical standpoint the porosity of a soil volume in the field tells us something about its compaction, and the volume of water that could enter the void space.

The measurement of bulk density on agricultural soils has several other useful purposes. The ease of root penetration (Pierce et al., 1983), prediction of water conductivity (Rawls et al., 1998; Wildenschild et al., 2001; and Saxton, 1986), and an indicator of soil quality (Lal et al. 1998; and Larson and Pierce, 1994).

Soil bulk density can be measured by driving a soil core into the soil matrix at the selected depth. The driving function is done without compacting the soil entering the core. Field cores can be taken using Soil Moisture® (2004) sampler and brass cores.

2.14 Soil particle analysis

Particle size analysis, PSA is a measurement of the various sizes of particles comprising the soil solids, or soil matrix (Gee and Or, 2002). The USDA system of classification (Soil Survey Staff, 1975) for mineral soils divides particles sizes into sand, silt and clay for particles less than 2000 μm (2 mm) as follows:

- Sand, < 2000 – 50 μm
- Silt, < 50 – 2 μm
- Clay, < 2 μm

Particles greater than 2000 μm are classified as gravel and cobbles.

PSA is used to evaluate textural class of mineral soils based upon the mixture of sand, silt, and clay. The Soil Survey Staff (1975) developed a textural triangle that placed 12 textural classes within the triangle based upon relative mixture of particles size. The USDA textural class triangle is shown in Figure 2.2.

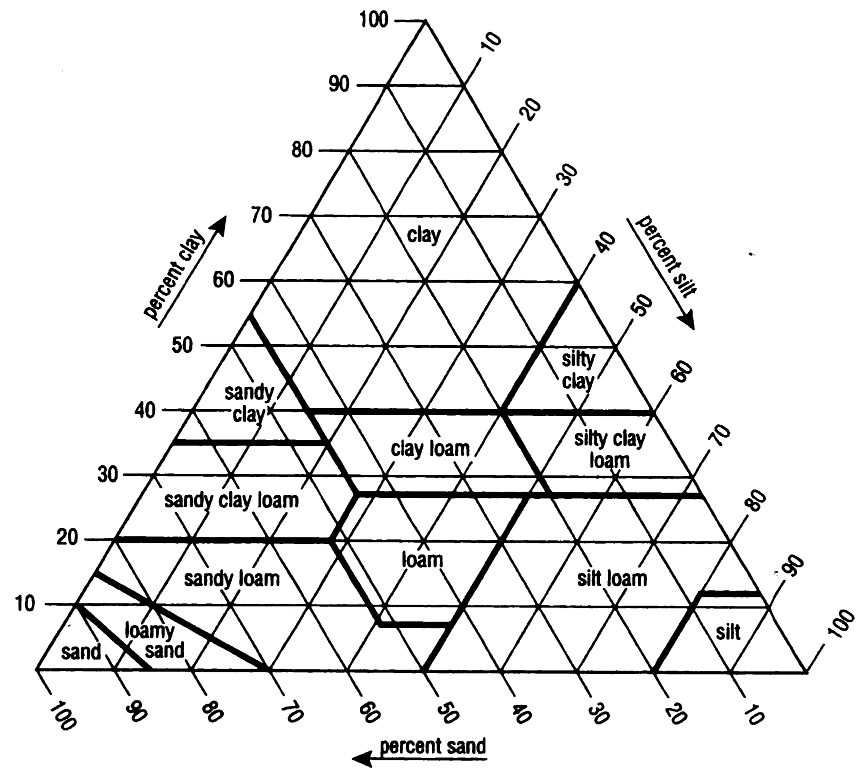

Figure 2.2 USDA textural class triangle illustrating location of twelve classes based upon percent sand, silt, and clay content of bulk soil

The PSA has been used to predict saturated and unsaturated hydraulic conductivity (Todd, 1964; Bloemmen, 1980). The PSA and bulk density have been used to predict water retention, or water release curves, and unsaturated hydraulic conductivity (Arya, 1999; Saxton, 1998; Arya et al., 1981; Arya et al., 1999; Assouline, et al., 1998; and Ahuja, et al., 1980; Todd, 1964; and Bloemmen, 1980). Table 2.1 lists the 12 USDA textural classes, typical bulk densities, total porosity, and typical saturated hydraulic conductivities (K_s) (Ahuja, et al., 1998).

Table 2.1 USDA textural classes and selected properties including bulk density, porosity, and saturated hydraulic conductivity

Textural Class	bulk density	porosity	K_s
	Mg m^{-3}	%	cm h^{-1}
sand	1.49	43.7	21.0
loamy sand	1.49	43.7	6.11
sandy loam	1.45	45.3	2.59
loam	1.42	46.3	1.32
silty loam	1.32	50.1	0.68
silt	1.35	49.1	0.68
sandy clay loam	1.59	39.8	0.43
clay loam	1.42	46.4	0.23
silty clay loam	1.40	47.1	0.15
sandy clay loam	1.51	43.0	0.12
silty clay	1.38	47.9	0.09
clay	1.39	47.5	0.06

Saxton (1998) developed a Soil Water Characteristic Tool based upon textural class. The values he derived are presented in Table 2.2.

Table 2.2 Saxton textural classes and related properties including bulk density, porosity, and saturated hydraulic conductivity

Textural Class	bulk density	porosity	K_s
	Mg m^{-3}	%	cm h^{-1}
sand	1.68	36.6	5.01
loamy sand	1.63	38.5	3.18
sandy loam	1.53	42.3	1.51
loam	1.44	45.7	0.89
silty loam	1.41	46.8	1.41
silt	1.49	43.8	3.22
sandy clay loam	1.40	47.2	0.27
clay loam	1.32	50.2	0.25
silty clay loam	1.29	51.3	0.39
sandy clay loam	1.33	49.8	0.12
silty clay	1.24	53.2	0.24
clay	1.26	52.5	0.15

2.15 Saturated hydraulic conductivity

The relationship between soil particle size and bulk density describes the arrangement of soil particles per unit space, or their distribution in a volume of soil. From these, porosity is known. Total porosity of a soil volume indicates volumetric water content if the soil is saturated, except for captured air in prose space. If a soil volume is saturated, i.e. the pore space is 90-95% filled with water, the volumetric water content of soil cannot be increased as more water is added to the soil surface. If a hydraulic head of water exists at the soil surface, then water flow through the soil volume is saturated flow, or what is known as saturated hydraulic flow.

Flow through a saturated soil volume is driven by gravimetric and pressure potentials (Tindall and Kunkel, 1999). Gravity exerts a potential energy on a volume basis in units of Pa or on a mass basis in units of J kg^{-1}. (Note, 1 Pa = 10^3 J kg^{-1}). The gravimetric potential is, therefore, the amount of work required to move a mass of water to some point from a reference datum (Young and Sissson, 1999). Work done by Darcy

(Philips, 1995) sought to define saturated flow in sands, and he proposed the following expression (Darcy's Law):

$$Q = K(A\Delta H)/L$$

Where

Q = volume of water that passes through a depth of soil per unit time, $cm^3\ h^{-1}$

K = hydraulic conductivity in $cm\ sec^{-1}$

A = cross section area of soil plane, cm^{-2}

ΔH = datum reference point change, head plus depth of soil, cm

L = length of soil depth, cm

If the change in head, ΔH is zero, then there is no flow. The head drop per length in the distance of flow ($\Delta H/L$) is the hydraulic gradient (Hillel, 1998). The specific discharge rate is known as the flux density (Q/A) and is indicated as q (small Q). The units of q are length per unit time, or $cm\ h^{-1}$. The units in Tables 1 and 2 list q in these units. This flux density q, is used to describe saturated conductivity while the large Q refers to the volume of water moving through the soil depth at a particular flux density and over a surface area, A. The head, or hydraulic gradient is placed in the numerator while the length or depth of the soil profile is placed in the denominator. A larger hydraulic gradient, i.e. one m instead of one cm, significantly increases q as a function of head.

Saturated flow of soil water through a volume of soil may be vertical and horizontal from the soil surface (Young and Sissson, 1999). Due to the heterogeneity of soils and soil particle distribution, which increase or decrease tortuosity per unit length, water movement through soils is termed anisotropic (Tindell and Kunkel, 1999).

Generally, water flux density q, is greatest when flow is parallel to plate shaped clay particles, and least when water moves perpendicular to these plates. A third flow may be described as orthogonal towards the clay particle. Work done by Fetter (1994) showed that flux density of water flow in saturated soil can vary by more than two orders of magnitude. His work showed that Q, or volume flow reflects many different q's, or flux density flows.

Saturated hydraulic conductivity obeys the Conservation Law of Mass, or what is known as the continuity law. Simply, it states a water volume entering the soil volume is equal to the volume leaving the soil volume. If the volume leaving is less, then an increase in volumetric water content occurs, and therefore water flow in the soil volume is not saturated flow. If water leaving the soil volume exceeds water entering, then a decrease of volumetric water content exists. These conditions are based upon a time period; inflows and outflows are expressed as volumes at some volume depth for a unit of time. The FWB is based exactly upon the continuity equation; otherwise a change in volumetric water based upon inflow and outflow of water could not be determined.

The soil volume may be the root zone or depth to a water table or depth to some soil profile based upon soil morphology or soil physical characteristics. Saturated water flow may be described as flow of water through multiple layers or soil horizons. Typically soil layers or horizons may be heterogeneous to the extent different flux densities occur throughout the complete soil volume. Each layer will have a different saturated (and unsaturated) hydraulic conductivity. As such, the total soil volume can be modeled as an anisotropic homogeneous layer or horizon (Freeze and Cherry, 1979). The entire soil volume is comprised of multiple soil layers j_n, each with an individual q (or K), or in the case of a specified surface area, Q, and each concurrent layer has its own hydraulic resistance R, where

$$R = d_j/K_j$$

Where

R = hydraulic water resistance for layer j

d_j = thickness of layer j

K_j = hydraulic conductivity of layer j

The summation of all layers $\sum d$ is the entire soil thickness; the R value is the resistance for each layer. K_z, the effective saturated hydraulic conductivity for the entire soil thickness is defined as follows (Tindall and Kunkel, 1999):

$$K_z = \sum d / \sum (d_j/K_j)$$

Where

K_z = saturated hydraulic conductivity of water through the entire soil thickness, cm hr-1

$\sum d$ = summation of all soil layers

$\sum (d_j/K_j)$ = summation of all R values of each individual soil layer, j

A comprehensive review of determining saturated hydraulic conductivity in soils by using laboratory and field techniques are given in the recently published Methods of Soil Analysis, Part 4, Physical Methods (Dane and Topp, 2002). The laboratory methods include using an undisturbed (as possible) intact soil core, and placing a head of water at some depth above the core. After equilibrium (constant or steady state flow), the volume is collected. The result is volume per unit time, or Q, whereas the flux density is known by removing area A, from the equation, with units as cm h^{-1}.

Field methods include ring infiltrometers (Youngs et al., 1997), concentric ring infiltrometers (Bouwer, 1986), pressure infiltrometers (Reynolds, 2000), multiple ring infiltrometers (Reynolds, 1993), constant head well permeameter (also known as the borehole permeameter method) (Elrick et al., 1989), and the auger hole method (Amoozeger and Warrick, 1986). Amoozeger and Warrick refined some early work by Kirkham (1945) and suggested what is known as the piezometer method. This method is based upon a inserting a solid wall tube inside an auger hole at a depth in the soil profile. Water is added until a steady state is reached, thereby a field estimate of water volume per unit time which leaves the tube is the saturated hydraulic conductivity. Individual soil layers or horizons can be fitted with multiple piezometers at the appropriate depths. The most commonly used methods are the auger hole and piezometer methods. Their performance is based on assuming the soil water is moving as saturated flow, thus the soil pore space is almost completely filled with water.

2.16 Unsaturated hydraulic conductivity

Movement of water into the soil volume from the soil surface is known as infiltration. Water entering the soil volume must replace air space. Infiltration occurs, therefore, when the soil volume has some air in its void space. As water enters the soil volume, the movement of water is known as unsaturated hydraulic conductivity. For the FWB, the rate of flow per unit time is important; changes in soil volumetric content are influenced by the rate (or ease) water moves through the soil. The driving force is the physical parameter known as pressure gradient (Clothier et al., 1983). Pressure gradients, or potentials, are the differences in one pressure locale from another. For instance the pressure gradient decreases from a soil root zone at FC (higher) to a tree leaf 10 m above the soil surface (much lower). The Second Law of Thermodynamics explains this gradient. Water always moves to a low-pressure from a higher pressure. When water enters the soil, the pressure potential is lowered.

Unsaturated flow may be influenced by gravity. The downward "pull" of water is a force that transpiration is always working against. As water flow is moving into the root, through the plant xylem and ultimately converted to vapor at the stomatal aperture, every step of the way gravity is slowing this flow. The water potential or transpiration gradient, therefore, must exert enough force (or greater gradient) to overcome this constant downward pressure (Taiz and Zeiger, 2002). For the FWB, gravity can work in favor by exerting an additional force pulling water into the soil volume, thereby encouraging infiltration.

2.17 Empirical infiltration models

Infiltration can be defined using empirical equations derived from actual measurements of cumulative water infiltration. Several intake rates, q are measured using a ponded water depth at the soil surface. Several measurements are made based upon soil physical characteristics (like textural class), from which a rate constant per unit time are derived. One of the first empirical equations was suggested by Kostiakov (1932) as infiltration:

$$I = at^b$$

Where

I = cumulative depth as the volume of water per unit soil surface area a and b = empirical parameters from field measurement

t = elapsed time

Kostiakov's equation disregarded the initial water content of the soil and did not perform well when the intake rate, i was long. Parlang et al. (1982) examined several soils' intake rate using the Kostiakov equation and found it worked well when the infiltration rate was fast and the soil volume was relatively dry.

The Horton (1940) equation was proposed as an improvement for the Kostiakov equation. It is also based upon an exponential decay constant.

$$I = i_f t + [(i_0 - i_f)/k]/(1 - \epsilon^{-kt})$$

And the intake rate as:

$$i = if + (i0 - if)\ \epsilon^{-kt}$$

Where

I = cumulative depth as the volume of water per unit soil surface area

t = elapsed time

i_f = final infiltration rate based upon steady state

i_0 = zero time

k = proportionality constant

The values i_0, i_f, and k are related to soil and vegetative properties (Tindall and Kunkel, 1998). Skaggs and Khaleel (1982) examined the Horton equation and suggested typical values for agricultural soils: 30 – 90 cm h^{-1} for i_0 (beginning infiltration), less than 1 to 30 cm h^{-1} for i_f (steady state infiltration) and up to 50 cm h^{-1} for k.

The USDA's Soil Conservation Service (USDA, 1972) proposed another empirical infiltration equation in what is now known as the SCS Equation. Scientists at

SCS (as it was known until 1992) were interested in developing rainfall runoff model, which could be applied in all parts of the US. Their focus was reducing the impact of water erosion on soils. Thus the runoff value R was used in the following equation:

$$R = [(P - 0.2f_w)^2[/(P + 0.8f_w)$$

Where

R = runoff in unit depth mm

F_w = initial soil water content

P = precipitation in depth mm

The SCS equation derived a runoff depth based upon initial soil water content, and therefore used infiltration as precipitation minus runoff. The SCS equation assumed a constant rainfall hydrograph with an initial abstraction, or water storage, of 25 percent of the rainfall event before runoff would occur. Logically, if the soil volume was near FC or saturated, the F_w term would be at or near zero, indicating an earlier and more pronounced runoff volume (Rawls et al., 1982).

Holton (1961) suggested yet another empirical equation which derived infiltration completely proportional upon the soil water content of the receiving soil. His equation is:

$$i_t = i_f + ab(\alpha - I)^{1.4}$$

Where

i_t = infiltration rate

i_f = final infiltration rate

a = constant related to surface conditions varying between 0.25 – 0.8

b = scaling factor

α = water deficit as the pore space per unit area of a cross section initially available for water, cm

I = accumulative water volume at t

t = time

Holton's work was an improvement over previous equations and models. Infiltration could be described during periods of little or no rainfall (Tindall and Kunkel, 1999). Holton et al. (1975) further modified his equation as follows:

$$i = GAI_p^{1.4} + i_f$$

Where

G is the growth index of vegetative cover in percent maturity varying from 0.1 to 1

A = infiltration capacity of available storage based upon soil porosity and root density

I_p = available water storage in the surface layer, or A horizon

i_f = final infiltration rate

The final infiltration rate i_f, or final constant infiltration rate concept was used by Musgrave (1955) to define the SCS Hydrologic Soil Groups based upon the Holton Equation. They are used today and appear in Table 2.3.

Table 2.3 SCS Hydrologic soil group infiltration rate as cm per hour and description of infiltration rate

SCS Hydrologic Soil Group	i_f (cm h^{-1})	Description of Hydrologic Group
A	0.76	low runoff potential, high rates of infiltration
B	0.38-0.76	moderate infiltration rates
C	0.13-0.38	low infiltration rates
D	0.0-0.13	high runoff potential, low rates of infiltration

2.18 Physically based infiltration models

Green and Ampt (1911) used a physically based approach to derive infiltration of water into soil. Their approach is particularly useful in course-textured soils that are initially dry soils. Water infiltration using the GA approach is based upon the following assumptions (Freyberg et al., 1980):

1. a distinct wetting front exists and the water content behind it remains constant
2. the soil volume is homogenous in terms of conductivity and water volumetric capacity
3. matric potential (as influenced by soil mineral attraction to water) remains constant throughout the wetting front
4. the soil volume is uniformly wet behind the wetting front

The basic parameters of the GA method are presented in Figure 2.3 (USEPA 1998).

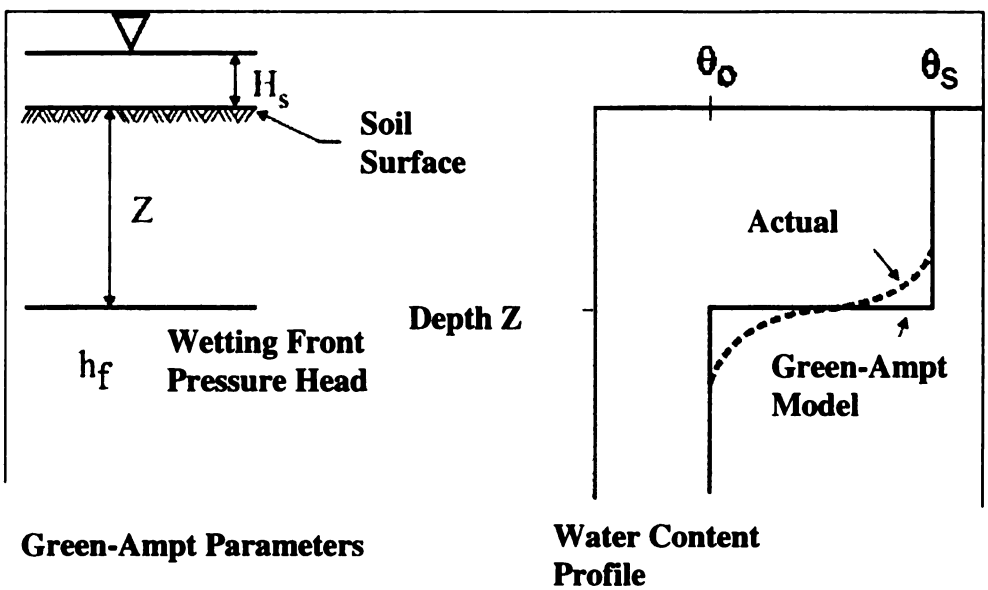

Figure 2.3 Green Ampt parameters and idealized illustration of water content profile

The piston type profile assumes saturated volumetric water θ_s, content down to the wetting front at depth Z. The ponded water H_s assumes a positive water pressure exerting some force on the water volume entering the soil volume at some depth Z. The soil water pressure at the wetting front H_f, is less than the surface pressure, H_s. The dotted line in Figure 5 part b is a suggested actual change in water content from dry soil θ_0 to saturated water content θ_s.

For the duration of time water is entering the soil, t, the infiltration of the wetting front will be depth Z. The relationship of infiltration into a non-saturated soil and Darcy's equation produced the following equation (Freyberg et al., 1980):

$$q = - K_s[(h_f - (H_s + Z)]/Z$$

Where

K_s = hydraulic conductivity of the surface water volumetric water content (used in saturated hydraulic conductivity equation

h_f = soil water pressure at the wetting front

H_s = soil water pressure at the soil surface

Z = depth of wetting front in vertical distance

The GA equation (USEPA, 1998) is presented as follows:

$$I = K_s t - (h_f - H_s)(\theta_s - \theta_0)\log[1 - (I/(h_f - H_s)(\theta_s - \theta_0))$$

Where

I = accumulative water volume at time t

t = time at depth Z for initial volumetric water content θ_0 to become saturated θ_s by the wetting front

The application of the GA equation is widespread. A lengthy review was conducted by workers at USEPA (1998) providing 20 referenced bibliographies. Tindall and Kunkel (1999) suggested that the GA equation could be applied if the user knew the saturated hydraulic conductivity K_s, suction at the wetting front h_f, initial volumetric water content θ_0, and what is known as the transitional volumetric water content, or θ_t. They suggest these values can be determined or estimated using laboratory measurements of saturated hydraulic conductivity and volumetric water content. Rawls and Brakensiek (1983) and Rawls et al. (1993) provide regression equations for fitting GA parameters if only one parameter is unknown.

Several modifications to the GA model have been suggested. Bouwer (1966) claimed that K_s should be modified by multiplying it by one half. Neuman (1976) derived expressions for hf based upon three time periods t, small, intermediate, and large. Several statistical correlations for K_s and h_f are listed (Brakensiek and Onstad, 1977; McCuen et al., 1981; Rawls and Brakensiek, 1982).

Richard (1931) took Darcy's equation and based infiltration into unsaturated soils upon matric potential driven by unsaturated hydraulic conductivity (Hillel, 1998). He proposed the following model:

$$q = -K(\psi)\Delta H$$

Where

q = water intake rate per unit time, or flux

K = hydraulic conductivity of soil at a given volumetric water content

ψ = matric potential

ΔH = hydraulic head gradient

If the continuity equation is introduced the Richards equation (Hillel, 1998) is:

$$d\theta/dt = \Delta[K(\psi)\ \Delta H]$$

Where

$d\theta/dt$ = change in volumetric water content as a function of total time

Philip (1957) coined the term sorptivity, which is the ability of a soil to absorb water by capillary process. Water is drawn to the soil mineral interface to the extent that it can flow against the gravity potential, i.e., upwards from a wet soil vertically into a drier soil (Clothier and Scotter, 2002). Philip (1957) proposed the following infiltration equation for vertical flow with water ponded on the soil surface:

$$I = St^{0.5} + A_p t$$

Where

I = cumulative water volume

S = sorptivity

A_p = saturated hydraulic conductivity if ponded

t = time

The vertical infiltration rate can be calculated by the following differential equation:

$$i = dI/dt$$

Where

i = infiltration rate

dI/dt = change in cumulative water volume as a function of total time

Youngs (1964) suggested a method for determining S as follows:

$$S = [2(\theta_t - \theta_i)K\Psi_f]^{0.5}$$

Where

θ_t = volumetric water content in the transition or wetting zone

θ_i = initial volumetric water content

K = hydraulic conductivity of soil at a given volumetric water content

ψ_f = matric potential at the wetting front

The Darcy-Buckingham Law (Wraith and Or, 2001) is the unsaturated soil analog version of the Darcy's saturated soil model. The DB Law is expressed as a flux q, or distance water moves through an unsaturated soil per unit time. The flux equation is:

$$q = -K(\theta)z\Psi(\theta)$$

Where

K = unsaturated hydraulic water conductivity of soil cm s^{-1} as a function of volumetric water content

q = water flux cm s^{-1}

θ = volumetric water content as a function of location and time

ψ = total water head as a function of volumetric water content

z = vertical coordinate

For this equation z is positive in the direction of gravity (vertical flow) with $z = 0$ at the soil surface. The differences between the DB Law and Darcy's Law (unsaturated versus saturated flow) are the dependence of hydraulic conductivity and the total head on the volumetric water content. The greater the ponded head, the more rapid the unsaturated hydraulic conductivity per unit time. A ponded surface for instance will yield a positive head, with z some value above the soil surface completely related to ponded depth.

Practitioners of the DB Law (Hillel, 1998) combine the continuity equation ($Q = vA$) into what is known as the Richard equation:

$$d\theta/dt = \Delta(K(\theta)\Delta h(\theta)) - (dK(\theta))/dz$$

Where

$d\theta/dt$ = change in volumetric water content as a function of time unit

Clothier and Smetten (1990) chose to write the formula using another form of the dependant variable $d\theta/dt$ adopted by Philip (1969):

$$d\theta/dt = [D(\theta)\ \Delta(\theta)] + [dK(\theta)/d\theta](d\theta/dz)$$

Where

D = soil water diffusivity defined as $K(\theta)dh/d\theta$

t = time

z = depth

K = hydraulic conductivity

These two analogs describe only vertical flow into unsaturated soils; the two dependant variable head h and volumetric water content θ can either be written in terms of h or θ. However, in all uses of various forms of Richards Equation, there are limitations. Philip (1969) described these limitations as follows:

- The representative volume of soil may not be representative based upon varying preferential pathways and macropores.
- Colloidal shrink and swelling of soils alters flow after soil colloids have shifted (even slightly).
- Soil movement as a function of wetting or drying significantly alters soil infiltration of water.

- Thermal inputs cause evaporation of water during infiltration and the redistribution of water flow in the soil volume (beneath the soil surface).
- Soil hysteresis may on the one hand increase water infiltration if drying, and decrease water infiltration if wetting; therefore unsaturated conductivity may be quite different in the same soil volume. Some soils will have higher volumetric water content when drying as compared to that soil when wetted at the same matric potential. Water in soils is less apt to leave a soil pore than water entering the soil pore, a phenomena known as the ink bottle effect.
- Sinks are neglected, i.e. plant roots may alter water infiltration and unsaturated hydraulic conductivity, and, plant roots extract water from the soil volume thereby reducing the volumetric water content per unit time.
- Flow q, is one dimensional (vertical, downward) and may suffice for rainfall events and irrigation applications over the field scale.

Wraith and Or (2001) offered three additional components, which helped, eliminate these limitations. They are:

- A boundary condition at the water supply surface, i.e. the surface area defined.
- An initial condition of all depths z, i.e. volumetric water content at any z at time = 0 equals $\theta_0(z)$.
- The given soil volume hydraulic parameters would be known: $K(\theta)$ and $h(\theta)$.

Richards Equation models deal almost exclusively with absorption of water through a volume of soil, which is not saturated. Little attention is given to redistribution over time and internal drainage (as affected by gravity but against a capillary gradient. Wraith and Or (2001) offer only that they are complicated for three reasons: infiltration and conductivity models (like GA and Richards Equations) do not explain redistribution of water once infiltration has ceased. This is important to the extent that after any rainfall event or irrigation application, there is a period of infiltration that occurs when the soil volume is not saturated. After the storm or irrigation has stopped, infiltration does not. That is, the continued movement of water based upon complexation variables (listed above by Philip (1969) occurs in all soils. Two, the initial conditions for the redistribution of water once absorbed are complicated and not easily modeled. Field soils may be and usually are hugely variable. Add to these variability's the differences in soil horizon properties, soil organic matter content and living root tissue, redistribution is extremely complicated. And three, the redistribution of water may be influenced by hysteresis near the surface over time, and capillary hysteresis at the lower boundary of a root zone.

Wraith and Or (2001) present a short description of various Richard Equation Models, which have been developed from Philip (1969) to Hills and Warrack (1993). However the bulk of work done in measuring infiltration and unsaturated hydraulic conductivity is based upon parameter estimation.

2.19 Parameter estimation

Characterization of water flow in soils is influenced by soil mineralogy (PSA), soil hydraulic properties, K_s and K, soil structure, i.e. the cohesive properties of the soil matrix with organic and inorganic compounds (roots, SOM, calcium carbonate, hydrogen ion or pH log), and three hydraulic potentials, or ψ energy state.

There are three forms of hydraulic potential (Hillel, 1998). They are:

- Gravimetric potential, ψ_g which represents the influence of gravity exerted on all water flow in soils, towards the lowest plane of the soil volume boundary from some depth z above this plane (usually soil surface), and through that plane in what could be called deep leaching. Movement of water against ψ_g requires work or energy (pumps are required), and movement of water at some point below the reference plane is assisted by ψ_g (water flows downhill).
- Osmotic potential, ψ_o is a function of the attraction of solutes in the soil volume. Salts, cations, and SOM exert an attraction to water molecules, thereby reducing flow per unit time, and may increase the volumetric water content given this affinity.
- Matric potential, ψ_m is the largest variable potential in soils. Potential in the case of soil water represents energy status of soil water. If, for instance, the soil water is at a pressure greater than atmospheric pressure, it is considered positive. The inverse is true. In soils that are at some volumetric water content less than saturation, the soil water is at some negative potential, or what is known as suction or tension. Matric potential exerts a force upon water, which is described using the same format. In soils that are at some volumetric water content less than saturation, the matric potential is increasingly less positive, or at a greater negative potential. Soil particles have a cohesive attraction to liquid and vapor water. As the volumetric water content decreases (drier soil) the remaining water in the soil matrix held more strongly to the mineral interface, thereby matric water has a more negative potential. Conversely as the volumetric water content increases, more water in the soil matrix is less apt to adsorb to water molecules

already physically closer to the mineral interface. In this case water flow increases because it has greater potential or less suction. Course textured soils have lower volumetric water holding capacity as the surface area of the bulk soil is much lower than fine textured soils. Finally, salts in soils tend to increase the volumetric water holding capacity given their attraction to water.

A reasonable approach at parameter fitting of unsaturated hydraulic conductivity was first established by deriving or fitting matric potential in units of energy of water potential to known volumetric water content of a given soil (Kosugi et al., 2002). The user assumes ψ_m is the driving independent variable in water flow, thereby establishing no influence ψ_o or ψ_g. One assumes the soil volume is homogeneous in terms of particle size distribution as a function of uniformity in three-dimensional space. An idealized water retention curve is usually based upon a log scale of matric potential, ψ_m and linear scale of volumetric water content. The volumetric water content is usually listed as a percent of total volume. A soil with a bulk density of 1.3 has a void space of 49%; therefore at potential saturation the soil has volumetric water content of 49%. An idealized water release curve appears in Figure 2.4.

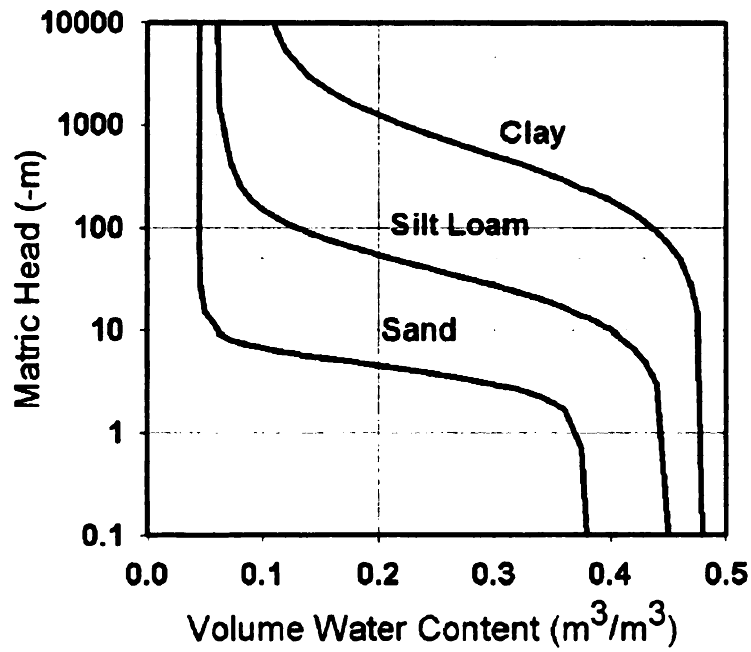

Figure 2.4 Idealized water release curve for sand, silt, and clay soils as matric head versus volumetric water content

Note the log scale of matric head on the y-axis. These values are matric head of pressure potential, which are negative values. At saturation the idealized soil volume has a matric potential of zero. As the soil dries the volumetric water content decreases. Course textured soils dry more readily with less negative water potential than do clayey soil. Related to this phenomenon is soil mineral surface area. Sand particles at 2mm to 0.05mm have a surface area of approximately one m^2 per gram of soil, whereas expansive clay like Smectite (2:1 layered) at 0.002 mm (2 μm) has a surface area of 750 m^2 per gram of soil (Flint and Flint, 2002).

Matric head or energy potential can be expressed in units of head. A water head of 1 m represents a pressure of 9.807 kPa, 0.0969 atm, and 0.0981 bar. The relationship between positive and negative potentials is equivalent. The values listed on the y-axis are negative potential, or increasing suction.

The water release curve, or Soil Water Characteristic Curve relates the energy state of water at a given volumetric water content. From a practical standpoint irrigators use these curves to schedule irrigation water to replace the used water through ET. For instance a sandy soil has a much narrower range of volumetric water content than clayey soils; the difference between FC and a 50% depletion value of 80 kPa is smaller in sands than in clays (Hillel, 1998).

Several assumptions are necessary before estimating parameters of a SWCC. They are:

- The volumetric water content θ, is equal to the saturated water content θ_s when soil matric potential ψ_m is zero. From a practice standpoint entrapped air causes an actual value of 0.85 to 0.9 θ_s.
- An air entry region on the curve at slightly negative potentials will not change the matric potential. This slight negative potential of water in a soil volume moves a slight amount of water out of the volume; this water volume is influenced only by slight negative potential and not matric potential. Physically, this water is a volume furthest away from the soil mineral interface and therefore the first to be moved out of the volume under a slight negative pressure.
- As the water potential becomes more negative the matric potential increases. The mineral interface begins to control movement of water, its cohesive attraction is slowing down flow and reducing the water potential. The air entry value is that point on the SWCC when water potential is controlled by matric potential.
- As the matric potential increases the volumetric water content decreases to a point known as residual water content, θ_r. From a practical standpoint θ_r may be

defined as some point on the matric potential curve which any further negative potential does not measurably reduce the volumetric water content.

- SWCC may be derived using a range $\theta_r < \theta < \theta_s$.

There are two predominant parameter models in use today (Kosugi et al., 2002). A review paper by Wang et al., 2002 provided some guidance for users in fitting BC parameters to derive a SWCC. The BC equation (Brooks and Corey, 1964) is:

$$S_e = (\theta - \theta_r)/(\theta_s - \theta_r) = (h_d/h)^n \quad h > h_d$$

$$S_e = 1 \qquad\qquad\qquad\qquad h < h_d$$

Where

S_e = effective saturation

θ = volumetric water content

θ_s = saturated volumetric water content

θ_r – residual volumetric water content

h_d = matric potential at air entry value

h = matric potential at some volumetric water content

n = power function which characterizes the width of the pore size distribution in the soil volume

Kosugi et al. (2002) examined the BC model and found it represented a good SWCC estimate for course textured soils with a clearly defined air entry value but not for finer textured soils and especially undisturbed field soils. Campbell (1974) altered the BC model by defining the dependent variable as degree of saturation instead of effective saturation.

van Genuchten (1980) provided a parameter estimation model and is today one of the most commonly used models in fitting data to derive a SWCC. His equation is:

$$S_e = [1 + (-\alpha h_m)_n]^{-m}$$

Where

S_e = effective saturation

α = a parameter to scale the matric potential

h_m = matric potential at some volumetric water content

n = value greater than one which establishes the curve slope

Carsel and Parrish (1998) used the VG model and fit two groups of soils. The first is Unsaturated Soil Database, or UNSODA (derived from the USDA ARS Soil Salinity Laboratory in San Bernardino California), and the Soil Survey Mechanics Laboratory in Lincoln Nebraska. The data in Table 2.4 are published in Or and Wraith (1999a).

Table 2.4 UNSODA and Soil Survey hydraulic parameters including water retention and saturated hydraulic conductivity values

Textural class	----- Water Retention-----					---- Saturated Hydraulic Conductivity ---	
	Nt	θr	θs	ă	n	Nt	Ks cm/d
				1/cm			
UNSODA							
Sand	126	0.058	0.37	0.035	3.19	74	505.8
Loamy sand	51	0.074	0.39	0.035	2.39	31	226.5
Sandy loam	78	0.067	0.37	0.021	1.61	50	41.6
Loam	61	0.083	0.46	0.025	1.31	31	38.3
Silt	3	0.123	0.48	0.006	1.53	2	55.7
Silt loam	101	0.061	0.43	0.012	1.39	62	30.5
Sandy clay loam	37	0.086	0.40	0.033	1.49	19	9.69
Clay loam	23	0.129	0.47	0.030	1.37	8	1.84
Silty clay loam	20	0.098	0.55	0.027	1.41	10	7.41
Silty clay	12	0.163	0.47	0.023	1.39	6	8.40
Clay	25	0.102	0.51	0.021	1.20	23	26.0
Soil Survey							
Sand	246	0.045	0.43	0.145	2.68	246	712.8
Loamy sand	315	0.057	0.41	0.124	2.28	315	350.2
Sandy loam	1183	0.065	0.41	0.075	1.89	1183	106.1
Loam	735	0.078	0.43	0.036	1.56	735	25.0
Silt	82	0.034	0.46	0.016	1.37	88	6.00
Silt loam	1093	0.067	0.45	0.020	1.41	1093	10.8
Sandy clay loam	214	0.100	0.39	0.059	1.48	214	31.4
Clay loam	364	0.095	0.41	0.019	1.31	345	6.24
Silty clay loam	641	0.089	0.43	0.010	1.23	592	1.68
Sandy clay	46	0.100	0.38	0.027	1.23	46	2.88
Silty clay	374	0.070	0.36	0.005	1.09	126	0.48
Clay	400	0.068	0.38	0.008	1.09	114	4.80

† Approximate sample size for Soil Survey database

Both groups of soils are listed using the 12 textural classes as defined by USDA. The columns represent values from laboratory analysis, the number of samples listed in the second column. The θ_r values are matric potentials at 1.5 MPa, or what is commonly known as Permanent Wilting Point. The θ_s values are given at a matric potential of zero. The next two parameters, α and n, are used to shape the SWCC. Listed on the far right are K_s, or the saturated hydraulic conductivity for each textural class.

These data are used to fit pairs of volumetric water content at a given matric potential, or θ_v,ψ_m. The USDA Soil Mechanics Laboratory uses the VG model to fit only two pairs of data: the volumetric water content at 0.033 MPa (FC) and the volumetric water content at 1.5 MPa (PWP). The UNSODA data are fitted with four or five data pairs. The data in Table 2.4 are fitted to the VG model and appear in Figure 2.5 (Leij et al., 1999).

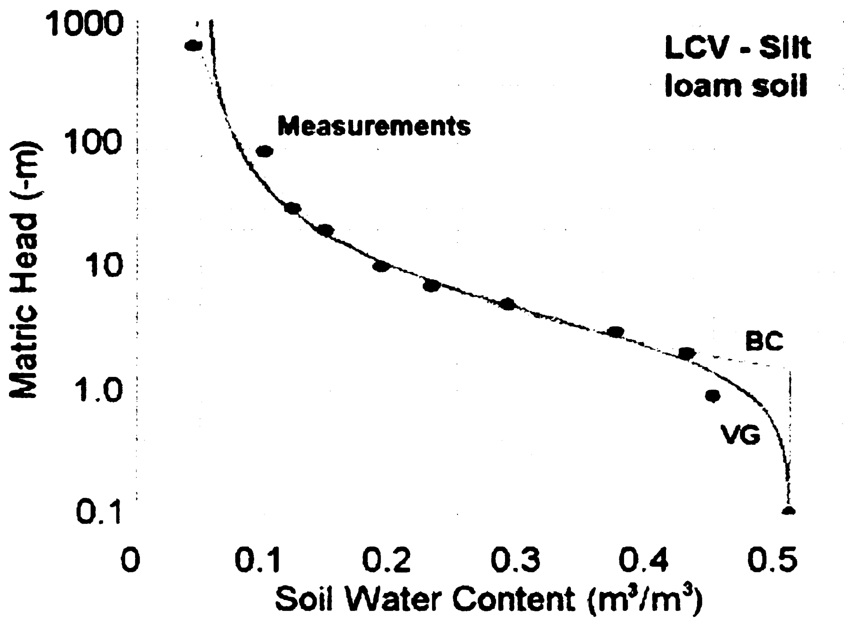

Figure 2.5 UNSODA and Soil Survey fitted water release curves (VG and BC parameters) for a silt loam soil

Note the volumetric water content is increasing from left to right in both graphs. The matric potential is listed in log h (head) form. In both figures the course textured sand and loamy sand SWCC curves dry with slight increases of soil matric potential. At the other end of the textural classification, the fine textured soils, clay and silty clay have higher volumetric water contents at higher matric potentials.

2.20 Layered soil profiles

The root zone of agricultural soils includes more than one layer of soils. The characterization of soil horizons is dependant upon textural class, bulk density, soil organic content, root mass, base cations, depth and temporal aspect of a water table, and farming practices (Tindall and Kunkel, 1999). Three properties of soil water in the root zone vary with different soil horizons. They are volumetric water content, matric potential, and unsaturated hydraulic conductivity. Volumetric water content is larger in finer textured soils. Matric potential increases (more suction or greater negative pressure) in finer textured soils. Unsaturated hydraulic conductivity is lower in fine textured soils. As clay particles increase in a horizon, water flow is slowed, water is held more tightly to soil particles (increased matric potential), tortuosity increases, and a volume of soil in this horizon contains more water than a horizon with courser textured soils (Hillel, 1998).

Such discontinuity of water flow and volumetric water content is problematic unless the relevant characteristics for each horizon are known. Differential horizonal or layer scenarios are presented below:

1. In clay over a sand layer, the flux rate is accommodated by greater matric potential in the clay layer. As more water is added to the clay surface, only when matric potential is near zero and gravimetric potential increases will water move into the sand layer. Water will not leave a small pore in clay due to significantly increased surface area and therefore matric potential, and enter the larger pore space in sand. Even though the sand

layer has higher unsaturated hydraulic conductivity, the clay layer controls flow until FC is reached.

2. In a typical agronomic field, a courser texture soil in the Ap horizon is above the E and Bt horizon. Clay has moved from the Ap through the E into the Bt. If the Bt is the bottom of the root zone, then water flux is slower, matric potential is higher, and volumetric water content is higher per unit volume of soil in this Bt horizon. In conventional tillage fields the Ap may have a lower bulk density than the E and Bt horizons, as well as greater soil organic matter and existing root mass. These increase water flux due to aggregation of soil particles and lower bulk density, but may increase volumetric water content due to organic molecules attraction to water. When organic matter is added to a course textured A or Ap horizon, volumetric water content is increased to the extent that farmers use this practice to reduce irrigation volume depths over the growing season. Organic matter additions provide energy for soil microbes as well.
3. For any given soil layer, as volumetric water increases matric potential decreases and approaches zero. As volumetric water content decreases matric potential increases, i.e. less water is more tightly bound to the soil mineral interface and thus greater negative pressure.
4. Large variances exist in well-aggregated soils. Water added to these layers, usually A or Ap horizons, will flow through soil in two processes. Water moving into large voids and cracks that exist outside of an aggregate flows rapidly. The attraction of water to the soil mineral

interface is negligible given the physical distance or space. Water flows via the gravimetric potential. Within the soil aggregate itself, however, water flux is slower, matric potential is greater and volumetric water content is increased. Soil aggregates may be saturated but overall unsaturated conductivity is slow.

0. Unsaturated conductivity is influenced by the presence of swelling clays. As the volumetric water content decreases the soil shrinks reducing pore size but creating cracks in the soil matrix. When this clay soil is rewet, the unsaturated conductivity is very rapid at the onset but as the clay swells it is reduced to almost zero. Factors that reduce this conductivity are reduced porosity, increased tortuosity, and reduction of pore conductivity as water leaves the large pores, and an increased water viscosity at the mineral interface.

The Green Ampt equation has been modified by Childs and Bybordi (1969) to describe infiltration in layered soils if the saturated hydraulic conductivity increases with greater soil depths. Hacham and Alfaro (1980) provided similar modifications using the GA equation in multilayered soils. Rawls et al. (1983) measured saturated hydraulic conductivity in multilayered soils and derived a FC value for individual layers based upon soil texture and bulk density. Starks et al., 2003 compared limited data with extensive empirical data to model the estimated root zone water content.

The objective of Stark's root zone water content work was simple: what are the minimum soil characteristics which must be known to derive root zone water content, or in the broader sense, the FWB? This work is unique in that similar work is not found anywhere in the literature. To the extent that a combination study involving minimal to maximal parameterization of both volumetric water content paired with a matric potential measurement, does provide an estimation of hydraulic conductivity in both saturated and unsaturated soils. Their premise's to describe or model infiltration, soil water conductivity, volumetric water content, and plant water uptake are:

1. The soil water characteristic curve, or SWCC, described as the paired relationship between the volumetric water content, θ and the matric potential Ψ.
2. Soil hydraulic conductivity K as a function of θ and Ψ.

Several laboratory and field methods are available for direct measurements on soil cores (Klute, 1986) but are tedious, time consuming, and costly (Starks et al, 2003). Other researchers have developed similar techniques to obtain these relationships from soil properties that are more easily measured, such as bulk density, soil texture, and FC (Rawls et. al., 1983; Woston and van Genuchten, 1988; Ahuja et. al., 1985; Williams and Ahuja, 1993; and Vereechen, 1995). Ahuja (1999) reviews many of these methods.

Ahuja and Ma (2002) suggested these methods fit into a hierarchy based upon simple to more complex. For volumetric water content, they are:

1. estimation from textural class only.
2. estimation from bulk density, textural class, and organic matter content.
3. estimation from (2) and one measured value of volumetric water content at some matric potential.
4. estimation from measuring the entire hydraulic function over the SWCC.

For estimation of conductivity, they are:

0. estimation of saturated hydraulic conductivity, K_s from textural class or effective porosity.
2. estimation of K_s from one of the four methods used to derive volumetric water content.

The Agricultural Research Service, ARS developed a process model called Root Zone Water Quality Model, RZWQM. This model used the volumetric hierarchy suggested by Ahuja and Ma (2002), and was therefore chosen for use. The user may chose any of the four hierarchal approaches (above) to determine the FWB based upon volumetric water content and the changes to this volume as a function of mass water balance (climate, irrigation, deep leaching, plant uptake, and evaporation) and time.

Starks, et al., (2003) asked the question "how well the limited data set simulates the hydrologic system and, in particular, gives satisfactory estimates from soil water profile (or FWB)? If a simpler data set could be used to estimate the FWB, thus time, energy, and resources could be saved, or they could be distributed over larger areas of interest (more fields). They further state:

> "Considering the time required for certain laboratory analyses, it would be of practical significance to determine the effect on soil water profile (FWB) estimates using soil hydraulic input data derived from standard laboratory analyses versus those obtained by relatively simple in situ techniques."

2.21 Root Zone Water Quality Model

The RZWQM integrates physical processes in time steps that predict the impact of agricultural practices, climate, and existing soil characteristics on the movement of water through the root zone (Ahuja, et al., 2000). The hydrologic component of this model controls the simulation of infiltration, redistribution, and plant uptake of water so that the change in soil water in the root zone can be estimated. The time period allows integration of climate events and agricultural practices with plant growth and volumetric water changes in the root zone in linear time. The shortest time period is five minutes, and the usual time period for a growing season or multiple growing seasons in a twenty-four hour period. Rainfall input mirrors hydrograph data; storm intensity and duration are given as breakpoint data.

The model requires an extensive amount of data. At a minimum RZWQM requires the driving variables of mass water balance (daily minimum and maximum temperatures, relative humidity, solar radiation, wind speed, and rainfall hydrograph) and the site-specific soil profile descriptions (soil horizons, hydraulic properties, reside cover, and crop physiologic specifications).

The hydrologic component of RZWQM includes a menu item: "soil hydraulics data input options" where the user may choose "limited data" or "full description." The limited data input include only two parameters, saturated hydraulic conductivity and volumetric water content at FC. The user may obtain these data from three sources listed within the model documentation (Hanson et al., 1962; Rawls, et al., 1983; and Ahuja, et al., 1988). The full description input allows the user to use any source including measured values and estimated values or any combination of the two.

RZWQM uses a modified GA equation for determining infiltration (Ajuha, et. al., 1993). The Modified GA equation is:

$$V = K_s[(\tau_c + H_0 + Z_{wf})/Z_{wf})]$$

Where

V = infiltration rate at any given time, cm h^{-1}

K_s = effective average saturated hydraulic conductivity of the wetting zone, cm hr^{-1}

τ_c = capillary drive or suction head (negative pressure) at the wetting front, cm

H_0 = depth of the surface ponding (vertical), cm

Z_{wf} = depth of the wetting front, cm

RZWQM uses a mass conservation numerical solution of Richard's Equation to solve the redistribution of water in the soil volume (Ahuja, 2000). The Richards Equation estimates the redistribution of water between rainfall or irrigation events. The equation is:

$$d\theta/dz = d/dz[K(h,z)(dh/dz) - K(h,z)] - S(z,t)$$

Where

θ = volumetric soil water content, $cm^3\ cm^{-3}$

t = time, h

z = soil depth, cm

h = soil water pressure potential, or head, cm

K = unsaturated hydraulic conductivity, cm h^{-1}

S(z,t) = sink term for water uptake by plant roots, cm h^{-1}

The GA and Richard Equations require saturated and unsaturated hydraulic conductivities, Ks and K, which can be estimated using the Brooks and Corey (1964) forms (Starks, et al., 2003). The θh and Kh relationships are modified in RZWQM as follows (Starks, et al., 2003):

$\theta h = \theta_s - A_1{*}|h|$

$\theta h = \theta_r + B|h|^{-\lambda}$

$Kh = K_s|h|^{-n_1}$

$Kh = K_2|h|^{-n_2}$

Where

A_1, B, λ, N_1, N_2, and K_2 are constants

θ_s = saturated soil water content, $cm^3\ cm^{-3}$

θ_r = residual soil water content, $cm^3\ cm^{-3}$

K_s = saturated hydraulic conductivity, cm h^{-1}

Starks et al. (2003) used five methods to determine the water in the soil profile, or FWB. The study area was located at the Little Washita River Experimental Watershed in Oklahoma. They methods were:

1. The soil profile depth was 60 cm. Each soil horizon was determined based upon soil textural class. Data were obtained from the USDA Soil Survey. RZWQM uses the textural class mean physical and hydraulic default values. This is the minimum level of input required by the model. These values are easily obtained with the appropriate Soil Survey; no laboratory or field investigation is required.
2. The second method includes the actual determination of sand, silt, and clay in the laboratory using the hydrometer method (Gee and Or, 2002), thereby more accurately defining textural class and therefore hydraulic parameters. Moist

bulk density is measured for each horizon (Grossman and Reinsch, 2002). Undisturbed (as possible) soil cores are obtained for each soil horizon when the soil is at or near FC (hence the term moist bulk density). Using PSA and BD values for each horizon, RZWQM derives soil texture and adjusts the saturated volumetric water content θ_s, based upon porosity. The mineral bulk density is set at a default value of 2.65 g cm^{-3}.

3. The third method includes the two measurements in method 2, with an additional measurement of volumetric water content at FC, or at a matric potential of – 0.033 MPa. Undisturbed field cores for each horizon are placed in a pressure tank at an atmospheric pressure of 0.033 MPa according to the Klute (1986) Method.
4. The fourth method is the same as method 3 except the volumetric water content at FC was measured in situ based upon two-day drainage data. The instantaneous profile method (Hillel, 1980) was used to determine soil hydraulic properties. Double ring infiltrometers were used; a 24-hour prewetting period was followed by periodic measurement of constant loss of water in the inner ring as the result of water moving into the saturated wetting zone at a constant rate. Once the vertical flux rate was constant conductivity was assumed to be in a steady state. Tensiometers were used to define that point when the soil layers were at FC. Gravimetric soil samples for each layer were obtained and given the known bulk density measurements, volumetric water content could be calculated. This method (4) differed from method 3 only in the way FC was determined. Method 3 used a laboratory analysis of

field cores, and method 4 the measurement was calculated after cores were obtained from a field adjusted wetting process using an instantaneous method of water infiltration from a ponded surface depth.

4. The fifth method included actual field measurements of tensiometers placed at different depths in the soil profile. The FC value was assumed to be the volumetric water content two days after saturated conditions with no additional water input (rainfall or irrigation). The K_s value was assumed to be constant for all horizons. This method (5) was included to mimic data that might be obtained from remote sensing (Mattikalli et al., 1998).

RZWQM requires vegetation data for determining plant water uptake and therefore removal of water from the soil root zone as transpired water. A number of agricultural crops may be selected, but crop growths curves and crop consumptive water use parameters can be used to build local crop databases. A turf or perennial grass crop component is based upon specifying rooting depth, LAI, and harvest cycles (Ahuja, 2000).

Landowner management practices are defined in RZWQM as inputs of tillage, planting, harvesting, and crop rotation if more than one growing season is simulated. Tillage depth, planting date with number of seeds per spatial area, harvest biomass, and length of growing season are examples the user obtains from the landowner. Irrigation water volume depths are obtained from the landowner and serve as water inputs with both a temporal and spatial stamp. Liquid manure as wastewater can be used as water inputs; nutrient components can be used for modeling nitrogen, phosphorus, potassium, and carbon. However, for the hydraulic component of RZWQM, irrigation of water and wastewater are given as volume depths (Ahuja, 2000).

The Starks et al., (2003) study included the use of TDR measurements for the 30-day duration of measurements at the south central Oklahoma site. The general vegetation in the 610 km^2 watershed was a mix of 60% rangeland, 20% cropland, and 20% forests, riparian areas, water bodies, urban areas, and oil waste land. The watershed is instrumented with 45 weather stations.

Starks et al. (2003) drew the following conclusions from this work:

1. RZWQM provided satisfactory results given that no hydraulic properties were calibrated or optimized over a linear time frame (except method 5), although some site specific measurements were used in methods three and four.
2. The study site was quite different from other studies that used RZWQM to determine the soil water profile on largely agronomic fields (Hanson, et al., 1999; Ma et al., 1998; Wu et al., 1996). The time study of 30 days was considerably shorter than what RZWQM was designed for: at least one growing season up to many growing seasons.
3. Martin and Watts (1999) stated the importance of correctly simulating plant water uptake via a crop growth curve, which correctly provide water consumptive values over the growing season. Not only is plant specie selection important, but also the root distribution in terms of three dimensional space is important in terms of water available in the root zone for potential plant water uptake.
4. One interesting yet surprising finding is that the use of hydraulic properties estimated from textural class show good agreement between predicted and

measured volumetric water content in the soil profile. And, in most cases the results were better than those where laboratory measurements were made (methods 2, 3, and 4). A similar study using RZWQM (Landa et al., 1999) showed the same results by using textural class data (USDA Soil Survey) to derive the soil water profile from predicted versus measured volumetric water content. Starks et al. (2003) claim that their study and the Landa study support the default values used in RZWQM as acceptable input for model applications which a have limited input data set.

5. Method 4, the in situ field measurements showed good agreement between the predicted and measured soil water profile over the 30 day study period. Starks et al. (2003) further state that these in situ measurements are preferable to those obtained by the detailed laboratory measurements in method 3. They base this conclusion on two factors. One, that there are large spatial variations in soil properties, and two, for a given textural class, the corresponding range of values can be large, thus using the average of each parameter range reduces the chance that a group of soil cores may not accurately reflect the spatial variability across the field surface and root zone. Further, Starks et al. (2003) state that using USDA Soil Survey mean values, or in situ field measurements require much less time, less expense, and importantly, may be considered more representative of actual field conditions.
6. Method 5 using TDR instruments that monitored volumetric water in continuous times steps (15 minutes) showed good agreement between predicted and the continuous measurements accumulated in a local data logger.

7. The most important values in this study were textural class, bulk density, saturated hydraulic conductivity, and volumetric water content at FC (- 0.033 MPa). The authors (Starks et al., 2003) conclude that limited data, i.e. the USDA Soil Survey, or the approach of measuring field in situ conductivity (using the double ring infiltrometer for determining steady state flux water infiltration) provided the best estimates of soil water profile (FWB) content. RZWQM is therefore parameterized with default values based upon the USDA Soil Classification Method that explain the physical and hydraulic properties based upon 12 textural classes of soils found in agronomic soils.

2.22 Literature summary

The FWB is determined by combining several components. The literature provides a number of methodologies for measuring these components. Integration of these measurements into an estimation of FWB requires a process strategy, or model like RZWQM. The model framework is built upon all components that establish the FWB, and more importantly, its change with respect to time. The flux of FWB, or the change in volumetric water content in the soil root zone over a specified time step (day, week, or growing season) can be known by combining the Mass Conservation Law and the Continuity Equation.

The FWB consists of two primary sets of components: those above the soil surface, and those below that surface. The literature includes apt description of both. The preferred equation for determining the FWB is set to zero; the additions and subtractions of water in the soil root boundary are characterized over a time step. The

Evett and Lascano (1993) equation [$0 = \Delta S + P + R - F - ET$] includes the additions of water above the soil surface, rainfall and irrigation as volume depths, and net water ponding that may occur if run-on exceeds runoff if the volume depth is applied at a rate faster than the infiltration rate of the receiving soil (P + R). The movement of water as matric flow upwards into drier soils in the soil root zone, from wetter soils below the root zone is an input below the soil surface. The converse is true. Water flow out of the root zone into soils beneath the rooting depth, or deep leaching occurs if the water potential gradient is downward as a result of gravitational potentials greater than matric potential. This below the surface input or output is described as the F term, denoting a flux. The final term is known by estimating water movement from the soil into the atmosphere as a vapor flux from the soil surface or from plant leaves. This is the ET term in the equation.

The change in soil water, ΔS, is a function of the soil parameters discussed earlier. These are variable and can be difficult to obtain. The determination of water in the root zone, or soil volume at some boundary, is influenced by the physical matrix of that volume, and how it behaves when the other additions and subtractions of water are known over that time step. For example a rainfall event of 5 cm as volume depth on the soil surface may entirely enter the soil matrix, may do so only in part, or may almost completely runoff the soil surface. To quantify the influence of this 5 cm rainfall event requires knowledge of the duration of that rain event, i.e. a thundershower lasting 20 minutes or a less intense storm lasting 20 hours. Course textured surface layers are likely to absorb water at a faster intake rate than fine textured soils. The relative bulk density of the surface soil may either increase or decrease this infiltration rate. Rainfall or storm duration and intensity are obtained from a local weather station; these data are published in almost all newspapers.

The run-on and runoff factor is more problematic to obtain. For agricultural fields, the assumption may be made that run-on and runoff are equivalent which thereby do not influence the change in water storage. However the redistribution of water in the soil profile can be influenced by the lateral or horizontal flow of water. This horizontal flux of water certainly occurs. If the scale of measurement is a field, the changes in horizontal flux may be balanced by the redistribution of the 5 cm rainfall event; the specific site, however, may receive more water (decreased horizontal flux) from another adjacent site, which has less water and therefore a higher horizontal flux.

The flux of water into and from the lower root boundary must be included in any FWB study. Once the rooting depth has been established, then this lower plane exists only as a depth and not an actual physical barrier. At a minimum the F term requires knowledge of the water table depth throughout the study period. If the water table is considerably deeper than the root zone boundary layer, then this saturation zone in soils will not influence the root zone water content.

When the upper layer of soils dries, water is moved from wetter soils at a lower depth into this dry layer. The term capillarity denotes the "wicking effect" of dry soils on water. This may also be termed redistribution of water in the soil root zone. If capillary water enters the lower boundary of the root zone, i.e. the soil layer beneath the root layer boundary is wetter, then this is a below surface input which may increase the water content of the root zone.

The change in soil water can be significant if crops are actively transpiring water to remain cool as water carries thermal energy into the atmosphere as a water vapor flux. Soils can lose water by evaporation during and outside of the growing season, thereby changing the soil water content.

Finally, the change in soil water is influenced by the physical parameters of the soil, including particle size, soil bulk density, and the SWCC. If the 5 cm rainfall event is moved completely into the soil matrix, the existing or antecedent soil water influences unsaturated hydraulic flow (conductivity) i.e. the redistribution of water in the soil matrix, and in turn, the amount of water that may be available to plants for transpiration, deep leaching, or surface evaporation. The importance of the SWCC cannot be overstated. The relationship of particular volumetric water content and its paired matric potential provides some knowledge of the influence of soil particles upon that volumetric water content. That is, if 5 cm of volume depth enters a soil that is near FC, the entering volume may cause deep leaching after a period of redistribution occurs. However, if another 5 cm volume depth enters a soil that is near PWP, then this volume may be almost entirely available for plant absorption if the growing crop is capable of extracting water from the root depth.

As a practical mater, the SWCC provides a range of volumetric water contents from which plants may absorb water, or available water capacity, AWC. Irrigation water management includes knowledge of this range. Irrigation schedulers use some percent of volumetric water depletion to schedule irrigation application at some volume depth. For instance if the average daily ET is 7 mm, and the AWC is 100 mm, then 50 % depletion (known as Maximum Allowable Depletion, or MAD) is 50 mm. An irrigation volume depth of 50 mm (2.2 inches) is applied every seven days. The irrigation scheduler knows that at 50 % MAD, the existing soil water is still available for plant absorption, but the hydraulic gradient is steeper to plant leaves from a drier soil. The scheduler knows that this steeper gradient may slow plant growth if the plant leaf warms and moves into a wilting stage.

The RZWQM is the state of the art model for determining the FWB. All of the equation parameters listed above are accounted for this model. Rainfall data are required in hydrograph form (duration and intensity). The ET components, wind speed, maximum and minimum ambient temperature, saturation pressure (relative humidity), and thermal input (solar radiation) are required as daily time steps. The duration of the growing season with crop growth stage curves are required. Tillage and other landowner activity are listed as activities which impact or alter the soil matrix (surface layer turnover, addition of organic matter, or application of fertilizer and herbicides), or addition water in the form of irrigation as a volume depth.

The model provides three scenarios for entering soil physical characteristics as mentioned earlier. These scenarios each provide the foundation by which RZWQM determines the two phases of water flow in soils: infiltration as originally described by Green and Ampt (1911) and redistribution as originally described by Richards (1931). RZWQM is the best model for deriving the FWB if enough parameters are known.

The use of RZWQM has included the evaluation of agronomic crops during one growing season in Midwest and Plain States. The study sites were called Management System Evaluation Areas, or MSEA. Wu et al. (1999) evaluated soil hydraulic parameters in Minnesota and found that over two corn-soybean rotations RZWQM performed well in predicting the FWB beginning in May of each year. Jaynes and Miller (1999) studied a MSEA site also using a two-season corn – soybean rotation in Iowa. Their particular interest was modeling herbicide transport, nitrate leaching, and crop yield. They found RZWQM performed reasonably well in predicting crop yield. Herbicide transport in drainage water and nitrate leaching were not accurately simulated; the authors state that field dynamics may not be captured in the model. They include macropore flow characterization, soil microbe activity in nitrogen cycling, and herbicide adsorption kinetics on the soil mineral interface.

Ghidey et al. (1999) studied the performance of RZWQM at a Missouri MSEA site. Again, the study was done on two years of corn-soybean rotation. The Model accurately predicted the FWB over the two years, but the soil water measurements were taken only during the growing season. The authors concluded that the model should have a parameter for cracking soils, thereby more accurately characterizing water flow and solute flow past the lower root boundary. In particular the authors had investigated the impact of runoff events that result from high intensity but short duration storm events. They concluded the model over predicted runoff events after long periods of dry weather; the presence of large cracks in the soil reduced runoff. The model has a macropore option that the author used to more accurately predict chemical losses due to seepage.

Workers in Nebraska (Martin and Watts, 1999) studied RZWQM on a MSEA site using two years of continuous corn. This site was irrigated instead of rain-fed as in the other MSEA sites. The authors used two irrigation rates and three fertilizer rates. The model accurately predicted soil water in the 150 cm profile during the growing season but simulated lower soil water content both before the growing season in spring and after the growing season in fall.

A study to integrate over winter analysis of soil water in a profile was conducted by Flerchinger et al. (2000) for a study site in Pullman, Washington and Akron, Colorado. Their interest was evaluating northern latitudes where soils freeze during some of the winter period. The authors combined a Simultaneous Heat and Water Model (SHAW) with RZWQM to modify the heat balance in the surface layer. RZWQM had assumed the soil surface temperature is the same as the ambient air temperature. Coupling SHAW output to RZWQM correctly accounted for the colder climates especially when the soil surface was frozen. However the authors state that in those soil layers that are frozen, the prediction of soil water was less accurate. The soil water content in soil layers beneath these frozen layers were accurately predicted.

Specific applications of RZWQM include soil water transport and drainage studies in Oklahoma (Ahuja, et al., 1993), North Carolina (Johnson et al., 1995), Illinois (Singh and Kanwar, 1995; Johnson et al., 1995), Minnesota (Cook, 1996), and Iowa (Walker, 1996; Kumar et al., 1998). Evapotranspiration studies were conducted by Farahani and Baush (1995) and Ma et al., 1998, on agronomic crops in Colorado and Nebraska. Organic matter and nitrogen cycling were simulated using RZWQM by Hanson et al., 1995 and Ma et al., 1998. Nokes et al., 1996, examined plant growth in an attempt to fine tune carbon deposition in plants and thus improve the crop growth curves for corn, soybeans, and wheat. Azevedo et al., 1997, simulated pesticide half-life and Ahuja et al., 1996 examined pesticide processes in soils.

Several papers were published which explained RZWQM itself. Hansen et al. (1999) provided calibration background processes that integrated the six components of the model into a research driven process-based tool for research work. Watts et al. (1999) discussed the effort to incorporate the MSEA project into RZWQM by studying corn and soybean production in several states. Ma et al., 1998, provided a comprehensive review of RZWQM applications.

2.23 Research needs

Knowledge of the FWB by landowners, including livestock farmers, is not well known. Yet the integration of this knowledge is required if irrigation water management is to be used, and some understanding about the FWB is required when livestock operators apply liquid manure to receiving soils in a field.

Livestock farmers may be required to install waste storage facilities on their farms. Technicians do not have a site specific tool for predicting the storage period length based upon meeting application criteria in performance standards (590 and 633 NRCS Standards). Any site specific tool will require knowledge of the FWB over a period of time, usually at least one year, both in and out of the crop growing period.

2.24 General scope

According to the U.S. Department of Agriculture's National Agricultural Statistics Service 2002 Census (USDA, 2004d)) there were slightly more than one million livestock owners in the United States. The farm gate value of livestock sold in 1997 was 98.8 billion dollars, accounting for 50.2% of all agricultural products sold. On these livestock farms, there were approximately 98.9 million cattle and calves, 18 million dairy animals, 61 million hogs and pigs, 7.8 million sheep and lambs, 2.4 million horses and ponies, 367 layers and pullets, and 125 million turkeys. The farm gate value of livestock production sold in 1997 was 101 billion dollars. The average size of farm with more than $10,000 of sales was 342 hectares, and the average age of farm owners was 54.3 years old. Finally, there were 375 million hectares of land in the U.S., with 41 percent of these ha in crop production. Of all land use in the U.S., 19 percent is cropland and another 22 percent is pastureland. The scope of farming activity across the U.S. landscape is significant, both in terms of spatial area and economic strength.

The distribution of production agriculture, however, has changed significantly during the mechanization and labor efficiency gains of this country. Beginning with the invention of the tractor, the plow, the seed drill, and the automatic milking machine in the first half of the 20th Century, farmers have moved towards automation and increased productive units. In the second half of the Century, herds were consolidated into larger herd sizes, small farms were combined into larger farms, and many farmers sold out or left the business resulting in fewer numbers of farmers across the rural landscape. These consequences are the result of economies of scale, machinery size, a well developed transportation infrastructure, a farm banking industry, advances in technical assistance through Land Grant Universities, and a population discovering other livelihoods besides farming (Gardner, 2002).

The U.S. Environmental Protection Agency reports (USEPA, 2003) a figure of 1.3 million livestock farmers in 2002. These livestock farms have dairy, swine, poultry, beef, and to a lesser extent other domestic species grown for meat, milk, and fiber. Some livestock owners grow agronomic crops for sale or harvest them as livestock feed for their own herd. For this reason, "farmer" will be used in this thesis to describe a livestock owner, a livestock rancher, or a landowner.

Larger herds are confined in barns for most or all of their productive lives. For dairy farmers, the drive through free stall barn is now a common housing and feeding facility. Many cows live their entire productive lives in these barns. The free stall is bedded with sand or organic bedding. The floor is concrete, and farmers clean these floors, or alleys, by scraping or flushing the manure volume into a reception tank or pit. Depending upon the facility, manure volumes are handled in one of three ways. One, manure is transported to a crop field for land application. The delivery system may be over the road hauling with a honey or slurry wagon, or pumped through buried or overland pipelines to an irrigation system. Two, manure may enter a treatment facility, such as an anaerobic digester, a solids separator, or settling basin. Three, the manure volume is discharged by gravity or pump to a manure storage pond. The storage pond usually contains milk house effluent and rainwater volumes; the rainwater can contribute a large volume of water into the storage pond if the drainage area is not diverted (roof, driveway, or any other non-manured surface).

A challenge for farmers and Technical Service Providers, TSP's (engineers, agronomists, nutrient management specialists, and contractors) is deciding when storage is necessary and if so, at what capacity? If a farmer with livestock in confinement and the TSP's decide that some storage is necessary, thereby shifting management of the manure volume from daily haul (option one above) to some form of manure storage, two questions arise. One, how much capacity is enough, and two, when is the storage period during the calendar year?

The Federal Clean Water Act of 1972 (USEPA, 1972), followed by the Federal Clean Water Action Plan of 1997 (USEPA, 1997) set the stage for the Environmental Protection Agency's effort to monitor and regulate point source and non-point source waste streams, including livestock manure, through a comprehensive program for protecting our Nation's water. Larger livestock farms have moved from NPS to Point Source designations as they have installed manure systems, especially manure storage ponds (USEPA, 2004). At the state level, Departments of Agriculture, Environmental Quality, or Natural Resources operate statewide monitoring and regulatory activity within the guidelines of the EPA General National Pollution and Discharge System Permit (USEPA, 2004). At the local level, governmental agencies further refine livestock manure activity with site-specific requirements, including buffer zones, storage pond location from wellheads, and air quality regulations.

Livestock owners can receive help from TSP's, who assist them with the technical components, system design, management, and regulatory permitting aspects of answering these questions correctly (USDA-NRCS 2004a). Manure systems are designed by the Natural Resources Conservation Service, or by private engineering firms. Some livestock owners participate in Federal Cost Share Programs, such as the Environmental Quality Incentive Program, or they chose to pay for the construction costs themselves. USDA-NRCS provides technical standards in the form of Engineering Construction Standards, Conservation Practice Standards, and various Field Office Technical Guide Sheets (USDA-NRCS 2004b). Public and private TSP's as well as livestock owners use these standards. The management criteria of manure systems are constantly changing. The USDA-ARS, USDA-NRCS, and Land Grant Universities are the usual providers. The components of a manure system, including technical, system design, management, and regulatory permit are compiled in a document known as a Conservation Plan (USDA-NRCS 2004c).

Most livestock owners have a conservation plan. Some are formal documents on file with the USDA Farm Service Agency Office and NRCS, as well as the state and local agency. Such conservation plans are part of the landowners RMS, or Resource Management System, in which Soil, Water, Air, Plant, and Animal (including Human Considerations) resources are considered in detail (USDA-NRCS, 2004c). Some are less formal. A conservation plan may consist of a Comprehensive Nutrient Management Plan (USDA-NRCS 2004c) that accounts for the spatial application of dairy manure nutrients on cropland at agronomic rates. Still other landowners may have an informal set of instructions as to how the farm manure system is managed.

2.25 Current scope

The Federal Environmental Protection Agency issued its Final Rule (USEPA, 2003) establishing permitting guidelines for livestock owners. EPA objectives include a robust monitoring program of Concentrated Animal Feeding Operation's, defined as large or medium size herds confined for at least 45 days with a waste-handling facility (USEPA, 2003). By definition, CAFO's are point sources of potential manure discharge. EPA estimates that in the U.S. there are 15,500 CAFO's that will require participation in the National Pollution Discharge and Elimination System (USEPA, 2003). The agency reports a national manure volume of 500 million tons of manure on all livestock farms, and for CAFO's, 300 million tons (USEPA, 2003). The impact of confining and concentrating animals into barns on concrete on these large CAFO's is clear: CAFO's make up approximately 1.5% of all livestock farms but produce 60% of the total manure volume in the country. EPA's goals include having farmers eliminate surface discharge of livestock manures into surface water bodies, applying manure nutrients at an agronomic rate, and reducing the impact of deep leaching of nutrients in groundwater (USEAP, 2003).

As owners of Concentrated Animal Feeding Operations, livestock owners are updating their conservation plans, CNMP's, and if necessary, adding or updating manure handling, storage, and application components. CNMP providers (TSP's) are being trained to meet this demand (USDA-NRCS, 2004a). The CNMP is a document based on the accounting and flowpath of manure nutrients, specifically nitrogen, phosphorus, and potassium based upon statewide standards, known as the NRCS 590 Nutrient Management Standard (USDA-NRCS, 2004b). Manure nutrients are applied to crop fields in amounts that meet expected crop uptake, similar to applying fertilizer to a non-manured crop field. Depending upon location and soil fertility, manure nutrients may be restricted to the first limiting nutrient, generally phosphorus or potassium. On fields where manure is applied, a field-specific risk assessment tool will be completed by the TSP and discussed with the livestock owner.

The importance of the 590 standard as a CNMP component cannot be overstated. The standard is maintained by the USDA-NRCS at the Federal and State Level (USDA-NRCS, 2004b). It is a practice standard that provides guidance to the farmer for manure nutrient accounting and flowpath in both a spatial and temporal framework. However, one deficiency in the standard exists and becomes the foundation of this research work.

2.26 Research gap

The technical knowledge for nutrient management is based upon a reasonable understanding of nutrient accounting and flowpath through the farm system. The technical knowledge for designing and building manure storage ponds to date is extensive (USDA-NRCS, 2004b). Primarily driven by NRCS specifications, farmers, regulatory personnel, and the public can be reasonably assured that if built correctly, manure storage ponds do not represent a hazard for leaching in excess of design criteria.

The technical assistance for properly applying liquid manure and irrigation water management as a function of field water status both in and out of the growing season are not sufficient. This deficiency may be stated as a research gap. Here is the wording of the National 590 Nutrient Management Standard:

- "Nutrients shall not be applied to frozen, snow-covered, or saturated soil if the potential risk for runoff exists.
- Nutrient applications associated with irrigation systems shall be applied in accordance with the requirements of Irrigation Water Management (NRCS Standard 449 Irrigation Water Management).
- The application rate (in/hr) for material applied through irrigation shall not exceed the soil intake/infiltration rate. The field capacity of the soil shall not be exceeded at any time." (Page 3).

Here is the wording of National 449 Irrigation Water Management Standard:

"The following principles shall be applied for various crop growth stages:

- The volume of water needed for irrigation shall be based on plant available water holding capacity of the soil for the crop rooting depth, management allowed soil water depletion, irrigation efficiency, and water table contribution.
- The irrigation frequency shall be based on the volume of irrigation water needed and/or available, the rate of crop evapotranspiration, and effective precipitation.
- The application rate shall be based on the volume of water to be applied, the frequency of irrigation applications, soil infiltration and permeability characteristics, and the capacity of the irrigation system."

Currently, these standard criteria are unanswerable. Farmers and TSP's lack the knowledge of the FWB to understand water flow as functions of infiltration, redistribution, drainage, and the relationships of volumetric water content and pressure potentials. In normal conservation planning activities, TSP's have avoided this step due to inadequate research, the lack of a model framework for extending the data set beyond the experimental field, and the use of a reductionist approach instead of a systems approach.

Chapter Three. Study Area

3.1 Willamette River Basin

A starting point for a systems research study is definition of macro scale, further defined by spatial and temporal boundary, and then comprised of field units. The macro scale component is the Willamette River Basin (WRB) [USGS Hydrologic Unit Codes: HUC 1709005 (North Santiam), and HUC 1709007 (Middle Willamette)] in Oregon (Hulse et al., 2002).

This geographical area is 160 km north to south and 161 km east to west (29,728 km^2), situated between the Coast Range to the west and the Cascade Range to the east. The latitude boundaries are approximately 121.38° W and 123.51° W. The longitude boundaries are 43.24° N and 45.70° N. Elevation varies from 3 m above mean sea level (confluence of the Columbia River) to a snow capped peak, Mt Jefferson, on the west side at 3199 m.

The WRB recent topography was derived from volcanic eruption, lava flows, and mudflows along with glacial outwash, and river alluvium. The northern end of the WRB (and the study site for this work) is underlain by basalt erosion over the last 15 million years. 15,500 to 13,000 years ago the ice dams formed large lakes in Montana that once broke free, caused sedimentary deposits to settle on the valley floor. Closer to the river systems, primarily the Willamette River, sediments were slightly coarser (larger) thereby giving rise to better-drained soils that become the primarily agricultural region of the basin.

Humans have lived in the Basin for about 10,000 years. Several Native American tribes, including the Calapooia, Luckiamute, Yamhill, Clackamas, and Kalapuyan lived on the landscape especially near the river systems. Euro-American Settlers moved into the Basin about 1820-1840. They were drawn here by fertile soils, moderate climate, and a river transportation system. The Oregon Trail is the journey of settlers arriving at the Basin; pioneers left the Midwest in search of a new life in the wilderness. Oregon was organized as a territory in 1848 and admitted as the thirty-third state in 1859 with a population of 13,294 settlers as they were known. One hundred years later the population of the WRB had grown to 1,521,341. The population of the Basin surpassed 2 million in the late 1980's, and the present population (2003) is approximately 2.3 million people. The three largest cities in the Basin are located on the Willamette River. Portland is Oregon largest city, Eugene is Oregon's second largest city, and Salem is Oregon's Capital City.

3.2 WRB weather

The WRB has a modified marine climate (Hulse et al., 2002). Influenced by the Pacific Ocean, the Coast range and the Cascade Range, the weather pathway is generally from west to east. The marine air is generally nearly saturated with water. The western Basin boundary, the coast range, cools the air as it rises in elevation. Due to a lower saturation vapor pressure at higher altitudes, the moisture condenses as water droplets and falls as rain or snow. Most of this precipitation falls on the west slope of the mountain range. A drier air flows into the Basin, although enough moisture exists for rainfall especially in late fall, winter, and early spring. As clouds near the Cascade

Range, the elevation lift once again condenses water as rain or snow. Land (foothills) near the Cascade Range can receive significantly more precipitation than more central valley locations.

The agricultural farming areas are found near the central valley locations. Here, about 70% of the annual precipitation of 1,120 mm occurs during November through March (150 days). During most of the growing season for agricultural crops, less than seven percent of annual precipitation occurs in June, July, and August. Accumulative snowfall is rare and if so, last no more than four to five days.

Average maximum temperatures are 17.8°C and average minimum temperatures are 5.6°C. Only an average of 15 days annually do temperatures drop to 32.2°C. Temperatures reach below freezing about 60 days annually and when they do, only slightly below freezing. In July, the driest month, RH averages 40%. The average for the year is 89%. The last freezing temperature day can fall in March or April and June in extreme cases, and the first fall freeze at the end of the growing season is usually in late October or early November. Therefore the growing season can be as long as almost nine months to as short as six and a half to seven. Typical growing seasons are 225 days or seven and a half months: April through the middle of October.

3.3 WRB Soils

An in-depth discussion of soils sampled for this research project is found in Chapter Three. The discussion in this chapter pertains to a general morphology and inventory of soils in the WRB (Hulse et al., 2002).

The soils in this Basin have formed from eight major kinds of parent material. Each is described below:

1. Recent Alluvium. These are the youngest soils in the Basin. They are flood remnants found near surface waters, streams and creeks, washed from basic igneous rock.
2. Gravelly Alluvium. These coarse soils were deposited as outwash from the Cascade mountain range during the late Pleistocene glaciation (15,000 –10,000 years ago). The predominant soils are gravel and sand.
3. Young Silty Terrace Alluvium. These soils are found in the best agricultural fields of the Basin, including the soils in this study. They are the result of floods settling stratified sand, silt and clay sediment that contains large amount of quartz, in regions above the flood plain (do not flood in modern times). These soils are somewhat modified by windblown material and slight weathering, but are no older than 20,000 years.
4. Weak Consolidated, Old Gravelly Alluvium. These are older, more highly weathered soils derived from basalt. They are found in elevations above the valley floor flood plain, in what are known as foothills. Primarily comprised of silt, they are easily eroded and therefore are usually planted to perennial crops like Fescue or Ryegrass seed.
5. Colluviums from Basalt and Massive Tuffs. These soils are derived from the Miocene and Pliocene, two to 20 million years ago, and are usually highly weathered. They are foothill soils and higher, populated by timber and brush. Agriculture crop production is minimal.

6. Sedimentary Alluvium and Colluviums derived from Tuffaceous Sandstone and Shale that are made from sandstone are quite old, 20-50 million years ago. Soils are suitable for timber and brush and are not usually farmed.
7. Glacial Till. These are recent soil laid down during the lattermost Glacial Period of 18,000 years ago during the Wisconsin Period. These soils are course textured or made up of gravel or cobblestones. Soils are suitable for timber and brush production and are not usually farmed.
8. Organic Material. These muck or peat soils were deposited in former shallow lakes during the Wisconsin Period. Little development of the soil profile has taken place; however these soils are quite productive for some agricultural crops.

3.4 Soil capability classification

Soil Capability Classification is a ranking system that describes a soils' suitability for agricultural crop production. The system ranks soils from I to VIII, for eight classification classes. A Class I soil has no limitations and therefore is the most adapted towards all kinds of agricultural crop production. A Class VIII has many limitations and is generally not suitable for any crop production. A graduating scale from productive to non-productive is further refined with lower case letters that designate what kind of restrictions make a particular Class of soil fit in that rank. Examples are e – erosion potential, w – wet soil, and s – shallow soil).

For soils in the WRB, 27% of all soils are found in Class I, Class II, and Class III, generally considered the soils that can be tilled, farmed, and used to support agricultural production. Classes IV though VII comprise 71% of all soils. These are soils suitable from timber, brush, Christmas trees, woodlots, and open meadow grass production. Class VIII soils, at the remaining 2%, are unsuitable for any plant growth other than a remote tree or brush plant having found a pocket of soil to grow. The soils examined for this study are Class II or Class III, and in a majority of fields, carry the restriction of w – wet soil.

3.5 WRB dairy industry

In 2002 according to Oregon Department of Agriculture, 94 dairy farms produce Grade A milk in the WRB (Oregon Department of Agriculture, 2004a). Herd size ranges to as few as 24 cows to as large 2,800. Dairy farms are predominately owned by Dutch and Swiss owners, having migrated from other parts of the U.S. or overseas. Many dairy farms are second and third generation; a fourth generation farmer, usually a graduate of a Land Grant University or technical college that offers dairy training, operate several farms. Latino workers are commonplace on these dairies.

The majority of milk enters the fluid or manufacturing pool and is transported interstate as finished dairy products. Few shipper handlers exist, but for those producing and processing milk, the end product is usually fluid milk. There is an increased interest in organic dairy farming in the WRB. These farmers produce for a growing market, and while finding organic feed is a challenge, for those smaller herds (<200 cows) this niche market helps them maintain profitability.

Dairy farmers in the Basin have built free stall barns that have individual stalls for cows at rest, and feeding mangers for handling the total mix ration volume of feed ration. Cows live their entire productive lives in these barns and the milking facility, except during the dry period when they may be grazed if the grazing paddock is dry enough. Floors are entirely concrete at slopes of one half to three percent; the predominant slope for alleys is one and a half percent, providing direction for the flush volume and ease of manure scraping flow. In both cases, the manure volume is directed to a reception pit or tank. From here, the manure volume flowpath may be one of three directions: directly hauled to a crop field, pumped or gravity flowed to a settling basin or treatment process, or pumped into a waste storage pond. Generally, the manure flowpath includes the manure storage pond. This pond also receives rainwater and wastewater from the milk house.

The four dairy farmers in this study own and operate typical facilities. All have manure storage ponds designed by USDA-NRCS and built by private contractor under the engineering guidelines of NRCS Engineering Staff. All systems were part of a cost share program through the U.S. Government.

3.6 Regulatory oversight

Oregon is an EPA Region 10 designated state (ODA, 2004b). Historically, Oregon Department of Agriculture maintained a General Water Pollution Control Facilities Permit that provided a regulatory permitting mechanism for dairy farmers across the state. A recent shift has occurred (2001) towards an EPA National Pollution Discharge Elimination System General Permit for the dairy industry in the state. The permit is jointly owned by Oregon Department of Environmental Quality, but is housed in and regulated by ODA. EPA has released its Final Rule in 2003. Oregon is adopting the necessary strategy towards maintenance of the General Permit, with the additional criteria of requiring a large Concentrated Animal Feeding Operation to obtain an individual Federal NPDES Permit (outside the boundary of the General Permit), or an Oregon Water Pollution Control Facilities Permit.

Federal Law 40 CFR Part 122 and Oregon Law ORS 468B.050 (Oregon Department of Agriculture, 2004c) prohibit the discharge of pollutants to waters of the state without a permit. ODA describes pollutants as: biochemical oxygen demand (BOD), total suspended solids (TSS), organics, bacteria, and the nutrients nitrogen and phosphorus. All dairy farms will have an updated permit and meet performance criteria by December 31, 2006. Two new criteria include requiring the farmer to keep a more robust set of records, such as soil test values, nutrient accounting and flowpath, and weather conditions, and an Annual Report (AR). The AR will provide ODA with a historical record of nutrient and volume fate. Additional inventory requirements track animal numbers, acres receiving manure, crop yield, and if performance criteria were actually met. An ODA employee will inspect dairy farms at least twice annually.

3.7 Study introduction

In October 1995, the investigator and several NRCS staff met in Salem Oregon for a technical transfer meeting. The end result of that meeting was the initial planning for this study. The author agreed to take the lead in a long-term study attempting to determine the FWB on four typical dairy farms in the WRB. The group of approximately 20 scientists and engineers identified this one objective as the most critical research gap for the dairy industry, the CAFO program in Western Oregon and specifically manure application on cropland as an acceptable agronomic and hydraulic practice in the WRB.

A proposal was submitted to the Oregon Dairy Farmers Association - Portland, Oregon Department of Agriculture - Salem, Oregon Department of Environmental Quality - Portland, Oregon NRCS - Portland, and Oregon State University – Corvallis. The proposal requested funding for the study and a 0.5 FTE by the author to conduct it. Both were approved. The majority of the funding came from a DEQ 319 Grant administered by Oregon DEQ and Region 10 EPA in Seattle. All other groups supported this study with additional dollars, material, field time, and equipment. During the first half of 1997, the 0.5 FTE of time (primary investigator) and the funding and additional support were ready to begin. The next section describes in some detail the materials and methods used for the initial implementation and the strategies used for maintaining the study for a five-year period.

3.8 Dairy cooperators in the WRB

The task of selecting cooperators was straightforward. Very large herds and very small herds were considered outliers and therefore not representative of a typical WRB dairy. The target herd size (range) was 250 to 500 cows.

Three selection criteria were used:

1. Cooperators would agree to a long-term study of five years. Access to the farm at any time for measuring any parameter, such as irrigation flow rate, obtain soil samples, or recording pump hours by the investigator or technician was an absolute requirement. Cooperators would agree to any examination and scrutiny of management practices, farming techniques, and records accumulated for this study. In other words, access to all records with nothing kept from the record

keeping process. One significant aspect of this particular requirement is the study duration of five years. During the initial selection period, the investigator interviewed 14 dairy farmers, and every one of them mentioned that this study duration was longer than any other study they had participated with.

2. Cooperators operated businesses that were likely to remain in business for the study period. The attrition rate of dairy farmers leaving the dairy business in Oregon is approximately five percent annually. A consideration was given towards the family dynamics. That is, an assessment of a stable farm family environment, among family members on the farm and away from the farm, as well as a labor force that exhibited enthusiasm for working on the farm with relatively low turnover. The investigator interpreted these assessments subtly. No written or formal evaluation was conducted.
3. Cooperators would agree to acknowledge, accept, and change any management practice and farming techniques during the study period based upon the recorded results and the recommendations of the investigator and other technicians. The objective of this requirement was the basis of all planning activity: records are used to monitor and evaluate performance. When the evaluation review suggests corrective change, then the farmer considered an alternative strategy.

Four dairy farms and cooperating farmers were selected during the summer 1997. The author made the selections. The agreement between the investigator and the farmer included the following items:

1. The investigator will provide the cooperators with individual record analysis during the study period. Specifically, soil test analysis, animal inventory, a

summary of water input for irrigation and liquid manure volumes, and a summary of crop yield. All of these were done on a field basis annually.

2. The investigator would cover all expenses incurred on each farm though the DEQ 319 Grant or other public funds. The investigator or SWCD or NRCS personnel would provide labor requirement.

The individual farm records are the property of the cooperator and the investigator. Cooperating farms are identified by numbers one though four. Analytical data derived from all laboratory analysis is the property of the cooperator and investigator, and identified only by farm number. Individual fields are numbered one through n.

3.9 Cooperating dairy farm descriptions

A description of each selected farm follows. All four owners and their families agreed to the selection criteria requirements, and the record keeping protocol. Each farmer had a good working relationship with NRCS and SWCD, the regulatory community, ODA, DEQ, and Oregon State University Extension Service. Each dairy had been in business at least 25 years and was now operated by at least the second generation. All have plans for change, primarily in improving efficiency not increasing herd size. In each case, the second generation is college educated with at least a two-year degree. There are young children on each farm (third generation), and in three out four farms, retired family members living on or near the farm. All farm owners were eager to participate and through the five- year period, endured the record-keeping requirement long after the newness worn off.

1. Farm 1. This dairy farm is located (facility headquarters) at 45.44°N and 123.31°W. Approximately 320 dairy cows are housed in total confinement free stall barns. Manure is scraped into two reception tanks and subsequently pumped directly into one of two storage ponds. Storage pond capacity is 30.8 x 10^3 m^3 (25 acre feet). Manure is applied using a traveling irrigator (big gun on a hard hose reel) with an average output of 1.211 m^3 s^{-1} (320 gpm). All animals are confined 365 days per year. Cropland includes 58 hectares (144 acres). Crop rotation is corn silage for a summer crop and annual ryegrass for a winter crop. Both are mechanically harvested as silage, stored in bunker silos on the farm, and fed to the dairy herd. This is a first, second, and third generation farm.
2. Farm 2. This dairy farm is located (facility headquarters) at 45.71°N and 122.93°W. Approximately 220 dairy cows and 200 dairy replacement heifers are housed in partial confinement free stall barns. Manure is scraped in two barns (heifers) and flushed in one barn (cows) into one reception tank. Manure is subsequently pumped over a sidehill manure separator before entering one of two storage ponds. Storage pond capacity is 7.4 x 10^3 m^3 (six acre feet (AF)). Manure is applied using a traveling irrigator with an average output of 1.022 m^3 sec^{-1} (270 gpm). Heifers are grazed about seven months per year, and cows are grazed about six months per year. Cropland includes 104 ha (258 acres). Crop rotation includes permanent pasture, corn silage and perennial grass silage for summer crops, and annual ryegrass following corn for winter crops. Most feed is mechanically harvested; some feed is grazed. All feed is fed to the dairy herd. This is a first, second, and third generation farm.

3. Farm 3. This dairy farm is located (facility headquarters) at 44.87°N and 123.02°W. Approximately 330 dairy cows and 380 dairy heifers are housed in total (cows) or partial (heifers) confinement free stall barns. Manure is scraped in three barns (heifers) and flushed in two barns (cows) into three gravity basins that remove a portion of the sand bedding. Liquid manure is subsequently gravity flowed via weir box to one of three storage ponds. Storage pond capacity is 39.4 x 10^3 m^3 (32 AF). Manure is applied using three traveling irrigators with an average output of 1.173 m^3 s^{-1} (310 gpm). Heifers are grazed about seven months $year^{-1}$. Cows are confined 365 days per year. Cropland includes 81 ha (201 acres). Crop rotation includes permanent pasture, corn silage and perennial grass silage for summer crops, and annual ryegrass following corn for winter crops. Most feed is mechanically harvested; some feed is grazed. This is a first, second, and third generation farm.
4. Farm 4. This dairy farm is located (facility headquarters) at 45.22°N and 122.51°W. Approximately 360 dairy cows and 400 dairy heifers are housed in total confinement free stall barns. Manure is flushed in all barns into one reception tank. Manure is subsequently pumped to a sidehill manure separator before entering one of two storage ponds. Storage pond capacity is 51.5 x 10^3 m^3 (41.6 AF). Manure is applied using two traveling irrigators with an average output of 0.946 m^3 s^{-1} (250 gpm). All animals are confined 365 days per year. Cropland includes 113 ha (280 acres). Crop rotation includes primarily alfalfa for silage and hay, but oats and pea silage is grown as a winter crop, and perennial and annual ryegrass is grown as well. This is a first and second generation farm.

A physical descriptive summary of each farm appears in Table 3.1.

Table 3.1 Cooperating farm physical descriptions including storage capacity, animal units per unit storage, hectares per unit storage, and hectares per animal unit

Farm	AU	ha	Crops	storage 1,000 m^3	AU/1,000 m^3	ha/1,000 m^3	ha/AU
1	221	58	corn/grass double crop	30.8	7.2	1.9	0.26
2	211	104	corn/grass, perennial grass	7.4	28.5	14.1	0.47
3	378	81	corn, perennial grass	39.2	9.6	2.1	0.21
4	307	113	corn, perennial grass, oat/peas, alfalfa	51.5	6.0	2.2	0.37

A map (Figure 3.1) shows the location of each farm, the location of two AgriMet WS, the location of the National Weather Service WS (NOAA), and the Willamette – Columbia River systems.

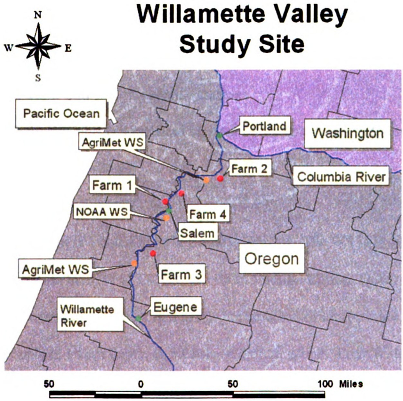

Figure 3.1 Study site farm and weather station location map

Chapter 4. Materials and Methods

4.1 Overview

There are three parts in this chapter that describe the materials and methods used in the study area:

- Installation and use of Weather Stations (WS) and Watermark conductivity sensors placed in each of ten fields in the study area. Data for RZWQM model parameterization includes AgriMet data.
- Site selection, soil core sampling, and determination of soil characteristics including bulk density, particle size analysis, and soil water characterization curve at specific depths for each field.
- The parameterization of RZWQM, including strategies for calibration and simulations of FWB derivation.

4.2 Installation and use of weather stations

There was one WS installed on each of the four farms in the study area. A description of each follows:

Farm One

This farm is located in Polk County, Oregon. The WS is located at:

- WS1 45.0453° N 123.0768° W USGS Mission Bottom Quadrangle, OR

The instruments include a rain gauge, an ambient air temperature gauge, a soil thermocouple at 10 cm depth, and a solar radiation gauge. Four Watermarks were installed at 30, 60, 90, and 120 cm depths in two fields. Field numbers and coordinate locations were:

- 1-1 45.0455° N 123.0773° W USGS Mission Bottom Quadrangle, OR
- 1-2 45.0442° N 123.0770° W USGS Mission Bottom Quadrangle, OR

All instruments including climate and below ground were hard wired to a Campbell Scientific Data Logger CX30 using 18 gauge copper wire wrapped in tensile fiber encased in plastic. The data logger was set to record climate and conductivity measurements on 15-minute intervals.

The WS itself was built on a 15 cm by 15 cm square treated post placed in the soil approximately 1 m deep and encased in concrete. Climate instruments were placed about 2.5 m above the soil surface, while the data logger was installed in a weatherproof epoxy coated electrical box. A 20 cm by 45 cm solar panel was installed on the post, facing approximately south at a 45-degree angle above a horizontal plane.

The WS was hard wired to a telephone pedestal placed within 1 m of the WS post. The pedestal was hard wired to a roadside pedestal, which was connected to the local telephone line that was oriented alongside the roadway. The telephone company assigned a specific telephone number to the WS, and the landowner was responsible for maintaining the payment for this telephone number. A Campbell Scientific COM300 Modem was installed in the WS. This modem was a voice synthesizer that converted CX30 telemetry into a digitized voice. This function allowed users to dial the WS using a standard landline or cellular phone, and obtain real time telemetry (given a 15 minute telemetry dump into the data logger) of climate and soil conductivity data for every field. The landowner liked this feature and made use of it every day. They were particularly interested in accumulated rainfall since midnight (the daily cycle function began at midnight), air temperatures, and the soil temperature especially in spring. The station WS1 became operational May 14, 1999. The landowner did not purchase telemetry software (MeasureTek©) for farm use.

Farm Two

This farm is located in Clackamas County, Oregon. The WS is located at:

- WS2 45.2983° N 122.6296° W USGS Canby Quadrangle, OR

The instruments include a rain gauge, an ambient air temperature gauge, a soil thermocouple at 10 cm depth, and a solar radiation gauge. Four Watermarks were installed at 30, 60, 90, and 120 cm depths in four fields. Field numbers and coordinate locations were:

- 2-3 45.2985° N 123.6320° W USGS Canby Quadrangle, OR
- 2-4 45.2987° N 123.6300° W USGS Canby Quadrangle, OR
- 2-7 45.3004° N 123.6294° W USGS Canby Quadrangle, OR
- 2-8 45.3009° N 123.6325° W USGS Canby Quadrangle, OR

The instrument package on WS2 is exactly the same as WS1, with the exception of an additional data storage unit and different telephone number. The station WS2 became operational June 6, 1999. The landowner (Farm 2) purchased telemetry software (MeasureTek©) for farm use.

Farm Three

This farm is located in Marion County, Oregon. The WS is located at:

- WS3 44.7663° N 122.0358° W USGS Sidney Quadrangle, OR

The instruments include a rain gauge, an ambient air temperature gauge, a soil thermocouple at 10 cm depth, and a solar radiation gauge. Four Watermarks were installed at 30, 60, 90, and 120 cm depths in three fields. Field numbers and coordinate locations were:

- 3-1 44.7670° N 123.0342° W USGS Sidney Quadrangle, OR
- 3-6 44.7649° N 123.0385° W USGS Sidney Quadrangle, OR
- 3-7 44.7658° N 123.0419° W USGS Sidney Quadrangle, OR

The instrument package on WS3 is exactly the same as WS1, with the exception of an additional data storage unit and different telephone number. The station WS3 became operational July 25, 1999. The landowner (Farm 3) did not obtain telemetry software (MeasureTek©).

Farm Four

This farm is located in Marion County, Oregon. The WS is located at:

- WS4 45.2019° N 122.8764° W USGS St. Paul Quadrangle, OR

The instruments include a rain gauge, an ambient air temperature gauge, a soil thermocouple at 10 cm depth, and a solar radiation gauge. Four Watermarks were installed at 30, 60, 90, and 120 cm depths in one field. Field number and coordinate location was:

- 4-1 45.2004° N 122.8783° W USGS St. Paul Quadrangle, OR

The instrument package on WS4 is exactly the same as WS1, with the exception of a different telephone number. The station WS4 became operational November 22, 1998. The landowner (Farm 4) purchased telemetry software (MeasureTek©) for farm use.

A photograph of WS4 is shown in Figure 4.1.

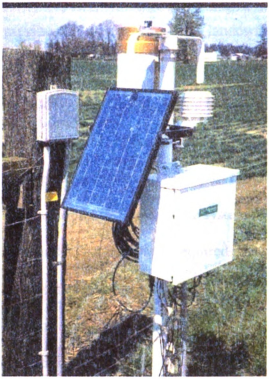

Figure 4.1 Weather Station, Farm 4

4.3 WS software

Two software packages were required to obtain and analyze telemetry. They were developed by MeasureTek© of Corvallis Oregon. A description of each package follows:

1. Connect+ This software was loaded on a remote laptop computer with a dialup modem. Each WS used the voice synthesizer modem as default. Upon laptop command, however each station could be called using the dialup routine, with an additional several second delay in the dialup routine so the voice modem would defer to the telephone modem. Once the modem linkage was established between

remote laptop modem and WS data logger, a downloading sequence began. Data were placed in a Microsoft Access database named for each station. At each dialup new data was added to existing data, creating a new file while storing the previous file as a backup. Two landowners (Farm 2 and 4) chose to purchase Connect$^+$ for farm use on local computers. Each downloaded the WS on their farms only. The remote laptop used in this study by the author was the only machine capable of downloading all four stations. As a precaution, each WS was configured with a local USBS port cable directly out of the data logger. This became useful if the telephone system failed (this occurred several time at each WS) and a data dump was required. The data logger system had a capacity of approximately three months before data was overridden. Connect$^+$ is a standalone Windows based software.

2. ResultX$^+$ This software was loaded on the same remote laptop as Connect$^+$. ResultX$^+$ compiles each WS access file into user graphic and table format. Data from ResultX$^+$ can be directly exported to Microsoft Excel, and this was the preferred method for this study. This software was designed to work in conjunction with Connect$^+$. Once the retrieving software (Connect$^+$) obtained new data via telephone delivery modems, and then ResultX$^+$ imported new data and placed it in an updated MS access file, thereby creating another backup of telemetry. Two landowners (Farm 2 and 4) chose to purchase ResultX$^+$ for farm use on local computers. ResultX$^+$ is stand alone Windows based software.

4.4 Watermark conductivity sensors

Watermark sensors were being installed in fields by many landowners as part of an irrigation water management program in the Willamette Valley Oregon, during the late 1990's and early 2000's. The rationale for their use was simple: they were inexpensive ($25-30 per sensor), durable (years of use), easy to install using a soil coring tool (T-Handle, 30 mm diameter auger, 1.5 m in length), and relatively easy to use once landowners purchased a relatively inexpensive ohmmeter. A photo of a handheld ohmmeter attached to one Watermark is shown in Figure 4.2.

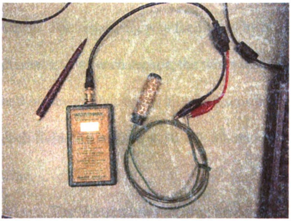

Figure 4.2 Watermark sensor and hand held ohmmeter

The Watermark sensor is made of gypsum crystals encased inside a permeable membrane and perforated stainless steel. Two 18 gauge wires enter the cap end of the sensor. These wires each have a stainless steel electrode embedded in the gypsum matrix approximately 10 mm apart parallel to each other. The wire cap and base end are green plastic resin that contain the gypsum, the membrane, and surround the stainless steel shell. The sensor can be purchased with wire lengths of 60 to 150 cm length.

For this study, the soil coring tool (mentioned above) was used to bore a hole into the soil at the desired depth. At each field location, the sensor was installed so the mid point of the sensor was approximately at the desired depth. The bore hole was at some angle based upon the coring direction, but for each sensor in the profile sat at approximately a 45 degree angle, with the soil surface at 0 degrees and a vertical direction at 90 degrees. Once the borehole was completed, a saturated sensor (wet in a five gallon bucket for at least 48 hours) was placed in the hole. A 6 mm steel rod was placed on the sensor cap. Carefully the sensor was shoved to the bottom of the borehole. The rod was removed. Soil was repacked into the borehole by taking the approximate soil at that point in the profile, thereby attempting to minimize textural changes for each depth. The repacking was facilitated by a wooden dowel approximately 25 mm in diameter. For each sensor, the wires were carefully kept unscarred as soil was repacked, and on several occasions an entire sensor was replaced because insulation was lost. For each field, the sensors at 30, 60, 60, and 120 cm depth required two hours installation time.

The Watermark sensor is based upon electrical resistance and variable conductivity in the soil based upon water content. The gypsum provides a soil buffer of ionic activity in soils. As the gypsum matrix in the soil is wetted, the conductivity of electrical current, i.e. voltage, increases. A wet soil will conduct an electrical current more readily than a drier soil. The hand held ohmmeter uses a 9-volt DC battery. A current of five volts is sent to one electrode in the sensor; some voltage is lost due to voltage resistance, or ohms. The twin electrode receives the remaining voltage and that is recorded in the ohmmeter as a function of the original voltage. The Watermark has a range of 0-200 centibars, or 0-2 Bars. An algorithm in the ohmmeter programming converts this change of voltage at each reading into an estimation of matric potential in the soil.

Generally, the understanding by technicians in the field is that a reading of zero means a fully wet soil, or as near to saturation as that part of the soil surrounding the sensor can get. As the soil dries, the relative change from one reading to another indicates that the soil is drying or wetting, but only in a qualitative sense. This is an important concept. For purposes of irrigation water management, technicians would instruct landowners that when the sensor yielded a reading of 70 to 80 centibars, an irrigation application was required. The irrigation application should rewet the sensor to 20-30 centibars, at or near field capacity. Many landowners checked their sensors arrays, a group of sensors placed at 15, 30, and 45 cm depths (approximating a root zone depth) every two or three days. Those using an irrigation water management strategy recorded these data on graph paper, and based upon the drying rate scheduled irrigation applications based upon sensor readings. However, landowners did not have these measurements quantified directly to some volumetric measurement in the soil. They knew, however, that for a particular field if the sensor was to be rewet to 30 centibars from 80 centibars, 40 mm of water was required if the uppermost sensor in the profile was at least 15 cm deep.

For this study, Watermark sensors were used to accomplish this same strategy, except that two additional criteria were added. One, a record of multiple depths and their relative wetting or drying trends would be recorded over a long interval in and out of the growing season. Two, some understanding of when the soil was greater than field capacity, i.e., at or less than 20 to 30 centibars, and when the soil was near or at saturation would be known. This second point was important for scheduling limited applications of liquid dairy manure outside of the growing season, thereby assuming that if the sensor had some reading greater than zero, then some void space existed and infiltration could occur.

The sensor array in each field was hardwired to the farm WS. A trencher was rented and used to dig a 10 cm wide by 60-90 cm deep trench between the array and the WS. Bundled 18-gauge wire was laid in the trench. At the array end, silicone connectors were used to seal the trenched wire and sensor wire end. This entire bundle was placed in a plastic boot approximately one half liter in size, sealed with silicone resin, and buried at a depth of 60 cm about one meter from the sensor array. The objective during trenching and sensor burying was avoiding tillage equipment plowing the uppermost sensor (30cm) out. One rationale for using these sensors was their low cost. Several 30 cm sensors were plowed out and actually lost over the study period. At the next dialup, the telemetry was dramatically different for these sensors; they were replaced once the trench wire was found.

4.5 AgriMet data

As described earlier in this thesis, AgriMet WS offer landowners a regional weather network for assessing above ground climate, including a calculated ET_r. For this study, two regional AgriMet WS were used. They are located in Aurora and Corvallis at the following coordinate location:

- Aurora ARAO 45.2811° N 123.7501° W USGS Canby Quadrangle, OR

- Corvallis CRVO 44.6339° N 123.1929° W USGS Lewisburg Quadrangle, OR

4.6 Resolution of WS data

RZWQM model requirements include two climate files: rainfall and climate data for determining ET_r. For this study, rainfall data from the local WS's were used when each station was operable during the five-year study period. For time periods outside these windows, NOAA data was obtained from the Salem, Oregon NOAA weather station based at the regional airport. The NOAA WS is based at the following coordinate location:

- Salem NOAA 45.9108° N 122.9956° W USGS Salem Quadrangle, OR

This WS was centrally located in the study site, with two farms north, one farm west, and one farm south of Salem. The rainfall climate file for RZWQM consisted, therefore, of regional data taken from the NOAA WS if the local farm based WS does not have these data.

The climate data file in RZWQM requires five parameters: minimum air temperature (C°), maximum air temperature (C°), wind run (km day^{-1}), relative humidity (0-100%), and solar radiation (MJ m^{-2} day^{-1}). From these, RZWQM calculates pan evaporation, and then ET_r. The AgriMet WS data from both stations was used in this study; The CRVO WS was used for all climate files beginning October 1997 until October 1998, when that station's data were used to populate the RZWQM for all four farms.

The resolution of weather data is complicated by the fact three different sets of WS systems are used: four local MeasureTek local WS's, two regional AgriMet WS's, and one regional NOAA station were used to populate RZWQM. The challenge was obtaining enough data over a multiple year study period, and the study period beginning before local and one AgriMet station became operational.

4.7 Soil characterization

The objectives of this soil characterization work were threefold:

1. Determine the bulk density and particle size analysis [PSA] (Gee and Or, 2002) for soils in ten fields (listed above) at four incremental depths (30, 60, 80, and 120 cm).
2. Using the Klute (1986) method, derive the soil water characterization curve [SWCC] based upon paired data of matric potential and volumetric water content over the range of saturation to 1.5 MPa for soil cores taken from these fields and depths.
3. Populate RZWQM soil database with data derived from each set of characterization data for model parameterization.

4.8 Soil coring field work

A soil-coring tool was purchased from Soil Moisture Corporation in Santa Barbara, California (see figure 4.3). This is a state of the art tool for obtaining as undisturbed as possible soil cores. The tool consists of a stainless steel shell that houses a set of internal brass rings. The tool has a handle for shoving the core shell into the soil matrix at the desired depth. An open bucket auger was used to auger vertically to the desired depth, then the coring tool was placed in the soil and extracted. Once out of the ground, the shell is removed from the handle, the brass rings are carefully removed from the shell, and using a putty knife, the cores or leveled at both ends. Two identical cores are taken. One was placed on a field scale and weighed. The other was wrapped in saran wrap, placed in a cooler, and eventually was used in the soil extractor method (Klute, 1986).

The soil removed during the open bucket auger coring was placed in a five gallon plastic bucket. A sample of this volume of soil (approximately 6 kg) was placed in a large plastic container and stored in another cooler. This disturbed bulk soil sample at a known depth was used to determine particle size distribution (Gee and Or, 2002).

The location in each field was determined by the placement of Watermark Sensors in each field. An assessment of field topography and the USDA Soil Survey, with input from each landowner was used. The objective was placing the sensors as typical as possible part in of the field. Once the site was determined and the Watermarks installed, the site was identified using a Survey Grade GPS supplied by USDA-NRCS technicians. The soil coring locations were based upon three replicates at an approximate distance of one m from the Watermark location at one third of a circumference, or 120^{o} from zero degrees, or North. These assignments were not exact; several times during the coring process a large rock obstructed the bore hole and another holes was began a few cm near the abandoned hole.

The wetness of the soil in each field at the time of soil sampling was considered. Soil coring was done at or near FC, thereby reflecting some similarity between bulk density measurements in the field and those used by USDA-NRCS Soil Laboratory in Lincoln Nebraska. Also, removing wetter soil as compared to drier soil enhanced core integrity. Users of this tool quickly discovered that sampling in dry soils is more difficult in terms of driving the stainless steel shell into dry soils, and once that was done, the soil literally fell out of the brass rings upon extraction. An additional challenge was avoiding compaction of the soil in the brass ring assembly. Driving the tool into the soil matrix at a depth even slightly beyond the total vertical depth of the tool shell will compact soil and therefore increase bulk density.

The measurement taken in the field, i.e. the mass of one of the rings containing a soil core was recorded. At every depth, the same brass ring was used to obtain a weight of soil, which included the brass ring. This particular brass ring, therefore, had a known mass and known volume. The bulk density measurement was immediately known given the total mass minus the mass of the ring itself, divided by the volume of the ring assuming water is 1 g cm^{-3}.

At the end of each field sampling, usually one half day of time, the undisturbed soil in plastic baggies and the soil cores in brass rings were taken back to the laboratory at Oregon State University. The bulk soil was spread on a newspaper for air-drying. After 48 to 72 hours at room temperature, the entire air-dry soil was placed back in its plastic container for storage at room temperature. The brass rings containing the soil cores remained in their plastic saran wrap and were stored in a refrigerator unit transport.

At this point the bulk density measurements were known, the bulk soil for PSA (Gee and Or, 2002) was air dried and stored, and the soil cores for the Klute (1986) method analysis were safely wrapped in plastic, stored in an environment minimizing water loss, and kept at a temperature that minimized soil microbial activity. A total of

120 bulk soil samples for PSA and 120 soil cores in brass rings for SWCC were inventoried and the fieldwork was completed.

Figure 4.3 shows an example of a soil core shell and soil just removed from the field bore hole.

Figure 4.3 Soil core shell and soil

4.9 Laboratory work, particle size analysis

The PSA is a measure of the distribution of particles in bulk soil less than 2 mm in size. The relative amounts of these particles, once known, can be used to accurately place the bulk soil on the USDA Textural Class Triangle mentioned earlier in this thesis. The PSA was used to evaluate soil texture, a term that describes the solid phase or mineral phase of bulk soil. It does not refer to bulk density, soil organic matter, soil fertility, or aggregation of soils, but PSA can be used to describe typical water conductivity through the matrix and the amount of water that might be in a profile. For instance, a course textured soil is expected to have a high rate of water conductivity, whereas a fine textured soil is expected to have low conductivity but relative to course textured soils, a high affinity for water, therefore a high water content on a volume basis.

There are four steps using the hydrometer method (Gee and Or, 2002) for determining PSA in this study. The work was done at MSU's Plant and Soil Testing Laboratory after transporting the bulk soil to Michigan from Oregon. The steps are:

1. Grinding and sieving. At the time of soil sampling the soils were near or at FC. Upon drying aggregation occurred and therefore required this physical step of grinding. This step was accomplished by grinding all bulk soil through a bulk grinder. Breaking aggregate soils into small, dispersed minerals is required in order to differentiate particle sizes. This physical process was done using a Soil Grinder under a hood; the grinder has two inversely rotating carbide drums that destroy aggregation but usually do not crack or destroy soil minerals in the sand size range. The second part of this step was sieving though a 2 mm sieve. This step removes any particles that were larger than 2 mm in the bulk soil that could be noted as fine gravel, coarse gravel, or cobbles. Upon completion of this step the bulk soil resembles a dry powder with sand particles dispersed in the soil.
2. A 100 ml solution of 0.1 M Na-hexametaphosphate was added to 50 grams of bulk soil, placed in a 500 ml bottle, secured with a lid, and placed in a rocking table for 12-15 hours. Typically the sample bottle is prepared the previous afternoon, and shaken overnight on the vibrating table.
3. Using the principal of Stokes Law (Gee and Or, 2002) larger particles of the same density will move through a liquid faster than a smaller particle in response to gravity. By extension, a sand particle is larger than a silt particle and these are both larger than a clay particle. Each particle will have a specific density of approximately 2.65 g cm^{-3}. The hydrometer method is begun using a 250 ml

graduated cylinder placed on a flat table surface. The soil samples were removed from the mixing table and while completely dispersed, the entire soil solution is added to a graduated cylinder. The sample immediately began to settle out, with the sand particles very quickly moving to the bottom of the cylinder. A mixing probe was immersed in the cylinder and twenty up and down movements were made to resuspend the particles. A timer was started, and 40 seconds later a hydrometer (ASTM 152 H-Type) was carefully dropped into the liquid. A reading was taken off the gauge scale on the neck of the hydrometer. At 7 hours from time zero the process was repeated. After this step a thermometer was placed in the liquid and a reading was taken and recorded. The typical approach was taking the first reading in the early morning and then the seven-hour reading later in the afternoon. At the completion of the final reading the cylinders were emptied and cleaned.

4.10 Laboratory work, soil water characterization

The development of the SWCC using soil cores is time consuming, demanding in terms of laboratory monitoring, and based upon a set of assumptions that must be used in order to bring value to a data set. The procedure is well established in soils laboratories; the author visited five Universities and sought out assistance before setting up a laboratory at MSU. Klute (1986) described in detail a pressure plate apparatus method, using soil cores, ceramic plates, a pressure chamber, and a manifold system for pressure regulation. Before describing this procedure, a list of assumptions follows:

1. Soil cores are representative of field conditions, i.e. the core of approximately 70 cm^{-3} is as nearly as possible the same mineralogy, compaction, and aggregation as field soil. We know that field variation is large so this assumption can be easily discounted. Nevertheless this method has been used by many researchers and the same assumption is given but is problematic of using a small soil core to describe a field specific process.
2. The soil in the core is always drying in response to pressure, rather than wetting in response to infiltration and redistribution. Given the wetting and drying hysteretic effect, the volumetric water content at a given matric potential, i.e. the end product of the SWCC, is always based upon the wetting cycle. Generally, a soil that is drying has slightly higher volumetric water content than a wetting soil at the same matric potential (hysteresis). For this reason the SWCC curves is always listed as desorption curve (drying as in this study) or a sorption curve (wetting).
3. The physics of air flow pressure and negative suction or the inverse of pressure is exactly equal. This seems reasonable, given that if a soil is pressured in a tank, or the tank is under a vacuum at some negative pressure, then the removal of water as desorption should be exactly the same. This is a laboratory procedure and cannot be used in the field.
4. The soil cores gradually lost some structural integrity over the wetting and drying cycles, especially for the final three matric potential points of 0.5, 1.0, and 1.5 MPa. This statement was based on visual observation

4.11 SWCC equipment

The pressure chamber used in this study was built as a replica of a 15 bar extractor marketed by Soil Moisture Corporation, Santa Barbara, California. The chamber is large enough to support five ceramic plates stacked vertically and separated by 8 cm. The chamber lid was scored to fit on a rubber O-ring inset on the chamber wall. The lid is held in place with eight grade 8 bolts. Two intake and five exhaust ports were built into the sidewall; the exhaust ports were at the same vertical elevation as the ceramic plates when stacked in the tank and loaded with soil cores.

A 150 psi air compressor was used to supply positive air pressure. A two stage manifold unit was built using two pressure regulators, a combination of valves and several pressure gauges. The first step was built to pressurize the chamber from zero to 0.3 bars. A water filled manometer was used for the first four air pressure extractions, 0.003, 0.01, 0.02, and 0.03 MPa (FC), thereby removing any gauge error at these very low pressures. A second stage series of gauges were used for the next set of pressures: 0.04, 0.05, 0.1, 0.2, 0.3, 0.5, and 1.0 MPa. Figures 4.4 and 4.5 shows the chamber and manifold in use in the laboratory.

Figure 4.4 SWCC chamber

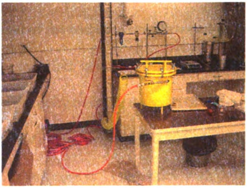

Figure 4.5 SWCC chamber and manifold

The ceramic plates were obtained from Soil Moisture Corporation, Santa Barbara, California, and MSU Soils Department (courtesy Dr. Alvin Smucker, MSU Crops and Soils Department). Plates were constructed out of ceramic material at specific bubbling pressures at which they will conduct water. The larger the ceramic plate porosity, the lower the bubbling pressure. The use of somewhat uniform ceramic plate bubbling pressures facilitates more uniform flow of water from soil cores into the plate at equilibrium, then movement out of the pressure tank at a given pressure.

The laboratory setup at MSU (Farrall Hall) was built for a maximum pressure of 150 psi, or slightly more than the 145-psi for the 1.0 MPa pressure. The final extraction at 1.5 MPa was done by transporting all soil cores back to Oregon State University and using a membrane extractor. This procedure will be explained following the MSU Laboratory description.

4.12 Soil water extraction

The principle of soil water extraction using the ceramic plate and pressure chamber method requires a hydraulic gradient between the two. The procedure therefore requires that for every extraction, both the ceramic plate and the soils cores are rewet to as near saturation as possible. The soil cores were removed from their transport canisters, unwrapped from the saran wrap, with one end of the soil core ring wrapped in cheesecloth held with a rubber band. The cheesecloth helped stabilize the soil particles on the core bottom thereby maintaining soil integrity over the duration of the extraction process. The cores were placed in a bath of distilled water with a 0.005 M concentration of calcium sulfate ($CaSO_4$) for 48 hours. The soil core is 33 mm thick with the addition of another two to three mm of cheesecloth material. The soil cores were placed in large pan type plastic containers and filled to a depth of approximately 25 mm. Special care was taken in avoiding overtopping the soil core. The objective was allowing water intake to occur from the bottom upwards as capillary flow. Some cores rewet sooner than others, but 48 hours appeared to be adequate for total rewetting.

During the same 48 hour wetting period five ceramic plates and one backup plate was immersed in distilled water. This step ensured the pores in each ceramic plate were saturated.

The pressure chamber was loaded by first installing a set of four legs, or plastic dowels, on the chamber floor. These legs were 15 mm high, and allowed the bottom – most plate to rest slightly above the floor, thereby assuring the ceramic rubber bladder enough space to slightly inflate at higher pressures. Just prior to placement in the chamber, each soil core was weighed. This step proved to be insightful; at each pressure interval, the wetted soil core had a saturation value, which could be compared to the previous values. Once the plate was installed, 12 soil cores were placed on the plate surface. Special care was taken to ensure the cheesecloth made complete contact with the wet surface of the plate, thereby assuring a hydraulic gradient. The next plate was added after installing four more plastic legs set in open spaces of the lower plate. Plates and cores were added until the fifth plate had been completed and the chamber held 60 cores. The total number of cores for extraction were 120, therefore one half of the total were extracted at any one time.

Once the lid was in place by sequentially tightening up the bolts, the manifold valves were adjusted admitting the desired airflow into the chamber. Generally, the soil cores and plates immediately lost some water that occupied the largest pores, thereby requiring very little airflow. The next step involved the variable of time to equilibrium, that point where air flow at some pressure had pushed all the water out of the soil core and ceramic plate but no more could be evacuated unless additional pressure was added. This step was accomplished by observation. Generally, the lower pressures required less time. The time period ranged from three days to 21 days.

When equilibrium had been reached, the chamber was depressurized. The lid was removed, and each soil core was weighed. Soil cores were placed in the plastic tray for rewetting, and the entire process was repeated. The sequence, in summary, was:

1. Saturation of soil cores and ceramic plates for 48 hours
2. Soil cores weighed at saturation just prior to chamber loading
3. Chamber loading of soil cores on ceramic plates: hydraulic gradient made
4. Pressurized for three to 21 days at some positive air flow (pressure) until equilibrium had been reached
5. Soil cores removed and immediately weighed
6. Step one repeated and the next higher pressure used in the process

For one set of soil cores, 60 samples, five months were required for the laboratory extraction work. The steps above required daily attention, monitoring, and safety concerns given the higher pressures that were used further along the process.

Figure 4.6 shows the soil cores on the fifth ceramic plate just prior to placing the lid on the pressure chamber.

Figure 4.6 Soil cores on ceramic plate in chamber

4.13 Final extraction

The 1.5 MPa required the use of a membrane extractor. Samples were transported to Oregon State University Soils Laboratory. The membrane process differs slightly from the ceramic plate method in two ways. First, the original soil cores are destroyed and remade into smaller cores approximately 10 cm deep. These cores were placed on a carbon membrane in a pressure chamber. The lid was fitted with rubber bladder, which at closing completely comes into contact with the top of each new soil core. The system was pressurized at 218 psi, or 1.5 MPa, and equilibrium was reached in three to four days. Soil core samples were removed and weighed.

The final step was converting the data into volumetric water content. This was possible only after the cheesecloth mass values were subtracted from the soil cores. This was accomplished by using four blanks, cores having no soil but having cheesecloth attached to them. The assumption was made that the average difference between saturation and dryness at each extraction pressure of these four blanks was the same for cheesecloth on the 60 cores having soil in them.

The paired values that make up the SWCC, i.e., matric potential (in this case assuming the inverse of positive air flow, or negative pressure) at a given volumetric water content (mass in the soil core at saturation minus mass in the soil core at that specific pressure) provided the SWCC over the range of soil drying.

4.14 RZWQM data requirements

The RZWQM requires four data sets. They are:

1. Weather data. Two meteorology files were built for each field.
    a. The first is a .brk file, with data obtained from the individual farm weather stations. This file was built by using daily rainfall in units of 0.01 inches of rain per 24-hour period. The study period for each farm was the time period these local farm WS were operable.
    b. The second weather file is a .met file, with data obtained from AgriMet WS in Corvallis and Aurora Oregon. This file was built using five sets of data: minimum air temperature (C^o), maximum air temperature (C^o), wind run (km d^{-1}), shortwave radiation (MJ m^{-2} d^{-1}), and relative humidity (%). There were data for every day in the five-year study period, i.e. 1,826 days.
2. Management data. There are seven groups of data that can be used to describe farming activities. All of these data were obtained from landowner records and personal observation.
    a. Crop selection, the name of either an annual or perennial crop type grown on a field.

b. Planting characteristics, a description of the crop planting date, with descriptions of data planted, planting density, row spacing and planting depth, harvest date, stubble height at harvest and residue left on the soil surface, and harvest type.

c. Manure applications, which include descriptions of application location (field), source, timing, method (liquid irrigation or solid spreading), mass per field of NH_4-N, mass per field of total solids, C:N ratio of bedding, C:N ratio of manure, and carbon content of manure volume. These data were obtained from landowner records, and represent some of the most important data obtained over the five-year study period.

d. Irrigation applications, which include field location, type of application (sprinkler), and total application volume depth (cm). This group of data included irrigation volume depth of liquid manure and irrigation volume depths of freshwater. Data were referenced with a time and spatial stamp assuming the volume depth was applied over the entire field at the same uniformity.

e. Fertilization, which users may place the applications of inorganic fertilizer if they are made. For this study, no inorganic fertilizer was applied to any of the ten fields over the five-year study period.

f. Pesticides, which users may populate with pesticide data. No pesticide data were collected from landowners for this study.

g. Tillage, which users can define in terms of timing of tillage before planting (preplant) date of tillage, tillage implement type, tillage depth (cm) tillage intensity (a measure of soil surface disturbance), and a description of the tillage operation performed (primary, compaction, or secondary). These data were obtained from landowners and personal observation.

3. Initial State. There are three initial state requirements that set the field parameters so the model can begin from a reference state. They are:
    a. Volumetric water content. The model must have a starting point for adjusting the FWB based upon hydrologic parameters that change every 24-hour period. For all ten fields, the value used was the first Watermark sensor reading in cbars, and then converted to volumetric water content using the SWCC for each individual field at the surface layer of 30 cm.
    b. Soil chemistry state. This component includes many different soil chemistry inputs of soil chemistry speciation, salt status, ion status, carbonates status and CO_2 flux are desired model outcomes. These were not used for this study. Two input fields were populated, however, soil pH and soil CEC.
    c. Pesticide state, which was not used in this study, so all input fields remained empty.
4. Site description. Several components of the field site are described in this model component. They are:
    a. General information, which includes where the field was located (spatially) and its elevation above mean sea level. A soil map unit name

was identified based upon a USDA Soil Survey. A number identifies the field.

b. Horizon description was an important part of this component; the soil texture as defined by the USDA Textural Class triangle, horizon depth (cm) particle size density (2.65 g cm^{-3}), bulk density, porosity, and fractions of sand, silt and clay as defined by the particle size analysis. The horizon depths were in increments of 30 cm depths to 1.2 m. The bulk density values were obtained from the field data derived at the time of soil core sampling. The particle fractions were derived from the soil laboratory work done at MSU Soil and Plant Nutrient Laboratory.

c. Soil hydraulics. There are three levels of parameterization. They match the objectives of this thesis. They are:

    i. Default value using USDA NASIS soil default values. This was the minimum input without any data input from the fieldwork and laboratory work.

    ii. Minimum input, using particle size analysis and bulk density data; the model uses these data and derives slightly different soil hydraulic control based on textural class.

    iii. Full description, using incremental soil depth volumetric water content at saturation, at 0.01 MPa, at 0.033 MPa (FC), and at 1.5 MPa (PWP). These data were derived from the laboratory work in deriving the SWCC for each incremental soil depth.

d. Hydraulic control. This component was used to further define field conditions, i.e. the presence of surface crusting, presence of subsurface drainage, presence of a water table, and the presence of a bottom boundary during internal soil water distribution. These parameters were populated if they were a component of each field.

4.15 RZWQM data parameterization

This study examined the parameters required to accurately determine the FWB over a long period of time, five years, in ten fields. Two model components are particularly important to achieve this determination. They are:

1. In the site description component, characterizing the horizons. The model is first populated with a soil survey description of the particular site based upon field map unit. The depths will be based on different criteria than the incremental 30 cm soil depths used when fieldwork was done. This approach reflects the least amount of parameterization necessary to run the model. This assumes that the user has access to soil survey data through USDA's NASIS Soil Database, found in eFOTG Section II on the Internet. The next level of parameterization is shifting to the incremental description of the soil profile using the 30 cm depths from which the particle size analysis and bulk density values were derived. All other fields in this component remain the same. This represents the second level of parameterization. The site descriptions for the second and third scenarios are the same.

2. The soil hydraulics component, which controls the rate of water flux in the soil profile as a function of the default or determined SWCC. The model was first parameterized using default values, based upon the actual soil map unit characterizations as derived by USDA's Soil Survey. Again, this represents minimal effort by the user for data input. The second scenario also required no changes in this component, other than the horizons will be based upon 30 cm incremental changes and the particle size analysis parameter based upon laboratory values at each depth. The hydraulic control of each layer was based upon default values as influenced by the changes from USDA's default values, to new empirical values based upon particle size analysis and bulk density. The third scenario included the volumetric water content at the four potentials listed earlier. The third scenario, therefore, represented the greatest effort required to populate the model and the greatest deviation from established default values found in the Soil Survey through NASIS.

4.15 RZWQM evaluation

Once the four database requirements were completed, the model provided a FWB for each of three scenarios. The three scenarios were compared to the Watermark data using Excel Statistical Software. The objective was finding the best fit in terms of matching model performance with field data. This evaluation step utilized the empirical evidence obtained in the field with model simulations over the time period when weather stations are operating on each farm. A sensitivity analysis was done using two rainfall distributions periods, two hours and 12 hours. The Nash Sutcliffe Efficiency values were used to rank the three methods of model parameterization.

The final step suggested the input parameters required for model parameterization so that RZWQM can be used to model the FWB on non-instrumented fields.

Note: images in this dissertation are presented in color

Chapter 5. Results and Discussion

5.1 Overview

There are three parts in this chapter that describe the results and discussions:

1. Describe the AgriMet and four WS data that were used in the RZWQM parameterization.
2. Describe the bulk density, particle size determination of bulk soils, and derivation of the SWCC for each of the ten field soils.
3. Describe the empirical versus model results based upon RZWQM parameterization. This third part will answer the question in hypothesis one: what degree of parameterization is necessary to model the soil water profile in soils on a field basis, and answer the question in hypothesis two: what are the suggested management options offered by model results?

5.2 AgriMet and WS data

Two AgriMet WS data sets were used in building the *.met file. One set was derived in Aurora Oregon, and the other set was derived in Corvallis Oregon. Both facilities are owned by Oregon State University.

RZWQM requires five kinds of weather data for determining ET: minimum air temperature, maximum air temperature both in degrees Celsius, wind run in km d^{-1}, shortwave radiation in MJ m^{-2} d^{-1}, and relative humidity expressed as a percentage. An alternative to these measurements is pan evaporation, but this alternative was not used in this study.

The farm based WS could not supply these measurement as they lacked the instrumentation. AgriMet, however did supply all of these measurements in the following format with conversions listed:

1. Minimum air temperature as degrees f (T_f), converted to degrees C ($T_c = (T_f - 32)*5/9$)
2. Maximum air temperature as degrees f (T_f), converted to degrees C ($T_c = (T_f - 32)*5/9$)
3. Wind run as miles d^{-1} converted to km d^{-1} (km = miles*1.609)
4. Solar radiation as Langleys (d^{-1}) converted to MJ m^{-2} d^{-1} (Langley*697.3*0.00006)
5. Relative humidity is expressed as percentage in both data sets

The RZWQM *.met file was built using these conversions from both Agrimet stations. Farms one, two, and four used the Aurora data set and farm three used the Corvallis data set. The distance to Agrimet WS were as follows: farm one, 33.6 km, farm two, 6.1 km, farm three, 25.6 km, and farm four, 14.4 km.

The rainfall climate data were obtained from the farm WS. Daily data were recorded. Two data files were built using breakpoint data in the RZWQM *.brk file system. The farm WS data was recorded in units of one hundredths of an inch volume depth as rainfall. The timer was based on midnight to midnight. The RZWQM *.brk file was built using increments of storm duration; therefore, the intensity and duration of a particular storm in hyetograph form. The daily farm WS data were distributed into two storm durations: two hours and 12 hours. For instance if the one days' rainfall totaled

0.77 inches of rainfall, one file would have that storm duration as 0.385 inches of rain per hour for two hours, and the other data set would have the same volume depth distributed over 12 hours, or 0.0642 inches per hour. In both cases the uniformity of the storm was the same over two hours or 12 hour, but the intensity during the two-hour model was six times as intense as the 12-hour model.

The rainfall data were local data, with the farm WS located within one km of the field sites for each farm. For each farm three climate files were created as follows:

1. *.met file based on nearness to AgriMet WS
2. *.brk$_2$ file based upon local farm WS and a storm duration of two hours
3. *.brk$_{12}$ file based upon local farm WS and a storm duration of 12 hours

5.3 Soil moist bulk density and particle size analysis

Soil bulk density was determined in the field at the time of soil coring. The soil cores were taken at or as near as possible field capacity, thus are defined as moist bulk density. The data are listed in Table 5.1.

RZWQM requires moist bulk density as one of its important soil physical characteristics. The model uses 2.65 g cm^{-3} as particle bulk density as default. The data are listed in Table 5.1. The PSA provides an estimation of the relative percentages of sand silt and clay based upon a bulk sample obtained at 30 cm increments in the ten study fields. Three replicates were analyzed, providing a mean value with standard deviation listed in Table 5.1. Note in column one Soil Map unit name, hydrologic group class, and crop at the time of sampling for each of the ten instrumented fields. Bulk density units are g cm^{-3}.

Table 5.1 Field bulk soil physical analyses, NASIS default, and RZWQM default values

Field ID	Field	laboratory				NASIS	Bulk density	Bulk density	Bulk density
Field ID	cm depth	Textural class	Sand %	Silt %	Clay %	Textural class	Mean	s.d.	RZWQM default
Field 1-1	30	Si C Loam	9	60	31	Si Loam	1.35	0.048	1.40
Amity	60	Si Clay	1	58	41	Si C Loam	1.29	0.020	1.38
HGC C	90	Si Clay	3	51	45	Si C Loam	1.28	0.023	1.38
rye/corn	120	Si Clay	1	57	41	Si C Loam	1.25	0.023	1.38
Field 1-2	30	Si C Loam	9	60	31	Si Loam	1.31	0.029	1.40
Amity	60	Si Clay	4	55	41	Si C Loam	1.27	0.056	1.38
HGC C	90	Si Clay	0	55	45	Si C Loam	1.35	0.060	1.38
rye/corn	120	Si Clay	2	57	41	Si C Loam	1.26	0.026	1.38
Field 2-3	30	Si C Loam	17	55	28	Si Loam	1.36	0.044	1.40
Powell B	60	Si C Loam	11	49	39	Si C Loam	1.33	0.041	1.40
HG C	90	Si C Loam	9	51	39	Si C Loam	1.24	0.010	1.40
per grass	120	Si C Loam	11	53	35	Si C Loam	1.28	0.019	1.40
Field 2-4	30	Si Loam	17	57	25	Si Loam	1.35	0.050	1.32
Powell C	60	Si C Loam	10	53	37	Si C Loam	1.37	0.018	1.40
HG C	90	Si C Loam	8	53	39	Si C Loam	1.35	0.073	1.40
per grass	120	Si C Loam	10	57	33	Si C Loam	1.36	0.049	1.40
Field 2-7	30	Si C Loam	13	59	28	Si Loam	1.31	0.016	1.40
Aloha	60	Si C Loam	7	53	39	Loam	1.24	0.070	1.40
HG C	90	Si C Loam	5	55	39	Loam	1.26	0.022	1.40
per grass	120	Si C Loam	8	57	35	Loam	1.28	0.016	1.40
Field 2-8	30	Si C Loam	12	59	29	Si Loam	1.30	0.019	1.40
Aloha	60	Si C Loam	9	55	35	Loam	1.22	0.015	1.40
HG C	90	Si C Loam	7	55	37	Loam	1.17	0.115	1.40
per grass	120	Si C Loam	8	55	37	Loam	1.20	0.018	1.40
Field 3-1	30	Si C Loam	11	61	28	Si Loam	1.37	0.022	1.40
Amity	60	Si Clay	6	52	41	Si C Loam	1.28	0.036	1.38
HG C	90	Si Clay	6	41	53	Si C Loam	1.27	0.013	1.38
per grass	120	Si C Loam	8	57	35	Si Loam	1.27	0.030	1.38
Field 3-6	30	Si C Loam	9	59	32	Si Loam	1.35	0.035	1.40
Willamette	60	Si C Loam	10	61	29	Si C Loam	1.44	0.021	1.40
HG B	90	Si C Loam	10	53	37	Si C Loam	1.33	0.056	1.40
per grass	120	Si C Loam	12	49	39	Si C Loam	1.30	0.025	1.40
Field 3-7	30	Si C Loam	7	65	28	Si Loam	1.41	0.052	1.40
Holcomb	60	Si Clay	7	49	43	Si C Loam	1.25	0.024	1.30
HG D	90	Si C Loam	10	53	37	Clay	1.22	0.041	1.40
per grass	120	Si C Loam	12	61	27	Clay	1.21	0.025	1.40
Field 4-1	30	C Loam	21	47	32	Si Loam	1.31	0.019	1.42
Amity	60	C Loam	21	45	33	Si Loam	1.25	0.064	1.42
HG C	90	Si C Loam	19	45	35	Si C Loam	1.22	0.047	1.40
alfalfa	120	Si C Loam	19	45	35	Si C Loam	1.38	0.043	1.40

There is a strong relationship between moist bulk density and textural class. The RZWQM default moist bulk density values are a function of textural class. If the model is parameterized using Soil Survey map data, two approaches may be used for moist bulk density values. For this study, one approach included only empirical field data, the use of field derived moist bulk density and laboratory PSA using field bulk soils. The bulk samples were taken within one meter of the Watermark array of soil moisture sensors, therefore an attempt was made to describe local soils (spatially) rather than field soils. The second approach used a method with minimal input: for a particular field find the predominant soil map unit in the Soil Survey, then find the textural class in the NASIS database. When these textural classes are used in RZWQM, each has its own moist bulk density; in Table 9 these are listed in the right in the right hand column under the heading default RZWQM. This second approach requires no field visits; attribute data can be based upon the accuracy of the Soil Survey, but more importantly, negate the local effects if a field is instrumented with some type of soil moisture sensor.

The particle size analysis (PSA) data appear in two columns. The left column is derived using the hydrometer method in the laboratory, derived from field bulk soil samples. Using the USDA –NRCS Soil Survey, the soil map units are selected based upon the water measurement site within each field. These soil map units appear in Figure 15. The parameterization of RZWQM requires a robust set of soil physical data, including PSA. Based on this study the selection of NASIS data would change the model parameters, thereby influencing the soil hydraulic characteristics. Of the 50 field bulk soil samples measured, 17 samples had the same textural class. Two fields, 2-3 and 2-4 had identical textural classes between field samples and NASIS. Four fields, 2-7, 2-8, 3-

1, and 3-7 had no similar textural classes, and two more, 1-1 and 1-2 had just one similar textural class.

Obtaining PSA data is relatively easy. Bulk soil is taken using an open bucket auger, which does not require the careful core sampling used in the SWCC laboratory procedure. The bulk soil requires no in-field measurements, except for depth (30 cm in this study). The laboratory procedure can be done in two days at relatively low cost. Based upon this study, RZWQM will require empirical field PSA rather than using NASIS data.

5.4 Soil water characteristic curve development

The development of the SWCC for each depth in ten fields was the major field effort of this study. As undisturbed as possible soil samples were obtained at or near field capacity, within one meter of the soil moisture Watermark arrays, then placed in the soil pressure chamber for repeated wetting and dying cycles at several different pressures.

The SWCC is derived from paired data: volumetric water content at some matric potential. The critical points are saturation, field capacity, and permanent wilting point. Volumetric water content at saturation may be measured based upon actual measurement, or calculated by assuming a theoretical saturation at complete filling of the void space. Given air entrapment, the void space is never completely filled with water, so the comparison between the two values will provide estimation between calculated and measured volumetric water contents at saturation.

5.5 Volumetric water content at saturation

The volumetric water at saturation data was compared using the f statistic for unequal variances (two-tail). This statistic showed the variances between calculated and measured were not significantly different ($P < 0.05$).

What is interesting about the two data sets is the calculated mean is slightly higher than the measured mean. One explanation is the measured samples were saturated; yet there was a greater amount of air entrapped in the soil matrix as compared to the calculated value, which assumes a theoretical complete filling with no air present. The calculated approach assumes a particle density of 2.65 g cm^{-1}; this value is placed in the denominator with the moist bulk density in the numerator. The product of this division is subtracted from one yielding pore space with the assumption pore space can be filled with water.

The two data sets were graphed using linear regression thus defining the coefficient of determination, or RSQ value. The data are shown in Figure 5.1.

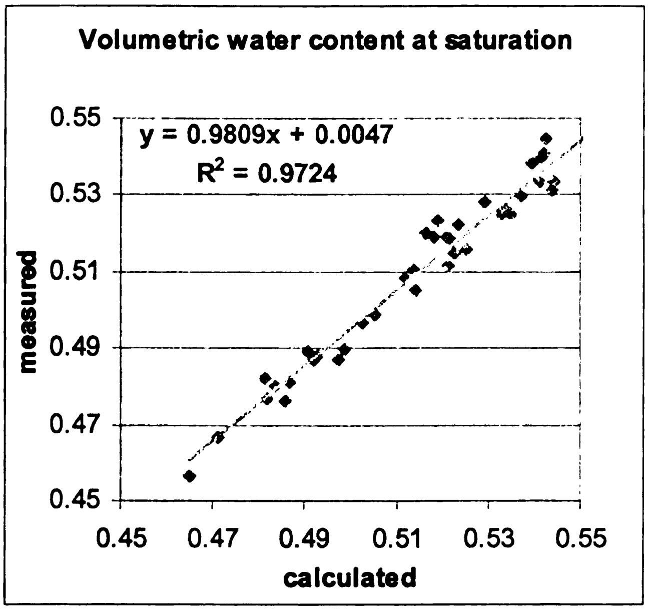

Figure 5.1 Volumetric water content (%) at saturation comparing calculated versus measured, with linear equation and R^2 value

Given that the two data sets were not significantly different the average value of measured volumetric water contents at saturation was used in RZWQM.

5.6 The SWCC complete curve

The SWCC is usually expressed as a log linear relationship. The matric potential is usually on the x-axis, as a logarithmic scale, and the volumetric water content is on the y-axis as a linear scale. The curve has a starting point at zero matric potential, denoting volumetric water content at saturation, and then as volumetric water content decreases, matric potential increases. An equation of this curve, due to its log-linear scale, cannot have a zero on the y-axis, corresponding to volumetric water at saturation.

One approach at defining the curve is dividing it into two equations. The first and second data pair of matric potential at 0 and 0.003 MPa can be written as a linear-linear equation. From 0.003 to 1.5 MPa the equation can be defined as log-linear. The justification for this approach is simple: the change in matric potential between these two points is small enough that it represents a slight change in volumetric water content. One additional rationale is the population in RZWQM. The values required for the complete defining of the SWCC are few: volumetric water at saturation, at 0.001 MPa, at 0.0033 MPa (FC), and at 1.5 MPa (PWP). The model does not use an equation. However the value of defining an equation is obvious: at any matric potential measurement the volumetric water content is known. For the irrigator installing some kind of matric potential measuring device, fitting data values to an equation is critical so that irrigation scheduling be accomplished correctly.

The SWCC figures below (5.2-5.21) illustrate specific matric potential-volumetric water content points at each sampling depth. The graphs are paired for each field: the linear x-axis for the 0 to 0.003 MPa and the log x-axis for the 0.003 to 1.5 MPa of matric potential. Each sampling depth is shown. The volumetric water content at measured saturation is shown in the linear-linear graphs on the x-axis point 0.

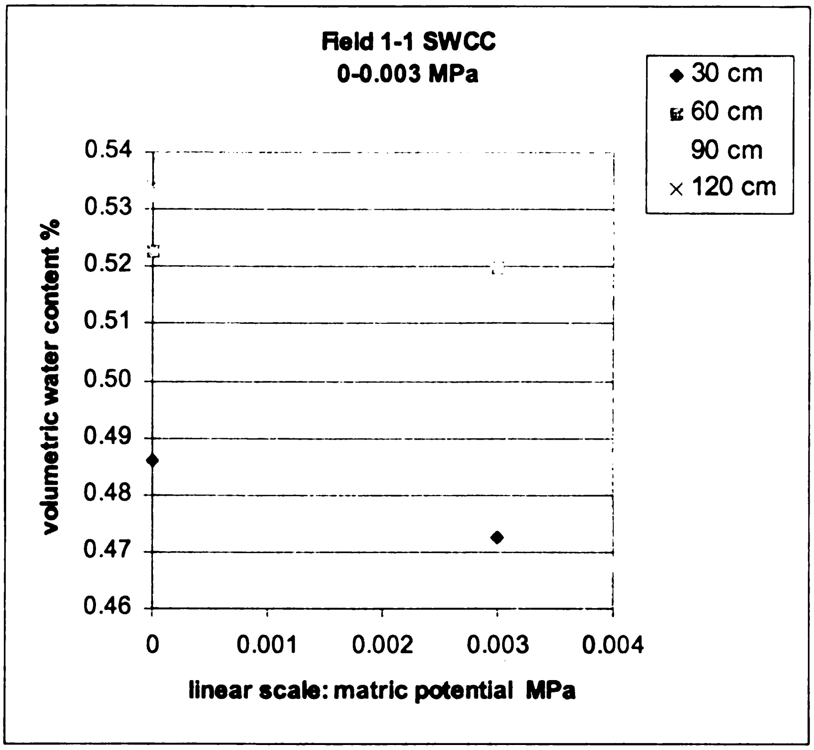

Figure 5.2 Field 1-1 linear scale 0-0.003 MPa matric potential-volumetric water content

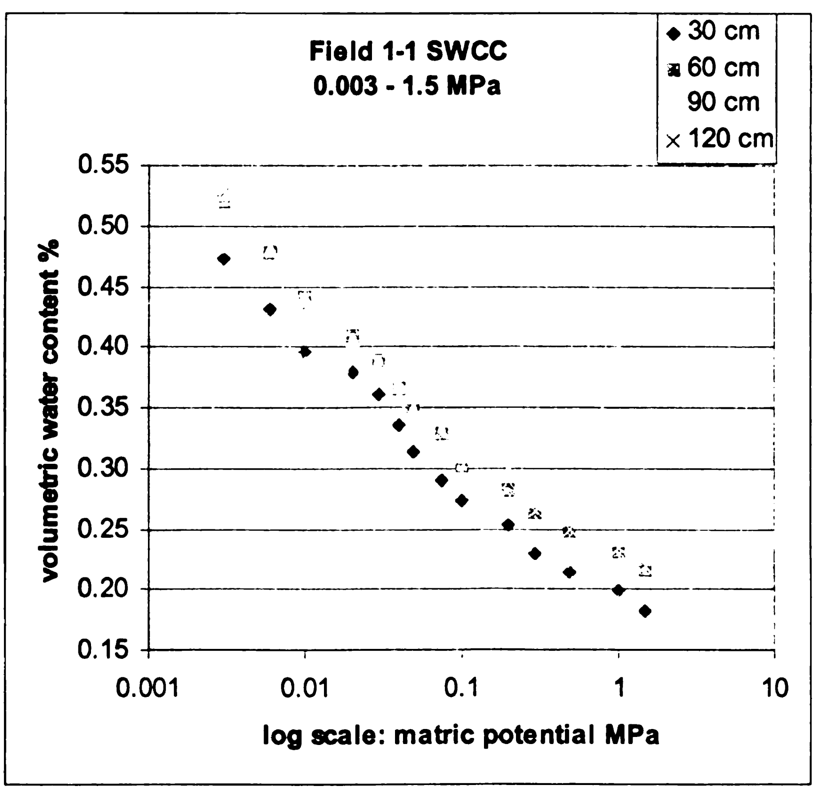

Figure 5.3 Field 1-1 log scale 0.003-1.5 MPa matric potential-volumetric water content

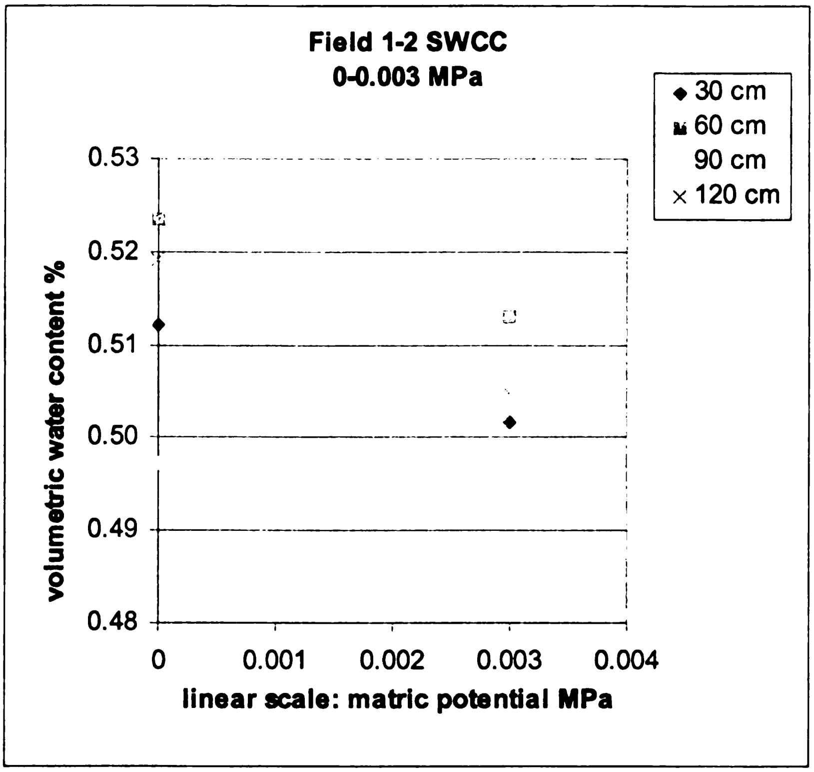

Figure 5.4 Field 1-2 linear scale 0-0.003 MPa matric potential-volumetric water content

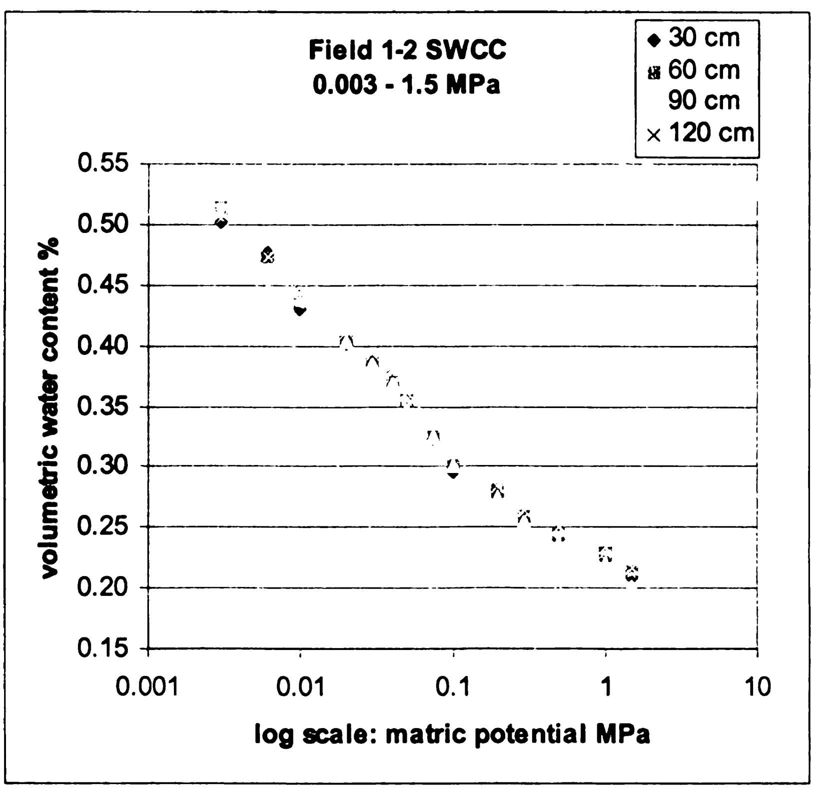

Figure 5.5 Field 1-2 log scale 0.003-1.5 MPa matric potential-volumetric water content

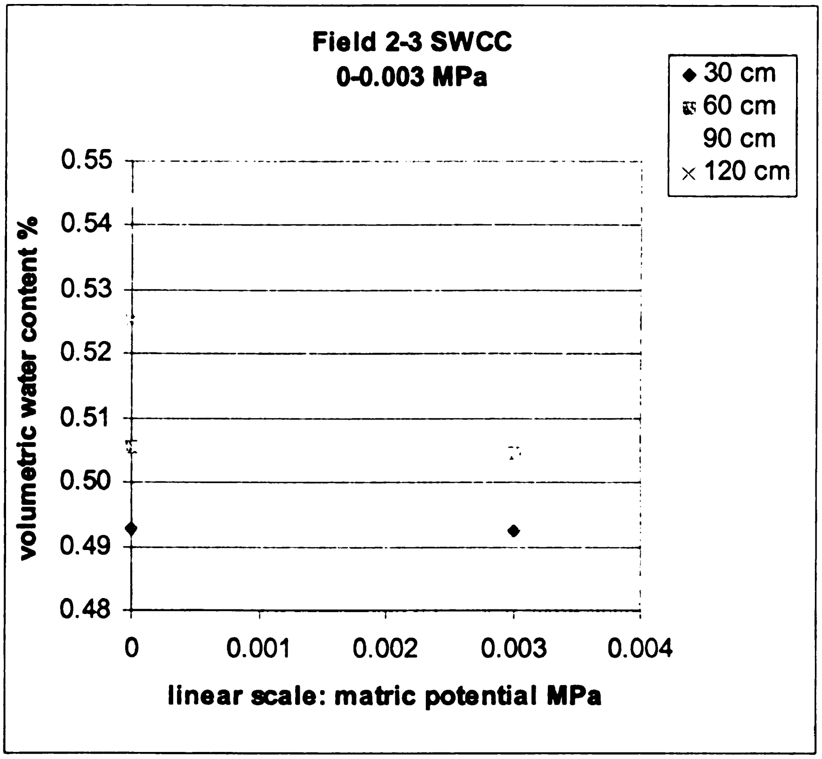

Figure 5.6 Field 2-3 linear scale 0-0.003 MPa matric potential-volumetric water content

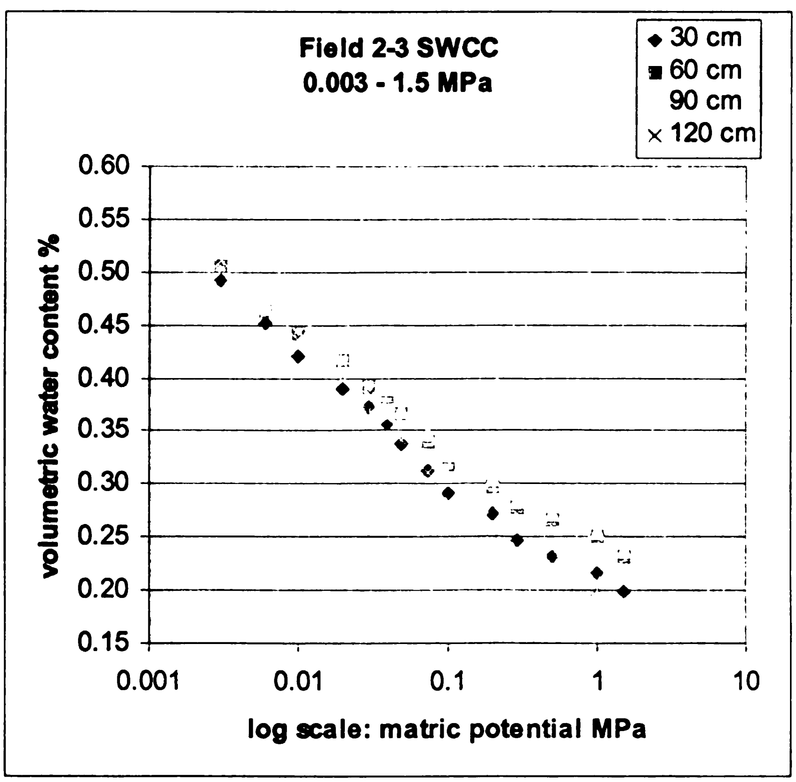

Figure 5.7 Field 2-3 log scale 0.003-1.5 MPa matric potential-volumetric water content

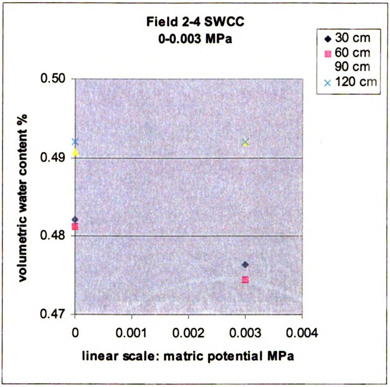

Figure 5.8 Field 2-4 linear scale 0-0.003 MPa matric potential-volumetric water content

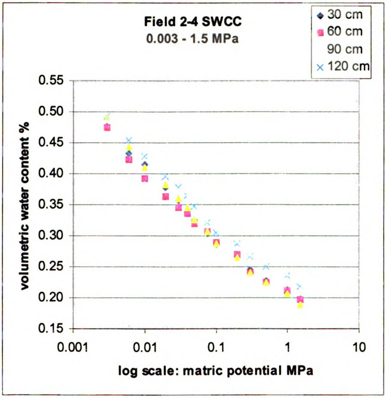

Figure 5.9 Field 2-4 log scale 0.003-1.5 MPa matric potential-volumetric water content

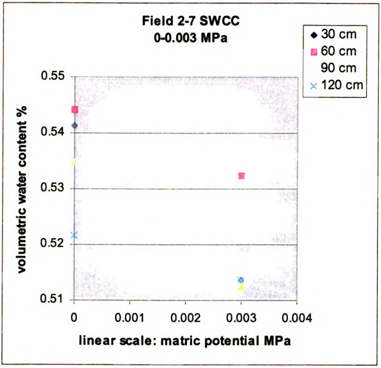

Figure 5.10 Field 2-7 linear scale 0-0.003 MPa matric potential-volumetric water content

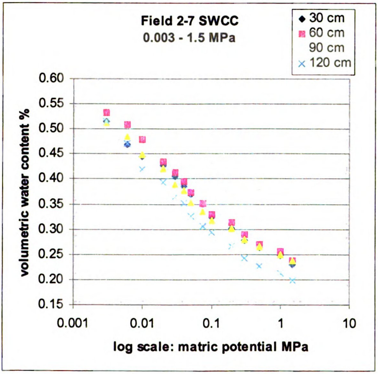

Figure 5.11 Field 2-7 log scale 0.003-1.5 MPa matric potential-volumetric water content

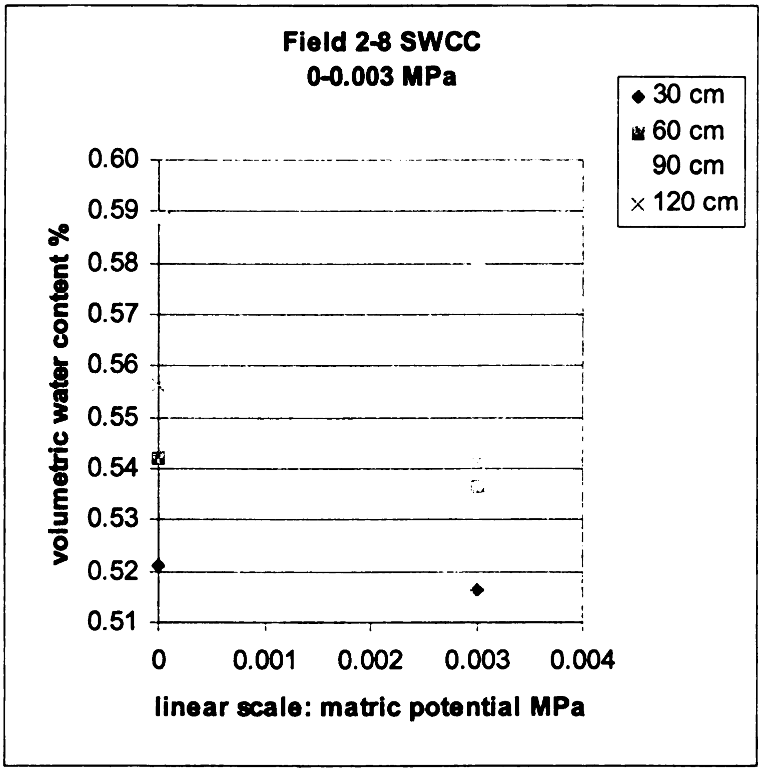

Figure 5.12 Field 2-8 linear scale 0-0.003 MPa matric potential-volumetric water content

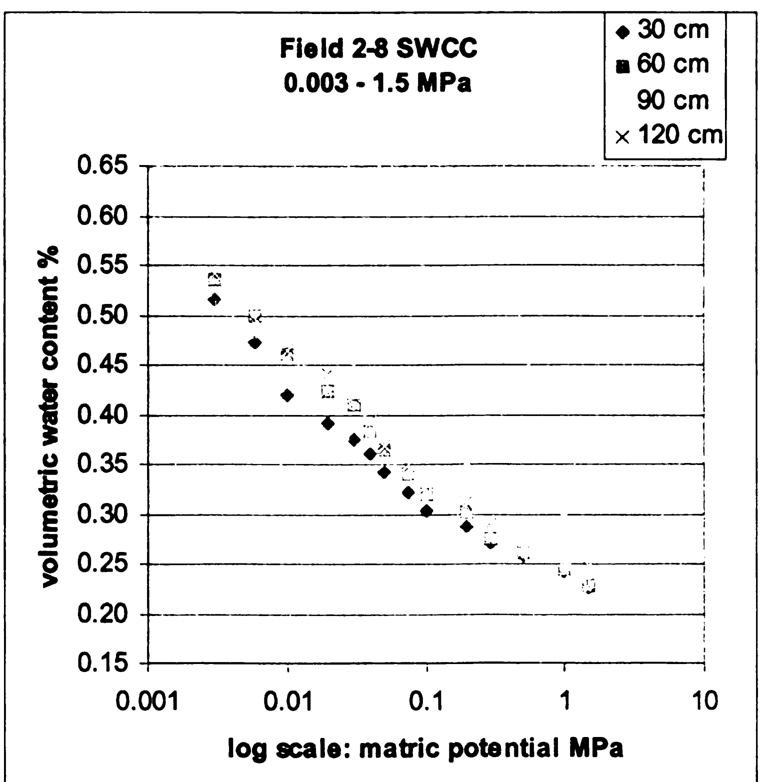

Figure 5.13 Field 2-8 log scale 0.003-1.5 MPa matric potential-volumetric water content

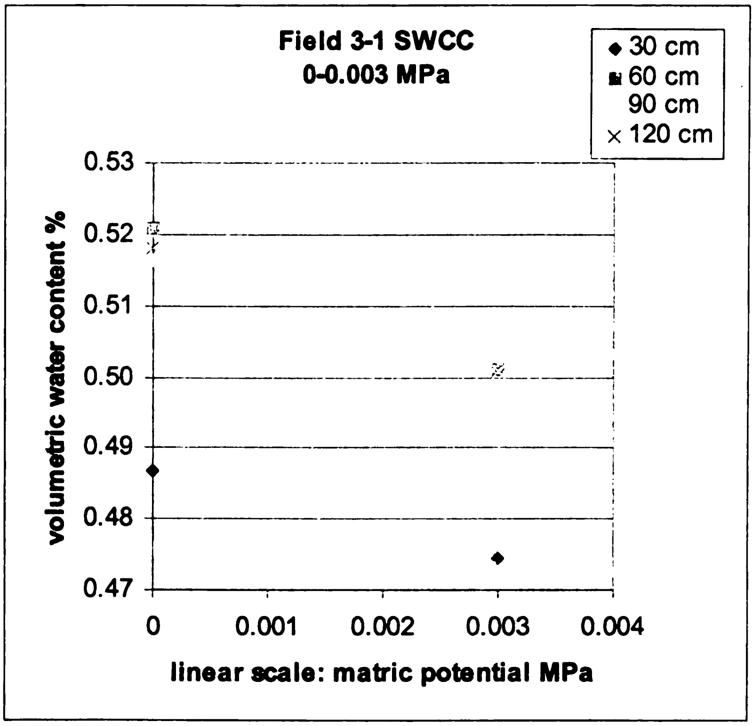

Figure 5.14 Field 3-1 linear scale 0-0.003 MPa matric potential-volumetric water content

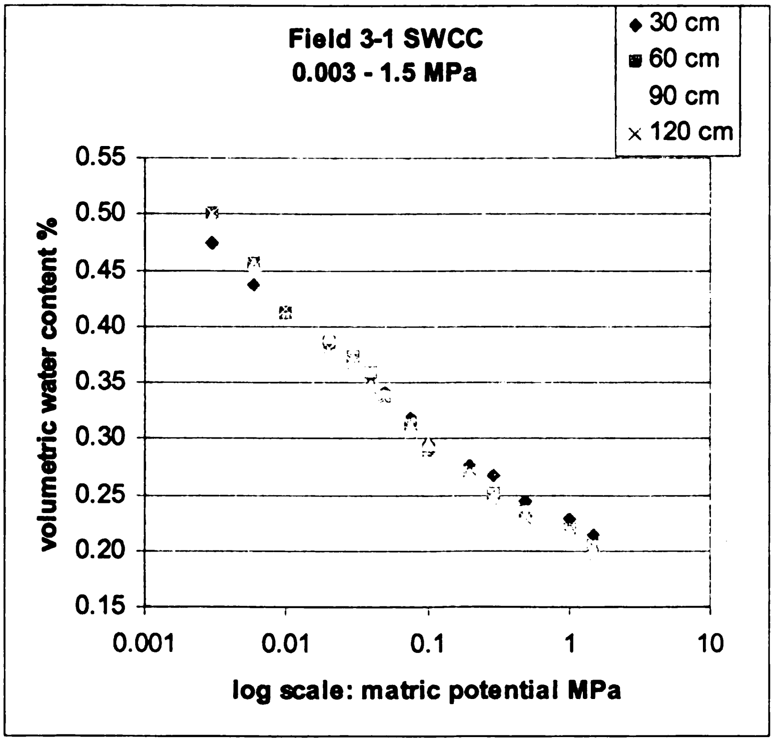

Figure 5.15 Field 3-1 log scale 0.003-1.5 MPa matric potential-volumetric water content

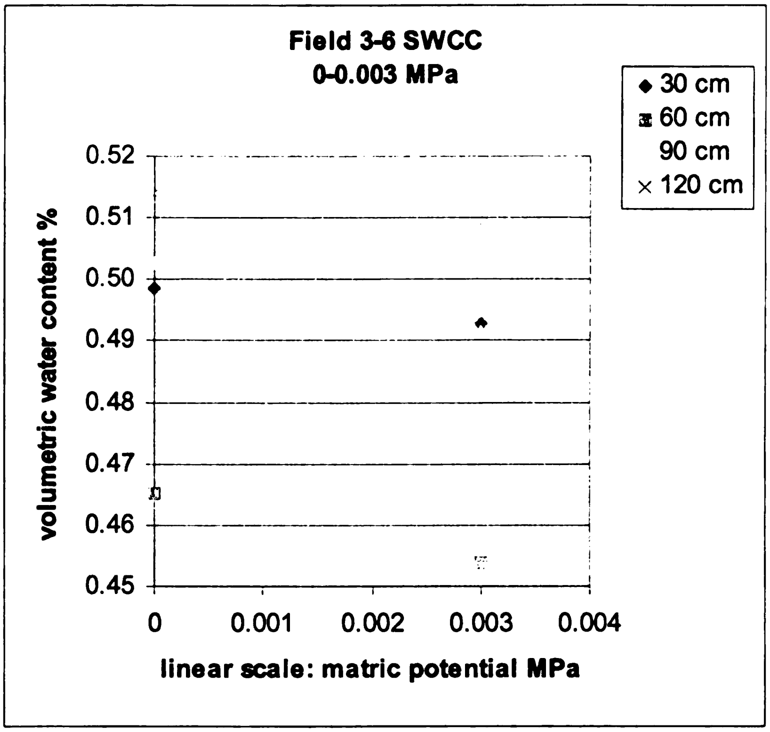

Figure 5.16 Field 3-6 linear scale 0-0.003 MPa matric potential-volumetric water content

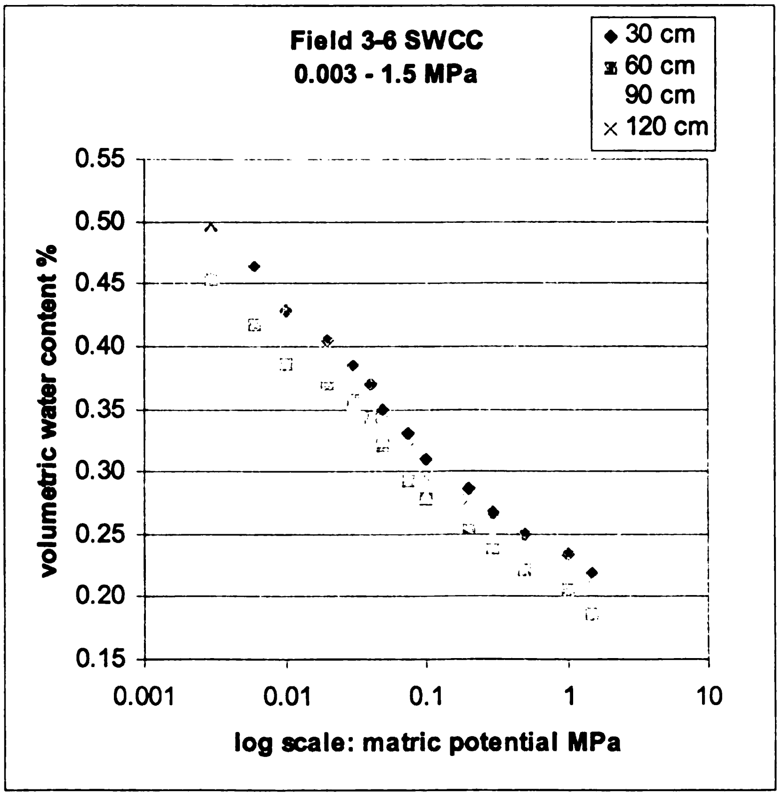

Figure 5.17 Field 3-6 log scale 0.003-1.5 MPa matric potential-volumetric water content

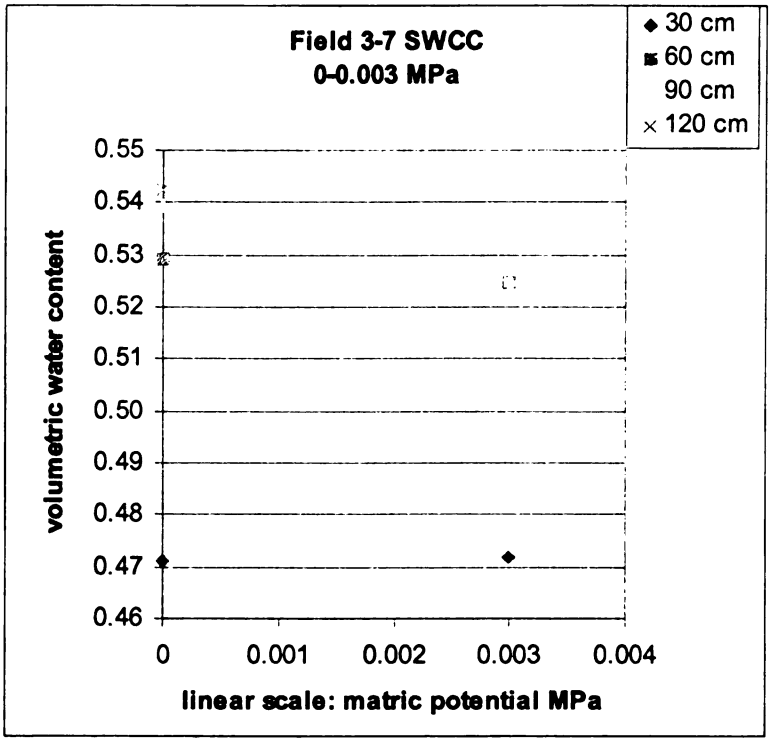

Figure 5.18 Field 3-7 linear scale 0-0.003 MPa matric potential-volumetric water content

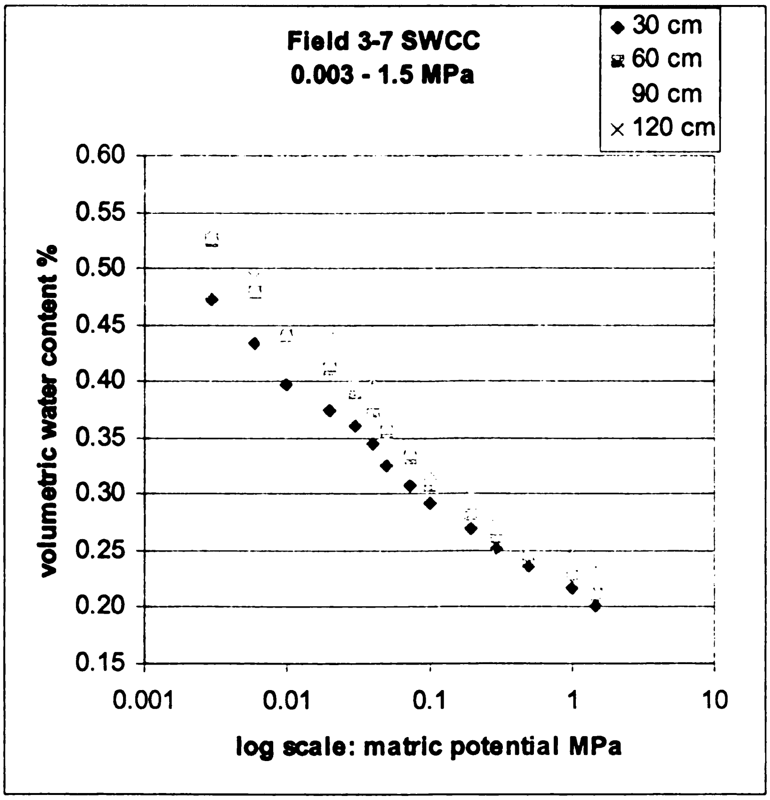

Figure 5.19 Field 3-7 log scale 0.003-1.5 MPa matric potential-volumetric water content

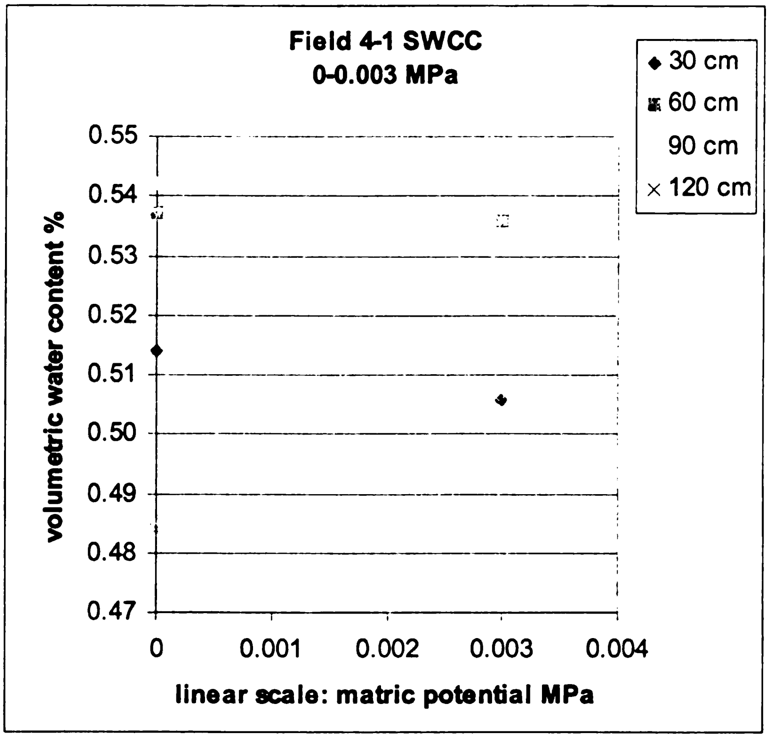

Figure 5.20 Field 4-1 linear scale 0-0.003 MPa matric potential-volumetric water content

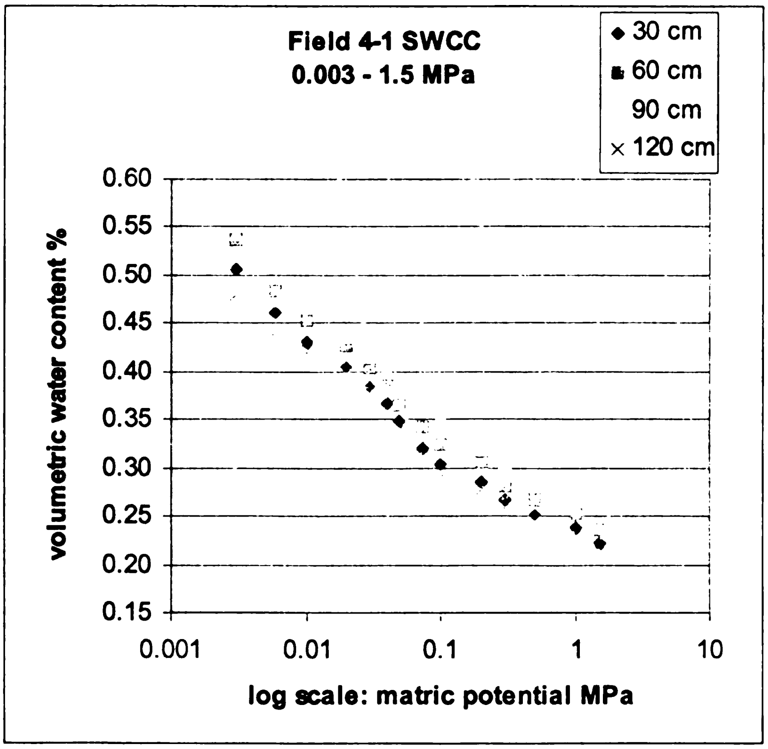

Figure 5.21 Field 4-1 log scale 0.003-1.5 MPa matric potential-volumetric water content

Table 5.2 contains equations for 0-0.003 MPa portion of the SWCC (linear-linear), equations for 0.003-1.5 MPa (log-linear), and the RSQ coefficient of determination values (R^2). The RSQ values indicate how well paired data, matric potential and volumetric water content fit the equation line. Because the x-axis data, as matric potential, has been converted to logarithmic values, the RSQ can be interpreted as a linear transformation. The average RSQ value is 0.98 with a standard deviation of 0.006. The logarithmic equations can therefore be used in RZWQM for determining volumetric water content for any matric potential data at or greater than 0.003 MPa. Because the linear equation has a RSQ value of 1 (only two data points, 0 and 0.003 MPa), this equation can be used in RZWQM for any matric potential data at 0 to 0.003 MPa. The final term in the linear equation is the volumetric water content at saturation for each field at the sampled depth (y-intercept).

Table 5.2 Field linear and log equations for SWCC, with RSQ, by depth

		0 - 0.003 MPa	0.003 MPa - 1.5 MPa	
Field ID	cm depth	Linear equation	Logarithmic equation	RSQ
Field 1-1	30	y = -4.4678(x) + 0.4858	y = -0.0474Ln(x) + 0.1828	0.981
	60	y = -0.9551(x) + 0.5227	y = -0.0496Ln(x) + 0.2124	0.977
	90	y = -2.2501(x) + 0.5325	y = -0.0475Ln(x) + 0.223	0.972
	120	y = -2.4605(x) + 0.5338	y = -0.0479Ln(x) + 0.2153	0.972
Field 1-2	30	y = -3.4803(x) + 0.512	y = -0.0491Ln(x) + 0.2082	0.980
	60	y = -3.5610(x) + 0.5236	y = -0.049Ln(x) + 0.2118	0.981
	90	y = -3.1242(x) + 0.4973	y = -0.0469Ln(x) + 0.2087	0.988
	120	y = -4.8239(x) + 0.519	y = -0.0482Ln(x) + 0.2197	0.987
Field 2-3	30	y = -0.2972(x) + 0.5054	y = -0.0478Ln(x) + 0.2009	0.985
	60	y = -0.1457(x) + 0.4929	y = -0.0444Ln(x) + 0.2355	0.985
	90	y = 2.6062(x) + 0.5439	y = -0.0486Ln(x) + 0.2363	0.980
	120	y = -4.5325(x) + 0.5253	y = -0.0556Ln(x) + 0.1803	0.982
Field 2-4	30	y = -1.9096(x) + 0.482	y = -0.0452Ln(x) + 0.1988	0.984
	60	y = -2.2501(x) + 0.4812	y = -0.0433Ln(x) + 0.1986	0.984
	90	y = -0.4371(x) + 0.4907	y = -0.0483Ln(x) + 0.1917	0.986
	120	y = 0.0162(x) + 0.492	y = -0.0444Ln(x) + 0.2208	0.985
Field 2-7	30	y = -9.2593(x) + 0.5413	y = -0.0463Ln(x) + 0.2344	0.987
	60	y = -3.9174(x) + 0.5441	y = -0.0497Ln(x) + 0.2383	0.981
	90	y = -7.4139(x) + 0.5348	y = -0.0459Ln(x) + 0.233	0.975
	120	y = -2.6709(x) + 0.5217	y = -0.0509Ln(x) + 0.1921	0.973
Field 2-8	30	y = -1.6835(x) + 0.5212	y = -0.0452Ln(x) + 0.2212	0.963
	60	y = -1.8292(x) + 0.5418	y = -0.0507Ln(x) + 0.2254	0.980
	90	y = -2.8004(x) + 0.589	y = -0.0459Ln(x) + 0.2813	0.974
	120	y = -4.9210(x) + 0.556	y = -0.0478Ln(x) + 0.2433	0.974
Field 3-1	30	y = -4.0469(x) + 0.4867	y = -0.0427Ln(x) + 0.2169	0.988
	60	y = -6.5883(x) + 0.5208	y = -0.0476Ln(x) + 0.2025	0.978
	90	y = -7.2358(x)+ 0.5164	y = -0.0484Ln(x) + 0.1978	0.982
	120	y = -5.7466(x) + 0.5181	y = -0.0489Ln(x) + 0.1922	0.977
Field 3-6	30	y = -1.9487(x) + 0.4985	y = -0.0456Ln(x) + 0.2207	0.988
	60	y = -3.7393(x) + 0.465	y = -0.0434Ln(x) + 0.1937	0.987
	90	y = -3.6908(x) + 0.5025	y = -0.0449Ln(x) + 0.2024	0.968
	120	y = -1.7321(x) + 0.5139	y = -0.048Ln(x) + 0.2107	0.973
Field 3-7	30	y = 0.2428(x) + 0.4712	y = -0.0432Ln(x) + 0.2052	0.988
	60	y = -1.4893(x) + 0.5291	y = -0.0507Ln(x) + 0.2115	0.983
	90	y = -3.626(x) + 0.5394	y = -0.049Ln(x) + 0.223	0.981
	120	y = -2.8328(x) + 0.5424	y = -0.0501Ln(x) + 0.2321	0.974
Field 4-1	30	y = -2.0490(x) + 0.5141	y = -0.0459Ln(x) + 0.2199	0.978
	60	y = -0.4047(x) + 0.5371	y = -0.048Ln(x) + 0.2341	0.979
	90	y = -0.0809(x) + 0.5422	y = -0.0461Ln(x) + 0.250	0.982
	120	y = -1.5864(x) + 0.4838	y = -0.0441Ln(x) + 0.2138	0.979

The important values of the SWCC are volumetric water content at saturation, FC, and PWP (expressed as a percentage). These values are shown in Table 5.3.

Table 5.3 Field saturation, FC, and PWP volumetric water % by depth

	Soil	Saturation %	FC %	PWP %
Field ID	depth cm	0 MPa	0.033 MPa	1.5 MPa
Field 1-1	30	0.49	0.34	0.16
	60	0.52	0.38	0.19
	90	0.53	0.39	0.20
	120	0.53	0.38	0.20
Field 1-2	30	0.51	0.38	0.19
	60	0.52	0.38	0.19
	90	0.50	0.37	0.19
	120	0.52	0.38	0.20
Field 2-3	30	0.51	0.36	0.18
	60	0.49	0.39	0.22
	90	0.54	0.40	0.22
	120	0.53	0.37	0.16
Field 2-4	30	0.48	0.35	0.18
	60	0.48	0.35	0.18
	90	0.49	0.36	0.17
	120	0.49	0.37	0.20
Field 2-7	30	0.54	0.39	0.22
	60	0.54	0.41	0.22
	90	0.53	0.39	0.21
	120	0.52	0.37	0.17
Field 2-8	30	0.52	0.38	0.20
	60	0.54	0.40	0.20
	90	0.59	0.44	0.26
	120	0.56	0.41	0.22
Field 3-1	30	0.49	0.36	0.20
	60	0.52	0.36	0.18
	90	0.52	0.36	0.18
	120	0.52	0.36	0.17
Field 3-6	30	0.50	0.38	0.20
	60	0.47	0.34	0.18
	90	0.50	0.36	0.18
	120	0.51	0.37	0.19
Field 3-7	30	0.47	0.35	0.19
	60	0.53	0.38	0.19
	90	0.54	0.39	0.20
	120	0.54	0.40	0.21
Field 4-1	30	0.51	0.38	0.20
	60	0.54	0.40	0.21
	90	0.54	0.41	0.23
	120	0.48	0.36	0.20

The scatterplot of these data are shown in Figure 5.22. The fields shown on the x-axis begin with field 1-1 at 30 cm depth, and sequentially match the progression of fields and depths in Table 5.3, ending with field 4-1, 120 cm depth.

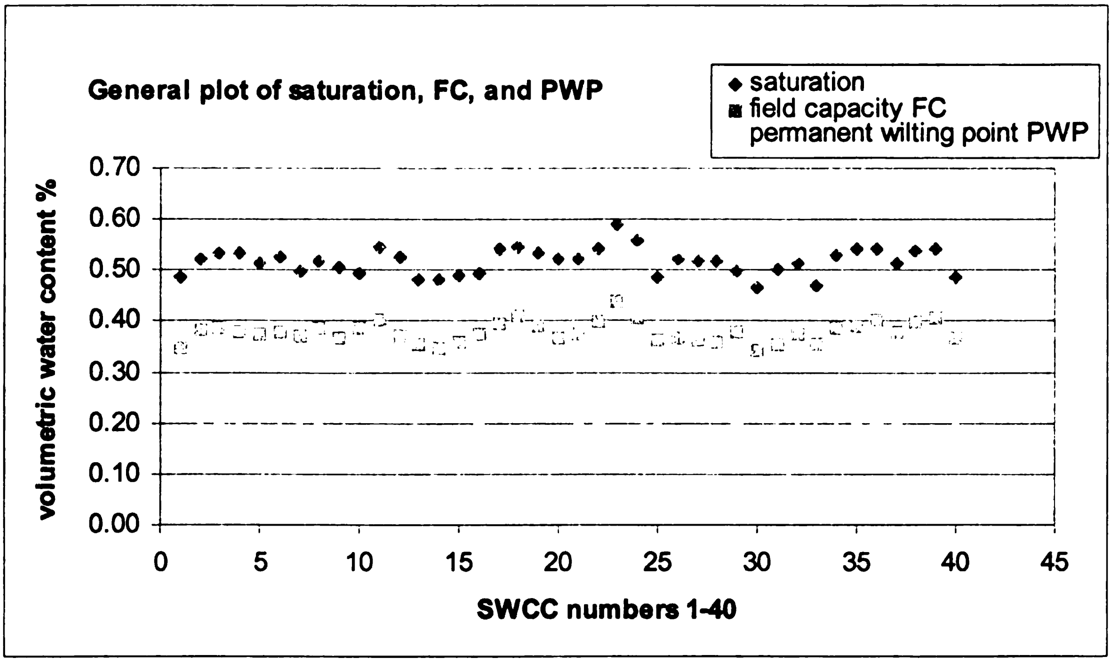

Figure 5.22 Field scatterplot of volumetric water content % at saturation, FC, PWP, by depth

The average volumetric water content at saturation for all soil depths and fields is 0.5168 with a standard deviation of 0.0252. In a 30 cm soil profile depth, this volume is 15.5 cm of water, with a standard deviation of 0.756 cm of water. The average volumetric water content at FC is 0.3774, with a standard deviation of 0.0199. In a 30 cm soil profile depth, this volume is 11.3 cm of water, with a standard deviation of 0.6 cm of water. The difference, 4.2 cm of water, is 27.1% of saturation. This is commonly known as gravitational water that during internal drainage is moved downward in the soil profile. The average volumetric water content at PWP is 0.1969, with a standard deviation of 0.0196. In a 30 cm soil profile depth, this volume is 5.9 cm of water, with a standard deviation of 0.59 cm of water. The difference, 5.4 cm of water, is commonly known as available water capacity (AWC) that is capable of meeting plant transpiration and soil evaporation. This difference is 35% of saturation.

In summary, the field soils in this study at all soil profile sampling depths averaged almost 52% saturation, almost 38% field capacity, and just less than 20% at permanent wilting point. As a function of volume depth, at saturation there is 15.5 cm of water, 11.3 cm of water at FC, and 5.4 cm of water at PWP. Gravitational water accounts for 27.1%, AWC accounts for 35%, and the remaining 37.9% is unavailable for plant transpiration.

5.7 Volumetric water contents: empirical field data

Given the volumetric water equations were built for all matric potential data from saturation to PWP, the next step was defining the field water profiles at each sampling depth based on the Watermark data. The Watermark data was compiled as matric potentials in units of 0-200 centibars, which are converted to units of MPa. All data points less than 0.003 MPa were converted to volumetric water content using the linear equation, and all data points to 0.2 MPa from 0.003 MPa were converted using the logarithmic equation.

The following figures 5.23-5.32 illustrate the volumetric water content for each of the ten fields at each sampling depth.

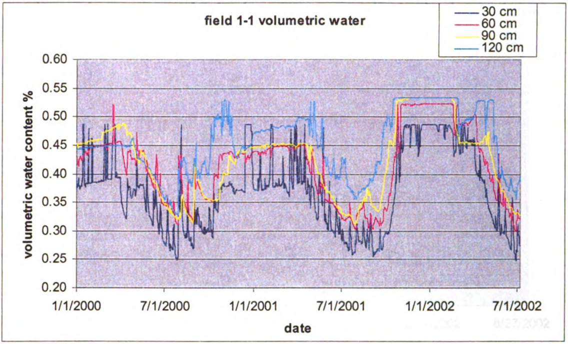

Figure 5.23 Field 1-1 Watermark volumetric water content % for study period, by depth

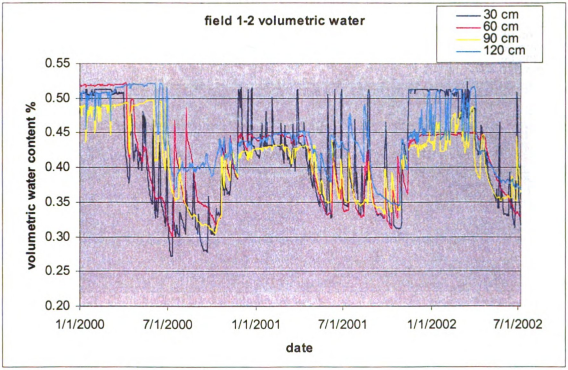

Figure 5.24 Field 1-2 Watermark volumetric water content % for study period, by depth

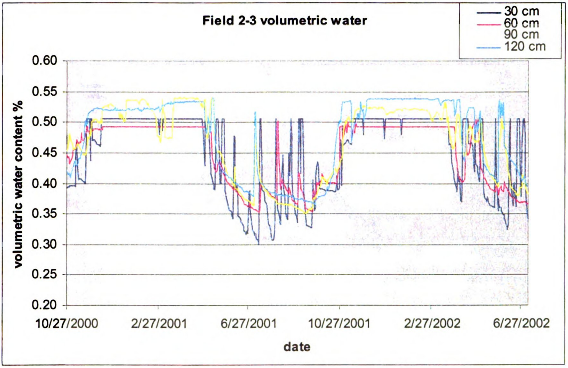

Figure 5.25 Field 2-3 Watermark volumetric water content % for study period, by depth

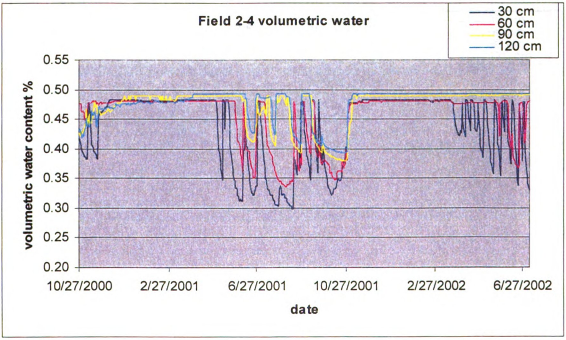

Figure 5.26 Field 2-4 Watermark volumetric water content % for study period, by depth

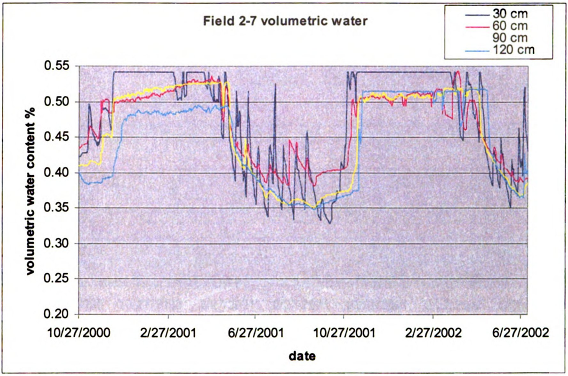

Figure 5.27 Field 2-7 Watermark volumetric water content % for study period, by depth

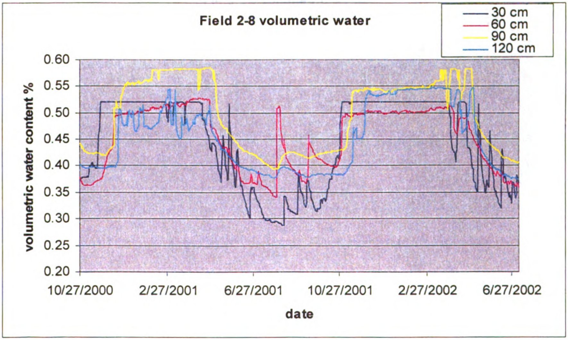

Figure 5.28 Field 2-8 Watermark volumetric water content % for study period, by depth

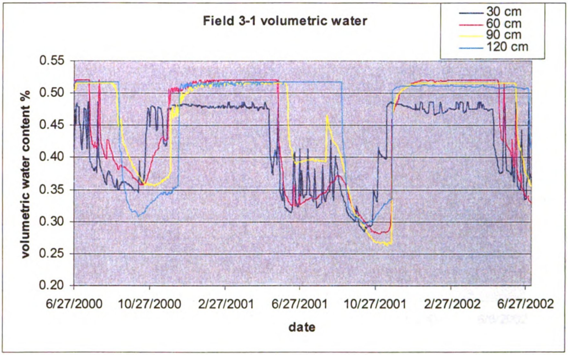

Figure 5.29 Field 3-1 Watermark volumetric water content % for study period, by depth

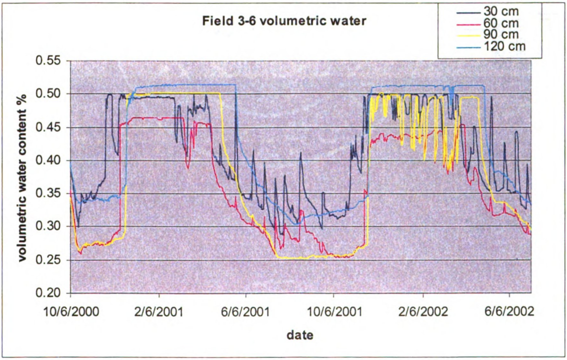

Figure 5.30 Field 3-6 Watermark volumetric water content % for study period, by depth

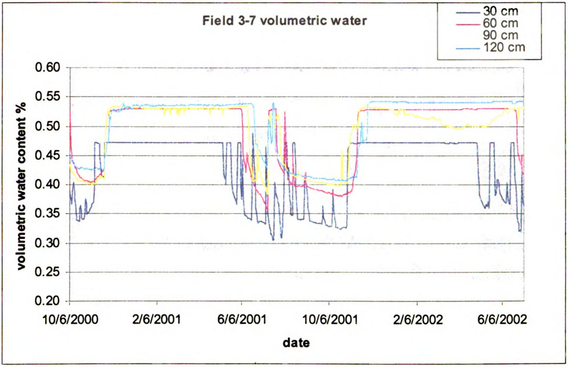

Figure 5.31 Field 3-7 Watermark volumetric water content % for study period, by depth

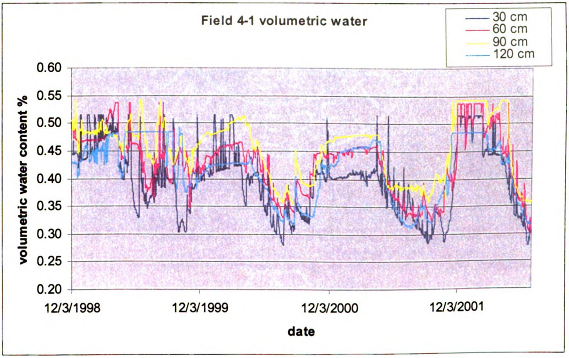

Figure 5.32 Field 4-1 Watermark volumetric water content % for study period, by depth

A general discussion of the graphs follows. The x-axis denotes the times during which the farm WS were operable. The data loggers were recording Watermark telemetry, and the rain gauges were recording rainfall. Each farm has different starting points, and these time frames are carried into RZWQM. The length of time periods differs; farm four has the longest time frame, and farm two the shortest. The volumetric water content on the y-axis denotes the results of matric potential data and the SWCC equations at each depth.

The more sensitive depth is 30 cm. The flux density of water into and out of this depth was a function of its adjacency to the soil surface, the atmospheric conditions causing evaporation and rainfall, and plant roots, responsible for plant transpiration during the growing season. More careful examination of each graph showed that during winter the soil profile was wetter, and in some fields at saturation for long periods of time. The soil water profiles were based upon landowner irrigation of freshwater and liquid manure wastewater as well. Examination of spikes of increased volumetric water content during the summer periods were the results of irrigation applications, however some were due to rainfall events albeit to a lesser degree.

5.8 RZWQM scenarios

The next step was calibrating RZWQM based upon the above water profiles. RZWQM was parameterized using the soil physical and hydraulic properties, climate data, crop data, and management data for each farm and field. This was an extensive requirement for modeling.

RZWQM uses the entire measurement depth of 120 cm. The physical and hydraulic parameters are based upon the Watermark depths of 30, 60, 90, and 120 cm depths. The model is also parameterized using NASIS data base default values, which alter the depth of each horizon.

Two versions of RZWQM were run. Fitting the model curves to the empirical (field) curves was the objective of calibration. A combination of measured (laboratory) and default (RZWQM, NASIS) values were required to fit the curves. The first and second version used the same parameters with the exception of the rainfall data, explained in the *.brk file:

1. The *.brk file used two hour rainfall data and 12 hour rainfall data. In version one, the total amount of rainfall that fell in the 24-hour period daily period was distributed over two hours. In version two, the same volume depth of rainfall was distributed over 12 hours.
2. The *.met file used Agrimet data
3. The management files were based upon landowner records of irrigation and wastewater application over the duration of the study period for each farm
4. The crop files were based upon each landowner cropping rotation, harvest cycles, and crop yield
5. Three physical and hydraulic parameters were modeled:
    a. Laboratory data, or full parameterization of data using bulk density, PSA, and SWCC data (field specific). The represent actual measurements.
    b. A combination of lab data and RZWQM default values. The laboratory values for textural class at each 30 cm increment was retained, but the

RZWQM data replaced the laboratory for all other parameters. The objective here was using the PSA analyses for each field site, and then using model values, thereby avoiding the need to determine the SWCC. The remaining *.brk, *.met, and management files remained the same.

c. NASIS data without the use of any laboratory data, using the following parameters:

    i. Soil horizons based upon Soil Survey identification

    ii. Soil hydraulic values based on mean values if a range are given or exact values if an exact data point is given. For instance the Ks is given as a range, whereas the bulk density if given as a data point, both conditional to textural class.

    iii. Soil physical values based upon default values in NASIS, including PSA, and soil horizon depth.

    iv. The remaining *.brk, *.met, and management files remained the same.

RZWQM version one and two models were built by field using the study period for which local rainfall data was available, therefore the starting date for each farm was different.

The data are presented in two forms: two figures illustrating each of the volumetric soil water profiles for version one (two hours) and version two (12 hours). A summary table is next, followed by explanatory text. The figures show four profiles:

1. Volumetric water content to 119 cm as measured Watermark data, i.e., measured or observed data: "Field"

2. Volumetric water content to 119 cm as modeled using full laboratory parameterization: "Lab"

3. Volumetric water content to 119 cm as modeled using PSA laboratory data, retaining 30 cm horizon increments, and RZWQM default values for all other physical and hydraulic parameters: "Lab RZ"

4. Volumetric water content to 119 cm as modeled using only NASIS Soil Survey data and thus no laboratory values: "NASIS"

The table for each field has both attribute data and statistical data. They were:

1. Attribute data:

   a. Field ID and model parameter, listing each field identification and model scenario as Lab, RZ, and NASIS.

   b. Textural class, which lists the PSA measured (laboratory) abbreviation for Silt Clay Loam (SiCL), Silt Loam (SiL), and Clay Loam (CL).

   c. Clay content, which lists the clay content as a decimal of one (if multiplied by 100 would be percentage of one).

   d. Volumetric water content that was actually measured in the Lab data, or used as a default value in RZWQM as a function of measured PSA, or the default value in NASIS as a function of the Soil Survey textural class.

   e. Rainfall in hours per day is version one at two hours and version 2 at 12 hours of volume depth distribution over time.

   f. R^2, or the coefficient of determination. This statistical function compares the measured or observed data as the independent variable (X_i) and the modeled data as the dependent variable (Y_i). The RSQ function can be interpreted as the variation on the modeled data that can be explained by the variation in the measured data. Values nearer one indicate greater similarity, whereas values nearer zero indicate a poor model fit with measured values. The R^2 formula is:

$R^2 = [[n(\Sigma XY)-(\Sigma X)(\Sigma Y)]/[(n\Sigma X^2-(\Sigma X)^2)(n\Sigma Y^2-(\Sigma Y)^2)]^{0.5}]^2$

g. Root Mean Square Error, or RMSE, defined as the standard deviation of the regression line. The greater this number the larger the variation of values either greater than or less than the regression line values. This statistic helps explain the goodness of fit, i.e., lower values show greater model agreement with measured or observed values. If this value is doubled, then approximately 95% of all values are found in the confidence interval. For these model scenarios the values are cm of volumetric water in the soil profile to 119 cm depth. The RMSE formula is:

$RMSE = [1/n\Sigma(meanY_i-X_i)^2]^{0.5}$

h. The Mean Error, or ME, is simply the mean value of the observed or measured data subtracted from the mean value of the modeled data. The ME is also described as the mean bias error, or MBE, which describes model predictions compared to observed or measured values. Positive ME values indicate the model tends to predict higher values than observed data and negative ME values tend to under predict model values. The two terms are determined using the same formula:

ME or MBE = meanY-meanX

i. Nash Sutcliffe Coefficient, or NSE (Efficiency). The NSE is used by modelers to explain model performance in terms of goodness of fit. The numerator is the sum of every paired X_i-Y_i squared. The denominator is the sum of each X_i-meanX squared. This value is subtracted from unity, or one. If the differences between the observed and simulated values are small, the fraction will be small, and the NSE will be nearer to one, indicating good model calibration. If the fraction value is greater than one, then the subtraction from one will yield a negative number, thus a poor model fit. The larger the negative number the less calibrated the model is at simulating the volumetric water content as compared to observed or measured values. A perfect model fit is one; the fraction is zero, indicating no variance between observed and modeled data. The NSE is unitless. Its value is relative to similar simulations so the model can be calibrated with the greatest NSE. However if all values are negative even the smallest negative value still suggests a poor model calibration. The NSE formula is:

$NSE = 1-[(\Sigma(X_i-Y_i)^2)/\Sigma(X_i\text{-mean}X)^2]$

j. Model rank is simply the rank of the six scenarios based upon the NSE value. The largest value is one; the most negative value is six.

5.9 Field 1-1

This field was conventionally tilled with corn silage grown in rotation with annual ryegrass as a cover crop. Both crops were harvested as dairy cattle feed (silage). Irrigation water and manure storage water were applied using a traveler big gun sprinkler system. The Watermark array of sensors, at 30, 60, 90, and 120 cm of soil profile depth were hard wired to the datalogger at the WS at the edge of the field. This field was located in Polk County Oregon, and had a NASIS Soil Map Unit of Amity Silt Loam.

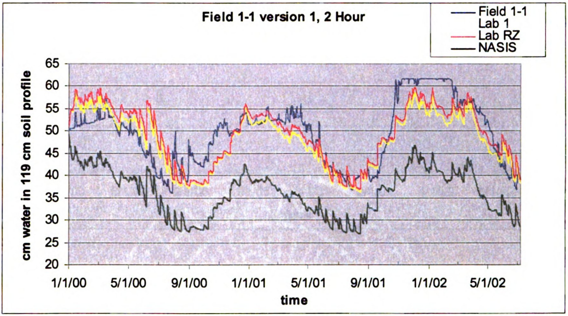

Figure 5.33 Field 1-1 two hour empirical versus simulation volumetric water content

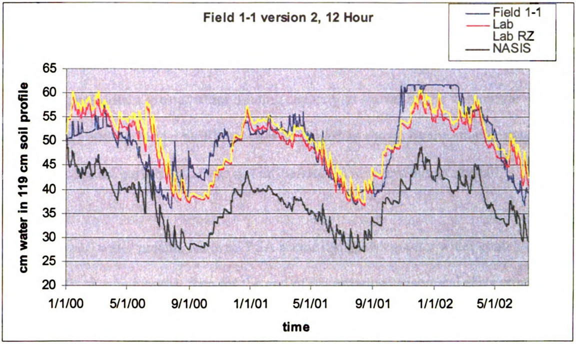

Figure 5.34 Field 1-1 12 hour empirical versus simulation volumetric water content

Table 5.4 Field 1-1 RZWQM simulation comparison and NSE model rank

Field 1-1	Textura l class	Clay conte nt %	Volumetric water FC %	rain hours d^{-1}	R^2	RMS E cm	ME	NSE	model rank
Lab	SiCL	0.31	0.34	2	0.64	4.48	-1.45	0.59	3
Lab RZ	SiCL	0.35	0.34	2	0.63	4.37	-0.20	0.61	1
NASIS	SiL	0.15	0.37	2	0.61	13.98	13.26	-2.96	6
Lab	SiCL	0.31	0.34	12	0.62	4.37	-0.45	0.61	2
Lab RZ	SiCL	0.35	0.34	12	0.61	4.56	0.82	0.58	4
NASIS	SiL	0.15	0.37	12	0.60	12.29	12.20	-2.42	5

The best model scenario were the two-hour lab PSA increment horizon with RZWQM default physical and hydraulic data, however the second ranked scenario had the same NSE but greater RMSE and ME. For scenario rank one, the FC volumetric water content was 48.4 cm of water; the RMSE value of 4.37 is 9.03% of FC. For both versions of rainfall time periods, the rankings were lowest. The negative NSE values indicate poor model performance. One explanation was decreased clay content as the NASIS Soil Map Unit, as a Silt Loam, had only 43% of the clay as the Silt Clay Loam soil (15% versus 35%). These data bear out the importance of using PSA. The increased clay content provides a greater water holding capacity as shown by the volumetric water content at FC, and the model performance is enhanced as shown by the smaller negative ME values. Model performance was not influenced by two versions of rainfall distribution.

The soil water profile, for local PSA scenarios, shows greater water content for the first eight or nine months, then for the end of the growing season and early winter an understated water content. The model simulations appear to closely resemble the Watermark data during the second year, but for the winter period tend to underestimate the water content in the profile. The default saturated hydraulic values were used in all scenarios: 1.5 cm h^{-1} for the surface layer, and 0.68 cm h^{-1} for the lower depths (< 30 cm). These values negated any surface runoff. This rationale was justified as the landowner reported and the researcher observed no surface runoff of any volume of irrigated water on the field at or immediately after an irrigation event. No field K_s data were obtained; this is one area of refinement that may improve the precision of the model.

5.10 Field 1-2

Field 1-2 was a field adjacent to field 1-1. The cropping and management program were the same. The Watermark array of sensors was hard wired to the same datalogger as field 1-1. Local rainfall data were the same for both fields. Like field 1-1, this field had a NASIS Soil Map Unit of Amity Silt Loam.

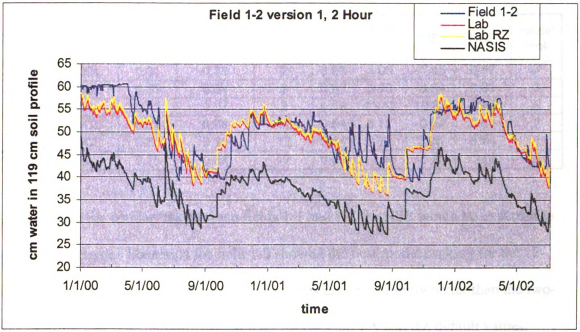

Figure 5.35 Field 1-2 two hour empirical versus simulation volumetric water content

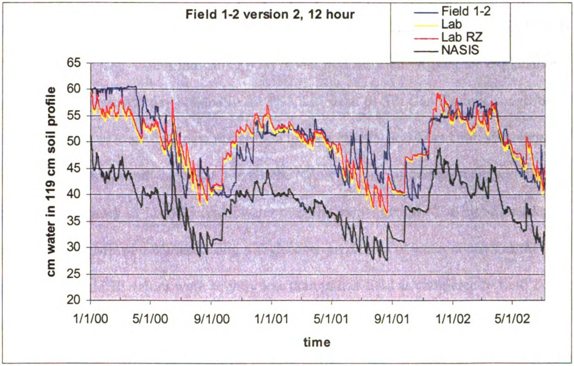

Figure 5.36 Field 1-2 12 hour empirical versus simulation volumetric water content

Table 5.5 Field 1-2 RZWQM simulation comparison and NSE model rank

Field 1-2	Textural class	Clay content %	Volumetric water FC %	rain hours d^{-1}	R^2	RMSE cm	ME	NSE	model rank
Lab	SiCL	0.31	0.38	2	0.63	4.05	-1.45	0.57	4
Lab RZ	SiCL	0.35	0.34	2	0.63	3.90	-0.84	0.61	3
NASIS	SiL	0.15	0.37	2	0.59	13.42	12.83	-3.68	6
Lab	SiCL	0.31	0.38	12	0.64	3.77	-0.54	0.63	2
Lab RZ	SiCL	0.35	0.34	12	0.64	3.73	0.06	0.64	1
NASIS	SiL	0.15	0.37	12	0.62	12.49	11.89	-3.05	5

Given the similarities between fields 1-1 and 1-2 the NSE would be expected to be nearly the same. Scenarios for field 1-2 showed the best model ranking for the 12-hour rainfall distribution, however the NSE values are only slightly better than the two-hour distribution. The highest NSE, at 0.64 for the lab PSA and RZ default values, compares to 0.612 for field 1-1. For both fields, the number one rank was PSA Lab data and RZ default values. For scenario rank one, the FC volumetric water content is 48.4 cm of water; the RMSE value of 3.73 is 7.71% of FC. The NASIS scenarios, like field 1-1, had negative NSE values indicating poor model performance. Again, the explanation might be the increased clay content in the PSA Lab data, as Silt Clay Loams, suggesting the importance of local field data rather than using a NASIS Soil Map Unit. The large negative ME values indicated that overall, the NASIS scenarios under predicted water content by as much as 12 to 13 cm of water over the model period. The highest ranked scenario had a ME of 0.06, indicating a slight over prediction of water content in the profile. The RMSE values were slightly less than in this field as compared to field 1-1, indicating slightly better model performance.

Model scenarios did not appear to fit Watermark data, as well, for the second year in contrast to field 1-1. The model more accurately predicted the water content during the second winter; unlike the same period in field 1-1, the Watermark data do not indicate the field is at saturation. The same default values of K_s were used in both fields on this farm. No observed runoff occurred on this field; the slope gradient is < 0.2%.

5.11 Field 2-3

Field 2-3 was a perennial ryegrass field that is used for grass silage production in spring and then grazed by dairy cattle during the summer and fall. The field was not conventionally tilled. The Watermark array was hard wired to a datalogger that was built on the WS frame. Local rainfall data were obtained from this WS. This farm was located in Clackamas County Oregon and had a NASIS Soil Map Unit of Powell Silt Loam.

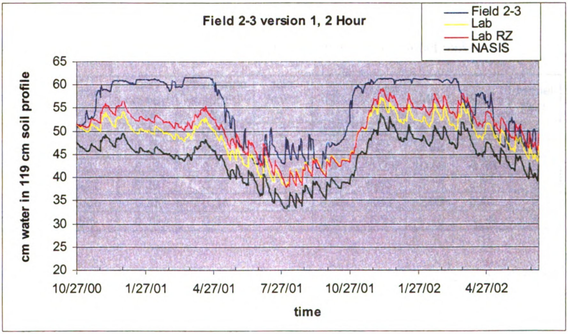

Figure 5.37 Field 2-3 two hour empirical versus simulation volumetric water content

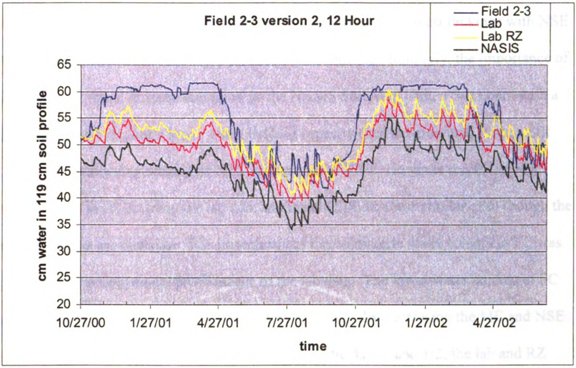

Figure 5.38 Field 2-3 12 hour empirical versus simulation volumetric water content

Table 5.6 Field 2-3 RZWQM simulation comparison and NSE model rank

Field 2-3	Textural class	Clay content %	Volumetric water FC %	rain hours d^{-1}	R^2	RMSE cm	ME	NSE	model rank
Lab	SiCL	0.28	0.36	2	0.69	7.35	-6.29	-0.23	4
Lab RZ	SiCL	0.35	0.34	2	0.64	5.80	-4.44	0.64	1
NASIS	SiL	0.15	0.37	2	0.67	11.34	10.66	-1.93	6
Lab	SiCL	0.28	0.36	12	0.66	6.53	-5.16	0.03	3
Lab RZ	SiCL	0.35	0.34	12	0.68	4.93	-2.99	0.45	2
NASIS	SiL	0.15	0.37	12	0.64	10.24	-9.40	-1.39	5

The highest ranked scenario was the lab PSA data with RZ default data; the NSE value of 0.64 for the two-hour rainfall distribution exceeds the second ranked scenario using the same attributes but with rainfall distributed over 12 hours. All scenarios had under predicted water contents in the 119 cm soil profile as shown in the ME data. The mean value of the highest ranked scenario was 4.44 cm of water less than the mean value of the Watermark data. The second ranked scenario had a smaller ME of 2.99 cm. As with both fields 1-1 and 1-2, the NASIS data was ranked at the lowest rankings with NSE values that are negative indicating poor model performance. Similarly, the importance of the PSA were found in these scenarios, as the NASIS Soil Map Unit, a Silt Loam with a clay content of 15%, has a lower water holding capacity than the measured PSA, a Silt Clay Loam with a clay content of 28%, an increase of 87%. However the volumetric water content at FC between the lab data and the NASIS data was similar even though the textural classes are different. The importance of the volumetric water content at FC was shown by the poorer model performance of the lab data. The lower water content at FC shifted the water content profile lower in the figure, thereby decreasing the ME and NSE and increasing the RMSE. This was not the case in fields 1-1 and 1-2; the lab and RZ water contents at FC were closer in agreement.

For both versions, the data appear to more correctly predict the water content during the growing season. There was only one full growing season for the modeled time period but the beginning of the second growing season was reflective of the first. One improvement was found in the second winter season period. The model did not under predict the water content as much as the first winter period. The K_s for this field were the same default values used throughout the modeling exercise. Field 2-3 was a B slope. At a rolling topographical slope of 2-6%, the landowner was concerned with runoff events. The risk was decreased by applying smaller irrigation volumes more often. The landowner mitigated water erosion by keeping this field in permanent vegetation; however, the K_s values may overstate hydraulic conductivity given what the landowner calls animal compaction. Decreasing K_s would increase the profile water content for much of the model period, thereby shifting the water profile upwards, reducing the negative ME, decreasing the RMSE, and possibly increasing the NSE. Increasing K_s would not increase the water content at FC.

5.12 Field 2-4

Field 2-4 was adjacent to field 2-4. This field was in conventional tillage for many years, a corn silage (summer) and annual ryegrass rotation (winter). The landowner, however, sought to mitigate water erosion in this C slope field (6-12%) by planting permanent vegetation. For the modeled time period the field was in perennial grass. The field was harvested as grass silage during the early part of the growing season and then grazed by dairy cattle for the rest of the year. The Watermark array was hardwired to the datalogger on the WS. Rainfall data were obtained from this local WS. This farm was located in Clackamas County and had a NASIS Soil Map Unit of Powell Silt Loam.

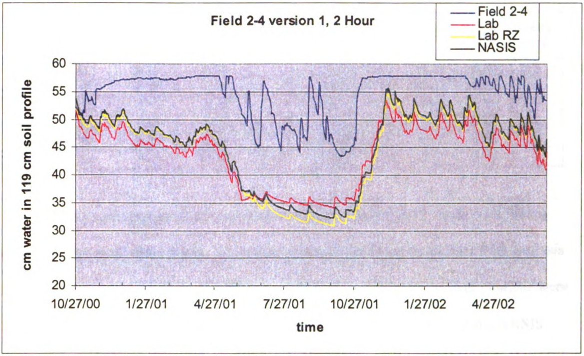

Figure 5.39 Field 2-4 two hour empirical versus simulation volumetric water content

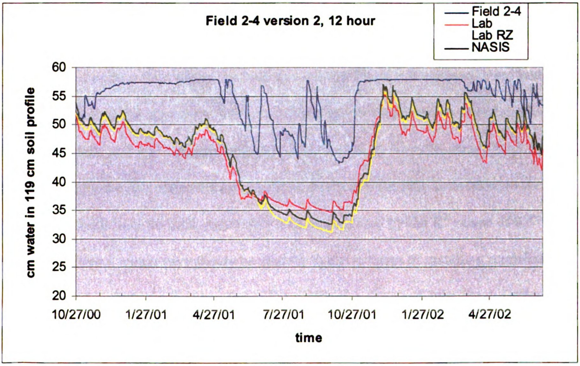

Figure 5.40 Field 2-4 12 hour empirical versus simulation volumetric water content

Table 5.7 Field 2-4 RZWQM simulation comparison and NSE model rank

Field 2-4	Textural class	Clay content %	Volumetric water FC %	rain hours d^{-1}	R^2	RMSE cm	ME	NSE	model rank
Lab	SiL	0.25	0.35	2	0.56	11.67	11.12	-6.85	6
Lab RZ	SiL	0.25	0.29	2	0.58	11.56	10.51	-6.70	5
NASIS	SiL	0.15	0.37	2	0.57	10.91	-9.89	-5.86	4
Lab	SiL	0.25	0.35	12	0.58	10.66	10.05	-5.55	2
Lab RZ	SiL	0.25	0.29	12	0.59	10.67	-9.52	-5.56	3
NASIS	SiL	0.15	0.37	12	0.59	10.04	-8.91	-4.81	1

Model performance in all scenarios was poor. The relatively high NSE values exceeded NSE in all other fields. In contrast to the above listed fields, this PSA analysis and the NASIS data both place this field as a Silt Loam. However the clay contents were different. The measured PSA lab content were 25% and the value used in the NASIS database is 15%. The increased water holding capacity in the Lab and Lab RZ scenarios did not improve model performance. The relatively high negative ME values indicated under prediction of water content in the soil profile. The RMSE for the Lab and Lab RZ scenarios were all greater than the first three field RMSE's.

This may be a field where the bulk soil surrounding the Watermark array and that sampled for use in the laboratory (PSA) had larger physical differences than the other fields. The bulk soil was collected approximately one meter from the array (in all fields), but this may be the one where the array soils do not match the bulk soils taken to the lab. The profile trend lines do track reasonably well as indicated by the R^2 values of 0.57 to 0.58. The second winter period may be slightly better in terms of matching modeled data with Watermark data, but the very end of the profile, i.e. June and July, show a steep decrease in water content when compared to Watermark data.

If there was one field in the study that would discourage a modeling effort, this is it.

5.13 Field 2-7

Field 2-7 was the third of four fields on farm two. This field was perennial grass, and resembles field 2-3 in terms of cropping and management practices. This was one two most productive fields on this farm. The watermark array was wired to the datalogger as part of the WS. Rainfall data were obtained from this local WS. This farm was located in Clackamas County and had a NASIS Soil Map Unit of Aloha Silt Loam.

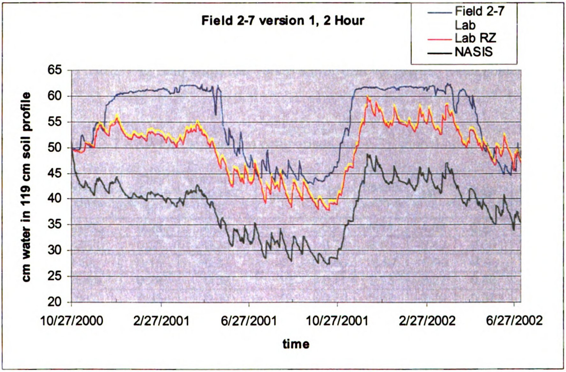

Figure 5.41 Field 2-7 two hour empirical versus simulation volumetric water content

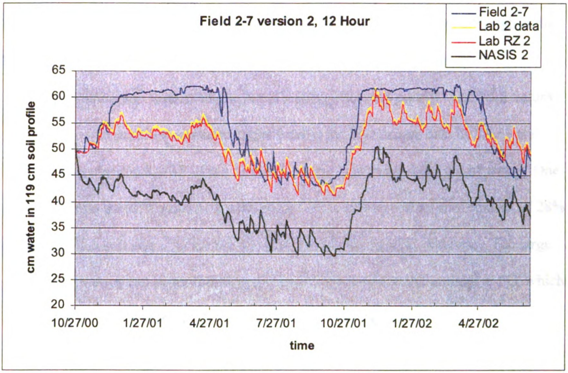

Figure 5.42 Field 2-7 12 hour empirical versus simulation volumetric water content

Table 5.8 Field 2-7 RZWQM simulation comparison and NSE model rank

Field 2-7	Textural class	Clay content %	Volumetric water FC %	rain hours d^{-1}	R^2	RMSE cm	ME	NSE	model rank
Lab	SiCL	0.28	0.39	2	0.71	6.11	-4.84	0.23	3
Lab RZ	SiCL	0.35	0.34	2	0.71	6.62	-5.42	0.09	4
NASIS	SiL	0.15	0.37	2	0.60	16.97	16.39	-4.96	6
Lab	SiCL	0.28	0.39	12	0.71	5.13	-3.27	0.46	1
Lab RZ	SiCL	0.35	0.34	12	0.70	5.52	-3.79	0.37	2
NASIS	SiL	0.15	0.37	12	0.59	15.51	14.85	-3.98	5

Two 12-hour scenarios ranked one and two with positive NSE values: 0.46 and 0.37. The two scenarios had similar ME, RMSE, and R^2 values. Both ME values indicated the model under predicts water content in the soil profile; the figures illustrate the typical curve at a lower volumetric water content than the Watermark data. The modeled scenarios fit the growing season portion of the model period better than the non-growing season. The second year modeled scenarios during the fall and winter period, November through March, predict the Watermark data more accurately, although at the very end of the curve, in June, the two curves depart from one another.

As with the previous fields the NASIS data performed poorly. The NSE values are negative. The modeled scenarios under predict the Watermark data by 14.85 and 16.39 cm of water; the RMSE of the NASIS data are 15.51 and 16.97 cm of water. One explanation was the difference between textural class, influenced by clay content of 28% for the Lab PSA soil and 15% for the Silt Loam soil in the NASIS database. The large negative ME values can be attributed to the lower volumetric water content at FC, which is a function of clay content and available water holding capacity.

5.14 Field 2-8

This was the fourth of four fields on farm two. This was the second of two most productive fields on the farm. The management and cropping program was similar to field 2-3 and 2-7. The watermark array was wired to the datalogger as part of the WS. Rainfall data were obtained from this local WS. This farm was located in Clackamas County and had a NASIS Soil Map Unit of Aloha Silt Loam.

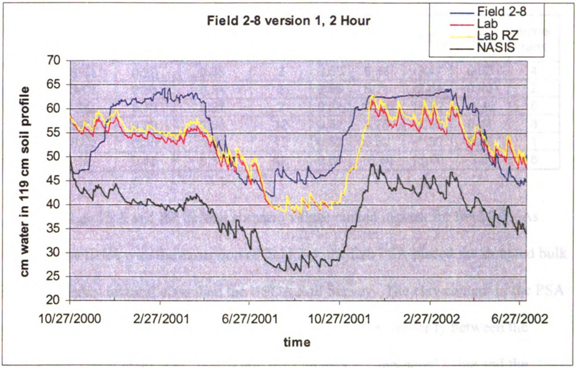

Figure 5.43 Field 2-8 two hour empirical versus simulation volumetric water content

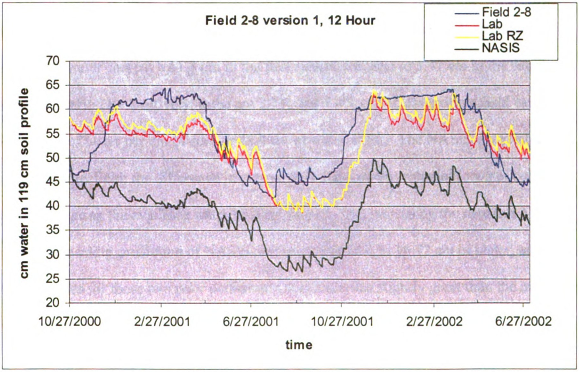

Figure 5.44 Field 2-8 12 hour empirical versus simulation volumetric water content

Table 5.9 Field 2-8 RZWQM simulation comparison and NSE model rank

Field 2-8	Textural class	Clay content %	Volumetric water FC %	rain hours d^{-1}	R^2	RMSE cm	ME	NSE	model rank
Lab	SiCL	0.29	0.38	2	0.55	6.15	-3.47	0.33	4
Lab RZ	SiCL	0.35	0.34	2	0.55	5.71	-2.44	0.42	2
NASIS	SiL	0.15	0.37	2	0.54	17.50	16.72	-4.42	6
Lab	SiCL	0.29	0.38	12	0.52	5.76	-2.35	0.41	3
Lab RZ	SiCL	0.35	0.34	12	0.52	5.52	-1.30	0.46	1
NASIS	SiL	0.15	0.37	12	0.50	16.50	15.60	-3.81	5

The Lab PSA and RZ default scenario values ranked highest for field 2-8. As with previous fields with the exception of field 2-4, the Lab PSA placed the sampled bulk soil in a different textural class than the USDA Soil Survey. The clay content in the PSA data was almost twice the content than the NASIS data. The similarity between the volumetric water content at FC is striking; the Lab data is a measured value and the RZWQM data is a default value as a function of identifying textural class. Model performance confirmed this positive relationship. The third and fourth ranked fields had slightly lower NSE values. The negative ME values indicate the model does under predict the water content by 1.3 cm in the first ranked scenario to 3.47 cm in the fourth ranked scenario. Respectively, these are 2.7% and 7.0% of FC, assuming a field capacity of 0.41 cm of water per cm of soil, or 48.4 cm of water at FC. The NASIS data reflect every previous field; the difference in clay content reduced the volumetric water content, thereby lowering the available water holding capacity and increasing the negative ME values. The under prediction of NASIS scenarios was 15.6 to 16.72 cm of water, and the RMSE values for these two poor performing scenarios was slightly great than the mean error values.

The two hour and 12 hours figures almost mirror each other. No precision in model performance was gained by changing the rainfall distribution. However one trend reflected in previous fields occurs in field 2-8. The second year of modeled data more accurately reflected Watermark data, although in both versions the final two months, May and June, show modeled data containing more water than Watermark data. This trend was found during the first growing year as well.

5.15 Field 3-1

Field 3-1 was the first of three fields on farm three. This field was perennial grass and has been for over two decades. The field was harvested for grass silage in early spring and then grazed by dairy cattle for the rest of the growing season. Fertility in this field was optimal. The landowner applied adequate water and liquid manure for ET, therefore there were no limitations for this cool season grass. The Watermark array was wired to the datalogger as part of the local WS located adjacent to this field. Rainfall data were obtained from this local WS. This farm was located in Marion County and had a NASIS Soil Map Unit of Amity Silt Loam.

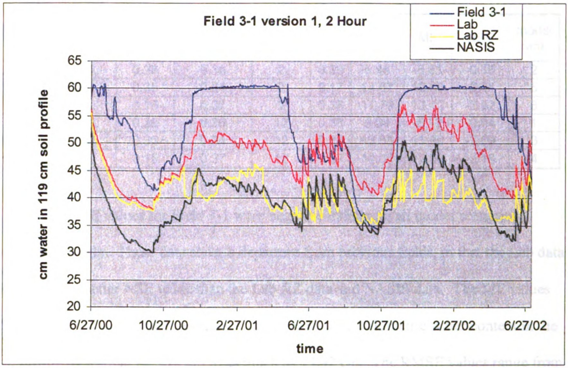

Figure 5.45 Field 3-1 two hour empirical versus simulation volumetric water content

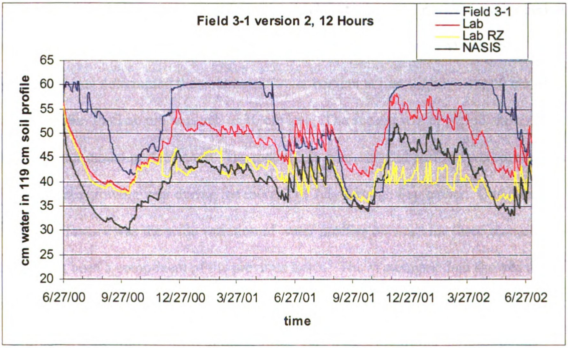

Figure 5.46 Field 3-1 12 hour empirical versus simulation volumetric water content

Table 5.10 Field 3-1 RZWQM simulation comparison and NSE model rank

Field 3-1	Textural class	Clay content %	Volumetric water FC %	rain hours d^{-1}	R^2	RMSE cm	ME	NSE	model rank
Lab	SiCL	0.28	0.36	2	0.39	8.48	-5.81	-0.16	2
Lab RZ	SiCL	0.35	0.34	2	0.17	14.57	12.66	-2.41	5
NASIS	SiL	0.15	0.37	2	0.38	14.79	13.42	-2.52	6
Lab	SiCL	0.28	0.36	12	0.38	8.04	-5.12	-0.04	1
Lab RZ	SiCL	0.35	0.34	12	0.16	13.85	11.80	-2.09	3
NASIS	SiL	0.15	0.37	12	0.37	14.06	12.58	-2.18	4

The NSE values for Field 3-1 were negative indicating all model scenarios performed poorly. These data show a departure from previous fields, in that the Lab data had a slightly better NSE value than the Lab-RZ data and NASIS data. The ME values for all scenarios were negative, thereby under predicting volumetric water content in the soil profile by a small as 5.12 cm to as much as 13.42 cm. The RMSE values range from a low of 8.04 cm to a high of 14.79 cm. The volumetric water content at FC was 45.8 cm using Lab data.

The figures illustrate especially poor model performance during the winter period in both versions for both years. For the months of November through March, the Watermark data determined the volumetric water content at just slightly over 60 cm of water, whereas the Lab are as much as 10 cm less. The second winter period show slightly better model performance. The model Lab scenarios did perform well during the first complete growing year during the months of July through September. One other interesting feature was the wide variation of water profiles between the three scenarios; this has not been a component of the previous fields. The Watermark data showed a drying period during the fall of the second growing period (October 2001). The lab data over predicted the water content in the profile. Taken with the winter periods, in this field the model scenarios were less responsive to water content changes than the Watermark data.

5.16 Field 3-6

Field 3-6 was the second of three fields on farm three. This field was perennial grass with the same cropping and management program as field 3-1. The watermark array was wired to the datalogger as part of the WS. Rainfall data were obtained from this local WS. This farm was located in Marion County and had a NASIS Soil Map Unit of Willamette Silt Loam.

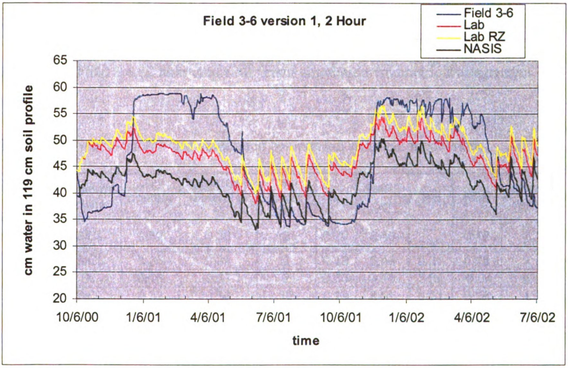

Figure 5.47 Field 3-6 two hour empirical versus simulation volumetric water content

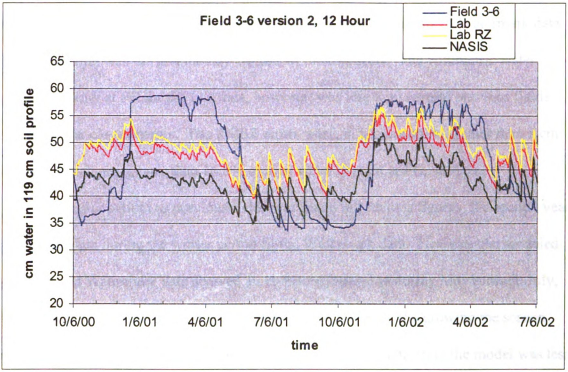

Figure 5.48 Field 3-6 12 hour empirical versus simulation volumetric water content

Table 5.11 Field 3-6 RZWQM simulation comparison and NSE model rank

Field 3-6	Textural class	Clay content %	Volumetric water FC %	rain hours d^{-1}	R^2	RMSE cm	ME	NSE	model rank
Lab	SiCL	0.32	0.38	2	0.22	8.46	-1.45	0.19	1
Lab RZ	SiCL	0.35	0.34	2	0.18	8.48	0.21	0.18	3
NASIS	SiL	0.15	0.37	2	0.35	9.58	5.64	-0.04	6
Lab	SiCL	0.32	0.38	12	0.19	8.51	0.81	0.18	4
Lab RZ	SiCL	0.35	0.34	12	0.19	8.38	0.20	0.18	2
NASIS	SiL	0.15	0.37	12	0.34	9.21	4.84	0.04	5

Field 3-6 had many of the same attributes as previous fields, specifically the difference in textural class between measured Lab PSA and NASIS data. The increased clay content in the Lab PSA data increases the water holding capacity of the soil, thereby increasing model performance. What was different was the positive ME values for the two rainfall distributions using the Lab-RZ scenarios. A positive mean error indicated the modeled data values have a mean slightly greater than the measured Watermark data. One explanation was the greater clay content of the Lab soils. The volumetric water holding capacity at FC for the Lab data, however, was less than several previous fields that had lower clay contents. The RMSE errors were, in all scenarios, greater than 8 cm of water, which are greater than 16.5% of total water content at FC, 48.4 cm.

A similar pattern as previous fields was found in previous figures; the second year of modeled data during the winter period fit the Watermark data. However the modeled scenarios and Watermark data showed an inverse relationship during May through July, 2002. For the model period, the water content was less during the growing the season and greater during the non growing season for all scenarios, indicating the model was less sensitive to water content changes as measured by the Watermark data. The NASIS data provided the poorest model performance in both rainfall distributions, ranking five and six.

5.17 Field 3-7

Field 3-7 was the third of three fields on farm three. This field was perennial grass with the same cropping and management program as field 3-1. The watermark array was wired to the datalogger as part of the WS. Rainfall data were obtained from this local WS. This farm was located in Marion County and had a NASIS Soil Map Unit of Holcomb Silt Loam.

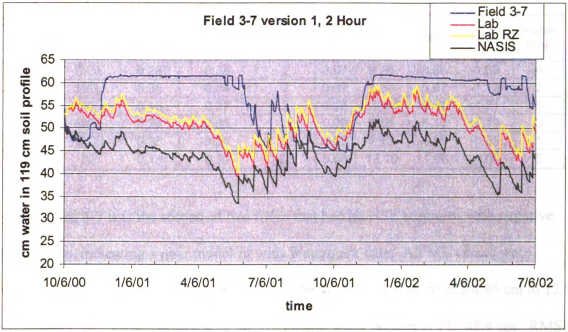

Figure 5.49 Field 3-7 two hour empirical versus simulation volumetric water content

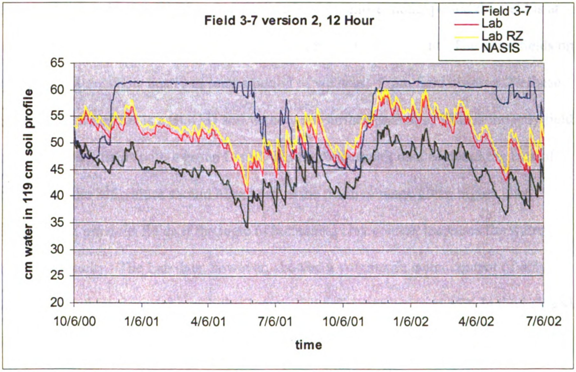

Figure 5.50 Field 3-7 12 hour empirical versus simulation volumetric water content

Table 5.12 Field 3-7 RZWQM simulation comparison and NSE model rank

Field 3-7	Textural class	Clay content %	Volumetric water FC %	rain hours d^{-1}	R^2	RMSE cm	ME	NSE	model rank
Lab	SiCL	0.28	0.35	2	0.07	9.26	-6.86	-1.53	4
Lab RZ	SiCL	0.35	0.34	2	0.07	8.50	-5.67	-1.12	2
NASIS	SiL	0.15	0.37	2	0.03	13.97	12.40	-4.71	6
Lab	SiCL	0.28	0.35	12	0.08	8.65	-6.13	-1.19	3
Lab RZ	SiCL	0.35	0.34	12	0.08	7.92	-4.95	-0.89	1
NASIS	SiL	0.15	0.37	12	0.05	13.19	11.66	-4.09	5

Field 3-7 was the second of two fields that had all NSE scenarios with negative NSE values, indicating a poor model fit with Watermark data. All ME values were negative; the model scenarios under predicted the Watermark data from a 4.95 cm to 12.4 cm of water, or 10.2% and 25.6% of the volumetric water content at FC, 48.4 cm. RMSE values were slightly higher than Mean Error values. One difference in Field 3-7 data was the relatively low R^2 values. These values are the lowest of all field scenarios. One explanation is evident in the figures. For much of the entire model period the field is at saturation, at about 62 cm of water, or 52% volumetric water content. The other fields on this farm did not show nearly as long a period of wetness. From field observation these data are accurate; this is a HGC D soil without subsurface drainage. This is the only field of the modeled fields with a group D soil, and the Watermark data captured the lack of drainage. The ME values should have been in the positive range given higher clay content than previous fields if the logic of increasing clay content increases the water holding capacity. The Lab data, however, showed a volumetric water content of only 35% at FC, which does not match that logic. The difference between 35% in the Lab and 40.67% as a default value in RZ was great enough that the R^2 values were lowest for this field. The Lab-RZ scenarios should have performed better as they did use higher water content at FC. This soil however, likely had more water at FC than the listed default value of 40.67% that would suggest model performance could be improved if clay content were included in the model parameters. The Lab-RZ scenarios were based on PSA data as measured in the lab, but the water content at FC was a default value based on textural class description. For field 3-7 the shift towards more clay content in the Lab PSA data was not captured in the water content FC value, and this caused poor model performance for all scenarios.

5.18 Field 4-1

This was the last of ten modeled fields. This field had the longest model time period, about three and a half years of Watermark data. On this farm the first WS was installed and tested before the remaining three were installed. Field 4-1 was the only alfalfa field in the study sites. It was the only field that had subsurface drainage (patterned tile on 12 m intervals). The landowner had used the Watermark telemetry for almost eight years as a tool for irrigation water management, and received a Water Quality and Quantity Award from the Oregon Department of Environmental Quality in 2000. The Watermark array was hardwired to the WS, and the rainfall data for this farm were obtained from this WS. This farm was located in Marion County and had a NASIS

Soil Map Unit of Amity Silt Loam. This was the fourth of four fields with Amity SiL.

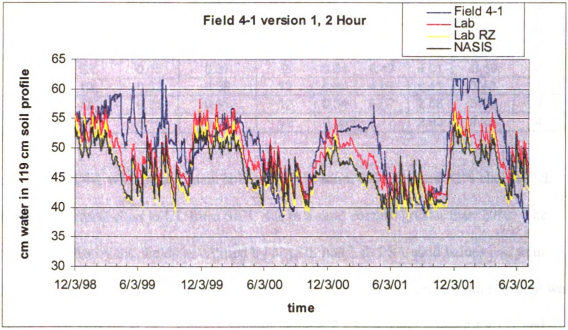

Figure 5.51 Field 4-1 two hour empirical versus simulation volumetric water content

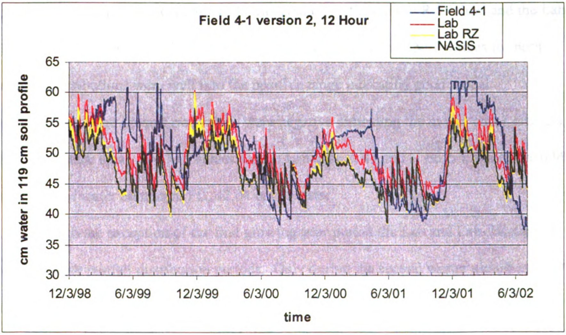

Figure 5.52 Field 4-1 12 hour empirical versus simulation volumetric water content

Table 5.13 Field 4-1 RZWQM simulation comparison and NSE model rank

Field 4-1	Textural class	Clay content %	Volumetric water FC %	rain hours d^{-1}	R^2	RMSE cm	ME	NSE	model rank
Lab	CL	0.32	0.38	2	0.45	4.85	1.66	0.38	2
Lab RZ	CL	0.35	0.31	2	0.39	6.41	4.22	-0.09	5
NASIS	SiL	0.15	0.37	2	0.34	6.42	4.01	-0.09	6
Lab	CL	0.32	0.38	12	0.44	4.64	0.41	0.43	1
Lab RZ	CL	0.35	0.31	12	0.34	5.67	2.68	0.15	3
NASIS	SiL	0.15	0.37	12	0.35	5.77	2.93	0.12	4

Field 4-1 was a Clay Loam soil, with 21% sand, 47% silt, and 32% clay, which shifts the textural class to CL from SiCL due to a sand content greater than 20%. The other three Amity SiL fields as defined by NASIS had Lab PSA sand values less than 20% and slightly larger silt values. One consequence of slightly greater sand content was lower water content at FC. The CL default value is 35.33% water content for CL and 40.67% water content for the SiCL. The Lab data scenarios had the best NSE values. One explanation was the inverse relationship between Lab data and Lab-RZ data. In previous fields the water content at FC was greatest in the default RZ values and the Lab data had lower values. Field 4-1 data were reversed. In fact the NSE values for both rainfall distributions were well into the positive range indicating good model performance. The Mean Error values were negative indicating the model under predicts the Watermark data. The ME values for the Lab data -0.41 and -1.66 cm, which are 0.9% and 3.9% of water content at FC, 42.04 cm of water.

With the exception of the first growing year period the Lab and Lab-RZ data fit well for both rainfall distribution periods. Only during the second winter period in 1999 did the data fit the Watermark data. For the other four winter periods the modeled data showed less water in the profile. The water profiles did not appear better further into the study period (years 2000-2002). If the logic is that with time the modeled data more closely resemble that of the measured Watermark data, the final year for this field did not support that logic. In previous fields this was suggested that during the second year of the model period the measured and modeled profiles showed better agreement.

5.19 Summary

Model performance was described based on the NSE factor, as a function of comparing six modeled scenarios with the measured Watermark data in ten fields. The Textural class was defined by PSA analysis in the laboratory and compared to the USDA NASIS Soil Map Unit for each field. The clay content was listed as measured or default NASIS values. The volumetric water content was listed as measured or default RZWQM or NASIS data. The mean error values are the mean differences in all water content values between the modeled data and the measured data. In almost all cases the modeled data under predicted the measured data. The RMSE values indicate the magnitude of variation from the linear regression lines; the greater the values as cm of water the greater the variance from that line. High values indicate wide variances. The model rank values are simply the rankings of NSE values from highest positive value to greatest negative value.

Chapter 6. Conclusions

6.1 RZWQM evaluation and performance

The modeling of volumetric water content over a time period on a field basis requires some knowledge of soil texture, soil physical characteristics, and soil hydraulic characteristics. RZWQM was selected to model the volumetric water content on ten fields in the Willamette Valley Oregon, all on dairy farms with cropping and management attribute data. Three methods were utilized, patterned after Starks et al. (2003) work in Oklahoma. Logically, the first approach was total parameterization of RZWQM using field soils and deriving PSA, bulk density, and the SWCC for each increment depth. The second was using just the PSA data and using RZ default values for all other parameters. The third was no field data at all; the model was parameterized using USDA Soil Survey NASIS data, easily obtainable by knowing where the field is located and selected the appropriate Soil Map Unit. These three approaches, identified as Lab, Lab RZ, and NASIS, were each used as modeled data.

Two versions of these models were run. RZWQM uses breakpoint rainfall data. Rainfall data, as volume depths, are listed over a period time defined by the volume depth per unit time per storm event. The parameterization of the breakpoint data is rigorous. One logical correction was using the 24-hour rainfall volume depth, and assigning that depth for a length of time. In this study version one is two hours, and version two is 12 hours. The difference between the two versions is rainfall intensity only; the rainfall volume in that 24-hour time period remained the same. Adjusting the intensity of rainfall for the 24-hour period served as a check of model sensitivity.

The change of volumetric water content per unit time is controlled by ET, capillarity, leaching > 119 cm soil depth, surface runoff, or lateral flow out of the field boundary. In this study the K_s parameters were 1.5 cm h^{-1} at 30 cm depth, 0.68 cm h^{-1} for lower depths (< 30 cm). Field studies were not done. At these K_s values, there was minimal runoff volume off the field. There was minimal deep leaching of water out of the root zone. The K_s value in RZWQM is one area that should be thoroughly investigated because this flux gradient drives volumetric water content flux per unit time. This study was not designed to model surface flow or solute leaching that might occur through deep leaching, but this next step is measuring K_s values defined by field measurement. The instantaneous method is suggested (Hillel, 1998). This study could have been improved by having these values.

The crop modeling subcomponent of RZWQM was not extensively parameterized. Input data included a rudimentary crop growth curve based upon harvest yield of biomass and N uptake rates. The four landowners supplied crop harvest yield data with nutrient composition. However the importance of defining ET_c for the crops grown on these or any other farm cannot be overstated. One additional crop input was depth of root zone. These were assigned book values. Field measurements would improve the relationship between ET_c, crop yield, and growth curve.

6.2 Statistical evaluation with Nash Sutcliffe Equation values

The analysis of model performance was accomplished using four statistical measures. The RMSE provided the standard deviation estimate comparing the independent variable, Watermark data (field or observed), with the dependent variable, model data (predicted or simulated). These units are in cm of water. The second, ME, is the mean error of predicted minus observed. The negative values in almost all scenarios gave some measure of model performance; the predicted values were less than the observed values. The figures provided visual confirmation of these negative ME values. Model performance was measured using one of the common hydrological model tools, the Nash Sutcliffe Efficiency value (dimensionless). A perfect fit is one; any negative value is poor. And the relative differences between scenarios can be compared using this NSE value.

In the previous chapter the interpretation of each of these measures was done using a table for each field. The tables included textural class, clay content, and volumetric water content at FC. After completing the study these three parameters seemed most important in defining the physical and hydraulic parameters required in this study.

Figure 6.1 illustrates the comparison of NSE values over the ten fields used in this study.

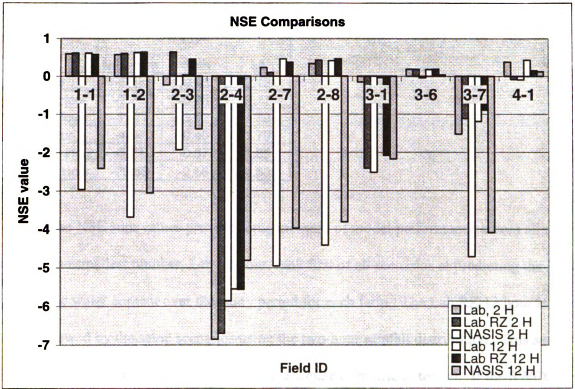

Figure 6.1 Field comparison Nash Sutcliffe Equation values

Three visual interpretations are evident. Scenarios using only NASIS data do not reflect Watermark data in either rainfall distributions, with the exception of field 3-6 (12 hour) and field 4-1 (12 hour). These two scenarios are slightly greater than zero. Secondly, field 2-4 and field 3-7 have no positive NSE values. Field 2-4 is especially poorly modeled. Third, farm one soils modeled particularly well with the exception of the NASIS data.

Table 6.1 presents the additive NSE values, the mean values, and their population standard deviation.

Table 6.1 Scenario sum, mean value, and standard deviation ranking

Scenario	NSE sum	mean	sd
Lab 2 Hour	-6.48	-0.65	2.15
Lab RZ 2 Hour	-7.76	-0.78	2.17
NASIS 2 Hour	-31.17	-3.12	1.89
Lab 12 Hour	-4.04	-0.40	1.79
Lab RZ 12 Hour	-5.71	-0.57	1.85
NASIS 12 Hour	-25.58	-2.56	1.63

The NSE sum values provide some measure of model performance across all ten fields. The smallest number, Lab 12 hour, rank first of all scenarios at predicting the volumetric water content over the study period for each farm. The Lab RZ 12 hour is next, followed by the same scenarios using the two-hour rainfall distribution. This seems reasonable. Watermark data provide a field estimate of matric potential. If the SWCC curve is measured on these soils, then model performance should improve. However the minimal data input of PSA values only, as reflected in the Lab RZ scenarios is only slightly less able to provide a good model fit.

The mean NSE values are grouped as –0.4 to –0.78, with the better fit using the 12-hour rainfall distribution. This also seems reasonable. The reason for using this particular sensitivity analysis was based on typical Mediterranean Climate; long-term storm events with low intensity volume depths. Thus 0.77 inches of rainfall falling over twelve hours is more likely in the Willamette Valley than that same volume depth falling in two hours.

Confirming the NASIS data scenarios in the previous chapter, the mean values for the two rainfall distributions are –25.58 and –31.17. NASIS data requires no field work, however, and the model user risks the accuracy of instrument readings in a different textural class.

6.3 Objectives met

The following two overall conclusions are made by answering the two objectives stated in Chapter One.

1. Several input parameters were obtained or measured using field and laboratory analysis. They are:
    a. NASIS soils data available on the Internet
    b. Moist bulk density from field cores
    c. Particle size analysis from bulk field soil
    d. Volumetric water content at specific matric potential, defining the SWCC and deriving paired data equations for these fields soil
2. RZWQM was evaluated using three methods of model parameterization. The minimal input method, using NASIS data default values clearly did not fit the measured field values using Watermark soil matric potential sensors. Further, with the exception of one field (2-4) the identified Soil Map Unit in the County Soil Survey did not match the textural class of the surface layer. The formation of these soils is ongoing; they are alluvial floodplain soils constantly changing as new flood events deposit new soils on these fields. In these nine mismatched fields, the clay content of the laboratory derived PSA was higher. The ME values of the NASIS data were largely negative, indicating the difference in textural class played a driving role in under estimating the water holding capacity of the profile at 119 cm depth. This study concludes that some field measurements are required. The extent of field measurement is less clear. However the model performed reasonable well using both the Lab and Lab RZ scenarios. The

derivation of the SWCC is time consuming and expensive. The problems of measurement are expanded given the multiple wetting and drying cycles required for complete description of the SWCC. The time period for this study was 18 months, including field sampling at or near FC, preparation, and extractor time. The NSE values for Lab and Lab RZ scenarios were similar; therefore this study concludes the derivation of the SWCC is not a necessary input for RZWQM performance. Starks et al. (2003) reached the same conclusion.

6.4 RZWQM input requirements

What then is the minimum input required for RZWQM as examined in this study? The answer to this question is one of most interest for the user of this model for predicting the volumetric water content over a period of time. The inputs are:

a. PSA. Clearly an estimation of the textural class, measured in this study using the hydrometer method, provided some refinement from using strictly NASIS data. The PSA provides users with sand, silt, and clay percentages, totaling 100%, which can be used to define textural class in RZWQM.

b. Clay content. This PSA component can help adjust the volumetric water content within a given textural class. For instance SiCL has a clay content range of 28-40%, and in this study almost all surface layer field soils used this textural class. However a volumetric water content curve as a function of this clay content range of 12 % (28% to 40% range) can refine the water holding capacity at FC.

c. Volumetric water content at FC. If the above curve is built then scenarios should better fit observed or measured data. Adjusting water content upwards as clay content increases is a reasonable adjustment for RZWQM.

d. Development of K_s values will refine water flux gradient per unit time, thereby refining water in and out of the three-dimensional field space. The use of a K_s value so that surface runoff is minimal is reasonable based upon field evidence as supplied by the landowner and the researcher. However less well known is water loss below the root zone as deep leaching. The K_s value can be used that minimize this loss, i.e. this study, but a more valid approach of field determination would refine this loss. This would be more important if RZWQM were used for simulating solute transport (nitrate, atrazine) below the root zone or vadose zone. Further, the use of K_s data would be required for modeling the application of liquid manure during the non growing season, whereas the surface soil horizon might contain some void space but the irrigation event would replace that void space with water. At greater than FC but less than saturation, if the intake rate exceeded infiltration the potential for surface runoff would increase. If the surface soil layer were saturated, then runoff would occur if irrigation rate continued and K_s was less than the intake rate.

e. Development of crop growth curves that help define ET_c will improve water flux gradient as transpiration over the growing season. Refinement of water flow through plants to a more robust model will help simulate different crop responses to irrigation volume depths, and the potential for solute transport through the root zone and beyond. In this study, the crop model parameters were minimal. Additional work might have helped fine tune the predicted water content in the profile especially during the growing season.

f. The climate parameters used in this study were reasonable. Some refinement of the rainfall distribution was done using a 12-hour period from a two-hour period. If runoff over a shorter period of time is simulated, then specific breakpoint data, i.e. hyetograph knowledge, is required. For the duration of this study daily data is reasonable, and the landowner certainly does not want runoff of liquid manure. This comment is addressed by the importance of knowing the irrigation volume depth (amount), the surface soil layer intake rate as infiltrability or permeability, and then knowledge of saturated hydraulic conductivity.

6.5 Needs for future work

These points are provided as insight for the next attempt at modeling the FWB on a field basis.

1. Placement of multiple soil moisture sensors in the field. Done again, this researcher would have instrumented just the surface layer at several locations in the field, thus comparing within field variation at the same depth. The lab PSA could be done for determination of in-field variability (explaining, possibly, the

layering of alluvial soils after repeated flood events after the soils were originally mapped).

2. Obtaining moist bulk density soil samples near the sensors at the time each sensor recorded 0.033 MPa potential, or FC. This one step could have helped define two necessary parameters: moist bulk density and gravimetric water content, which could have been converted to volumetric water content, and PSA. In this study the timetable was not as convenient; the field sampling of the nearly undisturbed soil cores (for SWCC determination) was not at the specific time the surface or subsurface Watermark sensors gave a reading of 33 cbars. This is an oversight that could easily be corrected. The point is that when a Watermark or other soil moisture sensor is planted in the soil at some depth, taking a bulk soil sample at the moment the instrument reads 0.033MPa will define the volumetric water content by multiplying the gravimetric water weight by the bulk density (in this case moist bulk density). In addition the saturation volumetric water content could be measured when the sensor recorded zero matric potential. As in this study the measured value can be compared with the calculated value of assuming pore space completely filled with water.

3. Some mention must be made of trying to define the FWB based upon an array of four soil matric potential sensors at some location in a field. Given the variation of the soil matrix over the entire field, the particular site selection can be typical or some location that is not typical. How do we decide the answer to this question: what is typical? In this study the measured data, or empirical observed data, was considered correct; the model simulations are compared to these values.

In modeling, who can say the model scenarios are correct and that it is the empirical data that are not representative of the field attributes? For this reason one might conclude that using multiple samplings within field of bulk soil to obtain volumetric water content at FC, then PSA, then measure K_s in multiple sites is correct methodology. In this study that seemed logical. This the following statement summarizes this study and what could have been done better: Rather than spend 18 months deriving the SWCC on selected soil cores from one relatively small (within one square meter) spatial area, a method that sampled more sites within that field using bulk soil taken with an open bucket auger in each specific horizon, and determining PSA, gravimetric water content, volumetric water content, at that moment in time when the soil moisture sensor read at FC, would be the right input parameters required to simulate the FWB on a field scale. And as stated earlier an assessment of K_s could be done in situ using the instantaneous profile method.

This study was required to reach that summary statement, and to that end, accomplished its two primary objectives.

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