UNIVERSITY OF SOUTHAMPTON
SCHOOL OF CIVIL ENGINEERING AND THE ENVIRONMENT

CONTRIBUTION OF UPWARD SOIL WATER FLUX TO CROP WATER REQUIREMENTS

by

James A. Dalton

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ABSTRACT

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It is widely acknowledged that irrigation forms the backbone of food production, especially in the denser populated and often poorer countries of the world. With the development of irrigated agriculture comes management responsibility. This responsibility is accountable for local, regional, and national food security, including the livelihoods of people dependent on irrigated agriculture.

One effect of irrigation is high groundwater, leading to waterlogging of land, reducing soil fertility and crop yields, and possible secondary salinisation of the land. This is due to a process called capillary rise when high soil moisture suctions in shallow soil cause water to flow upwards from shallow groundwater. In arid climates this soil moisture can supply crops with an alternative and economical water source, but long term can lead to soil salinity and reduced crop yields. Methods exist to estimate water flowing upwards from groundwater based on soil physical and hydraulic properties and crop water demand. These methods are often incorporated into complex numerical models or applied under controlled conditions in research stations and laboratories. They provide theoretical values for upward water movement, but do not provide practical water management information for irrigation purposes.

During the 2000 growing season at a site in the Arys-Turkestan irrigation system a silty loam soil was cropped with cotton (*Gossypium hirsutum L.*) and irrigated with fresh water. Shallow groundwater was present throughout the season between 1.5 and 3.5 meters deep. Soil hydraulic properties were determined from field investigation using the Campbell method. Monolith type lysimeters, tensiometers and ThetaProbe capacitance probes were used to monitor soil moisture conditions.

A method was developed based on observation of diurnal fluctuations in soil moisture between the soil surface and shallow groundwater. The method was based on understanding the change in soil moisture suction between nighttime and dawn when evapotranspiration was expected to be low and during daylight when the cotton was actively transpiring. Capillary upward moisture flux was observed throughout each 24 hour day. Results of the new method were compared with Darcy's method, observations of shallow groundwater use from static depths in lysimeters, Kharchenko's method and a soil moisture balance.

The new Diurnal method estimated average rates of upward flux between 1.6 to 2.5 mm/d, or between 43 to 67 % of seasonal crop water requirements. At times upward flux may have reached 6 mm/d, providing 100 % of potential ET. Darcy's method provided a similar rate of average upward flux of 1.86 mm/d. Results were consistent with estimates from lysimeters with groundwater at 1 m deep providing 72 % of crop ET, 1.5 m deep providing 59 % of crop ET, and 2 m providing 45 % of ET.

The new Diurnal method produced reasonable results, is easily adapted to other soil types and provides an estimation of upward flux without knowledge of unsaturated hydraulic conductivity, detailed soil properties or plant characteristics. The new method may be useful in determining crop moisture stress and estimating upward salt movement.

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GLOSSARY OF TERMS AND ACRONYMS USED

Absorption	:	The process or action of absorbing something into another
Adsorption	:	Water is adsorbed onto the surfaces of solid particles. The amount held is proportional to the surface area of the soil particle. Clay particles have a large surface area per unit mass. Sand particles have a much lower surface area, therefore, clay can 'hold' more water via adsorption than sand
ARTUR	:	Arys-Turkestan Irrigation System
Brigadier	:	A member of the village community responsible for delivery and timing of irrigation water for each tertiary channel
Capillarity	:	Water is held in soil pores by capillarity. The strength of capillarity depends on pore size, and is determined by the surface tension of water and its contact angle with solid particles
CIS	:	Commonwealth of Independent States (Kazakhstan, Uzbekistan, Turkmenistan, Kyrgyzstan, and Tadjikistan)
DAP	:	Days After Planting
DOY	:	Day of Year
ETc	:	Evapotranspiration
ETo	:	Reference Crop Evaporation
Extraction	:	Extraction represents moisture which has left a soil layer due to either plant root extraction and/or moisture which has moved upwards into a soil layer above
FAO	:	Food and Agricultural Organisation of the United Nations
Field Capacity	:	Following saturation soils drains for approximately 24 to 48 hours. At this point a soil is said to be a field capacity – the theoretical optimum in terms of soil water stored in the matrix for plants to use. It loosely defines the point where all 'free' water as drained and water is held in the soil at minimum suction (around ~330 cm)
FSU	:	Former Soviet Union
Gross extraction	:	Gross extraction for an individual soil layer represents moisture which has been extracted from the soil by plant roots, or which has moved upwards into a soil layer above (net extraction) plus the gross recharge of moisture from the soil layer below (i.e.: change in soil moisture storage). Each soil layer in a profile has a gross extraction value per day. The sum of these values represents actual crop evapotranspiration where no irrigation or rainfall occurs and a crop is present
Gross recharge	:	Net recharge plus the recharge which occurs over a full 24 hour period which is not evident on a diurnal curve. Each soil layer in a profile has a gross recharge value per day. The sum of these values is the gross recharge for the profile, or the profile upward flux (see upward flux)
Ha	:	Hectare, 1 ha = 100 x 100m
Kharif	:	Indian summer cropping season – mid April to mid October
Net extraction	:	Net extraction represents moisture which has left a soil layer due to root extraction, or moisture which has moved upwards into a soil layer above.

Net recharge	:	Net recharge represents moisture entering a soil layer which is shown on a diurnal curve, and due to constant moisture extraction from the soil during daylight is generally only evident during the night when moisture content stabilises or increases. Where no irrigation or rainfall occurs moisture enters a soil layer from the layer below
'norm'	:	A 'norm' or normative value (used throughout the FSU) is in Western phraseology an average or modal value derived from a survey on how resources are used. Normative values were instructions to farm operators to ensure the highest crop production. They are now irrelevant as farmers lack the resources and training to implement them (TACIS, 1999)
Phreatic	:	The point where pressure in the groundwater is equal to atmospheric pressure. This point is the interface between the unsaturated and saturated soil moisture zones
Piezometer	:	A small diameter pipe used to observe the hydraulic head of the watertable. Over an unconfined aquifer this is the same as the piezometric head
Recharge	:	Recharge represents moisture flowing into a soil layer due to downward gravitational drainage or upward capillary rise from a soil layer below. Where no irrigation or rainfall occurs all the moisture entering the profile comes from capillary rise when a shallow watertable is present.
Rabi	:	Indian winter cropping season – mid October to mid April
Secondary Salinisation	:	Primary soil salinity regards natural salinisation processes, such as the formation of saline soils along the sea cost or in inland evaporation basins. Secondary soil salinity regards man-made salinisation due to capillary rise and lack of drainage
Soil layer	:	A horizontal layer or band of soil of a fixed depth used to determine the movement of moisture and rates of soil moisture extraction and recharge in the soil profile
TDR	:	Time Domain Reflectrometry
Upward flux	:	When an entire soil profile is considered (between the soil surface and a shallow watertable) it is possible to estimate the total upward flux into the crop rooting zone, where upward flux represents the gross moisture recharge into the profile from shallow groundwater (see gross recharge)
U.S.	:	United States of America
U.S.S.R.	:	Union of Soviet Socialist Republics
Watertable	:	See Phreatic
ZFP	:	Zero Flux Plane

1. INTRODUCTION

1.1 Background to Study

Lieutenant Arthur Connoly of the 6th Bengal Native Light Cavalry, his skin darkened with dye, and posing as a Muslim Holy man was one of the first British agents to report on the deserts and steppe lands of Central Asia during the 1850s. What he, and many of his contemporaries found, were bustling trading cities, ruled by powerful Emperors and Khans, surrounded by fertile agricultural lands growing vegetables, fruits and cotton, irrigated with the fresh pristine waters from the surrounding mountains (Hopkirk, 1990). One hundred and fifty years later, irrigated agriculture in Central Asia is declining, not only in terms of raw agricultural production, but the once pristine waters and fertile lands are becoming toxic, salinised, waterlogged, and hazardous to life.

Agricultural production in arid and semi-arid regions has been greatly increased by the development of irrigation projects. However, the benefits of irrigation have been partially offset by the detrimental effects of rising water tables and salinisation, which have damaging consequences on the environment and threaten sustainable agricultural production (Carruthers *et al.*, 1997; IPTRID, 2001). Over 40% of the global food supply is grown by irrigated agriculture (World Bank, 1994). FAO (1996) anticipate that nearly all additional food production is most likely to come from irrigated agriculture, yet the opportunities for the continued geographical expansion of irrigated lands is fast diminishing. Even existing irrigated areas are threatened by salinity, pollution and water shortages due to the increasing demand for water from competing uses (Foster *et al.*, 2000; WHAT, 2000).

Of the total estimated 237 million ha currently irrigated, about 30 million ha are severely affected by salinity, with an additional 60 to 80 million hectares affected to some extent (FAO, 1993). IPTRID (2001) estimate that an additional 0.5 to 1 million ha of agricultural land per year becomes seriously affected by waterlogging and salinisation. Experiences in the Indian subcontinent suggest that serious waterlogging and salinity problems typically arise within 20 to 50 years of irrigation development and seriously effected 5 to 10% of the developed area in 1993 (IPTRID, 1993). Much of the global area developed for irrigation during the 1950 to 1980 period has now reached this critical stage (Smedema, 2000; Smedema and Ochs, 1998).

Worldwide, Grainger (1990) believes salinisation to be one of the main causes of desertification, whilst Rhoades (1990) considers it to be a serious threat to a countries national economy. As a result of irrigation in the Shepparton region of Australia, water table levels have risen from about 30 m below the land surface (150 years ago) to 2 m or less (Heuperman, 1999; Blackburn, 1977). This has resulted in salinity problems which affect productivity in the region (Robertson, 1996).

FAO (1997a) state that irrigation induced salinity and waterlogging reduces crop yields in Pakistan and Egypt by 30 per cent, whilst Joshi (1995) considers the same problem threatens the growth of the Indian national economy.

Burke and Moench (2000) estimate that the global land area abandoned annually due to salinisation is approximately equal to the land area developed for irrigation annually around the world. Such lands represent the loss of significant investments, both economically and environmentally (Postel, 1999).

1.2 Irrigation in Central Asia

Vast areas of agricultural land are losing productivity in China, India, Pakistan, the United States and Central Asia due to the buildup of salts in the soil (UNEP, 1996). The desiccation of the Aral Sea in Central Asia and the loss of agricultural productivity due to the mismanagement of water and soil salinisation is a globally recognised problem (Glantz, 2002a; Vinogradov and Langford, 2001; Verhoog, 2001; Tanton and Heaven, 1999; Dukhovny and Sokolov, 1998; McKinney, 1997; Micklin, 1996; Saiko, 1995).

The region of Central Asia historically contained one of the best climates for plant growth within the Former Soviet Union (FSU). Cultivation of crops such as sorghum, corn, rice and cotton was possible over much of the region. The Soviet Union rapidly expanded irrigation during the 1950's in an attempt to achieve 'cotton independence' (Saiko, 1995). Irrigation is now the dominant user of water in Central Asia, accounting for 90 percent of withdrawals, 95 percent of consumptive use, and accounts for 84 percent of return flows (O'Hara, 2000). O'Hara (1997) believes that the regional policy of 'cotton autonomy' has created a region that, at independence, was unable to meet its own food requirements.

The fundamental cause of the current water crisis in Central Asia is irrigation - water use for other purposes is small by comparison (Micklin, 1992b). Mismanaged irrigation systems, which applied excessive irrigation 'norms', seepage through unlined canals, together with inefficient and poor drainage caused the groundwater within the Aral Sea basin to rise (Babaev and Muradov, 1999; Reshetkina, 1975). Combined with the low efficiency of furrow irrigation, the main irrigation method adopted, large areas of land in Central Asia have become waterlogged. The concentration of salts in the surface zones of soils is now a major cause of land degradation and is primarily due to the natural high evaporation rates and the lack of precipitation to leach the salts out of the soil (Klötzi, 1994). Appendix A1 further discusses the development of irrigation and drainage in

Central Asia and the associated limnological changes in the Aral Sea, including their impact on the surrounding environment.

Even minor improvements in irrigation water-use efficiency could potentially free sufficient water to meet the future needs of other economic, environmental, and social sectors in Central Asia (Micklin, 1992b).

1.3 Focus of Research

Prathapar and Qureshi (1999) consider that a better understanding of the process of upward moisture flux will assist in the prevention of further land degradation, and contribute to the development of sustainable agricultural production systems. There is therefore a need to further understand the processes and underlying mechanisms involved in soil water movement in the unsaturated zone between the groundwater and the rooting zones of agricultural crops (Hendrickx and Walker, 1997). Sharma (1999) and Nielsen *et al.* (1986) have also highlighted the need for further research into the build up of salts and other pollutants in this unsaturated zone.

This thesis investigates the process of soil water movement beneath a cotton crop growing in the Syr Darya River Basin in South Kazakhstan. The threat of salinity and the associated decrease in crop production is worldwide (Plusquellec, 2002; Bhutta and Wolters, 1997), but is especially important in Central Asia where the rapidly growing population requires both food security, and also agricultural industry to support the many millions of livelihoods dependent upon it (DFID, 2000). Many specialists believe that we now have the ability to perform 'integrated water resource management' to full effect (Global Water Partnership, 2000; 2001; Sokolov, 1999; While, 1998). But, if we are to implement integrated, or even localised river-basin management we must have a comprehensive understanding of the threats to sustainable water and agricultural management, especially in the under resourced and under supported areas of salinity and drought management (Perry, 1999; Kovda, 1980).

It is clear that capillary upward moisture flux must be considered in soil moisture studies for accurate estimation of crop water use, the calculation of irrigation requirements and scheduling, groundwater recharge and use, and the potential salinity hazards in areas with shallow watertables. Further understanding of the movement of moisture beneath a crop will also assist in preventing further loss of soil fertility and the environmental degradation and pollution to groundwater currently taking place in many parts of the world (Stephens, 1998; Durant *et al.*, 1993), including Kazakhstan and the other Central Asian states. Based on a study by TACIS (1999) it was concluded that within the Central Asian republics:

'...at least half of the farms are likely to have sufficient capillary flow to make it necessary to account for this source of water in the irrigation schedules...'.

TACIS (2000) reported upward flux rates of between 2 to 4 mm/d in areas of Southern Kazakhstan where seasonal evapotranspiration of a maize crop reached approximately 800 mm. Upward flux must therefore be recognised as an important resource in these water poor regions but only when managed correctly to support agricultural production and drought management.

If the amount of water moving upwards into the crop rooting zone can be predicted then salt movement can also be estimated given the salt content of the irrigation and groundwater. Salt concentrations in ground and soil water will allow assessment to be made of possible salinisation problems, reductions in crop yield, and soil toxicity problems in the future, allowing remedial action to be taken in advance. Where water quality is not a concern, shallow groundwater can make a significant contribution to supplying crops with water and should be taken into account in effective irrigation scheduling and management. It has been estimated that the contribution of groundwater to crop production will become an increasingly important factor that as yet, is not considered in performance assessment and performance indicators (Bos, 1997; Molden *et al.*, 1998).

One of the main aims of this study was to develop a new, simple field based method to estimate the rate of upward soil water flux into crop-rooting zones. Current approaches to estimate soil moisture flux are based on the use of the empirical equation developed by Darcy (1856), which requires values for unsaturated hydraulic conductivity at corresponding soil moisture suctions. Unfortunately, unsaturated hydraulic conductivity is one of the most difficult parameters to quantify in irrigation science, especially in the field (Kabat and Beekma, 1994). Any method, which is able to predict upward flux without the need for unsaturated hydraulic conductivity would therefore be a valuable tool for irrigation science and agricultural water management.

The objective of this research was to establish the importance of upward flux in contributing to irrigated crop water requirements. Specific objectives were:

1. further understand the processes involved in soil water movement in a cropped soil;
2. develop an approach to estimate upward flux into a soil profile from shallow groundwater;
3. test and compare the validity of the new methodology for estimating upward flux with estimates made by other approaches such as Darcy's Law based methodologies; and
4. estimate the seasonal groundwater contribution to crop water requirements in an irrigation system in the Syr Darya basin in South Kazakhstan.

This study focussed on a research site in Kazakhstan, but the method has been developed as a general water management tool in response to the lack of research in this area.

1.4 Structure of Thesis

A review of the background literature to this study is set out in Chapter Two, supported by Appendix A2, which describes the theory of soil water flow. Chapter Two focuses on the existing information regarding diurnal moisture movement and its applications to the study of soil moisture flux. Chapter Three presents the Materials and Methods of the study, including the location of the experimental sites, the equipment used and some preliminary field observations.

The development of the diurnal method to calculate upward flux is described in Chapter Four, along with calculation examples. The more traditional approaches to estimate upward flux such as Darcy's Law and the soil moisture balance approach are also described.

Chapter Five contains estimates of upward flux using the diurnal method, as well as estimates using Darcy's Law and results from the lysimeters. Chapter Six includes additional discussion on use of the diurnal method and practical applications considering hydraulic conductivity.

Finally, Chapter Seven contains the conclusions of the study and makes recommendations for further research and development of the new method.

2. BACKGROUND AND REVIEW OF LITERATURE

2.1 Introduction

This chapter reviews the relevant background literature to the study of upward movement of water in the soil and reviews the need for a new approach to estimate upward flux. For completeness, Appendix A2.1 contains further background on soil water flow.

2.2 Groundwater Movement into Crop Rooting Zones

To understand the physical process of upward flux and capillary rise from the watertable it is necessary to briefly describe the basic field soil environment. Figure 2.1 identifies the different moisture 'zones' in the soil profile, which are individually discussed below:

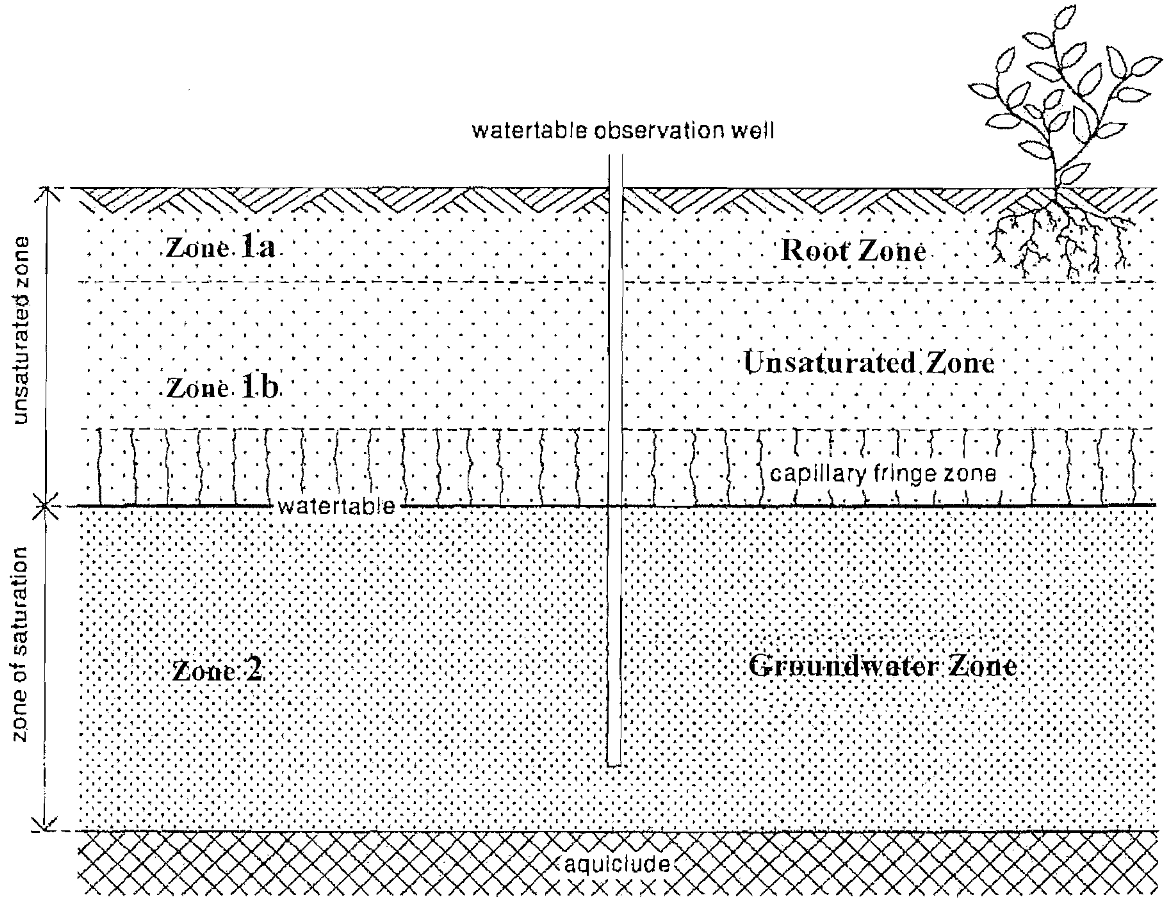


Figure 2.1 The Subsurface Moisture Zones of the Soil Profile
(*Source*: de Ridder and Boonstra, 1994)

Zone 1a – Unsaturated Root Zone

Crop demand for moisture is supplied via the roots in the **rootzone**. This area expands through the unsaturated zone as the crop's roots grow, with the depth varying for each crop, age of crop, and each soil type, normally ranging from 30 cm to several metres deep. It is rarely saturated except when the soil surface is irrigated or after heavy rainfall, or when the groundwater rapidly rises to the soil surface.

Zone 1b – Unsaturated Zone

The zone between the soil surface and the groundwater zone is called the **unsaturated zone** (this incorporates the rootzone). This zone consists of soil pores that are partially filled with water and partially with air. Water is held to the soil pores by capillary forces and adsorption. This zone also contains the **capillary fringe**. This is a zone above the watertable in the unsaturated zone where the moisture content is effectively controlled by the rate of capillary rise and evapotranspiration extraction rates from below the zero flux plane. The height of capillary rise depends on soil texture – the potential height of the capillary fringe varies inversely with particle size, being less than 0.5 m in sand and several metres in clay (Swartzendruber and Kirkham, 1956). The thickness of the unsaturated zone can range from zero in areas with a very shallow watertable, to many metres in areas with a deep watertable.

Zone 2 – Groundwater Zone

The **groundwater zone** is the area where the soil is saturated. The point where water pressure is equal to atmospheric pressure is defined as the 'watertable' or phreatic surface. In reality, the groundwater body will extend above the watertable due to capillary action (the capillary fringe), but the water is held there at less than atmospheric pressure (Hillel, 1982). The watertable can be considered as the interface between the saturated and unsaturated zones within a soil profile (Hillel, 1980a).

There is an upward flow of water into the capillary fringe zone which is driven by the suction potential of the soil. This is caused by a progressive drying of the upper soil layers by evapotranspiration which causes the larger soil pores to progressively drain with depth. This results in the smaller pores in the shallower layers exerting suction on the larger water filled pores below (Brady, 1974). When the watertable is at a constant depth due to deep lateral groundwater inflow (Ayars *et al.*, 2002; Bos *et al.*, 1996), the upward vertical unsaturated moisture flow direction within the soil will be perpendicular to the soil surface (Doering, 1963). By measuring this upward flow of water it is possible to quantify:

- the contribution from the groundwater to crop evapotranspiration;
- the water transmitting properties of the soil type; and,
- the potential build up of salts and toxic ions in the crop root zone.

These factors are important when attempting to provide:

- an efficient irrigation scheduling calculation system which accurately supplies water to the crop based on actual crop water requirements;
- an effective drainage system; and,
- a productive and sustainable irrigated agricultural system.

2.3 Capillary Rise

Capillary rise can be demonstrated using the capillary tube example (Moore, 1939; Hillel, 1980a). When a small diameter capillary tube is inserted in water, water will rise into the tube under the influence of capillary forces. Water molecules are attracted to the sides of the tube providing a curved air-water interface (Hillel, 1982). The pressure under this concave meniscus is less than atmospheric, causing the water in the surrounding vessel to push water up the tube (Brady, 1974). The upward force lifting the column of water can be described as:

$$F_{\uparrow} = \sigma \cos\alpha \times 2\pi r$$

[2.1]
(Kabat and Beekma, 1994)

where:

$F_{\uparrow}$	:	upward force (N)
σ	:	surface tension of water against air (σ = 0.073 kg s^{-2} at 20°C)
α	:	contact angle of water with capillary tube (rad) (cos $\alpha \approx 1$)
r	:	equivalent radius of the capillary tube (m)

As the water column in the tube has a mass, it will exert a downward force due to gravity that will oppose the capillary force acting upwards, hence:

$$F_{\downarrow} = \pi r^2 h \rho \times g$$

[2.2]
(Kabat and Beekma, 1994)

where:

$F_{\downarrow}$	:	downward force (N)
ρ	:	density of water (ρ = 1000 kg/m^3)
g	:	acceleration due to gravity (m s^{-2})
h	:	height of capillary rise (m)

When the downward gravitational force of the water in the tube equals the difference in force between atmospheric pressure and the pressure immediately underneath the meniscus, upward water movement will stop (Brady, 1974). Therefore, the height of capillary rise is inversely proportional to the diameter of the tube. Substituting the values of the various constants leads to:

$$h = \frac{0.15}{r}$$

[2.3]
(Brady, 1974)

Figure 2.2 demonstrates the phenomena of capillary rise using the capillary tube example (Swartzendruber and Kirkham, 1956).

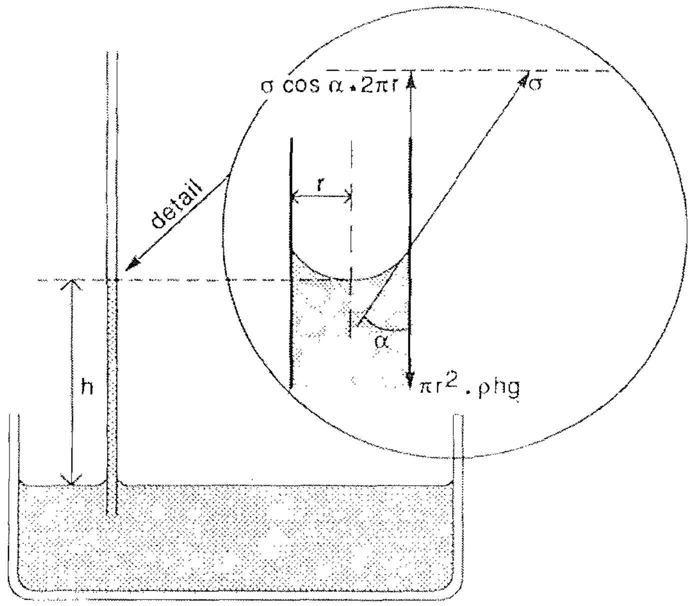


Figure 2.2 Capillary Rise of Water
(*Source*: Bos *et al.*, 1996)

Field soils are constantly subjected to capillary forces, but capillary pathways can often be broken due to the changing geometry of the pore water network. In practice the active capillary layer lies on the surface of soil particles in the small cracks and crevices which exist where soil particles approach each other.

Where groundwater is shallow and water is extracted from the groundwater by evapotranspiration and capillary rise, the watertable will fall if lateral inflow of groundwater is less than capillary rise. This results in a decreasing moisture gradient down the soil profile. Where a constant upward flow rate is present (from deeper soil layers to shallow soil layers) a constant hydraulic gradient must be present in the soil profile. Upward flux will continue until the hydraulic conductivity of the soil and magnitude of the hydraulic gradient reach a level where upward movement of moisture is slower than the evapotranspiration rate. In a vegetated soil profile plant roots extract moisture within their rooting zone. As roots extract moisture the suction gradient between shallow soil layers and deeper soil layers increases, increasing the potential rate of upward flux where hydraulic conductivity does not restrict moisture movement. However, depending on crop type roots will extend deeper to extract moisture from soil at higher moisture contents deeper in the profile as the shallow soil layers dry (Mauseth, 1991).

Shaw and Smith (1927), Raats, (1973), and Hartmann and de Boodt (1973) investigated the maximum heights to which moisture could flow vertically upwards due to capillary rise. Hartmann and de Boodt (1973) suggested that in Flanders, upward flux may reach 4 mm/d when the groundwater was 60 cm deep in fine sands. Raats (1973) concluded that maximum rates of upward flux were dependent on the hydraulic gradient within the soil, and produced a series of curves at corresponding moisture tensions and depths to groundwater. Many other researchers also produced curves relating upward flux to groundwater depth and the pressure potential (e.g.: Moore, 1939; Van Hoorn, 1978; De Laat, 1980). Figure 2.3 shows example curves relating capillary flow to the depth of the water table where the soil moisture suction at the surface is equivalent to 16 bar. The results were taken from lysimeter experiments in three different soil types.

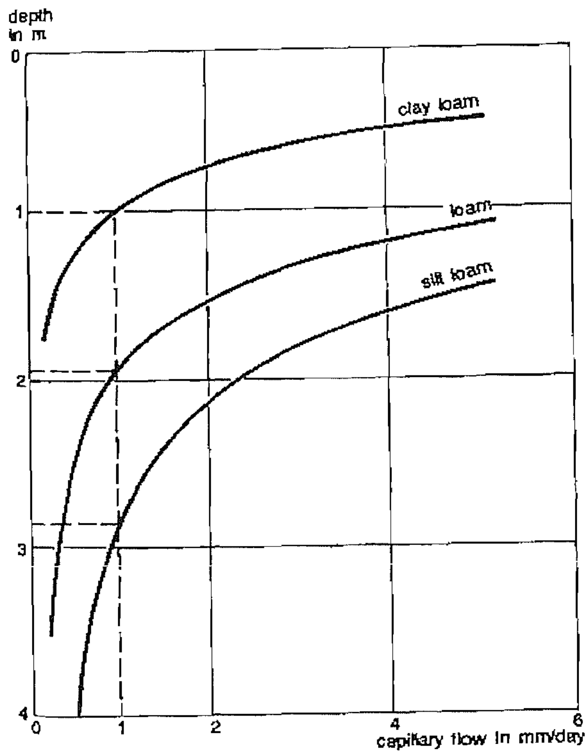


Figure 2.3 Relation Between Rate of Capillary Rise and Depth of Watertable
(*Source*: Van Hoorn, 1978)

Shaw and Smith (1927) concluded that when a watertable was deeper than 3 m in a bare loam soil losses from the groundwater by evaporation from the soil surface would be close to zero. In a cropped soil the watertable may fall due to the upward movement of moisture in response to an increasing hydraulic gradient (where groundwater inflow was less than evapotranspiration demand). Where crop evapotranspiration demand increases, driven by climate, the increasing root depth directly increases the hydraulic gradient in the soil as water is extracted. This results in the soil profile drying progressively deeper as roots grow where lateral inflow or irrigation is restricted. Gardner and Fireman (1958) claimed that provided the evaporative demand was available moisture could flow vertically upwards in fine soils from as deep as 9 m, therefore providing moisture to deeper crop roots.

2.3.1 The Soil Moisture Characteristic and Hysteresis

As water is removed from the soil the matric potential of the remaining water decreases (becomes more negative). If water is added to the soil the matric potential becomes less negative, i.e.: the hydraulic gradient decreases. The functional relationship between matric potential and soil water content is known as the soil moisture characteristic curve.

As a dry soil wets it produces an adsorption curve and as it dries, a desorption curve (Figure 2.4). The desorption curve is used for irrigation scheduling. The moisture content of a drying soil is needed to determine how much water in the soil is available for plants, and how much of this water is easily available (Childs, 1969). Soil moisture characteristic curves can be used to estimate the amount of water a soil retains at a given potential, and the amount of water that will be released between any two potentials (Skaggs *et al.*, 1980). Hence the water content of a soil will be different at corresponding matric potentials, depending on whether an adsorption or desorption curve is used (Gillham *et al.*, 1976). This phenomenon is called 'hysteresis' (Haines, 1930; Hillel, 1982). Due to the hysteresis effect, the water-content relationship of a soil depends on its wetting or drying history. Under field conditions this relationship is not constant (Hillel, 1982; Kabat and Beekma, 1994), for example:

- Wetting or drying can cause variations in soil packing and structure;
- Incomplete water uptake by swelling or shrinking soils;
- Entrapped air in the soil matrix;
- When soils initially take in water and wets, the empty pores between the soil particles will only take up water when tension is less than or equal to the tension related to mean particle diameters (to allow water to flow 'into' the air space due to suction). During drying, soil pore air entry values determine the tension needed for plants to withdraw water from the soil pores.

As water is removed from a soil pore the advancing meniscus lies at a different contact angle at the entrance to the soil pore than for a receding meniscus (when the soil wets). Consequently, water contents are inclined to show greater suctions during desorption than in (ad)sorption, i.e.: at the same moisture content it is more difficult for water to leave the soil, than to enter it.

Figure 2.4 shows the typical hysteresis effect between the adsorption and desorption 'boundary' curves. The smaller curves between the desorption and adsorption curves represent potential points where the two curves may well merge together, depending on the soil drying – wetting properties.

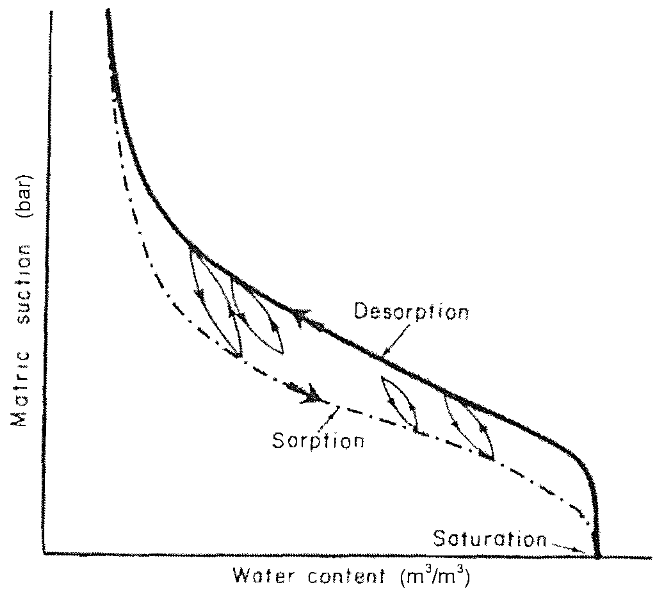


Figure 2.4 A Soil Moisture Characteristic Curve Showing Adsorption and Desorption
(*Source*: Hillel, 1982)

Russo *et al.* (1989), Jones and Watson (1987), and Schleusener and Corey (1959) observed how hysteresis could substantially influence calculated water fluxes in soil moisture studies. Consequently, a number of models exist which attempt to model the soil moisture characteristic curve, including the wetting curve, taking into account the hysteresis effects. Perhaps the most commonly referred to model was developed by van Genuchten (1980). It requires information on volumetric soil moisture content at specific soil moisture suctions. Where soil moisture content and suction are available simultaneously van Genuchten (1991) developed a series of complex mathematical techniques to fit field data to his earlier model.

Where accurate measurement of the soil moisture characteristic curve is not possible the relationship between moisture content and soil suction has been estimated from soil properties (Vereecken *et al.*, 1989). Pedo-transfer functions are used to relate measured soil data from one soil to another using pedological characteristics. This can include basic soil properties such as texture and soil organic carbon and have been developed and evaluated by various authors, e.g.: Vereecken *et al.*, (1989); Vereecken *et al.*, (1992); Tietje and Tapkenhinrichs, (1993). The problem arises when transferring data from one soil to another, as small errors at the basic moisture characteristic curve development stage affects all results thereafter. Indeed, the entire theory of pedo-transfer functions relies on the original quality of the soil experimentation. In some countries and situations, certain tests and data may not be available, or applicable, and the use of pedo-transfer functions can be open to major inaccuracies. An added complication is the need for well trained field and laboratory staff to develop the required information for development of the moisture characteristic curves.

Viaene *et al.*, (1994) reported that the most accurate model for hysteresis was that developed by Mualem (1974). The model describes moisture content on a 'moving' curve between the two main desorption and (ad)sorption curves (as indicated in Figure 2.4). This 'moving' curve represents soil wetting and drying between the boundary curves of a moisture content curve for specific soil types. For the successful application of the model it must be combined with a hydraulic conductivity model (i.e. Mualem, 1977). Mualem's (1977) model is written into unsaturated zone models, such as WAVE (Vanclooster *et al.*, 1994).

To overcome hysteresis effects in irrigation science it is usual to consider the soil moisture characteristic curve for the drying process only (Topp, 1969), as this determines the amount of water that needs applying to agricultural crops. Combined with evapotranspiration estimates, the irrigation interval time can be calculated. However, soil moisture re-distribution is a dynamic process, involving drying and wetting processes, particularly within the root zone. Any study that investigates soil moisture movement must therefore also consider the possible effects of hysteresis.

2.4 Use of Shallow Groundwater by Crops in Irrigation Scheduling

In the day to day management of an irrigation system, or even small farm vegetable plot, two decisions must be made, firstly when to apply water; and secondly how much to apply? The objective is to maintain an 'optimum' soil water environment to avoid loss of crop yield (Hess and Stephens, 1998; Jensen *et al.*, 1990). Optimum may not necessarily mean for maximum yield, but most economic yield, most efficient use of water, or highest crop quality. This process is termed 'irrigation scheduling'.

Irrigation scheduling was defined by Jensen (1981) as '*a planning and decision-making activity that the farm manager or operator of an irrigated farm is involved in before and during most of the growing season for each crop that is grown*'. This basic definition remains the typical view of irrigation scheduling today and a large volume of knowledge and understanding has been gained over the years to assist with the timings and quantities of water to be applied to crops.

To extract moisture from the soil the plant must exert an absorptive force greater than the adsorptive force that holds the water to the soil particles. This occurs when the soil becomes too dry, and irrigation is required. Naturally occurring salts present in the soil-water environment also cause an increase in the force required by the plant to extract water from the soil. This force is referred to as the osmotic potential (Ayers and Westcot, 1985). Where water is limited plants experience earlier moisture stress when growing in soil containing salts. The build up of salts within the soil will result in a reduction in crop yield due to the increased unavailability of water.

One consequence of irrigated agriculture is the unavoidable vertical deep percolation losses of irrigation water which results in a rise in groundwater. This is the result of excessive water applications in the field, and seepage flow from the water distribution systems (Garcia *et al.*, 1994). In large irrigation schemes a rising watertable can result in waterlogging of the rootzone which leads to yield reduction and a build up of salinity (Heuperman, *et al.*, 2002), although drainage systems can be constructed to transport drainage flows out of these irrigated areas to ensure that groundwater levels are controlled. This is traditionally designed to be below the crop rootzone and the main zone of capillary rise to prevent waterlogging and secondary salinisation of the land (Hillel, 1980b; Smedema and Rycroft, 1983).

Shallow groundwater has value however, when its quality allows sustained production of profitable crops at no detriment to soil quality. In areas with shallow groundwater the moist soil immediately above the watertable may extend into the rootzone of crops and vegetation (Bos *et al.*, 1996) and water may be directly drawn upwards into the shallow soil surface due to upward capillary forces. This process is known as an upward moisture 'flux', whereby moisture from the saturated zone moves vertically into the unsaturated zone. Here the moisture may be used by crops as evapotranspiration and in many irrigation schemes this upward flux is known to make a significant contribution to crop water requirements (Allen *et al.*, 1998). Where surface water is limited and groundwater makes a significant contribution to crop water requirements, installation of a subsurface drainage system can deprive crops of essential water from below the rooting zone.

The integrated management of irrigation and drainage systems as a single water provider for crops is not a new concept. Ayars (1996) termed '*groundwater uptake management*' as a process where groundwater is used to supplement surface irrigation. However, any use beyond the short-term benefit must also consider the potential concentration of soil salinity and toxic ions in the soil profile. With escalating energy and water costs for irrigated agriculture Benz *et al.* (1981) recommended an 'optimum' depth for crop groundwater use which complemented surface irrigation, limited salt movement into the root zone, and reduced irrigation water pumping costs. Hanson (1987) suggested an approach to managing irrigation and drainage systems that utilised shallow groundwater, at no detriment to the overlying crops. Using this approach an irrigation schedule was altered to promote groundwater uptake, increasing the irrigation interval time and reducing the total number of irrigations and therefore applied water. This is increasingly important for the many irrigated areas around the world facing future water shortages. Information regarding crop response to groundwater depth, vertical movement of moisture through the soil, and the effects of salinity are needed to guide management decisions such as crop selection and irrigation management options.

Where waterlogging does occur it poses a threat to agriculture as it results in decreased rooting volumes and reduced oxygen concentrations (Dougherty and Hall, 1995; Chaudhary, *et al.*, 1974). The ideal root environment and optimum crop yield depends upon the adequate aeration of the crop root zone (Garcia, *et al.*, 1994; Reichman, *et al.*, 1977). With very shallow water tables reduced aeration can restrict root growth, and therefore the volume of soil available for mineral nutrition (Shah *et al.*, 2000; Lamm *et al.*, 1995; Campbell and Turner, 1990).

In arid and semi-arid conditions the reality is that, despite the problems outlined above, when groundwater rises to within close proximity of the crop root zones this water is used by the plants to supplement surface irrigation. Shallow groundwater in large irrigation schemes is inevitable if there are surface water applications and inefficient or non-existent drainage. As water resources become more scarce, crops increasingly rely on shallow groundwater to supplement their transpiration water needs (Pereira *et al.*, 1996). In practice, many drainage systems convey approximately 30% of irrigation water out of irrigated areas (Bos, 1994b); often discharge into areas with no or little drainage, as in Southern Kazakhstan, while deep percolation losses may also cause regional groundwater rise. In many of these areas crops may be used as a form of drainage control, utilising upward flux from the water table as a valuable resource, without causing soil salinity when combined with appropriate surface irrigation management and selective drainage practices (e.g. studies by Fouss *et al.*, 1990a, 1990b; Shouse *et al.*, 1998; and Stulina *et al.*, 2005).

Traditionally, irrigation is scheduled based on soil moisture depletion to prevent or minimise soil moisture stress (Doorenbos and Pruitt, 1977) but in areas with shallow water tables water may be continuously provided for crop water use via upward flux and this is often overlooked in the calculation. Doorenbos and Pruitt (1977) reported upward flow rates from the watertable of between 2 to 6 mm/d for watertable depths between 2 to 4 m below the crop rootzone. Irrigation water still needs to be applied however, whenever the average crop root zone moisture content decreases to a level that will result in crop stress, or when salinity has exceeded a selected threshold level to prevent or minimise osmotic stress (Hanson and Kite, 1984). When this subsurface supply is considered in water management the amount of irrigation and hence seepage can be reduced (Meek *et al.*, 1980), although some drainage water will need to be removed from the soil profile to maintain a salt balance. This use of shallow groundwater for irrigation is most effective if low salinity water is available for irrigation (Fouss *et al.*, 1990a; Kite and Hanson, 1984). Ayars *et al.* (2001) used shallow groundwater as a supplement to subsurface drip irrigation, combining the benefit of low evaporative losses from the soil surface with shallow groundwater to reduce overall water applications.

When groundwater contribution is included in the soil moisture budget, or moisture balance the estimation of the rate at which crop available water is depleted is significantly reduced in many soils (Makkink and van Heemst, 1975; Fouss *et al.*, 1990b). This increases the interval between irrigation events, reducing the total number of irrigations (Bielorai and Shimshi, 1963; TACIS, 1999), and adds flexibility to irrigation schedules, especially in soils with low water holding capacities (Saini and Ghildyal, 1977). However, Bradford and Letey (1992) found that the excessive use of high groundwater in irrigation schedules gradually depletes the resource, possibly requiring excessive additional irrigations later in the season. Research by Van Bavel and Ahmed (1976) noted how the upward flux of moisture into the root zone of agricultural crops was a critical factor in promoting crop survival in areas with high evapotranspiration rates. This highlights the importance of constant monitoring and analysis to provide the optimum balance of groundwater and surface irrigation.

Ayars and Hutmacher (1994) used shallow groundwater uptake estimates (between 50 to 60% of ETc) to modify crop coefficients for cotton, leading to reduced irrigation requirements. Ayars *et al.* (2002) reduced irrigation applications to a cotton crop by between 60 to 67%, relying on groundwater contributions of 36% of crop evapotranspiration to produce identical yields. Campbell *et al.* (1960) found that in arid conditions, and with no irrigation, alfalfa produced the same yield with a watertable at between 1.5 to 2.7 m deep, as it did when six irrigations where applied. Mason *et al.* (1983) concluded that the amount of water available to a plant in the soil profile could not be considered accurate unless the rate of upward flux could be determined and included in the irrigation schedule.

A recent study attempted to incorporate groundwater contributions into the irrigation schedule of cotton using a simplistic daily water balance (Li and Dong, 1998). The study found that, depending on the regional climatic conditions, the crop increased or decreased groundwater use between dry and wet years. Groundwater use ranged from 30% of seasonal evapotranspiration when groundwater was 1 to 1.4 m deep, to 56% of seasonal evapotranspiration when groundwater was 0.5 to 0.8 m deep.

2.5 Watertable Quality and its Effects

Where groundwater salinity is high, or where applied irrigation water is saline salts accumulate in the soil and crop yield is reduced (Kruse *et al.*, 1993). Ayars (1996) grew cotton and tomatoes above a shallow watertable, producing no loss in yield from a 40% reduction in applied irrigation water. However, this approach was only viable for the tomato crop for a limited time due to rising salinity in the crop root zone. Additional salt in the crop root zone must be removed through the process of deep percolation or 'leaching' to maintain yield.

The application of water to the soil surface for deep percolation for the control of salinity is termed 'leaching' (Doorenbos and Pruitt, 1977). Leaching takes place by applying sufficient water so that a proportion (the leaching fraction) percolates through the entire crop root zone, carrying with it a fraction of the accumulated salts (Ayers and Westcot, 1985). This ensures a net downward flow of water through the crop root zone, and maintains a salt balance in the crop root zone, preventing any loss of yield (Hoffman *et al.*, 1980). Throughout the world most surface irrigation field applications of water appear to be inaccurate and often excessive. Whilst they may be inaccurate in terms of meeting the crop needs the excess water maintains an adequate salt balance, and provides an 'anonymous' salt leaching function.

In many surface irrigation systems throughout the world farmers and irrigators do not have the benefit of being able to determine the soil moisture deficit or salt induced crop moisture stress. They can often only irrigate when water is available which is often restricted and depends upon the water resources of the area and/or water availability within the water conveyance system. Where groundwater is close to the soil surface and is of a suitable quality the transport of moisture upwards due to capillary rise becomes a critical crop survival mechanism, which is unknowingly utilised by farmers.

Where water is scarce crops tend to be under irrigated and have insufficient water for salt leaching purposes. Where spring precipitation is low and the soil is dry at the beginning of the agricultural season, pre-irrigation is required to provide favourable conditions for germination and to remove any salt from the plough layer. Relying on the pre-irrigation however as a sole single application of water for salinity control purposes may not be sufficient to control salinity in the rootzone in areas with shallow saline groundwater and high evaporation rates such as those experienced in parts of the United States, Pakistan, India, and Australia.

Numerous studies have demonstrated that a wide variety of plants can make use of low salinity groundwater when it is within 2 m of the soil surface. Ayars and Schoneman (1986) estimated saline groundwater use by cotton to be between 19 to 25% of total crop evapotranspiration over two years. Kruse *et al.* (1993) studied the effect of shallow, saline watertables on the irrigation requirements of corn, alfalfa and winter wheat. The portion of total seasonal evapotranspiration supplied from saline shallow groundwater was strongly affected by watertable depth, and for corn and wheat, slightly affected by the salinity of the water in the saturated zone. They concluded that, when a shallow watertable is present irrigation can be reduced in arid and semi-arid climates, however, when the watertable is less than 0.6 m from the soil surface rapid soil salinisation can occur, resulting in excessive leaching water requirements, which in turn can raise the groundwater. This highlights the need to use groundwater as a sustainable supplementary resource for irrigated agriculture to minimise water use whilst maintaining both crop yields and soil fertility.

Where groundwater becomes saline through re-use, the value of groundwater for crop use will be determined by the salt tolerance of the plant (Doorenbos and Pruitt, 1977), the depth to groundwater, the soil salinity and the irrigation water quality (Talsma, 1963). Several studies (e.g.: Hutmacher *et al.*, 1996; Grismer and Gates, 1988; Chaudhary *et al.*, 1974) have demonstrated that a relatively salt tolerant crop such as cotton can extract between 30 to 60% of seasonal water requirements from a shallow (<2 m) saline (≈7 dS/m) watertable. In most surface irrigation schemes at least 30 to 40% of applied irrigation water enters the groundwater (this figure is affected by the efficiency of any drainage system). In practice however, only a small amount of water needs to be removed from the soil to maintain a healthy salt balance in most cases (Van Hoorn and Van Alphen, 1994).

Doering *et al.* (1982) proposed a shallow drain concept which would be effective in increasing crop water use from shallow groundwater. They proposed reducing the spacing and depth of drains in semi-arid areas with good quality shallow groundwater. These changes were to maintain a shallow depth (<2 m) watertable and promote extraction by plants. Whilst this has benefits in areas with good quality groundwater, Rhoades *et al.* (1989) and Mass and Hoffman (1977) argue that most crops have higher salt tolerance values than previously thought. This suggests that reduced drain spacing and depth may be applicable to many of the irrigated areas around the world. However, the importance of drainage for sustainable agriculture and for safeguarding the value of agricultural land has been reiterated (Scheumann and Freisem, 2001), but it needs to be used more effectively, for instance, seasonal use of drains in the non-growing season being used to maximise the use of groundwater while still controlling salinity.

Upward flux from shallow groundwater can be used for more complex reasons than as a supplementary water source. Mott MacDonald International Limited and Hunting Technical Services Limited (1992) introduced a concept called 'dry drainage', based on a previous study by Sir M. MacDonald & Partners and Hunting Technical Services Limited (1965a; 1965b). Dry drainage relies on the upward flux of moisture from the groundwater for the transportation of potentially harmful salts to the soil surface on uncultivated areas. The same process has been called the 'source-sink' effect (van Hoorn and van Alphen, 1994; van Hoorn, undated). In many areas of the Pakistan Indus Valley the groundwater is approximately 2.5 to 3 m below the soil surface. During the irrigation season localised groundwater rises beneath irrigated fields due to the applications of irrigation water. Watertable rise on the non-cultivated land during the 'Kharif' season (April to October) indicated the movement of groundwater into these areas. Without irrigation, these non-cultivated areas become salinised due to the evaporative demand of the atmosphere, which causes upward flux from the watertable. During the Rabi season (October to April) upward flux causes watertable decline in both cultivated and non-cultivated areas (Kijne, 1996).

Mott MacDonald International Limited and Hunting Technical Services Limited (1992) suggested that upward flux rates of between 3 to 4 mm/d were possible in the fine soil types of Pakistan when the watertable was 0.6 m from the soil surface. Salinisation of fertile soils in many areas has been prevented by the movement of salts out of higher lying irrigated land into lower non-irrigated areas where it evaporates by capillary rise and allows salinised soil to be contained within 'specific' areas – or 'salt sinks' (UNESCO, 2000). In other areas the lower lying land is irrigated and this becomes salinised by the shallow groundwater.

Crop yields are being reduced, and in many areas cropland is being lost because of waterlogging and high salinity levels (Prendergast *et al.*, 1994). To combat waterlogging problems, agricultural producers need a complete management 'package' that combines information about irrigation practices, crop types, capabilities for improving yield, economic returns, and water quantity and quality. But, for water management to improve the importance and role of shallow groundwater in irrigation scheduling must be recognised, not only as a potential resource (Garcia *et al.*, 2002; Shouse *et al.*, 1998; Bradford and Letey, 1991) but also as a threat to sustainable agricultural systems due to salt and pollutant mobilisation. Neglecting the existence of capillary rise, as is done in most irrigation scheduling and water balance models used for crop management is likely to lead to a false estimation of irrigation requirements.

2.5.1 Groundwater Balance Studies

Groundwater contributions to crop water needs can be significant under irrigated conditions (Benz *et al.*, 1984; 1985a). One of the simplest ways to determine the crop water use from the groundwater is using a soil moisture balance. This can be performed using two different approaches:

1) Field Studies

Water balances rely on the movement of water in and out of a 'system', where the system can represent an area of land from 1 m^2 to an entire irrigation system or watershed (Cuenca, 1988). For field research one-dimensional 'compartments' of soil are generally used to represent the crop root zone, or the soil profile to a given depth. A soil water balance equation can then be developed based on the initial moisture content and on the water entering and leaving the soil 'compartment' (Allison, *et al.*, 1994). Water inputs include irrigation, precipitation, and upward flux from the groundwater while outputs include evapotranspiration from the soil surface and plants, as well as deep percolation. Water balances can vary in complexity, some include run-off from the study area during irrigation, others divide the soil into smaller compartments and include the decrease in soil moisture content, as well as plant canopy interception. Water balances are effective when trying to identify the movement of moisture over large time periods, and provide a general introduction to the complexities in soil moisture movement (Jensen *et al.*, 1990).

However, it can be difficult to determine upward flux and deep percolation in the field, as the soil environment can not be controlled. To improve accuracy and determine a more comprehensive water balance a lysimeter can be used.

2) Lysimeter Studies

A lysimeter is an isolated and undisturbed column of soil, with or without a crop, in which one or more terms of the water balance can be assessed (Aboukhaled *et al.*, 1982). There are two types of lysimeter: weighable and non-weighable. In a weighable lysimeter the change in moisture storage can be easily identified by the change in mass, enabling reliable measurement of evapotranspiration. This is the basis for the calculation of crop coefficient curves recommended by the FAO (see: Doorenbos and Pruitt, 1977; Allen *et al.*, 1998) in their irrigation scheduling software used throughout the world (such as CROPWAT (Smith, 1992; Clarke *et al.*, 1998)).

In a non-weighing lysimeter a water balance can be performed and deep percolation and upward flux rates 'controlled' using an artificial water table (Vyishpolskiy *et al.*, 2001). To be considered accurate, lysimeters must contain soil that is representative of field conditions and must be filled with the same crop that is growing around the lysimeter (Aboukhaled *et al.*, 1982). Lysimeters have been widely used to estimate crop evapotranspiration and irrigation water demand for the design of irrigation systems (Leontyev, 1991).

Both field soil moisture balances and lysimeters have been used to estimate upward flux and the contribution of groundwater to crop evapotranspiration. Many of these studies have used different qualities and quantities of groundwater to determine root moisture uptake patterns in the soil (such as Majeed *et al.*, 1994; Follet *et al.*, 1974a; Hiler *et al.*, 1971).

Previous work on the effects of a watertable on root growth have been conducted both in glasshouses and in the field. Reicosky *et al.* (1972) measured soil water content and soybean root weight and length in soil columns with a watertable maintained at 1 m. Roots grew rapidly down the soil column to just above the watertable. Water uptake was not necessarily related to root distribution and as the upper soil layers dried, roots mainly absorbed water near the watertable where it is held at lower suction.

Reichman *et al.* (1977) discovered that sugarbeet used good quality groundwater in preference to applied irrigation water. Irrigation treatments did not affect the quality in terms of sucrose yield from the shallow watertable treatment, but for deeper watertables the sucrose yield significantly increased as irrigation increased. This suggested that a combination of the irrigation water and high quality deep groundwater produced higher sucrose yielding beet.

Follett *et al.* (1974b) found a different situation growing corn, sugarbeet and alfalfa in experimental plots on a sandy soil. Over a 2 year period they concluded that yields were greatest for all crops with a watertable 69 cm from the soil surface at the start of the season. When the watertable was deeper than 92 cm the crops relied on irrigation water and not groundwater; deeper than 145 cm the crops solely used irrigation water throughout the season. These differences in patterns of crop water use from the soil profile could be explained by the fact that the plant takes up water preferentially within the soil regions were it is most available. This behaviour has been observed by other researchers (Tardieu *et al.*, 1992; Tardieu, 1988; Saini and Ghildyal, 1977). Mauseth (1991) stated that it is easier for roots to extract water from 2 m depth at a soil suction of <1 bar, than at 0.5 m at a suction of >3 bar. This explains the use of soil moisture deeper in the soil profile.

Van Bavel *et al.* (1968) estimated upward flux rates on a bare clay loam soil in an attempt to determine a correction parameter representing upward flux in soil moisture depletion studies. Bare soil plots were irrigated and covered with plastic to prevent evaporation. Evaporative losses were determined using precision weighing lysimeters. Upward flux rates were determined using gravimetric soil sampling techniques and soil moisture characteristic curves, combined with the water balance method in the lysimeters. At 1.7 m depth upward flux was estimated as 2 mm/d eight days after irrigation. Following planting with sorghum upward flux rates reached peak values of 4 mm/d. Ignoring this upward component in soil moisture depletion studies does not allow for an accurate representation of the soil moisture balance. At the latter end of the crop season when roots were deepest, upward flux represented one-third of crop ETc. It is interesting to note that the water balance method used in the lysimeters produced consistently higher rates of upward flux than the calculated method used in the field plots. Van Bavel *et al.* (1968) suggested this may be due to high upward flux rates during the night, which they were not able to determine in the field due to the reduction in evaporative demand overnight. Other reasons such as increased leaf area and LAI could have also been the cause.

There are numerous studies that investigate groundwater contributions to crop water requirements and the role of capillary rise in irrigated agriculture. Stuff and Dale (1978) estimated capillary rise from a watertable to be 27% of the seasonal evapotranspiration of a corn crop. Benz *et al.* (1985b) investigated the effects of four shallow constant water table depths and three surface irrigation treatments on corn and sugarbeet yields grown in lysimeters. The watertable provided a large contribution to crop evapotranspiration, in one case 63% of total crop evapotranspiration when groundwater was maintained at a depth of 1.55 m. Namken *et al.* (1969) studied cotton in lysimeters and found that watertables between 0.91 and 2.74 m deep contributed between 54 to 17% of total water used by the crop. Soppe and Ayars (2000) estimated daily groundwater use by cotton to be 30% of evapotranspiration.

Despite these positive studies, Yang *et al.* (2000) found that lysimeters gave inaccurate estimates of evapotranspiration when groundwater maintained within them was constantly changing. This was due to the development of a moving capillary fringe which made it difficult to determine how much moisture was used by the plant, how much stored soil moisture drained back into the groundwater, and how much remained stored in the soil matrix.

Table 2.1 summarises key lysimeter and water balance studies.

Table 2.1 Key Lysimeter and Soil Moisture Balance Studies

Reference	Crop	Soil Type	GW Depth (m)	Q (mm/d)	Q (%)	Notes
Lysimeter Studies						
Benz *et al.* (1985b)	Corn Sugarbeet	SL	1.55	-	63	Where GW was at 0.46 m yields were low. Good yields, comparable to surface irrigation treatments were apparent where GW was maintained lower than 1 m
Ayars *et al.* (1996)	Cotton Tomato	ZC	1.5[a]	-	40	Use of groundwater by crops reduced irrigation applications by 6.5 x 10^5 m^3.
Dugas *et al.* (1990)	Soybean	L C	1	-	24 6.5	During some weekly periods the groundwater supplied between 55 to 64% of ETc
Hutmacher *et al.* (1996)	Cotton	CL	1.2	-	45-60	From different groundwater qualities, ranging between 0.3 dS/m to 31 dS/m
Meyer *et al.* (1989)	Wheat Soybean	L C	1-1.3	3.7 1.3[b]	36 15	This study pointed out the importance of the transient nature of capillary upward flow rates due to changes in root depth, GW levels, and crop canopy cover
Moisture Balance Studies						
Mason *et al.* (1983)	Maize Sorghum Sunflower	Fine soil	1.5	-	40 42 32	Tile drainage system was designed to keep GW at 1.8 m, yet observation pit showed GW at 1.5 m. This represented a high capillary fringe. Concluded that crop water use cannot be estimated from soil moisture depletion.
Wallender *et al.* (1979)	Cotton	L	>2	-	60	Majority of the upward flux contributed to ETc during the latter half of the season when root depth was maximum and the shallow soil layers were dry
Dalton and Clarke (2001)	Cotton	ZCL	2.5	1.4 to 2.5	29 to 52	At a seasonal average GW depth of 2.5 m daily rates of upward flux were between 1.4 to 2.5 mm at three different locations.
Maraux and Lafolie (1998)	Maize Sorghum Grass	ZL	-	1 to 2	-	Upward flux was critically important during periods of high transpiration which were different for each crop. For sorghum and grass upward flux contributed to 50% of ETc.
Gabrielle *et al.* (1995)*	Maize Bare soil	ZL	5	-	-	During the summer moisture conditions were underestimated by 30%. This was attributed to upward flux conditions in the soil. The model performed poorly on silty soils where upward flux played a significant part in supplying the crop with moisture

Notes: Soil Types: S – sand, L – loam, C – clay, Z – silt. Q (mm/d) is the amount of water used by crops in mm/d. Q (%) is the percentage of groundwater which contributed to crop evapotranspiration. [a] EC of groundwater ranged between 4 to 5 dS/m. [b] max daily upward flux rates, their data show some diurnal fluctuations in upward flux flow rates, however, due to overnight irrigation applications the nightly upward flux rates could not be identified. * This study performed an analysis and field evaluation of the Ceres Model (Jones and Kiniry, 1986) which uses Darcy's Law to estimate moisture fluxes. The study by Gabrielle *et al.* (1995) analysed the water balance component of the model, which is based on 'inputs' and 'outputs' within the soil profile.

What the studies in Table 2.1 and the others discussed earlier in this chapter show is that groundwater contributions to crop water requirements are highly variable and are difficult to predict. Contributions from the groundwater can range between approximately 15 to 60% of crop demand, even between similar soil types and crops. This suggests that there are many factors that influence the process of upward flux. Despite this groundwater is largely ignored in irrigation scheduling.

Both moisture balance and lysimeter studies indicate similar rates and amounts of upward flux. While lysimeter studies are more controlled, moisture balance studies can represent true field conditions, although studies are limited due to the difficulty in instrumentation and other factors such as regional groundwater fluctuations. Maraux and Lafolie (1998) argue that using moisture balances to estimate the amount of water remaining in the soil profile at the end of the crop season and therefore available for the next one is wrong. This is due to the complex and transient nature of upward flux and the influence of changing daily evapotranspiration rates within the soil profile.

Where permanently high watertables occur with no drainage crop yields will eventually diminish because of salinisation and waterlogging (Bajwa *et al.*, 1986; Mass and Hoffman, 1977). In areas where waterlogging occurs, it is necessary to assess water balances not only for an average year, but also for specific years and even seasons. It is relatively simple to perform a water balance for a cropped soil and estimate the groundwater contribution to evapotranspiration over the entire season in millimetres per day. However, it may not be accurate for irrigation scheduling purposes. Without this detail it is not possible to optimize irrigation efficiency.

Mott MacDonald (2002, pers. comm.) estimated an average seasonal upward flux rate to cotton of 1.8 mm/day in south Kazakhstan in a silty soil – but it is doubtful that this rate was constant over the five month period. However, Doering (1963), in one of the first comprehensive studies purposefully designed to investigate upward flux from a watertable, found that over a 341 day period the average rate of upward flux was 1 mm/d. A study by the EU WUFMAS team (TACIS, 1999) found considerable variation in upward flux rates due to differences in watertable depth, soil texture, crop rooting depth and the rate of evapotranspiration. Upward flux rates of 3 mm/d were observed in the Kyzl-Orda region of Kazakhstan. This was attributed to the shallow groundwater caused by the naturally occurring low-lying land, high seepage rates from damaged irrigation canals, and excessive water applications from rice cultivation in soils with infiltration rates over 12 mm/hr (INCO-COPERNICUS, 2002).

Models have been developed which attempt to replicate these complex interactions within the soil profile. The simplest of these use the water balance theory that divides the soil into a series of compartments or 'blocks' of soil, whereas the more complex rely on the use of flow equations and develop finite difference schemes (such as Belmans *et al.*, 1983). These are described below.

2.5.2 Soil Moisture Models

Soil water models may involve sophisticated numerical solutions to water flow equations, coupled to a root extraction and plant response model, e.g. SWATRE (Belmans *et al.*, 1983) and WAVE (Vanclooster *et al.*, 1994). Others rely on a simplified description of the soil and vegetation; the soil is assumed to drain instantaneously when wetter than field capacity and evaporation is usually a simple function of the potential rate and the soil water deficit (Torres and Hanks, 1989).

Many crop growth simulation models rely on detailed information of the soil water regime throughout the growing season. During the last two decades, a large number of mechanistic models have been developed to simulate transient water flow in unsaturated soils combined with uptake by plant roots. Earlier models include the Soil-Water-Atmosphere-Plant (SWAP) model developed by Feddes *et al.*, (1978), based on his earlier work with root water uptake functions (Feddes *et al.*, 1974). SWAP has been continuously developed, and now contains separate component models within it, such as SWACROP - specifically containing crop production functions (Kabat *et al.*, 1992), and SWATRE, which is the soil-water component (Belmans, *et al.*, 1983; Brandyk and Romanowicz, 1989). The SWAP model has been tested under a wide range of climate and agricultural systems, notably in Iran (Droogers *et al.*, 2001), Pakistan (Smets *et al.*, 1997) and for a cotton crop in Turkey (Droogers *et al.*, 2000).

The SWAP model is based on Richard's equation, combining Darcy's Law and the continuity equation (described in Appendix A2.1). The core part of the program is vertical flow in the unsaturated-saturated zone. In order to solve these equations the program uses a finite difference programme. Prathapar and Qureshi (1999) used the SWAP model to investigate the contribution of groundwater to crop water requirements in Pakistan. Their results indicated that, in the absence of a drainage system, the effect of a shallow groundwater is very pronounced on crop production. They concluded that areas with shallow groundwater resulted in a reduction of applied irrigation water of up to 60% of crop evapotranspiration but severely increased the chance of soil salinisation. The local agricultural practice of deficit irrigation in the Punjab and Sindh regions may produce good crop yields for the first 2 to 3 years following the inception of irrigation, but long term soils may become heavily salinised. Their results also indicated that some farmers applied more water than was necessary and yields were reduced, in some cases due to waterlogging.

Ahmad *et al.* (2002) recently used the SWAP model in the Punjab. They found that over an entire year 39% of crop water demand was met from upward flux under a crop of cotton and wheat, and 54% upward flux under a rice crop, despite combined irrigation applications and precipitation of 227 and 271 mm consecutively. Their research showed that excessive irrigations are often unnecessarily applied, although Prathapar and Quereshi's earlier work implies that groundwater should not be relied upon due to the threat of rapid salinisation.

Torres and Hanks (1989) used the Richards equation to estimate upward flux in lysimeters planted with wheat. This study was based on earlier experimentation by Nimah and Hanks (1973), who found there was approximately 100 mm upward flux to an alfalfa field from a watertable at 2 m depth. Torres and Hanks (1989) found that the contribution of the watertable to crop evapotranspiration was 90, 41 and 7% for 0.5, 1, and 1.5 m watertable depths respectively. Clemente *et al.* (1994), reviewing the models SWATRE, LEACHW and SWASIM, gave similar values for upward flux to a hay crop on a clay soil. Joshi *et al.* (1985) and Chopart and Vauclin (1990) found that upward flux should be accounted for in all soil moisture studies, based on their results using water balance models.

Virtually every simulation model that is used relies directly or indirectly on an estimate of evapotranspiration (Kabat and Beekma, 1994). In many models potential evapotranspiration is calculated from monthly, daily, or even hourly climate data, and from it an estimate is made of the actual evapotranspiration. When actual evapotranspiration is combined with precipitation data the surface boundary condition is established, allowing calculation of the water storage in the soil, moisture redistribution and drainage. Gardner *et al.* (1970), Nimah and Hanks (1973), Kastanek (1973), Saxton *et al.* (1974), De Laat (1980), Chung and Austin (1987), among others, have developed detailed numerical models that calculate water flow using Richard's equation.

In most of these models, water uptake by roots is represented as a volumetric sink term (further discussed in Appendix A2.1) and substitutes Darcy's Law into the equation of continuity for soil water flow. These models generally require an extensive knowledge of soil and crop characteristics including information about the response to changing soil water status, most of which are not readily available on a routine basis (Tietje and Tapkenhinrichs, 1993.). Worse, these characteristics are time consuming and costly to acquire. This requirement is generally not compatible with the availability of input data, especially meteorological information. Arora *et al.* (1987) and Youngs (1988) critiscised the use of Richard's equation as being too sophisticated for the 'real world' applications required for irrigation and drainage studies.

Evaporation and transpiration are generally determined by assuming that actual evapotranspiration is linearly related to the available soil moisture content (Van Bakel, 1981). Whilst these models can produce precise results and generally good mass balances, they depend on reliable evapotranspiration measurements, which, according to Gee and Hillel (1988) are at best accurate to 5 to 10%. Indeed, Robins *et al.* (1954) demonstrated errors arising from soil moisture movement in the profile when depletion was assumed to be due to evapotranspiration only.

Perhaps the most difficult parameter to establish is soil hydraulic conductivity and hence its estimation is the most limiting factor to soil moisture modeling. Large ranges in conductivity values in field soils occur, and the need in some models for accurate pedo-transfer functions all combine to limit the usefulness of models in other than specific sites (Wösten and van Genuchten, 1988; Vereecken *et al.*, 1992). When using such models caution must be exercised as they require complex soil data and rely heavily on computer applications, which are not always possible in practical irrigation science.

Torres and Hanks (1989) clearly state that results of specific model studies should not be extrapolated to other sites and conditions, as results may be poor in areas and under conditions the model was not developed specifically for. This is especially so in areas with shallow watertables which cause soil moisture conditions in the profile to be extremely sensitive to changes in the soil's hydraulic conductivity (Kabat and Beekma, 1994).

Although such detailed models may be excellent research tools, their large data requirements strongly limit their use as management tools (Chopart and Vauclin, 1990). Less-detailed water budget models that are physically reasonable and computationally efficient remain useful (Hess *et al.*, 2000). This is especially so where the available field data are limited or difficult to obtain, although the accuracy of the models can not be determined. The model developed by Hess *et al.* (2000) is a simulation model for the teaching and demonstration of issues involved in irrigation, drainage and salinity management. Whilst the model provides a useful teaching and learning package, its usefulness is limited to seasonal use for the correct estimation of drain spacing, and not for understanding the process of upward flux over short time periods.

When results from lysimeter and basic water balance studies are compared with results from more accurate soil moisture models, they can show a high variability in their estimation of the contribution of upward flux to crop evapotranspiration (Ayars *et al.*, 2002). There is no correct answer. Even in similar soil types and groundwater depths, with comparable climatic conditions, crops grow and behave differently. This is due to the different dynamic behaviour of soil moisture within the crop root zone.

Research suggests that both crop growth and yield may have already been reduced before there are any visible effects on the plant (Taylor, 1965). This indicates that moisture stress has already occurred, and that models may not necessarily replicate the true position in the soil due to upward flux from diurnal fluctuations in soil moisture.

It is clear that shallow groundwater plays an important part in sustainable irrigated agriculture and in the past 20 years we have come a long way in understanding its role and behaviour. It is also clear that we find it difficult to apply our understanding to effectively utilising shallow groundwater and maintaining its salinity within an acceptable range. A more replicable approach is required. By studying soil moisture movement in the profile, and developing a better understanding about the diurnal changes in soil moisture, it is hoped that soil moisture balances will become more accurate, and provide a true representation of soil moisture movement. For purposes of operational use, as well as to evaluate the success of the wide variety of models available, a simple and reliable method for estimating water fluxes in the field is needed.

2.6 Use of Darcy's Law in Irrigation Science to Estimate Upward Flux

Perhaps the most universal method to estimate upward flux is by separate measurements of the hydraulic gradient and the unsaturated soil hydraulic conductivity. The product of these two quantities then yields the hydraulic flux according to Darcy's Law. Darcy's Law is discussed in Appendix A2.1, along with the sensitivity of the equation to changes in the hydraulic conductivity of the soil. Efforts have been made to design a soil moisture flux meter (Cary, 1968), but these have so far not produced a practical field instrument, and the approach still relies on accurate field measurements.

It is not the purpose here to describe each study that has adopted the use of Darcy's Law to determine upward flux. Key studies will be mentioned to show the high variability in results under different conditions, as demonstrated using the previous methods described above.

Brandyk and Wesseling (1985) predicted rates of upward flux using Darcy's Law. They integrated the volumetric soil moisture profiles to enable them to estimate upward flux from a watertable depth of 1 m. Rates of upward flux ranged from between 1 to 5 mm/d for different soil types (using different hydraulic conductivity parameters). They concluded that for certain soil types, upward flux rates of 5 mm/d were sustainable, with no drying of the soil profile evident. Their study suggested that their approach could be used to help design drainage systems in areas with high watertables and layered soil types, because of the ability to adjust hydraulic conductivity values in their calculations for specific depths in the profile.

Ogata *et al.* (1960) measured the hydraulic gradient and from a known hydraulic conductivity characteristic determined the upward flux of moisture. In a sandy loam soil planted with alfalfa they found that a constantly shifting upward flux pattern gradually decreased as the soil moisture depletion increased and the hydraulic conductivity diminished. This caused the alfalfa transpiration rate to reduce and limited the potential yield of the crop. This was due to inadequate irrigation and insufficient sub-soil moisture fluxes.

LaRue *et al.* (1968) investigated the rate of upward flux over a deep watertable during a season when irrigation frequencies were altered. They used tensiometers inserted into a loam soil to determine the hydraulic gradient and measured unsaturated soil hydraulic conductivity to calculate upward flux using Darcy's Law. The study concluded that upward flux rates below a ryegrass rootzone could be as much as 2.5 mm/d, but that the rate of flux was determined by the amount of irrigation applied at the soil surface and the depth water infiltrated into the rootzone. This was due to the reduction in hydraulic gradient in the shallower soil where the surface applied water infiltrated.

This study was replicated by Rouse (1969), who found that upward flux contributed to 29% of total ryegrass evapotranspiration. Stone *et al.* (1973a) performed an identical study below a sorghum crop with the aim of understanding more about the process of upward flux above a deep watertable. Their results suggested that irrigation water initially 'lost' from the rootzone but then deep percolation moved back into the rootzone due to a reversal of the hydraulic gradient. Using tensiometers they determined an upward flux rate of 2 mm/d into the rootzone near the end of the study period. Hodnett *et al.* (1991) recorded a similar pattern of moisture re-distribution. Below a crop of drip irrigated sugarcane water applied during the day, which infiltrated below the root zone, would move upward back into the crop root zone overnight when transpiration was reduced.

Stone *et al.* (1973b) used an identical approach to their earlier study to estimate evapotranspiration from the same sorghum crop by combining the upward flux rate and soil moisture depletion values, and integrating the change in moisture content with respect to root depth. This method provided an alternative method to estimating evapotranspiration from lysimeter or meteorological measurements.

In Pakistan Moghal *et al.* (1993) calculated upward flux rates of 1 mm/d in a loam soil with a watertable depth of 2.5 m. At a watertable depth of 1.55 m upward flux rates were estimated up to 4 mm/d. Much higher rates of upward flux were suggested by Ragab and Amer (1986), who used Darcy's Law and a soil moisture balance approach to estimate upward flux below a maize crop on a clay loam soil. An average upward flux rate of 4.3 mm/d was maintained for a 75 day period when groundwater was maintained at a depth of 68 cm. Both approaches estimated total crop watertable contribution to be between 190 – 220 mm, approximately 40% of seasonal ETc. Wind (1955) found much lower rates of upward flux in the Netherlands. Using lysimeters to measure grass evapotranspiration, upward flux was, on average, less than 2 mm/d when groundwater was only 45 cm deep. However, evapotranspiration was low at an average of 3.5 mm/d, resulting in upward flux providing over 50% of the crop water requirement per day.

Darusman *et al.* (1997) used tensiometers buried in a silty soil planted with corn to determine upward flux rates and drainage below the crop root zone. They recorded seasonal upward flux rates of 124 mm at 1.5 m depth. They used this information to design the optimum drip line spacing, reducing drainage below the root zone, and yet utilising the upward flux for crop use. Saini and Ghildyal (1977) used a soil moisture balance approach to estimate upward flux, based on Darcy's Law. Under a winter wheat crop grown on a silty clay loam upward flux contributed between 36 to 73% of the total water requirement of the crop. The maximum daily rate of upward flux was 2.8 mm/d, with average rates between 1.2 and 1.6 mm/d. The study concluded that the rate of upward flux was highly dependent on the fluctuating groundwater below the root zone.

2.7 The Zero Flux Plane Method

The ZFP method is a comparatively robust physical method as it does not require a measurement or estimation of the unsaturated hydraulic conductivity in the unsaturated zone. Measurement or estimation of water flux in unsaturated soils is difficult. To use Darcy's Law to estimate moisture flux requires accurate values for hydraulic conductivity over the range of soil moisture contents found in the field (Hanks and Ashcroft, 1980). This approach is impractical because of the wide range of hydraulic conductivity values found in soils (typically varying over five orders of magnitude in a season (Gee and Hillel, 1988)), their spatial variation and hysteresis (Cooper *et al.*, 1990).

The zero flux plane concept is not new. Richards *et al.* (1956) first identified an area in the soil profile termed as the '*static zone*'. This was defined as the locus of points in the soil-water system above which water movement is upward, and below which water movement is downward. As soil moisture will move in the direction of decreasing potential, along the hydraulic gradient, moisture in the soil above the zero flux plane will move upwards towards the crop root zone and the soil surface. Soil water extraction by crop roots increases the water potential towards the upper soil layers, whilst a simultaneous declining water table and drainage of a previous irrigation or rainfall event through the soil profile may result in an increasing potential in the downward direction. Identifying the point at which the hydraulic gradient is zero (the zero flux plane) makes it possible to determine the unsaturated hydraulic conductivity as both the rate of moisture flux and the hydraulic gradient are already known (Cuenca, *et al.*, 1997a). By plotting the rate of moisture flux at corresponding hydraulic gradients as soil dries the relationship between moisture flow and suction, and therefore rate of flow through the soil can be identified.

Below the zero flux plane, assuming no uptake of roots at these depths, reduction in moisture content must be due to drainage out of the soil (i.e. groundwater recharge). Figure 2.5 shows the gravitational potential of an unsaturated soil above a shallow water table (i); and the matric potential of the same profile (ii). Figure 2.5 (iii) illustrates the total potential (matric potential corrected for gravitational head) showing a divergent zero flux plane, with (iv) showing the development of a convergent zero flux plane (ZFP).

Wellings and Bell (1980) introduced the concept of divergent and convergent flux planes. A divergent ZFP represents the focal point were moisture flowing upwards represents evapotranspiration and upward flux, and moisture flowing downwards represents drainage. If precipitation or irrigation occurs during this time, a second convergent ZFP occurs which moves rapidly down the profile (with infiltration) until it meets the original divergent ZFP.

When they meet the convergent ZFP 'cancels' the original divergent ZFP, at which point drainage throughout the profile is restored. If precipitation or irrigation does not occur and evapotranspiration and upward flux proceeds over the season the ZFP will move down the profile. Consequently a progressively greater depth of profile contributes to evapotranspiration and, therefore, upward flux over time.

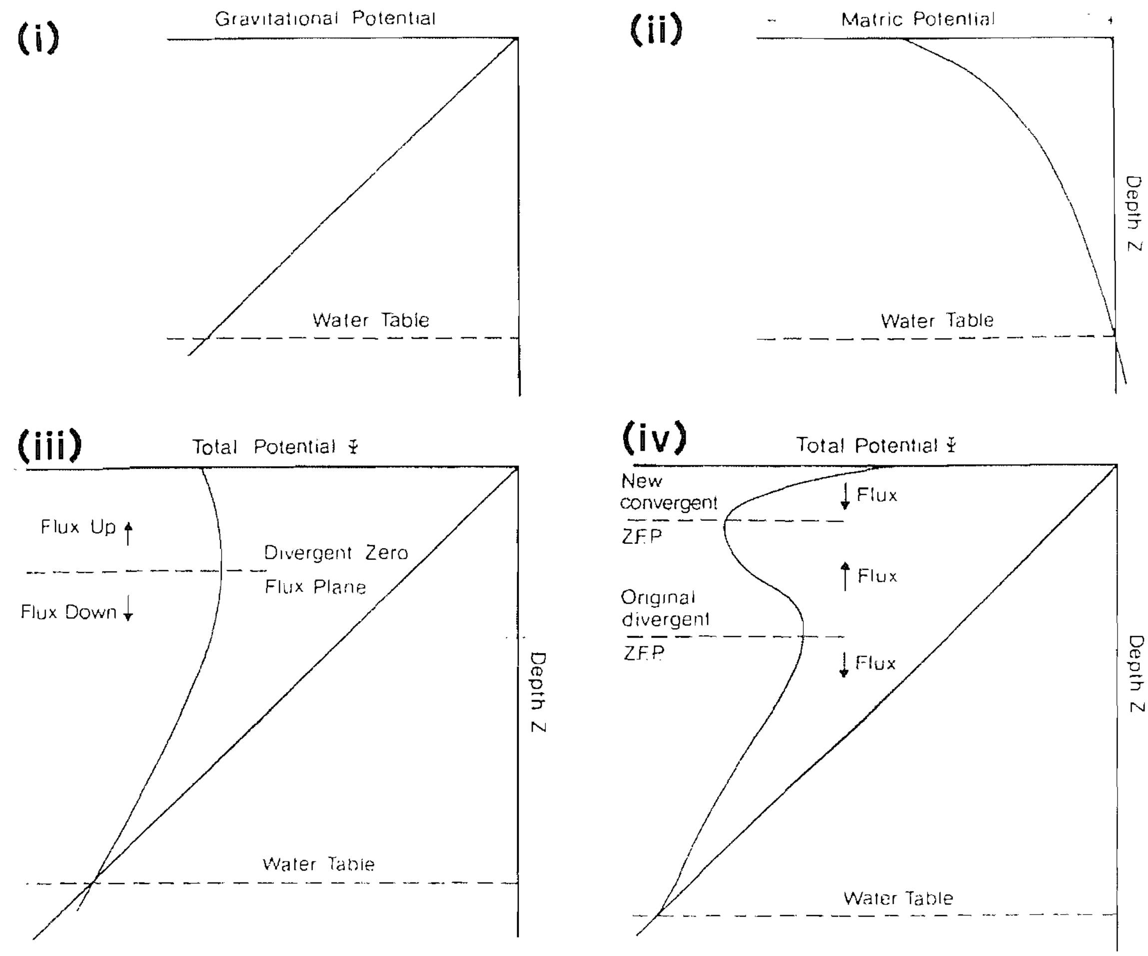


Figure 2.5 Development of a Zero Flux Plane in Unsaturated Soil
(*Source*: Hodnett *et al.*, 1991)

Stammers *et al.* (1973) developed a mathematical model that estimated the ZFP using Darcy's Law to identify the direction of moisture flow. Experiments were conducted on a bare silty loam soil. Their results indicated that the developed ZFP model was able to reasonably predict moisture loss from the soil when compared to the Penman (1948) evaporation calculation. However, the ZFP calculation loses accuracy where soil water seepage below the point of zero flux is ignored. This causes an over estimation of water leaving the soil, as water flowing downwards below the point of zero flux is as evapotranspiration within the ZFP equation. The equation developed by Stammers *et al.* (1973) has been successfully used by Cooper (1979) studying moisture fluxes under tea in Kenya and Cooper (1980) who used the ZFP method to estimate drainage rates to understand aquifer recharge in a forest.

The ZFP method is particularly suited to areas with low rainfall and long growing seasons, as this allows the development of large, deep zero flux planes, which make their identification easier. A divergent ZFP will move down the soil profile over the growing season, and depths of between 4.5

to 6 m have been recorded (Cooper, 1979; Wellings and Bell, 1980). Table 2.2 contains details of key Zero Flux Plane studies.

Table 2.2 Key Zero Flux Plane Studies

Reference	Crop	Soil Type	GW Depth (m)	Notes
Cooper *et al.* (1990)	Grass	L	10 to 90^	Results were used to estimate unsaturated hydraulic conductivity and actual evapotranspiration to estimate chalk aquifer recharge
Hosty and Mulqueen (1996)	Grass	L	4	ZFP present, with a maximum depth of 1.75 m.
Cuenca *et al.* (1997b)	Pine Forest	C to coarse S	-	Identified presence of both a DZFP at ≈ 50 cm and a CZFP at ≈ 1.1 m
Joshi *et al.* (1997)	Grass prairie	CL	5 to 7.5	Identified presence of both a DZFP at ≈2 m and a CZFP at ≈5 m
Shimada *et al.* (1999)	Red Pine Forest	Organic black loam soil	1.1 to 2.1	The shallow ZFP at 20 cm estimated 1.29 mm/day evaporation. The deeper ZFP at 70 cm estimated 2.87 mm/day transpiration
Tsujimura *et al.* (2001)	Grass	-	0.55 to 1	ZFP present at 30 cm
Subagyono and Verplancke (2001)	Corn	SL	Drainage only*	ZFP present at 25 cm

Notes: ^ Different sites were investigated with groundwater depths ranging from 10 to 90 m deep. * Experiments were conducted in drainage lysimeters. DZFP is Divergent Zero Flux Plane. CZFP is Convergent Zero Flux Plane.

Apart from Shimada *et al.* (1999) Table 2.2 does not provide actual rates of upward flux on a daily basis. This is due to the nature of the ZFP method. Above the point of zero flux moisture decreases as it is withdrawn by plant roots and surface evaporation. This makes it difficult to separate moisture moving into the soil above the point of zero flux (as upward flux) and moisture moving out of the soil above the point of zero flux (as root extraction or bare soil evaporation). Shimada *et al.* (1999) were able to determine daily rates due to the relatively low rate of evapotranspiration, a constant data set, and the presence of two zero flux planes.

The ZFP method requires consistent and unbroken data sets of soil moisture suction (or moisture content and accurate pF curve data) to be able to identify movement of the point of zero flux and thus calculate changes in soil moisture. However, in semi-arid and arid areas high evapotranspiration rates often cause disjointed data sets when tensiometers 'break' tension. An accurate knowledge of rooting depth is also required. Roots below the depth of the zero flux may be able to influence and even 'pull' the ZFP lower in the soil profile (Giesel, *et al.*, 1970; McGowan, 1973). This decreases the accuracy of the method. Due to the problems associated with the accuracy of the data required and the need for detailed interpretation of the hydraulic gradient to predict the direction of moisture flow, the ZFP method has not been widely adopted to measure upward flux in irrigation science (Allison, *et al.*, 1994).

Despite these problems concerning accuracy, the ZFP method has been used by a number of other researchers as a form of soil moisture balance, e.g.: Arya *et al.*, (1975); McGowan and Williams, (1980a; 1980b); Wheater *et al.*, (1982); Dolman *et al.*, (1988); Gardner *et al.*, (1989); Hodnett and Bell (1990); Kanamori, (1995).

2.8 Former Soviet Union Methods

There have been a number of studies to quantify the upward flux of moisture into the rootzone of agricultural crops, using different methods and equipment. It is not the purpose of this review to discuss every study, nor every method. Some methods to estimate upward flux are laboratory based, using specific chemical tracers or radioactive substances (e.g.: Scanlon and Milly, 1994; Scanlon, 1991; Nakayama *et al.*, 1973). These will not be discussed in this review, as the chemicals and methods used were not developed for practical field based use.

A large percentage of the irrigated land in Central Asia has a seasonal watertable less than 3 m deep from the soil surface (Sherokova, 1997; TACIS, 1995). Muratova (1958), Sukhachev (1958) and Legostaev (1958) all described significant quantities of upward flux occurring in the silty soils of Kazakhstan, in some cases before the development of the major irrigation systems. TACIS (1999) suggested that 74 percent of sample fields within the Central Asian republics had average watertable depths closer than 3 m from the soil surface. These high watertables have caused a significant increase in the crucial irrigation interval, and hence reduced the number of irrigations required, whilst contributing to the build up of salinity in crop root zones. In some areas irrigation is generally not available at the end of the cropping season, nor beginning of the next for adequate salt leaching activities (TACIS, 2000).

Kharchenko (1975) developed a formula to estimate the groundwater contribution to crop evapotranspiration based on experimentation in Central Asia. The constant m used in the equation was developed based on capillary properties of Central Asian soils calibrated using the Ivanov method for estimating reference crop evapotranspiration (further described in Chapter Three). TACIS (1999) reported average upward flux rates in Kazakhstan between June to September 1997 of between 2 and 2.5 mm/d using the local Kharchenko method. The Kharchenko method is described below and is used in this study for comparison to the newly developed diurnal method:

$$GW = \frac{ETo}{e^{[m(H-h)]}}$$

[2.4]

where:

GW	:	groundwater contribution rate to crop evapotranspiration (mm/day)
m	:	constant, dependent on the capillary properties of the soil
H	:	groundwater depth (m)
h	:	crop rooting depth (m)
ETo	:	reference crop evapotranspiration (mm/day)

It is clear from equation 2.4 that groundwater contribution is very sensitive to the rate of evapotranspiration, therefore upward flow of moisture is sensitive to the proximity of the watertable to the roots due to the exponential relationship between the rate of upward flow above a watertable (van Hoorn, 1978). The role of h (later added to equation 2.4 by Horst (TACIS, 1999)) allows the distance between a variable rooting depth and the watertable to be modelled, provided rooting depth is known or can be estimated.

Despite the widespread use of the Kharchenko method in Central Asia, TACIS (1997) showed poor agreement between the Kharchenko method and field estimated value. Reasons for this were found to be:

- lateral inflow of soil moisture, possibly via the capillary fringe, which did not effect the watertable level, and therefore not the calculation;
- incorrect estimation of the distance between the roots and the groundwater level;
- difference between soil classifications based on textural class, as the Kharchenko equation is based on Soviet soil classification, which is markedly different to International textural classes (TACIS, 1997).

International systems for classification of soil into different textural classes differ slightly but are consistent in defining the upper size limit of clay particles as 0.002 mm (Braun and Kruijne, 1994). Although this textural classification procedure is accepted internationally, Kachinksy later adopted different standards, which were based on the amount of physical clay (particles <0.01 mm). This can cause confusion when comparing soils for classification between the Soviet Kachinsky method and that of the USBR or similar method, as particles between <0.01 and <0.002 mm are classified as silt by non-Soviet methods, and clay by Soviet methods (TACIS, 1997). As the majority of soils in Central Asia fall within this range actual classification can be difficult.

Table 2.3 identifies some of the upward flux rates calculated by researchers in the FSU for some soils.

Table 2.3 Upward Flux Rates at an ETo rate of 7 mm/d

Depth to Groundwater (m)	Upward Flux (mm/d)	Reference
1	2.5	Kharchenko (1975)
1	8.2	Laktaev (1978)
0.5	7	Kovda (1961)
1.2	8	Kovda (1957)
1.4	8	Kovda (1957)
1.8-2.5	≈3	TACIS (1999)
2	2.2	Van Hoorn (1978)
1	9.6	Van Hoorn (1978)

It would appear that Soviet work suggests much higher rates of upward flux for deeper groundwater depths than previously shown by research conducted outside the former Soviet Union. This may be due to the extreme climate experienced in Central Asia, the deep rooting depths of some crops, and the presence of silty soils.

In some areas of Central Asia salinisation can effect crop yields quicker than anticipated (Vyishpolskiy, 2000). Although the surface water applied to crops may be low in salinity, inadequate drainage, canal seepage and ineffective leaching may contribute to regional groundwater and soil salinity. There is a need to address these problems before widespread salinisation and lack of water causes a significant reduction in yield production.

2.9 A Need for Improved Methods of Establishing Upward Moisture Flux

We have a good understanding of soil moisture balances for effective irrigation but lack information on the true role of groundwater in meeting crop water needs and a way to incorporate groundwater into practical irrigation water management. Improved estimates of shallow groundwater contributions to evapotranspiration as a function of plant growth stage and groundwater salinity are needed to refine irrigation management under shallow groundwater conditions. This would improve estimation of crop water use and the calculation of irrigation requirements and scheduling, groundwater recharge and use and potential salinity hazards in areas with shallow groundwater.

An understanding of the movement of moisture in the rootzone will allow the rate of upward and downward flux to be calculated. This is especially important in arid and semi-arid areas where agricultural land is threatened by salinity due to high groundwater (Cuenca *et al.*, 1997a; Nielsen, *et al.*, 1986). A sound knowledge of the dynamics of water movement into and out of the rootzone and the contribution of shallow watertables to crop water use of agricultural crops is needed to minimise irrigation input while optimising production returns.

This thesis investigates this area and develops a new methodology to estimate the contribution of groundwater to crop water demand. In particular it works to:

1. further understand the processes involved in soil water movement in a cropped soil;
2. develop an approach to estimate upward flux into a soil profile from shallow groundwater;
3. test and compare the validity of the new methodology for estimating upward flux with estimates made by other approaches such as Darcy's Law based methodologies; and
4. estimate the seasonal groundwater contribution to crop water requirements in an irrigation system in the Syr Darya basin in South Kazakhstan.

2.10 Previous Investigations of Diurnal Soil Moisture Change

Richards (1949) described the construction and use of a mercury manometer and porous ceramic cup for the measurement of the soil 'capillary potential' or unsaturated hydraulic conductivity. It was in this study that the diurnal change of soil moisture was first recognised as a phenomenon requiring further research.

Haise and Kelley (1950) responded to the call for further study by Richards, and performed a series of experiments under an alfalfa crop on a silt loam soil using mercury manometers. They recorded large diurnal variations in soil moisture suction, attributing the fluctuations to changes in the temperature at the soil surface within the shallow soil profile. However, the range of diurnal fluctuation decreased with depth and was negligible below the alfalfa rooting zone. Maximum moisture suction occurred between 19:00 and 21:00 hours, with minimum moisture suction at 06:00. Suction changes of 140 cm at 30 cm, and 120 cm at 60 cm depth were recorded.

Remson and Randolph (1958) investigated diurnal fluctuations in soil moisture tension at two sites, with tensiometers installed between the soil surface and the watertable. One site was in a recently planted field of beans, the other in a forest clearing. Maximum values of soil moisture suction occurred between 18:00 and 21:00, and minimum values between 05:00 and 08:00, similar to observations by Haise and Kelley (1950). Soil moisture suction fluctuations of 50 cm were recorded at depths of 2.5 m. Tensiometers recorded greater fluctuations in tension deeper in the profile, suggesting that air temperature had little effect on the diurnal change in soil moisture suction. Fluctuations in tension were recorded as deep as 3.35 m in the forest clearing, whilst some areas of the bean field recorded no tension due to the absence of deep roots. When the tensiometers were removed from the ground it was found that the majority of the roots were in the area of the soil horizon instrumented by the tensiometers. This suggested that the higher readings deeper in the profile resulted from daytime withdrawal of water by the roots and replenishment of water from the surrounding soil when the evapotranspiration decreased overnight.

Remson and Randolph (1958) did not experience a change in soil moisture tension with change in soil temperature (as experienced by Haise and Kelley (1950)), concluding that '*Pressure changes in soil water resulting from temperature changes are, therefore, not believed to be the cause of the diurnal fluctuations observed in tensiometer readings in the field...*'.

The absence of diurnal fluctuations in soil moisture suction data from the newly cropped bean field was attributed to the absence of deeper crop roots. Remson and Randolph (1958) linked the rate of moisture replenishment overnight and withdrawal by roots during the day to the unsaturated hydraulic conductivity of the soil profile at different soil moisture suctions. This explained the increase in diurnal tension fluctuations when the soil dried, representing the increase in suction required to actually allow the movement of water, and the smaller fluctuations when tensions were relatively low due to the lower suctions allowing the movement of moisture.

Remson and Randolph (1958) noted that diurnal fluctuations in groundwater level had been recorded by other researchers where growing plants used moisture from a shallow watertable (e.g.: Barksdale, 1933). White (1932) even stated that:

'*In some localities the groundwater level has been observed to decline during the day and to rise at night, the decline beginning at about the same hour every morning and the rise at about the same hour every night. This decline is due to the withdrawal of groundwater from the zone of saturation by plants, and the rise at night is due to upward movement of water ... from permeable beds of sand and gravel at some depth beneath the water-table*'.

The study concluded that the soil moisture suction fluctuations were two processes from the same trend, firstly, the daytime withdrawal of water by evapotranspiration, and secondly, the nightly replenishment of water by conduction from the water table.

Although recommendations have been made for further study of the process of diurnal soil moisture suction change there has been a distinct lack of research in this area. No study has yet reacted to Remson and Randolph's observations.

Similar conclusions to White (1932) were noted by Mead *et al.* (1996), who were unable to explain large moisture fluctuations recorded with capacitance probes deep in a soil profile and concluded that soils were able to 'refill' moisture overnight. They noticed that the wetter the soil, the higher the amplitude of fluctuating moisture content. In some cases moisture content changed between night and day by 0.05 m^3/m^3. They concluded that the dynamics of moisture movement and redistribution of moisture overnight required further study.

Vellidis *et al.* (1990) recorded the re-distribution and replenishment of soil moisture at 30 cm depth beneath drip emitters irrigating a tomato crop, attributing the replenishment to the periods of low or zero evapotranspiration during the night. This diurnal cycling of soil moisture was recorded throughout the crop season and raised important considerations for scheduling, as the irrigation system was designed to irrigate at a pre-determined soil moisture potential. As this changed due to overnight replenishment of soil moisture the question of water savings, at no loss to crop quality and production was raised, but no further study was performed.

Thomson and Threadgill (1987) used tensiometers to monitor soil moisture status under a maize crop. A threshold limit of soil moisture suction was pre-determined to 'trigger' the start of irrigation with a centre-pivot system. Due to diurnal fluctuations in soil moisture suction the time of irrigation was often delayed. Peak soil moisture suction readings were recorded at approximately 19:00, recovering overnight by up to - 300 cm. Irrigation set to start at a soil suction of 0.38 bar was always premature, as early morning readings registered a lower suction value than 0.38 bar. They concluded that the recharge capacity of the soil to replenish moisture overnight caused 'false' suction readings throughout the day.

In reality, it appears that the tensiometers indicated the amount of moisture extracted from the soil during the day by the crop. This shows the ability of the soil to replenish soil moisture from deeper within the soil profile as upward flux due to the hydraulic gradient which had developed during the daytime.

Van Bavel and Ahmed (1976) reported on the overnight replenishment of soil water. They developed a linear soil moisture balance model to investigate the progressive drying of a clay loam soil by a sorghum crop. Soil physical properties were laboratory determined, and the model was developed to replicate soil moisture status, crop leaf water potentials and root depth. Van Bavel and Ahmed (1976) noticed that towards the end of the experiment the upward flux of moisture into the root zone represented more than half the crop evapotranspiration, and therefore represented a critical factor to the survival of the crop. Many previous studies have found that upward flux of moisture from deep moist soil represents a large part of the total evaporation by the soil-water-plant system (e.g.: Prathapar *et al.*, 1992; Mason *et al.*, 1983; Meyer *et al.*, 1989).

Fiscus and Huck (1972) observed diurnal fluctuations in soil moisture suction using tensiometers buried at different depths in a fine sandy soil planted with cotton. Results showed that maximum soil moisture suctions occurred between 15:00 and 18:00, returning to a minimum between 03:00 and 07:00. Diurnal change in suction was between 1000 to 2000 cm (pF 3 to 3.3) at 53 cm deep in the profile and 2000 cm (pF 3.3) at 23 cm deep. Soil moisture suction stabilized each morning prior to sunrise. They concluded that these observations indicated significant upward movement of moisture into the cotton-rooting zone through the soil matrix, although no attempt was made to quantify the rate and amount of replenishment.

The experience of this research did, however, cause Long and Huck (1980) to design an automated water filled tensiometer system for measuring soil moisture potential below a maize crop. Diurnal fluctuations in moisture potential were recorded, showing lower tensions in response to periods of cloud cover and low radiation in the field. Diurnal 'replenishment' in soil moisture suction down to 100 cm depth was recorded by the tensiometers, despite a general drying of the soil profile as the crop developed.

Hillel (1975) developed a computer model that predicted soil moisture status from potential evaporation estimates, using field data from a site in Israel. The model was mechanistic and linear in format, and was purposefully developed to understand the process where soil at the surface dries throughout the daytime, yet re-wets overnight from deeper soil layers due to upward flux. The study was more of an investigation, rather than development of a practical field approach. Hillel was specifically interested in the changing moisture content at the soil surface, based on preliminary observations by Jackson *et al.* (1973; 1974) and Bruce *et al.* (1977) who observed the re-wetting of the top 7 cm of the soil surface due to moisture vapour flow. Vapour flow is not considered in this study, based on recommendations by Gardner (1958) who concluded that in an agricultural field vapour flow from deeper depths within the soil profile was unimportant in soil moisture studies.

Hillel (1975) indicated that fluctuating 'evaporativity' caused diurnal changes in moisture content in the soil surface layers, with an increase in moisture content of between 0.01 to 0.02 m^3/m^3 overnight. After a 10 day simulation using the developed model the amplitude of the diurnal moisture content fluctuations decayed with time, although daytime moisture content still decreased by 2.37% (of the total moisture content), and the nightime value increased by 5.54% (of the total moisture content). The experiment concluded that further studies involving deeper soil profiles were needed to understand diurnal fluctuations in moisture content.

Starr and Paltineanu (1998) used a series of capacitance probes to monitor soil moisture in a silt loam soil planted with maize. The capacitance probes allowed observation of diurnal fluctuations in moisture content, which were largely due to evapotranspiration demand from the crop. Results showed an increasing water demand at deeper depths within the soil profile as the maize roots developed. They used the diurnal fluctuations to identify internal profile drainage losses by assuming that any decrease in moisture content overnight was due to drainage, and not evapotranspiration. Molz and Remson (1971) showed how moisture can continue to be extracted from soil by plant roots into the night. Homaee (1999) confirmed this in his experiments where plant roots took up water in the evening. As photosynthesis can not take place without light and stomata are closed plants have no possibility to significantly transpire water overnight and it must be stored in the plant tissues. As a result, Homaee (1999) recorded increased leaf water potentials overnight (decreased suctions).

Consequently, the study by Starr and Paltineanu (1998) may have overestimated drainage due to root water uptake overnight, and underestimated evapotranspiration during the daytime using the assumption that roots do not extract moisture during the nightime.

Ayars *et al.* (1996) used weighing lysimeters irrigated with a buried drip system to monitor the influence of groundwater on cotton growth. The watertable was maintained at 2 metres in one lysimeter and in the other a constant drainage profile was maintained in the soil. The cotton crop used moisture from the soil profile during the daytime, yet the soil moisture deficit appeared to reduce overnight. Soppe and Ayars (2000) continued this study using weighing lysimeters planted with cotton in a silty loam soil to estimate evapotranspiration and groundwater use. They recorded an increasing soil moisture content overnight with capacitance probes at 90 cm depth, 30 cm above a fixed watertable. They attributed the increase in moisture content to upward flux from the watertable and the presence of the capillary fringe. When irrigation was decreased by 50% crop groundwater use increased in direct response to the increasing soil moisture deficit.

These studies raised important considerations for irrigation management combining groundwater use. Where crop roots were deep enough in the profile irrigation could be decreased, and groundwater could be used as a supplemental water source. Crops that are able to produce deeper rooting systems earlier in the season would be able to use groundwater earlier, and so reduce the total number of irrigations.

Vellidis and Smajstrla (1991) used lysimeters containing different soil types and fixed watertables to determine the groundwater use by a tomato crop. They reported that up to 34% of evapotranspiration was supplied from the groundwater during particular months. More importantly, they recorded diurnal patterns of moisture redistribution and fluctuations between irrigations and noted that this had been observed by previous studies, such as Long and Huck (1980). The diurnal fluctuations in moisture and replenishment were not taken into account, even though on certain occasions they caused an overnight decrease in soil moisture suction by approximately 100 cm.

Chen *et al.* (2004) recorded diurnal fluctuations of soil moisture at 30 and 50 cm depths in a maize field in China where the groundwater was between 2 to 3 metres deep. Both convergent and divergent zero flux planes were also evident. They concluded that the diurnal changes were due to adjustments in crop evapotranspiration during the night and day time and identified the 'heart' of the soil moisture redistribution system laying between 30 and 50 cm deep in the soil where the roots were most dense. Recent work by Nachabe *et al.* (2005) in Florida identified diurnal fluctuations in soil moisture using TDR profile probes and concluded that in humid, shallow watertable environments plant evapotranspiration demand may be supported by adjacent ecosystems. Their study, on a hillslope covered in grass and other indigenous woody vegetation concluded that estimates of evapotranspiration from diurnal fluctuations in soil moisture provided reasonable results when compared to a water balance.

Table 2.4 shows each study that has considered diurnal soil moisture changes.

Table 2.4 Previous Studies of Diurnal Soil Moisture Fluctuations

Reference	Type of Study	Crop	Soil Type	Equipment Used	Irrigation Method
Haise and Kelley (1950)	Laboratory based	Alfalfa	ZL	Tensiometers	No irrigation
Remson and Randolph (1958)	Field based	Beans and a Forest	-	Tensiometers	No irrigation
Vellidis *et al.* (1990)	Lysimeters & field study	Tomatoes	Fine S	Tensiometers	Drip
Van Bavel and Ahmed (1976)	Simulation Model	Sorghum	CL	-	-
Fiscus and Huck (1972)	Field based	Cotton	Fine SL	Thermocouple Psychrometers	No irrigation
Hillel (1975)	Model & field study	Bare soil	Fine SL	Tensiometers	No irrigation
Long and Huck (1980)	Field based	Maize	SL	Water filled tensiometers	Sprinkler
Thomson and Threadgill (1987)	Field based scheduling	Maize	-	Tensiometers	Centre pivot
Starr and Paltineanu (1998)	Field based	Maize	ZL	Capacitance probes	Sprinkler
Soppe and Ayars (2000)	Lysimeters	Cotton	ZL	Capacitance probes	Drip
Vellidis and Smajstrla (1991)	Lysimeters	Tomatoes	S/Fine S	Tensiometers	Drip
Chen *et al.* (2004)	Lysimeters & field study	Maize	ZL	Tensiometers & TDR	No irrigation
Nachabe *et al.* (2005)	Field based water balance	Indigenous woody vegetation	Course textured	Enviroscan (Capacitance)	No irrigation

Notes: - information not available.

The studies reviewed above have not attempted, or have been unable to quantify the amount of upward flux throughout the crop season. As crops grow and rooting systems develop the movement of moisture within the soil profile changes. This is in direct response to the increasing evapotranspiration rate of the plant, controlled by the atmosphere, combined with the interaction of the fluctuating groundwater level. These dynamic processes are constantly occurring within the soil profile. Consequently, upward flux rates will change throughout the season.

It is important to realise that studies with large time periods between measurements of soil moisture are unable to identify diurnal fluctuations in moisture content. Ignoring the diurnal movement of moisture in the soil profile results in the inaccurate calculation of crop water use and upward flux. This is especially evident when using the soil moisture balance approach to study soil moisture movement. Applications of Darcy's Law and the Zero Flux Plane method to study soil moisture movement are also liable to produce inaccurate results as the data used is often recorded over large time steps, such as weekly or fortnightly. As the global need for improved water management and water use efficiency increases the ability to improve irrigation scheduling procedures and actually 'match' irrigation applications with crop water demand is fundamental to improved water management.

2.11 The Development of a New Method to Estimate Upward Flux

There has been little study of diurnal moisture change since it was first recognised by Richards (1949), who reported that:

'*...tensiometer readings are subject to daily variation that has not been fully studied and explained. It may be due, in part, to change in moisture content of the soil because, for field installations, readings generally increase during the afternoon when the transpiration load is greatest*'.

The lack of further research in this area has been due, in part, to the lack of affordable equipment able to measure soil suction and/or moisture content in regular small timesteps.

Soil moisture suction (ϕ) is directly linked to soil moisture content (θ) over time. It can be assumed that where soil is homogenous and isotropic with depth:

$$\frac{\partial \phi}{\partial t} = fn\left(\frac{\partial \theta}{\partial t}\right) \qquad [2.5]$$

where:

ϕ : soil moisture suction (cm pressure)

θ : volumetric moisture content (m^3/m^3)

t : time

Due to the relationship between soil moisture content and soil moisture suction, when soil moisture suction changes there is a simultaneous and corresponding change in soil moisture content. Due to the non-linear nature of soil moisture characteristic curves and the effects of hysteresis, any change in suction is not directly proportional to a change in moisture content. This is due to the nature of the water holding properties of the soil. Where constant measurement in the soil profile of either suction or moisture content is possible, diurnal changes in soil moisture may be evident under cropped surfaces.

The diurnal fluctuation of soil moisture is not well understood, and in the past many studies have attributed the diurnal change to soil temperature variations (e.g.: Smiles *et al.*, 1985). Mohanty *et al.* (1998) monitored soil temperature and moisture content fluctuations on a bare soil using Time Domain Reflectrometry (TDR) probes and found little temporal fluctuation in moisture content, although the maximum depth studied was only 12 cm. This suggests that fluctuations in moisture content occur on cropped surfaces only. Huck and Hillel (1983) stated that diurnal changes in soil temperature and the effect on soil moisture content can be ignored due to the large heat capacity of soil.

Warrick *et al.* (1998) studied the diurnal fluctuations of tensiometer readings and concluded that the changes were mainly due to tensiometer design and shallow placement in dry soil. Although the study did identify some minor tensiometer fluctuations at 150 cm deep in the soil they concluded that hydraulic conductivity was the main factor which affected pressure fluctuations inside the tensiometer. Baver (1948) showed that a large change in daily air temperature of 18°C only caused a change in soil temperature of 3°C at 10 cm depth, concluding that the effects of temperature deeper than this were insignificant.

Throughout this study the effect of soil temperature on soil moisture movement was not considered. This was based on the assumption that the crop water demand at 100% canopy cover would far outweigh any temperature effects on soil moisture content, especially below 60 cm depth in the soil profile where upward flux rates were expected to be high. The shallow soil layers at the surface would also have a very low conductivity due to surface drying, and consequently any moisture flow would be due to vapour flow only.

Soil moisture suction changes diurnally in the rootzone of crops due to the change in incoming solar radiation and other climatic parameters, which in turn causes a change in evapotranspiration. During daylight hours when plants transpire the soil moisture gradient between plant roots and the transpiration demand at the leaf surface increases (Gardner, 1965). This is due to the rate of transpiration which, at peak rates, can not be maintained within the plant due to the high hydraulic gradient between the soil matrix and the root surface (Remson and Randolph, 1958). Soil moisture suction increases as water is extracted from the soil immediately around the plant roots (Remson and Fox, 1955). This in turn, due to the increasing hydraulic gradient in the surrounding soil, causes moisture to flow upwards towards the root extraction area (Hodnett *et al.*, 1991). The process of moisture removal from the soil profile by roots of an actively transpiring crop is termed 'extraction' throughout this study.

As soil dries the reduction in unsaturated hydraulic conductivity limits the rate of moisture movement and plant roots are unable to extract the amount of moisture required by the plant for transpiration needs. Moisture extraction by evapotranspiration will, in hot climates, nearly always exceed soil moisture recharge to the root zone by capillary rise due to the limitation of the soil transmitting properties (Soppe and Ayars, 2000; Hodnett *et al.*, 1991; Van Bavel and Ahmed, 1976; Remson and Fox, 1955).

During nighttime the plant's stomata close as plant moisture demand slows and may eventually almost stop. Moisture may continue to be extracted from the soil to reduce the plant tissue moisture deficit in preparation for the following day's photosynthesis (Homaee, 1999). Over a season as crops grow they can be seen to wilt during the afternoon and early evening, yet in the morning wilting has ceased and the crop leaves and stem become turgid, although irrigation or rainfall has not occurred.

Investigations by Ritjema (1965) showed that moisture extracted by plants from below the root zone during daytime was re-supplied overnight when capillary rise was able to return the soil to the antecedent moisture condition (confirmed in experiments by Hodnett *et al.*, 1991). Molz and Remson (1971) showed how roots increase their rate of moisture extraction as soil continues to dry in response to the increased transpiration demand and reduction in unsaturated hydraulic conductivity throughout the crop season.

It is clear that there has been little recent study into the overnight 'recharge' of moisture into crop rooting zones. This thesis focuses on this process to develop a new methodology to estimate the contribution of groundwater to crop water demand.

Appendix A2.2 contains example data to show the process of diurnal moisture movement and the processes of soil moisture 'recharge' and 'extraction'.

The next chapter describes the experimental sites used to collect data and the methodology developed to validate the new method to calculate groundwater contribution to growing crops.

3. MATERIALS AND METHODS

3.1 Introduction

This chapter describes the irrigation system in South Kazakhstan where field experiments were performed to estimate upward flux into the crop root zone.

The aim of this study was to develop a new approach to estimate upward flux from soil moisture data. Intensive field experiments were used to monitor soil moisture conditions within the active rootzone and gather hourly data to allow comparison between the newly developed method presented in this thesis with existing generic methods.

3.2 Study Location and Regional Geography

The Arys-Turkestan irrigation system (ARTUR) is located 20 km North East from the city of Turkestan (Lat: 43.12, Long: 68.30), in an important cotton-growing region of South Kazakhstan. The irrigation distribution system was constructed in the 1960s with the accompanying surface drainage network completed in 1963 (Vyishpolskiy, 1999a). The area has recently started to experience water shortages and other environmental problems associated with irrigation in Kazakhstan (McKinney and Kenshimov, 2000). These are further discussed in Appendix A1.

The ARTUR irrigation system sits on the foothills of the Karatau mountain range and has an arid climate, with evaporation exceeding precipitation. The Syr Darya river lies approximately 38 km to the west, but the ARTUR system is fed by the Arys and Bugun rivers, together with seven other minor water courses (with a combined average annual mean flow of 1000 Mm^3 and a watershed of 14,000 km^2 (Asarin, 1974)) (Vyishpolskiy, 1999a). The rivers are snow fed in spring, with a period of low flow from the end of June where river flow is exclusively from springs. Maximum precipitation is in March (Vyishpolskiy, 1999a). Figure 3.1 shows the Syr Darya basin, including the ARTUR irrigation system.

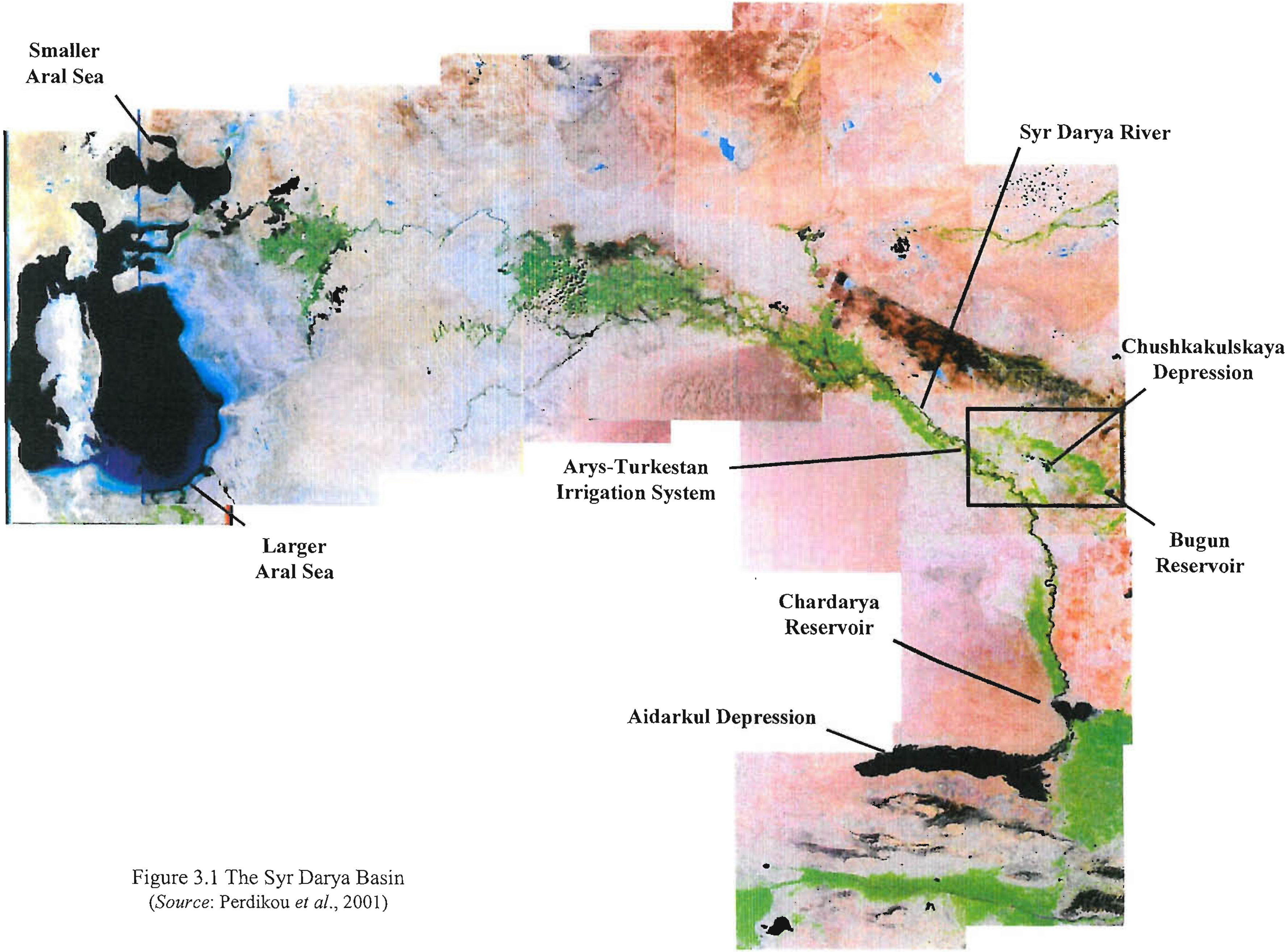


Figure 3.1 The Syr Darya Basin
(*Source*: Perdikou *et al*., 2001)

3.2.1 Description of the Arys-Turkestan System

The main irrigation canal is 140 km long, and has a flow rate of 45 m^3/s at its head (Vyishpolskiy, 1999a). The canal is supplied by the Bugun reservoir which was constructed in 1970, having a maximum water storage capacity of 370 Mm^3 (McKinney and Kenshimov, 2000). There is approximately 0.80 Mm^3/year return flow towards the Syr Darya from drainage flows from irrigation, the majority of which runs into the Chushkakulskaya depression (Vyishpolskiy, 1999b). The system has a potential Gross Command Area of 200,000 ha, although only 70,000 ha is irrigated (Karajeh *et al.*, 2000). Traditional crops include cotton, melons, vegetables, maize and wheat, although cotton is the primary crop of the region. Pumped groundwater from seepage canal water has always been used as an additional irrigation resource in some areas (Raskin *et al.*, 1992), but in reality, groundwater has only provided an increase in total water supply of between 15 to 20% (Vyishpolskiy, 1999a).

Irrigation is by furrow and water is supplied to farmers at fixed discharges over 24 hr periods. Since the break-up of the Soviet Union the large collective farms have been privatized, with individual farmers or conglomerates now owning land. Traditionally, field size in the ARTUR system ranged between 15 to 50 ha. This has now become much smaller (between 0.2 to 20 ha), with fields being sub-divided between farmers, families, and private companies.

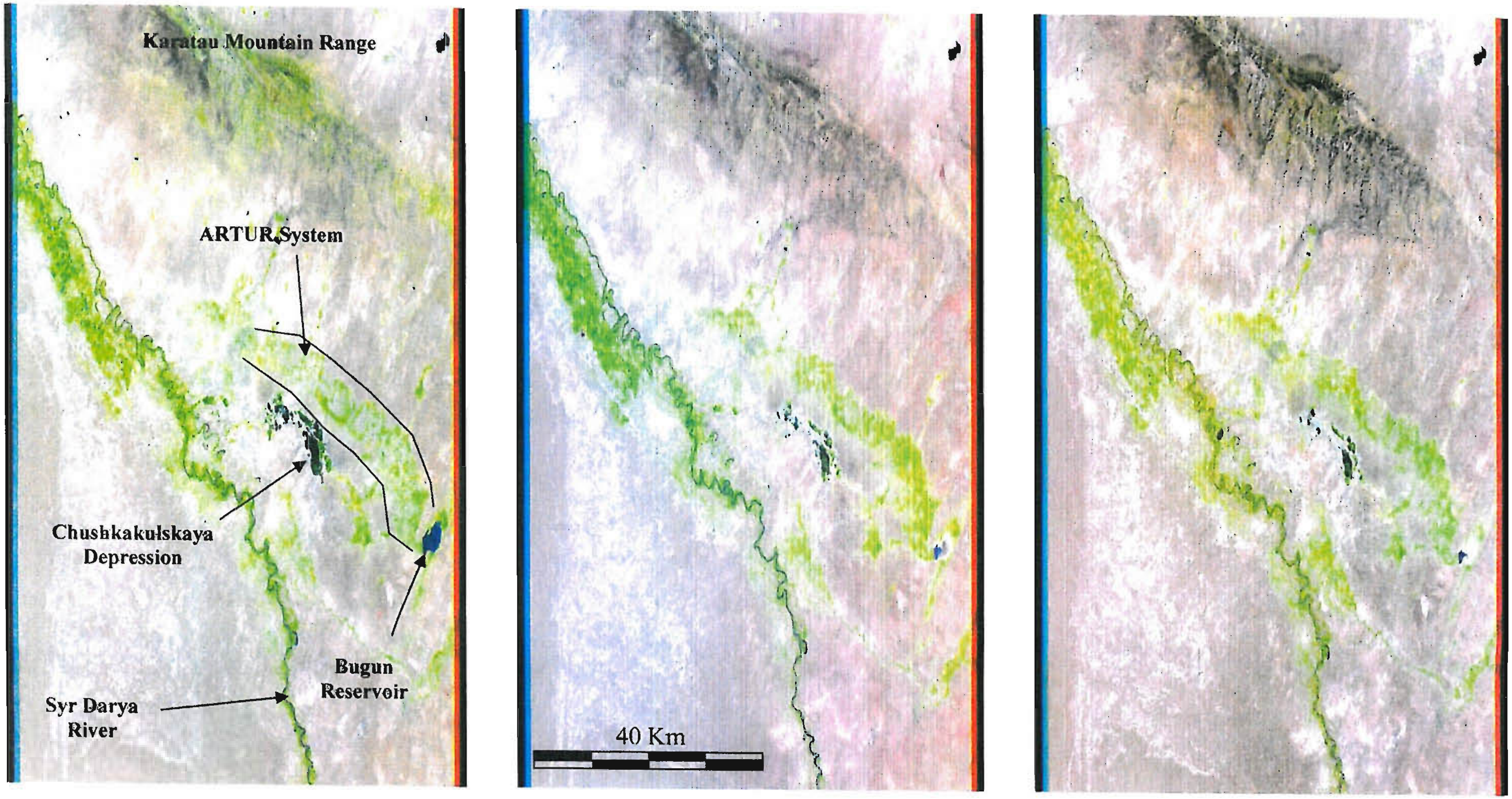
The main irrigation canal is usually opened in mid-April for pre-irrigation and land soaking activities and is closed in mid-August due to lack of water and to encourage cotton to mature in a short season. The silts of the irrigation system lie above gravel and sandy deposits (Vyishpolskiy, 1999a), which have high hydraulic conductivities. Consequently, the opening of the canal results in large amounts of seepage water entering the gravel aquifers. Combined with this, the majority of the annual precipitation occurs in early spring, normally around March. Annual precipitation is low at approximately 200 mm (Vyishpolskiy, 1999a) but coincides with increasing air temperatures and subsequent snowmelt recharge to the rivers. The combination of these effects causes a regional groundwater rise at the beginning of the agricultural season, with groundwater rising up to 1.50 m from the soil surface in April, gradually declining throughout the season to less than 3 to 3.50 m at the end of the season in October.

TACIS (1999) investigations showed that groundwater levels in the South of Kazakhstan rose at the beginning of the agricultural season due to excessive rates of leaching and pre-irrigation, as well as natural precipitation. Inefficient irrigation and poor lateral drainage also contribute to high groundwater levels at the beginning of the agricultural season. Over 90% of drainage systems in the middle reaches of the Syr Darya basin, where the ARTUR system lies, were found to have groundwater higher than between 2.5 to 3 m.

Where groundwater is less than 3 m from the soil surface upward flux has been considered to contribute to crop evapotranspiration in South Kazakhstan (Dukhovny 1981; TACIS, 1995). TACIS (1999) reported average upward flux rates for South Kazakhstan between June to September 1997 of between 1.8 to 2.5 mm/d. These rates are comparable to published results (e.g.: Van Hoorn and Van Alphen, 1994) for silty loam soil types where groundwater falls by 1 to 3 m over the irrigation season. No specific study of upward flux in the ARTUR irrigation system had been conducted, although Kazakh Research Institute of Water Resource Management (1989) suggested that, in silty loam soil types with groundwater between 1 to 3 m deep, upward flux could contribute between 32 to 57% of total crop evapotranspiration (between 2 to 3.6 mm/d where seasonal evapotranspiration was 900 mm).

Farmers in the system have recently experienced lower than average yields for all crops and attribute this to a shortage of water. Vyishpolskiy (2000) considers that the current loss in productivity is due to a recent 5 year dry period, with lower than average precipitation in the spring. The reduced rainfall has coincided with milder winters, reducing snowfall on the Karatau and Tien Shan mountain ranges, and hence the river flow vital to restore irrigation water in the Bugun reservoir. Prior to Independence, collective farms in Kazakhstan were supplied with different varieties of cotton every 3-4 years. This change in variety was combined with crop rotation practices (traditionally cotton 40 to 45% of cultivated area; alfalfa 20 to 25%; grain 15 to 20%; melons/vegetables 0 to 15%; and corn 10%). This lack of crop rotation may also have resulted in lower yields.

No reduction in yield has been attributed to salinity problems, although salinisation has reduced agricultural productivity in other areas of Kazakhstan (Tanton and Heaven, 1999). However, the soils have a high magnesium content in relation to the amount of calcium and hence are liable to deflocullation, sealing the soil surface and greatly reducing the rate at which water infiltrates the soil. Ongoing studies have shown that applications of gypsum improve soil quality, infiltration rate and yield (Oster and Schroer, 1979). Figure 3.2A shows the ARTUR irrigation system on 17/06/00 (Day of Year, DOY - 169) with the Bugun reservoir clearly full of water. The white covering on the surrounding land surface is salt which has been brought to the surface from the shallow groundwater via upward flux. Figure 3.2B shows the same area on 04/08/00 (day 217) with the Bugun reservoir clearly containing less water. The reservoir was closed on 01/08/00 (day 214) due to water shortage. Figure 3.2C is an image from 21/09/00 (day 265), which is near to the end of the agricultural season. The Bugun reservoir is clearly empty and salt covering the land surface has increased since day 169.



A3.1A 17/06/00 A3.1B 04/08/00 A3.1C 21/09/00

Figure 3.2 Satellite Image of Arys Turkestan Irrigation System, Showing Bugun Reservoir and Syr Darya River
(*Source*: USGS Internet Site)

3.3 Experimental Site Location and Data

Three field sites near the former collective farm village called 'Star Ikan' (43°12'N, 68°30'E, 208 m above sea level) were used in this study. Star Ikan village has an official irrigable area of 7,700 ha, yet this area is unofficially closer to 10,000 ha (Vyishpolskiy, 1999b). Figure 3.3 shows the entire ARTUR system and the Star Ikan experimental fields. These fields were chosen as they represented typical irrigated fields in the ARTUR system and were known to have shallow groundwater for a significant part of the year.

3.3.1 Description of Experimental Fields

Figure 3.4 shows the three experimental sites chosen within two separate Fields 'A' and 'B'. Experimental field site A contained six lysimeters. Field B contained experimental sites 'Field B1' and 'Field B2'. Table 3.1 contains agronomic information for each site.

Table 3.1 Experimental Site Agronomic Details (Summer 2000)

	Name of Experimental Site		
Parameter	Field A	Field B1	Field B2
Location	Field A	Field B	Field B
Total Field Size (ha)	26	18	18
Experimental Site Size (ha)	3.5	10	10
No. of Individual Farmer Plots per Field	6	2	2
Crop Grown	Cotton	Cotton	Cotton
Crop Variety	C-47-27	C-47-27	C-47-27
Planting Date/DOY	23 May/144	24 May/145	24 May/145
Planting Density (plants/m^2)	24.44	24.44	24.44
Irrigation Method	Alternate Furrow	Alternate Furrow	Alternate Furrow
Average Field Slope Down Furrow (m/m)	0.003	0.002	0.002
Soil Type*	Silty Clay Loam/Silty Clay	Silty Clay Loam/Silty Clay	Silty Clay Loam/Silty Clay

Notes: *Classified using the standard Soil Survey Staff (1975) classification. The equivalent Soviet Kachinsky soil classification categorised the soil type as a heavy to medium loam (TACIS, 1999).

Field A was divided between six farmers, with individual field blocks ranging from 2.5 to 8 ha. Field B was divided between two farmers, one having 10 ha, the other 8 ha. Short season cotton (*Gossypium hirsutum L.* var.'C-47-27') was grown on all experimental sites.

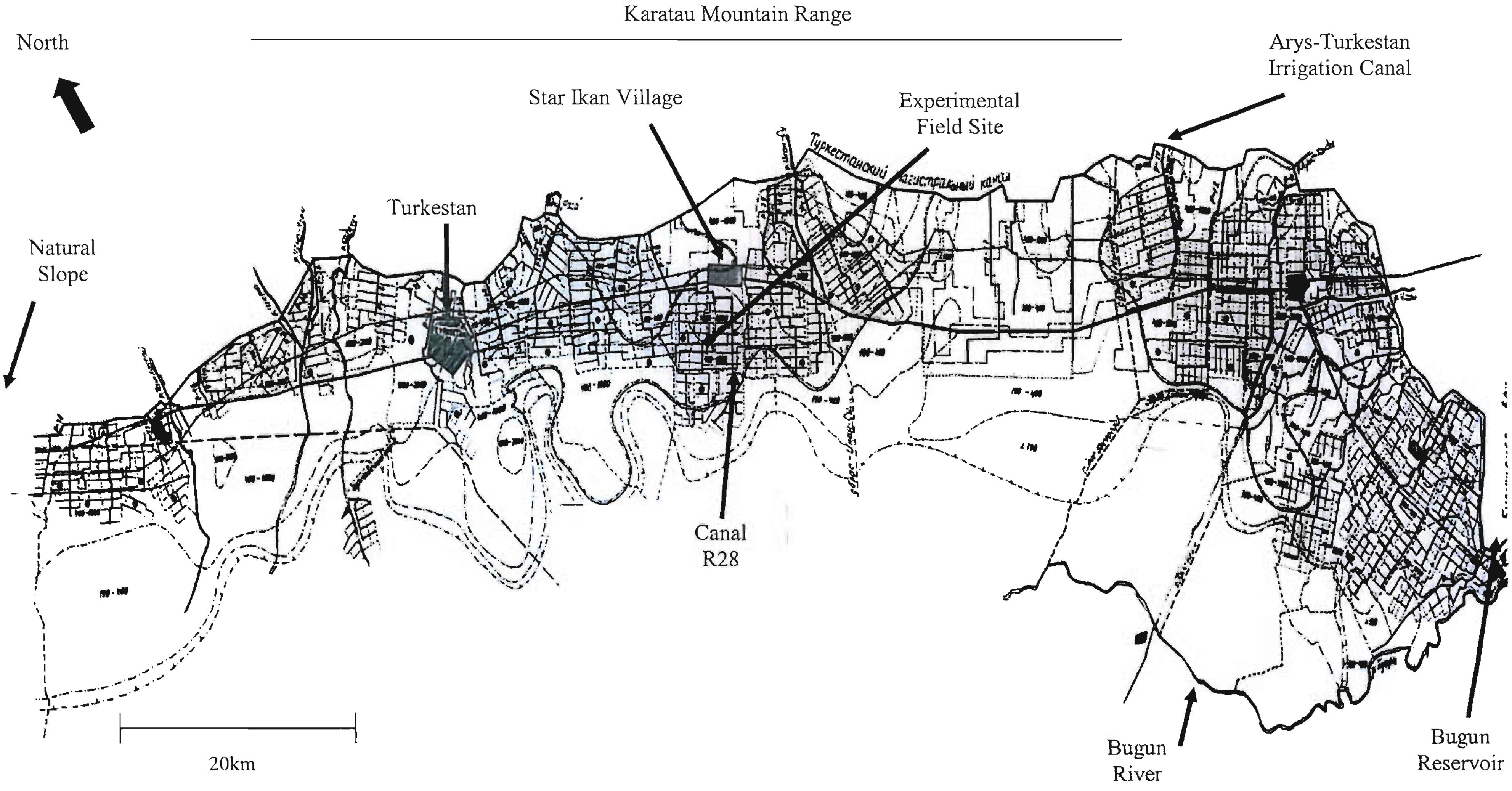


Figure 3.3 The Arys-Turkestan Irrigation System
(*Source*: Vyishpolskiy, 1999a)

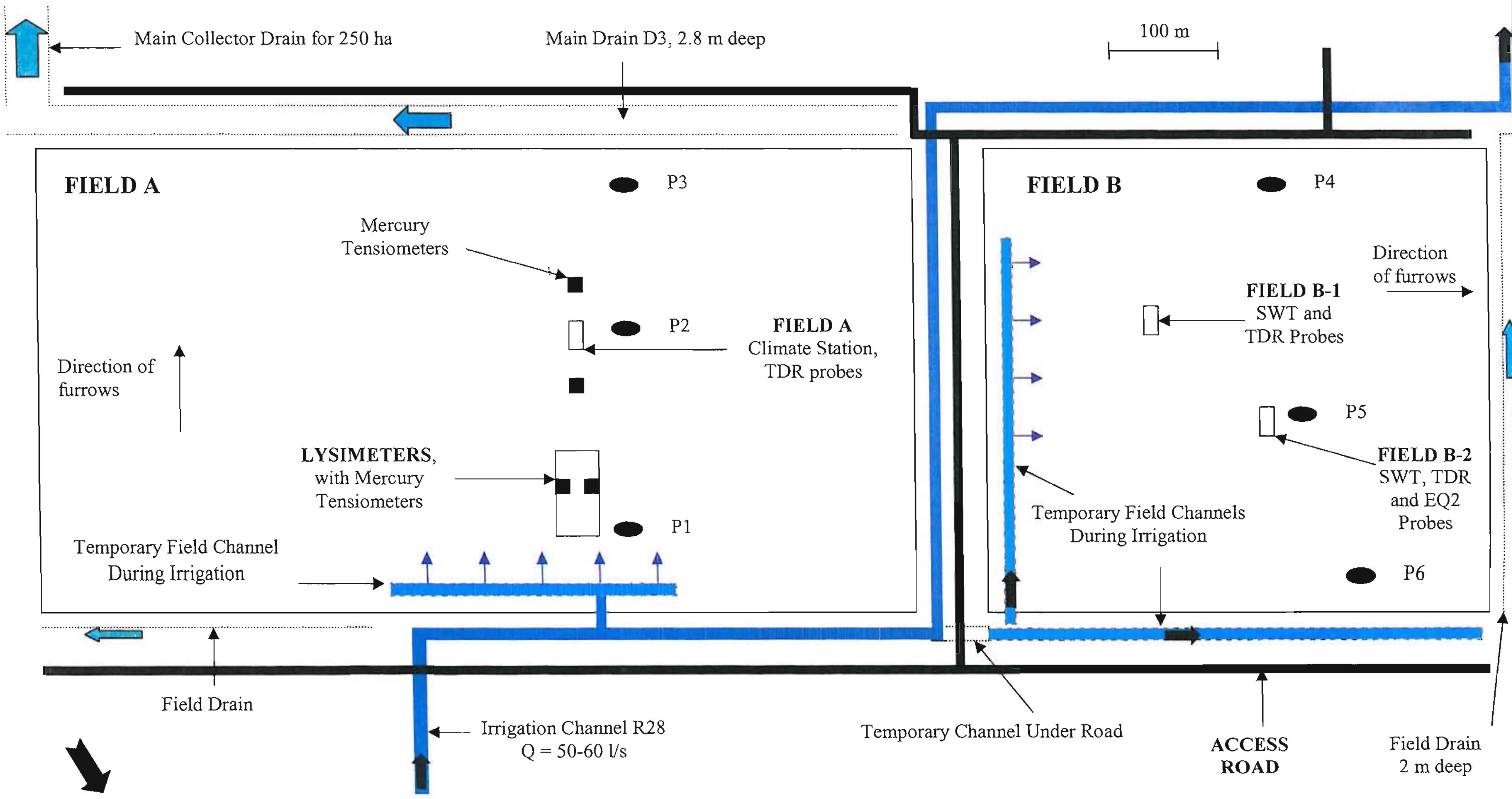


Figure 3.4 Layout of Experimental Field Sites

(*Notes*: TDR = ThetaProbes©, EQ2 = Equitensiometers©, SWT = Water Filled Automatic Tensiometers, P1-P6 = Piezometers. Blue arrows indicate direction of water flow in field)

3.3.2 Soil Characterisation Methodology

Soil samples (10 x 100g) were taken from 0-20 cm to 180-200 cm deep in 20 cm increments in each field. Particle size distribution tests (Braun and Kruijne, 1994) were performed on the samples. Soil dry bulk density was determined using gravimetric sampling (Hall *et al.*, 1977) with 140 samples taken from Field A, and 50 samples taken from both experimental sites Field B1 and Field B2. To determine the water holding capacity of the soil a standard pressure plate apparatus was used, with field capacity assumed at 0.33 bar, and permanent wilting point as 15 bar (Skaggs *et al.*, 1980). Five samples were taken at 0.30, 0.60, 0.90, 1.20, and 1.50 m depths from each field. Appendix A3 contains relevant field data.

Infiltration tests were performed using a single ring infiltrometer sited in a 1 m^2 area of soil. The 1 m^2 area was surrounded by an earth 'bund' designed to contain water around the infiltrometer. The infiltration ring and the soil within the bund were filled with water at the same time. This was a standard procedure within the FSU (Danilchenko, 1978) and replicates a double-ring infiltrometer test. Results are presented in Appendix A3.

Eighteen standard auger holes were fitted with a series of 3.4 m deep piezometers (Oosterbaan and Nijland, 1994) for monitoring groundwater depth and water quality.

3.3.3 Soil Characteristics

Comprehensive moisture characteristic and particle size distribution results indicated that the soil type in both fields were comparable, with similar water holding capacities and dry bulk densities. Appendix A3 contains particle size distribution and dry bulk density data showing that the soil was a silty clay loam/clay loam.

Results indicated that the soil type in both fields was comparable and uniform to 2 m depth, with an average of 14% sand, 26% clay and 59% silt. Summarised results in Table 3.2 suggest a possible compacted soil layer between 20 to 40 cm depth, indicating a potential plough pan and possible rooting problems for crops. If the soil profile is very compact, roots are unable to penetrate the soil and plant growth may be restricted, therefore yield will be reduced. Jordon (1983) suggested that soil bulk densities greater than 1.5 g/cm^3 are indicative of possible root penetration problems.

Table 3.2 Range of Soil Dry Bulk Density Values in Experimental Sites (g/cm^3)

Depth (cm)	Field A	Field B1	Field B2
n	100	50	50
0-20	1.47 to 1.59	-	-
20-40	**1.48 to 1.55**	**1.43 to 1.53**	**1.47 to 1.56**
40-60	1.37 to 1.43	**1.50 to 1.69**	-
60-80	1.34 to 1.54	1.28 to 1.54	1.41 to 1.51
80-100	1.34 to 1.43	1.36 to 1.52	-

Notes: n represents no. of samples. Figures in bold may indicate possible plough pan of compacted soil.

Soil samples taken from the field sites indicated that shallow horizons in the soil profile reached density values of 1.69 g/cm^3. This may have contributed to recent reductions in cotton yields. It was not possible to determine whether compaction was due to agricultural practices or natural soil properties.

Figure 3.5 shows three soil moisture characteristic curves for the experimental fields. The standard error is shown for each curve. The average Total Available Water (TAW) in the soil was estimated to be 203 mm/m, which confirms a silty clay loam/clay loam soil type based on published water holding capacities (e.g.: Kabat and Beekma, 1994) and particle size distribution results.

Appendix A3 contains the soil moisture characteristic curve for the lysimeters. Based on these results the soil moisture characteristic curves were considered to be as accurate as possible, based on field experimental conditions. However, it was recognised at an early stage that the use of a pF curve can be critiscised due to the many uncertainties concerned. To help compensate for this care was taken to extract the 75 undisturbed soil samples required for the development of an accurate curve.

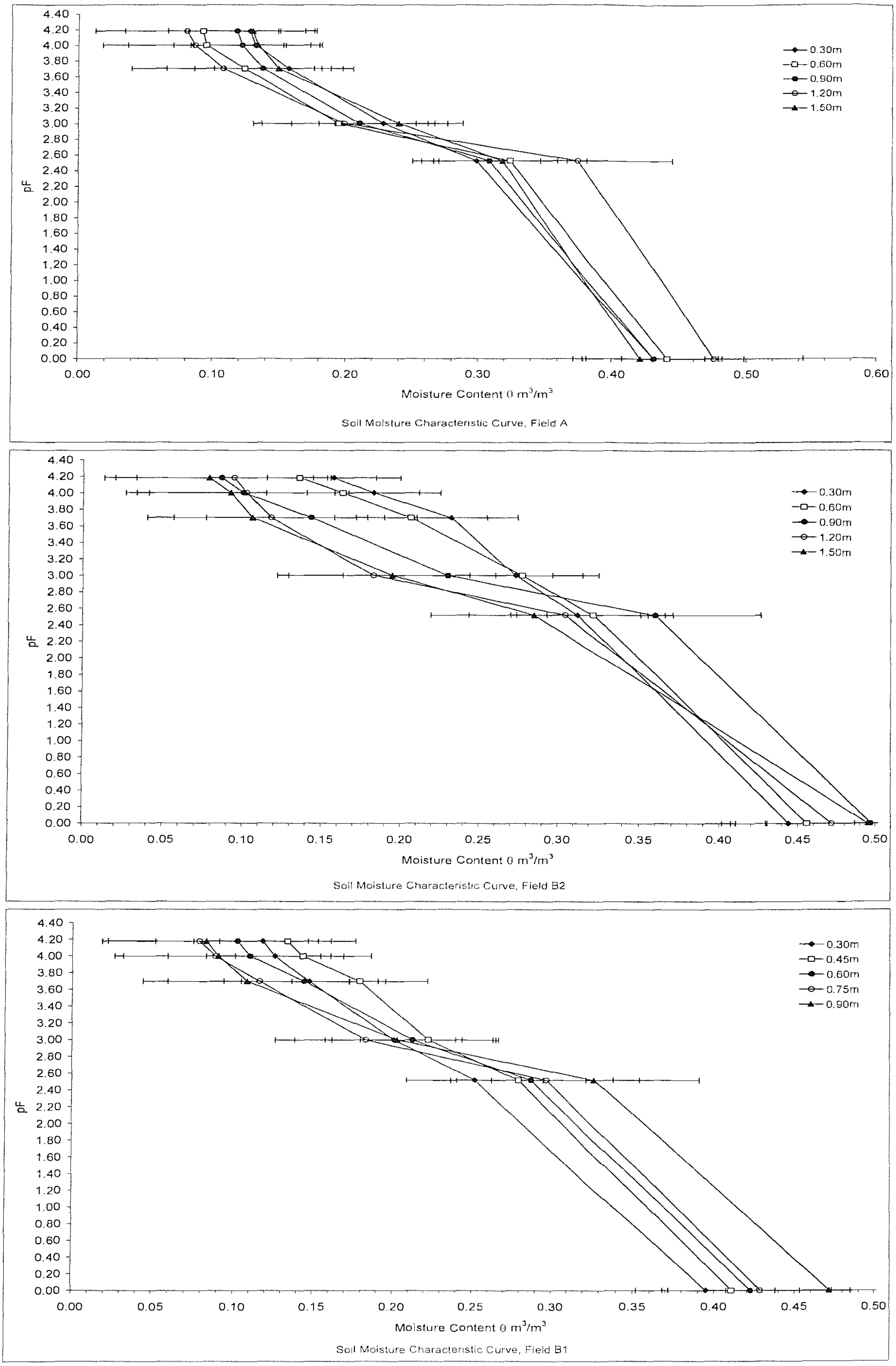


Figure 3.5 Soil Moisture Characteristic Curves for Experimental Fields

The surface 5 m of the soil horizon was stone free. Small stones and gravel were evident in the soil starting at approximately 5 m deep. From 9 to 10 m pebble-gravel sediments are found with sandstone in-fill to approximately 11 to 15 m depth. Lenses of sand of various thickness can be found between 11 to 20 m (Vyishpolskiy, 1999a). In some areas pebble horizons are divided by layers of clay, approximately 3 to 5 m thick. Deeper than 15 to 20 m the soil horizon is mainly gravel and light sandstone, providing a large aquifer 15 m thick, increasing to 35 m in some parts within the irrigation system (Vyishpolskiy, 1999a).

The steady state infiltration rate of the soil in both experimental fields was measured at 10 to 12 mm/hr. Appendix A3 contains example infiltration curves from Field A. Vyishpolskiy (1999a) measured infiltration rates between 11 to 15 mm/hr nearby. The ploughing depth saturated hydraulic conductivity (K) was calculated as 0.28 m/d, assuming infiltration was 12 mm/hr.

Average vertical saturated hydraulic conductivity (K) for Field A was 0.272 m/d (11 mm/hr infiltration rate) and 0.337 m/d (14 mm/hr infiltration rate) for Field B. The average for both fields was 0.305 m/d (12.7 mm/hr infiltration rate). Due to the lack of specific hydraulic conductivity data for the soils found in the ARTUR irrigation system saturated hydraulic conductivity was calculated using results from the auger hole tests performed in the field (Appendix A3).

Smedema and Rycroft (1983) give K values for a well structured clay loam between 0.5 to 2 m/d, but for poorly structured clay loams between 0.002 to 0.2 m/d. Davis (1969) suggests that K is so variable that rates between 0.1 to 1 m/d can be found in loamy soils. Smedema and Rycroft (1983) warn that identical soils based on textural class may display very different values for K due to differences in structure, especially in soils containing clay. Based on the results from the field, and the similarity in measured K compared to calculated K based on measurement of the infiltration rate, the average rate of 0.305 m/d was used throughout the study to represent vertical saturated hydraulic conductivity.

3.4 Calculation of Unsaturated Hydraulic Conductivity

The empirical method developed by Campbell (1974) was used to estimate the unsaturated hydraulic conductivity at corresponding soil moisture suctions as the soil dried. The complete method is:

$$K_{SAT}\left(\frac{\theta}{\theta_{SAT}}\right)^{2b+3} = K$$

[3.1]

where:

K	:	unsaturated hydraulic conductivity (m/d)
K_{SAT}	:	saturated hydraulic conductivity (m/d)
b	:	intercept obtained from a least squares fit of a straight line (pF as a function of θ)
θ	:	moisture content (m^3/m^3)
θ_{SAT}	:	saturated moisture content (m^3/m^3)

The method has been successfully used by a number of researchers (Hagi-Bishow and Bonnell, 2000; Prathapar *et al.*, 1992; Cardon and Letey, 1992; Wagenet and Hutson, 1989), and is relatively easy to use where soil moisture characteristic data are available. The Campbell method has been shown to agree well with direct laboratory measurements of hydraulic conductivity and other calculation methods (e.g.: Bruce, 1972; Bradford and Letey, 1992).

This method to determine unsaturated hydraulic conductivity was used instead of direct field methods, which are time consuming and restrictive due to the initial boundary conditions required (such as the free drainage of an initially saturated profile). This method was also more suitable than the laboratory approach, as facilities were limited and often unavailable on site, and problems can arise in the taking of large, undisturbed soil samples which can affect the soil water flow properties.

Campbell's equation was preferred over other methods such as those adopting pedo-transfer functions because of the simple application of the method using field data. Vereecken *et al.* (1992) stated that development and testing of methods which use pedo-transfer functions is far from complete, and errors in the calculation of soil water flow were due to inaccuracies in the pedo-transfer functions, rather than the soil moisture characteristic curve. As saturated hydraulic conductivity was known from field experimentation the need to use predictive parameters to estimate K was not required. One advantage of Campbell's equation is that it can be used over the entire soil moisture content range. It was anticipated that both very dry and very wet soil would be present in the soil profile simultaneously due to the intense summer climate and high groundwater experienced in the ARTUR irrigation system, and that Campbell's equation would be best suited to these conditions.

The above equation was used together with Darcy's Law to determine upward flux. Identification of the key 'point' where unsaturated hydraulic conductivity declines in field soils is crucial when estimating the rate and role of upward flux to crop survival, especially in areas which suffer from periods of water shortage. This critical 'cut-off' point for moisture flow is perhaps more important than the identification of field capacity.

3.5 Agricultural Practices

During the 1999 agricultural season prior to the experimental year in 2000, Field A was left fallow, and Field B had been planted with maize. Previous years both fields were planted with cotton. During 2000 the experimental fields were ploughed in May to an approximate depth of 25-30 cm. Following this, cultivation was performed and irrigation furrows prepared for pre-irrigation. After pre-irrigation, furrows were prepared in both fields for irrigation and seed drilling purposes. Seed drilling was conducted using a mechanical drill rear-mounted on a tractor. Seeds were planted on the 23 May at a rate of 70 kg ha^{-1} at a depth of 3 cm spaced at 22 plants per metre run. The seed bed/furrow spacing was 0.9 m from centre to centre, giving a plant density of 24.44 per m^2.

Shallow cultivation was performed before each irrigation using a tractor with a rear-mounted harrow. After irrigation, cultivation was performed again to 'mulch' the soil surface and reduce further surface capping. Soil capping was not a problem in Field A, but was severe at the end of Field B close to the minor field drain. This was due to a low calcium to magnesium ratio (<1) experienced in the field and poor field leveling at the end of the furrows. These combined problems caused water to collect and flood. As the water infiltrated into the soil a hard surface 'cap' was left, resulting in poor cotton development. This is illustrated in Plate A3.1 in Appendix A3. In both experimental fields regular cultivation practices could not be maintained due to lack of availability of equipment and fuel during the height of the season, when all farmers growing cotton required cultivation for weed control. The soil cap was the result of magnesium induced instability. INCO-COPERNICUS (2002) found that soil water extracts, irrigation water, and groundwater from the field site had an average pH between 8.1 to 8.4. This indicated the presence of an alkaline soil.

No herbicides or pesticides were applied to the crop. Nitrate fertiliser was applied during cultivation with two applications at a rate of 100 kg ha^{-1} prior to the first and second irrigations for both fields. Pre-Independence this rate ranged between 250 to 400 kg ha^{-1}. Applying fertiliser during cultivation allowed the fertiliser 'granules' to be placed 5 cm to the side of the cotton plants in the seedbed.

3.6 Irrigation System

Figure 3.4 indicates the position of the irrigation and drainage channels within the experimental site area. A main concrete lined tertiary irrigation channel (channel R28) supplied Fields A and B. This channel had a total command area of 250 ha; and a measured seasonal average discharge of between 50 to 60 l/s, and an average seasonal salinity of 0.50 dS/m (INCO-COPERNICUS, 2002). Spiles (concrete pipes) buried in the banks of channel R28 were used to direct water into temporary irrigation channels for distribution of water throughout the fields (Plate A3.2, Appendix A3).

Both Fields A and B were pre-irrigated with a similar volume of water equivalent to 120 mm depth, measured using a broad crested Ivanov weir. The discharge in furrows during irrigation events was monitored using small 90° V-notch weirs. Larger 90° V-notch weirs were also used for monitoring the main drain D3 discharge and run-off from Field A into this drain. After instrumentation of the sites it was possible to monitor irrigation applications using ThetaProbes©, as well as the weirs. The salt content of the irrigation water was measured using a portable electrical conductivity meter.

A member of the village community called the 'Brigadier' controlled each main tertiary irrigation channel in the system. The 'Brigadier' was responsible for the supply and timing of irrigation water to the farmers based on personal experience and water availability. Water was allocated to individual fields relative to their cropped area, based on a 'hydromodule' design value of 0.6 l/s/ha to 1 l/s/ha, depending on water availability from the main irrigation canal approximately 12 km away. The Brigadier told each farmer approximately one week before when water would be available. Water was supplied to large fields such as Field A on a rotational basis (approximately 24 hr water availability per farmer).

During irrigation the Brigadier made no measurement of discharge. The system operated on a supply, rather than demand led basis, with a system wide historical schedule of four irrigation's for maximum cotton production. In reality, this schedule had rarely been achieved in the last 12 years due to corruption and illegal channel offtakes (Vyishpolskiy, 1999a).

3.7 Field Experimentation and Equipment Used

Field experiments were carried out between May to October during 2000. This section describes the objectives of the field experiments and the equipment used in the fields, including calibration procedures.

3.7.1 Climate Monitoring

Figure 3.6 shows the location of the instruments that were used at each experimental site. To calculate crop water requirements climatic variables were measured using an automatic climate station. Data was logged with a time resolution of 60 minutes between DOY 150 and DOY 286 (136 day period). The monitoring system included a portable PC and a 60 channel DL2e Logger using a LAC1 Input card, powered by an external 12V battery. Mukhamedzhanov and Dalton (2001) further describe the equipment used.

Figure 3.6 shows the location of the automatic climate station. The proximity of the experimental fields, similar soil types, groundwater levels and crop ages cancelled the need for further meteorological instrumentation in the other research field. The following climatic parameters were recorded using the climate station:

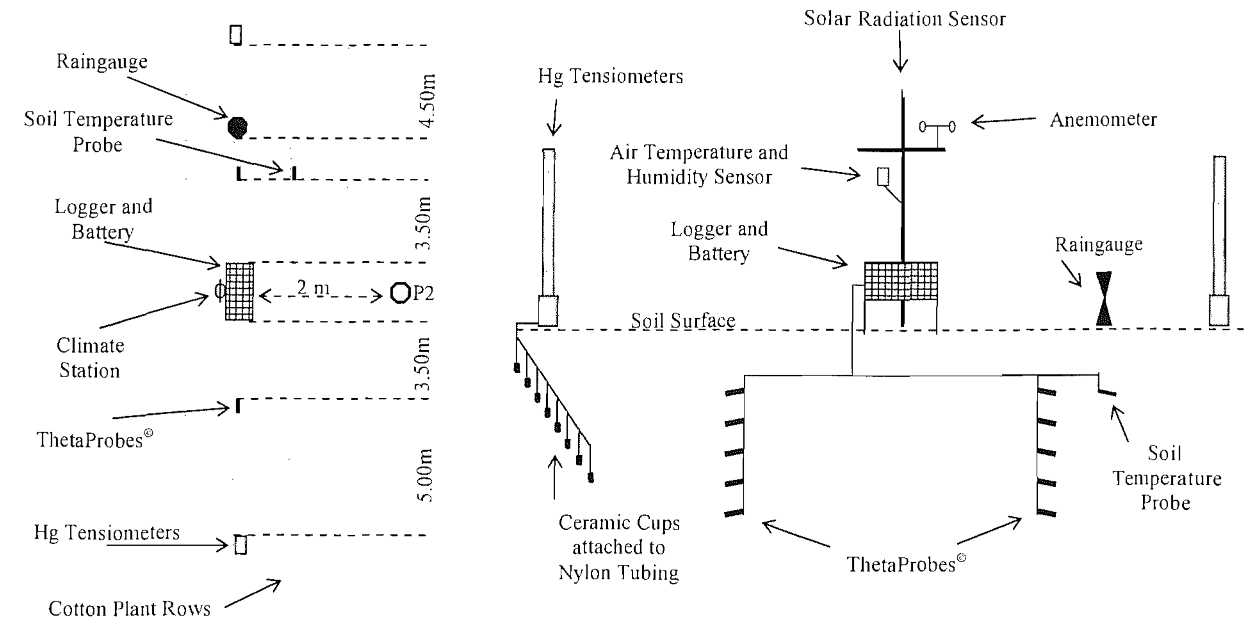


Figure 3.6 A. Field A, Plan and Cross Section View

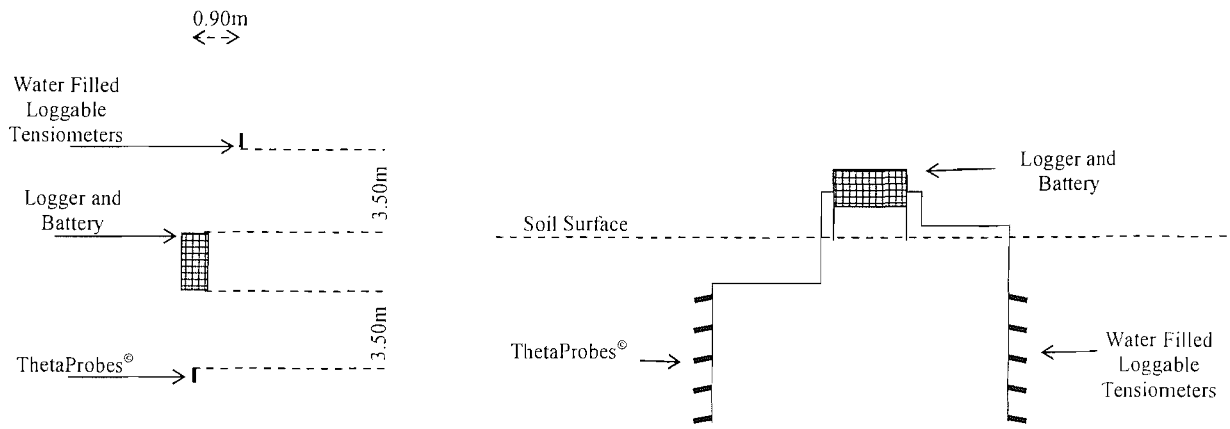


Figure 3.6 B. Field B1, Plan and Cross Section View

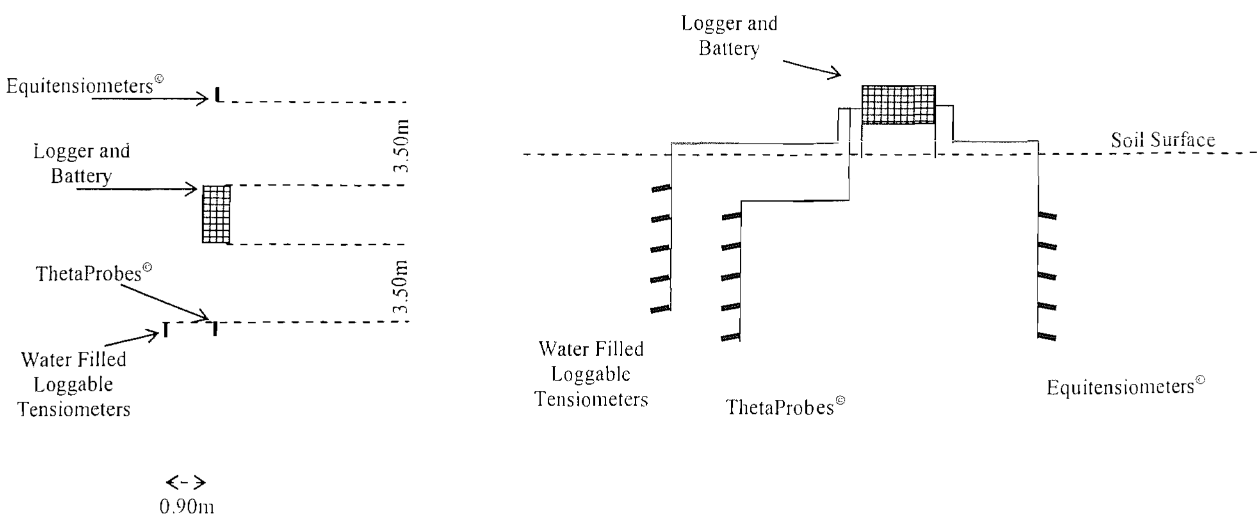


Figure 3.6 C. Field B2, Plan and Cross Section View

Table 3.3 Climatic Variables and Automatic Logging Frequency, Field A

Parameter	Unit	Sensor Type	Sensor Code	Frequency (mins)
air temperature*	^oC	Thermistor	TM1	60
air humidity*	%	Capacitance Sensor	RH1	60
windspeed*	m/s	Anemometer	AN1	60
rainfall	mm	Tipping Bucket	RG1	60
solar radiation	MJ/m^2	Blue Enhanced Silicone Photodiode Sensor	ESR	60
soil temperature^	^oC	Thermistor	TM1	60

Notes: * Measured at 2 m above the soil surface, ^ soil temperature measured between 25-35 cm only. Automatic climate station provided by Delta-T Devices, Cambridge, UK. Appendix A3 contains Plates showing the equipment used.

Rainfall for the entire season was recorded as 12 mm and therefore ignored in this study due to the minimal impact on soil moisture.

3.7.2 Soil Moisture Monitoring

Soil moisture was monitored using four different types of equipment; ThetaProbes©, Equitensiometers©, Water Filled Pressure Transducer Tensiometers and Hg tensiometers. These are all briefly described below. Plates in Appendix A3 show some of the equipment used, including meteorological equipment. Prior to these experiments ThetaProbes© and Equitensiometers© had not been used in Kazakhstan.

ThetaProbes©

The ThetaProbe© determines volumetric moisture content by responding to changes in the dielectric constant. These changes are converted into a DC voltage, proportional to the moisture content of the soil and stored in a data logger, after calibration to moisture content (Delta-T, 1998).

Twenty ThetaProbe© sensors (types ML1 and ML2) were installed at each of the three experimental sites. Wooden boards were placed over the area of soil where soil moisture monitoring equipment was to be inserted to avoid excessive soil compaction. The ThetaProbes© were inserted in the soil ridge per 'row', in line with the direction of the cotton plants, at an angle of 30° from horizontal into the soil, at different incremental depths. Vertical placement of the probes was avoided to decrease the possibility of preferential flow of moisture down the probes auger holes.

Five cm diameter augered holes were manually prepared, and a suspension of soil from the profile and quartz powder was poured into the augered hole immediately prior to ThetaProbe© insertion to ensure a firm connection. The insertion hole was back-filled with Bentonite clay to prevent preferential flow of water directly entering the soil profile at ThetaProbe© depth during irrigation events. Readings from the ThetaProbes© were logged with a time resolution of 60 minutes.

Equitensiometers©

Equitensiometers© (type EQ2) are ThetaProbes© embedded in a uniform ceramic matric material, which forms a hydraulic connection with the soil water. Moisture within the matric material is measured by the ThetaProbe© and converted to a suction measurement using a specific probe calibration. This allows monitoring of soil suction measurements up to 15 bar negative pressure. Five saturated Equitensiometers© were inserted using an identical procedure to the ThetaProbes©. Due to high soil moisture content in much of the soil profile, close to or at saturation at depth, and problems with the nature of the calibration of the Equitensiometers© at high moisture contents (at the manufacturing stage), limited readings were available and data from Equitensiometers© were not used in this study.

Water Filled Pressure Transducer Tensiometers

Permanent installations of tensiometers throughout the entire experimental period were preferred to more portable soil moisture suction measuring equipment. Strebel *et al.* (1973) showed how permanent tensiometers react quicker to changes in soil moisture suction, especially at higher conductivity values close to the groundwater. Direct suction measurement is also more accurate when accounting for the effects of hysteresis. Automatic pressure transducer tensiometers (type SWT3, Delta-T Devices) were used due to their simplicity and the ability to connect them to the DL2e data logger.

A pit was manually excavated approximately 70 cm deep and 50 cm wide in an un-irrigated furrow, close to the cotton seed bed. A 2.5 cm diameter soil auger was used to prepare insertion holes 20 cm deep and 30° from the horizontal. Tensiometers were inserted into the holes and fixed in position using a soil, irrigation water, and quartz powder suspension. Figure 3.6 shows the placement of the equipment in the experimental fields. Once all the tensiometers were in position and connected to the data logger the pit was carefully backfilled and sealed at the soil surface with Bentonite clay to prevent preferential flow of irrigation water. The tensiometers were connected to a DL2e data logger and readings were taken every 60 minutes.

Table 3.4 contains equipment insertion details for the ThetaProbes© and Equitensiometers©. Tables in Appendix A3 contain insertion details and the number of days measurement for water filled pressure transducer tensiometers.

Table 3.4 Equipment Insertion Details

Equipment	Field	No. of Arrays	No. of Days Measurement	Insertion Depths (m)
ThetaProbes©	A	2	137	0.30, 0.60, 0.90, 1.20, 1.50
	B1	1	104*	0.30, 0.45, 0.60, 0.75, 0.90
	B2	1	135	0.30, 0.60, 0.90, 1.20, 1.50
Equitensiometers©	B2	1	136	0.30, 0.60, 0.90, 1.20, 1.50

Notes: * The shorter measuring period for this site was due to equipment supply problems. Shallower root depths later in the season at one site resulted in the ThetaProbes© being inserted at shallower depths, to a maximum of 90 cm.

Hg Tensiometers

Laboratory constructed Hg tensiometers were used to monitor soil moisture suction in one of the experimental fields and in the lysimeters. Their design was based on the original manometer design by Richards (1949).

3.7.3 Groundwater Monitoring

Piezometric head was measured using six piezometers (P1 to P6), indicated on Figure 3.4. The piezometers were 3.4 m long, with a diameter of 84 mm, constructed from steel with a tapered end to ease insertion into the soil. The lower 80 cm of each piezometer was perforated with holes approximately 45 mm in diameter, located every 20 mm around the circumference of the piezometer in 30 mm incremental depths.

The piezometers were inserted into the soil in the cotton seed row by manually augering holes approximately 3 m deep using a hand operated auger. The diameter of the holes was approximately 5 mm wider than the piezometers. A small amount of gravel (2 to 75 mm diameter) was dropped into the bottom of the hole prior to insertion of the piezometers. The surface 0.5 m of soil was excavated to a radius of between 0.2 to 0.3 m around the piezometer. This excavated area was backfilled with a mixture of the excavated soil and bentonite to prevent preferential flow down the piezometer during irrigation events. Depth to groundwater was measured approximately every 2 to 3 days, and was adjusted to soil surface level. The water level in the piezometer was measured using a mechanical sounder, which consisted of a small steel tube closed at the upper end and attached to a calibrated measuring tape. When lowered into the pipe, the sounder made a characteristic sound when hitting the water and the depth to groundwater was read from the measuring tape.

3.7.4 Equipment Calibration

All climatic equipment was supplied calibrated by the manufacturers, and the appropriate calibration factors were entered into the DL2e data logger.

Calibration of ThetaProbes©

Calibration of the ThetaProbes© was performed at the end of the season when they were manually removed from the soil. The calibration calculations and results are presented in Appendix A3. The calibration was found to be approximately 1. This indicated that the ThetaProbes© were reading direct moisture content for the experimental site soil type.

The ThetaProbes© were connected to a DL2e Datalogger with a logging frequency of 60 mins. A generalized linear calibration curve provided by the manufacturer was used to convert voltage readings to m^3/m^3 moisture. The logger calculated the ThetaProbe© reading (m^3/m^3) by interpolating between data points. Soil specific calibration enabled the ThetaProbes© to be accurately calibrated using both linear and polynomial calibrations recommended by the manufacturers, together with gravimetric sampling. Chanzy *et al.* (1998) suggest that linear calibration is generally suitable where more than one probe is used to monitor soil moisture.

3.8 Instrumentation of Experimental Sites

To avoid excessive soil compaction when inserting climatic, soil moisture measuring equipment, and the lysimeters, wooden boards were placed around the area of soil where the equipment was to be inserted.

3.8.1 Climatic Equipment

The climate station was sited 180 m inside Field A. The location is indicated on Figure 3.4. Due to cultivation practices the pole that the climatic equipment was attached to was placed in the centre of a cotton seed bed. Appendix A3 contains detailed information on the insertion and setting up of the equipment at the research sites.

3.8.2 Lysimeter Design

Lysimeters were used so that controlled conditions could be maintained for a growing cotton crop and the rate of capillary rise determined from specific groundwater depths.

Six lysimeters were each designed with a water table water level control system at their base. Internal and external piezometers for groundwater monitoring were inserted, and the soil columns were instrumented with manometer tensiometers at key depths. Lysimeters had a diameter of 0.60 m and depths of 1.5, 2.0, and 2.5 meters, enabling the water table to be maintained at 1, 1.5, and 2 metres respectively. All depths had two replicates. The lysimeters were used for weekly and fortnightly calculations of the crop water balance and evapotranspiration; two lysimeters were able to maintain a groundwater to soil surface depth of 1 m, two at 1.5 m, and two at 2 m. Columns of soil ranged from 0.4 to 0.7 m^3.

Figure 3.6 shows the design of the lysimeters. Each lysimeter was designed as two separate sections; the soil monolith and a drainage section. The soil monolith section was an open ended steel tube. At pre-determined depths holes were made in the tube walls for the later insertion of tensiometers and their connection to Hg manometers. The water table control system consisted of a horizontal infiltration pipe in the base that was connected via an external U-connector to an exterior piezometer for the filling and monitoring of groundwater. A steel perforated drainage plate was placed between both the soil monolith and drainage section. Table 3.5 gives the dimensions of the lysimeters, and the target groundwater depths in each, together with the numbers and depths of Hg tensiometers inserted into each lysimeter.

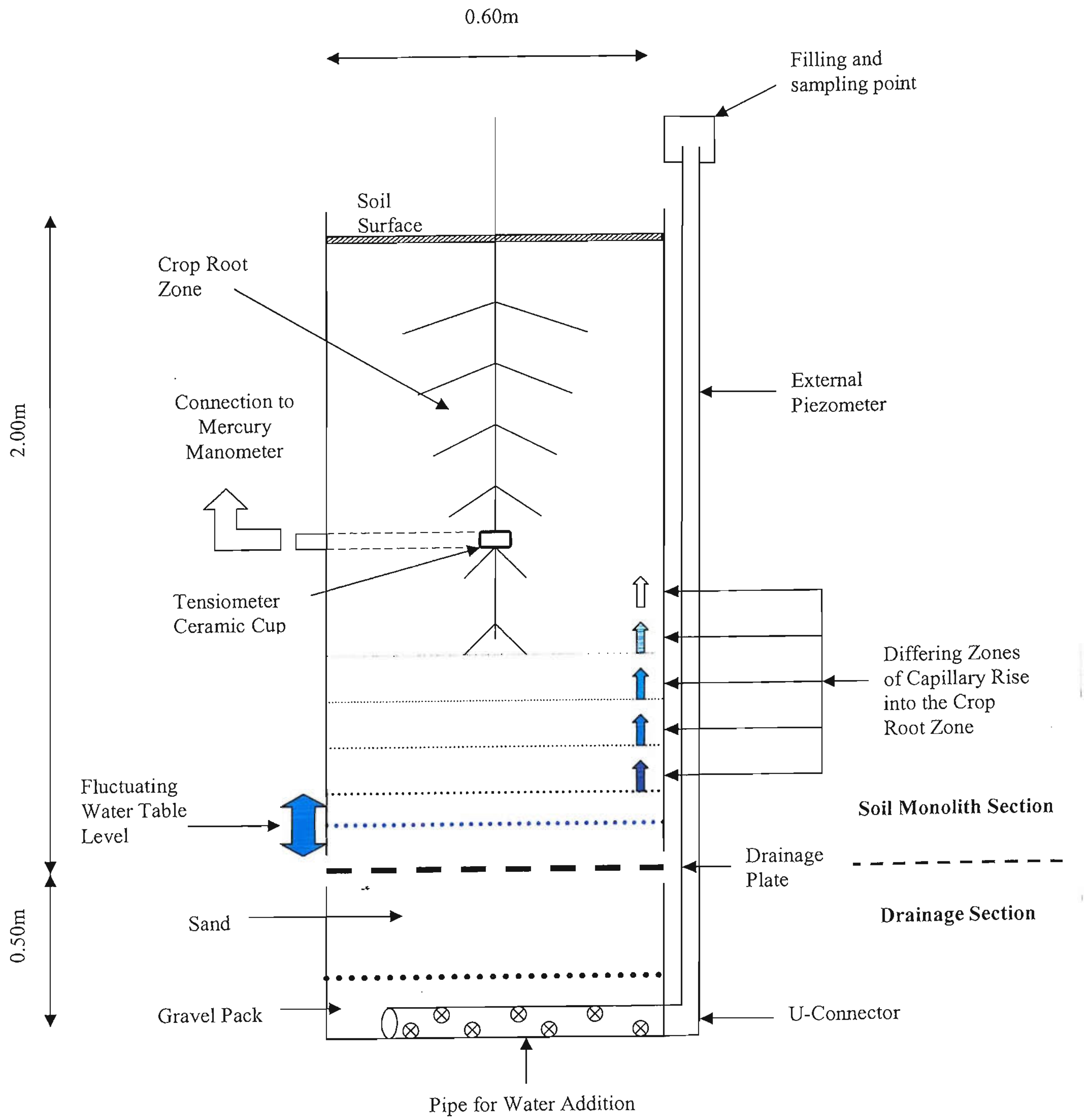


Figure 3.7 Lysimeter Design Showing Movement of Water Upwards from the Water Table
(Groundwater 2 m from Soil Surface)
Note: Internal piezometer not shown

Table 3.5 Lysimeter Design Parameters

Lysimeter	Lysimeter Length	Target Watertable Depth	Surface Area	Volume of Soil	No. of Tensiometers	Depth of Tensiometers
	(m)	(m)	(m^2)	(m^3)	(m)	(m)
A, B	1.50	1.00	0.282	0.423	2	0.40, 0.90
C, D	2.00	1.50	0.282	0.564	3	0.40, 0.90, 1.40
E, F	2.50	2.00	0.282	0.705	4	0.40, 0.90, 1.40, 1.90

3.8.3 Lysimeter Construction and Filling

The lysimeters were constructed from 10 mm thick steel piping or 'tubes'. The tubes had a diameter of 0.6 m and were 1, 1.5 and 2 m long. Instrumentation holes were drilled into the side of the tubes, starting at 40 cm from the top of the lysimeter. These were used for insertion of the tensiometers immediately prior to placing in the field.

A local site with a similar soil type (silty clay loam) was chosen for soil to fill the lysimeters. Appendix A3 contains the lysimeter soil particle size distribution results and shows the established pF curve. The site was pre-irrigated with 120 mm of water and allowed to drain for 48 hours. The lysimeter tubes were then individually sunk into the moist soil using the weight of each lysimeter pipe. This was achieved by manually pushing the lysimeter tubes into the soil, aided by a cutting ring at the lower end. Excess soil was removed from the sides to aid the filling of the cylinder. Plate 3.1 shows a lysimeter being filled with soil.

Whilst filling the lysimeters soil samples were taken to determine the:

- dry bulk density of the soil;
- soil type from a particle size distribution test;
- soil moisture characteristic curve; and,
- volumetric moisture content, measured manually.

Plate 3.1 Filling of Lysimeters with Undisturbed Soil

The undisturbed soil monoliths were rested for five days to allow soil settlement and the drainage section was attached to each lysimeter prior to insertion in the field. The lysimeters were transported to the experimental field and instrumented with tensiometers ready for connection to mercury manometers, immediately prior to being lowered into the ground. The ceramic cup of each tensiometer was inserted into the middle of the soil monolith (Plate 3.2).

Plate 3.2 Lysimeter Prior to Field Insertion
Showing Tensiometer Connections

The lysimeters were lowered into a large mechanically excavated hole approximately 2.80 m deep (Plate 3.3), along the same cotton row as the climate station and soil moisture measuring equipment. The position of the lysimeters is shown on Figure 3.4. Each lysimeter was placed on a gravel 'pack' which allowed the lysimeter to be maintained level (in relation to the soil surface) whilst the surrounding hole was backfilled. The soil surface in the lysimeters was 10 cm lower than the lysimeter rim, although soil inside the lysimeters was maintained at field soil surface level throughout the season.

Plate 3.3 Field Insertion of the Lysimeters

Figure 3.7 shows the layout of the lysimeters in the field. The lysimeters were planted with cotton on the same day as the surrounding fields (23 May/day 144). Row spacing and seed depth and density were identical to that in the surrounding field, as recommended by Tyagi *et al.* (2000). Traffic was minimised near the lysimeters so that crop and soil conditions would be representative of the bulk of the surrounding field. Wooden boards were placed between the lysimeters to minimise soil disturbance. Lysimeters were inspected daily, with the levels of groundwater measured in both the internal and external piezometers using a mechanical sounder. Water was added to the lysimeters via the external piezometer, when the groundwater dropped below the target depths.

Water added to the groundwater was taken from Drain D3 indicated on Figure 3.4, and transported to the site. The conductivity of the water added was measured before it was poured down the piezometer/groundwater filling pipe. The aim of the lysimeter experiment was not to water stress the cotton plants, consequently irrigation was applied according to the notional schedule adopted by the farmers. This schedule differed from observed irrigation applications in the field, which were constrained by the closing of the Bugun reservoir on day 214 (01/08/00).

Phenological development of the cotton was monitored towards the end of the season to assess the different groundwater treatments on plant development, such as the number of flowers, boll development, and final cotton yield.

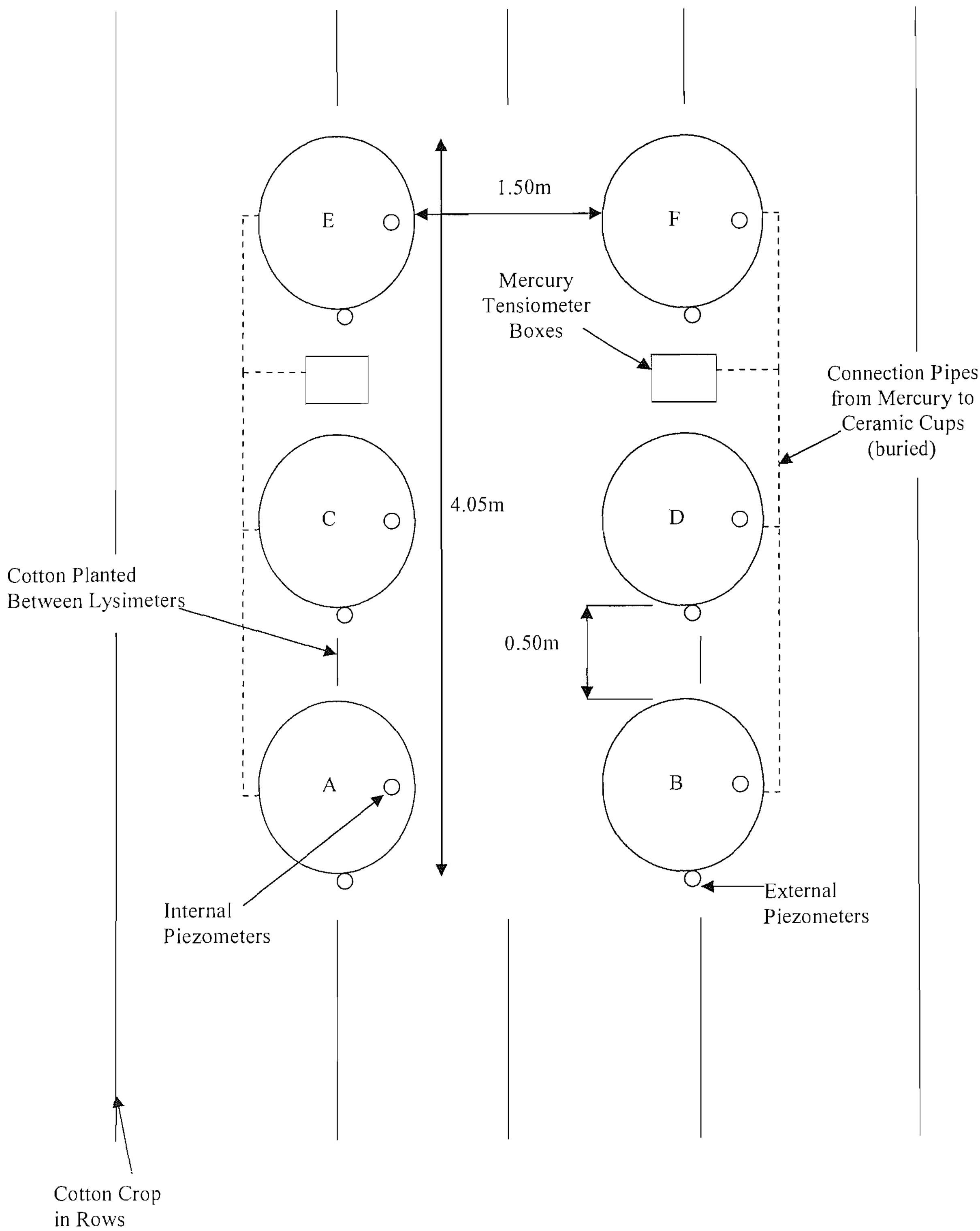


Figure 3.8 Lysimeter Layout in Field A, showing Lysimeters A & B (groundwater at 1 m), C & D (groundwater at 1.50 m), E & F (groundwater at 2 m)

3.9 Field Observations

Data was collected in the field with the aid of automated equipment. Where automatic data collection was not possible field observations were made such as during irrigation events and for groundwater observations.

3.9.1 Irrigation Events During 2000

Alternate furrows were irrigated, with a field command level of between 10 to 15 cm during irrigation events. Pre-planting irrigation was conducted in all experimental fields, following normal irrigation practice. Pre-irrigation discharge and application depth was estimated using a broad crested weir.

Throughout the season the 'Brigadier' decided when water was applied based on personal experience and water availability. No irrigation schedule was followed. Table 3.6 shows irrigation applications calculated from weir discharge measurements. Weir measured irrigation application depth in Table 3.6 was considered accurate ± 20%.

Table 3.6 Summary Irrigation Applications

Parameter	Water applied (range in mm)
Pre-irrigation	120
First Irrigation	80-103
Second Irrigation	80-144

Notes: Range of water applied is a result of different amounts being applied to different furrows.

Differences between weir measured water that infiltrated into the soil indicates that water did not adequately infiltrate into the soil and large amounts of run-off occurred from the end of the irrigation furrows. The excessive run-off during irrigation may have contributed to sustaining the groundwater close to the soil surface during the season. Although weir discharge measurements were closely measured, applying the discharge to the field uniformly may have been problematic due to run-off at the end of the field on some rows, soil infiltration problems due to localised compaction and soil stability problems, and uneven field slopes.

Due to uneven field slopes water distribution in the field was difficult and ineffective. Discharge into individual furrows was not regulated by the farmers and long furrows and limited water contact times meant that irrigation efficiency was low. INCO-COPERNICUS (2002) estimated furrow efficiencies between 20 to 40% using the SIRMOD surface irrigation program.

3.9.2 Crop Growth Monitoring and Evapotranspiration

Rooting depth was manually measured by excavating several randomly selected cotton plants. After June it became difficult to extract plants with entire root systems intact. No further measurements of root depth were made until the end of the season. During extraction of the soil moisture monitoring equipment, maximum root depth was recorded in the excavated pits.

Crop water requirements were estimated using the CROPWAT for Windows irrigation scheduling programme (Clarke and El-Askari, 1996; Clarke *et al.*, 1998). The program provides empirical crop coefficient values based on crop vegetative stages. Crop coefficient curves were adjusted using crop coefficients developed by Hunsaker (1999) to reflect the short season cotton variety grown (C-47-27) and the observed length of the crop stages observed in the field (Appendix A3). South Kazakhstan has a short cotton season of between 140 to 150 days which fits well with short season cotton.

Within the CROPWAT programme the reference crop evapotranspiration (ETo) is estimated using the Penman-Monteith equation (Allen *et al.*, 1994) which is described in Appendix A2.1. As a comparison the Ivanov method was also used to estimate crop water requirements. Within the Former Soviet Union (FSU) the Ivanov method was the recommended equation for calculating reference crop ETo, and was used during the design of the Central Asian irrigation systems (Ivanov, 1954). The simple equation using air temperature and humidity measurements is comparable to the Penman-Monteith method, provided it is calibrated using the correct microclimatic coefficient (Smith, 1997; INCO-COPERNICUS, 2002). Accuracy of the equation is improved when individual irrigation system climatic conditions are considered, which are often based on specific local information. The Ivanov equation requires a microclimatic coefficient which is based on the size of the irrigated area and its geographical location (Danilchenko, 1978). The Ivanov equation is described in Appendix A2.1.

3.10 Empirical Methods Used to Calculate Upward Flux

To assess the validity of the new method proposed in this study other ways to estimate capillary upward flux from shallow groundwater were also used. These included Darcy's Law, a standard soil moisture balance, both in the field and from lysimeter data, and a method developed for use in Central Asia by Soviet scientists.

3.10.1 Darcy's Law

The rate and direction of water movement through saturated soil obeys Darcy's Law (Darcy, 1856), which can be written as:

$$q = -K\frac{\partial H}{\partial z} \qquad [3.2]$$

where:

q	:	discharge per unit area (m/d)
K	:	hydraulic conductivity of the soil (m/d)
H	:	total soil water head (m)
z	:	elevation head (m)

Darcy's Law states that the rate of water movement through a soil is proportional to the gradient of the soil water potential or hydraulic head. In saturated soils the hydraulic conductivity is a constant depending on the type of soil (Rijtema, 1965). However, for unsaturated soils the hydraulic conductivity is dependent on the soil moisture content, which in turn is related to the soil moisture characteristic and the matric potential. Soil moisture suction and moisture content data was available from field experiments. Campbell's (1974) equation to estimate unsaturated hydraulic conductivity was therefore used in conjunction with Darcy's equation to estimate upward flux.

3.10.2 Soil Moisture Balance Method for Estimating Capillary Upward Flux

Water balances are based on the input and output of moisture from the soil expressed as water depth. The water balance equation used with data from the experimental fields was:

$$Uf_P = ETc - \left(\Delta S - \left(I + P - R_o - D_p\right)\right) \qquad [3.3]$$

where:

Uf_P	:	potential upward flux (mm)
ETc	:	crop evapotranspiration (mm)
ΔS	:	change in soil water storage (mm)

I	:	irrigation (mm)
P	:	precipitation (mm)
R_o	:	run-off (mm)
D_p	:	deep percolation losses (mm)

The units of equation 3.4 are always water depth (mm) over the evaluated time frame (e.g.: mm/day). Potential evapotranspiration was estimated using field climatic data and the Penman-Monteith equation.

Precipitation was ignored throughout the study as it was negligible. Due to the small amounts of infiltration into the profile that was measured during and after each irrigation event and low moisture content within the root zone deep percolation was assumed to be zero. Water run-off was evident in all fields, although this was very localised. It was not possible to accurately predict the average run-off from the entire study fields, as it was furrow specific.

A similar water balance approach was used in the lysimeters:

$$ETc = I + GW_L + \Delta S \qquad [3.4]$$

where:

ETc	:	crop evapotranspiration from lysimeters (mm)
ΔS	:	change in soil water storage (mm)
GW_L	:	groundwater added to the lysimeter to maintain constant watertable depth over the season (mm)

Darcy's and Kharchenko's equations were applied to field measured data, together with the soil moisture balance in the field and lysimeters.

The next chapter describes the development of the new method to calculate upward flux using soil moisture data.

4. CALCULATION OF UPWARD FLUX IN SOILS

4.1 Introduction

This chapter describes the development of a new method for calculating upward flux in field soils from the diurnal change in soil suction observed in field tensiometers and other moisture monitoring equipment placed at different depths.

Diurnal changes in the moisture content within and below the root zone occur when the rate of soil moisture depletion caused by evapotranspiration exceeds the rate of soil moisture recharge into the rootzone. Soil moisture recharge into the rootzone is supplied from downward gravitational drainage or upward capillary rise from a shallow water table for part of the day. The result is that soil moisture suction in the rootzone increases during the day, as evapotranspiration exceeds upward capillary rise but as the rate of evapotranspiration falls below the rate of recharge, and ceases at night as stomata close, soil moisture suction decreases.

4.2 Diurnal Changes in Soil Moisture Content

Early in the morning it is dark and the air is cool, relative humidity is at its maximum and plants stomata are closed. As the sun rises incoming radiation rapidly increases, the stomata open and start to lose water in response to increasing levels of radiation. Air temperature also rises and the relative humidity decreases further adding to evaporative demand. As plants extract water from the soil to meet evapotranspiration demand soil moisture suction increases in the rootzone (where water does not constantly enter the soil). When this suction gradient exceeds the gravitational gradient water moves upwards increasing the hydraulic gradient between the rootzone and deeper soil layers which contain more moisture.

Figure 4.1 shows a diagrammatic representation of the diurnal pattern of recharge and extraction of soil moisture observed within a 15 cm layer of the unsaturated zone of a soil profile with an actively growing cotton crop in a loam soil. In this example it is assumed that the average crop evapotranspiration rate was 8 mm/day, crop roots were at 1.2 metres maximum depth and a non saline watertable was present at 2.8 m. No irrigation or rainfall occurred.

Soil moisture recharge represents moisture flowing into the soil layer due to downward gravitational drainage or upward capillary rise from a soil layer below. In this case, as no irrigation or rainfall occurred all the moisture entering the profile came from capillary rise.

Soil moisture extraction represents moisture which has left the soil layer due to either plant root extraction and/or moisture which has moved upwards into the soil layer above.

Figure 4.1 shows the sinusoidal nature of the hourly rate of change in soil moisture content within the crop root zone over a 72 hour period. The hourly rate of change in moisture content can be calculated from either direct measurement of hourly soil moisture content or from the hourly measurement of soil moisture suction converted to moisture content using a soil moisture characteristic curve. The zero axis in Figure 4.1 represents the point of zero moisture change, where moisture moving into the 15 cm soil layer equals moisture moving out, or where no moisture entered or left the soil layer.

Above the zero axis moisture content shows an hourly increase, which eventually slows to zero (at the zero axis) close to dawn (in well watered conditions). When the hourly change in moisture content falls below the zero axis it indicates the hourly reduction in soil moisture content. This is illustrated on Figure 4.1. The process of hourly change in moisture extraction and recharge into each soil layers takes place throughout the soil profile. It shows that within any 24 hour period when evapotranspiration exceeds the rate of hourly moisture recharge in the day time moisture content in the unsaturated zone can rise and fall.

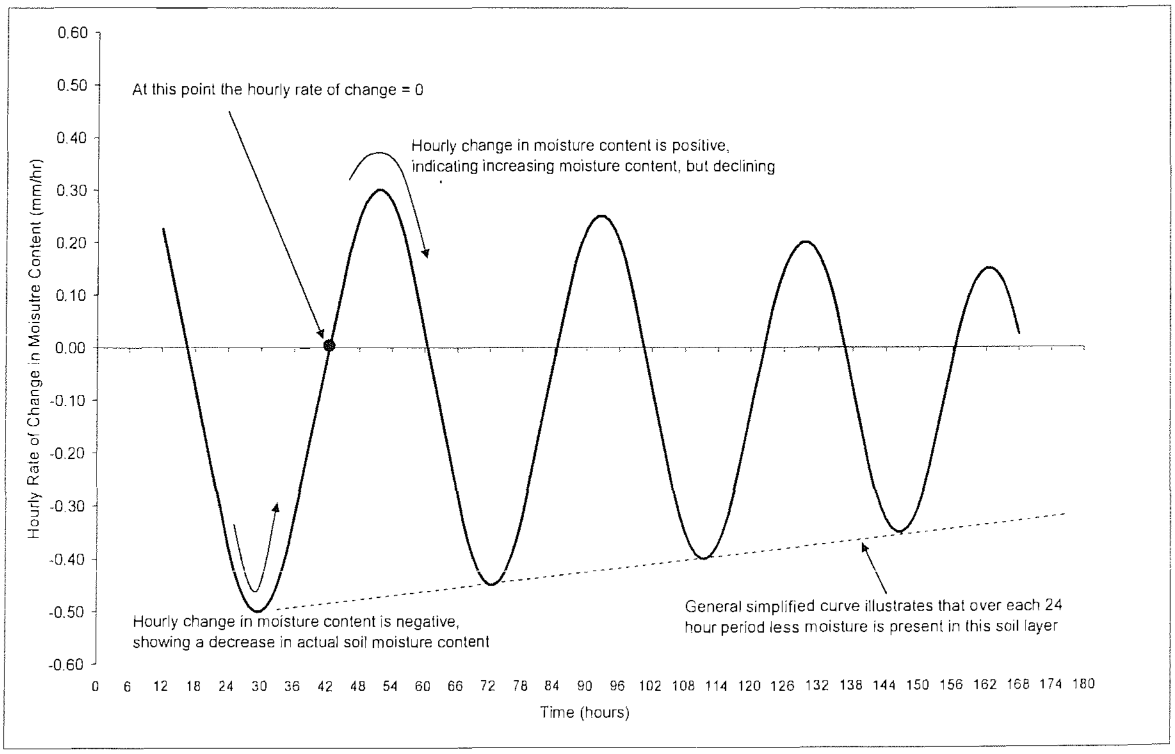


Figure 4.1 Diagram Illustrating the Hourly Rate of Change in Soil Moisture Status for a Single Soil Layer.

A simple curve is shown in Figure 4.1 to illustrate the gradual drying of the soil layer. Soil moisture recharge in the layer over each 24 hour period is expected to be fairly constant as there is only a small daily decline in the total amount of recharge each day due to the falling hydraulic conductivity as the layer dries. The reduction in hydraulic conductivity is a result of the general drying of the soil layer and total soil profile (where irrigation or rainfall does not occur).

Taking the soil profile in its entirety with a crop growing above shallow groundwater, soil moisture extraction from lower soil layers mainly occurs throughout the period of evapotranspiration during daylight hours. However, moisture extraction also continues within the profile after sunset as plants try to correct any daily water deficit and water moves upwards into dryer soil layers due to capillary rise. Throughout daylight the hourly moisture extraction rate increases until about 14:00 hours, approximately the time of the maximum rate evapotranspiration on a daily basis. This observation is similar to those of Haise and Kelley (1950), Remson and Randolph (1958) and Thomson and Threadgill (1987).

As the sun falls in the late afternoon and early evening incoming radiation declines and evapotranspiration decreases. The rate of soil moisture extraction by the plant reduces until the rate of extraction by the plants and moisture moving upwards out of each soil layer equals the rate of soil moisture recharge. At this time there will be no net change in moisture content within this particular soil layer.

Later in the day, however, as the rate of moisture extraction from the soil declines the rate of soil moisture recharge begins to exceed the rate of moisture extraction by the plant and movement to upper layers. Moisture recharge continues to increase where hydraulic conductivity allows until shortly after dawn when evaporative demand and transpiration begins once again. In reality, due to constant moisture extraction from the soil during daylight recharge may only be evident between midnight and dawn, when moisture content stabilises or increases.

Figure 4.4 shows the hourly change in soil moisture content using actual field data. Times are displayed to show that the maximum figure of recharge occurs in the middle of the night, but gets gradually later each day as the soil dries and unsaturated hydraulic conductivity limits the movement of moisture through the soil. To understand the process of moisture recharge and extraction in the soil profile on a temporal basis the soil profile can be considered as a series of 'layers' or 'compartments'. Figure 4.1 represents only one soil layer of 15 cm depth in the profile.

When the entire soil profile is considered it is possible to estimate the total upward flux into the crop rooting zone, where upward flux represents the gross moisture recharge into the profile from shallow groundwater.

The maximum diurnal fluctuation in soil moisture content is typically less than 5% of the total soil moisture in a layer and the diurnal change in soil moisture suction of a given soil layer is typically less than 1% of the total soil moisture suction in the same period. The major driving force for upward soil water flux on any day is therefore the average soil moisture suction rather than the small diurnal fluctuations.

Consequently, the peak hourly rate of soil moisture recharge at night, representing the point when evapotranspiration is at its lowest was taken as the average rate of recharge over the previous 24 hours. This is indicated by point A on Figure 4.2. This period represents the time of day when moisture transfer out of a soil layer to transpiration was lowest. This approach does not give an accurate picture of the water balance in a single layer due to moisture transfer out of the soil layer upwards into higher parts of the profile (extraction) and possible drainage occurring. However, the sum of daily recharge from all soil 'compartments' or layers in the profile will give a reliable estimate of gross recharge for the total soil profile.

Figure 4.2 shows an example 15 cm soil layer containing an hourly change in moisture content diurnal curve. The peak hourly rate of moisture extraction is shown at midnight (point A), and this value is assumed to represent the average rate of recharge over the previous 24 hours. When the daily rate of recharge is taken into account this represents the gross recharge for the soil layer. Net recharge represents moisture coming into the profile which is shown on the diurnal curve, and due to constant moisture extraction from the soil during daylight is generally only evident during the night when moisture content stabilises or increases.

Similarly, net extraction is shown which represents moisture which has left the profile due to root extraction, or moisture which has moved upwards into the soil layer above. This is also shown on the simplified diurnal curve presented.

Gross daily extraction for an individual soil layer represents moisture which has been extracted from the profile or which has moved upwards into the soil layer above (net extraction) plus the gross recharge of moisture from the soil layer below. Where recharge is not present in the soil layer above, and no rainfall or irrigation occurs gross daily extraction represents crop water use. Where recharge does occur into the soil layer above, gross extraction is net extraction plus any change in soil moisture storage for that soil layer only. Subtracting gross daily moisture extraction from the daily moisture recharge provides the net change in soil moisture content within the soil layer studied.

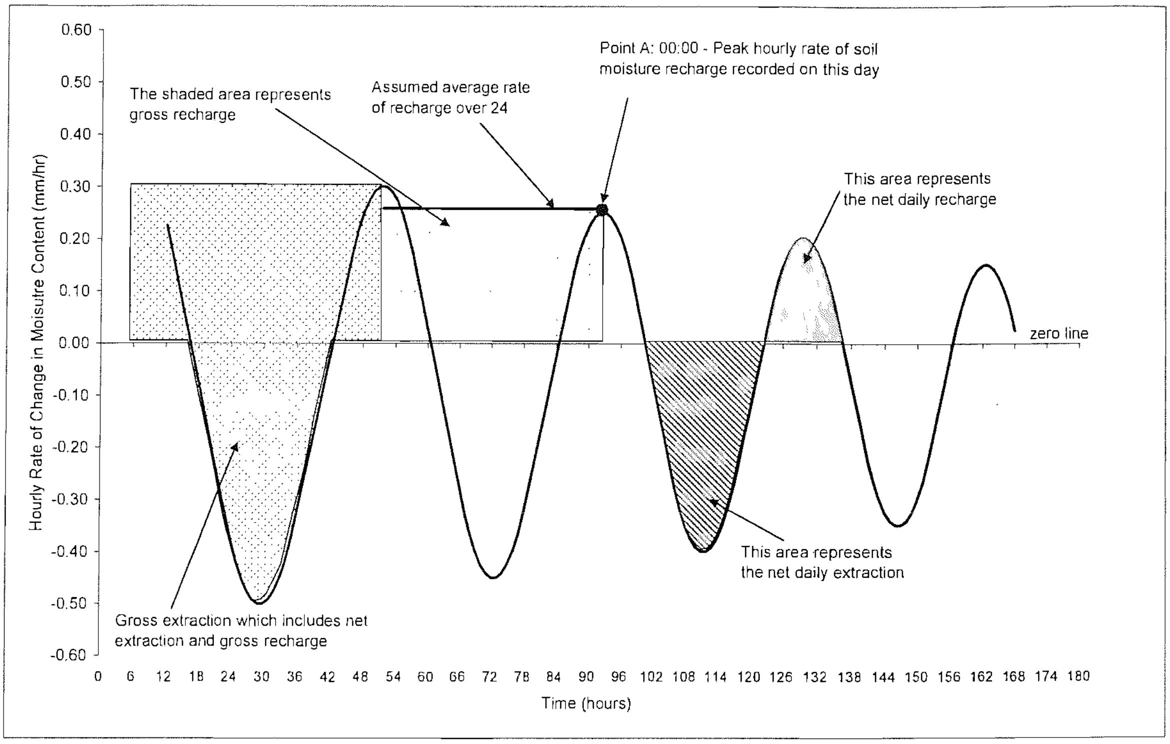


Figure 4.2 Diagram Showing Example Diurnal Curve for a 15 cm Soil Layer

Following this process for each soil layer within the crop root zone allows the calculation of the total gross recharge for each layer and therefore the profile. This represents total upward flux into the crop rooting zone.

It will be shown later that the changes in hourly soil moisture suction are relatively small compared with the change in soil moisture suction that occurs over an entire cropping season.

4.3 Division of Soil Profile into Compartments

Moisture content can increase or decrease in the soil due to irrigation, precipitation, groundwater rise, root extraction, or a combination of these factors, depending on time and the measurement depth. Establishing the soil properties and moisture content at different depths at the same time enables the direction of water movement to be established along with the hydraulic gradient.

Figure 4.3 shows how the soil profile was sub-divided at 15 cm depth intervals called equipment and soil 'compartments'.

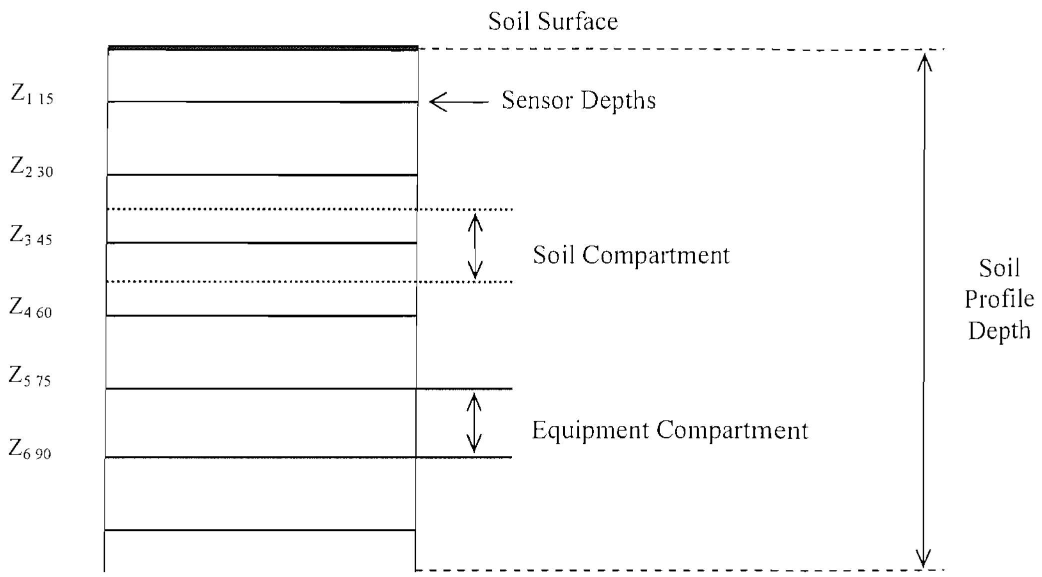


Figure 4.3 Concept of Soil and Equipment 'Compartments' Within the Soil Profile

Romano *et al.* (1998) state that water movement in the unsaturated zone is predominantly vertical. Due to the minimal slope of the experimental site, all moisture flow was assumed to be vertical (Giesel *et al.*, 1970). Dividing the profile into compartments enabled detailed monitoring of soil moisture status and changes in moisture content every 15 cm.

In Figure 4.2, Z_1 represents the depth of the first array of sensors from the soil surface, in this case 15 cm. The distance between each pair of soil moisture sensors and tensiometers established the depth and location of each compartment. The sensor data was then used to give an estimation of the soil moisture in each compartment as illustrated below.

The equipment compartment boundaries were subsequently adjusted by assuming that the reading from each device represented the average value between the midpoint distance from the soil compartments above and below the moisture sensors. This is illustrated in Figure 4.3 and calculated using the following example:

$$Z_{3_{45}} - Z_{2_{30}} = 15cm$$
$$\frac{15}{2} = 7.5cm$$

$$Z_{3_{45}} - 7.5 = 37.5cm$$
$$Z_{3_{45}} + 7.5 = 52.5cm$$

$$m_{(52.5-37.5)} = 15cm$$

[4.1]

where:

$Z_{3\ 45}$	:	depth of measuring device in the third equipment compartment (Z_3) measured vertically down from the soil surface at 45 cm depth (cm)
$Z_{2\ 30}$	:	depth of measuring device in the second equipment compartment (Z_2) measured vertically down from the soil surface at 30 cm depth (cm)
$m_{(52.5\text{-}37.5)}$	:	distance between equipment in profile taken as midpoint between $Z_{2\ 30}$ and $Z_{3\ 45}$ (37.5 cm) and $Z_{3\ 45}$ and $Z_{4\ 60}$ (52.5 cm) (cm)

In the above example the equipment compartment boundaries (between 30 and 45 cm deep) have been adjusted to between 37.5 and 52.5 cm deep. Using the same procedure the boundaries of the shallower compartment above become 22.5 to 37.5 cm. The same calculation was applied throughout the soil profile.

4.4 Use of Diurnal Fluctuations in Soil Moisture to Estimate Upward Flux

Soil moisture suction was recorded hourly at the experimental sites at various depths throughout the soil profile using automatic tensiometers. From this data it was possible to calculate the change in soil moisture suction for each soil layer from:

$$\left(\phi_{Z_1 t_2} - \phi_{Z_1 t_1}\right) = \frac{\partial \phi_{Z_1}}{\partial t}$$

[4.2]

where:

$\phi Z_1 t_2$	:	soil moisture suction recorded at depth Z_1 at time t_2 (cm)
$\phi Z_1 t_1$	:	soil moisture suction recorded at depth Z_1 at time t_1 (cm)
t	:	time (hours)

Soil moisture suction was expressed as negative pressure, as water held in the soil is held at less than atmospheric pressure (Hillel, 1982). To assist in the explanation of the calculation of recharge and extraction from the change in moisture content field measured absolute soil moisture suction values were used.

As in any soil profile containing a growing crop soil moisture suction increases and decreases over time, and hence the solutions to equation 4.2 were both positive and negative when using observed field data. A decrease in soil suction indicated an increase in moisture entering the soil profile at the measurement depth. This increase in moisture at depth, where irrigation and/or precipitation have not occurred, represents upward flux from the soil layer below. This represents net recharge into the soil layer (i.e.:a single soil layer, depth defined).

If the solution to equation 4.2 is positive, soil suction will have increased in the soil layer. This indicates that the soil has dried due to plant extraction and/or evaporation at the soil surface, or rapid drainage has occurred. This represents net extraction out of the soil layer. The exception to this is where a soil layer or 'compartment' rapidly drains after rain and/or irrigation. In this case the lower soil layers can indicate decreased suction due to the influx of moisture from above. Due to the intense summer climate in Kazakhstan this situation was expected to only occur after irrigation events when it was assumed that shallow soil layers would drain from saturation to field capacity, and was ignored for the purpose of this study.

Soil moisture suction (ϕ) data was converted to volumetric moisture content (θ) using site and depth specific pF curves determined from suction plate measurements (figures in Chapter 3). To convert from moisture content (θ) to mm moisture (depth) the following expression was used with hourly data:

$$(10\theta_{Z_1})m_{(n_1-n_2)} = \beta_{Z_1} \qquad [4.3]$$

where:

θ_{Z1} : moisture content at depth Z_1 (m^3/m^3)

$m_{(n1-n2)}$: distance between equipment in soil profile taken as midpoint from one soil 'compartment' to the next, between depths n_1 and n_2 (cm)

β_{Z1} : moisture content at depth Z_1 (mm)

Equation 4.3 is useful in that it allows conversion of moisture content to millimetres of moisture within the volume of soil $m_{(n_1 - n_2)}$. Plotting the change in moisture content as a function of time enables easy identification of net recharge and net extraction into each soil layer. Using the 'zero' line identified in Figure 4.1 as the reference level to determine the direction of moisture change (either 'net recharge' or 'net extraction') the following rule applies:

$$if \frac{\partial \beta_{Z_1}}{\partial t} < 0 = E_{N Z_1}$$
$$if \frac{\partial \beta_{Z_1}}{\partial t} > 0 = R_{N Z_1} \qquad [4.4]$$

where:

E_{NZ_l} : net extraction at depth Z_l (mm/hr)

R_{NZ_l} : net recharge at depth Z_l (mm/hr)

Figure 4.5 shows calculated results using measured field data (mm/hr) to illustrate the process of recharge and extraction over four 24-hour periods between 67.5 and 82.5 cm depth in a cropped profile. The data represents the period between days 210 to 214 (28/07/00 to 01/08/00) or between 67 to 71 days after planting (DAP). Maximum cotton root depth was estimated to be approximately 60 cm and the average ETo was 7.63 mm/day (Penman-Monteith). Root depth was estimated based on measurements taken in the field.

Replacing soil moisture suction with moisture content (converted to millimetres using equation 4.3) and using equation 4.4 allows the identification of periods of both net recharge and net extraction. Soil moisture content (θ) is also displayed on the second y-axis. The change in moisture content (m^3/m^3) follows a sinusoidal curve. Peak values of moisture content occur when net recharge equals the rate of net extraction (the 'zero' point of no change in hourly moisture content), and net extraction takes place throughout the period of evaporative demand.

Table A4.1 in Appendix A4 contains field-measured data showing the calculated hourly change in moisture content in the 15 cm soil layer (between 67.5 and 82.5 cm). Soil suction was measured in the field using tensiometers. From this it was possible to determine the hourly change in moisture content as either recharge or extraction. This data was used to plot Figure 4.5 and to calculate the daily rates of recharge and extraction.

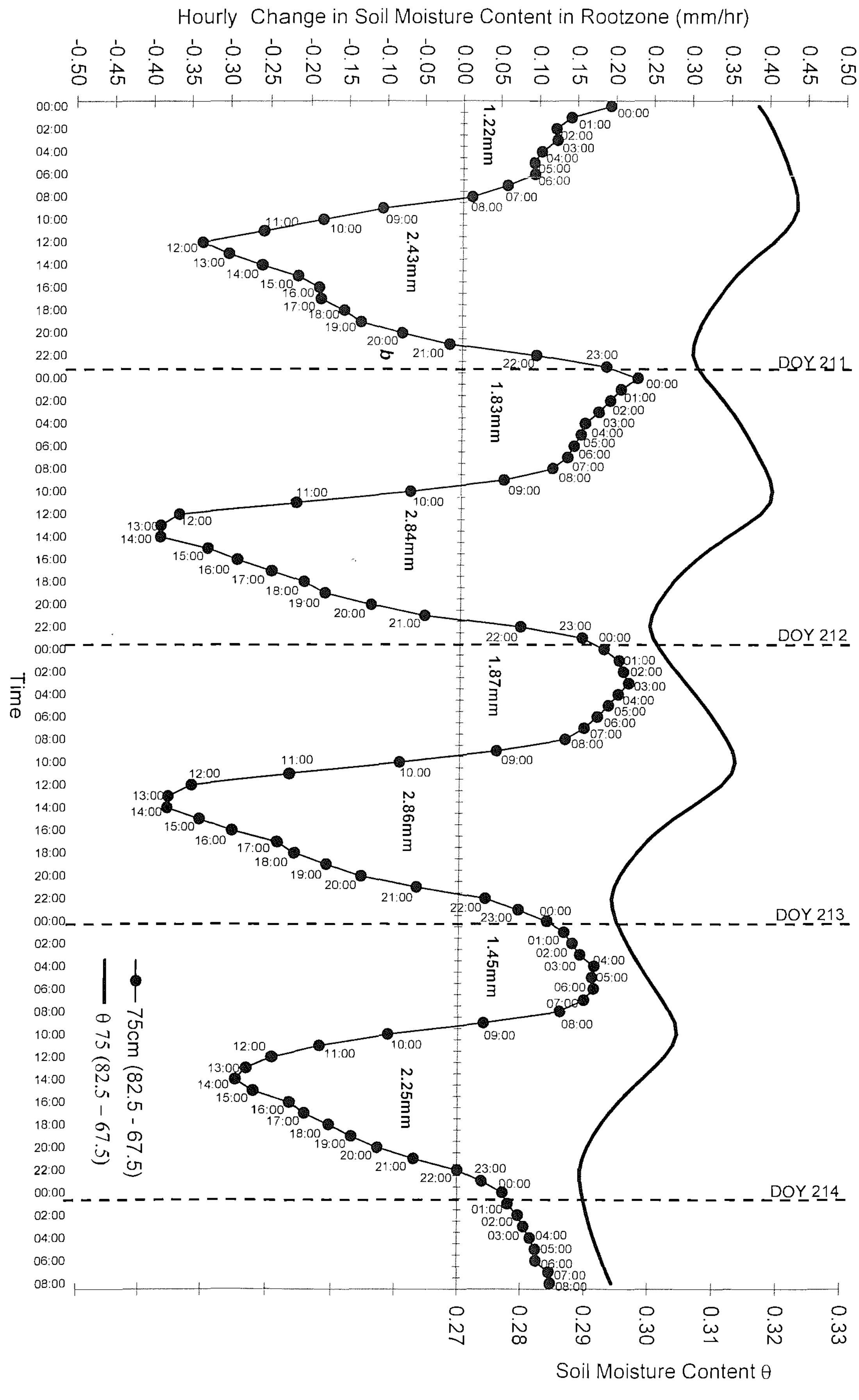


Figure 4.5 Hourly Rate of Change in Moisture Content in Rootzone (67.5 - 82.5 cm depth)

The diurnal pattern of soil moisture loss and uptake in this soil layer during this period had an average extraction rate of 2.6 mm/day and recharge of 1.6 mm/day. Moisture recharge or profile upward flux is a constant process (Van Bavel and Ahmed, 1976), occurring during both periods of evaporative demand and nighttime. As net extraction declines it reaches a point where it equals net recharge which results in the lowest daily soil moisture content due to the cumulative extraction of moisture during the day. As extraction continues to decline, recharge becomes the dominant process in the soil, replenishing much of the moisture withdrawn during the daytime.

The maximum observed hourly rate of soil moisture content change for a given soil profile is provided by the balance:

$$(Dp + UF_{\Uparrow}) - (T + D + UF^{\Uparrow}) \tag{4.5}$$

where:

Dp	:	down percolation gains (mm/hr)
$UF_{\Uparrow}$	:	net recharge into the rootzone measured (mm/hr)
$UF^{\Uparrow}$	:	net extraction out of the rootzone measured (mm/hr)
T	:	transpiration (mm/hr)
D	:	drainage losses (mm/hr)

In a soil profile under an actively transpiring well-developed crop, above the zero flux plane and in the absence of irrigation, drainage losses and percolation gains are zero, which means that the hourly rate of soil moisture content change is given by:

$$UF_{\Uparrow} - (T + UF^{\Uparrow}) \tag{4.6}$$

Since at night time transpiration losses are assumed negligible and after making up the days accumulated crop water deficit, net change in soil moisture content of a given layer can be given by:

$$UF_{\Uparrow} - UF^{\Uparrow} \tag{4.7}$$

Examination of Figure 4.5 shows that peak net recharge rates occur at different times of the night over the time period presented. In the first full 24 hour period (day 211) the maximum rate of recharge was achieved early in the evening when the cotton crop had taken up sufficient water to meet its daily accumulated water deficit. The rate of recharge then declined slowly until dawn when transpiration losses become dominant. This slow decline in the hourly net rate of recharge is thought to be the result in a change in the balance between the relative rates of capillary inflow from lower soil layers and upward capillary flow to the drier soil layers as the water becomes redistributed throughout the profile. These relative net rates are affected by changes in unsaturated hydraulic conductivity of the different soil layers. Similar observations in evapotranspiration water demand were made by Nachabe *et al.* (2005) who assumed that evapotranspiration would be effectively zero overnight for pine prairie and wooded wetlands in Florida. This was based on a diurnally fluctuating watertable in a humid environment. In irrigation systems, the constant influx of water into groundwater from irrigation and drainage water and seepage from canals will reduce fluctuations in the groundwater level, especially where upward flux is constantly recharging back up into the soil layer, ultimately making irrigation more efficient.

In the last 24 hour period presented in Figure 4.5 (day 213) the soil was drier and the maximum rate of net recharge occurs just before dawn. This indicated that either plants extracted water from the profile until dawn to make up their internal water deficit and/or water movement was restricted due to the declining hydraulic conductivity. This would cause a slower rate of upward movement.

Net rate of daily recharge rate for a soil layer was calculated from:

$$\frac{\sum_{R_N{}^m}^{R_N{}^d}}{n} 24 = R_{GZ} \qquad [4.8]$$

where:

$R_N{}^d$	:	net recharge at dawn (mm/hr)
$R_N{}^m$	:	peak recharge at night (mm/hr)
n	:	number of hours between peak value and dawn
R_{GZ}	:	gross recharge from the lower layer (mm/day)
24	:	number of hours in day

This approach is valid at the beginning of the season when moisture content is stable and recharge and extraction are minimal. Moisture extraction from all soil layers, combined with the upward moisture flux will represent the water used by the crop per day, and was calculated as:

$$R_G + E_N = E_{GZ} = ETc_Z$$

[4.9]

where:

E_N	:	net extraction per layer summed (mm/day)
R_G	:	gross recharge for profile (mm/day)
E_{GZ}	:	total daily rate of gross extraction for profile (mm/day)
ETc_Z	:	total daily rate of evapotranspiration (mm/day)

Absolute values for net extraction are required in the calculation. Equation 4.9 uses net extraction, representing the soil drying due to plant extraction and evaporation, and recharge representing upward flux into the profile from groundwater and upward flux into higher soil layers.

4.4.1 Calculation of Soil Moisture

Both 'inputs' of water as change in recharge and 'outputs' of water as change in extraction to and from the soil profile allow calculation of the change in soil moisture change using the following equation:

$$E_N - R_N = \Delta S$$

[4.10]

where:

E_N	:	net extraction (mm/day)
R_N	:	net recharge (mm/day)
ΔS	:	change in soil water storage (mm/day)

The change in soil moisture is the difference between moisture entering and leaving the soil profile. When the root zone depth is known equation 4.10 can be applied to determine daily moisture plant use for irrigation scheduling purposes. Where no irrigation and/or precipitation occurs soil profile moisture extraction represents the balance between capillary upward flux (recharge) and the change in soil moisture.

4.5 Applying the New Diurnal Method to Field Measured Data

To further illustrate the application of the new diurnal calculation process Table 4.1 contains summary results from the soil layer between 62.5 to 82.5 cm deep in Field B1. Actual field data are used to demonstrate the diurnal method process for a short time period only. The remainder of the data are presented in the next chapter.

From hourly soil moisture suction data recorded with in-situ tensiometers at 75 cm the daily values for upward flux and evapotranspiration were calculated using the new diurnal method described above.

The results gave a mean average net rate of recharge for this soil later of 1.59 mm/day for days 210 to 213. This represents the net moisture moving upwards from deeper within the soil profile into this soil layer (see Figure 4.1). The average daily rate of gross recharge was 4.25 mm/day calculated using equation 4.8. This represents the average hourly rate of gross recharge between night and dawn over the period measured. The period presented was for the highest rates of gross recharge measured. This was due to the pattern of irrigation and the fact that it was midsummer and the crop had a fully developed canopy. Root depth was estimated as approximately 60 cm deep during this period. Table 4.1 shows that both extraction and recharge in the soil layer were relatively constant over the four-day period.

Table 4.2 contains results for the entire soil profile between days 210 to 213 (end of July 2000). Rates of extraction and recharge were calculated per instrumented depth and then totaled to give results for the total moisture movement in the soil profile. The average rate of gross recharge for the profile was calculated as 4.96 mm/day. Although the period presented experienced the highest daily changes in moisture content this high average rate of recharge was not sustainable. Following the four days between days 210 to 213 recharge rapidly declined due to decreasing soil hydraulic conductivity.

Table 4.1 Calculation of Upward Flux - 75 cm Soil Layer Only (mm/day)

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	ϕ	$\delta\phi/\delta t$	β	E_N	R_N	R_N^d/R_N^m	R_G	ETc	ΔS
Day	cm	cm/hr	mm/hr	mm/d	mm/d	mm/hr	mm/d	mm/d	mm
210	480.80	-9.10	-0.11	2.43	1.22	0.14	3.27	5.70	1.21
211	-	-	-	2.84	1.83	0.19	4.52	7.36	1.01
212	-	-	-	2.86	1.87	0.21	4.98	7.84	0.99
213	-	-	-	2.25	1.45	0.18	4.25	6.50	0.80
Av	-	-	-	2.60	1.59	0.18	4.25	6.85	1.00

(1)	Day of Year
(2)	Hourly soil moisture suction recorded in cm pressure at 75 cm depth [as an example, at 18:00 hours soil moisture suction recorded was 480.80 cm. At 19:00 suction recorded was 489.90 cm].
(3)	Following the application of equation 4.2 to hourly data the average hourly change in soil suction was determined [480.80 - 489.90].
(4)	The hourly change in soil suction (cm) was converted to mm moisture using equation 4.3 [using depth specific pF curves].
(5)	Equation 4.4 allows identification of net daily water extraction. Column 5 contains actual field measurements.
(6)	Column 6 contains field measurements of net daily soil moisture recharge using equation 4.4 to identify recharge or extraction.
(7)	Results in column 7 represent the average hourly rate of net recharge between R_N^d [peak recharge at night] and R_N^m (net recharge at dawn). This is used to calculate gross recharge in equation 4.8.
(8)	Calculated daily **gross recharge** into the soil layer (mm/d) using equation 4.8.
(9)	Calculated daily **evapotranspiration** using equation 4.9.
(10)	Calculated the daily **change in soil moisture** using equation 4.10.

Average daily crop evapotranspiration over the entire same period was calculated as 9.93 mm/day using the new diurnal method (Table 4.2). For comparison, evapotranspiration (ETc) was 7.95 mm/day over the same period. This indicated a crop coefficient of between 1.2 to 1.3. This period coincided with the maximum growth stage for cotton (66 DAP onwards) when crop coefficients should be at their maximum (Jordon, 1983).

The next chapter contains the results of the new diurnal method for estimating upward flux and compares these values with previous methods of estimating upward flux.

Table 4.2 Calculation of Upward Flux for Entire Profile (mm/day)

	Day					
Parameter	210	211	212	213	Sum (days 210-213)	Average
30 cm					mm	mm/day
E_N	1.10	0.22	1.20	0.15	2.69	0.67
R_N	0.09	0.00	0.00	0.00	0.10	0.03
R_G	0.20	0.00	0.00	0.00	0.20	0.05
ETC	1.30	0.23	1.21	0.16	2.89	0.72
ΔS	1.00	0.23	1.21	0.16	2.59	0.65
45 cm						
E_N	1.16	0.14	1.98	0.16	3.45	0.86
R_N	1.29	0.02	0.05	0.00	1.37	0.34
R_G	0.04	0.00	0.13	0.00	0.17	0.04
ETC	1.20	0.15	2.11	0.17	3.62	0.90
ΔS	-0.13	0.12	1.93	0.16	2.08	0.52
60 cm						
E_N	0.79	0.49	0.29	0.00	1.58	0.40
R_N	0.00	0.00	0.00	0.01	0.50	0.12
R_G	0.77	0.02	0.07	0.34	1.20	0.30
ETC	1.56	0.52	0.37	0.34	2.78	0.70
ΔS	0.69	0.43	0.27	-0.30	1.08	0.27
75 cm						
E_N	2.43	2.84	2.86	2.25	10.38	2.60
R_N	1.22	1.83	1.87	1.45	6.37	1.59
R_G	3.27	4.52	4.98	4.25	17.02	4.25
ETC	5.70	7.36	7.84	6.50	27.40	6.85
ΔS	1.21	1.01	0.99	0.80	4.01	1.00
90 cm						
E_N	0.31	0.39	0.49	0.57	1.77	0.44
R_N	0.03	0.12	0.15	0.18	0.49	0.12
R_G	0.07	0.19	0.47	0.54	1.27	0.32
ETC	0.38	0.59	0.96	1.11	3.04	0.76
ΔS	0.28	0.28	0.33	0.38	1.28	0.32
Total Profile						
$\sum R_G$	**4.35**	**4.74**	**5.64**	**5.12**	**19.85**	**4.96**
$\sum ETc$	**10.15**	**8.84**	**12.48**	**8.27**	**39.73**	**9.93**
$\sum \Delta S$	3.06	2.06	4.73	1.20	11.04	2.76
ETc (Penman)	**9.63**	**8.29**	**6.80**	**7.08**	**31.79**	**7.95**

5. UPWARD FLUX MEASURED BY THE DIURNAL METHOD

5.1 Introduction

This chapter uses the new method for estimating upward flux described in Chapter Four and the tensiometer data gathered in Star Ikan to estimate the rate of upward flux into the root zone of a cotton crop. It compares these estimates of upward flux with estimates made using existing methods of estimating upward flux and looks at the role the method has to play in predicting total evapotranspiration from a field crop using field instrumentation.

5.2 Groundwater Contribution to Evapotranspiration Measured From Diurnal Changes in Soil Moisture Suction

Figure 5.1 shows the daily rate of gross moisture recharge into the root zone from upward flux per instrumented depth over a 40-day period in Field B1. Initially, upward flux was low at all depths, with the exception of 45 cm which showed some upward movement of water up to day 198. Very little upward moisture movement was evident at 30 cm depth. The fact that little moisture movement was evident up to around day 196 suggests that the soil contained adequate moisture for the young plants.

Below the figure showing upward flux is a figure which shows measured groundwater depth in Field B1 and estimated cotton root depth. Root depth was measured up to the point when it was not possible to extract the entire root system (form an average of seven plants). Final root depths were measured in the field at the end of the season and a linear relationship was developed based on the measurements available.

After irrigation between days 196 and 198 upward moisture movement is evident from all depths deeper than 60 cm. This may have just been the result of growing crop demand but may have also been influenced by the increased hydraulic conductivity resulting from the irrigation. As the plants grew and expanded their rooting systems deeper into the soil they accessed moisture deeper within the profile. Peak rates of upward flux occurred within the profile over a four-day period between 60 and 90 cm deep. The rapid reduction in upward flux between 60 and 90 cm deep was more than likely due to reduction in both the hydraulic conductivity in higher layers due to increased suction and decreased conductivity in lower soil layers as the deeper crop roots extracted water.

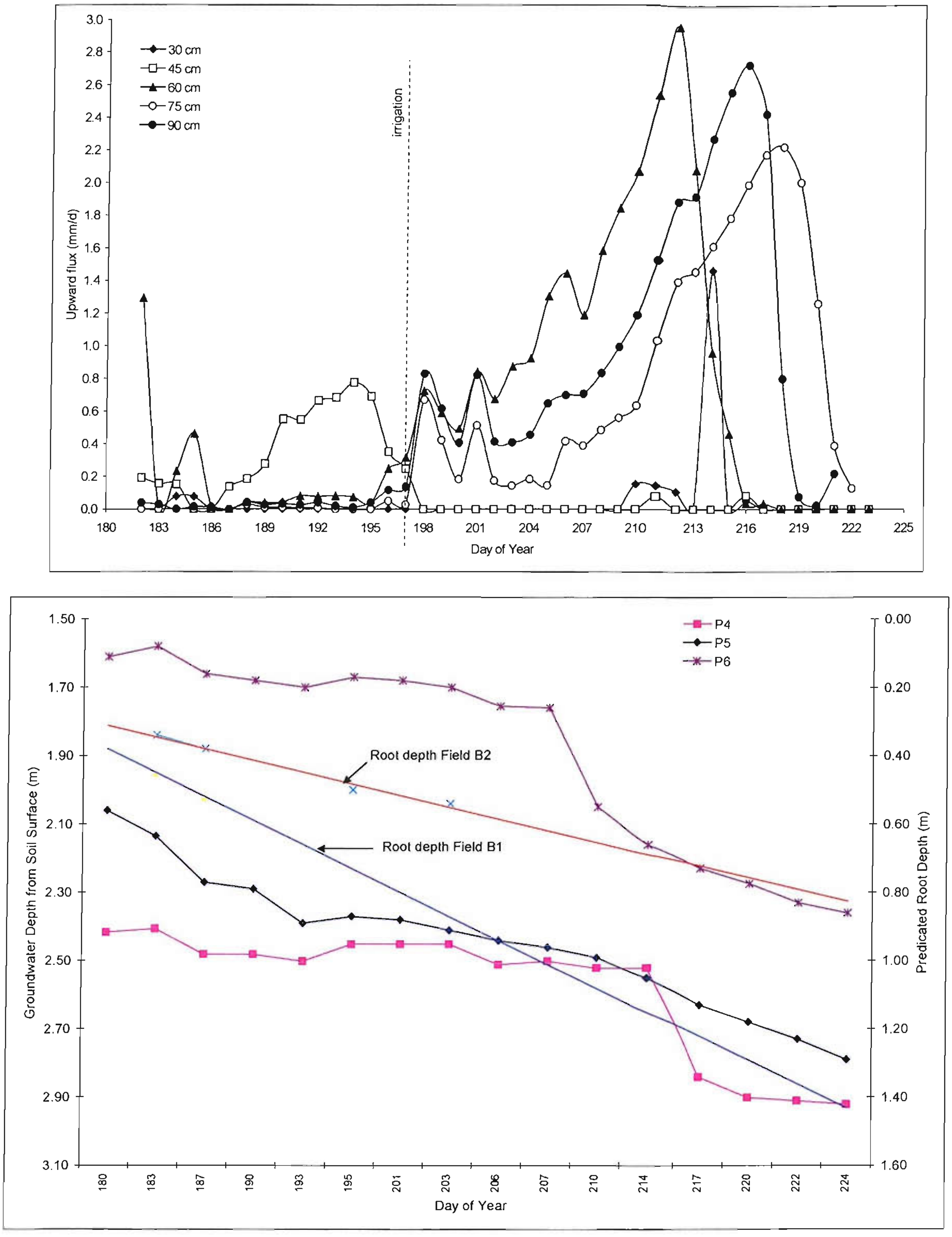


Figure 5.1 Daily Upward Flux (profile gross recharge) in Field B1 with Measured Groundwater Depth and Estimated Cotton Root Depths

In a soil with a relatively dry surface and limited irrigation soil moisture was constantly changing below the 60 cm depth where moisture content was adequate. Using tensiometers it was possible to monitor and record upward flux, which supplied moisture to the shallower parts of the profile. The shallow instrumentation of the profile recorded moisture in a dynamic part of the profile, where rapid root growth was expected. However, in order to record a true mass balance tensiometers needed to be deeper in the profile and at a higher density, such as 15 cm depth increments. As the groundwater dropped over the season upward flux will have decreased in the upper layers, but crop roots will have grown deeper into the profile to access soil containing more moisture and upward flux will have continued to provide the crop with water.

Cumulative values for gross recharge, soil moisture deficit and evapotranspiration calculated using the diurnal method are shown in Figure 5.2 for Field B1. Penman-Monteith potential evapotranspiration is also shown using Hunsaker (1999) crop coefficients for short season cotton. Irrigation between days 196 and 198 is indicated by the reduction in soil moisture deficit, where soil moisture was replenished by irrigation water.

Despite the irrigation, crop moisture stress was evident in the field after approximately day 215. This can be shown by the reduction in evapotranspiration and soil moisture deficit estimated using the Diurnal method. The reduction in gross recharge and general condition of the crop indicated that either upward flux was restricted, either due to changing soil properties as the groundwater dropped, or more likely it was not possible to record deeper upward flux due to the shallow depths of the tensiometers in the profile.

Potential ETc using the Hunsaker crop coefficients assumes that evapotranspiration was at potential. In reality this was not the case due to system wide water shortages. Instrumentation showed that gross recharge provided approximately 50% of potential evapotranspiration. Adequate instrumentation of the soil profile may have shown that much more moisture was available as upward flux, which contributed to crop evapotranspiration.

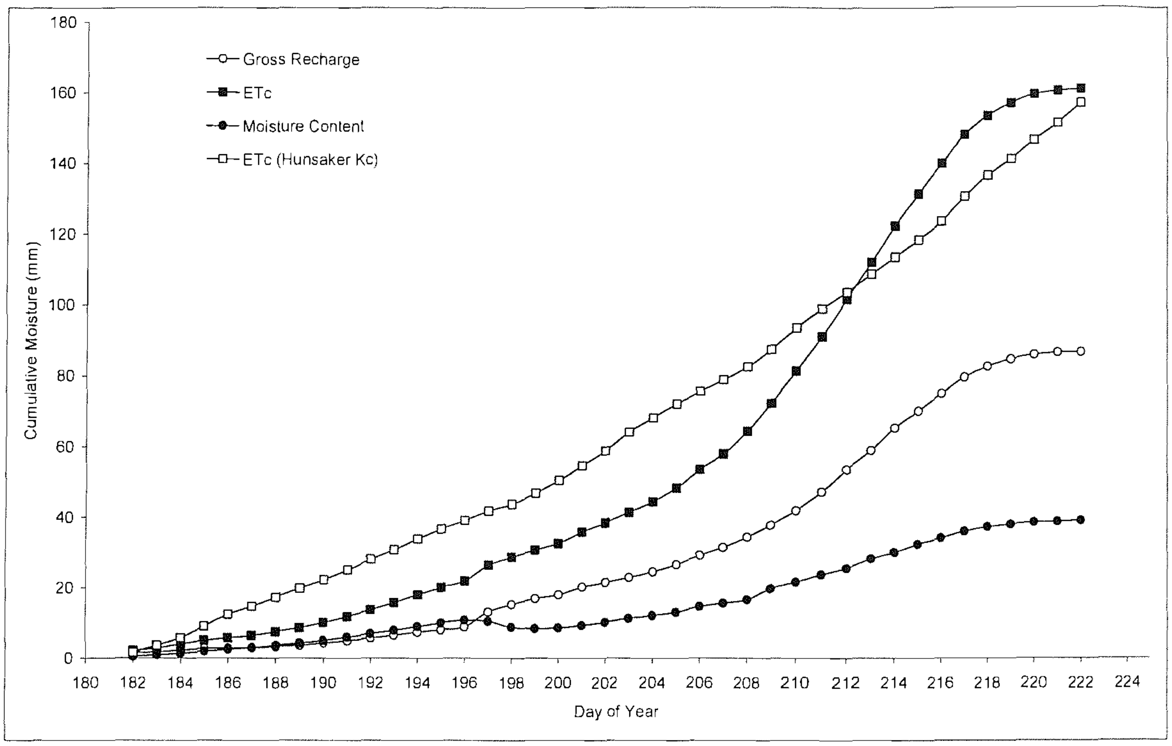


Figure 5.2 Cumulative Daily Upward Flux (profile gross recharge) in Field B1

Figure 5.3 shows the daily rate of moisture upward flux into the 30-90 cm depth in Field B2 using the diurnal method. Upward flux was low from all depths due to the immaturity of the crop as the canopy was not fully developed, although at 60 cm depth peak rates of up to 1 mm/d were evident for a short period around day 208. The majority of net upward flux occurred at 75 cm deep, with peak rates of 5 mm/d recorded around day 212 in an attempt to match crop water demand. These peak rates coincided with maximum rates of 3 mm/d between 60 to 75 cm depth in Field B1. Following the rapid increase and decline in net upward flux at 60 cm, net upward flux increases from the 90 cm depth. This could have been in response to a gradual drying of the upper net soil profile resulting in the reduced export to upper layers or the penetration of plant roots into deeper soil that contained more moisture. Upward flux increased up to 2.5 mm/d around day 230 before gradually declining. The significant net upward flux into the 90 cm soil layer indicates that there is likely to be significant upward flux from deeper layers which were not instrumented, leading to to an under estimation of upward flux.

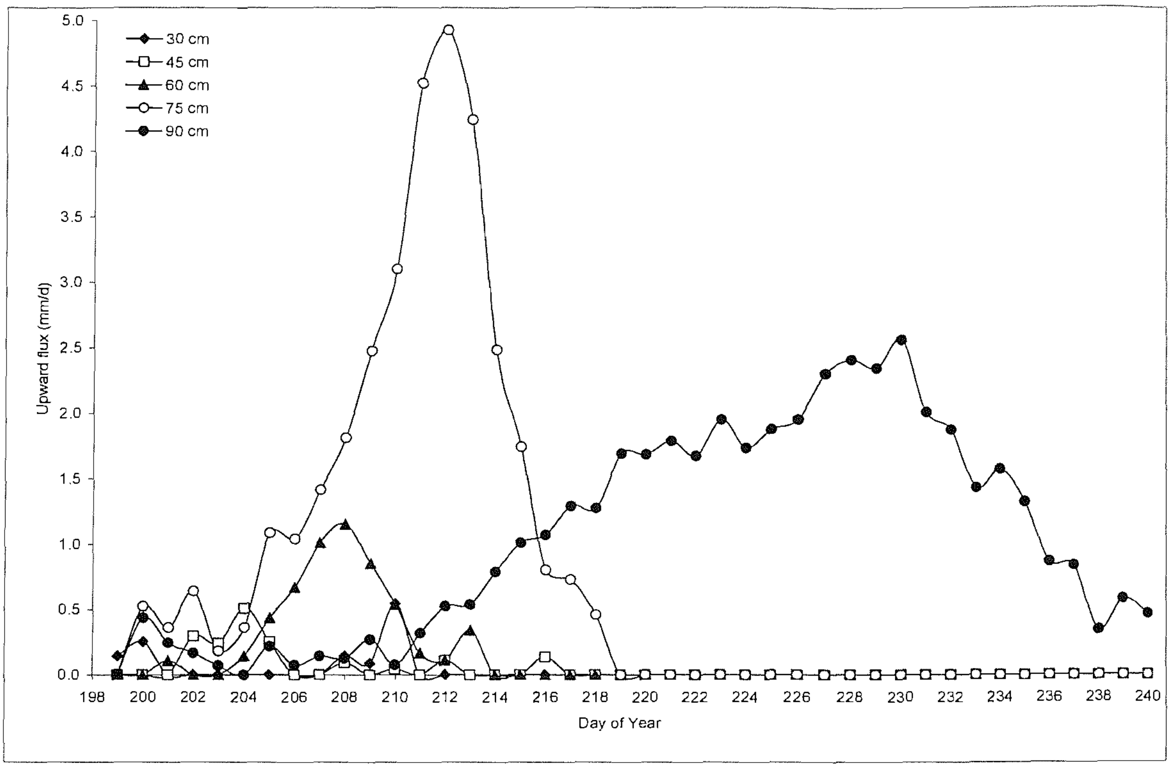


Figure 5.3 Daily Profile Upward Flux (profile gross recharge) in Field B2

The constant changing moisture status of the soil and the expansion of the crop rooting system deeper into the soil profile indicates that the plants were actively growing. The low rates of upward flux above the 60 cm depth were due to dry soil conditions. The 5 mm/d upward net flux recorded at 60 cm depth would have supplied around 80% of gross crop daily evapotranspiration. Recharge decreases at the 90 cm depth, from 2.5 mm/d to approximately 0.5 mm/d. However, because of the shallow instrumentation of the profile recharge from deeper than 90 cm could not be recorded. In reality gross recharge would have been more than 2.5 mm/d.

Figure 5.4 shows the gross daily rate of soil moisture recharge into the root zone from upward flux over a 60-day period in the experimental fields, calculated using equation 4.8. Initially the rates of upward movement were small, less than 1 mm per day which reflects the high moisture status of the soil and immature state of the cotton crop.

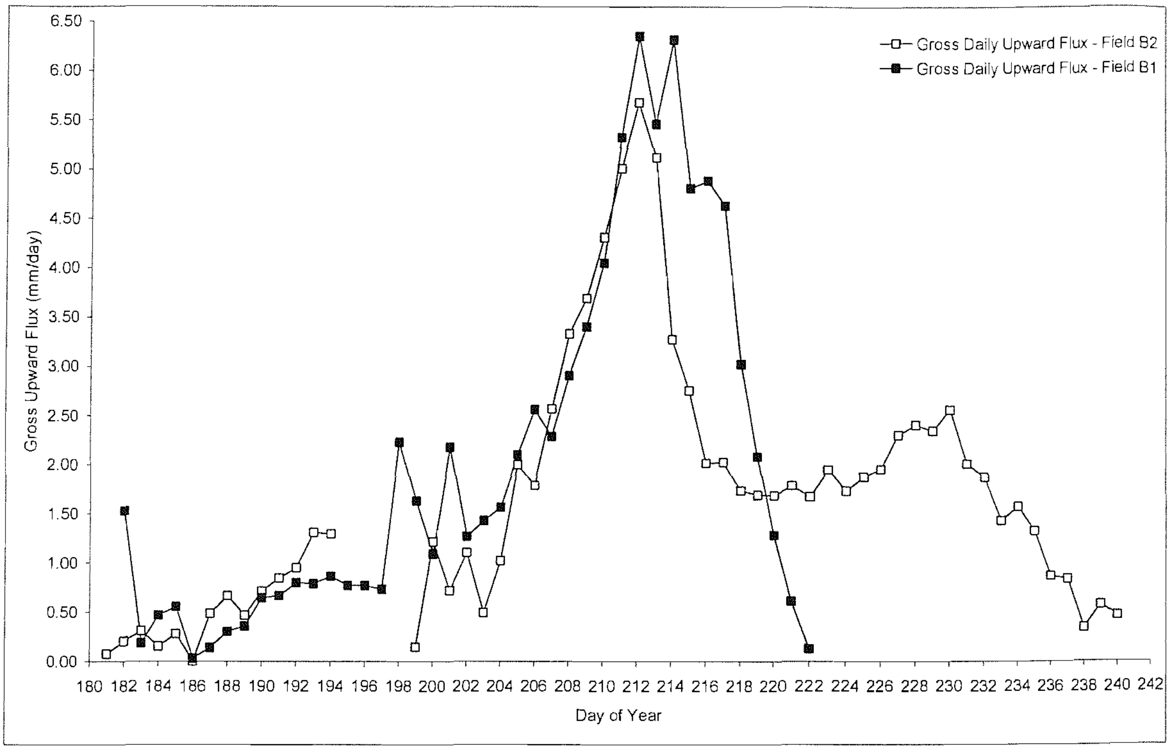


Figure 5.4 Upward Groundwater Flux into the Unsaturated Zone Calculated Using the Diurnal Method

Irrigation between days 196 and 198 resulted in an increase of recharge from irrigation as a result of a small amount of infiltration of irrigation water and moisture re-distribution within the soil profile. The comparative rapid rise in gross recharge indicates similar crop water demands at both locations, suggesting similar growth rates and climate changes. This is not surprising given the close proximity of the experimental plots and identical crop planting times. Maximum daily rates of gross recharge of about 6 mm/d occurred at approximately the same time as the maximum crop growth stage was reached and the high potential evapotranspiration rate (7 mm/day). Peak values of gross recharge suggest that almost all crop water demand was met from shallow groundwater for a short period of time during maximum crop growth periods (when using Hunsaker).

Figure 5.5 shows gross water recharge into the unsaturated soil profile similar to Figure 5.4, together with potential evapotranspiration (ETo). Standard cotton crop coefficients were adjusted based on observed crop growth rates together with coefficients developed by Hunsaker (1999) to reflect the short season cotton variety grown which was more relevant to this situation than using the standard FAO crop coefficients. Figure 5.5 shows that total profile upward flux regularly provided up to 80% of crop water requirements, and at times 100% of crop water requirements.

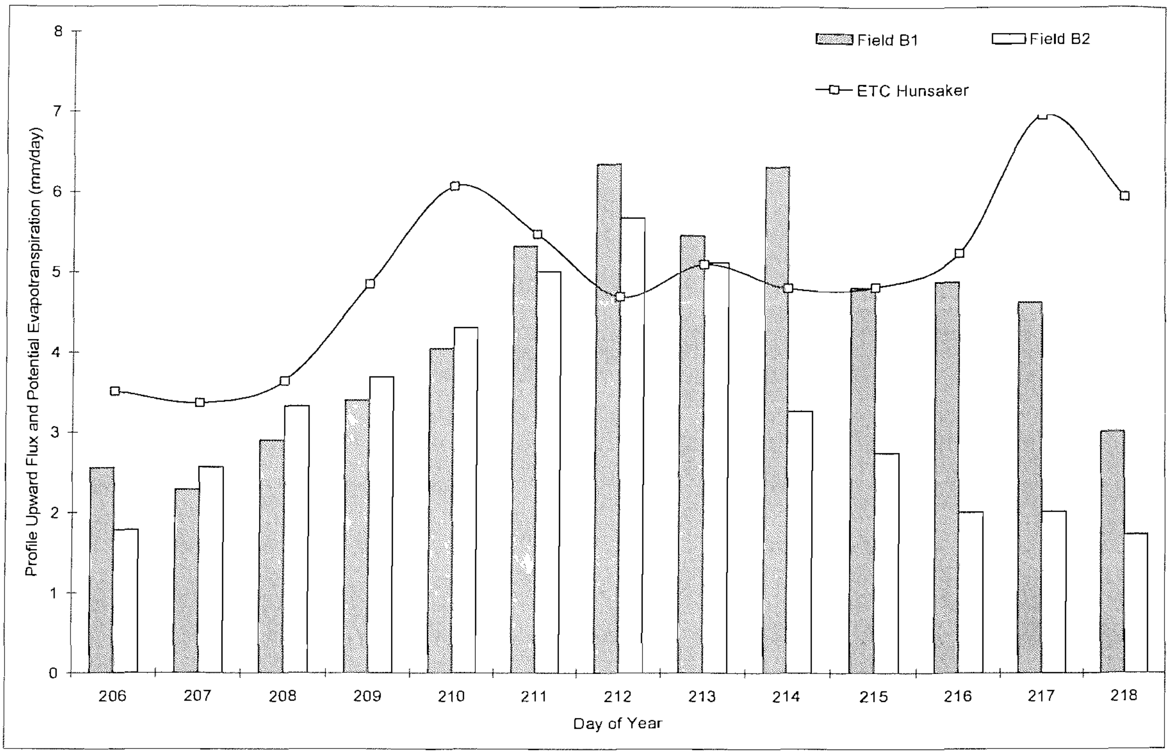


Figure 5.5 Profile Gross Recharge Estimated Using the Diurnal Method and Potential Crop Evapotranspiration

The complex nature of the relationship between unsaturated hydraulic conductivity, hydraulic gradient and moisture content means that as the soil dries, hydraulic conductivity declines and the rate of moisture flow through the soil decreases. The high moisture demands of the crop during maximum growth stages and the lack of adequate irrigation left a severe moisture deficit in the shallow layers of the soil profile. As upward flux supplied moisture to the crop the soil continued to dry to the point where moisture flow through the soil was minimal. The rapid drop in gross recharge in Figure 5.4 was due to this drying of the monitored profile and the reduction in unsaturated hydraulic conductivity.

The relationship between unsaturated hydraulic conductivity and soil suction is presented in Appendix A5 for the field soils. Similar patterns in hydraulic conductivity per depth within the soil profile were found at all study sites, although of different magnitudes. The large difference in values of K between study sites, which were located within 400 m of each other, highlights the possible variable soil moisture conditions experienced within one field.

Table 5.1 shows the water balance for the cotton crop using the diurnal method. On average groundwater entering the instrumented layers of soil contributed to between 50 to 59% of crop water use. Figure 5.4 shows that peak rates of upward flux can be high, and when calculated as an average over the time period studied range between 1.5 to 2 mm/d. Further instrumentation of the profile is likely to have revealed larger values for average upward flux.

Table 5.1 Soil Water Balance of Cotton (between days 180-240)

Parameter	Units	Field B1	Field B2
n	days	40	59
Irrigation*	mm	19	19
Change Soil Moisture Storage	mm	39	73
Groundwater contribution	mm	83	93
Groundwater contribution	mm/d	2.10	1.57
Av. groundwater depth (& range)	m	2.68 (2.41 - >3)	2.62 (2.24 - >3)
Total accountable water use	mm	141	185
Groundwater contribution	%	59	50
Potential ET_c**	mm	157	279

Notes: *Irrigation field application was measured as 80 mm/ha. However, data from the ThetaProbes© showed that only 19 mm infiltrated into the soil profile. ** Using Hunsaker crop coefficients for short season cotton over the 60 day period.

The results presented suggest that upward flux of water in these silt loam soils is essential for production of an adequate cotton yield. Poor in-field water management practices and water applications, an unreliable supply of irrigation water, combined with soil surface capping problems in these magnesium soils prevent effective irrigation.

Adequate instrumentation of the soil profiles, with deeper tensiometers and more frequent spacing down the profile would have provided more data. Shallower tensiometers and moisture monitoring equipment would have shown the young plants extracting moisture from the top 30-45 cm of the profile and upward flux from the 60 cm depth moving into the shallower layers. Appendix A5 contains volumetric soil moisture profiles for the experimental fields and shows the gradual drying of the profile with depth as the roots expanded deeper into the soil and utilised upward flux from deeper within the profile.

Later in the season upward flux must have supported the crops as little irrigation was applied. Figures 5.4 and 5.5 show that between 20 to 80% of potential evapotranspiration was met by upward flux into the 0 – 90 cm soil profile.

5.3 Lysimeter Moisture Balance

The net water balance of the field lysimeters at the end of the growing season is given in Table 5.2. It can be seen that of the total amount of water evaporated, groundwater contributed a significant amount of total water consumption, ranging from 67 to 43% of the total water evaporated, depending on watertable depth. Potential evapotranspiration (ET_o) was calculated as 860 mm during the growing season and seasonal crop water demand was estimated as 728 mm for short season cotton using CROPWAT and Hunsaker crop coefficients (Clarke *et al.*, 1998). The high figures obtained for evapotranspiration in these experiments were due to the extended canopy of the cotton crop in the lysimeters.

Table 5.2 Lysimeter Total Water Balance

Parameter	Units	**Designed Watertable Depth (m)**					
		1.00	**1.00**	**1.50**	**1.50**	**2.00**	**2.00**
Total SMD*	mm	41	41	87	76	172	167
Total ET_c^1 *(measured)*	mm	1199	1142	948	1211	945	839
Total Groundwater contribution	mm	818	761	521	795	433	332
Mean Upward Flux	mm/d	5.53	5.14	3.52	5.37	2.93	2.24
Mean Daily ET_c^2 *(Measured)*	mm/d	8.10	7.71	6.40	8.18	6.39	5.66
GW Contribution to ET_c	%	68	66	55	66	46	40

Notes: * **SMD:** Soil moisture deficit (initial moisture content - moisture content at the end of the experiment). $\mathbf{ET_c^1}$: is the total crop evapotranspiration (amount of water added to lysimeters to maintain groundwater levels at desired height + irrigation water + calculated soil moisture deficit. **Daily** $\mathbf{ET_c^2}$: (ET_c divided by the 148 day long season). Total seasonal irrigation water applied to the soil surface was 340 mm per lysimeter.

Mean cumulative water use from the groundwater measured in each pair of lysimeters is shown in Figure 5.6. Water use was the same for each groundwater depth up to week eight (26 July, 65 DAP). The rate of groundwater use slowed at approximately the same time for all lysimeters during week 16 to 17. This was due to the lowering potential evapotranspiration and the crop approaching full maturity and harvest of the cotton. The cumulative rate of increase in groundwater use was similar for the 1 and 1.5 m depths and slower for the 2 m depth. Appendix A5 contains detailed figures showing soil moisture suction in the lysimeters measured with Hg tensiometers and mean weekly rates of ETc measured from the lysimeters.

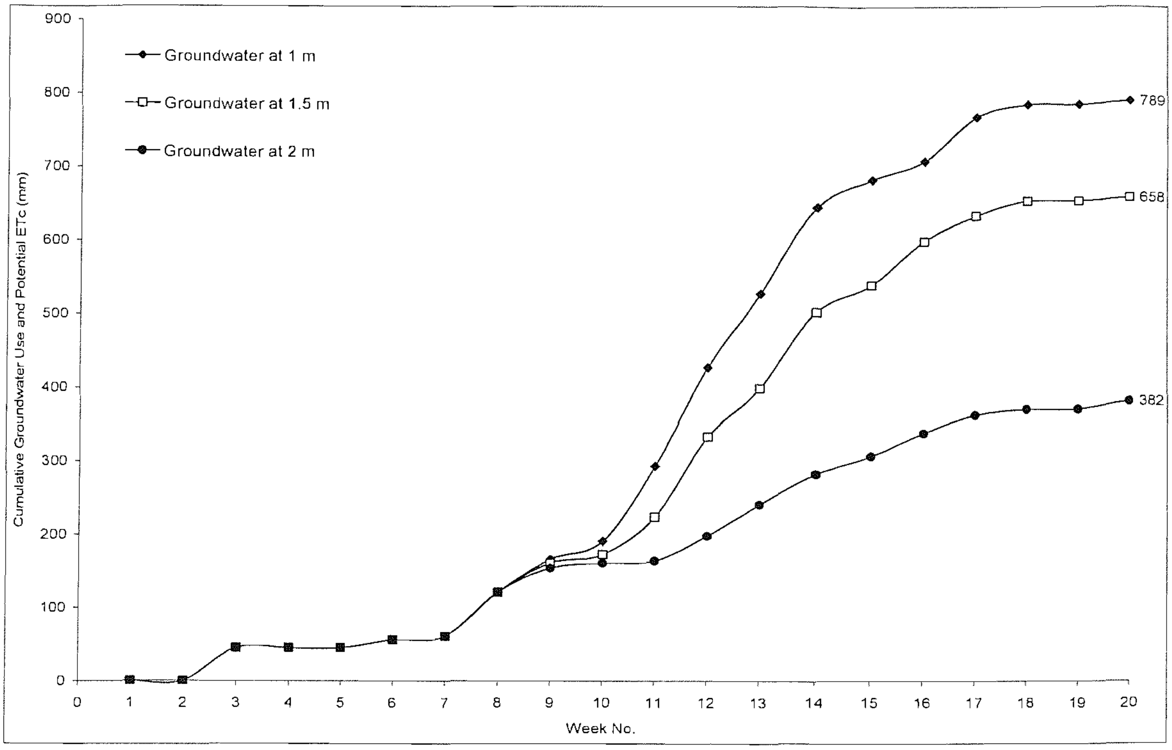


Figure 5.6 Mean Cumulative Upward Flux in the Lysimeters

At shallow groundwater depths high densities of plants can exploit groundwater efficiently (Ayars, 1996; Ayars *et al.*, 2002), but at deeper groundwater depths lower plant densities are better at utilising the groundwater. This is possibly due to reduced root competition for water when the groundwater is deeper.

Due to well-watered conditions in the lysimeters the cotton plants were able to grow tall and cover a larger surface area (due to a missing guard row) when compared to the cotton plants in the field. In terms of canopy area, the ratio between plants growing in the lysimeters and plants growing in the fields was, at 1 m groundwater depth: 1.02, at 1.5m groundwater depth: 0.71, and at 2 m groundwater depth: 0.40. Cotton in the lysimeters with groundwater at 1 m depth was similar in canopy cover to cotton growing in the fields, although slightly shorter. Cotton in the lysimeters with deeper groundwater was slightly taller than cotton growing in the field, but had larger canopy areas. The similar cotton size in lysimeters with groundwater at 1 m deep and cotton in the field was surprising, as it was anticipated this cotton would be more vigorous. This was most likely due to root and nutrient competition in the smaller soil monolith and possible waterlogging and soil aeration problems, a result of the consistently high groundwater at 1 m depth from the soil surface inside the lysimeter.

It is clear that the advective energy from the bare soil between the rows of lysimeters would also be expected to increase evapotranspiration when compared to estimation using the Penman-Monteith method. This 'clothesline' effect (Jensen *et al.*, 1990; Vellidis and Smajstrla, 1991), combined with a minor 'oasis' effect (Allen *et al.*, 1998), where soil inside the lysimeters contained more moisture than the soil in the surrounding field will have contributed to better crop development without water loss and ultimately yield production. These effects can also restrict deep rooting. Both the 'clothesline' and 'oasis' effects will have contributed to the higher evapotranspiration rates in the lysimeters than in the fields.

Figure 5.7 shows the average evapotranspiration from the lysimeters with different watertable depths. The potential evapotranspiration calculated using Penman-Monteith is also presented. Potential crop evapotranspiration calculated using Hunsaker Kc values is also displayed. The time of the maximum rates of evapotranspiration were similar for all three groundwater depths, suggesting that crop development and maturity were similar. However, the lower amount of evapotranspiration where groundwater was at 2 m deep was likely to have some detrimental affect on crop yield and quality. Where water is not freely available to plants and a moisture deficit is present it may cause early crop maturity and an early reduction in, or limit evapotranspiration (Mauseth, 1991).

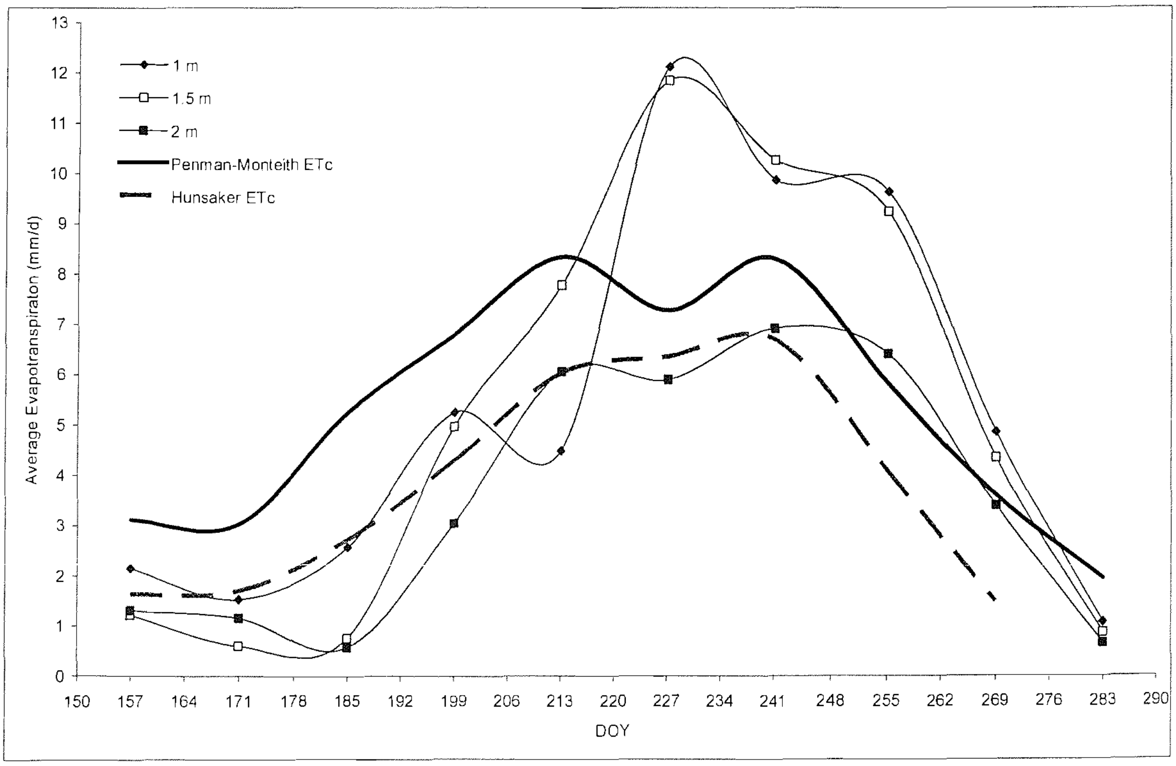


Figure 5.7 Weekly Mean Evapotranspiration from Each Pair of Lysimeters and Calculated Evapotranspiration

Figure 5.8 shows the relationship between actual cumulative lysimeter-measured evapotranspiration and cumulative groundwater use when the groundwater was maintained at different depths in the lysimeters. Based on a linear relationship:

- when the groundwater was at 2 m depth it contributed to approximately 45% of ETc,
- when maintained at 1.5 m depth this contribution increased to approximately 60% of ETc, and,
- at 1 m depth may have contributed up to 70% of ETc.

The slope of the three lines indicates that at similar rates of ETc quite different patterns of groundwater use can occur. However, the deeper groundwater at 2 m depth may have affected the seasonal evapotranspiration of the cotton as less water was available to the plants via upward flux from this depth (see Table 5.2).

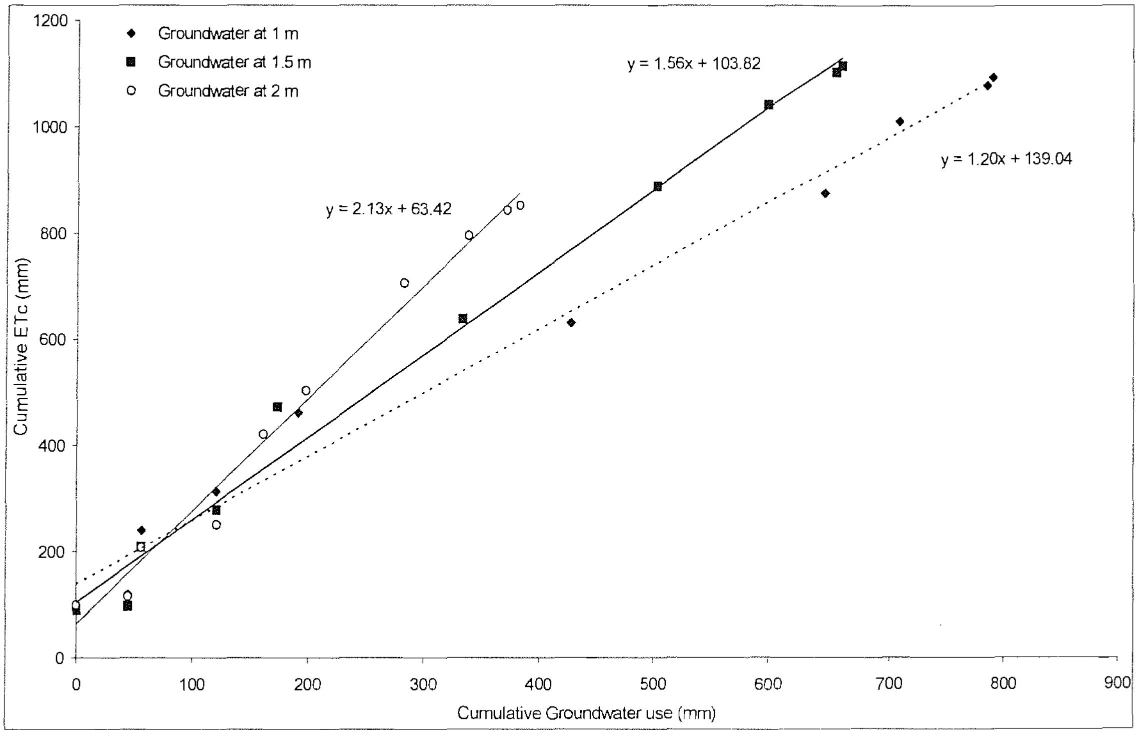


Figure 5.8 Relationship Between Cumulative Groundwater Use and Evapotranspiration Measured Using Lysimeters

Figure 5.9 shows the calculated weekly percentage of groundwater contribution to crop water use. It is clear that from the middle of the season groundwater contribution to ETc was almost constant for all groundwater levels. The period of constant groundwater contribution appears to start at approximately 480 mm cumulative water use. This suggests that the roots had reached a depth in the soil profile which encouraged them to use groundwater instead of irrigation water entering the soil higher in the profile. The decrease in percentage groundwater contribution at approximately 200 and 420 mm cumulative water use coincides with irrigation events in the lysimeters in weeks 6 and 10.

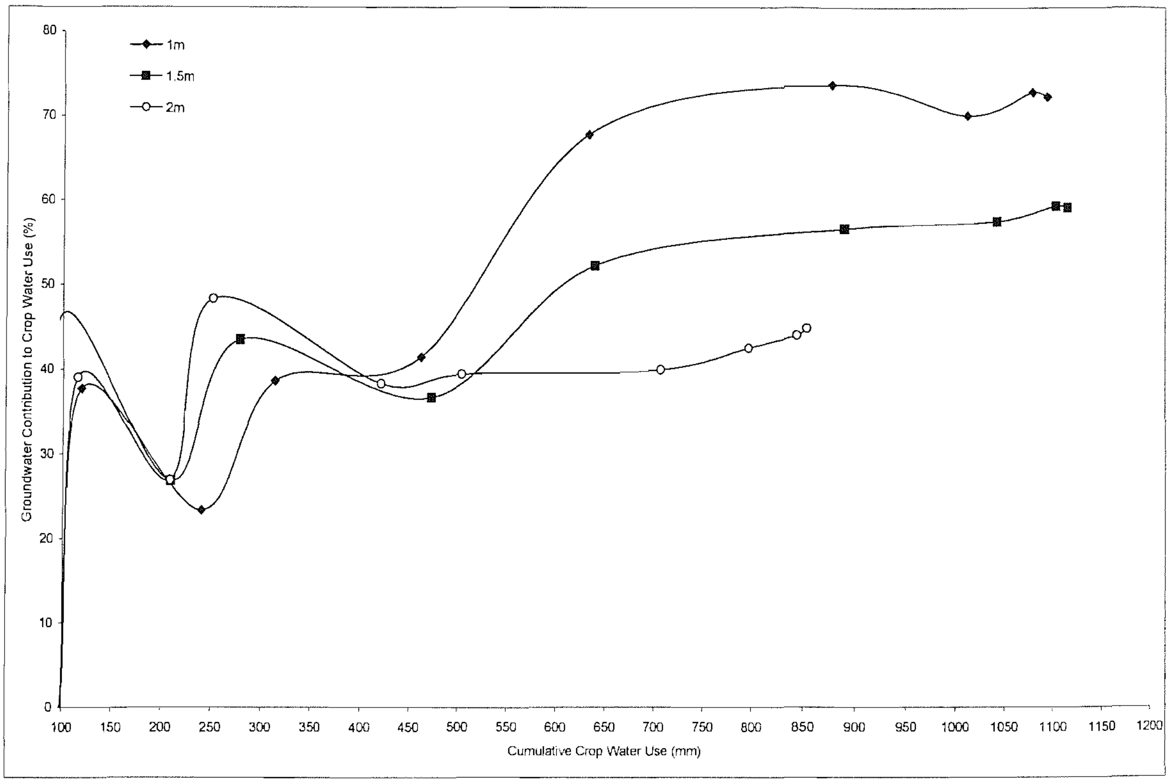


Figure 5.9 Percentage of Groundwater Contribution to Crop Water Use

This fluctuation in groundwater contribution suggests that when irrigation occurred the plants used this water in preference to groundwater, but that later in the season, once roots had penetrated deeper into the soil and evapotranspiration rates were close to or at maximum, groundwater provided the majority of the daily crop water requirements. The large final irrigation of 106 mm (applied at 900 mm cumulative crop water use) did not cause a reduction in groundwater use later in the season. If this was the case it suggests that irrigation applied later in the crop season was not used by the crop. This is consistent with findings by Wallender *et al.* (1979) and Reichman *et al.* (1977).

The Kazakh Research Institute of Water Resource Management (1989) found similar values to the lysimeter results for groundwater contribution to crop water requirements based on extensive studies in the major irrigation systems in Kazakhstan. Based on a Soviet categorised 'medium' soil type (silty loam), with evapotranspiration of 900 mm or over, and groundwater 1 to 1.5 m below the soil surface, upward flux supplied 57% (513 mm) of evapotranspiration, and 32% (288 mm) where the groundwater was between 2 to 3 m deep. These are similar values to those experienced during this study.

The average cotton yield for the ARTUR system during 1999 was reported as 2.5 t/ha (Vyishpolskiy, 1999b). Murray-Rust *et al.* (2003) reported average yields of 2.5 t/ha for collective and cooperative farms over 50,000 ha in the Syr Darya basin. This is comparable to average cotton yields[1] in California reported by Ayars *et al.* (2001). Lysimeters with groundwater maintained at 2 m depth produced a similar yield to the average yield for the system, whereas lysimeters with groundwater at 1 m depth produced almost double the average ARTUR system yield. The calculated yields based on the collection of cotton from each 0.28 m^2 lysimeter suggested that plants were not water stressed[2]. Ayalon (1983) and Jordon (1983) showed that where water applications exceed 900 mm cotton yields of between 4 to 6 t/ha are possible.

Soil moisture deficit values indicated that shallower groundwater was related to lower soil moisture deficit in the lysimeters. Similar responses were recorded by Bielorai and Shimshi (1963) and Shouse *et al.* (1998) who suggested that, where water is available, cotton roots will extract deeper water in place of moisture available at shallower depths which is held in the soil at higher suctions due to surface evaporation and rapid shallow root extraction.

The lysimeters provided an effective and practical approach to understanding the role of groundwater in cotton production in an area with shallow groundwater. The well-watered conditions in the lysimeters demonstrate that where moisture is available, groundwater can significantly contribute to crop water demand. The high rates of upward flux shown in the field calculated using the diurnal method in Figure 5.4 are comparable to the results from the lysimeters study.

5.4 Comparison of Upward Flux Estimated by the New Diurnal Method and Darcy's Law

Using field collected data it was possible to calculate unsaturated hydraulic conductivity of the field soil (see figures in Appendix A5). Figure 5.10 shows the daily average potential soil moisture change in Field B1 calculated using Darcy's equation (Appendix A5 contains an example calculation). Negative values on the y-axis represent upward moisture movement. Positive values represent moisture re-distribution within the profile including moisture extracted directly by plant roots. Cotton roots extended from 35 to 75-80 cm deep over this period (presented in Appendix A5 using the Borg and Grimes, 1986 approach).

[1] The global average yield for irrigated cotton is much less at 0.85 t/ha (Gillham, 1995).
[2] Cotton lint yields from the lysimeters were: 4.88 t/ha when groundwater was 1 m deep; 4.39 t/ha when groundwater was 1.5 m deep; and 2.66 t/ha when groundwater was 2 m deep.

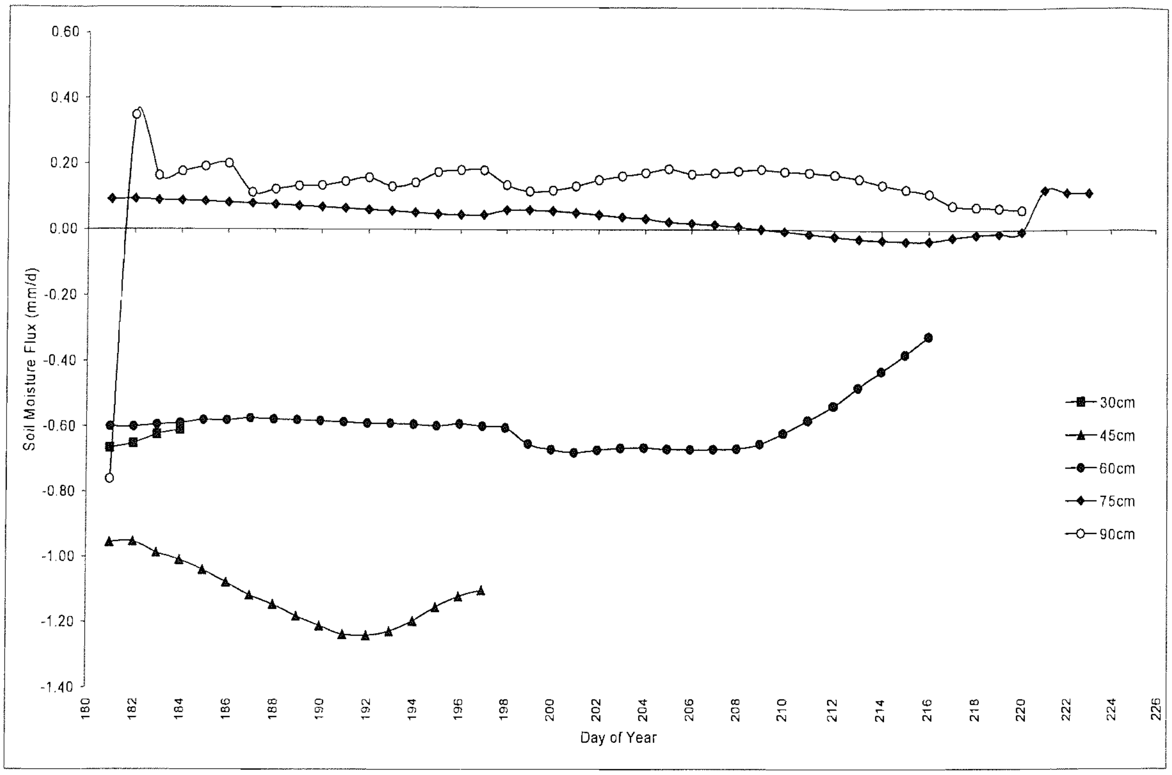


Figure 5.10 Daily Soil Moisture Change Calculated Using Darcy's Law, Field B1

Figure 5.10 shows that soil 60 cm deep within the profile provided the majority of moisture via upward flux to plant roots from deeper within the profile. Upward flux reached a peak rate of 1.22 mm/d before the soil dried and tensiometers broke tension. Below 75 cm deep minimal moisture movement occurred and the positive values may represent drainage, or when below maximum root depth percolation losses. Figure 5.10 demonstrates that between 60 and 75 cm deep a temporary zero flux plane existed which limited further upward flux from deeper into the profile into shallower soil. As crop roots extended deeper into the profile over the season the lack of irrigation and crop water demand resulted in moisture from deeper in the profile moving upwards into the expanding root zone.

Appendix A5 contains a series of figures which demonstrate the development of a zero flux plane in the experiment fields and the gradual movement of water from deeper in the soil upwards into shallower areas. As experienced with the diurnal experiments, it was not possible to monitor zero flux planes and soil moisture conditions deeper in the profile because of the lack of instrumentation. However, due to the limited irrigation deep percolation losses were expected to be minimal.

The drying of the profile and the low field unsaturated hydraulic conductivity will have 'limited' moisture flow within the soil matrix. The 'effect' of unsaturated hydraulic conductivity is not considered in soil moisture mass balance approaches. The drying of the soil caused the tensiometers to stop working after day 221 and further data were not available. This indicated that hydraulic conductivity was low and soil moisture suction was ≈ 800 cm or over.

Figure 5.11 shows the contribution of gross recharge to potential crop evapotranspiration. Potential evapotranspiration was estimated using the Diurnal Method. Daily and five-day average values are shown. The diurnal method estimates crop evapotranspiration based on profile moisture extraction and upward flux.

Based on Figure 5.11, the contribution of groundwater to crop evapotranspiration was different in both fields. Appendix A5 shows volumetric soil moisture profile observations. It is clear that soil moisture content increased more in Field B1 than in Field B2 following irrigation around day 198. The increase in moisture content suggests that water entered the soil and was re-distributed around the profile. Figure 5.11 shows that the cotton plants used this water in preference to groundwater and moisture held at higher suctions within the shallower parts of the profile. This is similar to findings by Ayars and Hutmacher (1994) and observations in the lysimeters.

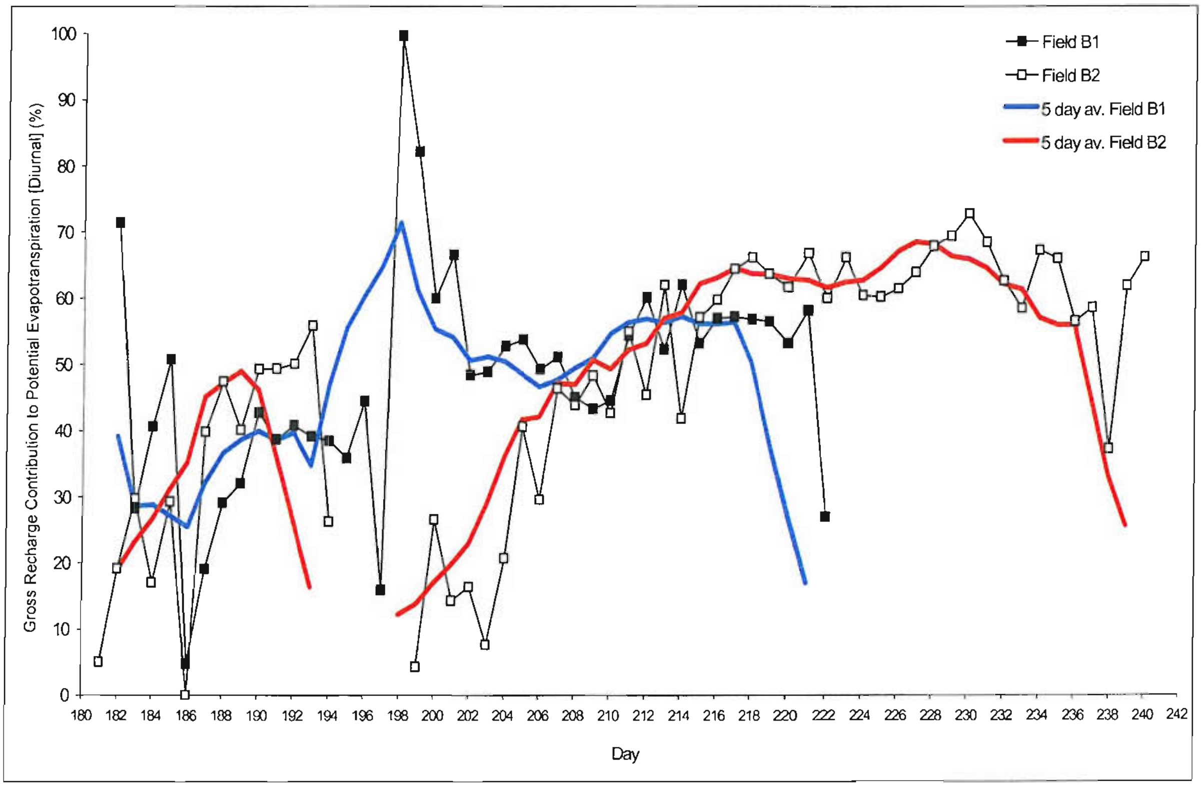


Figure 5.11 Contribution of Gross Recharge to Evapotranspiration Using the Diurnal Method

Figure 5.11 shows that upward recharge of moisture was similar across the research sites during the period shown. Consequently, any change in the percentage of groundwater contribution to evapotranspiration suggests that water was found 'elsewhere' – in this case it is likely that irrigation water was used in preference to groundwater in Field B2. Estimating potential evapotranspiration using the Diurnal method provides real time information on crop moisture status, rather than relying on potential values based on approaches developed under well-watered conditions.

5.5 Comparison of Upward Flux Estimated from Groundwater Level and Darcy's Law

The drop in groundwater over a specific time period provides an estimate of the amount of water extracted from groundwater. Detailed groundwater levels are shown in Figure 5.1 and in Appendix A5. The experimental field soils are silty clay loams which cover a gravel aquifer, in some places as shallow as 15 metres. At the start of the season when irrigation channels are filled; the fields flooded for pre-irrigation, and the snow melts on the Karatau mountain range the groundwater rapidly rises to 1.50 m from >3.50 m below the soil surface, indicating significant contributions from the aquifer. The estimate of the groundwater contribution is therefore likely to be conservative calculated in this way.

Average drainable porosity (μ) in the experimental fields was estimated as 7% (Appendix A5). Between days 181 to 197 (29/06 to 15/07) the groundwater in Field B1 dropped by 350 mm (approximately 16 mm/d). Based on the value of drainable porosity this fall in water level represents approximately 26 mm of groundwater use by the crop. This would be equal to a mean daily contribution of 1.63 mm/d to crop water use from shallow groundwater. These estimates are shown below in Table 5.3. The daily potential ET_0 value over this period, calculated using Penman-Monteith was 5.57 mm/day. Evapotranspiration using Hunsaker crop coefficients was much lower at 2.54 mm/day. Based on this 16-day period the groundwater supplied an average of 1.63 mm/day to the crop. Over the same period using Darcy's Law the daily value was similar at 1.86 mm/day. Based on the average daily evapotranspiration rate using Hunsaker, upward flux supplied between 64 to 73% of daily crop water requirements.

Table 5.3 Upward Flux Using Darcy's Method and Change in Groundwater Level, Field B1

Change in groundwater depth between days 181 and 197 (mm)	350
Water Available Due to Fall in Groundwater ($\mu = 0.07$) (mm)^	**26**
Average Rate of Upward Flux from Fall in Groundwater (mm/day)	1.63
Σ Upward Flux Using Darcy's Law (mm)	**32**
Average Rate of Upward Flux Using Darcy's Law (mm/day)	1.86

Notes: ^ Calculated using the procedure described in Appendix A5.

Due to the complexities in using Darcy's Law reliable upward flux data were only available for short periods of time. Values in Table 5.3 show similar rates of upward flux when compared to the fall in groundwater, but only for a short period.

Under cropped irrigation the drying of the soil profile and infrequent irrigations in the experimental fields due to water shortages meant that the use of Darcy's Law was not reliable for estimating upward flux. To record the development of deep zero flux planes and the capillary upward movement of moisture from deeper in the profile intensive instrumentation of the soil profile is required. Because Darcy's Law is reliant on estimation of the unsaturated hydraulic conductivity, which can change rapidly within the profile and over short horizontal distances in the field it did not prove to be a reliable method in this case.

5.6 Kharchenko's Method for Calculating Upward Flux

Potential upward flux was also calculated using the equation developed by Kharchenko (1975) as described in Chapter Three. Figure 5.12 shows the rate of upward flux from different groundwater depths calculated using Kharchenko's equation using field-measured data. Upward flux for each location was calculated using root depth measurements estimated over the entire season (presented in Appendix A5 and Figure 5.1). Seasonal groundwater depth was fixed at 1, 1.5, 2, 2.5 and 3 m to demonstrate the relationship between groundwater depth and upward flux for different soil types and rooting depths. Evapotranspiration (ETc) was estimated using Hunsaker (1999) crop coefficients for short-season cotton. Groundwater depth was fixed at different incremental depths and actual field estimated crop rooting depths where used in the equation.

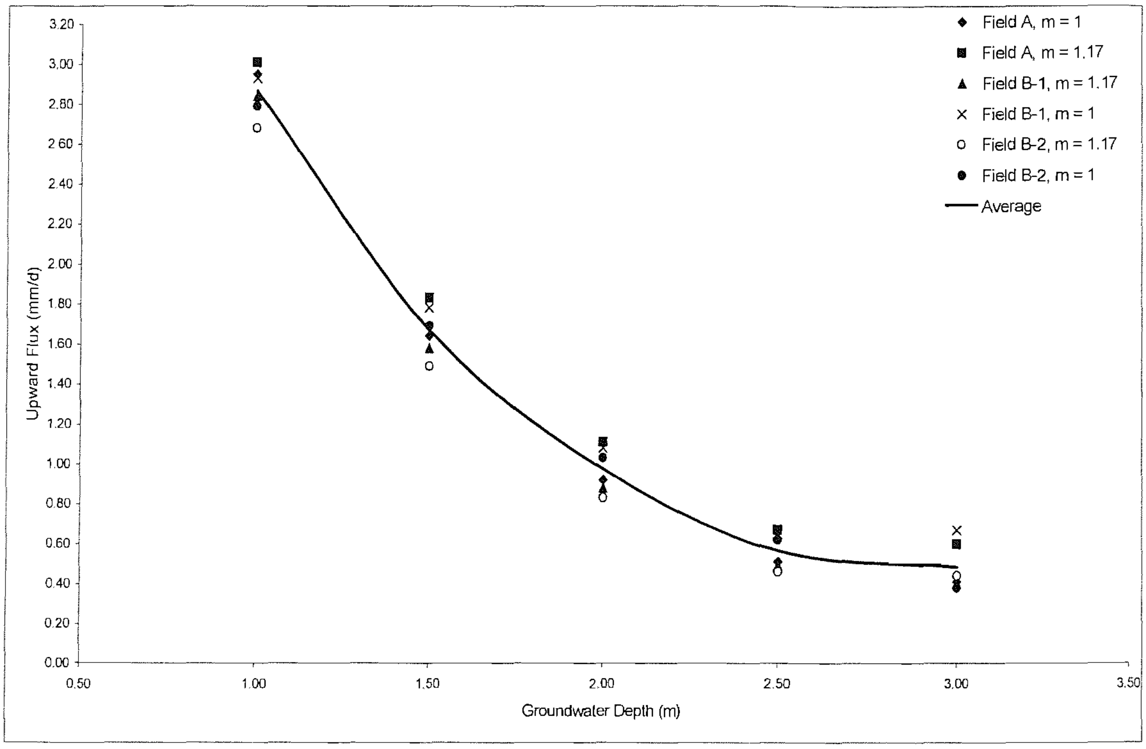


Figure 5.12 Estimation of Upward Flux Using Kharchenko's Equation

The constant *m* in Kharchenko's equation represents the capillary properties of different soil types. Based on International Soil textures the following values of *m* apply:

Table 5.4 Constant *m* in Kharchenko's Equation

Soil Type	*m*
Loam; Silty Loam; Silty Clay Loam	1.00
Clay Loam; Silty Clay Loam; Silty Clay	1.01
Clay; Silty Clay	1.17

Particle Size Distributions indicated that the experimental site soil type was silty loam/silty clay loam. Figure 5.12 shows upward flux calculated where $m = 1$ and 1.17 to illustrate the effect on upward flux in different fields using potential evapotranspiration rates.

Using field data Kharchenko's equation predicted that an upward flux rate of approximately 3 mm/d would be sustainable where groundwater was maintained at 1 m deep. Results from the lysimeters indicated that 3 mm/d would be sustainable where groundwater was between 1.5 to 2 m deep (Table 5.2).

Values for upward flux from the lysimeter study may also include water uptake by deep rooting cotton. Consequently, any reduction in groundwater will automatically have been attributed to capillary upward flux and not direct root extraction. This may have caused an over estimate of upward flux in the lysimeters, which contained deep rooting cotton plants. In reality, where the watertable is 3 m deep and roots are 1.5 m deep water has to rise 1.5 m before it can be used by the plants.

Kharchenko's equation indicates that where groundwater nears 1.5 m deep, upward flux rates of 2 mm/d are possible. This compares well with the upward flux rates of between 1.8 mm/d to 2.5 mm/d reported by TACIS (1999). Van Hoorn and Van Alphen (1994) suggest that upward flux of 2 mm/d can be maintained where the groundwater is at 2 m depth in a silty loam soil with a surface soil suction of 16 bar. During June and July groundwater levels in the fields ranged between 1.8 to 2.5 m deep. Based on results from the diurnal method a rate of 2 mm/d upward flux would be sustainable in this soil type where the watertable is static. In reality, deep crop roots contribute to the lowering of shallow groundwater (Shouse, *et al.*, 1998) and ultimately a reduction in the rate of upward flux.

Kharchenko's method is a relatively simple tool to use and is based on investigation of moisture flow through different soil types. However, correct identification of the soil type is required and the method is often applied on a regional basis (TACIS, 2000) resulting in local observations and conclusions being applied over much larger irrigation systems, reducing the accuracy of the method.

It is also clear from the tensiometer studies that the possible contribution of groundwater at different depths is not only dependent on the depth of the watertable to the surface but also the rooting depth of the crops.

5.7 Field Soil Moisture Balance

The cumulative soil moisture balance calculated from ThetaProbe© data using equation 3.4 are shown in Figure 5.13. The left hand Y-axis shows cumulative evapotranspiration using Hunsaker (1999) crop coefficients for short season cotton. The right hand Y-axis shows the cumulative soil moisture change for the instrumented parts of the profile per study site. Negative values at the beginning of the season indicate profile drainage.

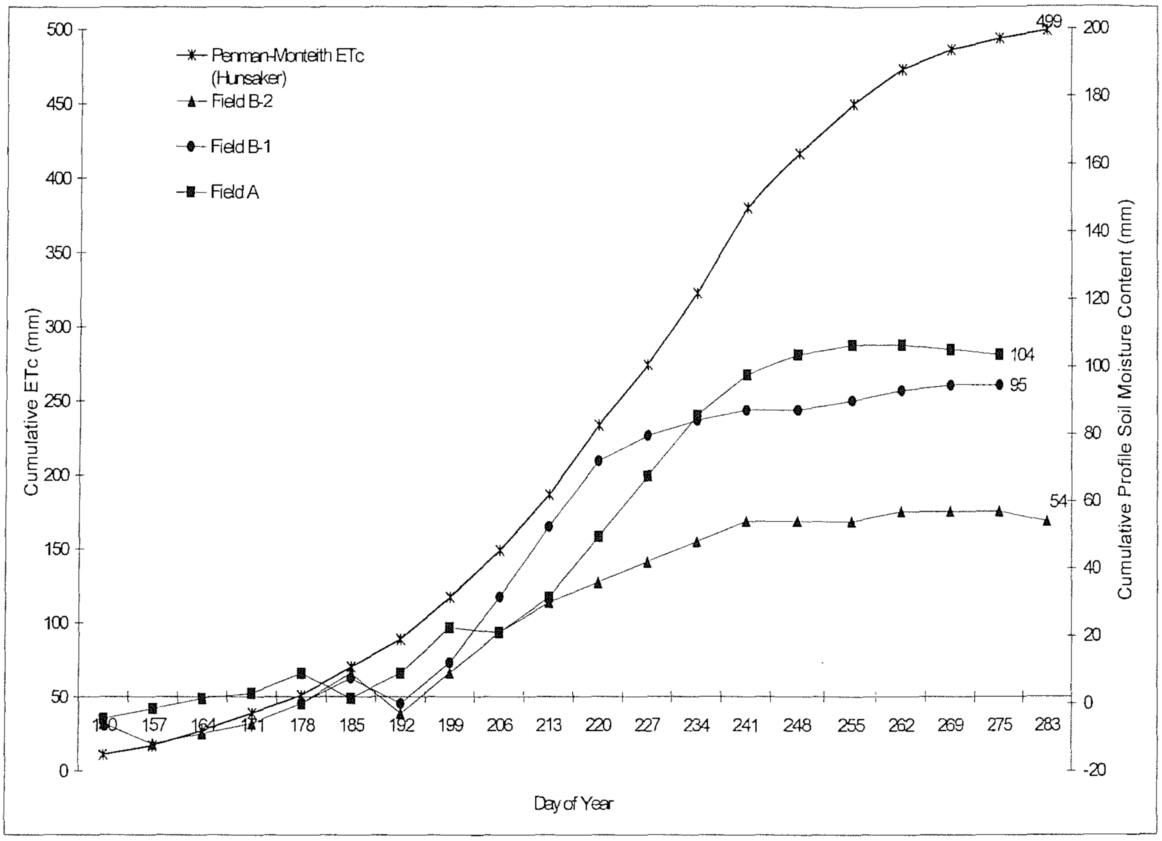


Figure 5.13 Cumulative Soil Moisture Change for Field Sites

Potential contribution of groundwater to crop water demand in each field was estimated by comparing measured soil moisture deficit with potential crop evapotranspiration using the Penman-Monteith equation. Figure 5.13 indicates that either considerable moisture was found by the cotton crop from outside the instrumented profile, or that a serious soil moisture deficit was experienced, but the latter conclusion was not compatible with observations of the physiological state of the crop in the field.

The different groundwater depths and crop growing conditions between the experimental sites enabled a range of scenarios to be studied. Table 5.5 contains summary results of the field water balance. The Balance Deficit was calculated from the difference between the inputs into the soil profile (irrigation water and the moisture extracted from the soil profile) subtracted from the ETc. The Balance Deficit represents potential upward flux into the soil profile. The calculated rates of upward flux are high when considered on a daily basis over the entire season and therefore can only be used with confidence when the crop was not water stressed (as experienced by Ayars, 1996).

Table 5.5 Field Soil Water Balance

Parameter	Units	Field A	Field B1	Field B2
Days Data Available	days	137	101	137
ETc*	mm	499	452	499
Irrigation	mm	51	35	35
Precipitation	mm	0	0	0
ΔS**	mm	128	102	81
Total Moisture Leaving Profile	mm	179	137	116
Average seasonal GW level***	m	2.47	2.57	2.52
Balance Deficit	mm	320	315	383
Cotton Yield	t/ha	2.30	0.70	0.70
Possible Upward Flux (assuming ETc values)	mm/d	2.34	3.12	2.80

Notes: * ETc calculated using Penman-Monteith equation using Hunsaker (1999) crop coefficients. Irrigation entering the soil profile and change in soil water storage measured with ThetaProbes© (represents ΔS in equation 3.4). Balance Deficit is Potential ETc - Irrigation + Precipitation - Soil Moisture Deficit. ** At the end of the season. *** See Figure 5.1 and Appendix A5-12.

Poor cotton yields harvested from Fields B1 and B2 indicate that a severe moisture stress was experienced by the crop. The crop harvested from Field A was close to the ARTUR irrigation system average of 2.5 t/ha (Vyishpolskiy, 1999b) and similar to the yield produced by lysimeters with groundwater at 2 m deep, suggesting comparable crop growth conditions. Field observations and lysimeter data show that a large percentage of crop water requirements were provided from shallow groundwater and the availability of this water affected the cotton yield produced.

5.8 Estimation of Crop Evapotranspiration from Climatic Data

Figure 5.14 shows estimated weekly reference crop evapotranspiration (ET_o) using the Penman-Monteith (Allen *et al.*, 1998) and Ivanov (1954) algorithms. The inset figure displays daily ET_o estimated using Penman-Monteith plotted against ET_o using the Ivanov formula. Appendix A5 gives the daily ET_o values. Maximum values occurred during early June, with average seasonal ET_o calculated as 6.28 mm/d (±0.18 mm) using Penman-Monteith, and 7.06 mm/d (±0.20 mm) using the Ivanov formula.

ET_o calculated using the Ivanov method was 11% higher throughout the season. This may be a result of the selected microclimate coefficients used, which may require adjustment (Smith, 1997).

The low ET_0 values for weeks beginning days 168, 199 and 237 were during periods when the average air temperature dropped, average relative humidity increased and average windspeed dropped.

Computed daily evapotranspiration results were analysed using a t-test assuming unequal variance, using the null hypothesis that there was no significant difference between Penman-Monteith calculated ET_0 and Ivanov calculated ET_0. The test indicated that the null hypothesis be rejected ($p<0.01$, df = 253, t = 2.75) as there was a highly significant difference between daily evapotranspiration results. An identical test was performed using weekly evapotranspiration results. The test indicated that the null hypothesis was accepted ($p>0.05$, df = 35, t = 1.24) and there was no significant difference between ET_0 calculated on a weekly basis. This suggests that reference evapotranspiration estimated using the Penman-Monteith and Ivanov methods must be compared on at least a weekly time scale, although it must be recognised that results from the two methods will be different.

The high potential evaporation rates were the combined effects of high temperatures, accompanied by high wind speed and high vapour pressure deficits. These high evaporation rates resulted in high crop water demand. The cotton is a short season short cotton (mean height of canopy ~ 70 cm) rather than the more typical long season cotton with higher canopy (~ 1 to 1.10 m high, (Hunsaker, 1999; Jordan, 1983; Laktaev, 1978)). FAO 56 (Allen *et al*, 1998) recommends a crop factor of 1.10 to 1.15 for mature standard cotton, although Hunsaker (1999) recommends a crop factor of 1.0 to 1.10 for short season cotton. The Hunsaker crop factor was used in this study.

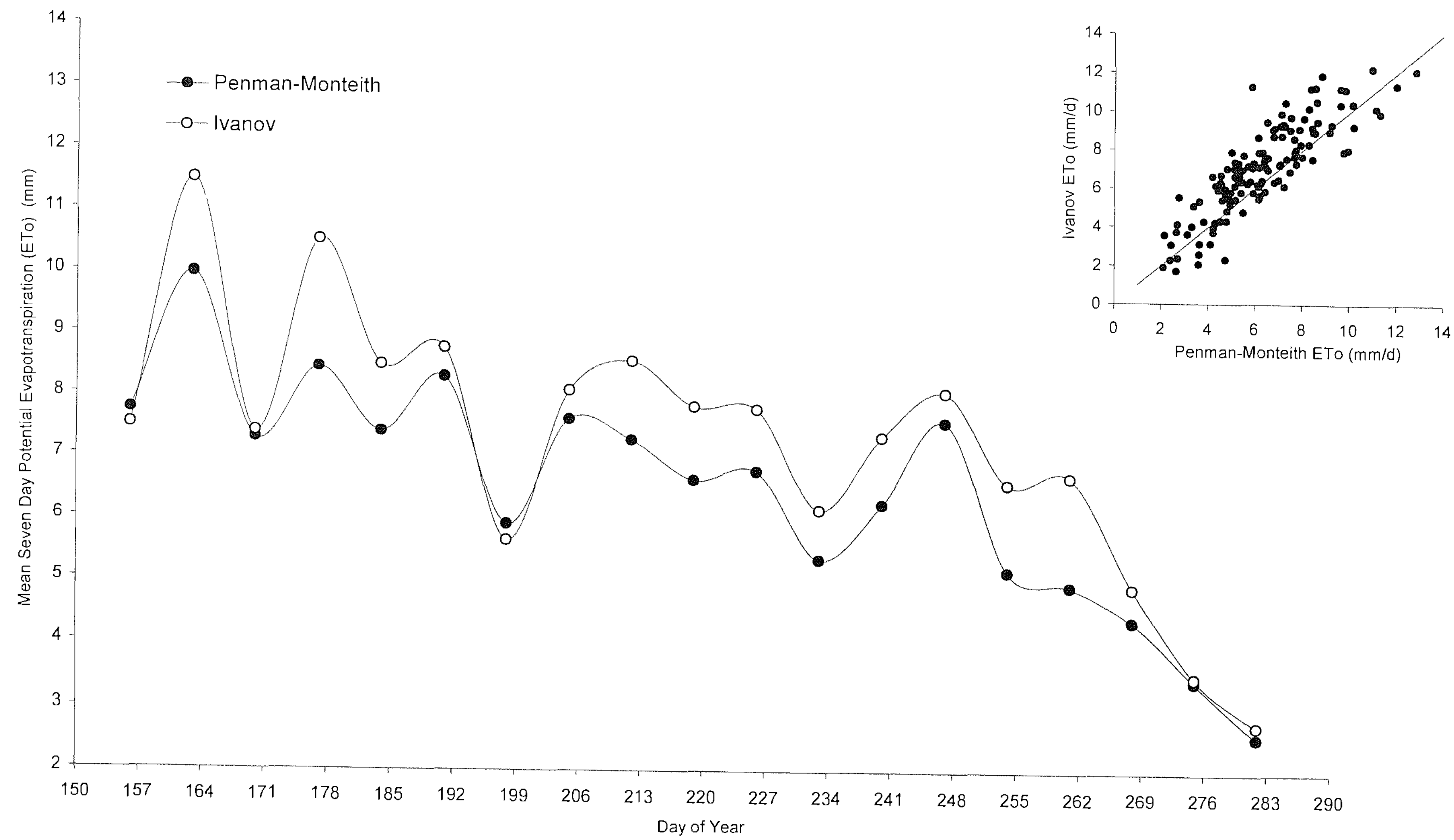


Figure 5.14 Reference Crop Evapotranspiration (ETo) Calculated using Penman-Monteith and Ivanov (mm/day).

5.9 Comparison of the Different Methods to Estimate Upward Flux

In order to analyse and validate the different methods used to estimate capillary upward flux summary results are presented in Table 5.6. Values from Darcy's method and the fall in groundwater represent a 16-day period only.

The average contribution of upward flux to crop evapotranspiration differed using the different approaches. The simple field moisture balance shows a relatively high and consistent percentage of groundwater contributed to crop evapotranspiration. Field data suggested that the crop grew and produced an average yield in Field A, but the low amount of irrigation water applied to the soil surface resulted in the crop producing deep roots to utilise upward flux from the shallow groundwater. This method is relatively simple to use in that it is based on the input and output of moisture from the soil expressed as water depth. However, the balance approach does not allow identification of the high and low periods of upward flux, merely providing a monthly or seasonal value which is often applied over large areas of irrigated lands to provide a baseline understanding of the role groundwater has in supplying moisture to actively growing crops.

Table 5.6 Summary Seasonal Upward Flux Data Using Different Methods

Method	Average Groundwater Depth (m)	Average Upward Flux (mm/d)
Field Moisture Balance[1]	2.52	2.75
Lysimeter Balance	1.0	5.33
	1.5	4.44
	2.0	2.58
Kharchenko	1.0	2.87
	1.5	1.67
	2.0	0.98
	2.5	0.57
	3.0	0.48
Diurnal Method	2.52	1.85
Darcy's Method[2]	2.24	1.86
Fall in Groundwater[2]	2.24	1.63

Notes: [1] Calculated upward flux mm/d ranged between 2.34 to 3.12 mm/d. [2] These values are based on a 16-day period when comprehensive data was available.

Cotton plants in the lysimeters received larger applications of water to the soil surface than the field-grown crop and experienced controlled watertable depth conditions. On average, despite the different groundwater depths, groundwater contribution to ETc ranged between 43 and 67%, or between 2.58 to 5.33 mm/d to meet a high evaporative demand. The well-watered conditions, whilst in part due to the irrigation applications of 340 mm, were also due to the large amount of water added to the groundwater. The fact that water needed to be frequently added to the groundwater due to crop water demand, and the high rate of evapotranspiration estimated from the operational data suggests that the crop extracted a significant amount of moisture from the shallow watertable.

When compared to the fields, additional water was added to the lysimeters at the surface to represent irrigation. This will have maintained a higher average moisture content in the soil monolith than in the field where irrigation applications were poor and occasional. These preferential moisture conditions in the lysimeters allowed the cotton to grow larger than the area of the lysimeters themselves resulting in an excessive evaporative demand.

Maintaining the shallow groundwater at pre-determined fixed levels within the lysimeters proved challenging. Applying water to the groundwater via the external piezometer caused rapid fluctuations in groundwater levels and most likely an increase in the height of capillary fringe. Although groundwater depth was closely recorded drainage from the capillary fringe back into the drainage section of the lysimeters will have occurred at the same time as moisture extraction by the plant roots. Consequently, actual groundwater levels recorded will have contained a margin of recording error.

The preferential method to maintain groundwater at a fixed level and to record water use would have been a Mariotte bottle principle or better still electronic controls that allow frequent water additions but this was not available.

Results from the lysimeters provided a valuable dataset on cotton water use from a range of different groundwater depths grown in actual field soil monoliths and clearly demonstrated the potential for groundwater to make a significant contribution to meeting crop water demand. Weekly mean evapotranspiration rates were useful for comparing controlled groundwater conditions with those of actual groundwater levels using the soil water balance and the newly developed diurnal method, as well as other empirical methods such as Darcy's Law. When used in conjunction with other methods data from lysimeters allow the development of background information for the region but they should be used with caution.

Figure 5.15 shows the daily average rates of upward flux from the groundwater per method. The four field measured approaches based on actual soil moisture data show similar daily upward flux results.

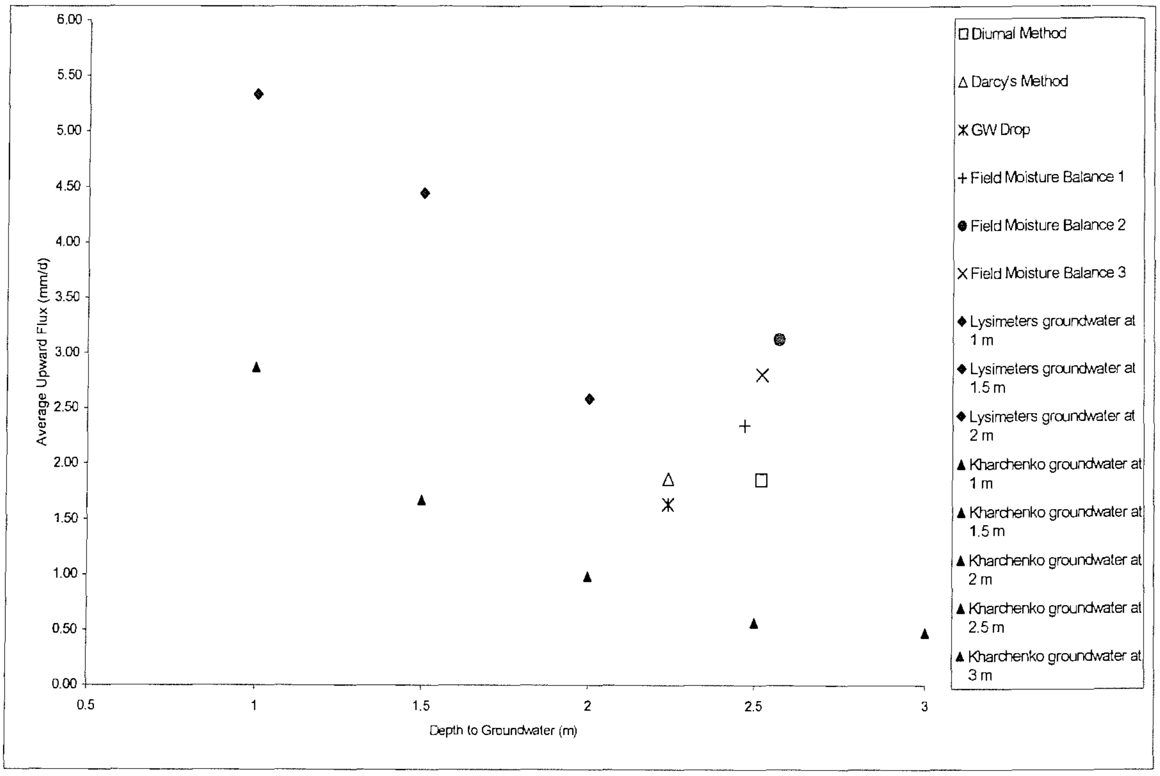


Figure 5.15 Summary Daily Average Upward Flux (mm/d)

Given the low yield of the cotton crop and the dry soil profile in Field B, values for upward flux calculated using the Kharchenko method need to be used with caution. Values from Kharchenko may show some consistency with well-watered and controlled lysimeter study values, and with peak rates of upward flux measured in the field using the Diurnal method, but these high values of upward flux are not sustainable for long periods of time due to declining unsaturated hydraulic conductivity.

The main concern with using the Kharchenko equation is that it is driven by values for potential evapotranspiration, which were historically calculated using the Ivanov formula within the FSU. When applied over large areas, using regional climatic data collected outside irrigated areas, and combined with microclimate coefficients, the values for upward flux and therefore groundwater contribution may have been over or under-estimated. In this study the cotton crop was severely moisture stressed and potential evapotranspiration was less than optimum – far less than the Penman-Monteith estimate. As evapotranspiration was low the Kharchenko equation assumes that plant moisture demand is lower, and therefore the amount of moisture utilised from the groundwater is less. Similar errors in estimating upward flux may occur when over-irrigation occurs and actual evapotranspiration is higher than predicted.

The simple fall in groundwater approach assumes that the moisture 'used' from the groundwater is in fact used by the growing crop. Where deep percolation does not occur or where there is no shallow underlying permeable aquifer, and ground slopes are minimal this is likely to be the case (Sevenhuijsen, 1994). In order to produce the value for upward flux using Darcy's Law requires knowledge of unsaturated hydraulic conductivity. As previously discussed in Chapter Three, estimates of unsaturated conductivity can vary widely, even in the same field and these values are difficult to determine even where boundary conditions can be controlled. Limited unsaturated hydraulic conductivity data was available to estimate upward flux using Darcy's method. The use of Darcy's Law is often criticised (e.g.: Cuenca *et al.*, 1997a; Cuenca *et al.*, 1997b) due to the data intensive nature of the method and often incorrect application of values over a large area, despite the variability in hydraulic conductivity.

The Diurnal method offers an easier approach, requiring soil moisture suction or moisture content measurements, and pF curve information. Soil moisture characteristic curve data are relatively easy to determine, requiring undisturbed soil samples only. The benefit of using the Diurnal method is that it does not require knowledge of unsaturated hydraulic conductivity of the soil.

Daily values for upward flux presented in Table 5.6 suggest that Darcy's and the Diurnal method produced similar values for the period studied, when adequate data was available to estimate unsaturated hydraulic conductivity. As the Diurnal method is based on direct measurement of soil moisture conditions the values produced by the method can be used with confidence.

The Diurnal method is able to provide daily values for upward flux. This is useful in understanding the dynamic changes which occur within the soil profile during the different growing stages of plants. It is also important to identify periods of high and low upward flux to understand the movement of potentially harmful salts into the rootzone, to further understand crop water demand, and to improve irrigation scheduling techniques for efficient water use. Better instrumentation would have clearly demonstrated that groundwater can make a significant contribution to crop water demand in silty soils. On some days upward flux from the groundwater may almost match potential evapotranspiration.

Although moisture balances are useful in determining patterns of water use over longer periods of time, the field and lysimeter moisture balances in this study were unable to provide detailed day by day values for upward flux. Consequently, the average value from the field balance of 2.75

mm/day presented in Table 5.6 is consistently high when compared to more detailed averages based on daily values of upward flux from the Diurnal and Darcy's methods, although 2.75 mm/day upward flux is a comparable figure to other results presented here.

Nonetheless, availability of both values is useful in understanding the range of moisture available to crops via upward flux. The Diurnal method forms a powerful tool to monitor and determine capillary upward flux from shallow groundwater, provided it is used with accurate soil moisture monitoring equipment that is placed deep in the soil profile and spaced appropriately.

5.10 Conclusions

The diurnal method for estimating upward flux offers a potential new experimental method for measuring the groundwater contribution to crop water demand and gives results comparable with flows determined with Darcy's Law.

Based on field measurements and observations the cotton crop received a large amount of its seasonal water requirements from shallow groundwater. Based on the application of the new Diurnal method, Darcy's Law and lysimeter observations using controlled groundwater levels, groundwater contributed between 43 to 67% of crop seasonal potential evapotranspiration. This translates into a daily range of between 1.8 and 5.3 mm/d upward flux. Much higher peak upward flux rates were recorded by the newly developed diurnal method, on some days upward flux from the groundwater matched potential evapotranspiration. Improved instrumentation would have demonstrated more accurately the significant contribution that groundwater can make to crop water demand in silty soils.

At the study location in the ARTUR irrigation system the cotton crop relies on groundwater as an additional essential source of water to supplement surface irrigation. This was due to poor irrigation practices and furrow preparation, inadequate cultivation, and general water shortages. The constant upward flux from shallow groundwater may over time cause secondary salinisation of the soil if groundwater quality falls (becomes more saline) and adequate leaching practices are not performed in the future, but in the meantime it is providing a cheap and cost effective essential supply of water.

Vyishpolskiy (2000) studied the salt balance of the ARTUR system over a period of three years and concluded that on an annual basis their was a stable removal of salt out of the soil profile by infiltrating water. This was in part due to the shallow pebble-gravel sediments containing fresh water flowing downslope in the general drainage direction towards the Syr Darya River, combined with the constant flow of water into the shallow groundwater from leaking irrigation channels. Although the irrigation season in the summer of 2000 was short due to lack of water, salt accumulations in the top three metres of the soil profile were estimated to be between 0.77 and 2.52 t/ha[1]. Under the normal irrigation water supply schedule adequate water is provided to adequately leach salt out of the soil horizon and into the fresh groundwater below. Long term Vyishpolskiy (2000) predicted a stable balance of salts in and out of the soil profile.

The ARTUR system is fed by snow melt from the Karatau mountain range and freshwater springs in the area. Irrigation water is fresh with average seasonal values recorded as 0.50 dS/m throughout this study. Average seasonal groundwater was recorded as 0.80 dS/m throughout the study period.

If recharge into the soil profile from shallow groundwater is not considered and evapotranspiration is equated with profile depletion only, seasonal crop water use will be underestimated. This may, in areas with reliable irrigation water supplies lead to over irrigation. Irrigation scheduling which relies on a moisture balance driven by potential evapotranspiration measurements and records of irrigation water applied to the soil without considering upward flux may also over apply water.

In irrigation systems where shallow groundwater is present but is not constantly replenished due to lateral inflow the fall in groundwater can be attributed to the constant process of capillary upward flux to meet crop water demand. The rate of capillary upward flux changes constantly in response to climatic conditions and the subsequent crop water requirements, the changing hydraulic gradient in the profile and the increasing distance between the groundwater and crop roots.

The conventional engineering approach to shallow groundwater is to lower the watertable by artificial drainage, but this requires large scale engineering solutions and comes with significant capital and maintenance costs (Boehmer and Boonstra, 1994). The environmental, economic and energy-efficient benefits of shallow watertable management through reduced pollution and increased yields are well documented (Mejia *et al.*, 2000). Consequently, an improved pragmatic understanding of the process of soil moisture movement within a profile above shallow groundwater will improve water management practices to maintain watertables at sustainable levels, decreasing upward salt movement into the rootzone and increasing soil aeration.

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[1] The ARTUR system is fed by snow melt from the Karatau mountain range and freshwater springs in the area. Irrigation water is fresh with average seasonal values recorded as 0.50 dS/m throughout this study. Average seasonal groundwater was recorded as 0.80 dS/m throughout the study period.

These approaches are quick to consider the benefits of shallow drainage but lack the true consideration that this can be at the cost of lowering the groundwater level and influencing the level of sub-irrigation. In fact without capillary rise it is clear that on the experiment site considerably more surface water would have had to be applied to maintain crop yields. It is also clear that many irrigation projects are perceived to have low water use efficiency due to canal and field deep percolation, with most large irrigation projects considered to be less than 50 % efficient. Clearly, many irrigation projects utilise shallow groundwater. The ARTUR irrigation system demonstrates good conjunctive use of irrigation water where groundwater is reused by the crop by capillary rise into the rootzone.

It is clear that using Darcy's Law to estimate upward flux is reliant on intensive data collection. Many of these parameters are often difficult to determine. Unsaturated hydraulic conductivity can be highly variable within single fields and is truly dynamic, changing constantly due to the process of wetting, drying and re-wetting taking place in the soil. It is often impractical to collect data to determine unsaturated K as control conditions are difficult to maintain in working irrigation systems, and as experienced during this study, field data of previous estimates of unsaturated K are either unavailable or unsaturated K has not been studied.

The variation of crops grown, soil types, watertable depths and quality, climate, and different irrigation schedules make it very difficult to extend and generalise results of groundwater studies (Meek *et al.*, 1980). The Diurnal method provides a practical approach to understanding and monitoring upward flux. The method provides frequent estimates of upward flux which can be used for practical irrigation scheduling practices. Chapter Six discusses the effects hysteresis may have on the Diurnal method and looks at other possible applications of the new method.

6. GENERAL DISCUSSION AND FURTHER APPLICATIONS OF THE DIURNAL METHOD TO ESTIMATE UPWARD FLUX

6.1 Introduction

This chapter discusses results of soil moisture observations and the effect of hysteresis on the new Diurnal method. Further applications of the Diurnal method are also considered for further study.

6.2 Zero Flux Plane and Soil Moisture Observations

The ZFP method is considered a robust physical method that does not require measurement or estimation of unsaturated hydraulic conductivity (Gee and Hillel, 1988). Observation of soil moisture suction in the profile throughout the cotton growing season allowed calculation of the hydraulic potential. The shape and curvature of each hydraulic potential curve allowed the identification of the direction of moisture flow, as water moves from a position of high hydraulic potential to a position of low hydraulic potential (Hillel, 1980b).

Areas of zero flux were identified, signifying the point where hydraulic potential was vertical and the moisture 'flux' or change was zero. Despite the large data set collected from the experimental fields it was not possible to practically apply the zero flux plane (ZFP) method in Star Ikan. This was because:

- the ZFP method works best in areas with low and consistent rates of evapotranspiration with low rainfall and long growings seasons. It is therefore well suited to experimentation in bare soils. Long growing seasons reduce the relatively rapid increase in profile moisture use associated with shorter growing seasons and higher evapotranspiration rates.

- the method benefits from instruments installed at 15 cm depths in the soil profile and at depth in the study areas.

- when the method is used with growing plants it is best suited to plants with deep rooting depths to limit the effect of soil surface drying. Shallow rooting plants make it difficult to separately determine root moisture extraction and upward flux from general profile drying.

Because of the number of criteria and the need for accurate measurement the ZFP method has mainly been used in temperate areas in forests in the UK (Cooper, 1980; Cooper *et al.*, 1990) and chalk grassland (Wellings and Bell, 1980; Gardner *et al.*, 1989; Hodnett and Bell, 1990) in the UK, tea estates in East Africa (Cooper, 1979) and in boreal forests in Canada (Stammers *et al.*, 1973; Cuenca et al., 1997b) and Japan (Shimada *et al.*, 1999).

6.3 Equipment Accuracy

Although a rigorous calibration procedure was performed for the ThetaProbes© based on the manufacturers guidelines, it is recommended that for further soil moisture investigations using ThetaProbes© moisture content is logged as millivolts and is later converted to soil moisture content (m^3/m^3) using a locally designed calibration curve. This will increase the accuracy of the measurements and decrease any potential error associated with linear interpolation between data points on the calibration curve entered into the data logger. Mason *et al.* (1983) concluded that an accurate water balance could not be conducted when solely relying on soil moisture content measurements above a shallow watertable. McGowan (1973) concluded that volumetric moisture content (m^3/m^3) as a unit of measurement was slow to respond to actual fluctuations in soil moisture status. McGowan (1973) suggested that soil moisture suction be used as the preferred form of measurement in soil moisture studies, although a combination of the two methods would provide a comprehensive dataset.

6.4 Factors to Consider When Applying the Diurnal Method

To use Darcy's Law to estimate capillary upward flux requires accurate values for unsaturated hydraulic conductivity over the range of soil moisture contents found in the field. In a field containing growing crops the hydraulic conductivity of the field soil may vary considerably and is therefore difficult to predict (Bouwer, 1978). It is often impractical to assess unsaturated conductivity in the field because of the wide range of conductivity values found in soils (typically varying over five orders of magnitude in a season (Gee and Hillel, 1988)), their spatial variation and hysteresis (Cooper et al., 1990).

As discussed in Chapter 2 hydraulic conductivity (K) is highly dependent not only on soil texture and structure, but also on the hysteresis state and moisture content of the soil. Within the variation of root zone soil moisture the hydraulic conductivity may widely differ. The error associated with estimating upward flux using the suction gradient - conductivity (Darcy's Law) method can be, as suggested by Gee and Hillel (1988) 'fraught with large potential errors'. This is because of the difficulty in accurately predicting the hydraulic gradient between two points in a soil profile where small changes in density and soil type can affect the suction gradient and therefore estimation of upward flux.

The majority of practical methods to estimate unsaturated K are relatively simple in concept, but impractical in field conditions due to the need to establish a free-draining profile and other restrictive boundary parameters. While Darcy's method provides confidence in assessing whether flow, as re-distribution within the profile or drainage, or upward flow (for evapotranspiration) occurs, the magnitude of the flow has a large associated uncertainty, often no less than an order of magnitude (Stephens and Knowlton, 1986).

In using the Diurnal method hydraulic conductivity does not need to be considered. This is an important advantage when attempting to develop practical water application procedures in the field. Hysteresis does need to be considered when using the Diurnal method, and this is described below.

6.4.1 Hysteresis and Hydraulic Conductivity

Figure 6.1 shows the hourly change in moisture content at two soil depths in the soil profile (75 and 90 cm) over a three day period. Maximum diurnal changes in soil moisture content occur on day 215, but these were small compared to the total soil moisture content at the same depth. For example, at 75 cm deep only 1.51 mm of water left the soil layer compared with a total moisture content of 43 mm in the 15 cm of soil between 67.5 and 82.5 cm deep.

Consequently, the change in soil moisture suction is minimal when expressed as a percentage of total suction at this depth (in this example 0.04%). This becomes less when the entire profile is considered (i.e.: change in suction from the soil surface to approximately 1.5 m deep). Hysteresis between the wetting and drying phase of the diurnal cycle is therefore expected to be minimal because of the small change in suction. The 75 cm depth was used as an example as it represented the most active moisture movement zone in the experimental fields.

It is assumed that any hysteretic effect may be kept to a minimum provided the amplitude of moisture recharge (by upward flux) and extraction (by the plants) increases or decreases at the same proportional rate (to each other). By moving proportionally the moisture content of the soil returns to similar values between wetting and drying soil moisture characteristic curves. Should the amplitude of moisture extraction suddenly increase whilst the amplitude of recharge stay the same the effect of hysteresis on moisture content will be high. This would be a result of the sudden increase in the proportional change in moisture content between wetting and drying curves; a consequence of increased crop extraction.

In reality this is unlikely to happen as hydraulic conductivity and gradient effectively controls the rate of moisture movement. If moisture is extracted by crop roots it can be either 'replaced' by moisture moving upwards from the groundwater or downwards from irrigation/rainfall. If no moisture is available for replenishment of the deficit the soil moisture profile follows the classic drying curve. Moisture extraction creates the soil suction demand, which is then replenished by recharge. Hysteresis will have little effect on the change in moisture content when only extraction or only recharge is apparent. Under 'normal' crop irrigation hysteresis is not expected to effect the calculation of gross recharge and extraction using the diurnal method.

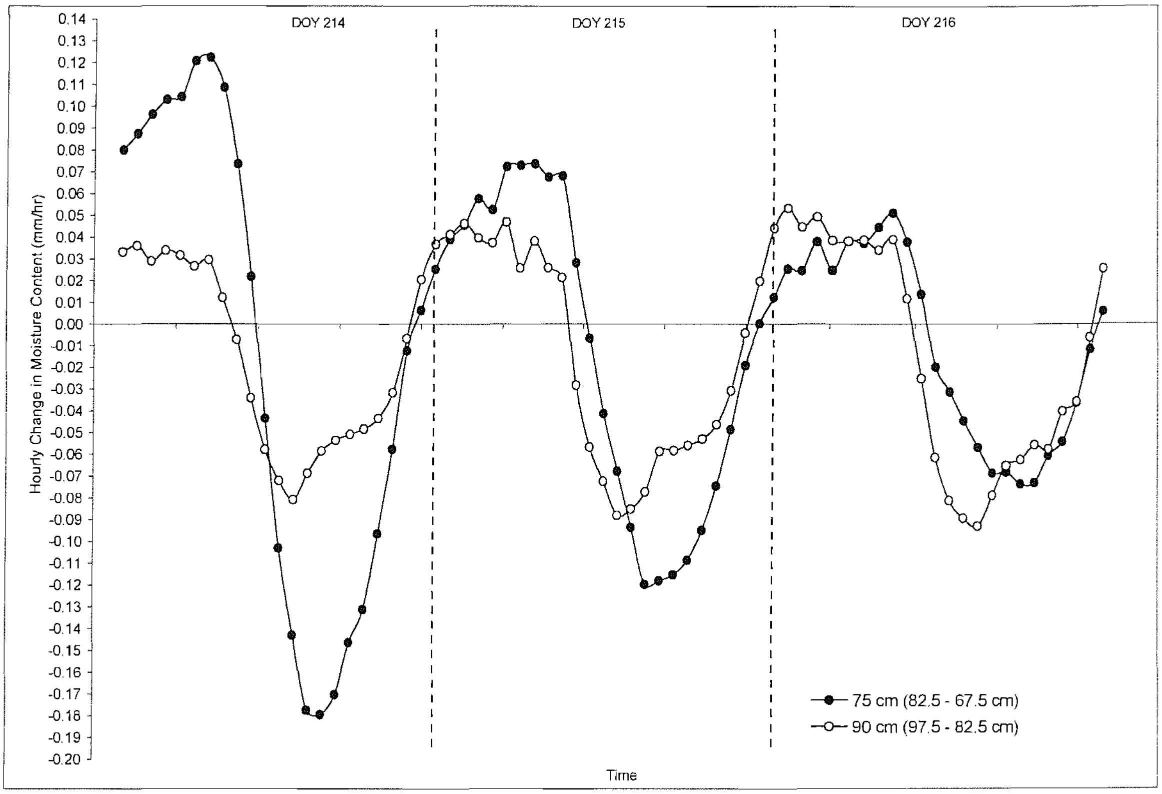

Figure 6.1 Diurnal Changes in Soil Moisture Status

Attenuation of the two curves in Figure 6.1 is evident. This is due to the decreasing hydraulic conductivity as the soil profile dried. As the soil dries the hysteretic effect decreases as moisture movement in and out of the profile decline at a proportional rate. Yang and White (1990) found that hydraulic conductivity effectively 'controlled' hysteresis effects in a laboratory based model where diurnal fluctuations in moisture content were constant in a shallow bare soil.

6.4.2 Using the Diurnal Method to Determine Plant Moisture Stress

Figure 6.2 shows soil moisture suction recorded at 23:00 hours each day plotted against daily gross extraction calculated using the Diurnal method. Only data from the 75 cm depth in the soil profile is presented. 23:00 hours was used as a reference time as soil moisture suction was expected to be low and recharge was expected to be at or almost at maximum. It can be seen that the extraction rate increased as a result of both upward flux and soil moisture depletion but at a critical suction of 600 cm the amount of water extracted declined rapidly as reducing hydraulic conductivity diminished the rate of upward flux.

The concept of 'field capacity' is used as an irrigation scheduling parameter, allowing irrigation quantities to be determined which provide adequate moisture to the crop without excessive irrigation quantities and deep percolation losses. Values for field capacity range between 200 to 400 cm soil suction. Where soil suction approaches 800 to 1000 cm plants will experience moisture stress and irrigation must be applied to ensure yield production (Skaggs *et al.*, 1980). In this example, plants were unable to extract significant amounts of water from the soil layer below 680 cm suction. The plants must have been suffering from serious water stress or extracting water from deeper soil layers. In irrigation situations, crop moisture extraction from the soil will always be higher than recharge into the profile from upward flux as roots continue to withdraw moisture above 1 bar suction, despite hydraulic conductivity reducing the movement of moisture through the soil matrix.

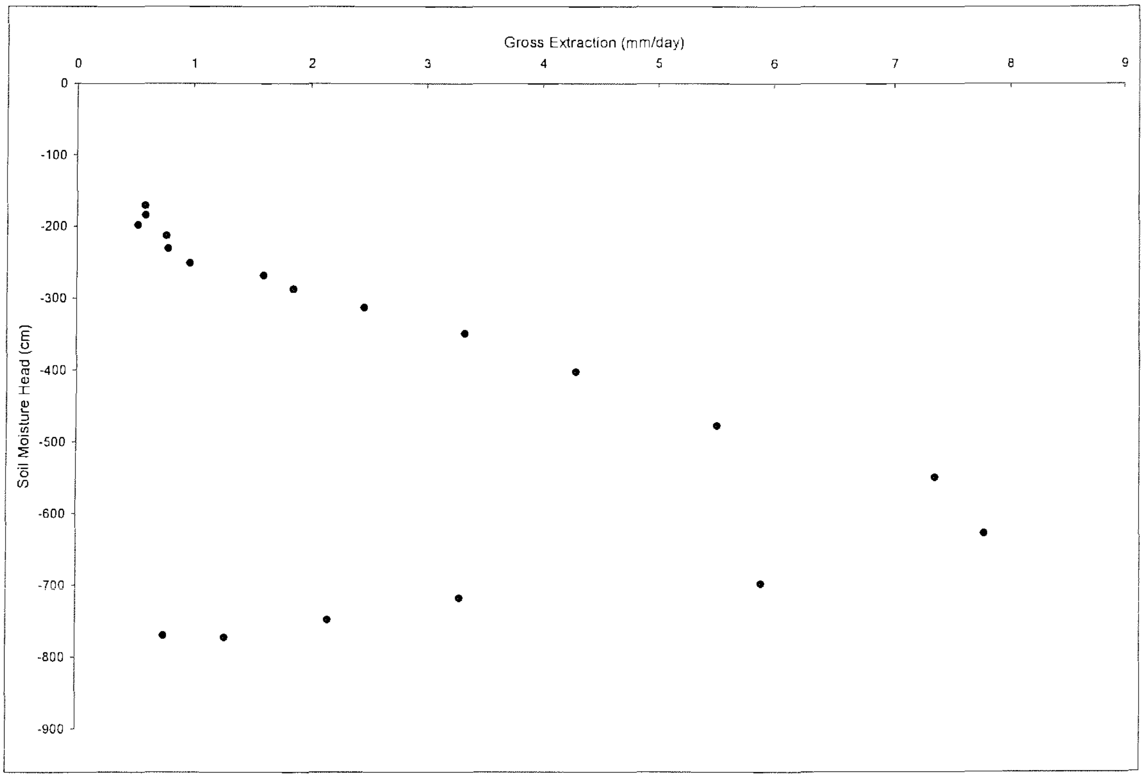

Figure 6.2 Gross Extraction and Soil Moisture Suction, 75 cm Depth Soil Layer

6.5 Irrigation and Groundwater Management

It is clear from this study that irrigation was inadequate and applied at the wrong times in the fields studied. This was due to the 'supply-led' water management strategy used by the water controller (Brigadier) which had to fit within the irrigation schedule decided by the irrigation authority that controlled the main Arys-Turkestan (ARTUR) canal.

Water from the main ARTUR canal was diverted down each main channel (in this case R28, Figure 3.2) based on cropped area planned at the beginning of the season, and the system hydromodule design value of between 0.6 to 1.0 l/s/ha. Conveyance and distribution losses were included in the calculation for discharge to each channel from the main canal. These losses were based on Soviet design parameters when channels were concrete lined with working gates and head regulators. Due to the current status of system infrastructure this has led to gross under and over estimates of irrigation requirements, with a large proportion of irrigation water entering the groundwater as seepage from the channels. This water effectively provided sub-irrigation for the farmer's fields.

Many of the irrigation channels contained water throughout the season. The Brigadier allocated this water to farmers further down the system. However, illegal water offtakes, especially at night caused the system to suffer additional water stress further down the system. Strong friendships and family ties, together with the social hierarchy system of the village maintained a rigid, although not equitable water sharing system.

Despite water allocations to the farmers from the Brigadier, results from the lysimeters show the shortfall in the irrigation schedule adopted by the farmers. Irrigation was applied to the cotton in the lysimeters based on the irrigation schedule farmers *would* have adopted, had water been available. Although, as results show, water did not infiltrate into the soil profile within the field, in the lysimeters 340 mm of water was applied. This amount of water was not enough to sustain the cotton plants and groundwater had to provide the additional water requirements. This was an important observation, as it suggested that even when water was available, farmers did not recognise the need to irrigate their crops and by default the groundwater was used as an additional and very valuable resource. In part this may have been due to a lack of understanding and adequate training of the farmers.

Regardless of the more formal irrigation schedule which should have been adopted, the cotton yields were good, with groundwater supplying a cost effective form of sub-irrigation with minimum water wastage. Salinity is not a problem in this area at present, and the current default irrigation schedule demonstrates good conjunctive use of water, providing a high irrigation efficiency. Further information on the agricultural experience of the farmers and possible water management options for the ARTUR irrigation system can be found in Appendix A6.

It is clear that groundwater plays an important part in the meeting of crop water demand and plays a major part in improving irrigation field efficiency. Given the importance of sub-surface irrigation and the predominance of shallow groundwater in all large irrigation schemes (Prathapar and Qureshi, 1999) it is surprising that most of the vast body of literature is written on crop water requirements and irrigation scheduling with little account of groundwater contributions. As the majority of irrigation is carried out on silty loam soils (Feddes and Lenselink, 1994) it is likely that in large irrigation systems groundwater is contributing to between 20 to 40% of total crop water requirements and irrigation efficiency is much higher than generally perceived.

6.6 The Experimental Approach Used and Recommendations

Revisiting the design of the experiments used to investigate upward flux a number of issues were identified. These are described below:

1. Monolith type free drainage lysimeters were constructed purposefully for this research. Free drainage lysimeters are known to create a 'false' layer of soil at high moisture content (more than in the surrounding field) immediately above the drainage material at the base of the lysimeters, in this case gravel and sand. This can create an unnaturally high capillary fringe (Aboukhaled *et al.*, 1982). For this study this effect was ignored, as the purpose of the lysimeters was to monitor rates of upward flux from static, controlled shallow watertables and a high capillary fringe was therefore expected.

2. Monolith lysimeters are often preferred over compacted soil as they contain a field representative soil column. This provides soil conditions that are as close as possible to field conditions. Despite this, the often-quoted study by Makkink (1959) reported that soil monoliths can still show considerable heterogeneity in soil characteristics and a large variation in permeability. Soil monoliths are also very difficult to extract and require costly equipment and resources.

3. In siting the lysimeters in the research fields care was taken to ensure that they were surrounded with a cotton crop of the same age in all directions and that a suitable buffer area was provided to increase the accuracy of evapotranspiration values. Surrounding soil compaction and disturbance was minimised. Failure to ensure that each lysimeter contained

an equal number of cotton plants affected data, as did the lack of a cotton guard row running between the lysimeters.

4. Shallow groundwater in the lysimeters provided preferential moisture conditions and cotton plants inside the lysimeters were taller than plants in the surrounding field. This increase in plant height is a common occurrence in lysimeters when the surrounding fields are not maintained under the same moisture conditions as the lysimeters. Taller plants and bare soil surrounding the lysimeters will have increased evapotranspiration from the lysimeters when compared to the surrounding fields estimated using Penman-Monteith. These 'effects' are difficult to reduce unless the surrounding fields form part of the same experiment. In any working irrigation system this is difficult to achieve.

5. Maintaining the shallow groundwater at pre-determined fixed levels within the lysimeters proved challenging. Applying water to the groundwater via the external piezometer caused rapid fluctuations in groundwater levels and most likely an increase in the height of capillary fringe. Although groundwater depth was closely recorded drainage from the capillary fringe back into the drainage section of the lysimeters will have occurred at the same time as moisture extraction by the plant roots. Consequently, actual groundwater levels recorded will have contained a margin of recording error. The preferential method to maintain groundwater at a fixed level and to record water use would have been a Mariotte bottle system. However, this was impractical at the experimental site due to (i) the number of lysimeters and large volumes of water would have required a large Mariotte bottle for each lysimeter. This would have required significant additional resources; (ii) equipment availability was a constant problem throughout the season even without a Mariotte bottle system, and; (iii) security was an ever present concern and every attempt was made to limit equipment visibility in the experimental fields.

6. A more reliable, but not representative situation would have been to block drains surrounding the study fields to raise the groundwater to a constant level and effectively sub-irrigate the cotton. This would have provided a constant rate of upward water flux which would have been easier to monitor.

7. Automatic logging of groundwater and drain water levels would also have improved understanding of the situation and increased data accuracy.

8. Tensiometers and other soil moisture monitoring equipment should be placed at 15 cm incremental depths vertically down the profile, and where practicable to a maximum depth of

1.5 m. This would provide adequate instrumentation of the soil in the rooting area of the cotton and, provided groundwater was stationary, would show the capillary fringe. Ideally, two replicates per cotton row would also show the infiltration of irrigation water into the rooting area of the soil. This would help in determining the effectiveness of the irrigation events.

Based on the above observations the lysimeters require intensive design and installation activities. Seasonal observations are provided but lysimeters require regular maintenance and are often impractical when used on working irrigation systems. Despite the criticisms of the methodology the findings strongly support field observations using tensiometers.

6.7 Conclusions

It is clear that whilst models and predictive methods are useful in the processes used to estimate upward flux, there are many errors associated with the measurement and use of unsaturated hydraulic conductivity. This is the key element when attempting to predict upward moisture movement. The Zero Flux Plane method (McGowan, 1973) ignores the need for unsaturated conductivity, and in some cases where data permits, allows K to be estimated. However, it is a time consuming method that relies on appropriate rooting profiles to allow accurate estimation of upward flux.

The Diurnal method is based on the extraction and recharge of moisture in the soil profile. Where drying and wetting of the soil profile occurs simultaneously the effects of hysteresis are limited provided wetting and drying occurs at proportional rates. If the amplitude of wetting and drying curves are different then the effect of hysteresis is likely to be more pronounced. When considering the effect of hysteresis it is important to recognise that the changes in soil moisture suction are small when compared to the total suction throughout the profile rooting depth.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Research Conclusions

The newly developed Diurnal Method for estimating upward flux offers a new experimental approach for measuring groundwater contribution to crop water requirements, providing comparable results with estimates from other approaches based on Darcy's Law. The research was conducted in the Syr Darya River Basin in South Kazakhstan using soil moisture monitoring equipment new to Central Asian conditions.

One of the main aims of this research was to establish the importance of upward flux in contributing to irrigated crop water requirements. Specific objectives were:

1. further understand the processes involved in soil water movement in a cropped soil;
2. develop an approach to estimate upward flux into a soil profile from shallow groundwater;
3. test and compare the validity of the new methodology for estimating upward flux with estimates made by other approaches such as Darcy's Law based methodologies; and
4. estimate the seasonal groundwater contribution to crop water requirements in an irrigation system in the Syr Darya basin in South Kazakhstan.

Based on this research it is clear that capillary upward moisture flux must be considered in estimating crop water requirements when planning irrigation scheduling, which needs to be considered with the potential salinity hazards in areas with shallow watertables.

A new method called the Diurnal Method was developed to estimate the rate of upward soil water flux into crop rooting zones. This method does not require knowledge of unsaturated hydraulic conductivity. Using the Diurnal method and more traditional approaches such as moisture balances and Darcy's Law an estimate was made of the groundwater contribution to crop water requirements.

Results of this research indicate that:

1. In the Arys-Turkestan irrigation system the new Diurnal Method estimated average rates of upward flux between 1.6 to 2.5 mm/d. At times upward flux may have been as high as 6 mm/d, providing 100% of potential crop water requirements.

2. The Diurnal method provided results which were consistent with field and lysimeter moisture balances and Darcy's Law based on the hydraulic gradient in the soil matrix. Average rates of

1.86 mm/d capillary upward flux were evident. Only short periods of upward moisture movement were evident when using Darcy's method due to the dry soil.

3. The new Diurnal Method can be easily adapted to other soil types with shallow watertable. This method also provides estimates of capillary upward flux and crop water demand without the need for detailed knowledge of soil hydraulic properties, subsurface flow patterns or crop and other vegetation characteristics.

4. At the height of the season, when crop growth rates and potential evapotranspiration are high, there is an obvious pattern of water extraction during the day time and recharge from deeper in the profile overnight. The onset, duration and proximity of the periods of extraction and recharge are transient in nature, determined by unsaturated hydraulic conductivity, crop moisture conditions and stress, and the climate.

5. The new Diurnal method should be used with caution. The nature of the dynamic processes driving moisture movement in the soil matrix requires adequate monitoring of soil moisture and groundwater depth.

6. The ARTUR irrigation system is heavily reliant on groundwater as a form of energy-efficient sub-irrigation.

7. Groundwater contributes between 43 to 67 % of seasonal average cotton water requirements.

8. Scheduling irrigation to maintain soil moisture suction above that of field capacity may be just as beneficial to plants that are able to use a supplementary water source, such as shallow groundwater. Where upward flux occurs the need to maintain low soil moisture suctions is not such a priority, provided crops are well established with adequate root development. This adds flexibility to irrigation schedules both in terms of timing (by extending the irrigation interval) and quantity of water.

9. When upward flux is not considered and evapotranspiration is estimated from soil moisture depletion data seasonal crop water use can be underestimated. Where irrigation water is in plentiful supply this may cause over-irrigation. This could, in some cases contribute to the further raising of shallow groundwater.

10. Results from lysimeters were similar to the rate of upward flux estimated using the Diurnal method. In the lysimeters, groundwater maintained at a depth of 1 m from the soil surface

may have contributed up to 72% of seasonal cotton evapotranspiration, up to 59% of seasonal cotton evapotranspiration when maintained at a depth of 1.5 m deep, and 45% of seasonal cotton evapotranspiration when maintained at 2 m deep.

11. Where a crop is not water stressed above a shallow watertable it will, depending on crop growth stage, use shallower water in the profile from irrigation. Cotton plants used irrigation water in preference to groundwater early on in the season. As roots developed and evapotranspiration rates increased groundwater became the preferred source of water. This may have been because it was the only source of water to the crop.

The paradox is that leaking irrigation channels and poorly maintained infrastructure combined with inefficient irrigation practices in the ARTUR system cause the high groundwater levels. High groundwater is inadvertently sustaining crops and producing adequate yields via upward flux. However, possible long-term gradual salinisation of the root zone and decreased soil aeration may cause problems in the ARTUR system, as it has in other Kazakh and Central Asian irrigation schemes.

This research has contributed to the development of new knowledge by:

1. developing the new Diurnal method to estimate capillary upward flux from shallow groundwater;

2. estimating groundwater contribution to crop water requirements in a working irrigation system under arid conditions, and

3. highlighted the crucial role of unsaturated hydraulic conductivity in providing shallow groundwater to crops, and the potential beneficial role shallow groundwater can play in irrigation schedules.

9.2 Recommendations for Further Research

Based on the findings of this study a number of recommendations have been made for further research:

1. The Diurnal Method requires further testing in different soil types, climatic conditions and watertable depths where different crops with shallow and deep rooting depths are grown. Controlled laboratory based experiments would provide the best environment to fully test

the new method. The method may then be useful in calibrating existing generic methods to actual field situations.

2. Further investigation is required using the Diurnal method to expand understanding on the process of moisture recharge overnight and the reduction in moisture extraction at the warmest part of the day. Reduction in moisture extraction during the warmest hours may represent a reduction in transpiration due to plant stress.

3. Identification of key soil moisture suction readings that allow moisture recharge would be useful for different soil types. This may lead to identification of key soil moisture contents at different depths that allow combination of groundwater and surface water in irrigation schedules. This may contribute to the debate over the use of empirical field capacity values and their use in practical irrigation schedules.

4. The Diurnal method may also allow the monitoring of moisture extraction by the plant together with soil suction. Further investigation on this approach is required, but this may allow the identification of potential values for hydraulic conductivity. This would be especially useful in areas with different soil types, as upward flux will occur at different rates. Applying generic rates for upward flux on a regional scale may therefore further increase water wastage. Further information on upward flux based on soil type, crop type and rooting depth would also add greater flexibility and value to existing crop water models such as CROPWAT and the widely used FAO Irrigation and Drainage papers.

5. During future soil moisture studies in the ARTUR system it is recommended that ThetaProbes are buried to a maximum depth of between 2 to 2.5 m and are logged directly in millivolts. Improved accuracy in soil moisture monitoring can be achieved by placing the probes at closer incremental depths in the soil profile, although this is difficult to achieve when inserting horizontally or at an angle. Care must be taken when extrapolating ThetaProbe readings wider in the soil profile as they only measure the moisture content of a small volume of soil.

6. It is understood that new electronic tensiometer equipment is currently under development that would enable soil moisture suction to be measured down to 3 bar suction. This would be useful for further testing of the Diurnal method. Accurate measurement of leaf water potential using a thermocouple psychrometer would provide a better understanding of crop moisture stress and may help in understanding the process of diurnal capillary upward flux from shallow groundwater.

7. Further investigation in the application of the new Diurnal method may provide key values for soil moisture suction which could aid in the determination of values for hydraulic conductivity. These values are useful when knowledge of soil moisture suctions are required to enable use of groundwater as part of an irrigation schedule. The Diurnal method may be useful in determining upward salt movement and aid in the early identification of secondary salinisation.

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APPENDIX A1

IRRIGATION AND DRAINAGE IN CENTRAL ASIA

A1. IRRIGATION AND DRAINAGE IN CENTRAL ASIA

A1.1 Irrigation and Drainage Development in Kazakhstan

Irrigation expansion began in Central Asia during the 1930's. At first, the gradual development of irrigated agriculture did not affect the regions hydrological balance or environment. In 1950 2.9 million ha of land in Central Asia was irrigated with 6 km^3 of water (Glantz, *et al.*, 1993; Hollis, 1978). However, between 1965 and 1970 irrigation expansion grew at 1% annually, reaching 2% annually between 1970 to 1975 (Saiko, 1998).

Despite some specialists warning of the dangers of further irrigation expansion (e.g. Borovskiy, 1978), others, such as Gel'bukh and Dzhogan (1975), suggested that current and future water use 'improvement measures' would increase available water for further irrigation expansion. By 1980 6 million ha was being irrigated (Tanton and Heaven, 1999) with over 100 km^3 of water (Hollis, 1978). This rose to 7.2 million ha by the late 1980's (Glantz *et al.*, 1993) and peaked at 8 million ha of irrigated land in 1990 using 134 km^3 of water (Micklin, 1992b).

During the 1950's many large scale irrigation projects were constructed within Central Asia with the aim of achieving 'cotton independence' (Glantz, *et al.*, 1993; Saiko, 1995), but this and other rapid economic development were followed by immense desertification problems (Bedford, 1996). Irrigation in Central Asia is by furrow, the least effective method with an efficiency of between 30 to 40% [1](Tanton and Heaven, 1999, Peterson, 1993; Reshetkina, 1975) (*although when a shallow groundwater is present much of the water may be recovered by capillary rise*), consequently, as water was abstracted from rivers and used for agricultural production and the filling of reservoirs less water flowed downstream. As millions moved to cities, little notice was taken of the environmental effects of intensive irrigated agriculture and urbanization (Suny, 1998).

As with any large irrigation system, drainage is an integral part, designed to transport surface run-off water and percolation flows away from the fields. This water can contain salts, and residual chemicals such as pesticides, herbicides and fertilisers. Provided the drainage system is designed correctly the water table can be maintained at an 'optimum' level (Dukhovny, 1981), also called the 'critical' depth (Filosofov, 1948; Kovda, 1961, van Hoorn, 1978). This level is based on the ability of the soil to transmit water and salts from the water table into the crop rooting zone, and ultimately the soil surface by capillary rise (Talsma, 1963; Smedema and Rycroft, 1983).

[1] Heaven *et al.* (2002) conclude that system wide irrigation efficiencies may be, in some cases <20%.

An extensive drainage system was constructed alongside the irrigation developments in the Aral Sea basin during 1950 to 1980, comprising mainly of open field drains, with some sub-surface tiled drainage (Sherokova, 1997). At the time, it was noted by specialists within Central Asia that high groundwater levels and soil salinisation was naturally occurring due to the minimal land gradients, soil types, shallow watertable and intense climate (Sukhachev, 1958). A few specialists expressed caution at some of the future plans for intensifying irrigation development (Legostaev, 1958). Gel'bukh and Dzhogan (1975), however, claimed that the complicated hydrological balance of the Syr Darya basin did not allow an accurate estimation of the available water resources of the region, and in reality much more water was available for irrigation.

Currently, the drainage system in the Aral Sea basin has a number of problems (Sherokova, 1997; Dukhovny, 1996). Many of the main collector drains discharge into the rivers and canals, increasing the salinity of irrigation water, with other collectors discharging into drainage sinks (Orlovsky *et al.*, 2001). These 'sinks' are natural depressions that have no outflow, causing localised waterlogging – and no return flows to the rivers. A large number of drains are in poor condition, are blocked or damaged, or were initially poorly designed (FAO, 1997b). It is estimated that only 10 percent of the vertical drainage systems are in use due to the high costs of pumping (FAO, 1997b). Vertical drainage, in non-saline areas, can use pumped groundwater as an irrigation resource, whilst lowering the watertable. In some areas this has the added advantage of lowering the groundwater into more permeable materials that have a higher hydraulic conductivity (Vyishpolskiy, 1999a).

Irrigation in Kazakhstan is said to currently consist of controlled irrigation on 2.5 million ha and spate irrigation on 1.10 million ha (FAO, 1997b). The evolution of the irrigated area over the last 20 years has shown progressive and constant increase in the areas equipped for surface irrigation, while spate irrigated areas have started to decrease (FAO, 1997b). The new financially autonomous water management bodies are struggling to control the irrigation systems. Staff shortages and lack of funds combined with the existing poor irrigation infrastructure cause irrigation efficiencies to decrease further. Seepage from unlined canals and rigid irrigation scheduling has lead to further waterlogging and losses in production.

A1.2 Limnological Changes of the Aral Sea and their Impact

The Aral Sea is a landlocked lake located in the deserts of Central Asia and is primarily fed by two large rivers, the Amu Darya and the Syr Darya. Over the past 40 years the sea has shrunk considerably, as the expanding irrigation systems reduced the river flows reaching it (Williams, 1996).

A range of environmental and human problems has accompanied the Aral Sea's desiccation. These are well documented by many authors (e.g.: Glantz, 1999; Ivanov *et al.*, 1996; Klötzi, 1994; Saiko, 1995; Sinnott, 1992; Kotlyakov, 1991). In 1960 the Aral Sea was the world's fourth largest lake, with a healthy fish population and a major source of local employment, supporting paper making, logging and hunting industries (Micklin, 1992a). The reduction of river inflow to the sea for irrigation purposes decreased inflow from between 62-72 km^3 per year in 1960, to only 7 km^3 in 1996. The surface of the sea was reduced by 33,000 km^2 and the sea level fell by 37 m (Tanton and Heaven, 1999; Bortnik, 1996), becoming saline and devoid of any aquatic life (Williams and Aladin, 1991). The sea is continuing to shrink and has now formed two lakes, the smallest is hyper-saline and no longer sustainable (Glazovskiy, 1991; Micklin 1991a), whilst the larger has the potential to be maintained at its current level (Aladin *et al.*, 1995; Kotlyakov *et al.*, 1992).

Evaporative losses from any shrinking water body diminish as its area decreases, forcing the water balance toward equilibrium. However, the Aral Sea is still decreasing as the difference between inflow and net evaporation is currently large and negative (Micklin, 1992b). As the sea continues to shrink large quantities of salts are left exposed on the dry sea bed, an area of approximately 30,000 km^2 (Micklin, 1994). The salt concentration does not allow natural or artificial vegetation re-growth on the seabed, leaving the salt exposed. Consequently, the airborne transport of salt and dust has become a severe problem, with salt storms moving over the ecologically and agriculturally important delta of the Amu Darya River (Nasonov and Ruziev 1998. Micklin, 1991b). The salts, deposited as aerosols by rain and dew are toxic to plants, harmful to animals who ingest them during grazing, and have been reported to cause electrical shorting of power lines leading to fires when they are deposited on insulators (Precoda, 1991).

Deterioration of the environment has led to an increase in human morbidity and mortality. The reduction of river flow, the salinisation and pollution by agricultural, industrial, and urban effluents, and the lowering of groundwater levels close to the Sea have caused drinking water supply problems (Akchurin, 1992; Kuznetsov, 1992; Postel, 1999). Drinking water contamination is believed to be the main cause of high rates of intestinal illnesses, viral hepatitis, kidney failure, liver ailments, typhoid, cardiovascular diseases, gastrointestinal problems, high rates of congenital deformation, and oesophageal cancer (Razakov *et al.*, 1996; Ellis, 1990). O'Hara *et al.* (2000) found that dust deposition rates south of the Aral Sea were among the highest in the world, with considerable contamination of airborne dust with the organophosphate phosalone[2]. The child mortality rate has increased in the region, allegedly by 15 times over ten years in some areas (Micklin, 1992b). Reports are common on the contamination of mothers milk, another concern for

[2] An organophosphate pesticide once widely used throughout the region.

an area with a life expectancy 20 years or less than the rest of the Central Asian Republics (Glantz, *et al*, 1993).

The sea also provided regulation of the Central Asian climate, reducing the impact of harsh Siberian winds, and lowering summer temperatures. The Aral Sea basin covers two distinct climatic zones, that of subtropical latitudes and the southern limit of temperate latitudes. The basin is surrounded by deserts, is a long distance from the ocean and therefore has a distinct arid climate. However, with the desiccation of the sea, a noticeable continental climatic effect has been observed (Bedford, 1996). Cooler winters are more common, the humidity has decreased, and summers are generally shorter but warmer (Peterson, 1993). This climatic effect was originally confined to within 50 to 60 km of the former sea shoreline (Micklin, 1988), but is now affecting a much larger area along the Syr Darya basin according to some researchers such as Glantz (2002b); Ragab and Prudhomme (2002); Zolotokrylin (1999); Glantz *et al.* (1993); and Raskin *et al.* (1992).

The shrinking of the Aral Sea and the problems associated with it are well documented by many Western and FSU authors, and the reader is referred to these (e.g.: Micklin and Williams, 1996; Bortnik *et al.*, 1992; Gorodetskaya and Kes, 1978; Pearce, 1992; Perera, 1993; Rafikov, 1983).

One concern in Kazakhstan at present is that other water bodies may follow the example of the Aral Sea. Kraznova (2000) suggests that Lake Balkash in Eastern Kazakhstan is shrinking, as river flow is reduced from the Tien Shan mountains. As China's population continues to grow, they are themselves diverting more water for irrigation purposes, and hence reducing headwater river flow into Kazakhstan.

Water conveyance and utilisation consumes large amounts of energy in Central Asia. Water supplies are necessary not only for irrigated agriculture, but also hydropower generation, industry, recreation and the environment. Policy makers who allocate funds to assist in the balance of water supply and demand require good data in the form of water balances. This will become increasingly important in Central Asia as the expanding population requires the national development of water supply and sanitation services, and the need for further energy generation (McKinney and Kenshimov, 2000). As water shortage may cause regional tensions and even conflict in the future (ICG, 2002; Horsman, 2001; Vinogradov, 1996; Klötzi, 1994) the need for more accurate water balances increases. HABAR (2000) and Tabyshalieva (undated) indicate that water shortages may have already caused local conflicts in water supplies and usage between farmers in Central Asian states.

UNESCO (2000) believes that the basic strategy for water management in the Aral Sea basin should concentrate on salt storage. Reduction in salt mobilisation can be largely achieved through localised activities, whereas strategic salt storage needs a broader approach. At present, salt is stored in irrigated areas where drainage is not maintained, in desert depressions, some of which are nearing capacity, and in the Aral Sea itself. It is inevitable that areas within the region will need to be assigned as 'salt sinks'. Reducing salt mobilisation would in turn decrease the need for leaching irrigated areas. Decreasing salt mobilisation would further reduce water demand for irrigation.

APPENDIX A2

THEORY OF SOIL WATER FLOW

EXAMPLE OF DIURNAL SOIL MOISTURE MOVEMENT

A2.1 THEORY OF SOIL WATER FLOW

A2.1 Theory of Soil Water Flow

Soil water flow is the transport process within the soil where water is moved from one point to another. This is dependent on a number of factors. Irrigation and precipitation water enters the soil due to the process of infiltration, which is controlled by the rate of soil water movement below the soil surface (Nielsen *et al.* 1964; Biswas *et al.* 1966). Soil water movement also controls the supply of water for plant uptake and for evaporation at the soil-atmosphere interface.

Plants obtain most of their water needs by draining the water within pores of the soil within the rootzone. As these drain, soil suction in the rootzone increases which causes water with a higher potential (i.e.: in the saturated zone) to flow upwards towards it. This water supplements the root supply.

A2.2 Water Movement in Response to a Potential Gradient

The majority of the soil profile underlying agricultural crops is unsaturated. For optimum capillary rise to occur, the soil must contain the correctly sized particles to allow water to flow upwards. Fine textured soils can 'raise' water higher than sandy soils, due to the small size of the pores, but the rate of rise is slow due to friction losses (i.e.: a sandy loam can raise water 0.5 m above the water table, whereas clay soils can raise water more than 2 m). In sandy soils, capillary rise can be rapid, but the height of rise is not great as many of the pores are non-capillary (Wind, 1955; Childs, 1969).

Water movement in soil also occurs as a result of thermal and osmotic gradients. The forces governing soil water flow can therefore be described by the energy concept. According to this principle, water moves from points with high energy status to points with lower energy status (Kabat and Beekma, 1994). The energy status of water is called the 'water matric potential' for flow in the unsaturated zone (Nielsen *et al.*, 1986), which is a result of the interaction between cohesive and adhesive forces of air, water and the soil matrix. The total potential of soil water (ϕ) is, the sum of several energy components and can be written as:

$$\phi = \phi_m + \phi_{ex} + \phi_{en} + \phi_{os} + \phi_g \qquad [A2.1]$$

(Feddes *et al.*, 1988)

where:

ϕ : total soil water pressure head or potential (m or bar)

ϕ_m	:	matric potential arising from interactions between the soil matrix and water
ϕ_{ex}	:	potential arising from the external gas pressure
ϕ_{en}	:	overburden potential arising from an external load such as swelling of the soil
ϕ_{os}	:	osmotic potential arising from the presence of solutes in the soil water
ϕ_g	:	gravitational potential, arising from the gravitational force.

The process of water movement through unsaturated soil was recognised by Buckingham (1907). He related the flow of water to suction gradients within the soil material and later introduced the pressure or head term (h), which is used in hydrological studies. To explain the components and assumptions of equation A2.1 further:

- The matric head in unsaturated soil is negative, as work is required to draw water against the soil-matric forces. At the phreatic surface (the position in the soil horizon where pressure in the groundwater is equal to atmospheric pressure) $\phi_m = h_m = 0$;
- A change in the matric head may also be due to changes in the localised pressure of air; in natural soil conditions this change is regarded as negligible, therefore $\phi_{ex} = h_{ex} = 0$;
- Clay soils that swell and exert a pressure will increase the pressure on the total water head. In non-swelling soils $\phi_{en} = h_{en} = 0$ (Feddes *et al.*, 1988);
- Normally, in soil water studies the osmotic potential is regarded as zero. This is because the soil water is assumed to have the same chemical composition as the groundwater, and in general, does not significantly affect water flow (Hillel, 1971). Where this is not the case, as for many irrigated soils, $\phi_{os} = h_{os}$ must be adjusted accordingly;
- When water is located at an elevation different from that of the reference level, the gravitational potential or head $\phi_g = h_g$ must be included. Normally h_g is referred to as z – an elevation above a reference level, being positive above it and negative below it.

The sum of all these components is referred to as the total soil water pressure ϕ or head H (H = Σh) or soil moisture suction, and can be measured in the field using a waterfilled tensiometer (Shaw, 1988), but only for a limited range of head (normally ≤0.80 bar) (Richards, 1949; Jim-Yeh and Guzman-Guzman, 1995; Otto, 1998). Richards (1949) investigated the use of porous cups and vacuum gauges to measure the capillary force potential proposed in the work of Buckingham (1907), and his clarification on the design and use of tensiometers is the basis for soil water potential measurement today.

Water potential or head may be used to denote the mechanical work required to transfer a unit of water from a standard reference, where the potential is zero, to a point where the potential has a defined value (Smedema and Rycroft, 1983). Kabat and Beekma (1994) used an example where the distance between two points equalled zero to show the relationship between the mechanical force and energy water potential concepts. The force acting on water in any direction can be defined as:

$$\frac{F_T}{m} = -\frac{\partial H}{\partial z}$$

[A2.2]
Phene *et al.* (1990)

where:

F_T	:	total of forces (N)
m	:	mass of water (kg)
H	:	total soil water head (m)
z	:	elevation head (m)

According to equation A2.2, the difference in head determines the direction and magnitude of soil water flow, a negative sign indicating force working in the direction of decreasing water potential, i.e.: as the suction force of the soil increases (Brady, 1974). Figure A2.1 illustrates the pattern of matric potential at depth in a soil profile with a water table present. After irrigation, soil moisture redistributes within the profile until matric potential is equal, but opposite in direction to the gravitational potential or head. The water in the soil is held in a state of static equilibrium and no force exists for water movement.

Figure A2.1 also shows the volumetric moisture content throughout the soil profile. At the watertable and within the capillary fringe the soil is saturated and hence has a saturation moisture content (0.41 m^3/m^3). Within the unsaturated zone the moisture content will decrease approaching the soil surface due to surface evaporation of soil water, depending on local climatic conditions (curve t_1). If vegetation is present, roots aid drying of the soil by extracting water from deeper in the profile indicated by curve t_2. Should irrigation or rainfall occur the surface may become initially super-saturated (curve t_3) before the profile equilibrates back to uniform moisture conditions, and eventually curve t_1 conditions due to crop evapotranspiration.

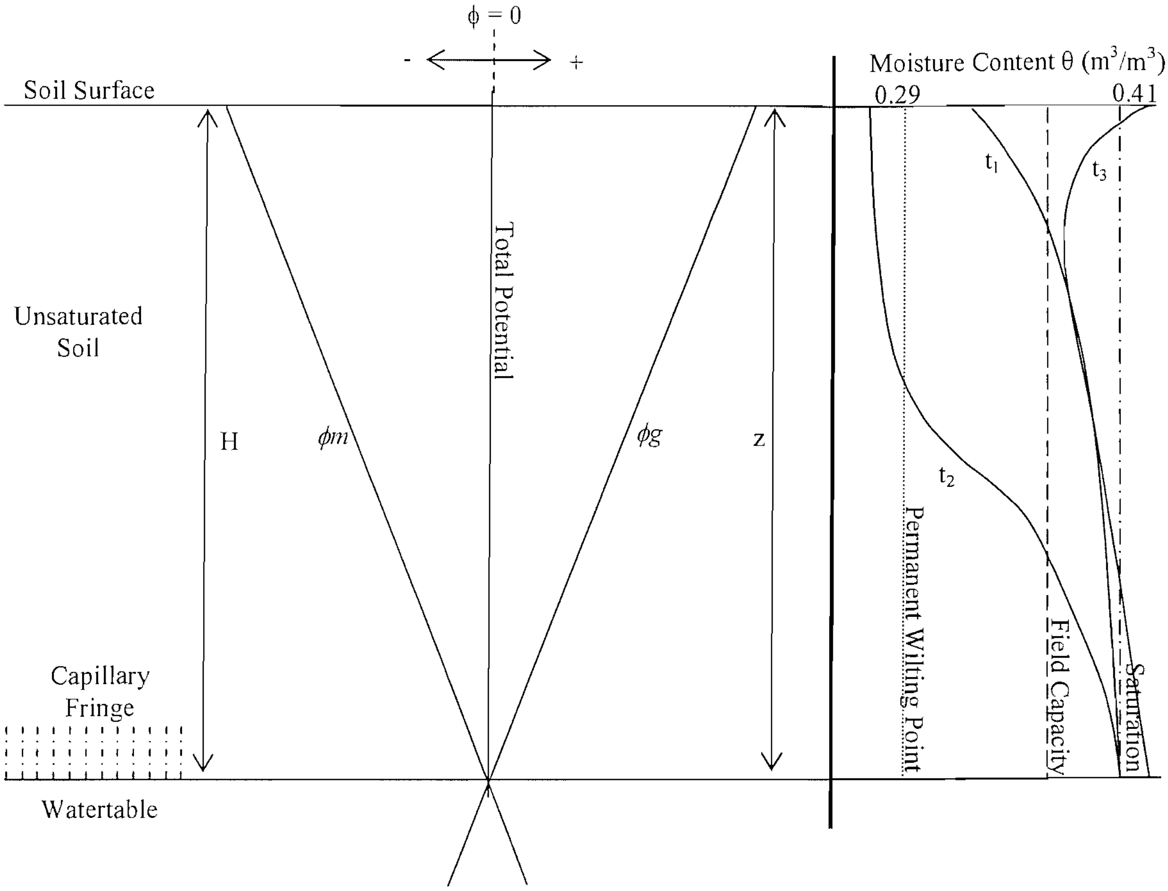


Figure A2.1 Example Soil Water Potentials and Moisture Contents in a Static Equilibrium Soil Water Profile
(*Source*: adapted from Smedema and Rycroft, 1983)

Figure A2.1 indicates possible values for field capacity and the permanent wilting point. For clarification, in this study the following definitions apply:

- **Moisture Content** – in this study represents soil moisture content on a volumetric scale (θ) unless specifically stated in other units. Volumetric moisture content (%) is determined by multiplying the weight of water by the dry bulk density of the soil ad dividing by the dry weight of the soil to give the amount of water held in the soil on a volume basis (m^3/m^3);
- **Field Capacity** – when soil is saturated all the pores are full of water. Large pores drain easily under gravity and are soon replaced by air (Veihmeyer and Hendrickson, 1931). However, a large amount of water may still be retained in the smaller soil pores. The moisture content at the point where drainage stops is called field capacity and is represented volumetrically (m^3/m^3). Field Capacity is only a momentary situation in a soil profile and the rate that it occurs depends on the soil type, existing moisture content of the soil and depth to groundwater;

- **Permanent Wilting Point** – once the soil has reached field capacity no more water is lost through gravitational drainage. The remaining water can be used by plants and is removed from the soil by plant roots. As water is removed, smaller and smaller soil pores are emptied. Finally, the remaining water is held so tightly by adsorption and capillarity that roots cannot extract water at a sufficient rate to meet the plants water demand (Veihmeyer and Hendrickson, 1949). At this point the soil moisture content is at the permanent wilting point (m^3/m^3) and plants wilt and cannot recover;
- **Total Available Water** - the difference between moisture content at field capacity and permanent wilting point. This represents the proportion of soil water that is potentially available for plants to use and is expressed in millimetres of available water per metre depth of soil (mm/m) (Kabat and Beekma, 1994; Hall *et al.*, 1977);
- **Easily Available Water** – is the amount of water a plant can 'easily' extract. A figure of 50% is often used as the proportion of Total Available Water which is 'easily' available (Hillel, 1982). Plants will experience stress when the amount of easily available water is exceeded (normally >1 bar soil moisture suction) which leads to reductions in crop yield.

A2.3 Soil Water Flow and Hydraulic Conductivity

Section A2.2 described how soil water flow is caused by differences in hydraulic head, and will strive to attain equilibrium conditions within the soil-water system. The rate and direction of water movement through saturated soil obeys Darcy's Law (Darcy, 1856), which can be written as:

$$q = -K\frac{\partial H}{\partial z}$$

[A2.3]
(Darcy, 1856)

where:

q	:	discharge per unit area (m/d)
K	:	hydraulic conductivity (m/d)

Darcy's Law states that the rate of water movement through a soil is proportional to the gradient of the soil water potential or head for isothermal conditions. The hydraulic conductivity K is the constant of proportionality, which represents the discharge per unit area at unit hydraulic gradient (Wind, 1960; Smedema and Rycroft, 1983).

In saturated media, the hydraulic conductivity is a constant depending on the type of soil (Rijtema, 1965). However, for unsaturated soils the hydraulic conductivity is dependent on the soil moisture content, which in turn is related to the soil moisture characteristic and the matric potential. The hydraulic conductivity of a field soil may therefore vary considerably (Bouwer, 1978).

Figure A2.2 shows the decrease in hydraulic conductivity and the corresponding increase in soil moisture suction as *h* in cm of water. K_h/K represents the ratio between unsaturated hydraulic conductivity (K_h) and saturated conductivity (K). Where soil moisture suction is less than – 25 cm all three soil types show unsaturated conductivity is the same as saturated conductivity ($K_h/K = 1$). The general shape of the three curves reflects the proportional distribution of the soil water held in the macro pores, in micro pores, and finally as film water. Sand has a higher proportion of macro pores through which water is able to flow freely, resulting in a higher K_h/K value but this rapidly decreases to zero at a low soil moisture suction when most of the macro pores have drained and soil moisture decreases to the point where water in the soil no longer forms effective hydraulic continuity.

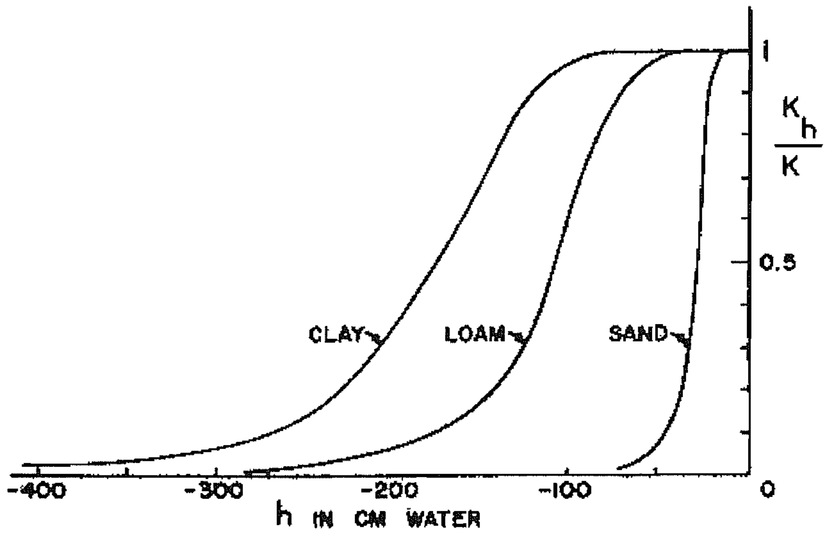


Figure A2.2 Relationship Between Soil Water Suction (h) and Magnitude of Change in Hydraulic Conductivity (K_h/K) for Different Soil Types
(*Source*: Bouwer, 1978)

During saturated flow in soil, the total pore space is filled with water, and is therefore available for flow. During unsaturated flow a proportion of the pores are filled with air and do not participate in flow. Water then flows only through the finer pores, which may still be saturated depending on the media, or else via films around the soil particles. Thus, with decreasing soil water content, or increasing soil matric suction the area available for flow decreases, and the unsaturated hydraulic conductivity decreases. Nielsen *et al.* (1972; 1973) state that it is not unusual for hydraulic conductivity values to range logarithmically for water contents measured in the field, and

Poulovassilis and Tzimas (1975) reported differences in hydraulic conductivity of as much as 100 percent in equally wet soil that had different wetting and drying histories. The majority of moisture flow to plant roots; infiltration and moisture re-distribution after irrigation, or rainfall moves through the soil as unsaturated flow. More importantly for this study, the unsaturated zone provides the link between the groundwater and surface water environments.

Youngs (1982) suggested that minor changes in soil structure and the effects of current and ancient plant roots change the sensitivity and therefore accurate measurement of unsaturated conductivity. Nielsen *et al.* (1986) state that the hydraulic conductivity of a soil can change an order of magnitude by merely altering the concentration or the kinds of cations associated with the charged soil particles. Compared with saturated conditions, during unsaturated flow the importance of film flow and water-solute-particle pore surface interactions become increasingly important as the soil becomes progressively drier.

Despite the importance of unsaturated flow it is still a difficult parameter to measure; yet the relationships between hydraulic conductivity, moisture content and soil matric potential are crucial parameters for understanding moisture movement in the soil. Over the last fifty years several methods have been developed to determine these relationships, both in situ and laboratory based. The future need for increased accuracy of predicting these relationships is unlikely to diminish, as research continues to highlight the rapid spatial and temporal variations in moisture and suction relationships within small experimental areas (Nielsen *et al.*, 1973).

The simplest method to estimate K_{unsat} is from soil moisture characteristic data. The soil moisture characteristic is relatively easily determined from soil samples or statistical pore-size distribution models (Mualem, 1976). A number of conductivity models exist such as Gardner (1958); Campbell (1974); and Van Genuchten (1980).

The most direct method to determine the unsaturated hydraulic conductivity for a given moisture content has been used by Childs (1945), Bouwer and Jackson (1974) and many others (e.g.: Ragab *et al.*, 1986; Hillel, *et al.*, 1972; Moore, 1939; 1940), using the long soil filled column technique. Water is applied to the top of a column of soil at a constant rate q that is less than the product of the saturated hydraulic conductivity K and the cross sectional area A of the soil column. This produces unsaturated flow through the soil column. The water is allowed to drain freely from the bottom of the column. The remainder of the soil column will be at uniform moisture content θ and pressure head h. A constant h value throughout the soil column results in a hydraulic gradient of 1, resulting in unsaturated conductivity being the same as downward flow rate (q/A). Frequent measurement of h in the soil column with tensiometers at different q rates yields the relationship between unsaturated hydraulic conductivity and h.

The disadvantage with the long soil column technique is the length of time required for establishing equilibrium after q is changed, especially for fine textured soils. Watson (1967) speeded up this procedure by creating a zone of entrapped air in the soil column by first saturating the soil, draining it at the bottom, and then re-wetting the soil by ponding water on the surface. When a specific q rate was maintained at the top of the soil column different θ values occurred in the unsaturated zone. Measuring h values at a number of points to determine the vertical hydraulic gradients then allowed calculation of various corresponding values of conductivity and θ for a single q value. The long soil column technique has been slightly adapted for field use by Hillel and Gardner (1970) and Bouma et al. (1971) by applying water through surface crusts or impeding 'layers' to create unsaturated downward flow in underlying material.

Many other techniques have been developed for determining unsaturated hydraulic conductivity such as the 'instantaneous profile method' (Watson, 1966; Subagyono and Verplancke, 2001), which is described by Hillel *et al.* (1972). This relies on the saturation of a free draining soil in the field, which is then covered to prevent evaporation. The hydraulic conductivity is calculated by applying Darcy's Law to frequent measurements of pressure head and water content during the drying phase. These direct methods are relatively simple in concept, but are not practical to use as they are time consuming, especially under field conditions where restrictive initial boundary conditions need to be maintained (such as free drainage of a soil profile). Klute and Dirksen (1986) provide a comprehensive overview of laboratory methods to predict unsaturated conductivity, and Green *et al.*, (1986) for field methods.

The majority of the methods described briefly above rely on Darcy's Law, which was not intended for use in unsaturated conditions, as movement of moisture was dependent on the soil moisture head. Darcy's Law was extended by Richards (1931) to include unsaturated flow, with the provision that the hydraulic conductivity became a function of the soil water content [$K = K(\theta)$]. As θ is related to soil matric potential (suction) via the soil moisture characteristic curve (where pF = log h in cm), then hydraulic conductivity as a function of the soil moisture suction [$K = K(\phi)$] also applies. However, Mualem and Klute (1984) and Ragab and Amer (1986) reported that the relationship $K(\theta)$ shows less hysteresis than $K(\phi)$ and should therefore provide more accurate results when hysteresis is ignored or during drying only.

Substituting Darcy's Law into the equation of continuity which states that *'net inflow must equal the rate of gain of water by the volume element of soil per unit time'*, yields:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left(K(\theta)\frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(K(\theta)\frac{\partial H}{\partial y}\right) + \frac{\partial}{\partial z}\left(K(\theta)\frac{\partial H}{\partial z}\right)$$

[A2.4]

where:

θ : volumetric moisture content (m^3/m^3)

t : time

K : hydraulic conductivity of the soil (m/d)

H : total soil water head (m) [in the x, y, and z directions]

For saturated flow the moisture content does not change with time ($\partial\theta/\partial t$). Richards (1931) presented the differential equation for soil water flow using an analogy to heat flow in a non-homogenous, isotropic, porous media, confirming his theory with a laboratory experiment. In terms of the pressure head, the Richards' equation applies to saturated as well as unsaturated flow. Taking the co-ordinate z as positive downward (i.e. from a soil surface) where the term H is substituted by $z + h$, the Richards' unsaturated flow equation becomes:

$$C(h)\frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left(K(h)\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K(h)\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K(h)\frac{\partial h}{\partial z}\right) + \frac{\partial K(h)}{\partial z}$$

[A2.5]

where:

$C(h)$: specific water capacity (slope of the moisture characteristic curve) = $\partial h/\partial t$

As the majority of soil moisture investigations within irrigation science are concerned with one-dimensional vertical flow, especially when attempting to understand upward flux, Richards' equation can be simplified to:

$$\frac{\partial \theta}{\partial t} = C(h)\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\left(K(h)\frac{\partial h}{\partial z} + K(h)\right) - S(h)$$

[A2.6]

where:

S : sink term, notably plant root extraction

The term S in equation A2.6 is the most difficult to quantify and represents water extraction by a homogenous and isotropic element of the root system. The sink term is important as plant water uptake can be more than half the total change in water storage in the crop rootzone over the entire season (Kabat and Beekma, 1994). Feddes *et al.* (1988) assumed a homogenous root distribution over the soil profile and related the depth of the root zone to the amount of water that could be extracted for transpiration. Prasad (1988) developed this idea further and assumed that plants extracted water from within their rootzone in a linear manner, assuming zero extraction at the bottom on the rootzone. Homaee (1999) contains further details on root extraction models. It is not the purpose here to discuss plant root extraction theory and the reader is referred to detailed investigations by Raats (1973) and Molz (1981).

Richards (1931) equation is used as the primary mathematical expression for unsaturated flow phenomena. However, Miller and Miller (1956) noted that the equation fails to take account of hysteresis effects. To overcome this soil suction or moisture content must be assumed to be monotonic – which is a difficult assumption considering the dynamic movement of water in an irrigated soil profile, especially within a 24 hour period where evapotranspiration occurs in a cropped soil.

Experimental evidence indicates that Richards' equation may not be wholly valid for fine textured soils at low flow rates. Swartzendruber (1963) suggested that a threshold hydraulic gradient may exist below which no flow occurs. In some of Swartzendruber's experiments the proportionality rule in Darcy's Law did not hold true at low moisture contents. Darcy's Law is also thought to be invalid at high flow rates when flow ceases to be laminar (Bos, 1994a). Flow in the unsaturated zone is usually laminar, but it is important to note that exceptions to Darcy's Law may be relevant during near-saturated conditions, for example; Vachaud (1967) claimed that at the point where saturated hydraulic conductivity approaches unsaturated conductivity it is difficult to accurately determine the hydraulic gradient. Freeze (1969) confirmed this by modelling soil moisture flow at the moving boundary between the unsaturated and saturated moisture zones immediately above a fluctuating water table.

Unsaturated flow also poses the problem of flow continuity between inter-aggregate pores and vapour flow, where conventional equations may not be valid. Richards and Moore (1952) identified the possibility of vapour flow moving in the direction of localised temperature gradients, whilst soil moisture film flow moved in the opposite direction due to a hydraulic gradient. Gardner (1958) concluded that in an agricultural field, where a soil tilth is evident, vapour flow of moisture from deeper depths within a soil profile was unimportant in soil moisture studies.

However, recent work by Jalota and Prihar (1992) indicated that at the interface between the soil tilth and untilled layer the profile below was able to supply moisture during low evaporative periods in fine soils, as both liquid and vapour flow. It is doubtful that this moisture would be available to deep rooting agricultural crops. Parlange, *et al.* (1998) observed water vapour movement in a bare silt loam. They estimated very low values for upward moisture movement between 7-10 cm, with a maximum value of 5 x 10^{-6} cm moisture. Such small flows will not contribute to the water available for agricultural crops, although the importance of a moist barrier in the soil surface, preventing further upward vapour movement from deeper in the profile must be recognised (Schelde *et al.*, 1998).

A2.4 Water Movement in Response to Temperature

Changes in soil temperature have a marked effect on several properties related to soil-water transport. Taylor and Stewart (1960) showed that for some soils, temperature effects could exert a greater influence on water content than the pressure potential. Bouyoucos (1915) demonstrated that temperature affected pressure gradients in soil columns under isothermal gradients. Moore (1940) subsequently showed that temperature has a considerable effect on the soil hydraulic properties, mainly due to its effect on viscosity and surface tension.

Soil moisture content influences soil heat flow and distribution, but the converse process also occurs. Soil temperature gradients promote soil moisture movement, particularly in drying soils as moisture movement occurs due to the increase of saturation vapour pressure with temperature (Jensen *et al.*, 1990). In a partly dry soil, the water phase is not continuous between pores, but is present only at certain preferred locations within the soil matrix. In these circumstances, moisture movement is predominantly due to vapour diffusion (Richards and Moore, 1952). In the presence of a temperature gradient, water tends to be distilled from warmer regions to condense in cooler regions (Smiles *et al.*, 1985; Danfors, 1963). Nielsen *et al.* (1986) reported that due to latent heat effects, this process may also transfer heat and could potentially make a significant contribution to total heat flow as soils dry.

Because of the heat storage and relative constant temperatures of deeper soil layers, the moisture flow due to temperature gradients is usually downward in summer and upward in winter (Constantz, 1982). The upward movement in winter is partly responsible for the freezing of 'dry' soils, and the subsequent muddiness on thawing, even when no precipitation or irrigation has occurred.

The most commonly used physically based model for estimating the flow of soil moisture and heat in unsaturated soil is that of Philip and de Vries (1957). They developed a theory to predict water movement as a consequence of gradients in temperature and water content. This was later generalised by Sophocleous (1979) and Milly (1982) to make the theory applicable to non-homogenous soils by introducing the pressure head as the dependent variable instead of the moisture content.

Several simulation models have been based on this theory (e.g.: Schieldge *et al.*, 1982; van de Grind *et al.*, 1985; Braud *et al.*, 1995; Schelde, *et al.*, 1998) and have been used for numerical investigations of soil moisture in the laboratory and in the field. Milly (1984) showed that the liquid and vapour flows due to temperature gradients are much less important than the flows due to gradients in pressure potential. The omission of all thermal effects in his simulations introduced only a small error with respect to the total soil evaporation. The effect of temperature on soil moisture potential was therefore not considered in this study.

A2.5 Evaporation and Transpiration Demand

Evaporation may take place from an open water surface, the soil surface or from intercepted water on plant leaves. The rate of evaporation is controlled by the surrounding climate. Transpiration is the loss of water by plants to the atmosphere through stomata on the leaf's surface. It is influenced by the physiology of the plant and the climate. Both terms are combined to form evapotranspiration. The water that is lost to the atmosphere via evapotranspiration is the irrigation required or the crop water requirement (Feddes and Lenselink, 1994). Water applied to agricultural crops is estimated from evapotranspiration calculations or measurements, and irrigation is applied to the soil for the benefit of the crops with the aim of producing a satisfactory yield. The crop moisture demand or evapotranspiration demand directly influences the flow of moisture upward from the groundwater via the unsaturated zone.

Many empirical equations have been developed to estimate the potential evapotranspiration. Empirical methods are often valid only for the local conditions under which they were developed, however some methods are physically based, which have a wider applicability. Predictive methods are often more appropriate, owing to the difficulty of obtaining accurate field measurements. For evapotranspiration to occur three basic physical requirements in the soil-plant atmosphere system must be met:

1. a continuous supply of water;
2. energy to change liquid water into vapour;
3. a vapour gradient to maintain a flux from the evaporating surface to the atmosphere.

The methods for determining evapotranspiration are based on one or more of these requirements. To explain:

- the soil water balance approach relies on measurement of the soil water content;
- the energy balance approach relies on calculation of the energy exchange between water and the atmosphere, and
- the combination method, first introduced by Penman (1948), relies on the energy transfer and the vapour gradient.

Penman's study estimated the evaporation of water from an open surface, which, when multiplied by a crop coefficient (Kc) provided an estimate of the potential evapotranspiration from a cropped surface. Monteith (1965) revised the original Penman (1948) equation by combining it with an equation to describe the process of transpiration from a '*dry, extensive, horizontal, and uniformly vegetated surface, fully covering the ground, that is optimally supplied with water*'. This is known as the Penman-Monteith method.

After analysing a range of data from lysimeters, Doorenbos and Pruitt (1977) proposed the Penman-Monteith method as the standard approach to estimate evapotranspiration. This equation assumes that evapotranspiration from grass largely occurs in response to climatic conditions. Doorenbos and Pruitt (1977) also recommended three other methods; the Blaney-Criddle, radiation, and pan evaporation procedures, which were useful for areas where detailed climatic measurements were unavailable.

Advances in research and the more accurate assessment of crop water use have revealed weaknesses in these previous methodologies. It was found that the Penman-Monteith method frequently overestimated evapotranspiration by as much as 20 percent for low evaporative conditions (Allen *et al.*, 1998). Following an expert consultation on evapotranspiration calculation methods, Allen *et al.* (1994) revised the calculation procedures for calculating reference evapotranspiration. The Penman-Monteith method is recommended as the sole standard method for estimating crop evapotranspiration, with computerised versions of the equation built into specific irrigation scheduling software programs (Smith, 1992; Clarke *et al.*, 1998). To calculate evapotranspiration using the Penman-Monteith method the following equation is applied:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

[A2.7]
(Allen *et al.*, 1998)

where:

ET_o	:	reference evapotranspiration (mm/day)
R_n	:	net radiation at the crop surface (MJ/m^2/day)
G	:	soil heat flux density (MJ/m^2/day)
T	:	mean daily air temperature at 2 m height (^{o}C)
u_2	:	wind speed at 2 m height (m/s)
e_s	:	saturation vapour pressure (kPa)
e_a	:	actual vapour pressure (kPa)
e_s-e_a	:	saturation vapour pressure (kPa)
Δ	:	slope vapour pressure curve (kPa/^{o}C)
γ	:	psychrometric constant (kPa/^{o}C)

Estimation of crop water requirements within the FSU relied on a number of methods. Alpatiev (1954) suggested a method based on the vapour pressure deficit and number of crop growth days, calculated by estimating the growth stage of the crop. Kharchenko (1975) suggested the use of a heat balance equation to estimate soil water loss from a cropped surface. Ostapchik (1975) was the first to use a bioclimatic factor, similar to a crop coefficient, which allowed the use of an equation throughout the FSU, providing that accurate bioclimatic coefficients could be established. The bioclimatic coefficient is based on crop growing degree-days, which is considered an accurate method of estimating crop growth stage (Gates and Hanks, 1967).

Talalaevsky (1977) applied simultaneous calculations of water and heat balances to cropped areas to determine the moisture loss from a growing crop. He concluded that evaporation relied on the daily moisture deficit from the soil, a coefficient determined from the average air temperature, and a 'microclimatic coefficient'. Danilchenko (1978) introduced the 'microclimatic coefficient' based on the size of the irrigated area and its geographical location. The size of the irrigation systems and different climatic effects due to the large deserts and mountain ranges within Central Asia demanded a simple approach to understanding the local advection effects of the climate on crop water requirements.

Despite the many methods for estimating crop evapotranspiration within the FSU, the method by Ivanov (1954) was the recommended procedure, and was used during the design of the Central Asian irrigation systems. The equation is:

$$E_o = 0.0018\mathrm{M}(25+t)^2(100-\alpha)$$

[A2.8]
Ivanov (1954)

where:

E_o	:	evaporation (mm/month)
t	:	average monthly air temperature (°C)
α	:	average monthly relative humidity (%)
M	:	micro-climatic coefficient (Nov – May = 1, June + October = 0.9, July – Sept = 0.8)

The simple equation using air temperature and humidity measurements is comparable to the Penman-Monteith method, provided it is calibrated using the correct microclimatic coefficient (Smith, 1997; INCO-COPERNICUS, 2002). The accuracy of the equation is improved when individual irrigation system climatic conditions are considered, which are often based on specific local information. Therefore, the use of Ivanov's method on a wider scale may not be as accurate as predicted. As the region may currently be experiencing a climatic change due to the desiccation of the Aral Sea, the use of Ivanov's method has become a debatable issue. Throughout this study both the Penman-Monteith and Ivanov methods were used to estimate evapotranspiration.

A2.2. EXAMPLE OF DIURNAL MOISTURE MOVEMENT

This appendix contains example data to show the process of diurnal moisture movement and the processes of soil moisture 'recharge' and 'extraction'. Figure A2.1 shows water-filled tensiometer measured soil moisture suction at different depths recorded over an 80 hour period in a cotton field. Tensiometers respond to soil moisture suction conditions due to the hydraulic connection between the water in the tensiometer and the water held in the soil. Hillel (1982) maintains that tensiometers are the best tool available for monitoring plant moisture status and therefore the requirement for irrigation. The soil type was a silty clay loam and cotton rooting depth was estimated as between 50 to 60 cm deep. The age of the cotton crop was 66 to 69 days after planting (DOY 210 - 27 July to 213 – 30 July). Penman-Monteith average reference evapotranspiration for the four days was 8 mm/d. Soil moisture suction represents the average suction over 15 cm vertical depths, per measured depth. The missing data for the 30 and 45 cm soil layers was due to tensiometers 'breaking' hydraulic connection with the soil water in the shallower depths of the profile. Tensiometers are not able to record soil moisture suction above approximately -800 cm due to the limitations of the tensiometer porous ceramic cups. Above -800 cm the ceramic cups allow air to enter the tensiometer and the hydraulic connection between porous cup and the soil matrix is broken (Jim-Yeh and Guzman-Guzman, 1995).

Figure A2.1 clearly shows that there are diurnal fluctuations in soil moisture suction at 60 cm. The fluctuations are more noticeable at 75 cm, and only slightly evident over the last 48 hrs at the 90 cm depth.

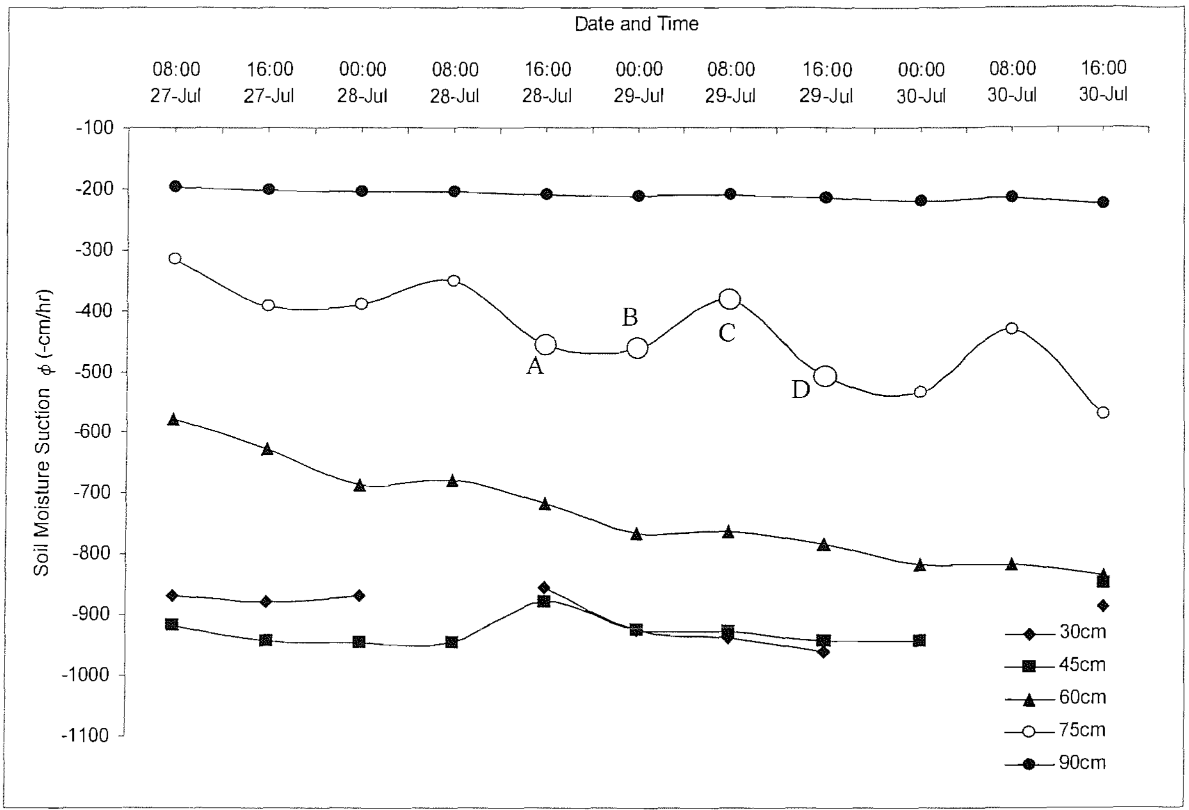


Figure A2.1 Diurnal Fluctuations in Soil Moisture Suction

To demonstrate the processes of 'extraction' and 'recharge' points A, B, C, and D on Figure A2.1 are identified in Table A2.1. Point A represents a soil moisture suction of -458 cm, and Point B -462 cm. Between points A and B a slight increase in suction occurs. Point C represents – 383 cm suction, a decrease of – 79 cm suction over 8 hours from Point B. Point D represents – 508 cm suction, an increase of – 125 cm or pF 2.09 from point C over 8 hours, between 08:00 to 16:00 hrs. The increase in soil moisture suction between Point C and Point D represents the crop evapotranspiration demand at the 75 cm depth on 29 July.

Between midnight on the 28-29 July and 08:00 on the 29 July soil moisture suction decreased by pF 1.90, indicating recharge into the profile at 75 cm. Any soil moisture study that ignored this reduction in suction overnight and relied on soil moisture suction measurements at Points A and D would show an increase in suction by -50 cm (pF 1.69). This represents the increase in soil moisture deficit due to evapotranspiration, but does not take into account recharge into the profile. This would result in a false interpretation of soil moisture movement, crop water status, and soil moisture deficit within the crop root zone.

Table A2.1 Diurnal Fluctuations in Moisture Suction Indicated in Figure A2.1

Point	Suction (-cm)	Date (DOY)	Time (hrs)	Suction Change (cm (pF))	Increase (↑) or Decrease (↓) in Suction
A	458	28/07/00 (210)	16:00		
B	462	29/07/00 (211)	00:00	+4 (0.60)	↑
C	383	29/07/00 (211)	08:00	-79 (1.90)	↓
D	508	2907/00 (211)	16:00	+125 (2.09)	↑

At all depths the soil moisture potential increases over the total 80 hour period, with the 30, 45, 60, and 75 cm depths indicating similar increasing gradients in soil moisture suction over time. The largest diurnal fluctuations occurred approximately 10 to 15 cm ahead of the estimated root depth (50 to 60 cm). McGowan (1973) associated this effect with the point of 'zero moisture flux' and claimed that this area, immediately ahead of the roots, is the area of accelerated water loss due to root extraction, which is 'recharged' due to upward flux.

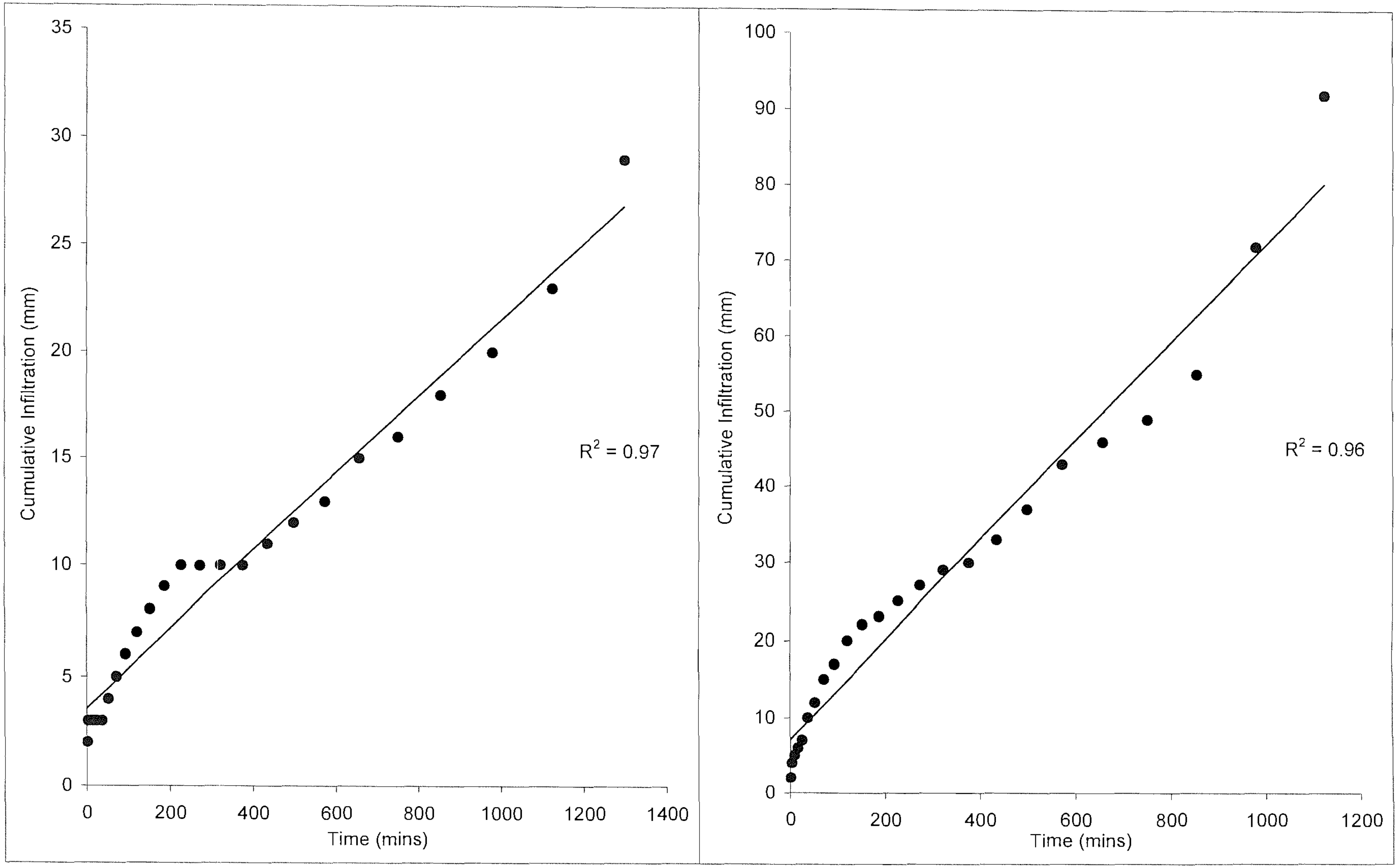
APPENDIX A3

SUPPORTING INFORMATION TO CHAPTER THREE

Table A3.1 Summary Soil Moisture Characteristic Results for all Experimental Sites

	Porosity (m^3/m^3)			Field Capacity (m^3/m^3)			Wilting Point (m^3/m^3)			Available Moisture (mm)		
Depth (cm)	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
30	0.423	0.444	0.395	0.287	0.312	0.252	0.134	0.157	0.118	153	155	134
45	0.411	-	-	0.279	-	-	0.134	-	-	145	-	-
60	0.439	0.456	0.422	0.311	0.324	0.287	0.110	0.136	0.092	201	188	195
75	0.428	-	-	0.297	-	-	0.079	-	-	218	-	-
90	0.466	0.497	0.430	0.331	0.360	0.326	0.095	0.118	0.083	236	242	243
120	0.473	0.475	0.472	0.340	0.375	0.305	0.087	0.094	0.081	253	281	224
150	0.457	0.495	0.420	0.301	0.318	0.285	0.104	0.130	0.079	197	188	206
Mean	0.446	0.473	0.426	0.310	0.325	0.288	0.107	0.110	0.103	203	215	185
St. Dev.	0.023	-	-	0.022	-	-	0.021	-	-	40.149	-	-
*Range (%)	5.249	-	-	7.213	-	-	20.185	-	-	19.778	-	-

Notes: * represents the percentage range of the standard deviation from the average mean value. Mean values for Porosity and for Field Capacity per depth are similar. Wilting Point values range 20% from the standard deviation probably due to the 26% clay content which will have released moisture at different rates as pressure increased, and hence the 20% range value for Available Moisture. Mean values for 45 and 75cm depths are average values calculated between 30 and 60, and 60 and 90cm depths. Max and Min values are based on five samples per depth, per site.



Infiltration Curves for Field A

Table A3.2 Summary Particle Size Distribution Results for all Experimental Fields

Site	Field A					Field B-1					Field B-2				
Depth (cm)	Sand (%)	Clay (%)	Silt (%)	Soil Type	DBD (g/cm^3)	Sand (%)	Clay (%)	Silt (%)	Soil Type	DBD (g/cm^3)	Sand (%)	Clay (%)	Silt (%)	Soil Type	DBD (g/cm^3)
0-20	27	22	51	ZL/L	1.47 to 1.59	20	27	53	ZL/CL	-	18	23	59	ZL	-
20-40	22	21	57	ZL	**1.48 to 1.55**	14	32	54	ZCL	**1.43 to 1.53**	7	35	58	ZCL	**1.47 to 1.56**
40-60	20	22	58	ZL	1.37 to 1.43	17	30	53	ZCL	**1.50 to 1.69**	9	34	57	ZCL	-
60-80	21	19	60	ZL	1.34 to 1.54	16	22	62	ZL	1.28 to 1.54	12	24	64	ZL/ZCL	1.41 to 1.51
80-100	12	28	60	ZCL	1.34 to 1.43	21	20	59	ZL	1.36 to 1.52	12	24	64	ZL/ZCL	-
100-120	22	21	57	ZL	1.37 to 1.46	11	24	65	ZL	1.30 to 1.41	8	27	65	ZCL	1.20 to 1.43
120-140	34	21	45	L	1.37 to 1.44	12	26	62	ZCL	-	11	32	57	ZCL	-
140-160	8	31	61	ZL	1.38 to 1.44	12	40	48	ZC	-	19	21	60	ZL	1.34 to 1.46
160-180	2	40	58	ZCL/ZC	1.38 to 1.45	10	25	65	ZL/ZCL	-	7	21	72	ZL	-
180-200	6	38	56	ZCL/ZC	1.40 to 1.49	5	28	67	ZCL	-	12	23	65	ZL	1.32 to 1.47
Mean	17	26	56	-	1.431	14	27	59	-	1.456	12	26	62	-	1.424
St. Dev.	10.08	7.63	4.85	-	0.060	4.85	5.68	6.43	-	0.098	4.20	5.34	4.77	-	0.082

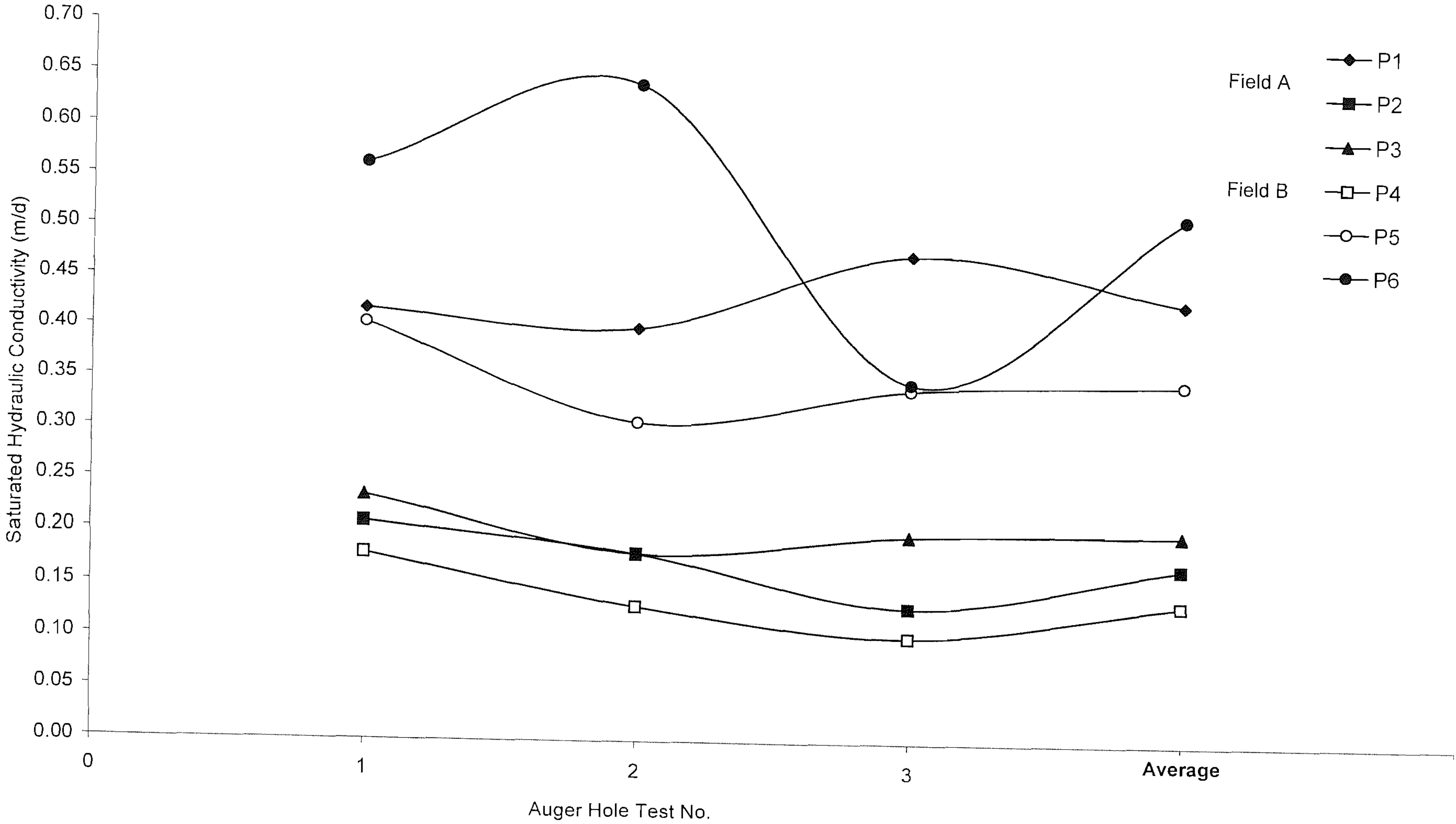
Notes: DBD is Dry Bulk Density. Total number of samples for PSD test = 10 x 100g samples per depth. Total number of samples for DBD test = 140 for Field A; 50 for Field B-1; 50 for Field B-2. Different depths were sampled in each field according to experimental equipment depth. Soil classified using USDA-Soil Conservation Service Tables (1975) where Z is silt, C is clay and L is loam. According to the Soviet Kachinsky method soil type for Field A was medium loam; Field B-1 was medium to heavy loam; Field B-2 was heavy loam/clay. Figures in bold identify possible plough 'pan' formation.

Table A3.2 Summary Particle Size Distribution Results for all Experimental Fields

Site	Field A					Field B-1					Field B-2				
Depth (cm)	Sand (%)	Clay (%)	Silt (%)	Soil Type	DBD (g/cm^3)	Sand (%)	Clay (%)	Silt (%)	Soil Type	DBD (g/cm^3)	Sand (%)	Clay (%)	Silt (%)	Soil Type	DBD (g/cm^3)
0-20	27	22	51	ZL/L	1.47 to 1.59	20	27	53	ZL/CL	-	18	23	59	ZL	-
20-40	22	21	57	ZL	**1.48 to 1.55**	14	32	54	ZCL	**1.43 to 1.53**	7	35	58	ZCL	**1.47 to 1.56**
40-60	20	22	58	ZL	1.37 to 1.43	17	30	53	ZCL	**1.50 to 1.69**	9	34	57	ZCL	-
60-80	21	19	60	ZL	1.34 to 1.54	16	22	62	ZL	1.28 to 1.54	12	24	64	ZL/ZCL	1.41 to 1.51
80-100	12	28	60	ZCL	1.34 to 1.43	21	20	59	ZL	1.36 to 1.52	12	24	64	ZL/ZCL	-
100-120	22	21	57	ZL	1.37 to 1.46	11	24	65	ZL	1.30 to 1.41	8	27	65	ZCL	1.20 to 1.43
120-140	34	21	45	L	1.37 to 1.44	12	26	62	ZCL	-	11	32	57	ZCL	-
140-160	8	31	61	ZL	1.38 to 1.44	12	40	48	ZC	-	19	21	60	ZL	1.34 to 1.46
160-180	2	40	58	ZCL/ZC	1.38 to 1.45	10	25	65	ZL/ZCL	-	7	21	72	ZL	-
180-200	6	38	56	ZCL/ZC	1.40 to 1.49	5	28	67	ZCL	-	12	23	65	ZL	1.32 to 1.47
Mean	17	26	56	-	1.431	14	27	59	-	1.456	12	26	62	-	1.424
St. Dev.	10.08	7.63	4.85	-	0.060	4.85	5.68	6.43	-	0.098	4.20	5.34	4.77	-	0.082

Notes: DBD is Dry Bulk Density. Total number of samples for PSD test = 10 x 100g samples per depth. Total number of samples for DBD test = 140 for Field A; 50 for Field B-1; 50 for Field B-2. Different depths were sampled in each field according to experimental equipment depth. Soil classified using USDA-Soil Conservation Service Tables (1975) where Z is silt, C is clay and L is loam. According to the Soviet Kachinsky method soil type for Field A was medium loam; Field B-1 was medium to heavy loam; Field B-2 was heavy loam/clay. Figures in bold identify possible plough 'pan' formation.

Auger Hole Results to Determine Saturated Hydraulic Conductivity



Saturated Conductivity for All Experimental Fields

Water Filled Pressure Transducer Tensiometers

Field B1

Single array of five tensiometers at 0.30, 0.45, 0.60, 0.75, and 0.90 m depths. Table A3.3 shows the number of days measurements were made. At 0.30 and 0.45 m tensiometers were occasionally re-filled when tension broke. Later in the season they required re-filling every 24-48 hours and no accurate measurements of suction could be made.

Table 1 Tensiometer Measurement Periods, Field B1

Depth (m)	Start Date/DOY	End Date/DOY	Total No. of Days Measurement
0.30	30/06/00 – 182	03/08/00 – 216	34
0.45	30/06/00 – 182	03/08/00 – 216	34
0.60	30/06/00 – 182	04/08/00 – 217	35
0.75	30/06/00 – 182	10/08/00 – 223	41
0.90	30/06/00 – 182	07/08/00 – 220	38

Field B2

Single array of five tensiometers at 0.30, 0.45, 0.60, 0.75, and 0.90m depths. Table A3.4 shows the number of days measurements were made. At the 0.30 and 0.45m depths the tensiometers were occasionally re-filled when tension broke. Later in the season they required re-filling every 24-48 hours and no accurate measurements of suction could be made.

Table 2 Tensiometer Measurement Periods, Field B2

Depth (m)	Start Date/DOY	End Date/DOY	Total No. of Days Measurement
0.30	29/06/00 – 181	02/08/00 – 215	34
0.45	29/06/00 – 181	03/08/00 – 216	35
0.60	29/06/00 – 181	01/08/00 – 214	33
0.75	29/06/00 – 181	05/08/00 – 218	37
0.90	29/06/00 – 181	28/08/00 – 241	60

Hg Tensiometers

Field B1

A double array of nine Hg tensiometers was inserted between 0.30 and 1.50 m in 0.15 m incremental depths. Due to high soil moisture suctions the shallow tensiometers frequently stopped working and were re-primed using distilled water. Table A3.5 shows the number of days measurement for each tensiometer.

Table 3 Hg Tensiometer Measurement Periods for both Arrays, Field A

Depth (m)	Start Date/DOY	End Date/DOY	Total No. of Days Measurement
0.30	20/06/00 – 172	24/07/00 – 206	34
0.45	20/06/00 – 172	28/07/00 – 210	38
0.60	20/06/00 – 172	02/08/00 – 215	43
0.75	20/06/00 – 172	02/08/00 – 215	43
0.90	20/06/00 – 172	03/09/00 – 247	75
1.05	20/06/00 – 172	02/09/00 – 246	74
1.20	20/06/00 – 172	07/08/00 – 220	48
1.35	20/06/00 – 172	07/09/00 – 251	79
1.50	20/06/00 – 172	22/09/00 – 266	94
0.30	20/06/00 – 172	22/07/00 – 204	32
0.45	20/06/00 – 172	22/07/00 – 204	32
0.60	20/06/00 – 172	04/08/00 – 217	45
0.75	20/06/00 – 172	04/08/00 – 217	45
0.90	20/06/00 – 172	12/08/00 – 225	53
1.05	20/06/00 – 172	18/08/00 – 231	59
1.20	20/06/00 – 172	03/09/00 – 247	75
1.35	20/06/00 – 172	03/09/00 – 247	75
1.50	20/06/00 – 172	22/09/00 – 266	94

Instrumentation of Field Sites

Climatic Equipment

A 3.5 m long and 80 mm diameter steel pole was vertically inserted into the soil profile and concrete was placed around the pole to ensure stability. Approximately 2.8 m of the pole remained above ground level. A horizontal aluminium pole was attached to the vertical steel pole at 2 m above the soil surface and the anemometer was attached. The air temperature and humidity sensors were attached to the steel pole 2 m above ground level. The solar radiation sensor was attached and leveled horizontal on top of the steel pole at approximately 2.8 m above ground level. Approximately 12.5 m from the steel pole along the same line of cotton plants a 0.3 m^2 area was leveled. The tipping bucket raingauge was placed on a leveled steel plate in the 0.3 m^2 area and concrete placed around the plate to ensure the raingauge did not tip over. The top of the raingauge was 0.6 m above ground level in the middle of the cotton row. The soil temperature probe was placed 25 to 35 cm deep in the cotton row 0.9 m to the West of the climate station. The temperature probe was placed down an augered hole, which was backfilled with the excavated soil. All equipment communication wires were buried and connected to the datalogger, which was secured in a steel box raised above ground level at the foot of the steel pole, and painted white to prevent overheating.

Lysimeters

A narrow cutting ring was inserted into the inside of the bottom end of the steel tubes. The steel tubes were painted black on the outside, apart from the top 30 cm of each lysimeter which remained above ground level after insertion in the field. The top 30 cm was painted white to prevent excessive heating of the soil surface within the lysimeters.

A local site with a similar soil type (silty clay loam) was chosen for soil to fill the lysimeters. The site was pre-irrigated with 120 mm of water and allowed to drain for 48 hours. The lysimeter tubes were then individually sunk into the moist soil using the weight of each lysimeter pipe. This was achieved by manually pushing the lysimeter tubes into the soil, aided by the cutting ring at the lower end. Excess soil was removed from the sides to aid the filling of the cylinder. Once fully inserted the soil column was cut from the subsoil with a steel wire. An identical soil filling process was performed for each lysimeter.

The drainage section's were made from identical 10 mm thick steel tubing with a bottom plate attached at one end. Piezometers were externally connected to the lysimeters immediately prior to insertion in Field A, and were used to monitor the groundwater depth, and for re-filling the groundwater when it fell below target experimental depth. The drainage section was filled with 0.25 m of gravel (2 to 75 mm diameter) and stones (75 to 200 mm diameter), followed by 0.25 m of sand (0.05 to 2 mm diameter).

Soil inside the lysimeter tubes that extended beyond the bottom of the steel tube was 'cut' to a smooth surface. A steel perforated plate was welded to the bottom of the lysimeter tube (Plate A below). This ensured that when connecting the drainage section to the main soil monolith the soil did not move position inside the lysimeter. This also provided stability when transporting the lysimeters to Field A. The steel perforated plate was welded so that the soil inside the lysimeter rested upon it, allowing a hydraulic connection between the soil section and drainage section of the lysimeters.

Plate A. Perforated Drainage Plate
Welded to Bottom of Lysimeters

The lysimeters were placed on their sides horizontally in the field. A 2.5 cm diameter soil auger was used to prepare insertion holes 30 cm deep in the soil via the instrumentation holes in the wall of the lysimeters. Prior to insertion a suspension of the augured soil, irrigation water, and quartz powder suspension was poured down the holes to secure the ceramic cup in the soil. To prevent water from entering the lysimeters via the instrumentation holes during irrigation events, the nylon tubes from the ceramic cups to the mercury were sealed with plastic coatings.

Table A3.3 ThetaProbe© Manufacturers Calibration Calculation Procedure

Symbol*	Description	Calculation	Unit
θ	Field soil sample measurement of moisture content using ThetaProbe©	measured	m^3/m^3
θ_{Vw}	Field soil sample measurement of voltage using ThetaProbe©	measured	V
$\sqrt{\varepsilon}_{wLINEAR}$	Relationship provided by manufacturers of ThetaProbe©	$1.1+4.44\theta_{Vw}$	-
$\sqrt{\varepsilon}_{wPOLYNOMIAL}$	Relationship provided by manufacturers of ThetaProbe©	$1.07+6.4\theta_{Vw}-6.4\theta_{Vw}^2+4.7\theta_{Vw}^3$	-
W_w	Soil sample wet field mass	measured	G
sd	Soil sample diameter	measured	cm
sh	Soil sample height	measured	cm
L	Soil sample volume	$\pi r^2 sh$	cm^3
	Oven Drying at 105°C for 24 hours		
V_o	Dry soil sample measurement of voltage using ThetaProbe©	measured	V
W_o	Dry soil sample mass	measured	g
$a_{0LINEAR}$	Relationship provided by manufacturers of ThetaProbe©	$1.1+4.44\ V_o$	-
$a_{0POLYNOMIAL}$	Relationship provided by manufacturers of ThetaProbe©	$1.07+6.4\ V_o-6.4\ V_o^2+4.7\ V_o^3$	-
θ_w	Moisture content of original field sample	$(W_w-W_o)/L$	m^3/m^3
$a_{1LINEAR}$	Relationship provided by manufacturers of ThetaProbe©	$(\sqrt{\varepsilon}_{wLINEAR}-a_{0LINEAR})/\ \theta_w$	-
$a_{1POLYNOMIAL}$	Relationship provided by manufacturers of ThetaProbe©	$(\sqrt{\varepsilon}_{wPOLYNOMIAL}-\ a_{0POLYNOMIAL})/\ \theta_w$	-
$\theta_{c(\sqrt{\varepsilon})}$	Soil Calibrated ThetaProbe reading© using manufacturers method	$(\sqrt{\varepsilon}_{wLINEAR}-a_{0LINEAR})/\ a_{1LINEAR}$	m^3/m^3
$C_{f(\sqrt{\varepsilon})}$	Calibration factor determined using manufacturers method	$\theta_{c(\sqrt{\varepsilon})}/\theta$	-
Check $\sqrt{\varepsilon}$	According to Roth *et al*, (1992), $\sqrt{\varepsilon}_w\approx(a_0+a_1)\theta$	$(a_{0LINEAR}+a_{1LINEAR})\theta_{c(\sqrt{\varepsilon})}$	-
C_{fg}	Calibration factor determined using gravimetric result	θ_w/θ	-
θ_{cg}	Soil Calibrated ThetaProbe reading©	$\theta\, C_{fg}$	-
Error	Difference between original field measured moisture content and calculated	$\theta-\theta_{cg}$	m^3/m^3

Notes: * symbols are the same as used in Table A3.4. From $\theta_{c(\sqrt{\varepsilon})}$ only the linear calculation is explained, although for calibration purposes both the linear and polynomial calculations were performed for comparison.

Table A3.4 Summary ThetaProbe Calibration Results (Linear Relationship $\sqrt{\varepsilon}$ to V), Field A

Sample No.	Probe Depth	θ	θ_{Vw}	$\sqrt{\varepsilon_w}$	W_w	sd	sh	L	V_o	W_o	a_0	θ_w	a_1	$\theta_{c(\sqrt{\varepsilon})}$	$C_{f(\sqrt{\varepsilon})}$	Check $\sqrt{\varepsilon}$	C_{fg}	θ_{cg}	Error $(\theta-\theta_{cg})$
Units	cm	m^3/m^3	V		g	cm	cm	cm^3	V	g		m^3/m^3		m^3/m^3					m^3/m^3
1	30	0.18	0.439	3.047	272.87	5.550	6.700	162.088	0.102	243.59	1.551	0.181	8.281	0.181	**1.004**	1.776	**1.004**	0.179	0.001
2	30	0.25	0.559	3.584	273.76	5.550	6.700	162.088	0.103	236.07	1.557	0.233	8.716	0.233	**0.930**	2.389	**0.930**	0.249	0.001
3	30	0.23	0.523	3.421	277.69	5.550	6.700	162.088	0.104	239.87	1.561	0.233	7.973	0.233	**1.014**	2.225	**1.014**	0.229	0.001
4	60	0.23	0.521	3.414	264.15	5.550	6.700	162.088	0.119	227.47	1.630	0.226	7.884	0.226	**0.984**	2.153	**0.984**	0.229	0.001
5	60	0.24	0.583	3.687	266.74	5.550	6.700	162.088	0.110	228.94	1.587	0.233	9.002	0.233	**0.972**	2.470	**0.972**	0.239	0.001
6	60	0.24	0.573	3.643	269.30	5.550	6.700	162.088	0.103	229.52	1.557	0.245	8.501	0.245	**1.023**	2.468	**1.023**	0.239	0.001
7	90	0.15	0.401	2.881	258.67	5.550	6.700	162.088	0.120	234.49	1.631	0.149	8.381	0.149	**0.995**	1.494	**0.995**	0.149	0.001
8	90	0.18	0.435	3.032	268.40	5.550	6.700	162.088	0.103	241.84	1.557	0.164	9.003	0.164	**0.910**	1.730	**0.910**	0.179	0.001
9	90	0.16	0.445	3.078	254.89	5.550	6.700	162.088	0.100	230.00	1.544	0.154	9.984	0.154	**0.960**	1.770	**0.960**	0.159	0.001
10	120	0.16	0.440	3.054	266.98	5.550	6.700	162.088	0.120	240.80	1.634	0.162	8.793	0.162	**1.009**	1.684	**1.009**	0.159	0.001
11	120	0.15	0.398	2.869	270.67	5.550	6.700	162.088	0.116	245.41	1.617	0.156	8.034	0.156	**1.039**	1.504	**1.039**	0.149	0.001
12	120	0.16	0.442	3.064	276.95	5.550	6.700	162.088	0.103	249.93	1.556	0.167	9.045	0.167	**1.042**	1.767	**1.042**	0.159	0.001
13	150	0.18	0.456	3.126	274.25	5.550	6.800	164.507	0.102	246.38	1.555	0.169	9.275	0.169	**0.941**	1.835	**0.941**	0.179	0.001
14	150	0.18	0.479	3.225	269.78	5.550	6.700	162.088	0.109	237.87	1.583	0.197	8.338	0.197	**1.094**	1.953	**1.094**	0.179	0.001
15	150	0.19	0.501	3.325	265.56	5.550	6.700	162.088	0.125	234.68	1.654	0.191	8.775	0.191	**1.003**	1.987	**1.003**	0.189	0.001
Mean		**0.190**	0.480	3.230	268.71	5.550	6.707	162.249	0.109	237.79	1.585	0.191	8.666	0.191	**0.995**	1.947	**0.995**	**0.191**	0.001
St. Dev.		0.036	0.060	0.267	6.307	0.000	0.026	0.625	0.008	6.970	0.038	0.035	0.558	0.035	**0.047**	0.326	**0.047**	0.036	-

Table A3.4 Summary ThetaProbe Calibration Results (Polynomial Relationship $\sqrt{\varepsilon}$ to V), Field A

Sample No.	Probe Depth	θ	θ_{Vw}	$\sqrt{\varepsilon_w}$	W_w	sd	sh	L	V_o	W_o	a_0	θ_w	a_1	$\theta_{c(\sqrt{\varepsilon})}$	$C_{f(\sqrt{\varepsilon})}$	Check $\sqrt{\varepsilon}$	C_{fg}	θ_{cg}	Error $(\theta\text{-}\theta_{cg})$
Units	cm	m^3/m^3	V		g	cm	cm	cm^3	V	g		m^3/m^3		m^3/m^3					m^3/m^3
1	30	0.18	0.439	3.042	272.87	5.550	6.700	162.088	0.102	243.59	1.659	0.181	7.656	0.181	**1.004**	1.683	**1.004**	0.179	0.001
2	30	0.25	0.559	3.470	273.76	5.550	6.700	162.088	0.103	236.07	1.666	0.233	7.759	0.233	**0.930**	2.192	**0.930**	0.249	0.001
3	30	0.23	0.523	3.338	277.69	5.550	6.700	162.088	0.104	239.87	1.671	0.233	7.147	0.233	**1.014**	2.057	**1.014**	0.229	0.001
4	60	0.23	0.521	3.333	264.15	5.550	6.700	162.088	0.119	227.47	1.751	0.226	6.990	0.226	**0.984**	1.978	**0.984**	0.229	0.001
5	60	0.24	0.583	3.556	266.74	5.550	6.700	162.088	0.110	228.94	1.702	0.233	7.951	0.233	**0.972**	2.251	**0.972**	0.239	0.001
6	60	0.24	0.573	3.519	269.30	5.550	6.700	162.088	0.103	229.52	1.666	0.245	7.552	0.245	**1.023**	2.262	**1.023**	0.239	0.001
7	90	0.15	0.401	2.911	258.67	5.550	6.700	162.088	0.120	234.49	1.752	0.149	7.769	0.149	**0.995**	1.420	**0.995**	0.149	0.001
8	90	0.18	0.435	3.031	268.40	5.550	6.700	162.088	0.103	241.84	1.666	0.164	8.327	0.164	**0.910**	1.638	**0.910**	0.179	0.001
9	90	0.16	0.445	3.066	254.89	5.550	6.700	162.088	0.100	230.00	1.651	0.154	9.215	0.154	**0.960**	1.669	**0.960**	0.159	0.001
10	120	0.16	0.440	3.048	266.98	5.550	6.700	162.088	0.120	240.80	1.756	0.162	8.002	0.162	**1.009**	1.576	**1.009**	0.159	0.001
11	120	0.15	0.398	2.901	270.67	5.550	6.700	162.088	0.116	245.41	1.736	0.156	7.478	0.156	**1.039**	1.436	**1.039**	0.149	0.001
12	120	0.16	0.442	3.055	276.95	5.550	6.700	162.088	0.103	249.93	1.665	0.167	8.341	0.167	**1.042**	1.668	**1.042**	0.159	0.001
13	150	0.18	0.456	3.104	274.25	5.550	6.800	164.507	0.102	246.38	1.663	0.169	8.506	0.169	**0.941**	1.723	**0.941**	0.179	0.001
14	150	0.18	0.479	3.182	269.78	5.550	6.700	162.088	0.109	237.87	1.697	0.197	7.545	0.197	**1.094**	1.819	**1.094**	0.179	0.001
15	150	0.19	0.501	3.262	265.56	5.550	6.700	162.088	0.125	234.68	1.778	0.191	7.790	0.191	**1.003**	1.823	**1.003**	0.189	0.001
Mean		**0.190**	0.480	3.188	268.71	5.550	6.707	162.249	0.109	237.79	1.698	0.191	7.868	0.191	**0.995**	1.813	**0.995**	**0.191**	0.001
St. Dev.		0.036	0.060	0.213	6.307	0.000	0.026	0.625	0.008	6.970	0.044	0.035	0.561	0.035	**0.047**	0.277	**0.047**	0.036	-

Table A3.4 Summary ThetaProbe Calibration Results (Linear Relationship $\sqrt{\varepsilon}$ to V), Field B1

Sample No.	Probe Depth	θ	θ_{Vw}	$\sqrt{\varepsilon_w}$	W_w	sd	Sh	L	V_o	W_o	a_0	θ_w	a_1	$\theta_{c(\sqrt{\varepsilon})}$	$C_{f(\sqrt{\varepsilon})}$	Check $\sqrt{\varepsilon}$	C_{fg}	θ_{cg}	Error $(\theta$-$\theta_{cg})$
Units	cm	m^3/m^3	V		g	cm	cm	cm^3	V	g		m^3/m^3		m^3/m^3					m^3/m^3
1	30	0.23	0.590	3.721	276.42	5.550	6.700	162.088	0.114	242.39	1.606	0.210	10.076	0.210	**0.913**	2.452	**0.913**	0.230	0.000
2	30	0.21	0.525	3.432	268.38	5.550	6.700	162.088	0.100	236.46	1.545	0.197	9.584	0.197	**0.938**	2.192	**0.938**	0.210	0.000
3	30	0.18	0.545	3.521	270.33	5.550	6.700	162.088	0.114	240.24	1.608	0.186	10.304	0.186	**1.031**	2.211	**1.031**	0.180	0.000
4	45	0.21	0.546	3.526	285.15	5.550	6.700	162.088	0.119	253.65	1.630	0.194	9.756	0.194	**0.925**	2.213	**0.925**	0.210	0.000
5	45	0.23	0.578	3.664	288.56	5.550	6.700	162.088	0.115	255.72	1.608	0.203	10.146	0.203	**0.881**	2.382	**0.881**	0.230	0.000
6	45	0.19	0.547	3.528	279.56	5.550	6.700	162.088	0.103	248.37	1.558	0.192	10.238	0.192	**1.013**	2.270	**1.013**	0.190	0.000
7	60	0.16	0.478	3.221	260.78	5.550	6.700	162.088	0.096	227.86	1.528	0.203	8.332	0.203	**1.269**	2.003	**1.269**	0.160	0.000
8	60	0.19	0.438	3.043	260.19	5.550	6.700	162.088	0.110	226.85	1.587	0.206	7.077	0.206	**1.083**	1.782	**1.083**	0.190	0.000
9	60	0.16	0.456	3.123	245.62	5.550	6.700	162.088	0.095	221.19	1.520	0.151	10.637	0.151	**0.942**	1.832	**0.942**	0.160	0.000
10	75	0.13	0.354	2.671	242.68	5.550	6.700	162.088	0.084	224.74	1.472	0.111	10.834	0.111	**0.851**	1.362	**0.851**	0.130	0.000
11	75	0.16	0.454	3.114	236.01	5.550	6.500	157.249	0.097	216.26	1.532	0.126	12.596	0.126	**0.785**	1.774	**0.785**	0.160	0.000
12	75	0.17	0.453	3.112	259.43	5.550	6.700	162.088	0.108	233.40	1.579	0.161	9.544	0.161	**0.945**	1.786	**0.945**	0.170	0.000
13	90	0.15	0.411	2.923	290.29	5.550	6.800	164.507	0.102	260.11	1.552	0.183	7.471	0.183	**1.223**	1.655	**1.223**	0.150	0.000
14	90	0.16	0.471	3.191	222.43	5.550	6.400	154.830	0.093	195.07	1.512	0.177	9.501	0.177	**1.104**	1.946	**1.104**	0.160	0.000
15	90	0.12	0.386	2.814	245.38	5.550	6.500	157.249	0.102	224.98	1.553	0.130	9.719	0.130	**1.081**	1.462	**1.081**	0.120	0.000
Mean		**0.177**	0.482	3.240	262.08	5.550	6.660	161.120	0.103	233.81	1.559	0.175	9.721	0.175	**0.999**	1.955	**0.999**	**0.176**	0.000
St. Dev.		0.033	0.071	0.315	20.421	0.000	0.106	2.554	0.010	17.137	0.043	0.032	1.345	0.032	**0.135**	0.328	**0.135**	0.033	-

Table A3.4 Summary ThetaProbe Calibration Results (Polynomial Relationship $\sqrt{\varepsilon}$ to V), Field B1

Sample No.	Probe Depth	θ	θ_{Vw}	$\sqrt{\varepsilon_w}$	W_w	sd	sh	L	V_o	W_o	a_0	θ_w	a_1	$\theta_{c(\sqrt{\varepsilon})}$	$C_{f(\sqrt{\varepsilon})}$	Check $\sqrt{\varepsilon}$	C_{fg}	θ_{cg}	Error $(\theta-\theta_{cg})$
Units	cm	m^3/m^3	V		g	cm	cm	cm^3	V	g		m^3/m^3		m^3/m^3					m^3/m^3
1	30	0.23	0.590	3.585	276.42	5.550	6.700	162.088	0.114	242.39	1.723	0.210	8.868	0.210	**0.913**	2.224	**0.913**	0.230	0.000
2	30	0.21	0.525	3.347	268.38	5.550	6.700	162.088	0.100	236.46	1.652	0.197	8.608	0.197	**0.938**	2.021	**0.938**	0.210	0.000
3	30	0.18	0.545	3.419	270.33	5.550	6.700	162.088	0.114	240.24	1.725	0.186	9.121	0.186	**1.031**	2.014	**1.031**	0.180	0.000
4	45	0.21	0.546	3.423	285.15	5.550	6.700	162.088	0.119	253.65	1.750	0.194	8.604	0.194	**0.925**	2.012	**0.925**	0.210	0.000
5	45	0.23	0.578	3.537	288.56	5.550	6.700	162.088	0.115	255.72	1.726	0.203	8.938	0.203	**0.881**	2.161	**0.881**	0.230	0.000
6	45	0.19	0.547	3.424	279.56	5.550	6.700	162.088	0.103	248.37	1.667	0.192	9.133	0.192	**1.013**	2.078	**1.013**	0.190	0.000
7	60	0.16	0.478	3.179	260.78	5.550	6.700	162.088	0.096	227.86	1.632	0.203	7.616	0.203	**1.269**	1.878	**1.269**	0.160	0.000
8	60	0.19	0.438	3.039	260.19	5.550	6.700	162.088	0.110	226.85	1.702	0.206	6.502	0.206	**1.083**	1.687	**1.083**	0.190	0.000
9	60	0.16	0.456	3.102	245.62	5.550	6.700	162.088	0.095	221.19	1.622	0.151	9.820	0.151	**0.942**	1.725	**0.942**	0.160	0.000
10	75	0.13	0.354	2.741	242.68	5.550	6.700	162.088	0.084	224.74	1.564	0.111	10.640	0.111	**0.851**	1.351	**0.851**	0.130	0.000
11	75	0.16	0.454	3.095	236.01	5.550	6.500	157.249	0.097	216.26	1.636	0.126	11.613	0.126	**0.785**	1.664	**0.785**	0.160	0.000
12	75	0.17	0.453	3.093	259.43	5.550	6.700	162.088	0.108	233.40	1.692	0.161	8.725	0.161	**0.945**	1.673	**0.945**	0.170	0.000
13	90	0.15	0.411	2.944	290.29	5.550	6.800	164.507	0.102	260.11	1.661	0.183	6.997	0.183	**1.223**	1.588	**1.223**	0.150	0.000
14	90	0.16	0.471	3.156	222.43	5.550	6.400	154.830	0.093	195.07	1.613	0.177	8.731	0.177	**1.104**	1.828	**1.104**	0.160	0.000
15	90	0.12	0.386	2.857	245.38	5.550	6.500	157.249	0.102	224.98	1.661	0.130	9.218	0.130	**1.081**	1.411	**1.081**	0.120	0.000
Mean		**0.177**	0.482	3.196	262.08	5.550	6.660	161.120	0.103	233.81	1.668	0.175	8.876	0.175	**0.999**	1.821	**0.999**	**0.176**	0.000
St. Dev.		0.033	0.071	0.251	20.421	0.000	0.106	2.554	0.010	17.137	0.051	0.032	1.273	0.032	**0.135**	0.264	**0.135**	0.033	-

Table A3.4 Summary ThetaProbe Calibration Results (Linear Relationship $\sqrt{\varepsilon}$ to V), Field B2

Sample No.	Probe Depth	θ	θ_{Vw}	$\sqrt{\varepsilon_w}$	W_w	sd	sh	L	V_o	W_o	a_0	θ_w	a_1	$\theta_{c(\sqrt{\varepsilon})}$	$C_{f(\sqrt{\varepsilon})}$	Check $\sqrt{\varepsilon}$	C_{fg}	θ_{cg}	Error $(\theta-\theta_{cg})$
Units	cm	m^3/m^3	V		g	cm	cm	cm^3	V	g		m^3/m^3		m^3/m^3					m^3/m^3
1	30	0.31	0.646	3.970	287.78	5.550	6.600	159.669	0.121	239.27	1.638	0.304	7.676	0.304	**0.980**	2.830	**0.980**	0.309	0.001
2	30	0.31	0.649	3.979	286.85	5.550	6.600	159.669	0.124	237.84	1.651	0.307	7.584	0.307	**0.990**	2.835	**0.990**	0.309	0.001
3	30	0.31	0.651	3.992	287.98	5.550	6.600	159.669	0.103	238.56	1.559	0.310	7.860	0.310	**0.998**	2.916	**0.998**	0.309	0.001
4	60	0.29	0.647	3.971	274.48	5.550	6.700	162.088	0.102	230.28	1.555	0.273	8.860	0.273	**0.940**	2.840	**0.940**	0.289	0.001
5	60	0.29	0.641	3.944	271.71	5.550	6.700	162.088	0.098	227.26	1.536	0.274	8.778	0.274	**0.946**	2.829	**0.946**	0.289	0.001
6	60	0.29	0.643	3.955	273.68	5.550	6.700	162.088	0.104	229.34	1.560	0.274	8.754	0.274	**0.943**	2.822	**0.943**	0.289	0.001
7	90	0.25	0.513	3.379	263.19	5.550	6.700	162.088	0.102	222.23	1.551	0.253	7.236	0.253	**1.011**	2.220	**1.011**	0.249	0.001
8	90	0.21	0.517	3.397	253.24	5.550	6.700	162.088	0.109	216.21	1.582	0.228	7.945	0.228	**1.088**	2.176	**1.088**	0.209	0.001
9	90	0.27	0.657	4.019	256.54	5.550	6.700	162.088	0.105	212.51	1.565	0.272	9.034	0.272	**1.006**	2.879	**1.006**	0.269	0.001
10	120	0.34	0.741	4.389	274.29	5.550	6.700	162.088	0.099	218.04	1.540	0.347	8.210	0.347	**1.021**	3.384	**1.021**	0.339	0.001
11	120	0.29	0.647	3.973	254.70	5.550	6.700	162.088	0.101	207.18	1.549	0.293	8.270	0.293	**1.011**	2.878	**1.011**	0.289	0.001
12	120	0.30	0.630	3.898	247.33	5.550	6.700	162.088	0.096	204.71	1.527	0.263	9.017	0.263	**0.876**	2.773	**0.876**	0.299	0.001
13	150	0.27	0.608	3.799	264.56	5.550	6.500	157.249	0.115	218.41	1.611	0.293	7.455	0.293	**1.087**	2.661	**1.087**	0.269	0.001
14	150	0.29	0.617	3.841	262.29	5.550	6.700	162.088	0.114	216.44	1.607	0.283	7.898	0.283	**0.975**	2.689	**0.975**	0.289	0.001
15	150	0.27	0.611	3.814	265.70	5.550	6.600	159.669	0.105	218.67	1.568	0.295	7.625	0.295	**1.091**	2.708	**1.091**	0.269	0.001
Mean		**0.280**	0.628	3.888	268.28	5.550	6.660	161.120	0.107	222.46	1.573	0.285	8.147	0.285	**0.998**	2.763	**0.998**	**0.285**	0.001
St. Dev.		0.030	0.055	0.244	12.813	0.000	0.063	1.530	0.008	10.964	0.037	0.028	0.606	0.028	**0.060**	0.282	**0.060**	0.030	-

Table A3.4 Summary ThetaProbe Calibration Results (Polynomial Relationship $\sqrt{\varepsilon}$ to V), Field B2

Sample No.	Probe Depth	θ	θ_{Vw}	$\sqrt{\varepsilon_w}$	W_w	sd	sh	L	V_o	W_o	a_0	θ_w	a_1	$\theta_{c(\sqrt{\varepsilon})}$	$C_{f(\sqrt{\varepsilon})}$	Check $\sqrt{\varepsilon}$	C_{fg}	θ_{cg}	Error $(\theta-\theta_{cg})$
Units	cm	m^3/m^3	V		g	cm	cm	cm^3	V	g		m^3/m^3		m^3/m^3					m^3/m^3
1	30	0.31	0.646	3.802	287.78	5.550	6.600	159.669	0.121	239.27	1.760	0.304	6.722	0.304	**0.980**	2.577	**0.980**	0.309	0.001
2	30	0.31	0.649	3.811	286.85	5.550	6.600	159.669	0.124	237.84	1.775	0.307	6.632	0.307	**0.990**	2.581	**0.990**	0.309	0.001
3	30	0.31	0.651	3.822	287.98	5.550	6.600	159.669	0.103	238.56	1.669	0.310	6.958	0.310	**0.998**	2.670	**0.998**	0.309	0.001
4	60	0.29	0.647	3.803	274.48	5.550	6.700	162.088	0.102	230.28	1.664	0.273	7.846	0.273	**0.940**	2.593	**0.940**	0.289	0.001
5	60	0.29	0.641	3.779	271.71	5.550	6.700	162.088	0.098	227.26	1.642	0.274	7.792	0.274	**0.946**	2.587	**0.946**	0.289	0.001
6	60	0.29	0.643	3.789	273.68	5.550	6.700	162.088	0.104	229.34	1.670	0.274	7.746	0.274	**0.943**	2.576	**0.943**	0.289	0.001
7	90	0.25	0.513	3.305	263.19	5.550	6.700	162.088	0.102	222.23	1.659	0.253	6.513	0.253	**1.011**	2.065	**1.011**	0.249	0.001
8	90	0.21	0.517	3.319	253.24	5.550	6.700	162.088	0.109	216.21	1.696	0.228	7.106	0.228	**1.088**	2.011	**1.088**	0.209	0.001
9	90	0.27	0.657	3.847	256.54	5.550	6.700	162.088	0.105	212.51	1.675	0.272	7.994	0.272	**1.006**	2.626	**1.006**	0.269	0.001
10	120	0.34	0.741	4.210	274.29	5.550	6.700	162.088	0.099	218.04	1.646	0.347	7.387	0.347	**1.021**	3.135	**1.021**	0.339	0.001
11	120	0.29	0.647	3.805	254.70	5.550	6.700	162.088	0.101	207.18	1.656	0.293	7.329	0.293	**1.011**	2.634	**1.011**	0.289	0.001
12	120	0.30	0.630	3.738	247.33	5.550	6.700	162.088	0.096	204.71	1.631	0.263	8.014	0.263	**0.876**	2.536	**0.876**	0.299	0.001
13	150	0.27	0.608	3.651	264.56	5.550	6.500	157.249	0.115	218.41	1.729	0.293	6.550	0.293	**1.087**	2.430	**1.087**	0.269	0.001
14	150	0.29	0.617	3.688	262.29	5.550	6.700	162.088	0.114	216.44	1.725	0.283	6.940	0.283	**0.975**	2.451	**0.975**	0.289	0.001
15	150	0.27	0.611	3.664	265.70	5.550	6.600	159.669	0.105	218.67	1.679	0.295	6.739	0.295	**1.091**	2.480	**1.091**	0.269	0.001
Mean		**0.280**	0.628	3.735	268.28	5.550	6.660	161.120	0.107	222.46	1.685	0.285	7.218	0.285	**0.998**	2.530	**0.998**	**0.285**	0.001
St. Dev.		0.030	0.055	0.214	12.813	0.000	0.063	1.530	0.008	10.964	0.043	0.028	0.547	0.028	**0.060**	0.257	**0.060**	0.030	-

Table A3.4 Summary ThetaProbe Gravimetric Calibration Results, Field A (Av. DBD 1.429 g/cm^3)

Sample No.	Probe Depth	θ	θ_{Vw}	W_w	W_o	M_w	M_{sr}	θ_w	C_{fg}	θ_{cg}	Error (θ-θ_{cg})
Units	cm	m^3/m^3	V	g	g	g	g	m^3/m^3		m^3/m^3	m^3/m^3
1	30	0.18	0.439	423.60	394.32	29.28	150.73	0.172	**0.954**	0.172	0.008
2	30	0.25	0.559	433.93	396.24	37.69	160.17	0.228	**0.913**	0.228	0.022
3	30	0.23	0.523	433.17	395.35	37.82	155.48	0.225	**0.980**	0.225	0.005
4	60	0.23	0.521	410.17	373.49	36.68	146.02	0.230	**1.002**	0.230	0.000
5	60	0.24	0.583	433.89	396.09	37.80	167.15	0.236	**0.983**	0.236	0.004
6	60	0.24	0.573	430.51	390.73	39.78	161.21	0.248	**1.032**	0.248	-0.008
7	90	0.15	0.401	410.48	386.30	24.18	151.81	0.147	**0.982**	0.147	0.003
8	90	0.18	0.435	417.12	390.56	26.56	148.72	0.157	**0.872**	0.157	0.023
9	90	0.16	0.445	409.35	384.46	24.89	154.46	0.155	**0.967**	0.155	0.005
10	120	0.16	0.440	418.67	392.49	26.18	151.69	0.155	**0.971**	0.155	0.005
11	120	0.15	0.398	415.98	390.72	25.26	145.31	0.147	**0.981**	0.147	0.003
12	120	0.16	0.442	409.56	382.54	27.02	132.61	0.154	**0.966**	0.154	0.006
13	150	0.18	0.456	394.29	366.42	27.87	120.04	0.162	**0.898**	0.162	0.018
14	150	0.18	0.479	425.26	393.35	31.91	155.48	0.192	**1.065**	0.192	-0.012
15	150	0.19	0.501	411.58	380.70	30.88	146.02	0.188	**0.990**	0.188	0.002
Mean		**0.190**	0.480	418.50	387.58	30.92	149.79	0.186	**0.970**	**0.186**	0.006
St. Dev.		0.035	0.060	11.482	8.741	5.580	11.540	0.037	0.048	0.037	-

Table A3.4 Summary ThetaProbe Gravimetric Calibration Results, Field B1 (Av. DBD 1.458 g/cm^3)

Sample No.	Probe Depth	θ	θ_{Vw}	W_w	W_o	M_w	M_{sr}	θ_w	C_{fg}	θ_{cg}	Error (θ-θ_{cg})
Units	cm	m^3/m^3	V	g	g	g	g	m^3/m^3		m^3/m^3	m^3/m^3
1	30	0.12	0.386	391.40	371.00	20.40	146.02	0.132	**1.102**	0.132	-0.012
2	30	0.16	0.471	377.91	350.55	27.36	155.48	0.204	**1.278**	0.204	-0.044
3	30	0.15	0.411	410.33	380.15	30.18	120.04	0.169	**1.128**	0.169	-0.019
4	60	0.17	0.453	405.45	379.42	26.03	146.02	0.163	**0.956**	0.163	0.007
5	60	0.16	0.454	391.49	371.74	19.75	155.48	0.133	**0.832**	0.133	0.027
6	60	0.13	0.354	362.72	344.78	17.94	120.04	0.116	**0.895**	0.116	0.014
7	90	0.16	0.456	378.23	353.80	24.43	132.61	0.161	**1.006**	0.161	-0.001
8	90	0.19	0.438	405.50	372.16	33.34	145.31	0.214	**1.128**	0.214	-0.024
9	90	0.16	0.478	412.47	379.55	32.92	151.69	0.211	**1.317**	0.211	-0.051
10	120	0.19	0.547	434.02	402.83	31.19	154.46	0.183	**0.964**	0.183	0.007
11	120	0.23	0.578	437.28	404.44	32.84	148.72	0.187	**0.814**	0.187	0.043
12	120	0.21	0.546	436.96	405.46	31.50	151.81	0.181	**0.862**	0.181	0.029
13	150	0.18	0.545	431.54	401.45	30.09	161.21	0.183	**1.015**	0.183	-0.003
14	150	0.21	0.525	435.48	403.61	31.87	167.15	0.197	**0.936**	0.197	0.013
15	150	0.23	0.590	436.59	402.56	34.03	160.17	0.205	**0.890**	0.205	0.025
Mean		**0.170**	0.482	409.82	381.56	28.25	147.74	0.176	**1.008**	**0.176**	0.001
St. Dev.		0.033	0.071	25.182	21.149	5.359	13.852	0.030	0.154	0.030	-

Table A3.4 Summary ThetaProbe Gravimetric Calibration Results, Field B2 (Av. DBD 1.439 g/cm^3)

Sample No.	Probe Depth	θ	θ_{Vw}	W_w	W_o	M_w	M_{sr}	θ_w	C_{fg}	θ_{cg}	Error (θ-θ_{cg})
Units	cm	m^3/m^3	V	g	g	g	g	m^3/m^3		m^3/m^3	m^3/m^3
1	30	0.25	0.625	438.51	390.00	48.51	150.73	0.292	**1.167**	0.292	-0.042
2	30	0.25	0.623	447.02	398.01	49.01	160.17	0.297	**1.186**	0.297	-0.047
3	30	0.25	0.627	443.46	394.04	49.42	155.48	0.298	**1.192**	0.298	-0.048
4	60	0.23	0.647	420.50	376.30	44.20	146.02	0.276	**1.201**	0.276	-0.046
5	60	0.22	0.641	438.86	394.41	44.45	167.15	0.281	**1.279**	0.281	-0.061
6	60	0.23	0.643	434.89	390.55	44.34	161.21	0.278	**1.210**	0.278	-0.048
7	90	0.22	0.553	415.00	374.04	40.96	151.81	0.265	**1.206**	0.265	-0.045
8	90	0.21	0.507	401.96	364.93	37.03	148.72	0.246	**1.174**	0.246	-0.036
9	90	0.24	0.657	411.00	366.97	44.03	154.46	0.298	**1.242**	0.298	-0.058
10	120	0.29	0.741	425.98	369.73	56.25	151.69	0.371	**1.280**	0.371	-0.081
11	120	0.27	0.647	400.01	352.49	47.52	145.31	0.330	**1.222**	0.330	-0.060
12	120	0.28	0.630	379.94	337.32	42.62	132.61	0.300	**1.070**	0.300	-0.020
13	150	0.24	0.686	384.60	338.45	46.15	120.04	0.304	**1.267**	0.304	-0.064
14	150	0.27	0.617	417.77	371.92	45.85	155.48	0.305	**1.129**	0.305	-0.035
15	150	0.20	0.611	411.72	364.69	47.03	146.02	0.309	**1.547**	0.309	-0.109
Mean		**0.243**	0.630	418.08	372.25	45.82	149.79	0.297	**1.225**	**0.297**	-0.053
St. Dev.		0.026	0.052	20.605	19.267	4.348	11.540	0.029	0.105	0.029	0.021

Table A3.5 ThetaProbe© Gravimetric Calibration Calculation Procedure

Symbol*	Description	Calculation	Unit
θ	Field soil sample measurement of moisture content using ThetaProbe©	measured	m^3/m^3
θ_{Vw}	Field soil sample measurement of voltage using ThetaProbe©	measured	V
W_w	Soil sample wet field mass	measured	g
Oven Drying at 105°C for 24 hours			
W_o	Dry soil sample mass	measured	g
M_w	Mass of water contained in sample	W_w-W_o	g
M_{sr}	Mass of soil sample ring	measured	g
θ_w	Soil sample moisture content determined gravimetrically	DBD(M_w/(W_o-M_{sr}))	m^3/m^3
C_{fg}	Calibration factor determined using gravimetric result	θ_w/θ	-
θ_{cg}	Soil Calibrated ThetaProbe reading©	$\theta\, C_{fg}$	m^3/m^3
Error	Difference between original field measured moisture content and calculated	$\theta - \theta_{cg}$	m^3/m^3

Notes: * symbols are the same as used in Table A3.3. DBD used in the calculation for θ_w is the Dry Bulk Density of the soil (g/cm^3).

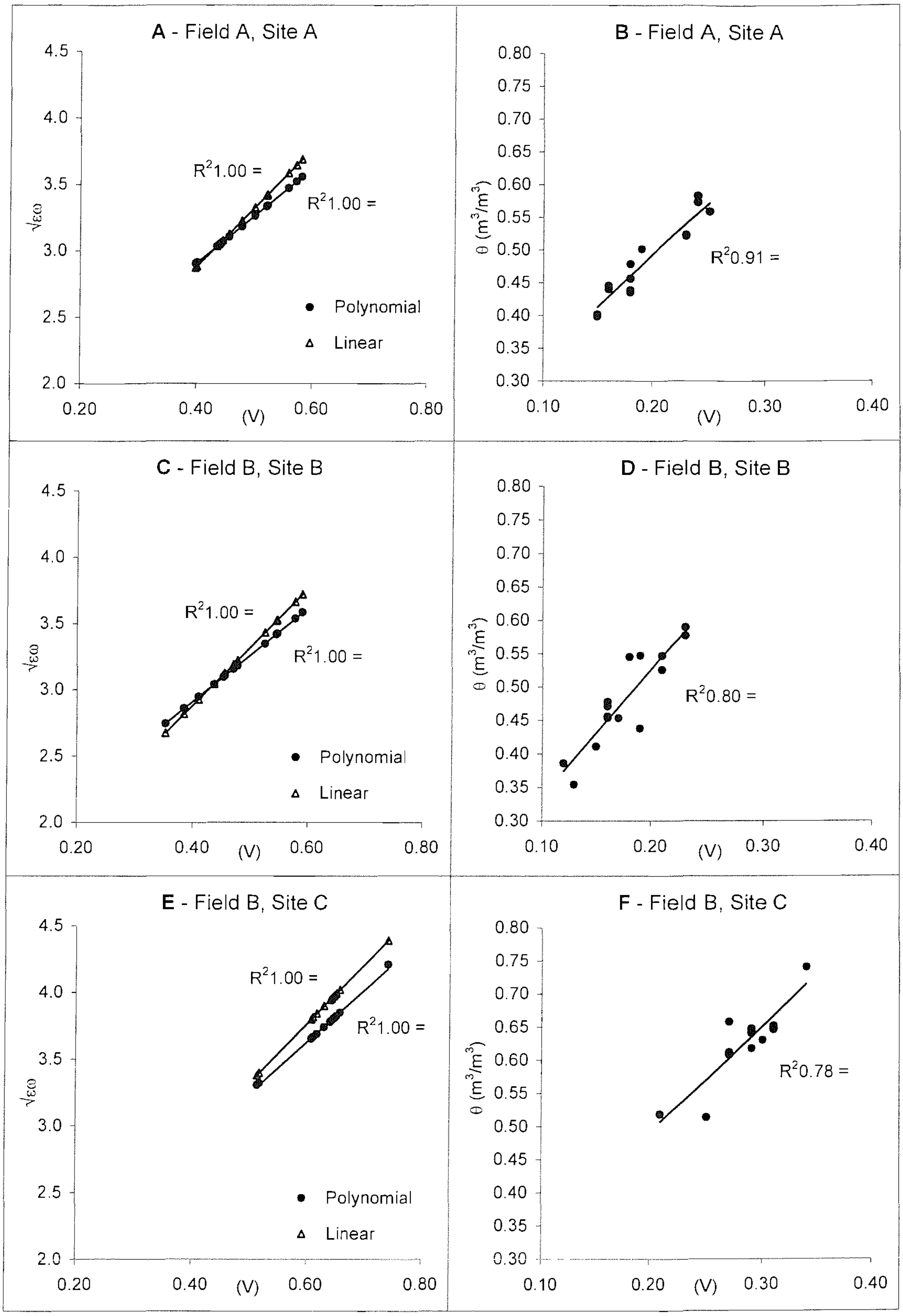

A - Field A, Site A
4.5
4.0
3.5
3.0
2.5
2.0
√εω
R²1.00 =
R²1.00 =
Polynomial
Linear
0.20
0.40
(V)
0.60
0.80
B - Field A, Site A
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
θ (m³/m³)
R²0.91 =
0.10
0.20
(V)
0.30
0.40
C - Field B, Site B
4.5
4.0
3.5
3.0
2.5
2.0
√εω
R²1.00 =
R²1.00 =
Polynomial
Linear
0.20
0.40
(V)
0.60
0.80
D - Field B, Site B
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
θ (m³/m³)
R²0.80 =
0.10
0.20
(V)
0.30
0.40
E - Field B, Site C
4.5
4.0
3.5
3.0
2.5
2.0
√εω
R²1.00 =
R²1.00 =
Polynomial
Linear
0.20
0.40
(V)
0.60
0.80
F - Field B, Site C
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
θ (m³/m³)
R²0.78 =
0.10
0.20
(V)
0.30
0.40

Table A3.6. Summary Particle Size Distribution Results for Lysimeter Soil

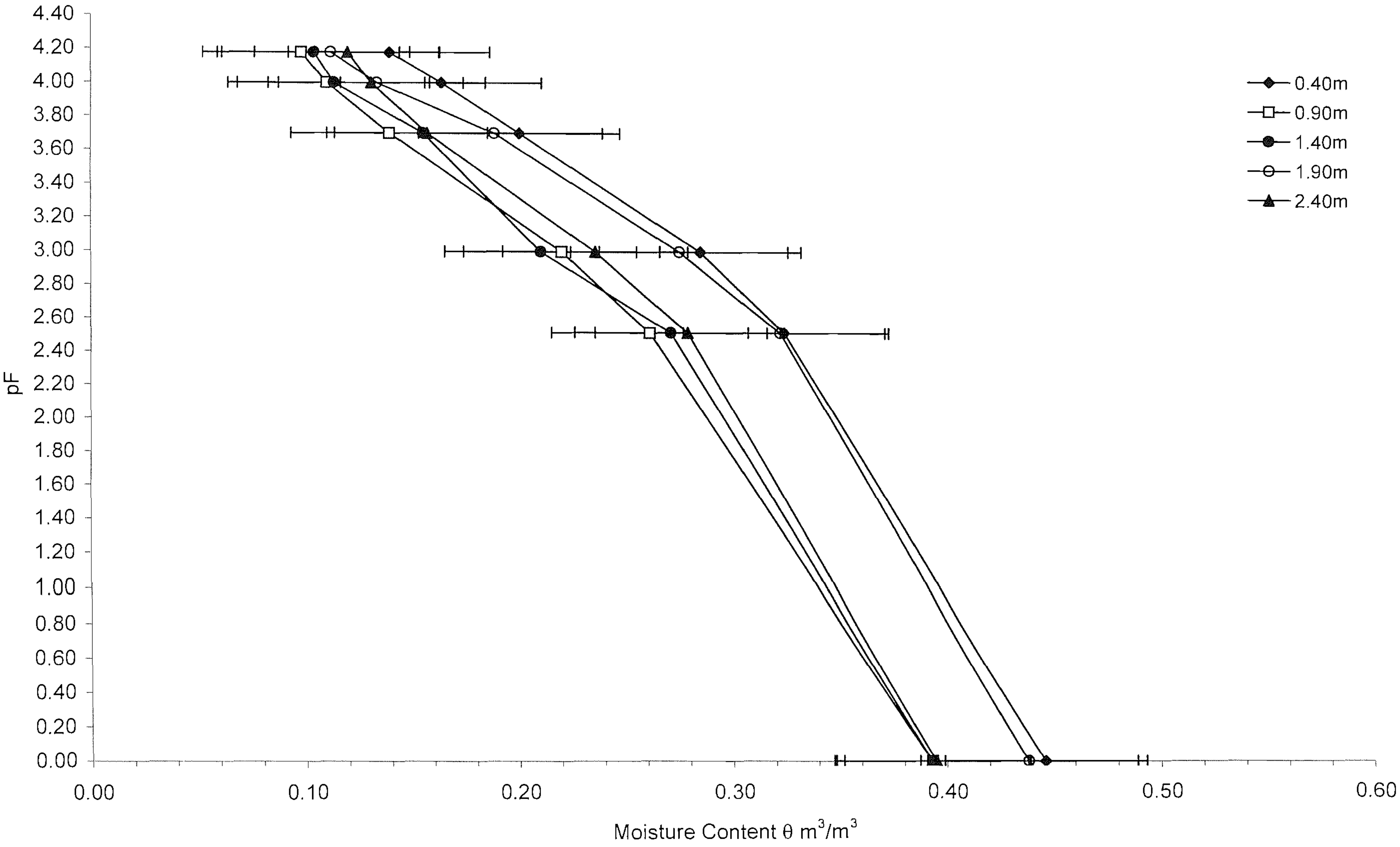
Site	Lysimeter Soil Type				
Depth (cm)	Sand (%)	Clay (%)	Silt (%)	Soil Type	DBD (g/cm^3)
0-10	19	24	57	ZL	-
10-30	12	29	59	ZCL	-
30-50	13	28	59	ZCL	1.415 to 1.448
50-70	10	28	62	ZCL/ZL	-
70-90	10	29	61	ZCL	1.474 to 1.561
90-110	10	30	60	ZCL	-
110-130	14	25	61	ZL	-
130-150	12	26	62	ZL	1.484 to 1.524
150-170	11	30	59	ZCL	-
170-190	8	23	69	ZL	1.487 to 1.514
190-210	12	30	58	ZCL	-
210-240	17	19	64	ZL	1.542 to 1.581
>240	17	19	64	ZL	-
Mean	13	26	61	-	1.497
St. Dev.	3.25	3.93	3.18	-	0.045

Notes: DBD is Dry Bulk Density. Total number of samples for PSD test = 2 x 100g samples per depth. Total number of samples for DBD test = 50. Soil classified using USDA-Soil Conservation Service Tables (1975) where Z is silt, C is clay and L is loam. According to the Soviet Kachinsky method soil type was heavy loam/clay.

Table A3.7. Summary Soil Moisture Characteristic Results for Lysimeter Soil

	Lysimeter Soil Moisture Content (m^3/m^3)			
Depth (cm)	Porosity	Field Capacity	Wilting Point	Available Moisture (mm)
40	0.446	0.324	0.140	184
90	0.393	0.261	0.098	163
120	0.393	0.271	0.104	167
190	0.438	0.322	0.112	210
240	0.395	0.279	0.120	159
Mean	0.413	0.291	0.115	177
St. Dev.	0.027	0.030	0.016	20.959
*Range (%)	6.450	10.141	14.239	11.868

Notes: * represents the percentage range of the standard deviation from the average mean value. Mean values for Field Capacity and Wilting Point are similar to values for the Experimental Site Soil. Porosity moisture content is higher for the lysimeter soil than soil from the Experimental Sites.



Soil Moisture Characteristic Curve for Lysimeters

Plate A3.1 Soil Capping in Field B

Plate A3.2 Irrigation Using Spile, Field A

Plate A3.3 Raingauge

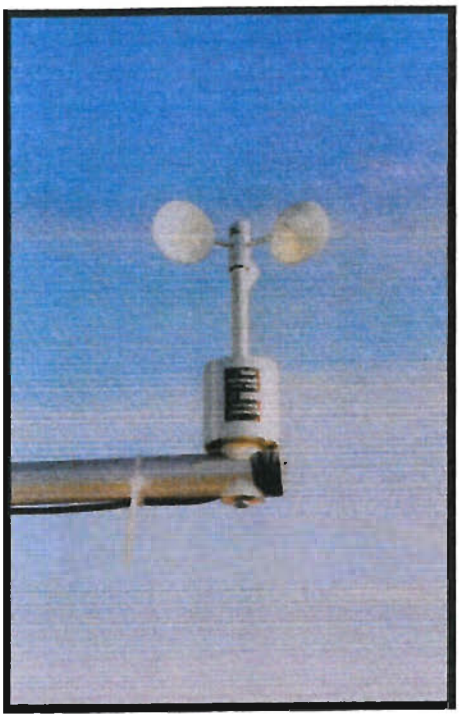


Plate A3.4 Anemometer

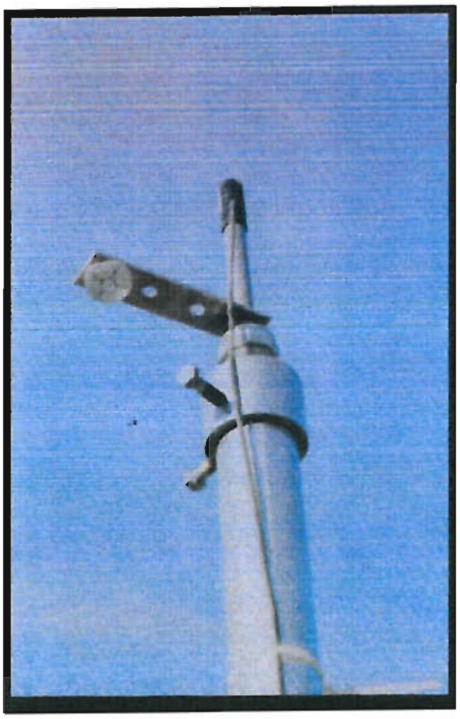


Plate A3.5 PAR Solar Radiation Sensor

Plate A3.6 Air Temperature and Relative Humidity Sensor

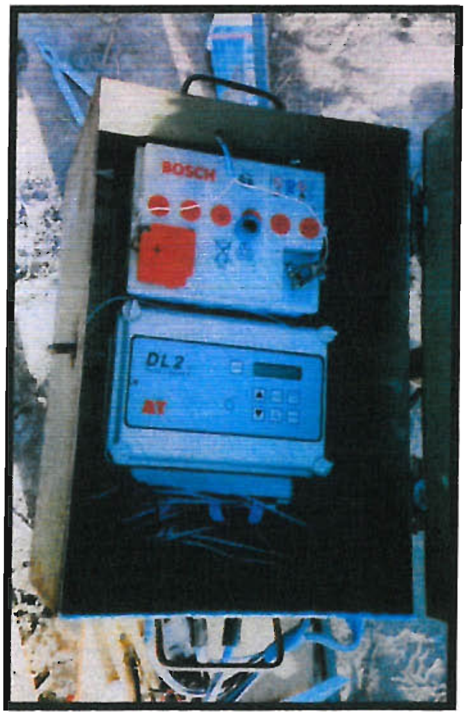


Plate A3.7 DL2e Logger and External 12V Battery

Plate A3.8 Water Filled Pressure Transducer Tensiometers and
Single Equitensiometer Prior to Field Insertion

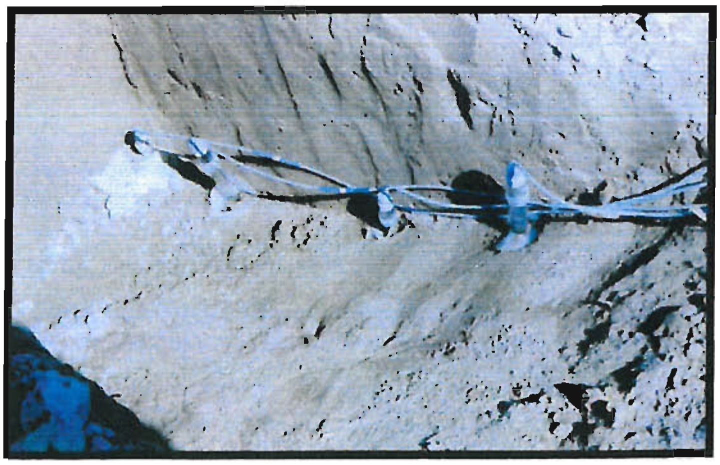


Plate A3.9 Water Filled Pressure Transducer Tensiometers

APPENDIX A4

EXAMPLE CALCULATION OF UPWARD FLUX USING THE NEW DIURNAL METHOD

Appendix A4.1
Field Measured Data Used to Calculate Hourly Rate of Change in Moisture Content (75 cm deep)

Date	Time	Measured Soil Moisture Suction	Soil Moisture Content	Moisture within Soil Layer	Hourly Change in Soil Moisture
	Hour	cm	m^3/m^3	mm	mm/hr
28/07/2000	00:00	-391.20	0.3174	47.6126	0.1925
28/07/2000	01:00	-383.30	0.3184	47.7538	0.1412
28/07/2000	02:00	-376.60	0.3192	47.8755	0.1217
28/07/2000	03:00	-369.90	0.3200	47.9991	0.1236
28/07/2000	04:00	-364.40	0.3207	48.1020	0.1029
28/07/2000	05:00	-359.50	0.3213	48.1948	0.0928
28/07/2000	06:00	-354.60	0.3219	48.2887	0.0939
28/07/2000	07:00	-351.60	0.3223	48.3467	0.0580
28/07/2000	08:00	-351.00	0.3224	48.3583	0.0117
28/07/2000	09:00	-356.50	0.3217	48.2521	-0.1062
28/07/2000	10:00	-366.20	0.3205	48.0682	-0.1840
28/07/2000	11:00	-380.20	0.3187	47.8099	-0.2583
28/07/2000	12:00	-399.10	0.3165	47.4739	-0.3360
28/07/2000	13:00	-416.80	0.3145	47.1714	-0.3025
28/07/2000	14:00	-432.60	0.3127	46.9106	-0.2608
28/07/2000	15:00	-446.10	0.3113	46.6942	-0.2164
28/07/2000	16:00	-458.20	0.3100	46.5049	-0.1892
28/07/2000	17:00	-470.40	0.3088	46.3185	-0.1865
28/07/2000	18:00	-480.80	0.3078	46.1628	-0.1557
28/07/2000	19:00	-489.90	0.3069	46.0289	-0.1339
28/07/2000	20:00	-495.40	0.3063	45.9490	-0.0799
28/07/2000	21:00	-496.60	0.3062	45.9317	-0.0173
28/07/2000	22:00	-489.90	0.3069	46.0289	0.0972
28/07/2000	23:00	-477.10	0.3081	46.2178	0.1889
29/07/2000	00:00	-461.90	0.3097	46.4479	0.2301
29/07/2000	01:00	-448.50	0.3110	46.6563	0.2084
29/07/2000	02:00	-436.30	0.3123	46.8507	0.1944
29/07/2000	03:00	-425.30	0.3135	47.0301	0.1794
29/07/2000	04:00	-415.60	0.3146	47.1916	0.1615
29/07/2000	05:00	-406.40	0.3157	47.3478	0.1562
29/07/2000	06:00	-397.90	0.3166	47.4948	0.1470
29/07/2000	07:00	-390.00	0.3176	47.6339	0.1391
29/07/2000	08:00	-383.30	0.3184	47.7538	0.1199
29/07/2000	09:00	-380.20	0.3187	47.8099	0.0561
29/07/2000	10:00	-383.90	0.3183	47.7430	-0.0669
29/07/2000	11:00	-396.10	0.3168	47.5263	-0.2167
29/07/2000	12:00	-417.40	0.3144	47.1614	-0.3649
29/07/2000	13:00	-441.20	0.3118	46.7721	-0.3893
29/07/2000	14:00	-466.20	0.3092	46.3822	-0.3899
29/07/2000	15:00	-488.10	0.3070	46.0552	-0.3270
29/07/2000	16:00	-508.20	0.3051	45.7661	-0.2891
29/07/2000	17:00	-525.90	0.3035	45.5195	-0.2465
29/07/2000	18:00	-541.10	0.3021	45.3135	-0.2061
29/07/2000	19:00	-554.60	0.3009	45.1346	-0.1789
29/07/2000	20:00	-563.70	0.3001	45.0162	-0.1184
29/07/2000	21:00	-567.40	0.2998	44.9685	-0.0477
29/07/2000	22:00	-561.30	0.3003	45.0472	0.0788
29/07/2000	23:00	-549.10	0.3014	45.2070	0.1598
30/07/2000	00:00	-535.00	0.3026	45.3955	0.1885
30/07/2000	01:00	-519.80	0.3040	45.6037	0.2081
30/07/2000	02:00	-504.60	0.3054	45.8171	0.2134
30/07/2000	03:00	-489.30	0.3069	46.0377	0.2205

30/07/2000	04:00	-475.30	0.3083	46.2447	0.2071
30/07/2000	05:00	-462.50	0.3096	46.4387	0.1940
30/07/2000	06:00	-450.90	0.3108	46.6186	0.1799
30/07/2000	07:00	-440.60	0.3119	46.7817	0.1631
30/07/2000	08:00	-432.00	0.3128	46.9204	0.1387
30/07/2000	09:00	-429.00	0.3131	46.9693	0.0489
30/07/2000	10:00	-433.90	0.3126	46.8895	-0.0798
30/07/2000	11:00	-447.90	0.3111	46.6657	-0.2238
30/07/2000	12:00	-470.40	0.3088	46.3185	-0.3473
30/07/2000	13:00	-496.00	0.3063	45.9404	-0.3781
30/07/2000	14:00	-522.90	0.3037	45.5608	-0.3796
30/07/2000	15:00	-547.80	0.3015	45.2242	-0.3366
30/07/2000	16:00	-570.40	0.2995	44.9300	-0.2942
30/07/2000	17:00	-589.30	0.2979	44.6916	-0.2384
30/07/2000	18:00	-607.00	0.2965	44.4743	-0.2173
30/07/2000	19:00	-621.60	0.2953	44.2992	-0.1751
30/07/2000	20:00	-632.60	0.2945	44.1696	-0.1296
30/07/2000	21:00	-637.40	0.2941	44.1136	-0.0559
30/07/2000	22:00	-634.40	0.2943	44.1485	0.0349
30/07/2000	23:00	-627.70	0.2948	44.2271	0.0785
31/07/2000	00:00	-617.90	0.2956	44.3432	0.1162
31/07/2000	01:00	-606.40	0.2965	44.4816	0.1384
31/07/2000	02:00	-594.20	0.2975	44.6309	0.1493
31/07/2000	03:00	-581.40	0.2986	44.7905	0.1595
31/07/2000	04:00	-567.40	0.2998	44.9685	0.1780
31/07/2000	05:00	-553.90	0.3010	45.1438	0.1753
31/07/2000	06:00	-540.50	0.3021	45.3215	0.1777
31/07/2000	07:00	-528.30	0.3032	45.4866	0.1651
31/07/2000	08:00	-518.60	0.3041	45.6203	0.1337
31/07/2000	09:00	-516.20	0.3044	45.6537	0.0334
31/07/2000	10:00	-522.90	0.3037	45.5608	-0.0929
31/07/2000	11:00	-536.30	0.3025	45.3780	-0.1828
31/07/2000	12:00	-554.60	0.3009	45.1346	-0.2434
31/07/2000	13:00	-575.90	0.2991	44.8600	-0.2747
31/07/2000	14:00	-599.00	0.2971	44.5719	-0.2881
31/07/2000	15:00	-621.00	0.2954	44.3063	-0.2655
31/07/2000	16:00	-639.90	0.2939	44.0846	-0.2217
31/07/2000	17:00	-657.60	0.2925	43.8821	-0.2025
31/07/2000	18:00	-672.80	0.2914	43.7120	-0.1702
31/07/2000	19:00	-685.60	0.2905	43.5712	-0.1407
31/07/2000	20:00	-695.40	0.2898	43.4650	-0.1062
31/07/2000	21:00	-700.80	0.2894	43.4071	-0.0580
31/07/2000	22:00	-700.80	0.2894	43.4071	0.0000
31/07/2000	23:00	-697.80	0.2896	43.4392	0.0322
01/08/2000	00:00	-692.30	0.2900	43.4985	0.0593
01/08/2000	01:00	-686.20	0.2904	43.5647	0.0662
01/08/2000	02:00	-678.90	0.2910	43.6446	0.0799
01/08/2000	03:00	-671.00	0.2915	43.7319	0.0873
01/08/2000	04:00	-662.40	0.2922	43.8280	0.0961
01/08/2000	05:00	-653.30	0.2929	43.9309	0.1029
01/08/2000	06:00	-644.20	0.2936	44.0350	0.1041
01/08/2000	07:00	-633.80	0.2944	44.1555	0.1206
01/08/2000	08:00	-623.40	0.2952	44.2778	0.1223

APPENDIX A5

SUPPORTING INFORMATION TO CHAPTER FIVE

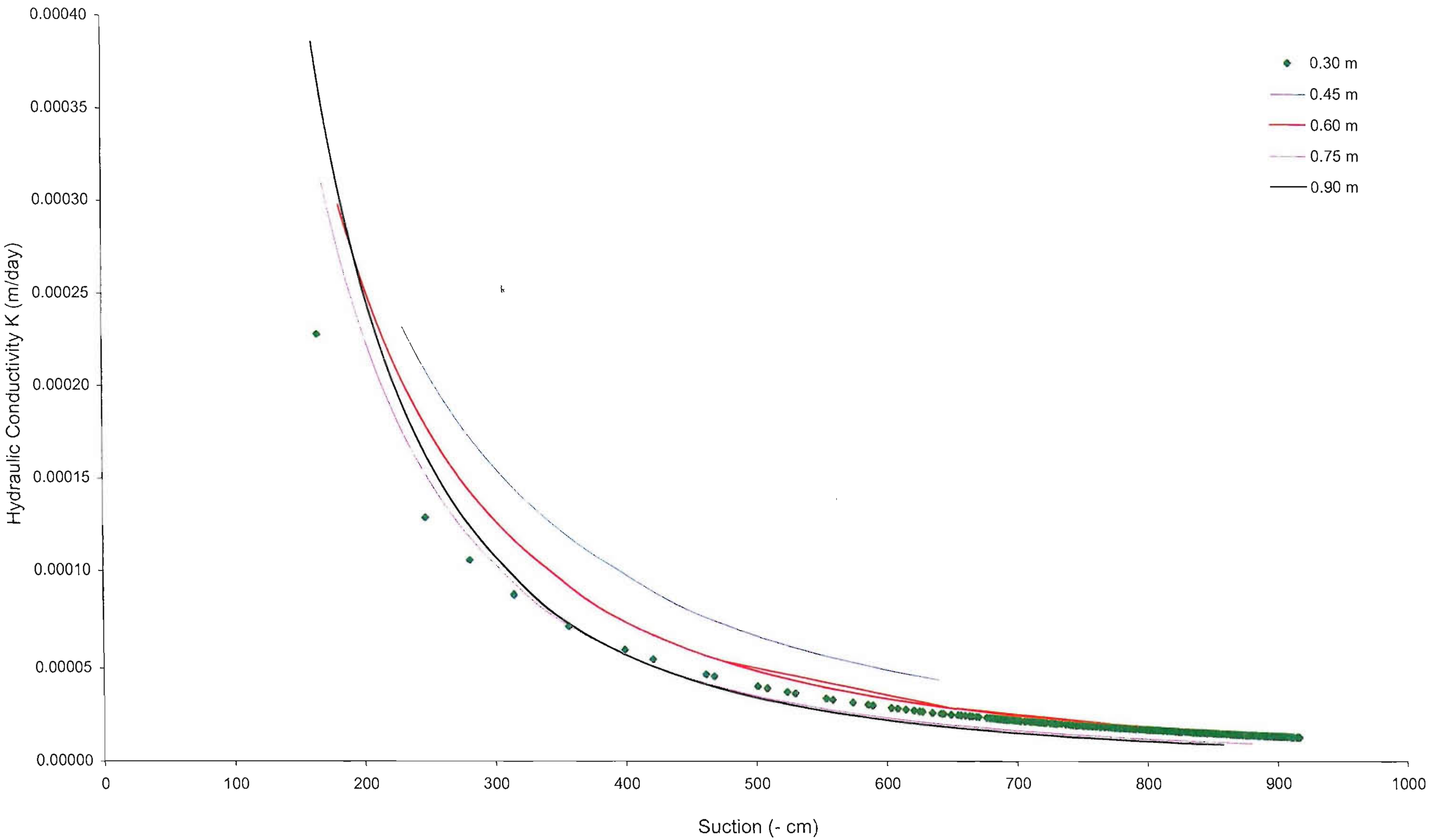
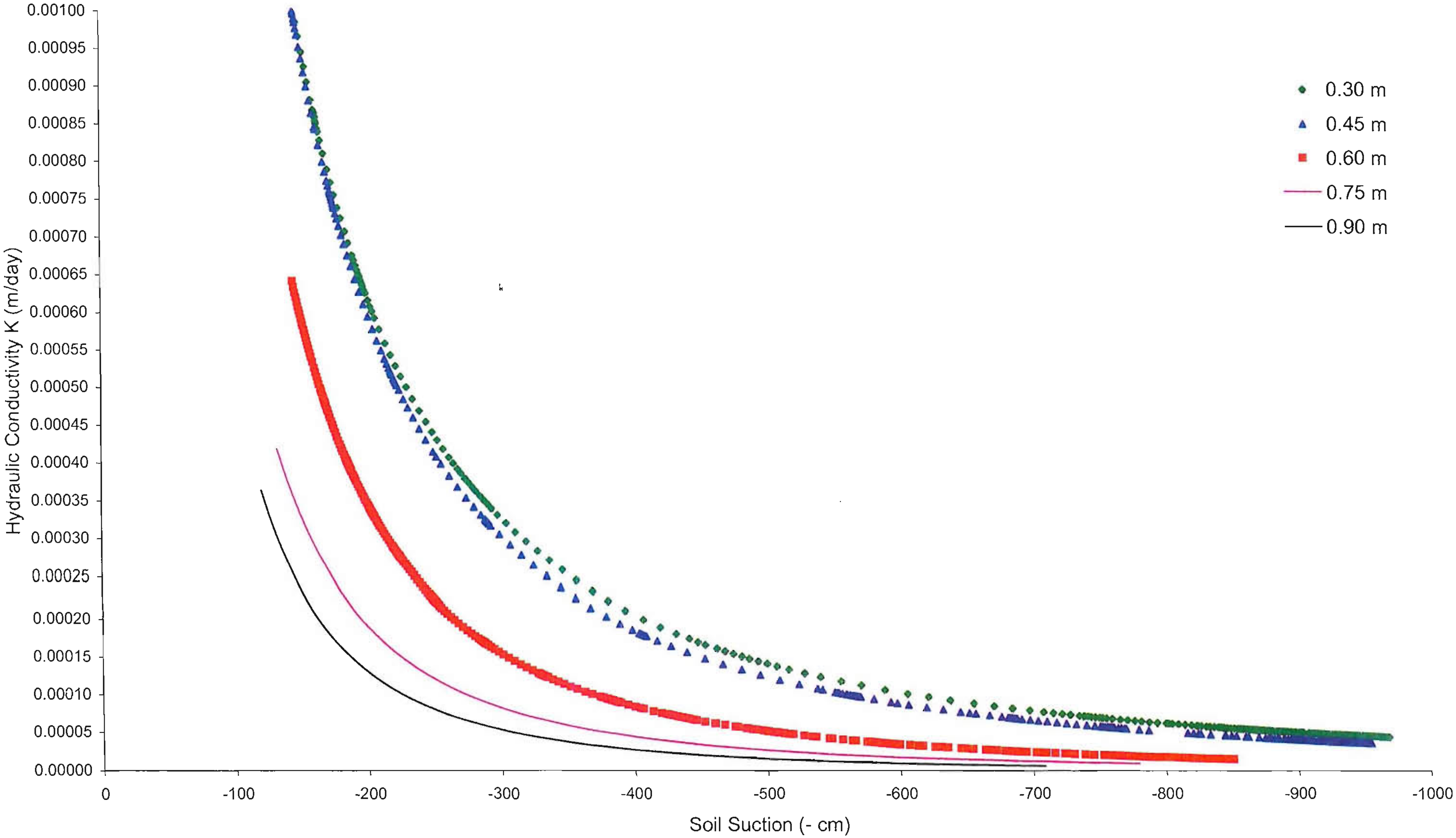


Figure 6.2 Hydraulic Conductivity as a Function of Soil Moisture Suction Using Campbell's (1974) Equation, Field B-1



Hydraulic Conductivity as a Function of Soil Moisture Suction Using Campbell's (1974) Equation, Field B-2

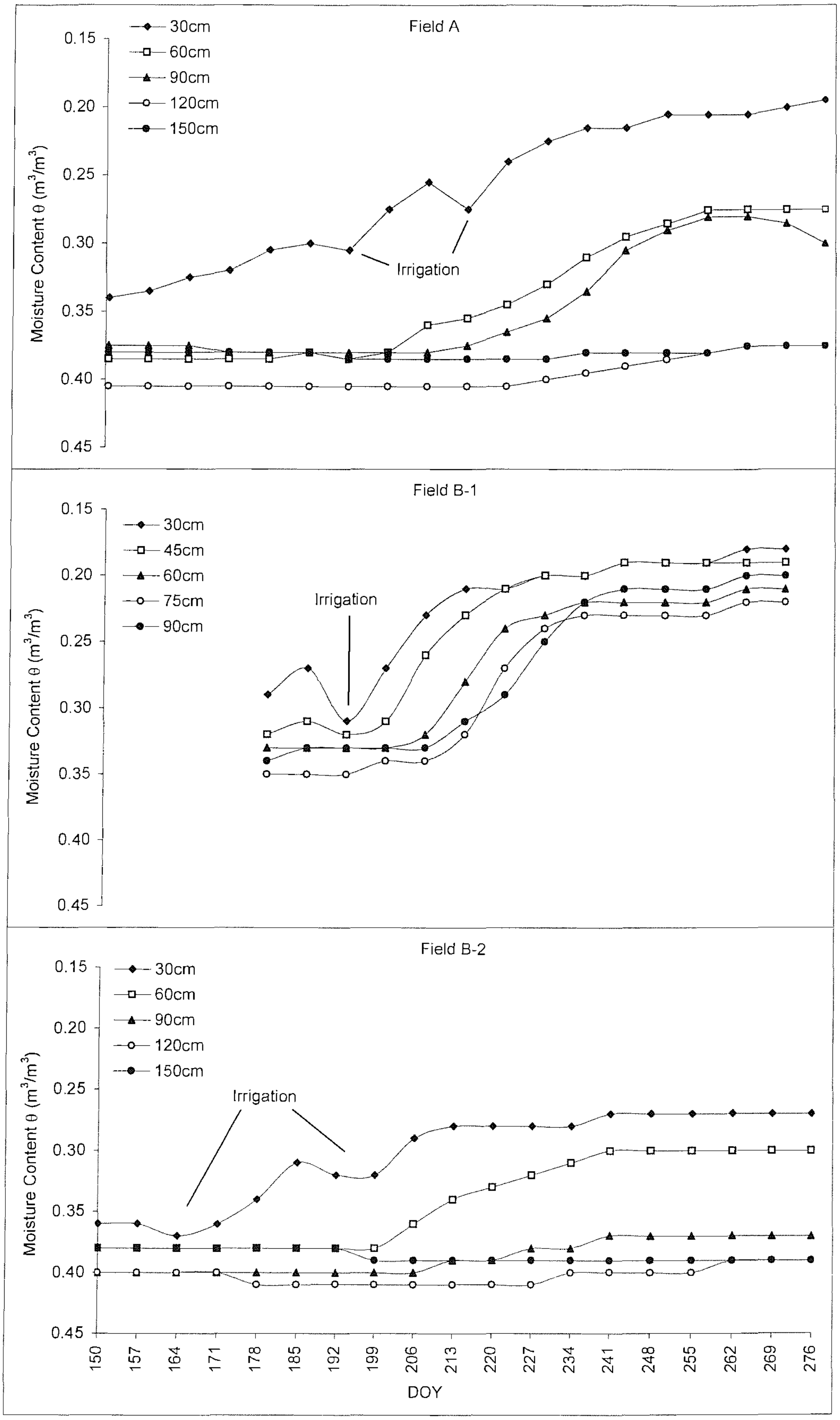
Weekly Field Soil Moisture Balance

The Figure overleaf shows the weekly soil moisture balance for the experimental sites. Irrigation events and the beginning of the cotton harvest are indicated. Negative values represent moisture entering the soil profile and positive values represent moisture leaving the profile. The moisture balance for both arrays of ThetaProbes© (1 and 2) used in Field A are both shown.

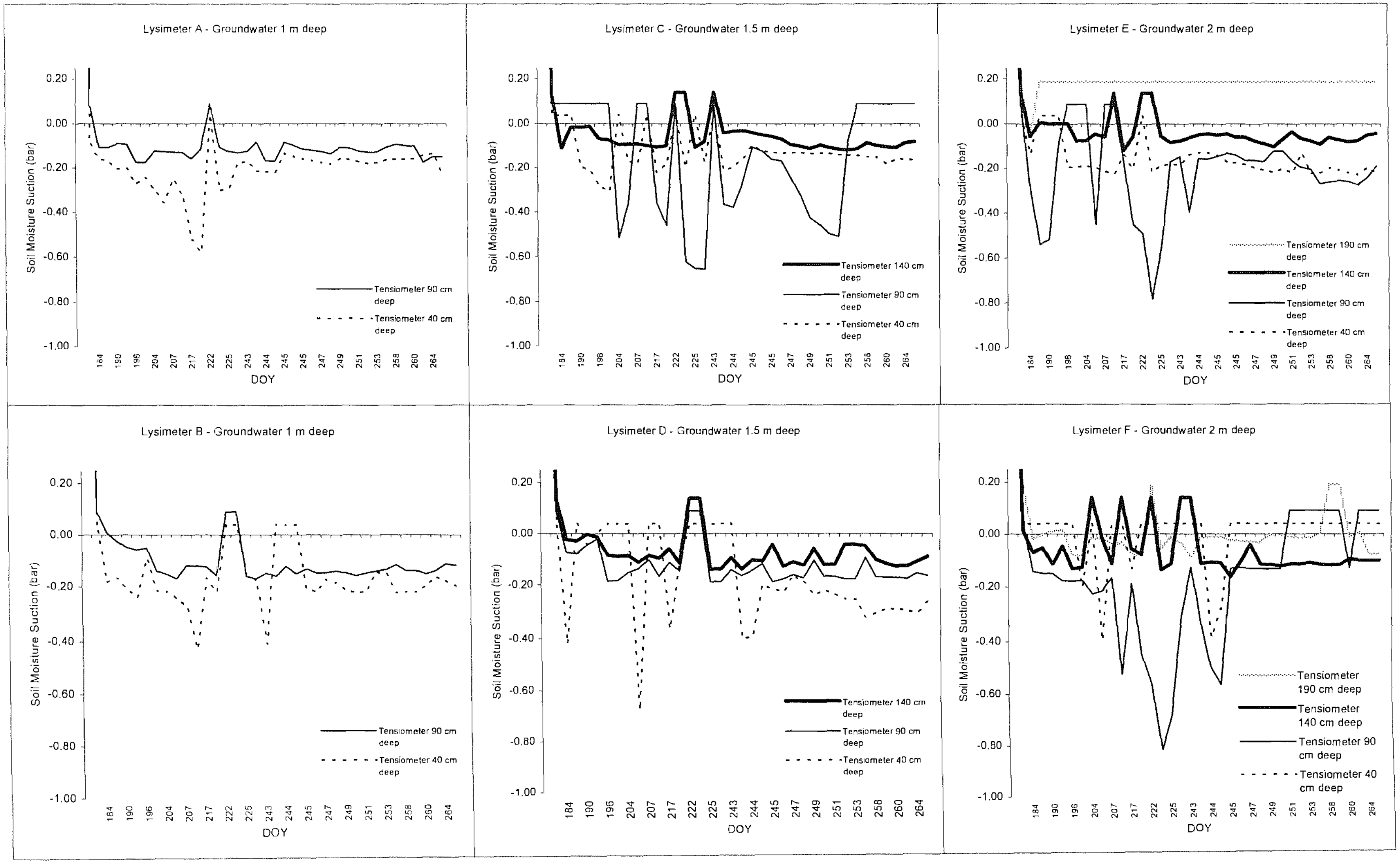
Irrigation water is shown entering the soil at Field A (Array 2) and Fields B1 and B2. Array 1 in Field A did not show moisture entering the profile during irrigation. Increasing moisture extraction is apparent between weeks beginning Day of Year 192 to 234, indicating increased crop evapotranspiration during the vegetative cotton growth stages.

Maximum moisture extraction occurred in Field A, which also produced the deepest rooting crop and maximum cotton yield. Both ThetaProbe© arrays recorded maximum weekly moisture extraction rates two weeks apart. This may be due to different phenological development rates between the cotton plants in Field A between the ThetaProbe© arrays. Alternatively, the second irrigation recorded with Array 2, but not at Array 1, may have triggered rapid crop development for plants located close to ThetaProbe© Array 2.

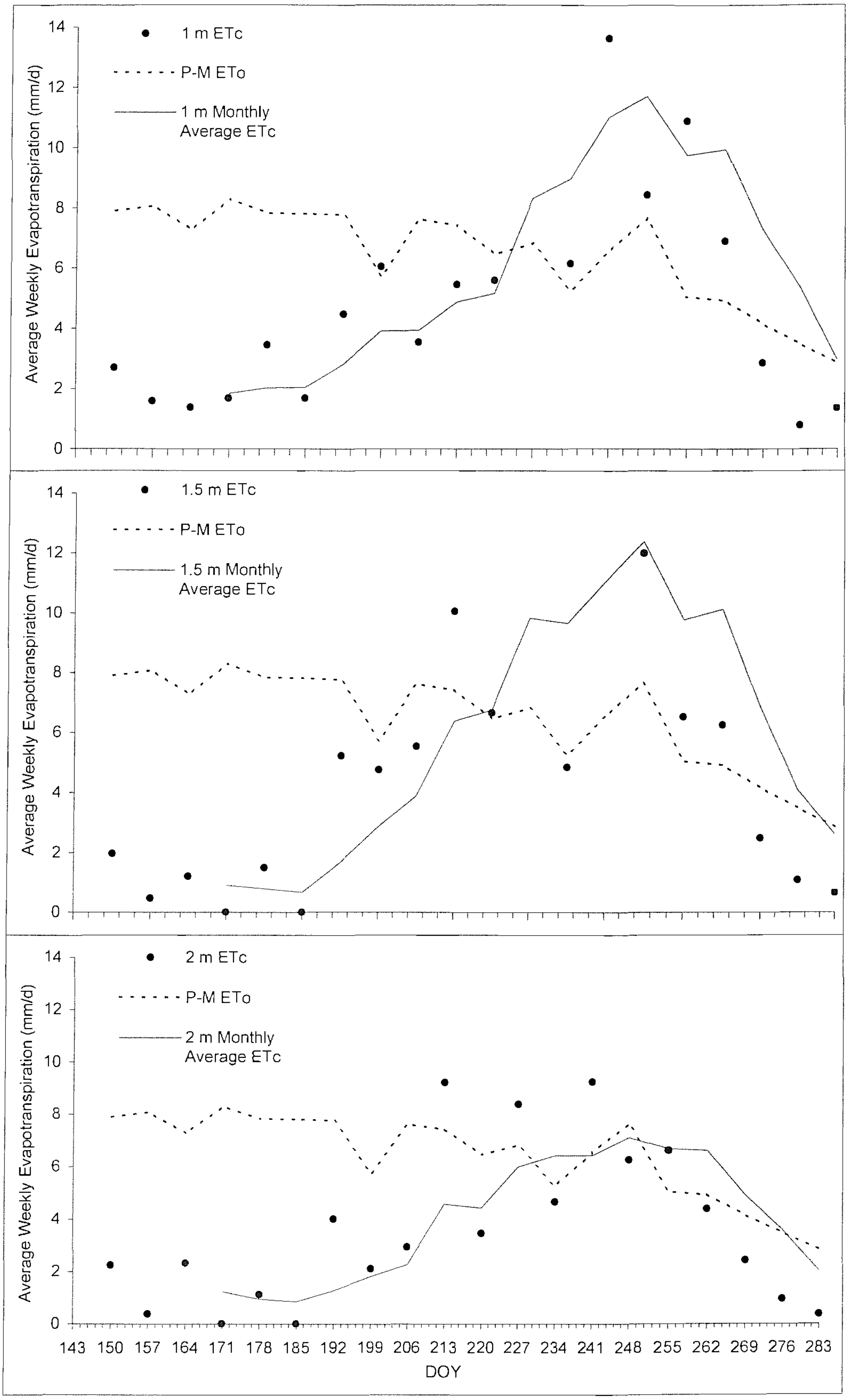
Moisture extraction rates in Fields B1 and B2 were lower than Field A. Field B-2 showed minimal moisture extraction. This suggests that the crop was not transpiring at the potential peak rate, or that the crop was extracting water deeper than instrument depth in the profile.



Volumetric Soil Moisture Content in the Study Fields



Soil Moisture Suction Recorded in Lysimeters with Hg Tensiometers



Mean Weekly Evapotranspiration from Lysimeters

EXAMPLE CALCULATION OF UPWARD FLUX IN SOILS USING DARCY'S LAW

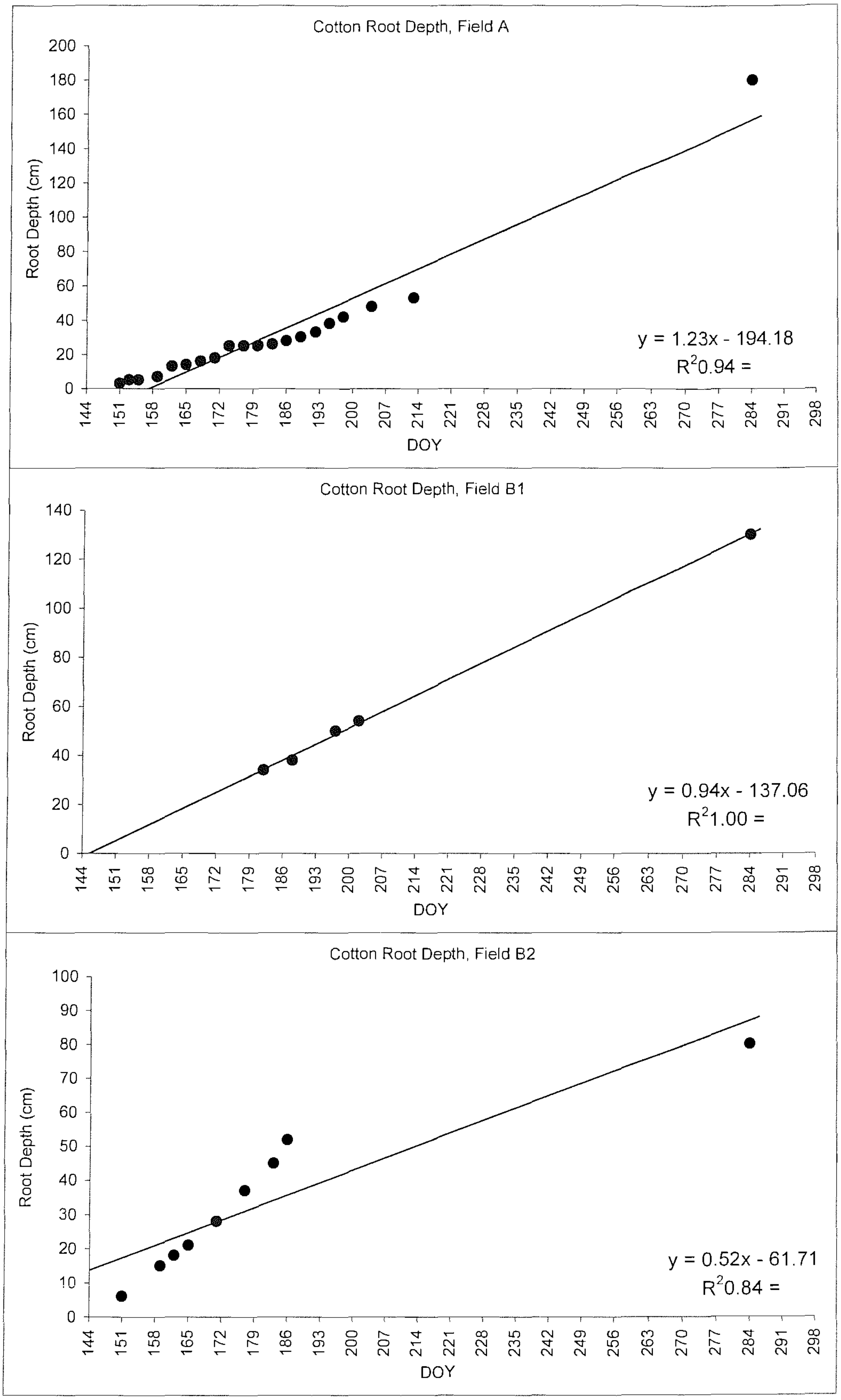
Table A5.1 contains an example calculation procedure from the 45 cm depth in Field B1. Soil moisture suction was recorded with water-filled tensiometers, corrected for gravity and used to calculate the hydraulic gradient between 45 and 60 cm's depths. The depth and site specific pF curves allowed conversion of suction to pF and moisture content (θ).

The Campbell equation to calculate hydraulic conductivity and Darcy's equation to determine moisture flux are described in Chapter Four. Each calculation was performed on an hourly basis, with upward flux estimated per hour, and an average rate calculated per day. The similarity between the hourly rate and daily rate of upward flux suggests that an almost constant rate occurred throughout this period between 45 and 60 cm's.

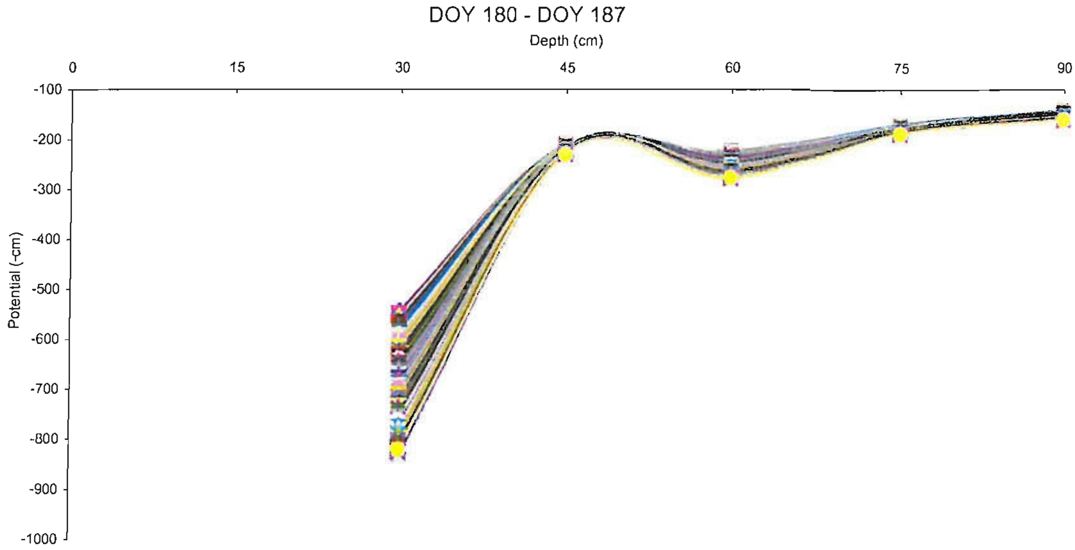
Table A5.1 Calculation of Upward Flux Using Darcy's Law - 45 cm Depth

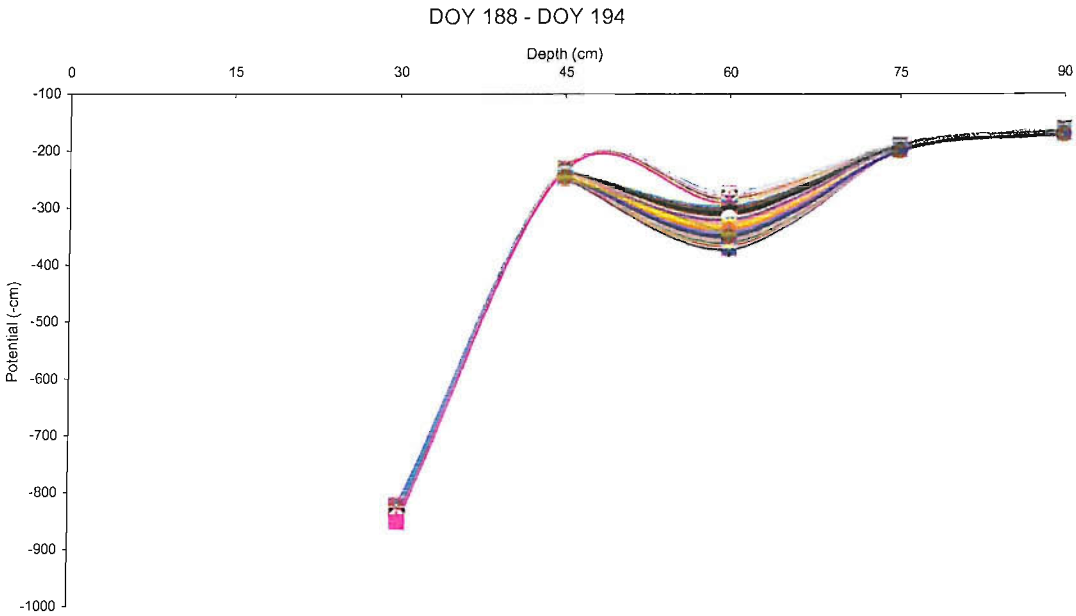
1	2	3	4	5	6	7	8
	ϕ	$\delta H/\delta Z$	pF	θ	K	q	q_{avg}
Units	cm	cm/cm		m^3/m^3	m/d	mm/hour	mm/d
181	-276.02	-4.11	2.441	0.259	0.000232	-0.954	-0.956
182	-281.38	-4.29	2.449	0.258	0.000224	-0.962	-0.953
183	-288.52	-4.61	2.460	0.257	0.000215	-0.989	-0.988
184	-296.83	-4.95	2.473	0.256	0.000204	-1.011	-1.010
185	-306.93	-5.43	2.487	0.255	0.000193	-1.047	-1.041
186	-321.53	-6.09	2.507	0.254	0.000178	-1.082	-1.079
187	-337.30	-6.87	2.528	0.253	0.000163	-1.121	-1.119

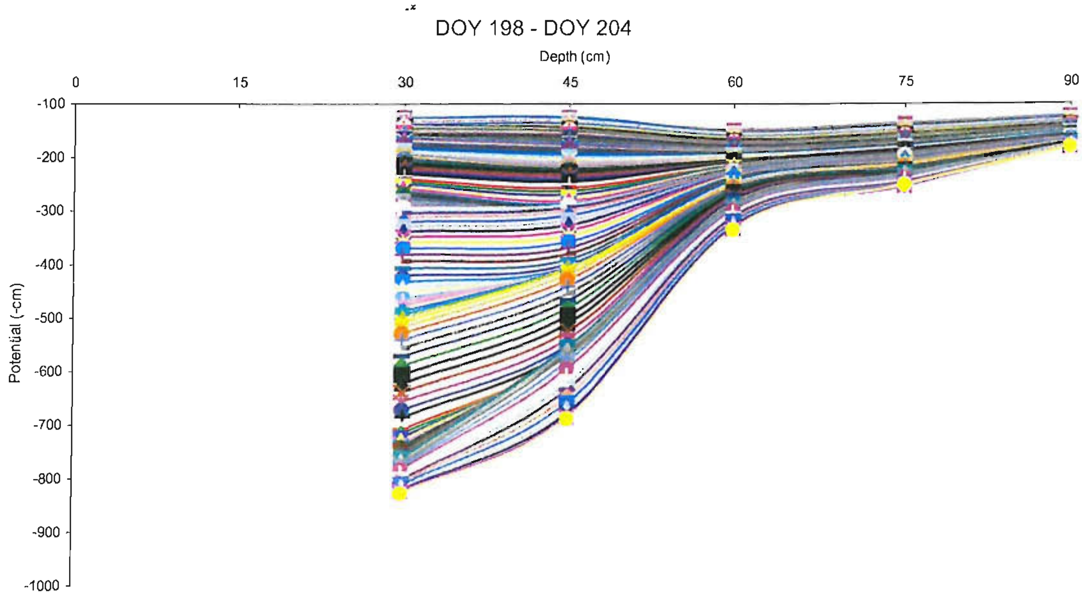
(1)	Day of Year
(2)	Hourly soil suction recorded in cm's pressure at 45 cm depth [corrected for gravity].
(3)	Hydraulic gradient between 45 and 60 cm's depth. Calculated from the suction at 45 cm [276.02] minus suction at 60 cm [214.34] divided by the difference in depth [60 - 45].
(4)	Suction from column 2 converted to pF [Log ϕ].
(5)	Moisture content converted from pF or suction using depth and soil specific pF curve for location. In this case [(-0.0666(pF))+0.4211].
(6)	Hydraulic conductivity calculated using Campbell's equation [Equation 3.1], where K_{SAT} = 0.305 m/day, θ_{SAT} = 0.411 m^3/m^3, and b = 6.2588.
(7)	Upward flux (where negative values indicate upward flow) calculated using Darcy's equation [Equation 3.2]. All results are based on hourly measurements.
(8)	Average rate of upward flux per day based on 24 measurements. Note the similarity between the hourly results in column 7 and the daily average, indicating almost a constant rate of upward flux.



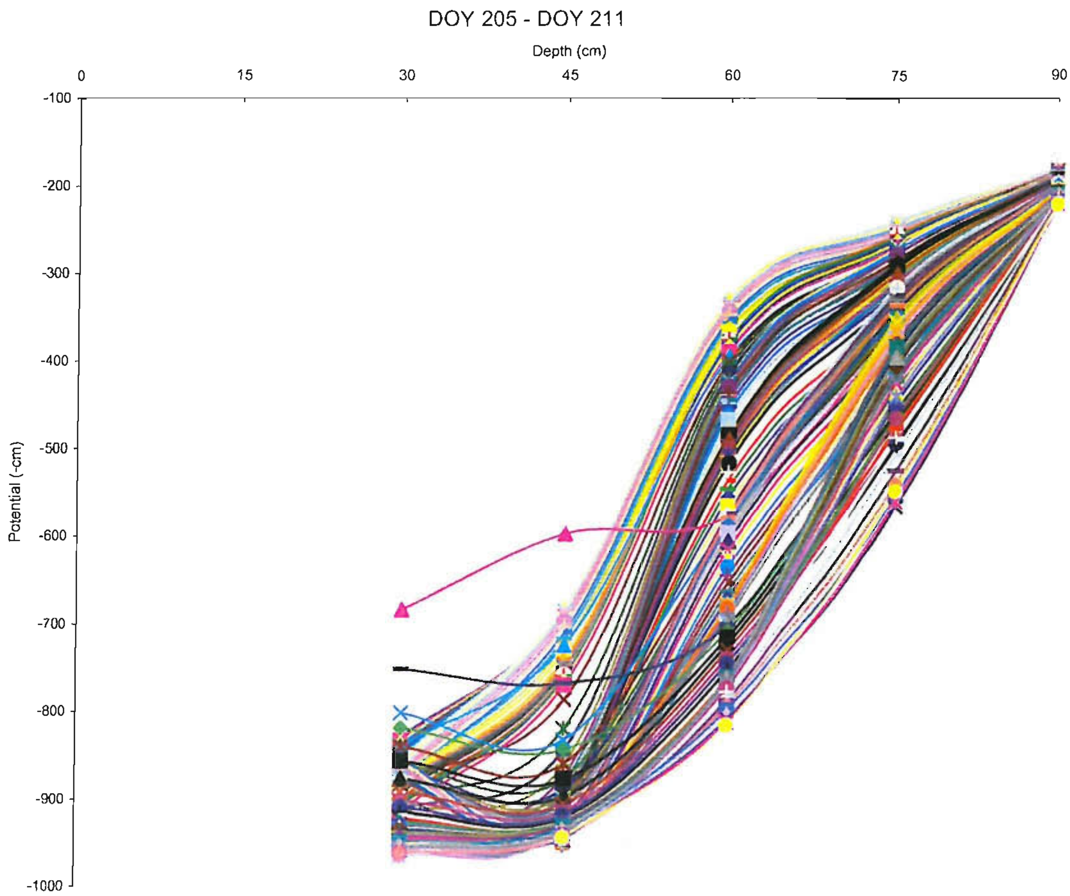
Cotton Rooting Depths

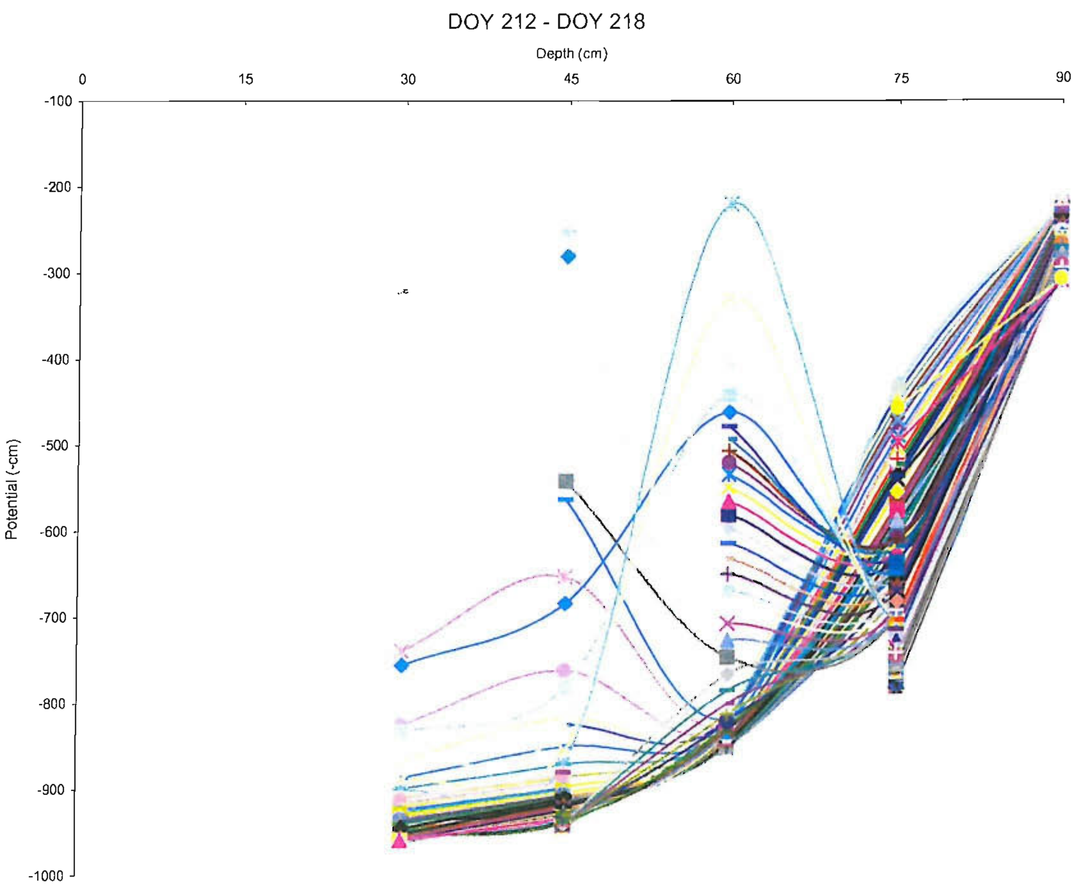




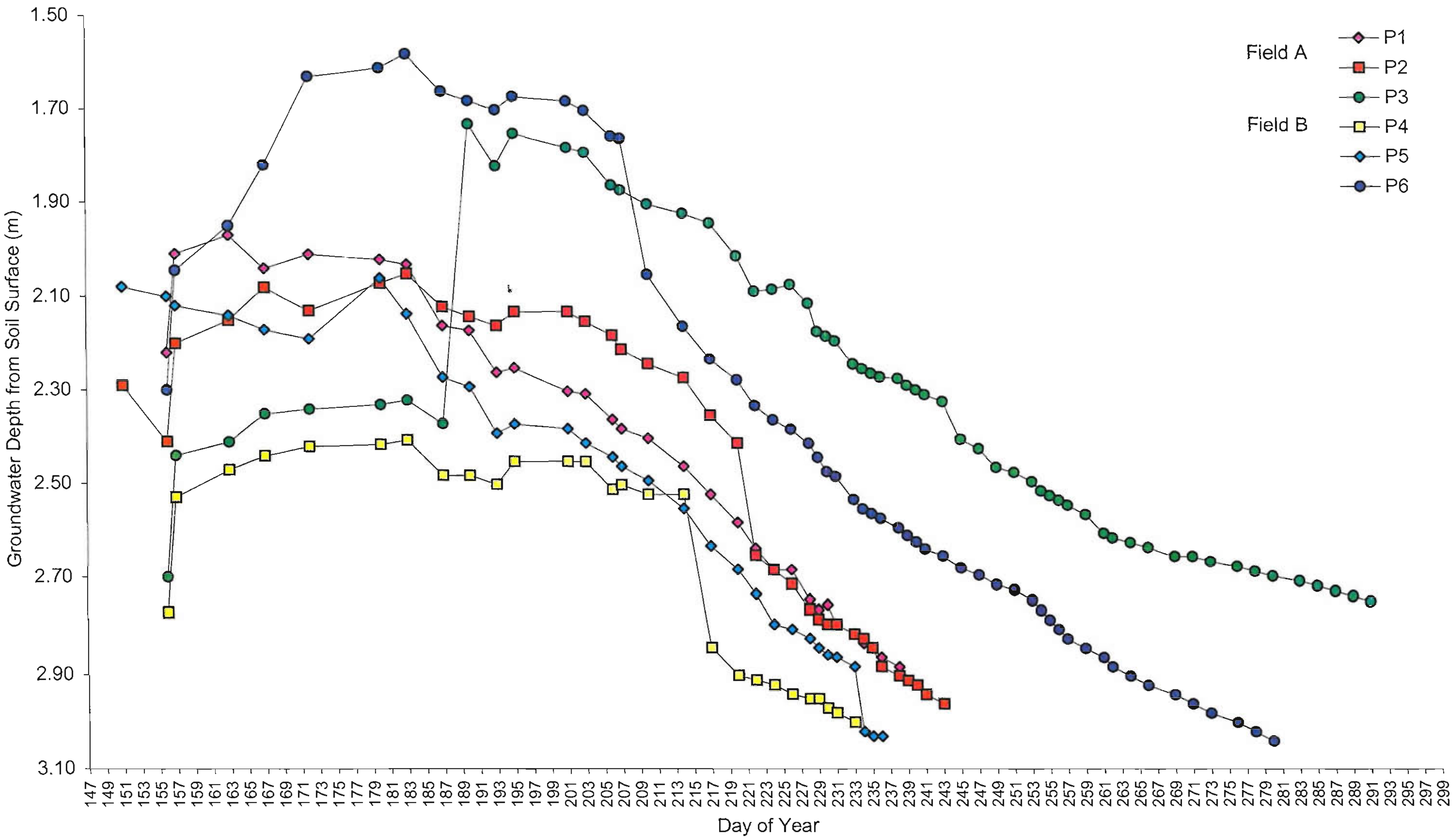


Development of Soil Moisture Potential in Field B2 Throughout Later Part of Growing Season (Day of Year 181 - 218)





Development of Soil Moisture Potential in Field B2 Throughout Later Part of Growing Season (Day of Year 181 - 218)



Experimental Site Groundwater Levels
(Piezometer locations are indicated on Figure 3.4)

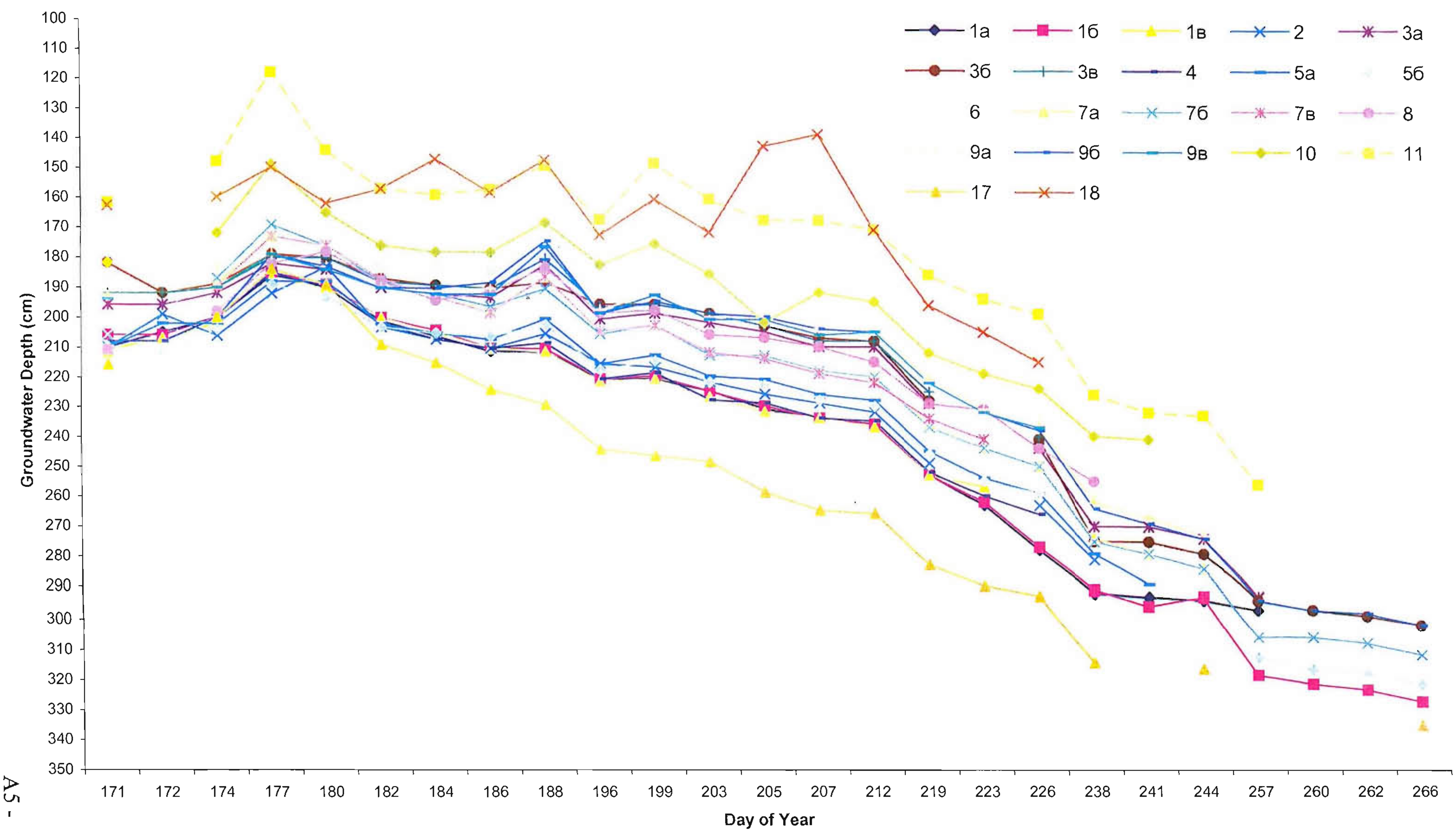
Groundwater Measurements in Neighbouring Fields from ICARDA study (Vyishpolskiy, 2000)

DOY	cluster of piezometers №1			piez №2	cluster of piezometers №3			piez №4	cluster of piezometers№5		piez №6	cluster of piezometers№7			piez №8	cluster of piezometers№9			piez№ 10	piez№ 11	piez №17	piez №18
	a	b	c		a	b	c		a	b		a	b	c		a	b	c				
171	210	206	211	210	196	182	192	208	210	210	188	212	206	211	211	193	194	194	182	162	216	163
172	205	206	207	199	196	192	192	208	202	212												
174	200	200	202	206	192	189	190	200	202	204	183	189	187	190	198	200	200	190	172	148	200	160
177	186	185	187	192	182	179	180	185	188	189	172	173	169	173	182	179	179	179	149	118	184	150
180	189	189	190	183	184	180	180	190	188	193	177	176	176	176	178	183	183	184	165	144	189	162
182	201	200	200	203	190	187	188	202	202	203	183	188	188	187	188	190	190	190	176	157	209	157
184	206	204	205	207	192	189	189	207	205	205	183	193	192	193	194	191	190	192	178	159	215	147
186	211	210	210	210	193	190	190	210	207	206	184	197	196	198	191	190	188	192	178	157	224	158
188	211	210	211	205	182	188	180	208	200	202	171	186	190	186	183	174	174	176	168	149	229	147
196	220	220	221	215	200	195	196	220	215	217	191	205	205	204	198	197	198	198	182	167	244	172
199	220	219	220	216	198	195	195	218	212	214	188	202	202	202	197	191	194	192	175	148	246	160
203	224	224	226	221	201	198	198	227	219	221	194	211	212	211	205	199	198	200	185	160	248	171
205	230	229	231	225	204	202	202	228	220	222	194	212	212	213	206	199	199	200	201	167	258	142
207	233	233	233	228	209	206	207	233	225	227	199	217	217	218	209	203	203	205	191	167	264	138
212	236	235	236	231	209	207	207	234	227	229	199	219	219	221	214	203	204	204	194	170	265	170
219	252	252	252	248	228	227	224	251	244	245	219	235	236	233	228	220	221	221	211	185	282	195
223	262	261	256					259	253	254	227	243	243	240	230	230	231	231	218	193	289	204
226	277	276		262	243	240	239	265	258	258	233	249	249		243	236	237	236	223	198	292	214
238	291	290		280	269	274			278		258	273	274		254	261	263		239	225	314	
241	292	295			269	274			288			278	278			266	268		240	231		
244	293	292			273	278						283	283			272	273			232	316	
257	296	318			292	293				312			305				293			255		
260		321				296				316			305				296					
262		323				298				317			307				297					
266		327				301				321			311				301				335	
GW Fall	86	121	45	70	96	119	47	57	78	111	70	71	105	29	43	79	107	42	58	93	119	51
No. Days	86	95	52	67	86	95	55	55	70	95	67	73	95	52	67	73	95	55	70	86	95	55
Rate of Fall (cm/d)	1.00	1.27	0.87	1.04	1.12	1.25	0.85	1.04	1.11	1.17	1.04	0.97	1.11	0.56	0.64	1.08	1.13	0.76	0.83	1.08	1.25	0.93

Average Rate of fall 1.01 cm/d Min. Rate of Fall 0.56 cm/d - above average 0.45 cm/d

Max. Rate of Fall 1.27 cm/d + above average 0.27 cm/d n 22

Depth of piezometers a - 3m; b - 4m; c - 2.5m



Groundwater Depth Recorded in Study Fields by ICARDA Study (Vyishpolskiy, 2000). Numbers of piezometers refer to preceeding table

A5. Calculation of Drainable Porosity (μ)

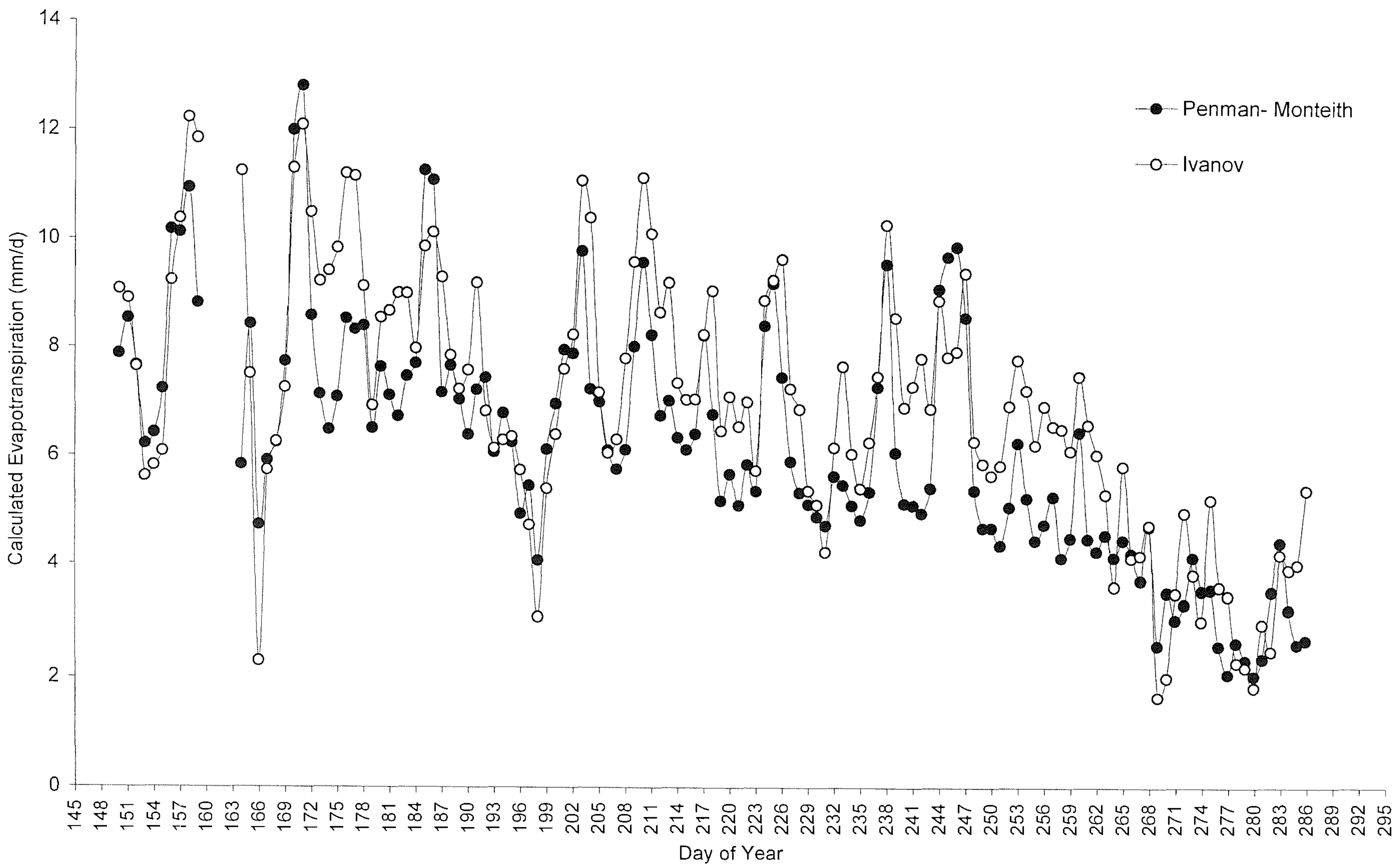
Drainable porosity was calculated from:

$$\frac{\text{Change in the amount of soil moisture storage}}{\text{Change in water table depth}}$$

To calculate drainable porosity (μ) the following calculation was used:

$mm_3/((d_2-d_1)*1000)$

It was anticipated that, based on the assumption that different soil 'layers' would drain to different moisture contents, the estimates of drainable porosity would be conservative.



Calculated Evapotranspiration Using Penman-Monteith and Ivanov (mm/d)

APPENDIX A6

AGRICULTURAL WATER MANAGEMENT IN THE ARTUR IRRIGATION SYSTEM

A6. AGRICULTURAL WATER MANAGEMENT ISSUES WITHIN THE ARTUR IRRIGATION SYSTEM

A6.1 Agricultural Experience

Many of the landholders within the ARTUR irrigation system are not farmers. Collective farms employed large numbers of people who dealt with every aspect of agricultural communal living. When the Soviet Union disbanded and Kazakhstan became a republic land was 'given' to the people living on collective farms, based on their length of employment and social standing (Suny, 1998). Consequently, large areas of land were given to senior officials who now let land to others, or who formed private agricultural companies, monopolising the existing collective farm machinery and local expertise.

Large amounts of land are also owned by the remainder of the collective farm staff, many of which have little or no agricultural or irrigation experience. This lack of experience has more than likely contributed to the gradual decline in crop productivity (O'Hara, 2000). Responsibility for maintenance of the irrigation system now lies with the farmers themselves, but the cost to maintain, and then provide security to protect their assets is too high. The irrigation authority is only responsible for the main ARTUR irrigation canal from the Bugun reservoir.

Some farmers had discussed setting up Water User's Associations but the costs and arrangements required were considered, at the time, too high and too difficult. Although the irrigation authority had left operation and maintenance of the system to the farmers themselves, lack of finances, legal status and social tensions has caused many farmers to seek additional income elsewhere.

The costly exercise of repairing and maintaining the existing irrigation infrastructure in the fields needs to be complemented with a more equitable and flexible irrigation supply system from the main ARTUR canal.

One of the most surprising factors was the farmer's inability to harvest the cotton crop when it was ready. Lack of available workforce and agricultural machines resulted in many low yields as the cotton was blown off the plants by the wind. Some farmers also used loans to buy seed and fertiliser. Under certain loan agreements a proportion of the cotton yield was to be returned to the lender. During harvest many fields were visited by moneylenders eager to find farmers who owed them both money and cotton. The majority of the moneylenders worked at the only cotton-processing factory in the region in Turkestan.

A6.2 Proposed Water Management Options for the ARTUR Irrigation System

Observations of groundwater levels indicate that it regionally fluctuates in response to the start and end of the irrigation season, returning to very similar levels each year. This suggests that water used throughout the summer months is balanced by groundwater rise during the winter at present.

The shallow gravel and light sandstone aquifer below the ARTUR system fills with water at the beginning of the irrigation season. This combined with the general slope of the land towards the Syr Darya river from the Karatau mountain range ensures that groundwater is always of high quality for irrigation purposes. Weekly recorded groundwater electrical conductivity was always less than 0.80 dS/m. Irrigation water had an average seasonal electrical conductivity of 0.50 dS/m (INCO-COPERNICUS, 2002). Water quality was therefore not a concern within the ARTUR system as drainage water flowed out of the system towards the Syr Darya River. However, before reaching the river the water entered the Chushkakulskaya depression. It would appear from local knowledge and satellite images that the majority of the drainage water enters the depression. Consequently, little water returns to the Syr Darya River.

The poor state of the drainage network within the ARTUR system more than likely encourages the existence of shallow groundwater and therefore contributes to the constant rates of upward flux. Based on this study, without shallow groundwater the cotton would have died much earlier in the season and yields would have been low.

Vyishpolskiy (2000) considered the recent reductions in productivity of the ARTUR system to be attributed to a five year dry period, with lower than average precipitation in the spring and less snowfall on the Karatau mountain range over the winters. There is no doubt that the ARTUR system experienced severe water shortages during summer 2000, and the Bugun reservoir had to be closed early in the irrigation season. However, a number of other factors may have also contributed to the recent loss in productivity. These are discussed below:

- Although pumped groundwater has historically been used as an additional water resource (Raskin *et al.*, 1992), especially during dry years, these systems are no longer in operation due to theft, damage and disrepair. Restoration of the vertical drainage systems would provide a valuable and needed addition to the current irrigation supply but the following two factors would need to be considered:

    1. The current high watertables are due in part to seepage from irrigation channels. Pumping from the groundwater into the irrigation system will not initially improve

equitable water distribution, as the Brigadiers of the system would remain responsible for water allocations. Illegal offtakes and night-time irrigation may also increase. While night-time irrigation reduces surface evaporation it is more difficult to control and effectively apply, thereby further reducing already low water application efficiencies.

2. On average shallow groundwater provides the cotton crop with approximately 40 to 50% of current seasonal water requirements. If the groundwater is lowered this may cause many farmers to abandon their land if they can not gain access to other water sources.

A6.3 Field Irrigation Strategies

Appropriate cultivation practices may assist in the reduction of capillary rise and ultimately soil salinisation where the groundwater is saline and close to the soil surface. Cultivation, such as deep sub-soiling must also be performed prior to the winter to take advantage of the free-thaw effect and the break up of compacted soil layers deeper in the profile. Shallow cultivation should also take place prior and post all irrigation applications (where machinery, labour and fuel are available).

A thorough pre-irrigation saturating the profile will allow good germination and root development, including the downward flux of any salts. Provided roots can get through the dense layers of soil at 30 to 50 cm deep and groundwater can be maintained at high levels the need for irrigation later in the season can be removed.

During dry years where water is scarce there may be a case to temporarily close certain drains using earth embankments or locally constructed gates. This would cause a local rise in groundwater levels as a temporary water source for sub-irrigation. This would add flexibility to irrigation schedules and reduces the need for further surface water applications.

Following pre-irrigation further water applications should be applied in a way that ensures adequate infiltration. This will require changes to current irrigation practices such as shortening of furrow lengths, re-levelling of some fields, and the matching of discharge to furrow size. This could include the use of 'shokh-aryk' furrows which run parallel to existing field furrows and are designed to convey water throughout fields with long furrows to reduce run-off and distribute water more evenly. These 'shokh-aryk' furrows are used in the Fergana Valley irrigation systems (see Horst *et al.*, 2005).

To assess the affect of adequate pre-irrigation and upward flux a number of scenarios were modelled using CROPWAT with actual field climatic data. Results of the scenarios are shown in Table A6.1 and in Figures A6.1 to A6.5.

Scenario One assumed a constant average rate of 1.80 mm/day upward flux, totalling 259 mm over the season. Four irrigations of 60 mm were applied on days 157 (13 DAP), 171, 185, and 198. Three different initial soil moisture conditions were used to represent different levels of pre-irrigation. Soil moisture deficit was initially 10% of the Total Available Water, followed by 60 and 80%. This represented good, moderate and poor pre-irrigation situations. Scenario Two was identical but assumed an average upward flux rate of 2.20 mm/day.

Table A6.1 Irrigation Scenario Results Using CROPWAT

Average Daily Upward Flux	Initial SMD	Total ETc	Total Irrigation	Lost Irrigation	Yield Reduction	Upward Flux*
mm/day	%	mm	mm	mm	%	mm (%)
1. 1.80	10	804	240	11	11	259 (32)
	60	786	240	0	13	259 (33)
	80	774	240	0	14	259 (33)
2. 2.20	10	837	240	22	8	317 (38)
	60	829	240	0	9	317 (38)
	80	818	240	0	10	317 (39)

Notes: * % represents the percentage of groundwater contribution to total evapotranspiration. Irrigation was assumed to be 30% efficient. In this example yield reduction does not include the error of approximately 4% due to an error in CROPWAT.

It is clear that, even when initial soil moisture deficit is high at 80% the reduction in yield is low and little irrigation is 'lost'. Even though crop evapotranspiration is high the amount applied as irrigation was kept low at 240 mm in four separate applications, based on the ideal scenario preferred by the farmers themselves. A water application of 60 mm is quick and easy to apply when compared to larger more infrequent irrigations. The addition of the groundwater makes the irrigation schedule much more realistic, given the water shortages experienced in the system.